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Isotope techniques in water resource investigations in arid and semi-arid regions

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FOREWORD

The scarcity of water resources is becoming one of the major impediments to social and economic development and is most acute in arid and semi-arid regions, which cover almost one third of the Earth's land surface. Rapidly growing population as well as unfavourable climatic events and recurrent droughts emphasize the ever growing need for effective, well-managed and sustainable use of water resources for human, agricultural and industrial purposes.

The main sources of reliable fresh water supplies in arid regions are invariably the groundwater resources which are being extensively exploited all over the world. Groundwater reserves suffer either from pumping rates that often exceed the natural recharge rate, or from human or naturally induced salinisation and pollution. Furthermore, when the rate of groundwater withdrawal exceeds the natural recharge rate of aquifers, especially in arid and semi-arid areas, groundwater exploitation must be considered as mining. Such over-exploitation must be avoided through better management and use of water resources.

Moreover, this valuable groundwater resource is unfortunately under continuous threat due to growing anthropogenic impacts, mostly in the form of (1) increasing pumping directly from these highly sensitive water reserves, (2) sewage effluents and, (3) industrial and agricultural-induced pollutant being discharged directly into aquifer systems as return flows *via* river, irrigation channels or tailings ponds.

Where availability of the renewable fresh water resources falls below 1000 m^3 per capita per year, chronic scarcity is observed, and the lack of adequate water is one of the main constraints on economic development and on human health and well being.

Therefore, adequate knowledge of the hydrogeology and hydrology as well as the quantification of residence time, recharge and precipitation/evaporation rates in such systems is becoming a key issue in assessment and management of groundwater resources in many parts of the world.

In arid and semi-arid regions, isotope techniques provide one of the best approaches that can be used to estimate recharge rate and thus provide critical information for the management and prevention of over-exploitation of groundwater resources. Furthermore, they can be used to better understand their vulnerability to pollution that may help to design adequate prevention and remediation strategies.

The contents of this technical document provide a cross-section of different applications of isotope techniques to water resource issues in arid zones and should serve as a useful guidance to scientists and practitioners on methodologies that are applicable in arid and semi-arid zone hydrology.

The IAEA officers responsible for this publication were C. Gaye and J. Turner of the Division of Physical and Chemical Sciences.

EDITORIAL NOTE

CONTENTS

SUMMARY

The Co-ordinated Research Project (CRP) on the Use of Isotope Techniques in Water Resources Investigations in Arid and Semi-arid Regions was initiated with the aim of contributing to the assessment of groundwater resources in arid areas through the use of environmental isotope techniques, and thereby to help in better management of these valuable fresh groundwater resources. The main emphases identified were in three key areas: (i) the evaluation of water balance components such as recharge rate estimation and recharge and discharge cycles at different spatial scales, (ii) palaeohydrology and hydroclimatic change and (iii) anthropogenic impacts and the assessment of the vulnerability of arid zone groundwaters to salinisation and pollution impacts.

- *Water balance and recharge-discharge of groundwater.* Recharge of groundwater is a critical factor in resource management, and isotopes can help determine both the area and rate of recharge. Measuring ^{18}O and ^{2}H contents and correlating them to the altitude at which precipitation could have infiltrated can identify the area where recharge occurs. The rate can be measured by tracing levels of ^{3}H for example, in the soil profile at various depths. The position of the tritium "peak" with depth indicates the distance traveled by the infiltrating water since it was released as tritium fallout in the 1950's and 1960's. Carbon-14 and ^{36}Cl are also valuable isotopic tracers in groundwater recharge and discharge assessments.

- *Palaeohydrology and hydroclimatic change.* The water resources inventory of arid zones is known to be highly sensitive to climate fluctuations. Palaeohydrological studies in these regions therefore help to distinguish between groundwater that is being actively recharged in the present day from that which is entirely inherited from previous climatic periods, thus indicating whether the resource is being over-exploited or mined. Methodologies that can be used include: ^{3}H, ^{14}C for residence time estimation over time scales ranging from the present-day to 10^5 years; U/Th series; ^{37}Cl and the stable isotopes $^{18}O/^{16}O$, $^{2}H/^{1}H$ that are used to determine the deuterium excess parameter variations which reflect the palaeoclimatic signature.

- *Anthropogenic impacts.* The anthropogenic impacts on water resources comprise agricultural, industrial and urban impacts on water quality, as well as groundwater over-exploitation. The methodologies used include those listed above, but in addition ^{15}N and ^{34}S.

In response to these key points, the major themes covered during the implementation of the CRP, as well as the results of scientific and technical investigations are summarised in the following section.

RESULTS

- *Water balance and recharge-discharge of groundwater*

D. Djoret and Y. Travi investigated (i) groundwater replenishment and the mechanism of recharge related to aquifer vulnerability in the Sahel zone of Chad in the Chari-Baguirmi Plain, and (ii) the relationship between these results and environmental changes in the southeastern Chad Basin.

Three recharge mechanisms are involved: (i) direct recharge which is largely influenced by rainfall amount and evaporation characteristics (quantity, distribution, intensity), and by the depth of the piezometric level; (ii) local recharge of surface runoff, ponds, or via the Chari River; and (iii) recharge via Lake Chad.

W.M. Edmunds presents an overview paper on issues related to groundwater recharge in the Sahara and Sahel arid regions. Some examples of field studies from different African countries such as Senegal, Niger, Nigeria, and Sudan as well as from Cyprus were given.

As is now well known, groundwater that is being exploited at present in these arid and semi-arid regions was mainly recharged during former humid episodes, in contrast to modern recharge which is generally either non-existent or too small and variable in comparison to the rate of abstraction. In such cases, it has been demonstrated that hydrogeochemical (especially Cl mass balance) and isotopic techniques can provide the most effective way to estimate modern recharge and to investigate recharge history, since physically based water balance methods are generally inapplicable in semi-arid regions.

In all these countries, the direct recharge rates may vary from zero to around 40% of mean rainfall, depending on soil depth and lithology. The spatial variability of recharge over a range of scales presents a significant difficulty in any recharge investigation based on point estimates obtained from vertical, one-dimensional unsaturated zone profiles. In some cases, the multidisciplinary study of groundwater may permit the extrapolation of the available reliable point estimates of recharge to an entire region, because at a regional scale, groundwater integrates the spatially variable processes that occur in the unsaturated zone. Unsaturated-zone studies show that there are limiting conditions to direct recharge through soil, but that present-day replenishment of aquifers can take place *via* wadis and channels.

B Th Verhagen presents a summary of four case studies involving the use of the environmental isotopes ^{14}C and ^{3}H to understand the recharge process in the arid to semi-arid Kalahari region of Southern Africa. Diffuse, local recharge was found to be the dominant recharge mechanism while recharge via river beds was found to be of limited importance at the regional scale. Quantitative estimates of recharge rates as low as 1-2 mm/yr are derived from ^{14}C measurements on groundwater

K-P. Seiler used stable isotopes to investigate the importance of bypass flow in the unsaturated zone, which leads to unproductive water loss during flood irrigation. Field results from experiments carried out in Jordan and Pakistan showed that there is not only an advective component of flow (bypass flow) but also a diffusive tracer exchange between piston and bypass flow. Infiltration calculations and analysis of tracer distributions show that bypass flow amounts to about 25% of water recharged during winter. This estimate is important as it provides an assessment of the amount of water that passes the root zone and directly recharges groundwater.

- *Palaeohydrology and hydroclimatic change.*

A.R. Nair and co-authors performed an environmental isotope study of a palaeochannnel aquifer located in Jaisalmer that is disconnected from its supposed basin head in the Himalayan ranges. The present study indicated that in the Southern Rajasthan region, shallow aquifers receive recent recharge through direct infiltration/floods during episodic rainfall events. In contrast, and although deep fresh groundwater is available in many parts of the desert, the absence of ^{3}H and very low ^{14}C activities determined on samples from Northern

Rajasthan indicate no or very minor modern replenishment. This groundwater reserve has to be considered as a mined resource. Proper management of such a scarce groundwater resource is thus urgently required since over-exploitation is presently observed in many areas of Rajasthan.

V.I. Ferronsky and co-authors studied the problem of replenishment phases of aquifers and lakes in the Central Asian and Caspian arid regions during the Late Pleistocene-Holocene transition time, via the isotopic composition of groundwaters and lacustrine sediments. During the climatic cooling which occurred over the Eurasian continent at the end of the glacial period, the humid zone was extended towards arid regions. Intensive melting of the glaciers during this transition time provided effective replenishment of the aquifers and lakes. This statement is valid not only for glacial-interglacial epochs but also for current climates. Prediction of short, periodic climate change based on interpretation of isotope and chemistry records in lake sediments and fossil groundwaters are thus an important goal of arid zone hydrology.

O. Saighi, described work on the isotopic composition of precipitation in the Ahaggar Massif (Central Sahara, Algeria).

The first problem tackled during this study was the sampling of scattered, heterogeneous precipitation occurring in the Ahaggar Massif, and the determination of its stable isotope composition such that it could be used as an input composition for analysis of the recharge process to groundwater. It has been demonstrated that air masses generating the precipitation have a double or even multiple origin throughout the year:

(i) the Guinean monsoon in summer, and (ii) the Atlantic and/or Mediterranean regions via northerly or westerly-derived winds from Morocco in winter. Furthermore, the deuterium excess demonstrated the participation of continental recycled moisture in rainfall.

In the Ahaggar Massif, fresh groundwater resources mainly come from minor phreatic aquifers, recharged by sporadic wadi floods. Two major aquifers can be considered: (i) the alluvial aquifer characterized by low mineralised water with isotopic contents corresponding to that of modern precipitation, and (ii) the underlying aquifer in the weathered zone and marked by isotopically depleted, mineralised waters. The absence of ^{3}H and low ^{14}C shows that this latter aquifer is not replenished at present and that the main part of groundwater was recharged during the last Holocene humid episode.

- *Anthropogenic impacts.*

M.F. Hussein and co-authors presented isotopic and chemical data obtained on three unsaturated zone profiles augured in fallow lands in the Nile Delta.

The rate of water loss from soils by evaporation is regulated by atmospheric conditions, soil texture and structure as well as the depth to the water-table. Although evaporation is currently cited as one of the main mechanisms of causing soil salinisation in arid and semi-arid zones, the contribution of the capillary rise in the regional water budget is poorly known, and the evaporation component in the soil water budget is usually integrated in the evapotranspiration term due to technical difficulties in the separation of the two components.

One of the main results of this study was that using environmental isotopes it could be shown that almost one billion cubic meters of water is lost each year from fallow soils in the

Nile Delta. Since three times this amount (through capillary rise) has been determined as the supply to the crops during the growing season, a modified water strategy will allow water use/management at a regional scale to be optimised by taking into account this loss by upward water flow.

CONCLUSIONS

The case studies presented in this CRP demonstrate that there is still significant scope as well as a strong need for the application of isotope techniques in groundwater resources investigations in arid zones, mainly applied to:

- the assessment of recharge and discharge rates;
- the distinction between the scarce, modern-recharged groundwater compared to that replenished during former climatic phases;
- the assessment of efficiency of water harvesting through artificial schemes;
- anthropogenic impacts (agriculture, industries and urban activities).

The significant volume of results that were gathered within this CRP and presented during successive meetings, as well as the personal scientific communications related to this subject confirm the great scientific and socio-economic interest in using isotope techniques to investigate groundwater resources in arid and semi-arid areas.

In such studies, the main difficulty remains how to obtain accurate and reliable data on the input function of the groundwater budget. The input function in the water balance corresponds to the recharge rate, which can be tackled through the direct quantification of the precipitation/evaporation ratio, or through the study of infiltration rate in the unsaturated zone.

RECOMMENDATIONS FOR FUTURE INVESTIGATIONS

The specific case studies implemented during the CRP generated important progress and conclusions on the qualitative and quantitative estimation of recharge rates, whereas recommendations given below are made concerning the comprehensive study of the unsaturated zone on one or more selected key sites:

The definition of the recharge area and input function, on which the original isotopic signature of groundwater depends (A.N. Nair and co-authors, India; D. Djoret and Y. Travi, France);

The quantification of (i) the input function, specifically in non-accessible areas such as the hyper-arid region of Central Sahara (O. Saighi and co-authors, Algeria), and (ii) water losses linked to agricultural practices (M.F. Hussein, Egypt) ;

The quantification of recharge rates and groundwater residence times in areas liable to contain fossil groundwater and therefore be subject to mining (O. Saighi and co-authors, Algeria; A.R. Nair and co-authors, India).

Certain specific recommendations for (i) future work in arid zone hydrology, (ii) new development of isotopic tools, and (iii) practical application on the study of the unsaturated zone were given, as follows :

1) Any attempt to obtain ^3H-profiles integrating the remaining bomb ^3H peak, should be:

- taken in areas for which substantial additional information, including isotopic data, on the saturated zone either should be available or at least obtainable. This would enable conclusions regarding water and solute transport to be constrained by the hydrological and hydrochemical situation of the underlying groundwater body ;

- screened by performing test borings which are first analysed for chloride, for instance, to reasonably ensure the existence of the useful ^3H peak.

2) A holistic approach should be made for study of unsaturated zone profiles. They should therefore be conducted at experimental sites, where e.g. a meteorological station has been in operation for some time (providing mid- or long-term records of hydroclimatic parameters). Such studies should aim at a better integration of all the data available.

3) In relation to the need for the use of "inert" chemical tracers, it was noted that nitrate and sulphate, as well as their isotopes could play a role in the future. Here too, the concept of "experimental" sites was regarded as important, with the linking of isotope methods into sensitive areas of the ecosystem.

4) A major problem foreseen in the unsaturated zone studies is the fact that the results, by their very nature, will be localised. Making regional conclusions requires careful extrapolation of such data. This is a problem facing not only isotope data, but all other techniques as well.

5) In order to add significant value to the technical content of these results, future investigations should give consideration to the broader scale water resource management issues and in particular how local managers should use the results in management decision making. Managers need quantitative data on which to base management decisions, and every attempt should be made to provide such data in a form that can be applied to appropriate decision making.

At the same time, and as a response to, these questions and recommendations, a Co-ordinated Research Programme was launched by the Agency on " Isotope based assessment of groundwater renewal and related anthropogenic effects in water scarce regions". This CRP will bring an understanding on mechanisms of infiltration and diffusive evaporative discharge (through the unsaturated zone) for selected aquifers.

In conclusion, it should also be emphasised that the present status of hydrological systems such as their geometry, hydrodynamics, chemistry and isotope geochemistry, is of a transient nature, reflecting past hydrological conditions, in response to or as a result of natural climatic, tectonic and anthropogenic forcing. To forecast the future evolution of groundwater resources and therefore to efficiently assess and manage them, it is indispensable to gain a better understanding of the current behaviour of such systems as well as to have a sound knowledge of past hydrological and environmental conditions.

ISOTOPIC CHARACTERISTICS OF METEORIC WATER AND GROUNDWATER IN AHAGGAR MASSIF (CENTRAL SAHARA)

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Abstract

The mean contents of both oxygen-18 and deuterium in precipitation from the Ahaggar massif (central Sahara) are : $\delta^{18}O$ *= -3 ‰ and* ^{2}H *= -15 ‰. The heterogeneity in meteoric events and the great scattering of these isotopic contents can be ascribed to the origins and the histories of air masses. The main contribution comes from the inflow of the Guinean monsoon during summer months. During winter, the N/W winds, arriving in the area from the Maroccan coast, provide some rains. The deuterium excess of these precipitation are up to +10 ‰, indicating that the air masses generating these rains are supplied by the recycling of the continental air moisture.*

Groundwater resources are produced in some little phreatic aquifers, which are recharged by sporadic wadi floods. Aquifer zones that are the most favourable are located in the valleys and occur as three overlying levels of unequal importance : the alluvial aquifer, the weathered zone of the underlying substratum and the deep aquifer of fissured basement. The alluvial aquifer contain weakly mineralised water (0.3 g/l). Their stable isotopes contents ($\delta^{18}O \approx -2.7$ *‰) and* ^{14}C *activity of them (>100 pmc) are comparable to present meteoric water, allowing modern meteoric waters to be identified. The weathered zone groundwater's are more mineralised (0.8 g/l) and its isotopic contents (*$\delta^{18}O \approx -4.2$ *‰) and intermediate radiocarbon activity, prove their old water component. The basement's groundwater are more mineralised (> 1 g/l) and their very depleted isotopic contents (*$\delta^{18}O \approx -9$ *‰) diverge clearly from the present precipitation. Furthermore, the absence of* ^{3}H *and* ^{14}C *activity of them, prove an old heritage, resulting from recharge during the last humid episode of the Holocene.*

1. INTRODUCTION

In Ahaggar area, data on the isotopic of precipitations and groundwater are non existent or extremely limited. Thus, the aim of this study is on one hand, the isotopic characterization of the meteoric waters and on the other, the determination of the main factors controlling the variations of heavy isotopes in rains, and the origin of the air mass generating these precipitations.

The second part of this study concerns the use of chemical and isotopic techniques for evaluation of recharge in crystalline and igneous aquifers, under arid zone.

2. GEOGRAPHICAL POSITION OF THE STUDIED AREA

The massif of *Ahaggar* is situated just in the middle of the Sahara desert (fig. 1), which is known for its extreme aridity and important thermal disparities [1]. However thanks to its high elevation (2918 meters at the *Tahat* mountain), it benefits from relatively soft and humid climate conditions lower than the surrounding of the Sahara bad lands.

The *Asserkrem's* meteorological station (23°.3 N ; 5°.6 E and 2726 meters of altitude) is located in central part of the high massif. At this station, 78 samples of rain have been gathered during the period :1992 - 1996. On the south side of the *Assekrem,* at 1376 meters of altitude, is located the meteorological station of *Tamanghest* (fig. 2) where 23 samples of rain have been collected during the same period.

3. GENERAL CLIMATIC BEHAVIOUR

The available meteorological data of 70 years observation at Tamanghest, and 41 years at Assekrem [2], comprise the amount of monthly precipitation, mean monthly surface air temperature and relative humidity.

The pluviometic regim of this region is essentially controlled by the extreme Northward displacement of Intertropical Convergence Zone (ITCZ) and the available pluviometric data show that the precipitations happen generally in summer. Thus, about 70 % of the total meteorological events take place between May and September (fig. 3). Nevertheless, sporadic rains happen in winter and spring.

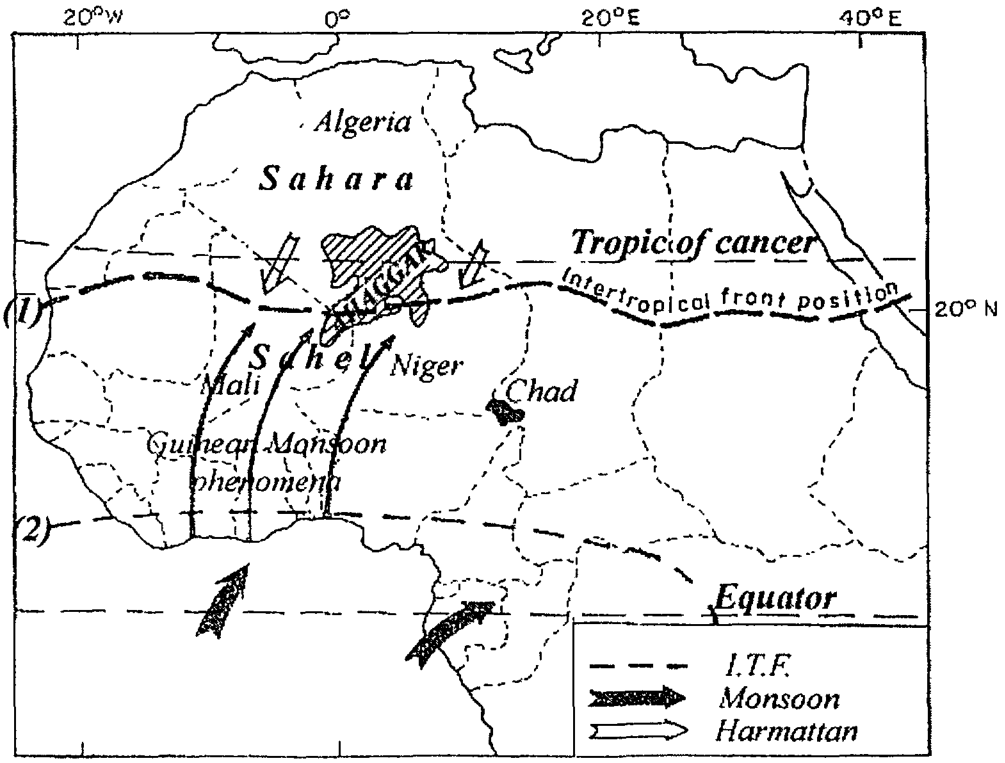

FIG. 1. Location map of Ahagga with Intertropical front position (ITCZ): (1) in July; (2) in January (after Dorize, 1976, modified).

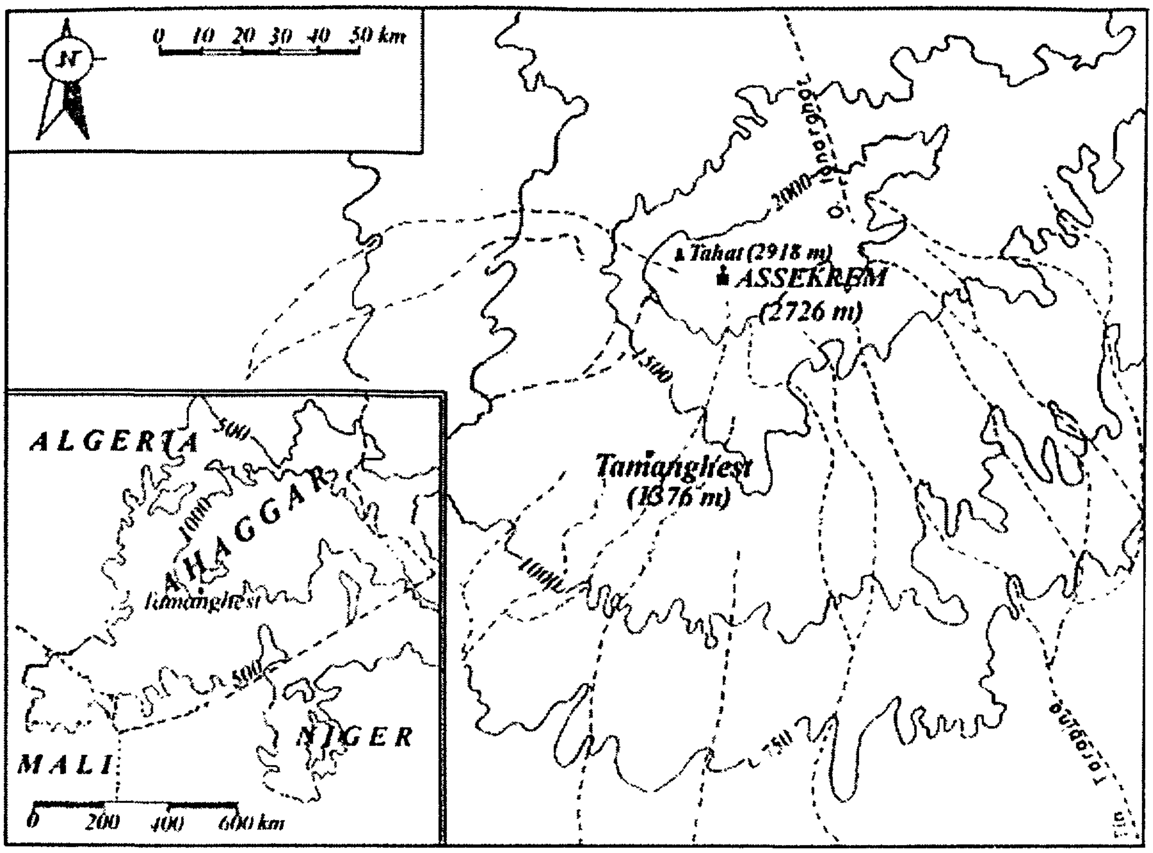

FIG. 2. Location map of two main meteorological stations of Ahaggar.

The annual rainfall is about 118 mm at the *Assekrem* station, and 45 mm at Tamanghest [3]. These precipitation present a great inter-annual irregularity: it is effectively possible to have many successive years of dryness, as 1969 to 1974. The studied period (1992 - 1996) seems to be more humid than the previous one (262 mm in 1993).

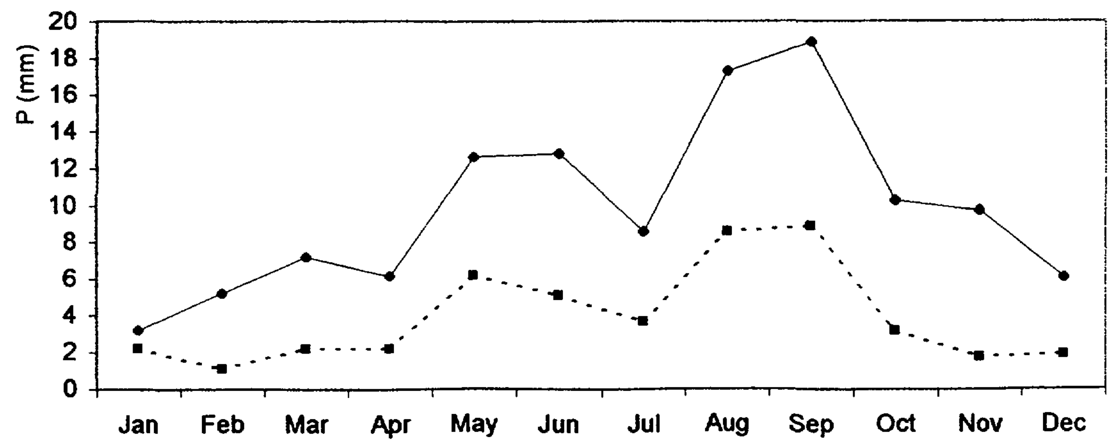

FIG. 3. Monthly precipitation distribution
(----) Assekrem (period: 1955-1997)
(- - -) Tamanrasset (period: 1925–1997)

The mean annual temperature is 13.5 °C at Assekrem. The warmest months are June and July (≈20°C), whereas the coldest ones are December and January (≈ 6.5 °C). At Tamanghest, temperature values are generally 10 °C higher than those in Assekrem.

The relative humidity process evolutes inversely to that of temperature. The values are high in cold season (about 40 % at Assekrem and 30% at Tamanrasset) and lower in hot season (28% and 16% respectively) which, paradoxically, corresponds to the monsoon wet air incursions [4]. Consequently, the temperature impact on the hygrometry is determinant.

4. STABLE ISOTOPES CONTENTS OF PRECIPITATIONS

The isotopic composition of the precipitation reaching the soil, depends on geographic and climatic parameters such as continental effect [5], the altitude effect [5, 6, 7] and the amount effect [5, 8].

Furthermore, the thermal and hygrometry effects are determinant, in arid zones : the superheated lower layers of the atmosphere, generally very unsaturated, provoke a total or partial re-evaporation of the rain droplets during their fall, involving an enrichment of the remained liquid, with heavy isotopes [9].

4.1 The oxygen-18 contents for rainfall events at Assekrem

At the Assekrem station, we have collected 91 samples, during 1992 –1997 period, corresponds to all rainfall events. The ^{18}O and ^{2}H measurements were carried out at the *Laboratoire d'Hydrologie et de Géochimie Isotopique* (University of Paris-Sud), and at *Centre de Developpement des Tecchniques Nucléaires* (Algiers).

The results obtained (Table 2 and 3) show a varying range of values from $\delta^{18}O$ = -11.8 ‰ to + 4 ‰ vs *SMOW*. The arithmetic mean content is $\delta^{18}O$ = -3 ‰, with a standard deviation of 3.4 ‰.

Table. 1. Oxygen 18 mean contents (in ‰) of precipitations from Assekrem

	Mini.	Maxi.	Mean	Stand. Devi
Oxygen-18	-11.8	4	-2.81	3.4
Deuterium	-72	23	-14.6	20
Deut. Excess	-7.7	27	9.7	8.3

The frequency histogram of contents (fig. 4) allows to distinguish two groups:

- the main group is centred at the value $\delta^{18}O$ = -1 ‰. It represents precipitations of summer, in relation with that of the *Guinean monsoon inflow* above the Sahel region,
- the second group, $\delta^{18}O$ = -6 ‰, corresponds to the cold season rains which are in relation with other origin sources.

Table 2. Isotopic Composition of rainfall events from Assekrem station

Date	*Oxygen18*	*Deuterium*	*Tritium (UT)*	*P (mm)*	*T (°C)*	*RH (%)*
23-24/5/92	-0,99	3,0		6,5	15	
7-16/7/92	3,40	20,0		1,9	22	
5-25/8/92	2,20	2,4		4,3	22	
28/08/92	-1,80	-7,0		3,5	18	
31/08/92	-3,30	-16,8	13,9 +/-2	4,6	19	
22/08/93	-1,70	2,6		3,3	17	
22/08/93	-2,16	-3,5	8,2 +/-1,3	16,5	15	
23/08/93	-1,00			5,4	16	
24/08/93	-1,20	1,2	16,4 +/-2,5	9,9	16	
30/08/93	-7,17	-43,0	12,2 +/-1,8	48,0		
30/08/93	-5,40	-33,0		48,0		
12/09/93	-4,40	-18,7		3,7	18	
27/10/93	2,28	5,1		7,0	8	
23/11/93	-0,20	-10,5				
23-24/11/93	-8,57	-49,9		10,5	4	
24/11/93		-14,3			8	
24-25/11/93	-7,70	-40,9	8,7 +/-0,4	80,0	6	
20/01/94	-1,65	2,4		4,5	5	
14-15/3/94	-0,80	14,1		2,8		
15/03/94	-0,44	11,0		3,5	7	
05/08/94	-4,50	-23,4		2,3		
23/08/94	0,40	3,2	5,1 +/-1	10,0		
25/08/94	1,90	14,1		1,0	13	85
25/08/94	-1,80	-7,8		10,0	22	96
25/08/94	-1,70	-11,2		6,0	14	80
25-26/8/94	0,40	2,3			12	98
27/08/94	-1,60	3,9		3,0	14	100
28/08/94	-1,00	3,1		4,0	18	42
29/08/94	-1,10	-4,6	11,8 +/-2	7,7	15	85
04/09/94	-1,90	-11,0	8,1 +/-2	11,5	14	95
14-15/9/94	1,40	5,0	10,9 +/-2	6,3	12	80
17/09/94	-4,40	-21,4	15,4 +/-2,4	8,7	17	55
18/09/94	-4,20	-26,0		5,3	15	80
19/09/94	-5,60	-23,0			14	70
19-20/9/94	-5,70	-34,6		8,0	10	100
12-13/10/94	-9,00	-68,0	8,6 +/-2,5	6,4	8	100
13/10/94	-9,40	-59,0	< 0,3	7,5	11	97
15-16/10/94	-10,80	-61,0	15,1 +/-2,8		5	100
15/10/94	-11,80	-71,3		42,0	5	100
15/03/95	-6,00	-35,0		4,1		
15/3/95	-7,40	-44,0		14,1		
15/03/95	-7,10	-40,0		14,1		
15-16/3/95	-6,10	-35,0		19,1		
16/03/95	-4,50	-20,0		3,3		
16/03/95	-6,40	-32,0		9,3		
16-17/3/95	-6,20	-32,0		22,3		
1-2/4/95	2,90	23,0		2,2		
14-15/4/95	-1,10	1,2		4,5	14	30
20/04/95	-6,10	-33,0				
20/04/95	-5,70	-29,0		2,3	13	60
20/04/95	-5,60	-27,0		2,3	15	65

Table 2. (suite)						
Date	*Oxygen18*	*Deuterium*	*Tritium (UT)*	*P (mm)*	*T (°C)*	*RH (%)*
22/04/95	-0,90	-27,0		6,3	8	97
30/05/95	-3,30	-16,0		2,0	12	70
09/06/95	2,50			0,8	16	
10/06/95	-3,40	4,0		2,5	11	84
21-22/6/95	-0,50	1,0		5,6	17	70
29/07/95	1,50	8,0		6,0	18	60
29/07/95	-0,10	7,0		4,0	18	92
26/08/95	-3,50	-18,0		2,6	18	58
29/08/95	4,00	16,0		0,8	20	58
30/08/95	-0,10	1,0		1,8	20	68
10/09/95	-3,20	-18,0		3,0	17	57
10/09/95	-0,10	-6,0		0,8	19	47
14/09/95	0,50	1,0		1,5	14	75
02/10/95	-1,30	-5,0		8,7	12	95
02/10/95	0,30	+7,0		3,4	10	93
03/10/95	-2,20	-6,0		3,5	12	90
04/10/95	-5,00	-22,0		6,0	11	95
05/10/95	-1,50	-10,0		4,2	10	92
06/10/95	-0,60	9,0		1,7	12	80
09/12/95	-5,90	-38,0		3,6	5	80
11-12/3/96	-7,30	-38,0		11,0		
12/03/96	-6,27			10,8		
12-13/3/96	-4,00	-9,0		30,0		
15/04/96	0,80	19,0		1,3	7	96
15-16/4/96	-2,40	2,0		5,0	7	70
16/04/96	-7,30	-32,0		8,8	3	96
24-25/4/96	-1,20	5,0		5,8	8	

Table 3. Isotopic composition of rainfall events from Tamanghest station.

date	*Oxygen18*	*Deuterium*	*Tritium*			
02/07/92	2,80	-2,5				
28/07/92	-1,40	-7,3				
29/07/92	-1,60	-4,0	4,7 +/-0,7			
29/08/92	0,60	3,0	4,9 +/-0,8			
24/08/93	4,95	22,7				
30/08/92	0,37	2,9				
25/08/94	4,90	22,0				
25/26/8/94	6,08	34,0				
29/08/94	3,30		13,9 +/-2,2			
13/10/94	-5,50	-35,0	14,8 +/-2,2			
14/10/94	-5,00	-38,0				
15/10/94	-5,50		23 +/-3,7			
16-17/10/94	-4,80	-18,0	7,1 +/-1,3			
17/10/94	-3,70	-14,0	6,7 +/-1,1			
16-17/3/95	-2,80	-13,0				
10/06/95	2,20	10,0				
21/06/95	3,20	12,0				
30/06/95	7,90	38,0				
12/03/96	-4,09	-8,3				

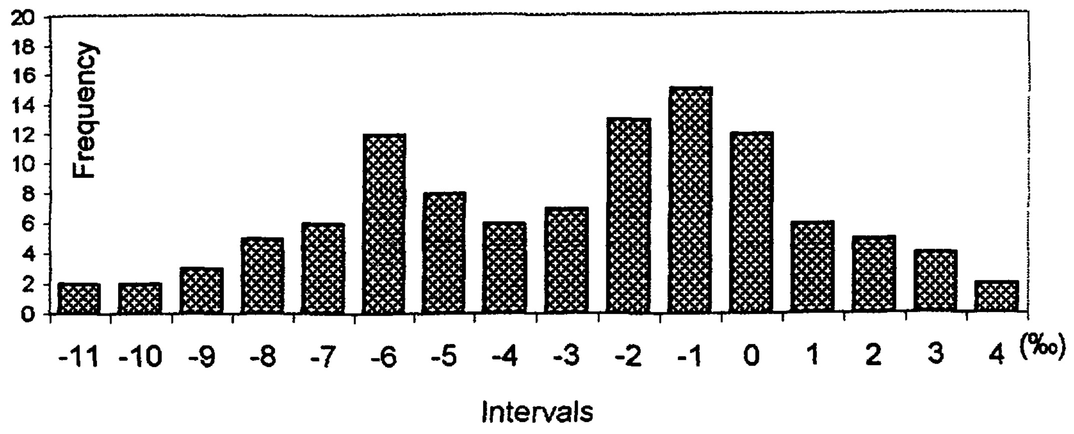

FIG. 4. Frequency distribuytion of oxygen-18 contents for rainfall events from Assekrem, period 1992–1996 (91 samples).

4.2 The deuterium

The deuterium contents vary between $\delta\, ^2H$ =–71 ‰ and + 30 ‰ vs *SMOW*. Even in this case the values also confirm a bimodal configuration : the most important group shows a mean value of $\delta\, ^2H \approx -0.5$ ‰ (of summer rains) whereas the other remaining precipitations have a mean value of $\delta\, ^2H \approx -25$ ‰ (of winter rains).

The deuterium excess defined as d= $\delta\, ^2H$ - $8\delta^{18}O$ varying between -18 to +28 ‰, and its arithmetic mean value is 9.5 ‰. The frequency distribution of deuterium excess shows a maximum at 12.5 ‰ (fig. 5).This finding is of great importance when interpreting the isotopic data in rain in terms of origin of air masses and indicating, as suggested in many studies, that theses precipitations are supply of recycled continental moisture of the atmosphere reservoir. The deuterium excess values of 2-10 ‰ have been observed for summer rains, whereas greater values (10-20 ‰) have been found for winter rains.

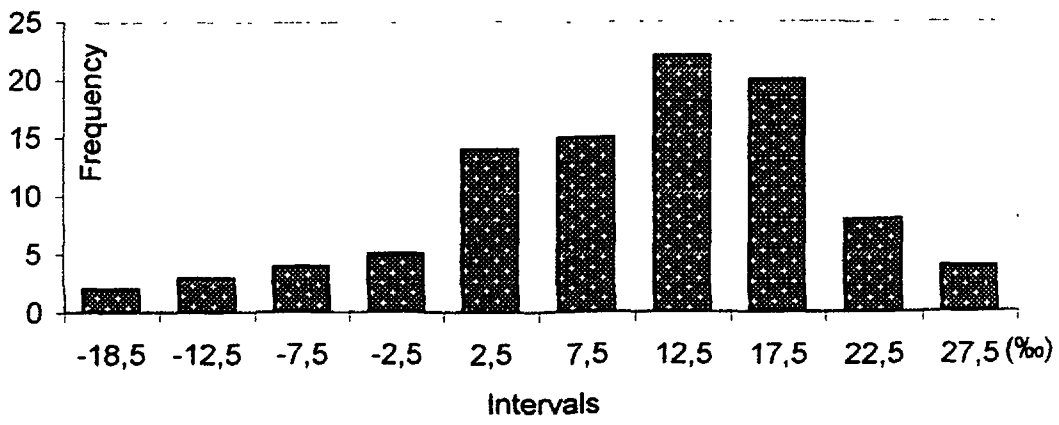

FIG. 5. Frequency distribution of deuterium excess in the precipitations from Assekrem.

4.3 The $\delta\ ^{2}H$ vs $\delta\ ^{18}O$ relationship

The fractionation process, for oxygen 18 and deuterium being the same during the condensation, in the graph $\delta\ ^{2}H$ vs $\delta\ ^{18}O$, the non-evaporated rains are along the *Global Meteoric Water Line (GMWL)* defined by the equation of which is $\delta\ ^{2}H = 8\ \delta\ ^{18}O + 10$ [7]. But the enrichment by the evaporation process is in ratios other than those indicated on the GMW*L* [10], the points which are under this line present an oxygen 18 excess, indicating an re-evaporation of rain droplets during the fall [9, 10, 11], while the points located above, represent an excess of deuterium superior to 10, which characterise the local vapour recycling [12, 13].

The $\delta^{2}H$ - $\delta^{18}O$ relationship for all samples from Assekrem (fig. 6) define a local meteoric water line according to the equation:

$\mathbf{\delta\ ^{2}H = 5.9 \star \delta\ ^{18}O + 3.2}$; with a regression coefficient R of 0.89.

The slope of the local meteoric water line, inferior to that of GMWL, indicates that a great part of the rainy events are isotopically modified by evaporation and that the rain out process occurred under non equilibrium conditions. The re-evaporation processes seems to be more important during summer, particularly with weaker rains [15, 16, 17]. Thus, summer rains fall generally under the GMWL, along an evaporating straight line of slope 5. Whereas cold season rains, more depleted, are distributed above the GMWL. Consequently, cold season rains are particularly generated by the recycled continental vapour.

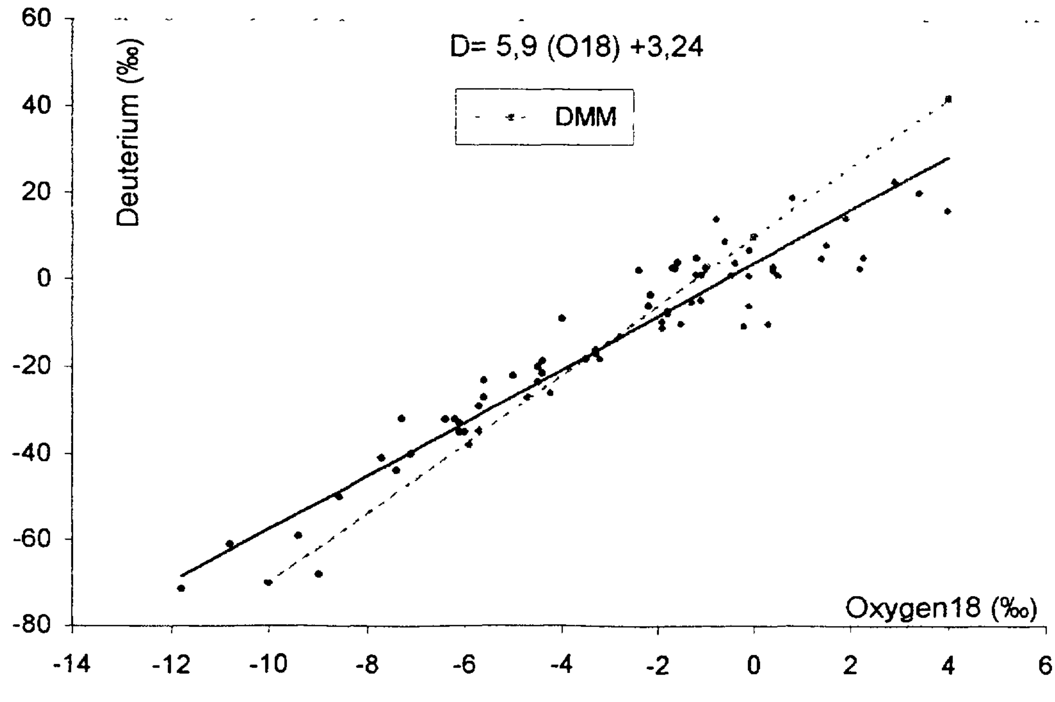

FIG. 6. Deuterium — oxygen-18 relationship of precipitations from Assekrem.

4.4 The altitude gradient

Some samples (23) taken from Tamanghest station which is lower, hotter and less rainy than the Assekrem, show that the rains in this case, are always more enriched with heavy isotopes, than in the high area of Assekrem. The minimum is $\delta^{18}O$= -5.5 ‰, the maximum is $\delta^{18}O$= +6 ‰ and the mean value is near 0.5 ‰.

The mean altitude gradient, calculated for few couples of samples collected at the same time at Assekrem (2726 m) and Tamanghest (1376 m) is equal to : 0.41 ‰ /100 m, for oxygen-18.

4.5 Climatic factors effects

The factors controlling the distribution of ^{18}O and ^{2}H contents in precipitations are principally the temperature and the relative humidity of the atmosphere and secondary the rain characteristics, such as the amount and the frequency of precipitations.

4.5.1 Thermal effect

At the Ahaggar, temperature seems to be the main factor controlling heavy isotopes ratios of rains, because of its action on the atmospheric relative humidity, that remains moderate in summer, despite the wet air inflow of the monsoon phenomena, during this season.

The $\delta^{18}O$=f (T) relationship obtained for all samples or for each year collection (fig.7) expresses an isotopic enrichment related to temperature increase. Thus, the season effect which is well noticed, in regard to the thermal considerations, shows that high isotopic contents correspond to the hottest months, and vice-versa.

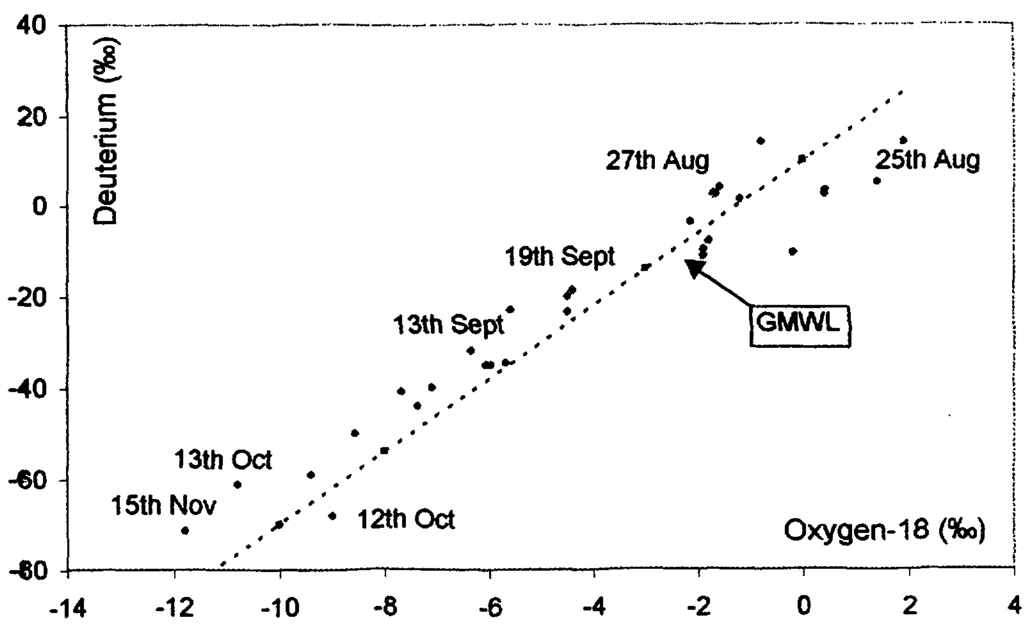

FIG. 7. Saisonal variation of isotopic contents of precipitations from Assekrem (year: 1994).

However, this behaviour is not in good agreement with the observed schema in the Sahel and the sub-tropical region [15, 16, 19]. From this schema [20], in August (optimum of the monsoon phenomena), the amount and the frequency of the precipitation are greater and that the heavy isotopic contents are more depleted than the rest of the year . At the Ahaggar this schema is not respected, because the isotopic contents are higher during August, which is the rainy period.

4.5.2 Humidity role

The $\delta\ ^{18}O = f\ (HR)$ relationship is not very significant because the hygrometry degree varies widely and suddenly during the rains events. It can pass, during a very short time, from few per cent of humidity to completely saturated profile. Thus, the first droplets arriving in a particular dry atmosphere (< 15%) are very enriched, but during thunder, the atmosphere becomes progressively saturated, the isotopic contents weaker. Thus, many downpours happen the same day show even when the temperature remains constant, more and more negative isotopic contents and this, because of the progressive increase of the moisture of the atmosphere.

4.5.3 The Amount effect

The $\delta^{18}O = f\ (Pmm)$ relationship obtained shows the overall behaviour as a negative exponential (fig. 8). Therefore the correlation shows a divergence between the lower contents and the most precipitation and distinguishes :

- one superior branch corresponding to summer precipitation,
- one inferior branch characterising winter precipitation on which the amount effect seems to be the best expressed.

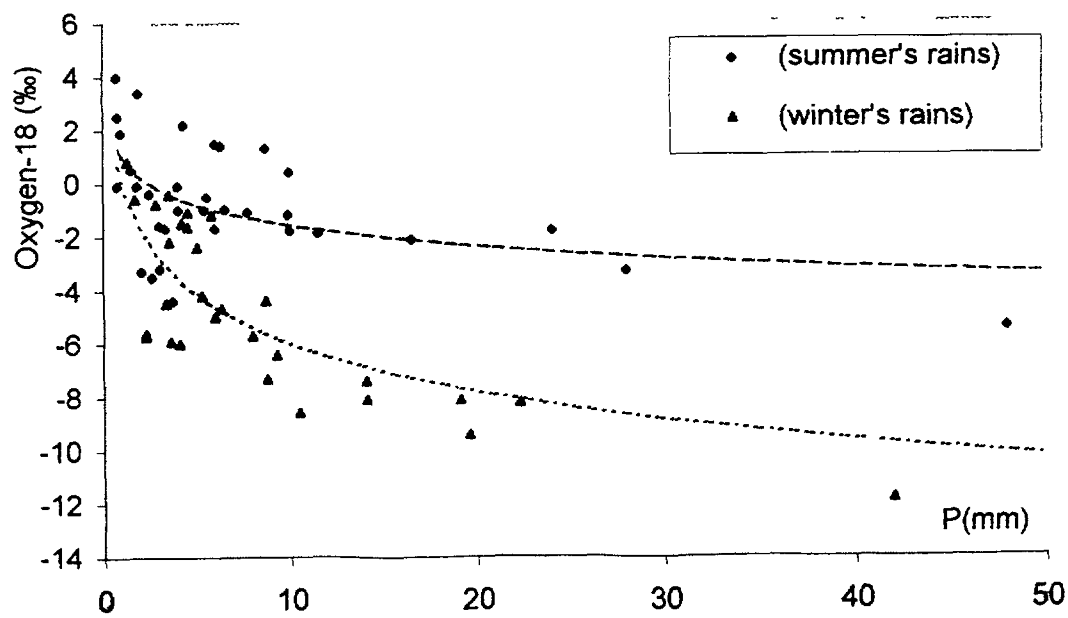

FIG. 8. Oxygen-18 —precipitation relationship: "amount effect".

5. CHEMICAL AND ISOTOPIC CHARACTERISTICS OF GROUNDWATER AND THEIR RELATION WITH RECHARGE OF AQUIFERS

5.1 Geological context

The geological facies are represented by crystalline and igneous formations of Pre-Cambrian age: Gneiss, mica-schist and granite [21], or some volcanic formations (basalt) deposits during Tertiary an Quaternary Period [22].

This region is structured in large stretch, of meridian direction, approximately 100 km of width, limited by major faults [23].

At the periphery of the crystalline an igneous massif, exits sedimentary rocks, essentially represented by sandstone of Palaeozoic age, and making the Tassili mountains.

5.2 Hydrogeological context and hydrodynamic characteristics

These geological formations are usually characterised by very weak parameters of porosity and permeability and do not acquire favourable aquifer character without some fissuration and consecutive weathering [24; 25]. The question raised is to known if, in spite of the weakness of precipitation, the Pre-Cambrian basement of Ahaggar, extremely fractured allows to hope thanks to the presence of a secondary porosity of cracks, the existence of potential reservoir. However, the aquifer zones that are the most favourable are located in the valley, that underline the major faults [26]. The recharge of the aquifer is assumed by sporadic wadi floods [27]. The piesometric level varies from 5 m, near recharge area, in the central parts of the massif, and more than 30 m in the neighbouring plains.

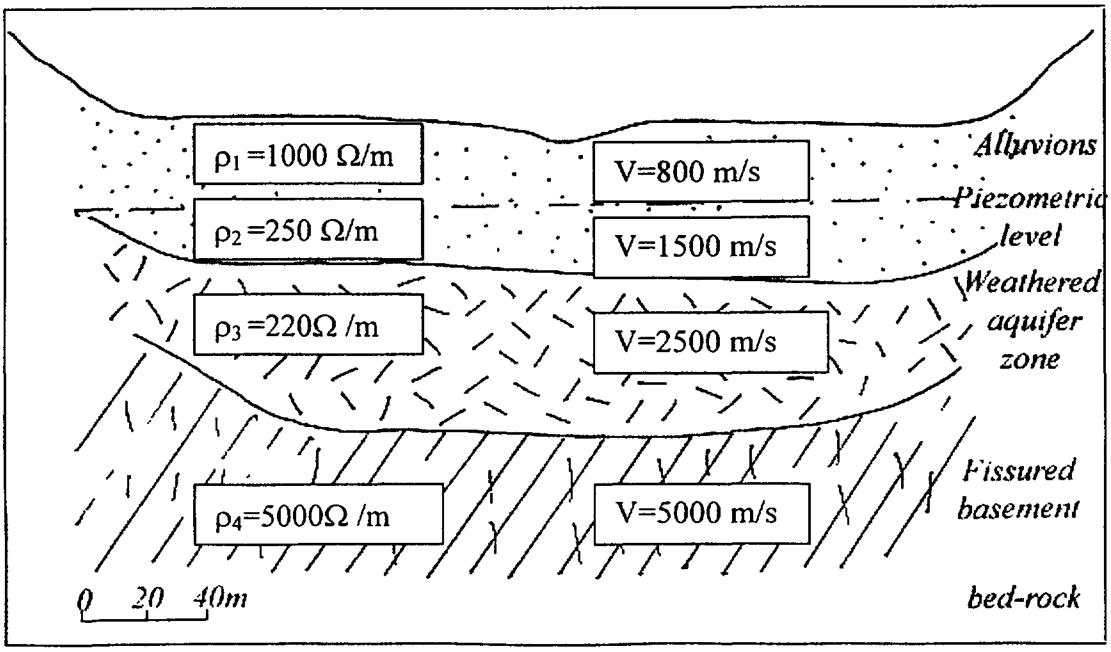

FIG. 9. Geological profile across oued Tamanghest and geophysical characteristics (electric resistivity and sismic velocity).

The geological profile is presented as three superimposed levels, of very unequal hydraulic characteristics :

- The alluvial deposits of subsurface (≈10- 20 of thickness) which constitute the main aquifer, because their transmissivity and porosity are relatively very high ($T = 2.10^{-2}$ m^2/s; ϕ =10%) [28],
- The underlying weathered aquifer zone (≈20 - 30 m). Its transmissivity decreases progressively with depth [29],
- The fissured basement aquifer which passes progressively towards the bed-rock.

5.2 Groundwater Chemistry

The chemistry of Ahaggar's groundwater is generally characterised by a moderate solute content, about 0.5 g/l. However, we can note an increase of these concentrations with the depth, presented by a stratification of the hydro-chemical types, where three fundamental groups can be:

- The first group corresponds to the shallow groundwater from the alluvial layer. It is characterised by a low mineralisation (0.2 - 0.3 mg/l) and this chemical type is homogeneous in the whole of this aquifer and translates the good mixture of waters. This testify the high permeability of the alluvial deposits, which benefit from a high recharge.
- The second group concerns groundwater from the subjacent weathered zone aquifer, where bicarbonate are prevailing. Their salinity is more important, about 0.8 g/l and it is the reflection of the mixture zone between recent precipitation and fossil water components.
- The third group represents the basement aquifer of paleo-recharge origin. It contains groundwater of significantly greater salinity, ranging from 1500-3000 mg/l and is the reflection of the long interaction between water and rock.

Table. 4. Mean chemical concentrations (in mg/l) of groundwater from Ahaggar

Type of Aquifer	Ca^{++}	Mg^{++}	Na^{+}	K^{+}	Cl^{-}	SO_4^{--}	HCO_3^{-}	NO_3^{-}	S.E.C. (µS)	PH
Alluvial aquifer	40	15	15	3	20	30	165	20	300	7.5
Weathered zone	75	22	75	10	20	50	450	10	800	6.5
Basement	154	125	107	1	400	427	153	3	1400	8.2

The shallow groundwater is characterised by calcium and bicarbonate chemical type. Homogeneity of this facies in the whole alluvial suggests good water exchange and permeability episodically assured by wadi floods.

The weathered zone aquifer presents several water types, according to the local variations of mineralogical composition of rocks. However it presents some analogy with the previous type, which suggests to become connected with shallow groundwater and that the aquifer is slightly recharged.

The basement aquifer water samples with prevailing chloride and sulphate, represents old formation water, partially subject to evaporation and with long residence time.

The Piper diagram shows the hydro-chemical plot of water quality of some selected samples, from different aquifers.

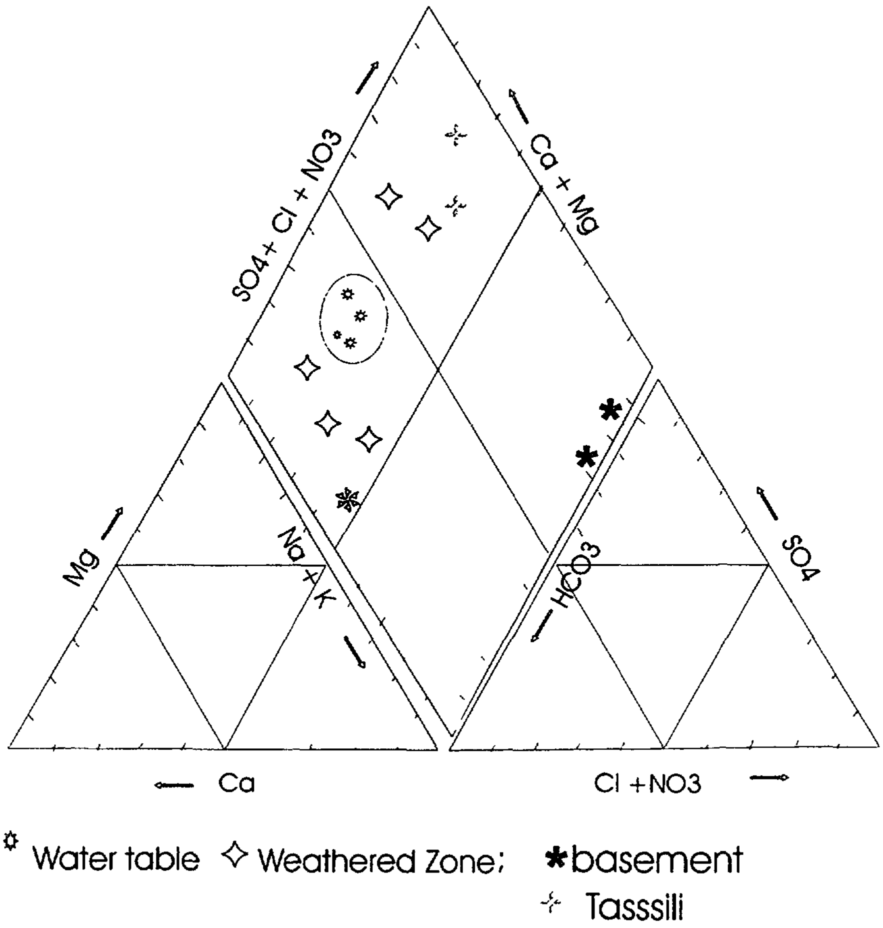

FIG. 10. Piper diagram of the chemical composition of groundwater from Ahaggar.

5.3 Isotopic contents of groundwater

As well as hydro-chemical concentrations, the isotopic contents are presented by several horizontal stratification, underlined by lowering of heavy isotopes with depth and lithologic nature of the aquifer. The oxygen18 contents vary from $\delta^{18}O$=-11‰ to 1‰, versus SMOW.

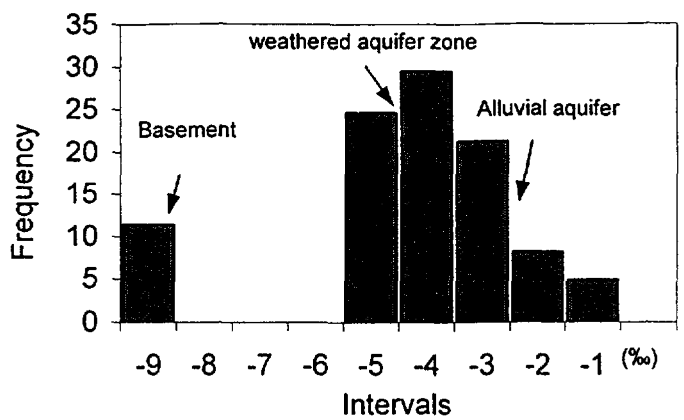

FIG. 11. Frequency distribution of oxygen-18 contents for groundwaters from Ahaggar.

However, these values are summarily clustered in 3 fundamental groups: The first group represents groundwater which is isotopically enriched ($\delta^{18}O \approx -2.7$ ‰) and corresponds to the youngest groundwater, located in the upper part of the aquifers water. Their tritium concentration which range between 8–16 TU and ^{14}C activity (110–115) pmc) is similar to the recent precipitation. Their results confirm that shallow groundwater are regularly recharged by the wadi floods.

In the weathered aquifer zone, the mean isotopic contents is: $\delta^{18}O$=- 4.2 ‰ and $^{3}H \approx 80$ TU. This results indicate that the weathered zone is connected with the alluviums of subsurface but is characterised by a low permeability and is slightly recharged.

The third group represents some samples collected in deep boreholes and in *Tassili* zone where the rainfall is below 10 mm/year. Their stable isotopic contents are very depleted ($\delta^{18}O \approx -10$ ‰) and diverge clearly from the recent precipitation. Furthermore the absence of ^{3}H and ^{14}C activities, prove an old heritage, resulting from a paleo-recharge, during the last humid Holocene episode. The basement aquifer represents a confined aquifer which is not recharged now.

Table .5. Oxygen-18, ^{13}C, ^{14}C and ^{3}H meancontents of groundwater from Ahaggar

Aquifer	Oxygen-18 (δ‰)	^{13}C (δ‰)	^{14}C (pmc)	^{3}H (UT)
Alluvial aquifer	≈ -2.7	-11	115	15
Weathered zone	-5	-5 to -2	≈ 75	50 to 120
Basement	-10	-3	< 3	< 1
Zone of Tassili	-10	-	-	-

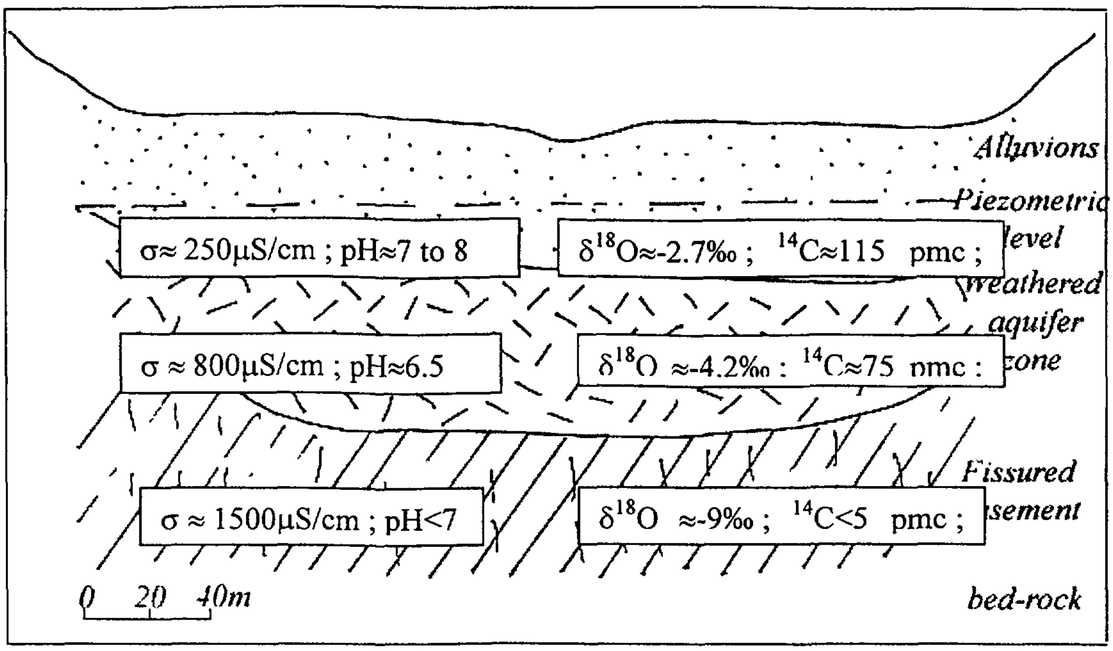

FIG. 12. Chemical and isotopic profile of classical aquifer.

The $\delta\,^{2}H$- $\delta\,^{18}O$ relationship of groundwater shows that the plots of the isotopes data for all samples cluster along the global meteoric water line, with the spread varying from aquifer to aquifer, being relatively high for the shallow groundwater. The diagram presented

Table 6. Isotopic composition of groundwater samples

Surface-water	O 18	D	Carbon13	Carbone 14	Tritium
Teguit	-2,9				
El ounifi	-3,8				
Crue O. Outoul: début de crue	-2,6	-8,4			
Crue O. Outoul 12 h après	-0,7				
Amsel barrage 1	-1,9				
Amsel barrage 2	-1,4	-4,4			
Guelta Tamagh T.	14,7				
Guelta Rocan	19,0				
Guelta Afilal 1/94	-4,3				
Guelta Afilal 4/94	-4,4				
Guelta Afilal 4/95	-3,4				
Water table					
Hadriane amont	-3,1	-15,6			
Guetaa el oued 1	-2,9	-18,3			
Outoul P2	-2,8	-15	-10,69	115 +/-0,9	19,1 +/-3,4
Outoul P7	-2,5	-14,5			13,2 +/-2,5
Outoul P8	-2,9	-15			19,6 +/-3,6
Outoul P11	-2,3	-13			10,9 +/-2
Outoul P14	-2,3	-8			11,6 +/-2,2
Outoul P 16	-2,6	-13			
Outoul st pompage 1	-2,7	-18			
Outoul st pompage 2	-2,3	-14			
Outoul village	-2,9	-17,8			
Outoul jardin	-3,9	-16,7			
Tit 1	-3,1				
Tit 2	-3,2	-16,9			
Esli sekin	-2,3	-11,8	-8,3	110 +/-1	20 +/-3,7
In Eddid 1	-2,6	-11,3	-11,4	115 +/-0,9	13 +/-2,5
In Eddid 2	-3,6	-14,4			
Iglene	-2,7				
Abalessa 1	-3,6	-18			
Abalessa 2	-3,3				
Abalessa 3	-3,1				
Ezerzé	-2,2	-8,9			
Amsel 1	-1,3				
Amsel 2	-2,7	-16			
Amsel 3	-3,0	-16			
Amsel 4	-2,6	-12			
Tin Amzi (ggf)		-17			
Tin Amzi 2	-2,5	-12,7			
Tazrouk selemedj	-2,8	-13,6			

Table 6. (cont.)

weathered aquifer zone	O 18	D	Carbon13	Carbone 14	Tritium
Forage 10	-4,2	-27,5			54 +/-1
Hadriane Hamou	-5,3	-29	-1,31	14,4+/-0,9	77 +/-2
Hadriane kaolin.	-4,5	-24			
In Zaouène camping	-4,7	-30,7	-0,96	21+/-0,9	63 +/-1,7
In Zaouène	-4,5	-31,4			
Tamanghest	-4,4	-26,3			
Sersouf Nord	-4,3	-26,7			
Observatoire	-4,3	-27			
Fraternité (S)	-4,0	-26			
Antoine	-3,3	-19,3			
St. Rec. Zone desert.	-4,4	-20,4			
Soro mosquée	-3,5	-21,6			
Amsel P27	-4,0	-23,5	-2,27	19+/-0,9	53 +/-1
Amsel vas 1	-5,0	-29,8			
Taghaouhaout	-4,7	-23			120,8 +/-10
Outoul granite	-4,2		-1,39	22,1+/-1	14 +/-1,5
Forage Abalessa	-5,3				
Silet (ggf)	-4,1	-24	-8,97	74,7+/-0,6	
Ideles el gueraret	-4,3	-26,2			
Ideles palmeraie	-4,3				
In M'guel F3	-5,0	-29			
In M'guel F7	-3,9	-24,6			
Tahifet AEP	-4,4	-23,5			
Tahifet école	-4,5	-26,5			
Hirafok Coop.		-26,6			
Tahabort 11/ 81	-10,3	-73			<1,6 +/-0,1
Tahabort 3/ 82	-9,9	-57			0,3 +/-0,1
Tahabort 4/93	-9.9	-72			
Tahabort 6/ 93	-10,1				
Tahabort 8/ 93	-9,7	-62			
Tahabort 10/93	-10,4	-74			
Tahabort 1/94	-9,9				
Tahabort 4/94	-9,8	-67			
Tahabort 8/94	-10,3	-71			
Tahabort 4/95	-9,9	-69,2	-3,05	2,4+/-0,5	<1,3 +/-0,1
Tahabort 1/96	-9,8	-67			
Ahidja 1/94	-9,4				
Ahidja 1/96	-9,1	-61			
Aquifer zone of Tassili (sandstone; Cambrian-Ordovician)					
In Azaoua/Algeria	-8,5	-60			
In Azaoua/Niger	-9,1	-67,3			<3 +/-0,2
In Ateil	-8,5	-60			
In Guezam aérod.	-9,8	0			
In Guezam fer.	-8,8	-66,6			
In Guezam ggf	-9,0	-68			<3+:-0,2

in fig. 13 reveal substancial difference between isotopic contents of water from the fissured basement aquifer water and alluvial water table.

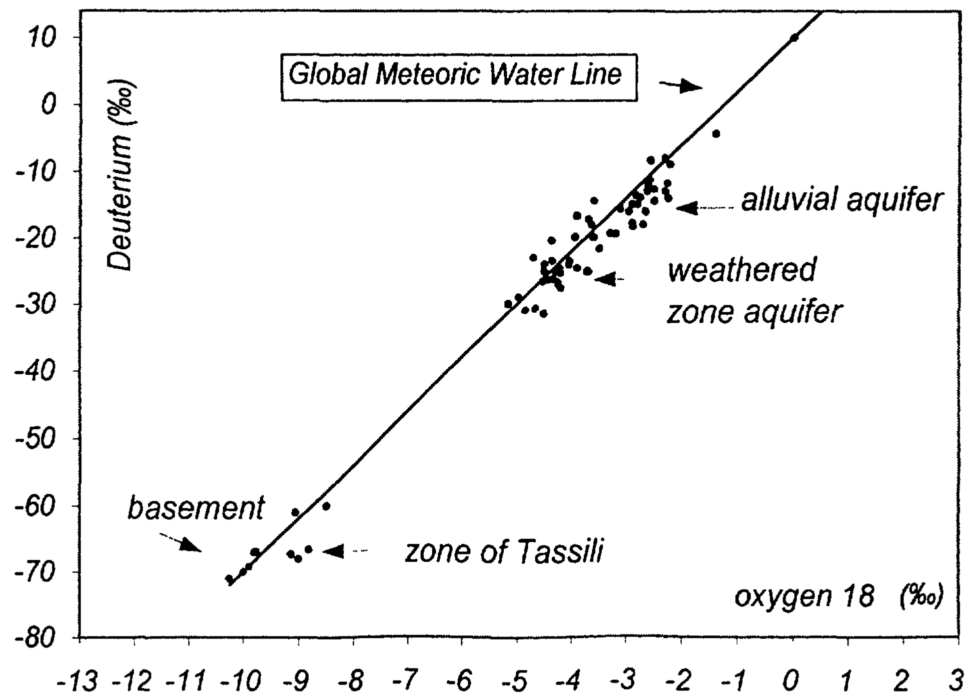

FIG. 13. Deuterium vs oxygen-18 relationship of groundwater from Ahaggar.

This result indicates two different period of recharge : the first is actual, characterised by relatively enriched isotopic contents, the second corresponds to the Holocene period, when the thermal conditions were cooler and the moisture content higher.

8. CONCLUSION

Thanks to its high altitude effect, the Ahaggar massif seems to be a region able to regenerate wet air mass of the Guinean monsoon phenomena, very weakened at this latitude. Thus, the most important rains happen in summer. During winter and spring, the rains of smaller importance and recycled, would be tied to other origin sources, particularly to some disturbances coming from the N/W Atlantic. Despite the influence of different phenomena, rainfall on the wettest area of the massif, does not pass beyond 118 mm/year.

Stable isotopes contents of these rains are around an average of -3 ‰, for oxygen-18 and -15 ‰ for deuterium. The slope of the local meteoric water line is weaker than that of the global meteoric water line, explains the evaporation process, concerning these rains during the fall. Some rains, most affected, arrive to the soil as trace. Thus, rainfall in the Ahaggar massif, would be more important if they do not evaporate in the lower layers superheated and very unsaturated, of atmosphere. The deuterium excess value of these precipitations, generally superior to 10, particularly for winter rains, indicates they are supply of recycled continental moisture of the atmosphere reservoir.

Finally the ordinate at the origin of the local precipitation line, representative of the generating vapours, formulate the problem of the multiple or double origin of these precipitations. The only summer precipitation having some similarities with the oceanic wild is due to the wet air mass incursions from the Guinean gulf. Winter rains having a deuterium excess superior to 10, could come from local vapours recycling. Consequently, the Ahaggar massif seems to be a transition and/or a meeting region of many climatic regimes, among them, the monsoon which happens in summer and is preponderant.

In regard to hydrogeological characteristics of this crystalline and igneous region, water resources are almost produced in phreatic aquifer, contained in wadi alluviums. This is the only aquifer type which benefits from renewal rate. Hydro-chemical and isotopic stratification types explain a rapid decrease of infiltration to depth.

ACKNOWLEDGEMENTS

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ENVIRONMENTAL ISOTOPE PROFILES AND EVAPORATION IN SHALLOW WATER TABLE SOILS

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Abstract

Environmental isotope methods have been employed to evaluate the processes of evaporation and soil salinisation in the Nile Delta. Stable isotope profiles ($\delta^{18}O$ and $\delta^{2}H$) from three sites were analysed using a published isothermal model that analyses the steady-state isotopic profile in the unsaturated zone and provides an estimate of the evaporation rate. Evaporation rates estimated by this method at the three sites range between 60 and 98 mm y^{-1} which translates to an estimate of net water loss of one billion cubic meters per year from fallow soils on the Nile delta. Capillary rise of water through the root zone during the crop growing season is estimated to be three times greater than evaporation rate estimate and a modified water management strategy could be adopted in order to optimize water use and its management on the regional scale.

Introduction

The rate of water loss form soils by evaporation is regulated by atmospheric conditions, soil texture and structure conditions, and depth to water-table. In drainage basins, the estimation of evaporation (from fallow soils) is not straightforward and the determination of capillary rise (from cultivated soils).is far from being a simple matter. Evaporation is currently cited as one of the main mechanisms of soil salinization in the arid and semi-arid zones. The contribution of the capillary rise in the regional water budget is poorly known. Its estimation, despite its significance in water management in irrigated lands - particularly in the presence of a shallow phreatic water-table - is rarely attempted. Evaporation from soils is usually integrated in the evapotranspiration term due to technical difficulties in the separation of the two components.

Sampling

A brief overview is given on three sites for which isotope profile data ($\delta^{18}O$ and $\delta^{2}H$) is used to estimate evaporation rates (Tables 1 and 2) assuming steady-state isothermal conditions.

a. Mansoury Profile. Moderately saline clay loam soil which was not cultivated for several years in the Mansoury Experimental Irrigation Station, near Giza (about 15 km to the west of Cairo).

b. Hoch-Issa Profile. Saline clay loam soil (with clay-rich bottom layers) in the Hoch-Issa reclamation project area at the north-western sector of the delta, near Damanhour City, 150 km to the north west of Cairo.
c. Om El-Sienne Profile. Highly saline clayey soil, sampled at Om El-Sienne site, Kafr El-Sheik Governorate, in the middle northern saline belt of the Nile Delta, 120 km north of Cairo. A nearby experimental station and data from Hussein, (1975) provided the soil characteristics (texture, salinity and sodicity levels) of the studied site.

Soil profiles have been sampled in the corresponding sites since they were known to have a shallow phreatic water-table (less than 2 meters deep) and subjected to long-term fallow conditions and received no surface water applications since more than one year. Each profile can be divided into three layers with regard to soil water movement.

1. upper layer (few centimeters thick) with dominant soil water vapor flow and possible isotope exchange between soil moisture and the atmospheric humidity.
2. intermediate layer where vertical unsaturated flow (upward during evaporation and redistribution stages, but downward during a fraction of the redistribution stage) is the dominant soil moisture flow type which could be governed by the plant roots water uptake when some halophytes are present. The solution of the vertical unsaturated flow problem in this layer is sometimes carried out using a pseudo-steady-state model suitable for soils with shallow phreatic water-table.

Table 1. Isotope composition at the lower boundary water reservoir and the evaporation front.

Profile	$\delta^{18}O$ res	$\delta^{2}H$ res	$\delta^{18}O$ ef	$\delta^{2}H$ ef
Mansoury'ya	1.60	-6.00	9.97	13.20
Hoch Issa-Hararah	-1.00	-3.00	8.34	17.40
Om El-Sienne	3.50	10.00	9.19	17.00

Table 2. Evaporation rates as estimated from the isothermal steady-state isotope model.

Profile .	Depth* cm	Slope**	Slope***	Evaporation Rate mm y^{-1}
Mansoury'ya	8.0	1.74	5.42	60
Om El-Sienne	7.5	2.70	6.03	98
Hoch Issa, Hararah	3.5	3.64	5.85	65
Data compiled from three profiles		2.17	5.11	

* depth to evaporation front, cm.

** $\delta^{18}O$ - $\delta^{2}H$ slope for data points from the layers below the evaporation front.

** * $\delta^{18}O$ - $\delta^{2}H$ slope for data points from layers above the evaporation front.

3. lower layer which is limited from underneath by the permanent shallow phreatic water-table. Its humidity is greatly influenced by the near-saturation conditions which is prevailing in the few centimeters above the water-table (the active capillary rise fringe).

Sampling was performed in summer-time to ensure maximum soil moisture deficit. Isothermal steady-state (second-stage) evaporation conditions are assumed, neglecting temperature gradient. Since the studied profiles were fallow and subject to evaporation for more than one year, the isothermal assumption is not realistic enough.

Seasonal temperature change, in soils in the south of the Nile Delta, has been shown (Abdel Kader, 1975) to be in the range 12-20' C with more or less positive gradient in summer and net negative gradient in winter. Moreover, the isotopic composition of soil water in the upper layers undergoes a certain diurnal change (Bariac et al, 1987) even in the temperate zone soils (France), where the highest $\delta^{18}O$ values are attained at noon with 2, 3, and even 4 per mil increase compared to the values measured in the morning.

Methods

Despite the fact that most of the delta area is cultivated and few large-scale areas are permanently left fallow, the cropping rotation pattern permits the presence of considerable sporadic fallow soil patches. So, significant evaporation water losses are believed to take place. These patches (assumed to represent 25% of whole the delta area) are exposed to evaporation due to shallow phreatic water-table, heavy soil texture and favourable climate. If the annual evaporation rate is estimated (by the isotope profile model, as given in this paper), if the per year time fraction (during which soil is left fallow) is determined, and if the fallow area is known, water loss through the intermittent fallow soil can be evaluated. When, under normal cultivation conditions (during the rest of the year) capillary rise is assumed equivalent (at least) to the evaporation term from the fallow soils, the amount of water that can be saved each year (by cultivation under certain water stress, i.e. higher soil moisture potential) could be approximated. Separate estimation of the evaporation term from fallow soils could be obtained by modeling the isotope profile data (Zimmermann, 1967, Allison and Barnes, 1983 and Allison and Hughes, 1983 and 1985). The application of the isothermal steady-state isotope model (Allison , Barnes and Hughes, 1983a and 1983b) given in this paper is based on the analytical data for the above-mentioned profiles. The punctual estimation is extended to obtain an evaluation of the regional evaporation losses and extrapolated to estimate the capillary water supply to the root zone in the delta. Soil material of each layer was preserved in tightly sealed cans during sampling. Soil moisture was quantitatively extracted under vacuum in the laboratory using appropriate differential temperature gradient (+80 to - 180° C) using liquid nitrogen. Measurements were conducted with a double inlet isotope ratio mass spectrometer after gas phase preparation (by equilibrium with carbon dioxide for oxygen- 1 8 and by water reduction into hydrogen for deuterium).

Results and Discussion

The results based on the isothermal steady-state isotope model (Allison, Barnes and Hughes, 1983a and 1983b), applied to isotope data for the extracted soil moisture, are summarized in Tables 1 and 2.

Evaporation rate, capillary rise and water management

In irrigated soils with shallow water-table, moisture could be supplied from the water-table during plant growth season when soil moisture potential-depth-distribution is favorable for upward flow. Since second-stage evaporation from fallow soils is irreducible and an estimate could be obtained from it for capillary rise in cultivated soils, a modified water management should take into account the contribution of the capillary upward flow so that the applied irrigation water could be reduced (on both the farm and regional scales) since the expected capillary water flow is used by roots in the cultivated soil if certain higher soil moisture potential is acceptable. Adopting an upper limit for the steady state evaporation rate as double the highest value in Table 2 (i.e. 200 mm/y) and assuming that capillary rise in the cultivated soil is (at least) equal to this rate under fallow soil conditions, capillary rise in the delta cultivated soils amounts to I km'/y throughout a period of 3 months a year, i.e. during the same time period of fallow conditions (or equivalent to 25% of the delta area). Since capillary rise takes place during 9 months whereas evaporation occurs only during 3 months a year, capillary rise is 300% of the 200 mm/y rate mentioned above, i.e. it is 3 km^3/y. The sporadic fallow areas in the Nile Delta are estimated, using remote sensing techniques (Abdel Hady et al, 1983), as 18% of whole the delta area of 20 000 km^2 in winter only, whereas we have adopted 25% on a year-round basis. Accordingly, a huge Nile discharge is unjustifiably delivered to the delta. It is clear that for a year-to-year operational estimation of such discharge, an annual estimation of the fallow soil area is needed. This could be obtained through updated remote sensing data to have accurate evaluation of such an area each year.

Moreover, the problem of determining the evaporation first-stage (water losses under transient soil moisture conditions) could be tackled by the application of an isotope numerical method which is under development (Walker, G, personal communication, IAEA meeting, August, 1994).

Scatter of $\delta^{18}O$ - δ^2H values

The interpretation of the observed $\delta^{18}O$ - δ^2H scatter in the binary δ-diagram (not shown) in the studied profiles is that evaporation takes place under non-isothermal conditions, whereas the model is merely an isothermal one. Allison et al (1983b, page 393) have obtained more scatter for the experimental points under the non-isothermal conditions compared to the isothermal ones. The obtained $\delta^{18}O$ - δ^2H slopes (1.74, 2.7 and 3.64) in the lower liquid-water dominant flow zone (Table 2) for all the studied soil profiles are much lower than 5. Slope 5 is characteristic for evaporation from open water bodies (under steady-state equilibrium between the liquid and vapor phases) and solely attributed to the slight chemical potential difference between the isotope species. The obtained low slopes clearly indicate the prime importance of kinetic fractionation under fallow conditions below the evaporation front. Kinetic fractionation is very noticeable since a sufficiently long evaporation time was permitted.

Conclusions

An estimated one billion cubic meters of water is lost each year from the Nile Delta fallow soils using a physical model based on environmental isotope profile data. Three times this amount is supplied to the root zone during the crop growing seasons though capillary rise. A modified water strategy could take into account this upward flow in order to optimize water management on the regional scale. The evaporation rate estimation and its extrapolation of capillary rise evaluation are presented, subject to the working assumptions. Some factors lead to certain difficulties, namely: the presence of secondary evaporation planes, highly developed structure cracking at the soil surface, clay dispersion in the lower layers, sporadic winter rains, micro-climatic fluctuations, slight depletion in the inner water molecules compared to bulk pore water due to the history of soil material humidification and, finally bulk density errors in shrinking-swelling soils.

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GROUNDWATER VULNERABILITY AND RECHARGE OR PALAEORECHARGE IN THE SOUTHEASTERN CHAD BASIN, CHARI BAGUIRMI AQUIFER

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Abstract

Stable isotopes and major chemical elements have been used to investigate present or ancient groundwater renewal in the multilayered aquifer of the Chari-Baguirmi plain, South of Lake Chad. On the Western side, recharge mainly occurs from the Chari River during the flood period.. Within the Ndjamena area, the rise of the piezometric level in the contaminated subsurface zone provokes an increase in nitrate concentrations. Rainfall recharge is mainly located close to the outcropping basement, *i.e.* on the Eastern side of the area and does not occurs in the central part of the plain where groundwater also presents a stronger evaporative signature. This supports the hypothesis attributing a major role to evaporation processes in the formation of piezometric depressions in the Sahel zone. There is no evidence of present day or ancient water recharge from Lake Chad.

1. INTRODUCTION

The aim of the Chari Baguirmi study was, using chemical and isotopic tools, to investigate present or fossil groundwater renewal, and to relate these results with environmental changes in the Southeastern Chad Basin.

A large variety of recharge mechanisms may be involved :

- directly by the rainfall through the soil and the unsaturated zone. In such a case, the recharge is largely influenced by rainfall and evaporation characteristics (quantity, distribution, intensity, etc...), and by the depth of the piezometric level ;
- local recharge of surface runoff, ponds, or through the Chari river-bed;
- recharge by the way of lake or palaeolake, especially in Chad.

The study of these mechanisms can also be of great importance to evaluate the aquifer vulnerability, mainly around the urban centers like N'Djamena.

Two specific zones are concerned :

1. near N'Djamena, for studying the relationships between the Chari River and the shallow groundwater, as well as the implications of the recharge in groundwater pollution ;
2. North and East N'Djamena, across the Chari Baguirmi piezometric depression (Figure 1). The objective is to characterize the recharge and to evaluate the role of the palaeolake related to the recent river water or rain recharge ; the results are also to be used to verify the theory of recharge deficit and evaporative process in the genesis of piezometric depressions.

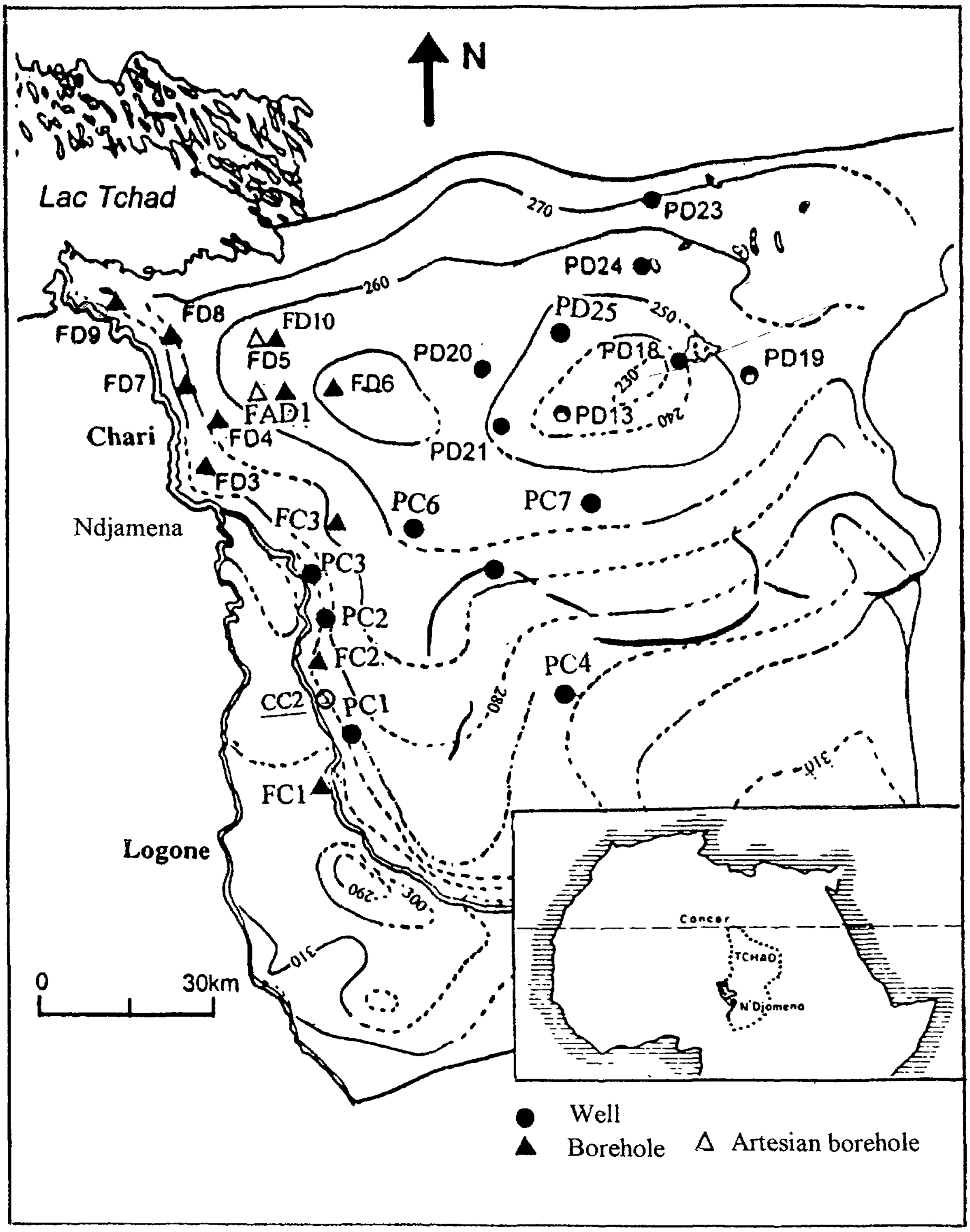

Figure 1 – Sampling sites and piezometric map in the Chari Baguirmi plain

2. METHODS OF INVESTIGATIONS

Hydrogeological and geochemical studies have included stable isotope analysis of rainfall as the input signal to the hydrogeological system. Within the project area, each event was sampled at the airport station of N'Djamena, during the rainy season 1995.

The results have been compared to the isotopic rainfall data obtained from the IAEA Network (IAEA/WMO/GNIP Network, 1998 ; stations of N'Djamena, Kano, Khartoum, Geneina). Hydrochemistry and isotope hydrology have been used to establish the geochemical evolution of groundwater, and relative ages in order to characterize the interconnections between the unconfined groundwater, Chari River, Lake Chad and rainfall. Samples of modern or old shallow groundwater were obtained from traditional wells or boreholes. The sampling campaigns have been carried out every month during a complete hydrological cycle (April 1995 to April 1996). Groundwater samples were taken from traditional wells and boreholes : 12 wells and 2 boreholes in N'Djamena ; 7 wells and 8 boreholes in the Chari Baguirmi plain. Filtered samples were collected ; the sample for anion analysis (250 cm3) was unacidified and that for cation analysis was acidified with nitric acid. Major cations and anions (including bromide) were determined respectively by atomic absorption spectrometry and ionic chromatography at the Avignon laboratory.

At every step of the sampling, *in-situ* measurements of pH, Alkalinity, Electric Conductivity and Temperature were carried out.

3. HYDROLOGICAL AND HYDROGEOLOGICAL SETTINGS

The Chari Baguirmi Basin is limited to the Northwest and to the South by basement rocks, to the West by the Chari River, and to the North by Lake Chad. This basin forms the Southwestern part of the Chad Basin which is filled by continental sediments of Continental Terminal (CT) to Quaternary.

Quaternary deposits consist of clays and sandy loam alluvial deposits, and lacustrine or deltaïc sediments. The thickness varies from 10 to 50 m.

Deep groundwater occurs mainly in the sediments of CT and Lower Pliocene. The CT, composed of clays and sandy clays, has a low permeability compared to that of the Lower Pliocene formation. The latter is confined under 300 m of low permeability sediments (Pliocene) and artesian discharge can occur in the boreholes in the Western part of the basin.

Unconfined and semi-confined groundwater occurs mainly in Quaternary sediments which may form multilayered aquifers and present piezometric depression. This aquifer system presents a great variability in lithology, and as a consequence, transmissivity shows values ranging from 10^{-3} to 10^{-8} m^2s^{-1} (Table 1)

Table 1 Hydrodynamic parameters of the Chari Baguirmi upper aquifer system (From : Artis and Garin, 1991 ; BRGM, 1987 ; Schneider, 1967)

	Discharge $m^3.h^{-1}$	Specific discharge $m^3.h^{-1}.m^{-1}$	Permeability $m^2.s^{-1}$	Transmissivity $m^2.s^{-1}$	Storage coefficient
Old boreholes	0,7 to 108	0,07 to 8,7	1,5 10-3 to 4,7 10-4	3 10^{-4} to 7 10^{-3}	3 10^{-3} to 5 10^{-2}
Recent boreholes	3,02 to 11,80	0,7 to 14,6		1,2 10^{-3} to 2,8 10^{-8}	

It seems that there is a coupling between the hydrogeological systems of the confined and unconfined aquifers, the phreatic shallow aquifer being sustained by the deeper aquifer. The low recharge rate existing since the beginning of the Holocene period has caused the water table to attain depth up to 50 m, and present-day measurements of the piezometric level recorded since 1963 show a continuous decrease. This decline of the piezometric surface represents the depletion from water storage from a wetter climatic period.

All the hydrogeological data have been recently compiled by Schneider and Wolff (1992). In the Northeast part of the lake, there is evidence of very low recent recharge : isotopic data have been interpreted as a mixing between old evaporated lacustrine water and modern recharge (Fontes *et al.*, 1970). Considering the structure and the depth of piezometric levels, present-day and old recharge could preferentially occurred to the East of the area where the basement outcrops, to the West from the Chari River, and to the North from the lake.

During Holocene humid spells, the levels of Lake Chad were probably some 40 m higher than today. During the wettest periods (around 8 000 and 6 000 yr B.P. ; Servant, 1983), Lake Chad or flooding systems covered the main part of the Chari Baguirmi plain and could have constituted an important source for aquifer recharge

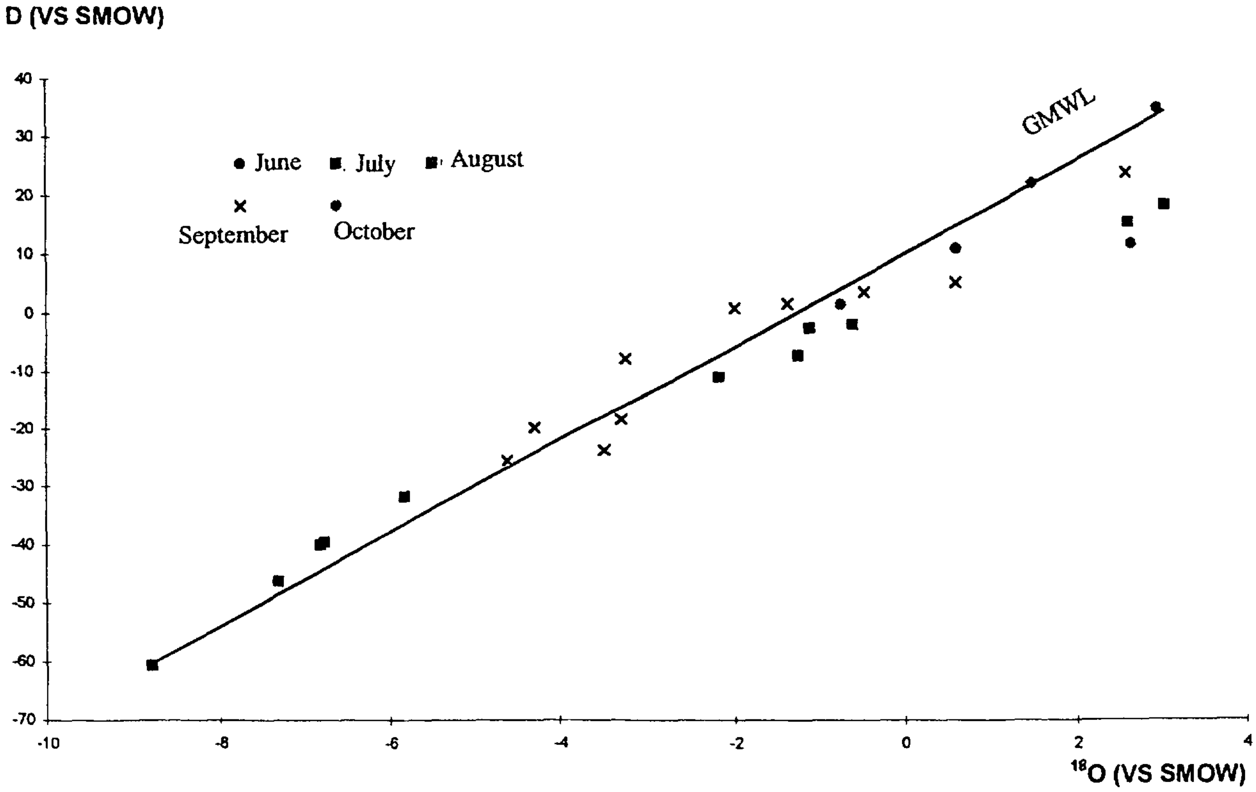

Figure 2 - Relation between ^{18}O and ^{2}H of the rainfall (rainy season 1995)

4. RESULTS AND INTERPRETATION

Up to date, all ^{14}C analyses on groundwater are not still available. As a consequence, only provisional interpretations may be provided on the Chari Baguirmi plain. The main results can be summarize as follows :

- The rainfall signal has been well defined during the rainy season ; the isotopic composition of precipitation is well correlated with the monsoon mechanisms (Figure 2). Relative positive values are observed at the beginning of the rainy season with some evaporated waters while more depleted values occur at the end of July, during August and the beginning of September. Then, non-evaporated rain water is characterized by more positive values. Similar results have been observed in Senegal some years ago (Travi *et al.*, 1993).
Considering the $\delta^{18}O$ weighted mean value and IAEA data, we can consider that the present-day rainfall signal value ranges between -5 and -6 ‰ *vs* SMOW.

- Groundwater hydrochemical data plotted on a Piper diagram show water evolving from Ca-Mg-HCO_3-dominated fresh water near the Chari River and the Eastern border, to higher alkaline $NaCO_3Cl$ or $NaCO_3$-SO_4-dominated more saline water in the Northern and central parts of the Chari-Baguirmi plain. This chemical evolution suggests a modern recharge on the two sides of the plain (East and West), whereas very few recharge is evidenced in the area of the piezometric depression zone.

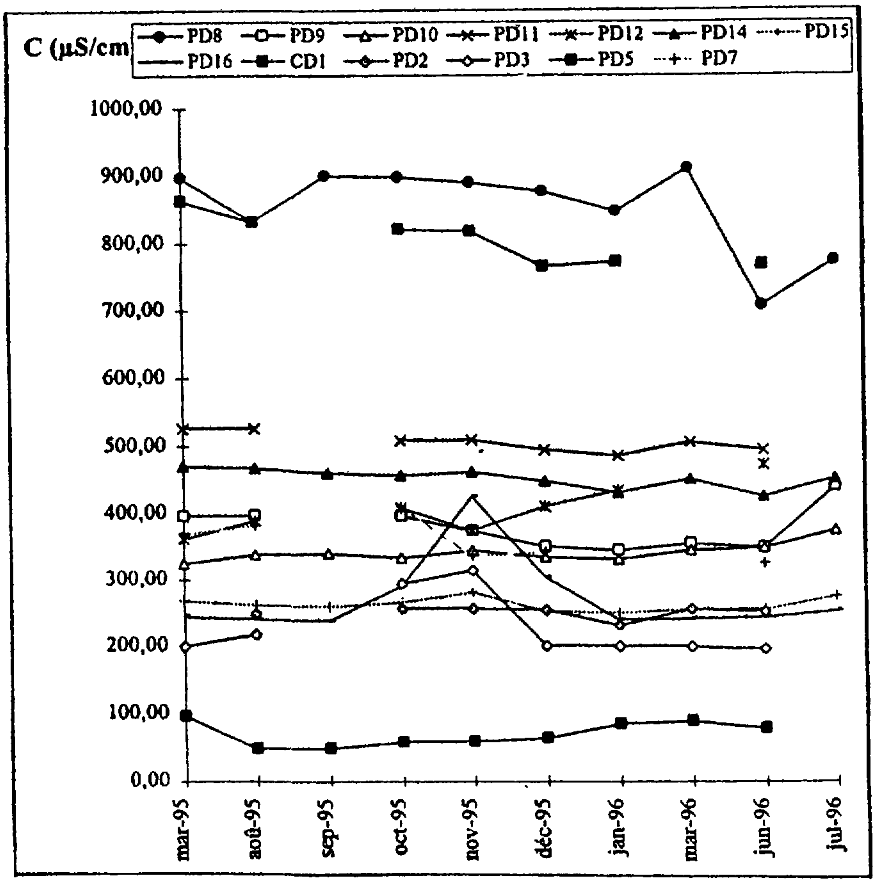

Figure 3 - Conductivity response pattern of wells and boreholes near NDjamena

- Near N'Djamena, the Electric Conductivity which was used as a general marker of groundwater hydrochemistry, coupled with ^{18}O measurements along two profiles show evidence of replenishment of the aquifer from the Chari River during flood periods (Figure 3 and 4) : conductivity is increasing with the distance from the river and $\delta^{18}O$ contents of samples taken from most of the wells correspond to the Chari River values during floods. The two peaks in conductivity observed in Figure 3 are related to nitrate contamination occurring during the flood period due to the rise of piezometric level in the contaminated subsurface zone (latrines and waste deposits). This is confirmed by the evolution of annual nitrate contents. The concentration of nitrate across the area is variable, and ranges from 5 to 150 $mg.l^{-1}$., the higher values being observed at the end of the flood period when the piezometric level reaches its maximum.

- All along the Western border of the plain, the oxygen- 18 contents close to -3 ‰ confirm the annual recharge from the Chari River during flood period (October and November).

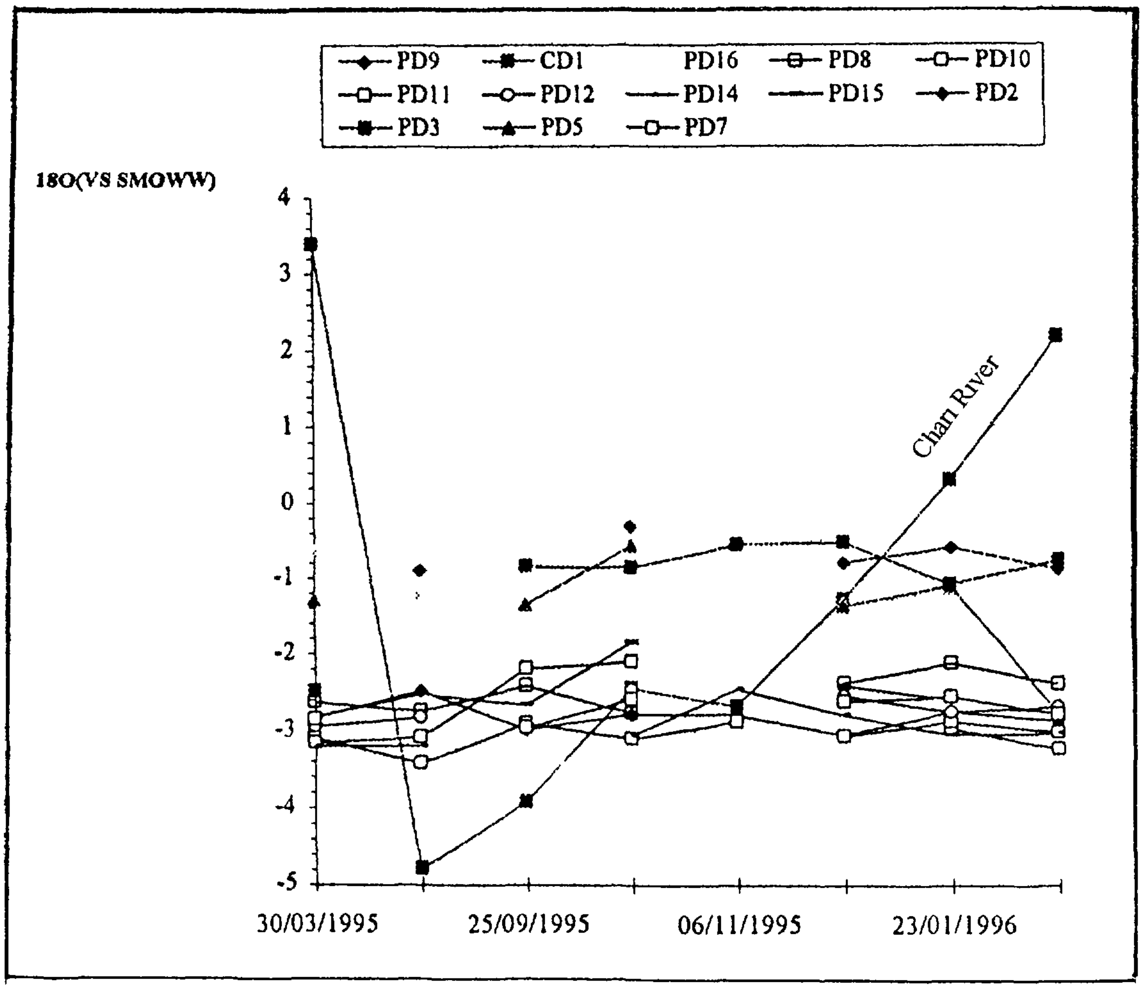

Figure 4 - Isotopic response pattern of Chari River and groundwater near NDjamena

- On a ^{2}H versus ^{18}O diagram almost all of the groundwater have isotopic composition which lies below the Global Meteoric Water Line (GMWL) (Figure 5) Recharge from rainfall occurs, to the East, near the outcropping basement ; this recharge is characterized by an evaporative line which intersects the GMWL between — 4 and – 5 ‰ vs SMOW, for ^{18}O. Samples taken from the central part of the plain near the piezometric depression (PD24, PD23,PD13,FD11) fall on an evaporation line with its origin close to more depleted values (probably older rainfall episodes in agreement with preliminary tritium results) and show a stronger evaporative signature. This could support the hypothesis attributing major importance to evaporation processes in the formation of the regional piezometric depressions in West Africa (Ndiaye *et al* , 1993) But an age gradient between the East side and the middle of the depression has to be confirmed by expected ^{14}C values

- There is no evidence of direct recharge in the Center part of the plain coming from rainfall or from present or ancient lake water

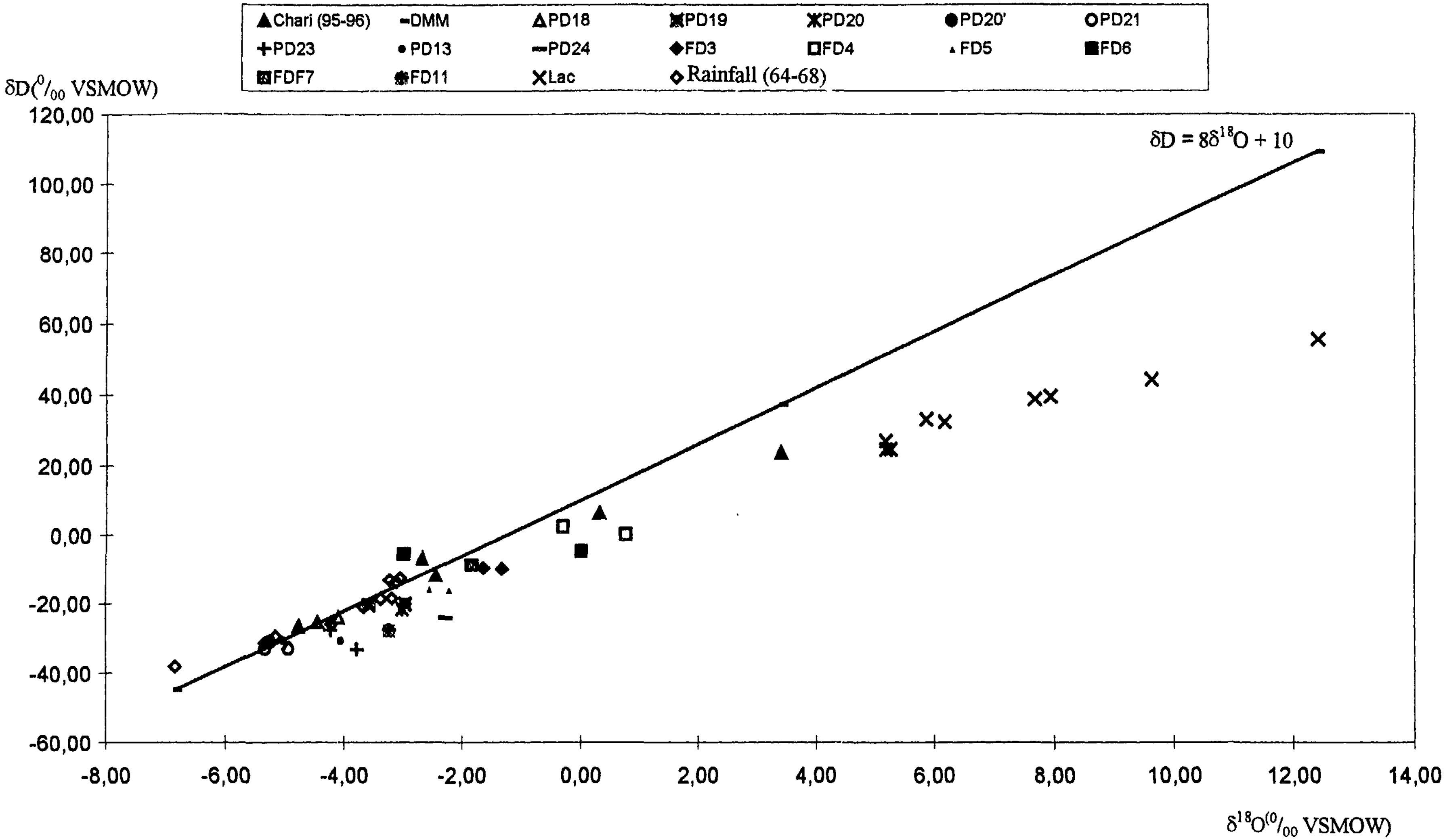

Figure 5 - Relation between ^{18}O and ^{2}H of rainfall at Ndjamena (64-71), Chari River (95-96) and Lake Chad (1967)

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ENVIRONMENTAL ISOTOPE STUDIES IN THE ARID REGIONS OF WESTERN RAJASTHAN, INDIA

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Abstract

An environmental isotope study carried out along an 'identified' buried river course in Jaisalmer showed that its expected head water connection with present day Himalayan sources to be very remote. The groundwater along the course is old as indicated by absence of tritium and low carbon-14 values.

In an effort to understand the contribution of canal waters and return flow of irrigation waters to the groundwater and related problems in the command area of a large irrigation project, the area affected by canal water could be delineated. The ground water salinity is attributed both to the uplift of local saline groundwaters caused by water logging in the area as well as to evaporation from shallow groundwaters.

Deep fresh groundwater is available in many parts in the desert region, which have been identified as palaeowaters. Over exploitation of these old waters in some areas is indicated by their mixing with shallow groundwaters. Modern recharge is possible in the southern part of the state where comparatively higher precipitation is received.

1. INTRODUCTION

The Thar Desert extends from the western side of the Aravalli Mountain ranges in India to the limit of Indus Valley in Pakistan. It includes about sixty percent of the area of

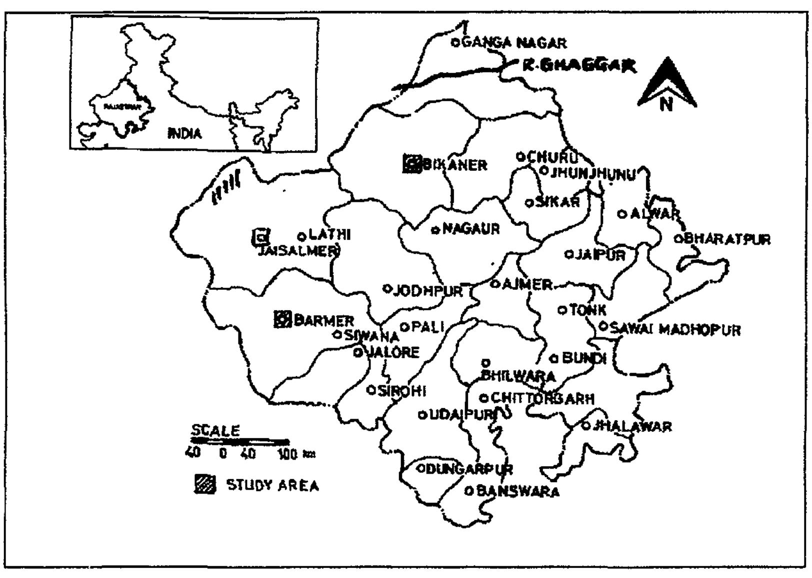

FIG. 1. Locations of isotope studies in Western Rajasthan

tectonic events in the region, ending up in the present course of the river Ghaggar. The river built up a wide alluvial plain of considerable thickness. It is thought that the courses of the river in the area are still maintaining their head water connection with the Himalayan sources and could form potential sources of groundwater.

Rajasthan state, which is situated in the northwestern part of the country (Fig. 1). Having about 38% of the state's population, this is one of the most populated desert regions of the world. With constant increase in human as well as livestock population, the common problems faced by desert regions like scarcity of water, land degradation, deteriorating pasture lands etc., have become acute in this region.

The land is covered by sand dunes with interdunal plains in the north, west and south and alluvium in the central and eastern parts. The climate of this part is characterised by extremes of temperature ranging from below freezing point (at times) in winter to over 50°C in summer. Precipitation is low and erratic, varying from about 130 mm in the northwestern part to over 300 mm in the southeastern side. Streams are few, ephemeral in nature and confined mostly to the rocky part of the desert, the prominent being the Luni River in the southwestern side. Groundwater forms the major source of water in this region. Efforts are being made by the State Groundwater Department to study known groundwater resources and explore potential ones in the area.

In the other extreme, water brought to some of the areas from distant river sources through canals under a large irrigation project, while helping development has also brought in problems like water logging and secondary soil salinization. Efforts are under way to identify the causes leading to these problems as well as to adopt methods to reclaim or utilise the affected areas to the extent economically viable.

Isotope techniques have been successfully used by many investigators to solve problems in arid regions, many times with advantage over conventional techniques [1]. A few studies carried out by the authors, employing environmental isotopes ^{2}H, ^{18}O, ^{3}H, ^{13}C, and ^{14}C along with available chemical and hydrogeological data to obtain valuable information useful for the management of groundwater in the area, are given below.

2.1. ISOTOPE STUDIES ALONG A BURIED RIVER COURSE, JAISALMER.

Interpretation of satellite imagery of the western parts of the Jaisalmer district revealed the buried course of a river in the NE-SW direction [2,3]. In spite of the highly arid condition of the region, comparatively good quality groundwater is available along the course below 30m depth. The aquifer consists of medium to fine sand with very little clay. Figure 2 shows the study area with sample locations. A few dug wells in the area do not dry up even in summer and the tube wells do not show reduction in water table, even after extensive utilisation for human as well as livestock consumption. Groundwater away from this course is saline. This course is seen to have link with the dry bed of Ghaggar River in the northeast, while in the southwest it is met with or even cut across the surviving courses of Hakra or Nara rivers in Pakistan. The above course is thought to belong to the legendary river Saraswati of Himalayan origin, mentioned in many early literary works and known to have existed before 3000 BP [4,5].

It is well established that changes in the climate, in consonance with the global climatic changes, influenced the relative dominance of the fluvial and aeolian processes in

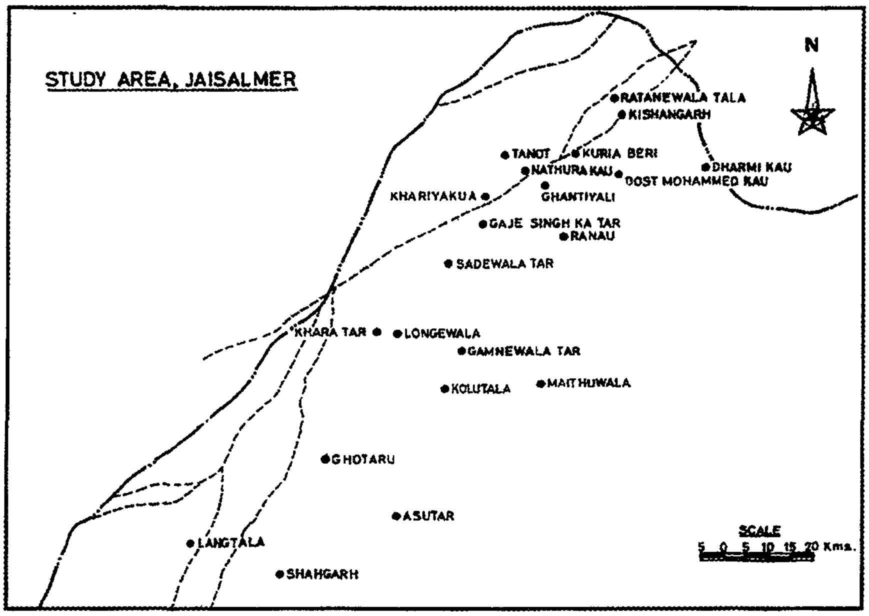

FIG. 2. Jaisalmer study area showing sample locations

the desert region. The morphological and stratigraphic records confirm the pattern of fluctuating climate as dry and wet phases during the Quaternary. The mighty Saraswati River, originally flowing in a southwesterly direction, is supposed to have changed its course many times in the past as a result of changes in climatic conditions as well as

To confirm the above scenario, an environmental isotope study was initiated at the request of Groundwater Department, Rajasthan. Samples were collected from existing dug wells (DW), a hand pump (HP) and tube wells (TW) in the area for analysis of δ^2H, $\delta^{18}O$, ^3H, ^{13}C and ^{14}C as well as for chemistry. Dug wells are quite deep with water levels below 30m or more. Tube wells are cased with screens below 60m depth. Figure 3 shows a cross section of the study area. Table 1 gives the results of analyses and other details for the collected samples.

The electrical conductivity of samples indicates the possibility of interconnection between shallow and deep groundwaters at a few locations. Figures 4(A) & 4(B) show trilinear diagrams prepared for dug wells and tube wells respectively. Both dug wells and tube wells show similar characteristics, as being evolved towards Na-Cl- type.

Figure 5 shows δ^2H versus $\delta^{18}O$ plot for the samples. It is seen that the groundwaters, both from dug wells and tube wells, in general, show similar stable isotope values. They cluster together around a $\delta^{18}O$ value of -6.0‰, along the Meteoric Water Line. These samples are enriched compared to that of present day Himalayan rivers ($\delta^{18}O$: -11‰ to -9‰). Precipitation samples collected from Jaisalmer town showed enriched values (δ^2H: -22‰ and $\delta^{18}O$: -4.3‰). A hand pump sample from Langtala is enriched in stable isotope values and shows evaporation effect. This area is thought to receive recharge from across the border. The best fit line for the tubewell samples show some correlation and indicates to have originated from meteoric water of Himalayan origin.

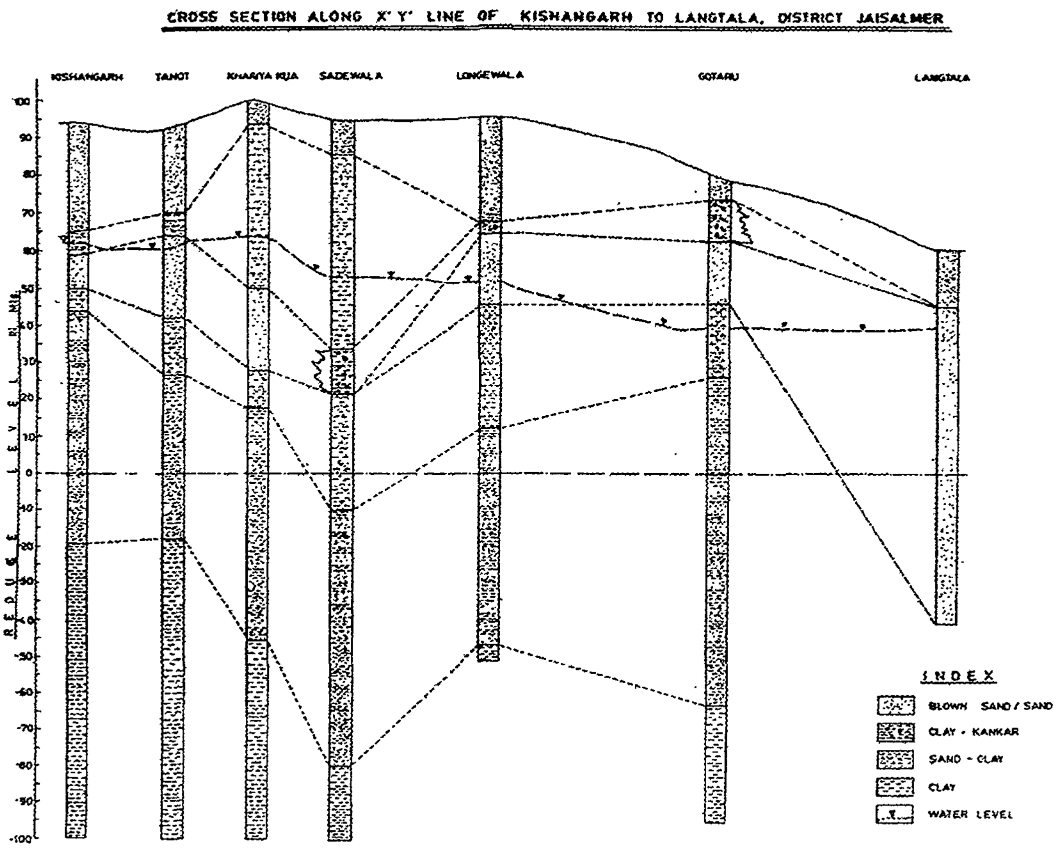

FIG. 3. Cross-section of the study area, from Kishengargh to Langtala (not to scale).

Tube wells as well as most of the dug wells have negligible tritium indicating absence of modern recharge. However, a few dug wells (D1, D2, D7, D8, D10, D12, D14 and D17) do show small components of modern recharge.

^{14}C values of the dug wells (50-80 pMC) indicate that they are old groundwaters, but no flow pattern is discernible from the results. ^{14}C values for tube wells vary from 7 to 49 pMC. The lowest value is from the saline pocket, Sadewala. There is a trend of increase in the apparent ^{14}C age for groundwaters from Kishengarh to Loungewale, along the suspected course. From the relative ages, a groundwater velocity of about 5 m/a may be inferred, which is a normal value expected under similar desert conditions. Relatively higher carbon-14 values at Ranau and Gotaru could be due to mixing with younger waters as indicated from their lower chloride levels. Possibility of recharge from eastern side in these areas is indicated by the existence of dry stream channels. A comparable groundwater velocity could be estimated from ^{14}C values for this section as well.

A possible recharge area for the groundwaters in the study area could be the dry bed of River Ghaggar, which is in Pakistan, where the higher Himalayan waters could get enriched. To study the possible linkage between the dry riverbed and the study area, groundwater samples were collected from Ganganagar area in the northern part of Rajasthan. The samples have marginally depleted ^{18}O values compared to the samples from the study area. They have high content of tritium and ^{14}C content in the range 70-102 pMC. The chemistry of the samples indicates them to be mixtures of local groundwater and that of canal water [Figure 4(C)]. This could be expected from the extensive irrigation in

Table 1 Results of analyses of samples collected from Jaısalmer study area

ID No	Location	Well type	rwl# (m)	Depth* (m)	EC (µS/cm)	δ^2H (‰)	$\delta^{18}O$ (‰)	$^3H \pm 0$ 5 (TR)	$\delta^{13}C$ (‰)	$^{14}C\pm(1\sigma)$ (pMC)
D1	Dharmıkua	DW	63 2	50	2330	-	-7 5	2 1	-9 6	79 5 (2 2)
D2	Kıshengargh	DW	61 8	35	4180	-40 9	-	1 1	-	91 9 (1 7)
T1	,,	TW	-	-	3460	-41 7	-5 6	0 3	-5 7	47 3 (1 4)
D3	Kurıaberı	DW	56 3	39	2100	-42 6	-5 7	0 5	-8 3	58 8 (1 6)
D4	Nathurakua	DW	62 3	35	3040	-38 4	-6 3	0 3	-7 9	69 3 (1 8)
D5	Ghantıyalı	DW	57 9	38	2820	-41 2	-6 0	0 6	-	54 9 (1 5)
T2	Ghantıyalı	TW	-	-	3660	-45 6	-6 6	0 5	-4 0	31 2 (1 2)
D6	Kharıakua	DW	63 8	-	8900	-	-4 8	-	-	-
D7	Gajesıng ka tar	DW	64 1	40	4620	-	-4 7	2 1	-7 7	64 9 (1 9)
D8	Ranau	DW	54 8	55	2060	-46 1	-6 0	1 7	-	-
T3	,,	TW	-	62(74-147)	1890	-45 3	-6 2	0 6	-7 4	48 8 (1 5)
D9	Sadewala	DW	52 8	45	9120	-43 6	-6 3	0 8	-13 6	-
T4	,,	TW	-	35(87-161)	7600	-	-3 4	0 4	-7 7	~~0~~6 6 (0 9)
D10	Loungewala	DW	51 6	45	9370	-39 9	-5 9	1 0	-	-
T5	,,	TW	-	-	2740	-44 0	-6 2	0 4	-5 6	10 4 (0 9)
T6	Gumnewala	TW	-	65(87-147)	4060	-30 0	-6 1	0 6	-	-
D12	Ghotaru	DW	39 7	42	3650	-41 1	-6 4	1 1	-	62 7 (1 9)
T7	,,	TW	-	40(91-157)	2270	-48 7	-6 9	0 4	-7 3	20 7 (1 0)
D13	Asutar	DW	37 4	65	2390	-	-	0 3	-	-
T8	,,	TW	-	68(73-95)	2560	-47 0	-6 3	0 4	-7 5	36 1 (1 3)
D14	Langtala	DW	39 0	23	2380	-46 1	-6 0	1 0	-	64 8 (1 7)
H14		HP	-	-	3400	-39 6	-5 0	0 3	-6 2	68 6 (2 0)
T9	Shahgarh	TW	-	-	10090	-38 0	-6 0	0 4	-	-
D16	Ratnewala	DW	-	28 3	10330	-	-4 7	-	-	-
D17	Dostmohamed kua	DW	-	47 2	1380	-	-6 5	1 0	-7 6	49 7 (1 5)
D18	Mıtuwala	DW	-	71 7	6780	-	-4 6	0 6	-11 0	57 9 (1 7)
D19	Kolutala	DW	-	-	-	-	-5 8	0 3	-	-

rwl reduced water level, (*) depth to water level wıth depth for screens ın TW gıven ın bracket, TR Trıtıum Ratıo, pMC percent Modern Carbon

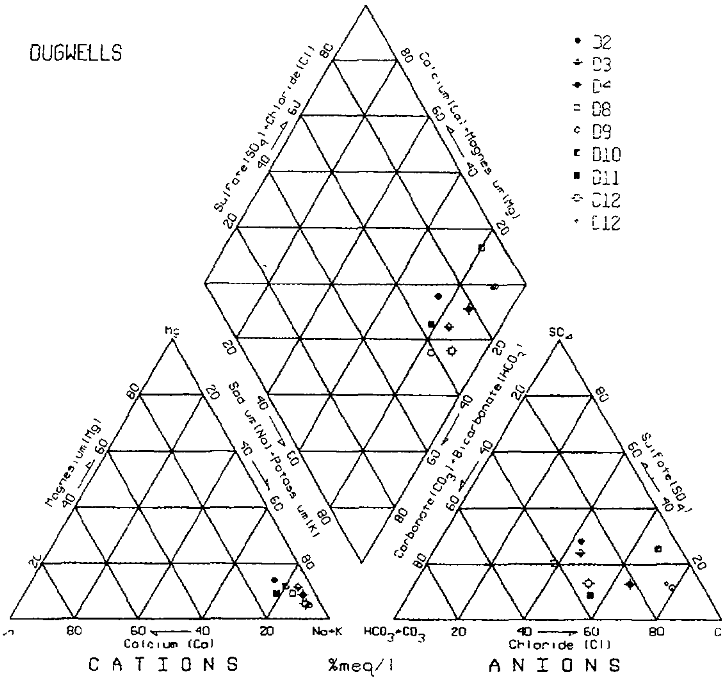

FIG 4(A). Trilinear diagram for dugwell samples.

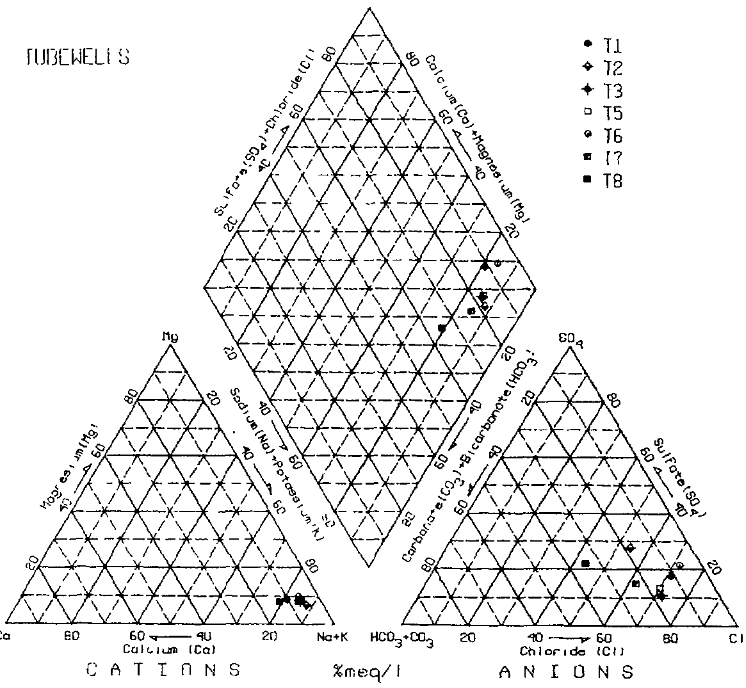

FIG. 4(B). Trilinear diagram for tubewell samples.

Table 1(B). Ganganagar samples

ID No.	Location	Well type	Depth (m)	EC (μS/cm)	$\delta^{18}O$ (‰)	$^{3}H \pm 0.5$ (TR)	$\delta^{13}C$ (‰)	$^{14}C \pm (1\sigma)$ (pMC)
G16	Pelibenga	DCB	125	2720	-6.4	23 6	-7.5	94.4 (1.5)
G17	Near Anupgargh	,,	120	830	-5.9	17.6	-7.6	101.9 (1 6)
G18	Near BSF post	,,	118	2360	-5.4	18.2	-11.8	97.0 (1.4)
G19	Gharsana	,,	-	1730	-7 7	20.6	-6.3	71 7 (1.3)
G20	Vijaynagar	,,	85	4520	-7.0	22.5	-12.3	102.0 (1.4)
G21	K. Bishnoi	,,	70	740	-6.3	16.5	-	89.8 (1.5)

DCB. dug cum borewell

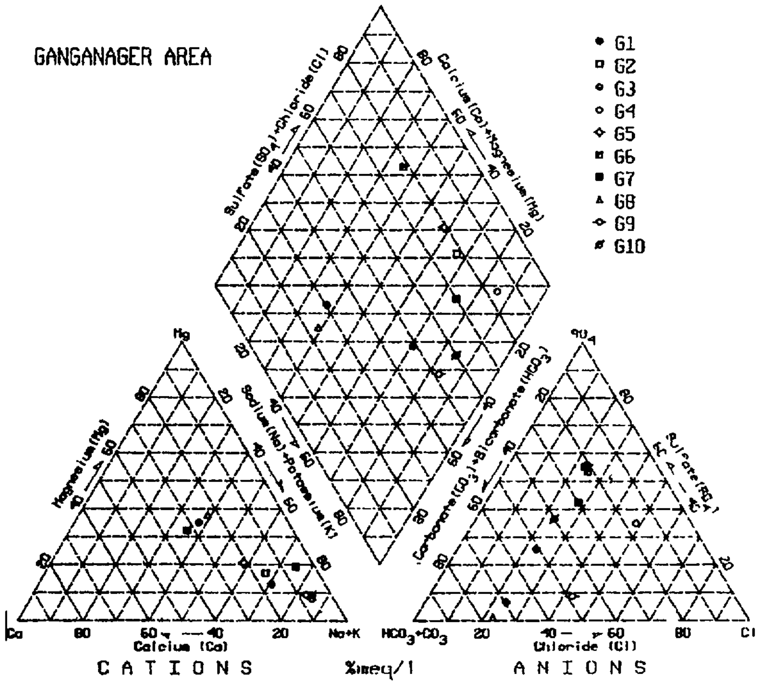

FIG. 4(C). Trilinear diagram for samples from Ganganagar area

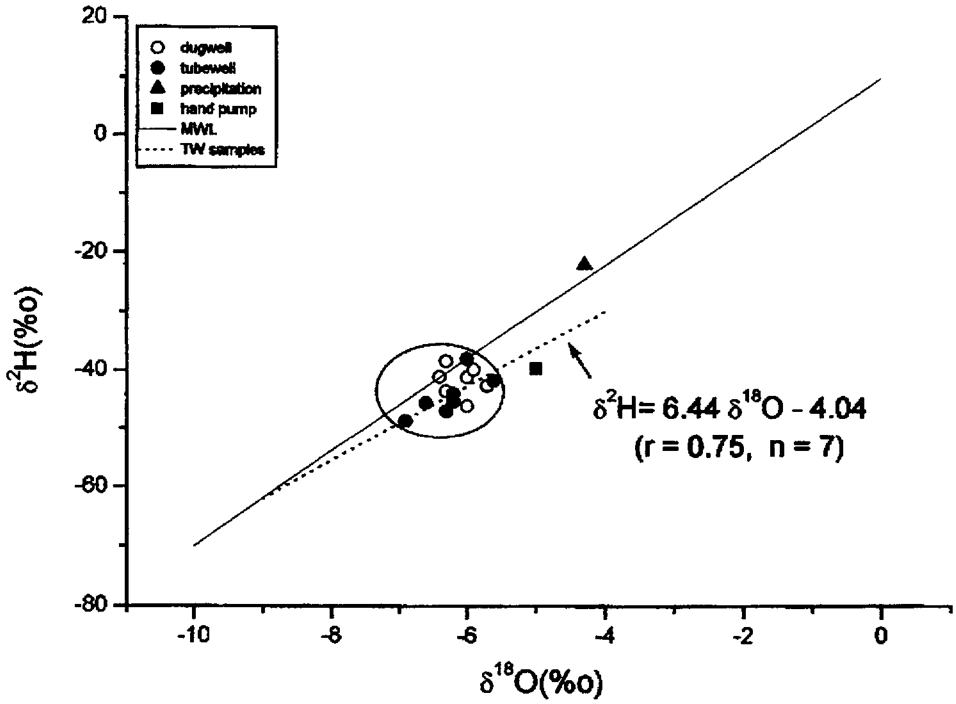

FIG. 5. δ^2H - $\delta^{18}O$ plot for samples from Jaisalmer study area

the area through canal network and is indicated by the high tritium values shown by the samples. No sample with a signature of unaffected native groundwater could be collected from the area.

It is interesting to mention a similar but more exhaustive study reported, which was conducted in the area across the border in Pakistan, covering the dry bed of river Ghaggar [6] From the relative stable isotope values, the groundwaters of our study area do not seem to have originated from the Ghagger bed

In conclusion, the study indicates that any direct headwater connection to the groundwaters in the study area from present day Himalayan sources seems to be remote The groundwater is slow moving with a velocity, which seems to be normal under similar desert conditions The groundwaters do not indicate to have undergone high evaporation The stable isotope, tritium and radiocarbon values indicate that they are palaeowaters

2.2. ISOTOPE STUDY IN THE INDIRA GANDHI NAHAR PARIYOJANA AREA.

The Indira Gandhi Nahar Pariyojana (IGNP) in the northwestern Rajasthan, with a command area of about 15 4 lakhs hectors, is one of the largest irrigation cum drinking water project ın the country It caters to five districts of Rajasthan State The main canal is 450 km long The project area where the isotope study was carried out is in Bikaner and Ganganagar districts, in the northern part of the state Stage 1 of the project has been completed and Stage 2 work is in progress With the availability of large quantities of water, the project is facing twin problems of water logging and development of salinity over substantial parts in the command area

2.2.1. Geology and Hydrogeology

From lithologs of the area, it has been observed that consolidated sedimentary formation/ sandstone is encountered at depths of 135 to 200 m Younger and older alluvia of Quaternary age are the main water bearing formations The former, comprising of consolidated to loosely consolidated sediments of sand, silt, clay and kankar (calcrete), is seen in narrow stretches adjoining the canals, their distributaries and in the Ghaggar flood plains and bear good quality groundwater (TDS < 2000) The older alluvium comprises of sandy and gypsiferous clays with kankar The quality of ground water is generally saline and the salinity increases with depth [7] Groundwater generally occurs under water table conditions, but at a few places it also occurs under semi confined conditions owing to the presence of overlying impermeable clay horizons

2.2.2. Water logging and salinization

Groundwater levels, which was about 40 to 60 m below the surface before the inception of the canal, have been rising at the rate of 0 3 to 1 2 m per year, affecting many areas, changing them to critical or potentially critical areas This also has resulted in uplifting of the native saline groundwaters Together with evaporation from shallow water levels, salinization of soil and groundwater has become an acute problem in many parts along the project area Many factors have been identified for the development of above situation [7, 8]

- presence of hydrological barrier layers In almost along the entire flow in the command area, hydrological barrier layers are encountered at varying depths The command area is covered with aeolian sand deposits along with flat interdunal plains The aeolian deposits comprise fine sand, silt and kankar, which have restricted permeability compared to the over lying permeable layers of fine to medium grain sand The interdunal flats mostly consist of lens shaped clay formations, impasto gypsum layers etc., which affect the rate of infiltration.

- lack of on-farm development facilities such as field drain, land shaping etc., resulting in poor water utilization and its application.
- excess irrigation and return flow of irrigation waters: Availability of large quantity of water and absence of control mechanisms resulted in non-optimum utilization.
- seepage losses from canals: Though the main canal and tributaries are lined ones, seepage losses are visible at many places.
- sparse use of groundwater due to its poor quality.

2.2.3. Isotope study

An isotope study was initiated in collaboration with the Groundwater Department, Rajasthan to study the contribution from canal and return flow of irrigation waters to the groundwater as well as interconnection between the shallow and deep aquifers. Two sets of samples from Stage 1 of the command area, with an interval of two years between them, were collected from canal waters (CW), surface waters (SW), shallow groundwaters (piezometers), and deep groundwaters (piezometers and tube wells). They were analysed for environmental Deuterium, Oxygen-18, Tritium and Carbon-14. Figure 6 shows the study area and sample locations and Table 2(A) and 2(B) give the details and results of analyses of the samples collected.

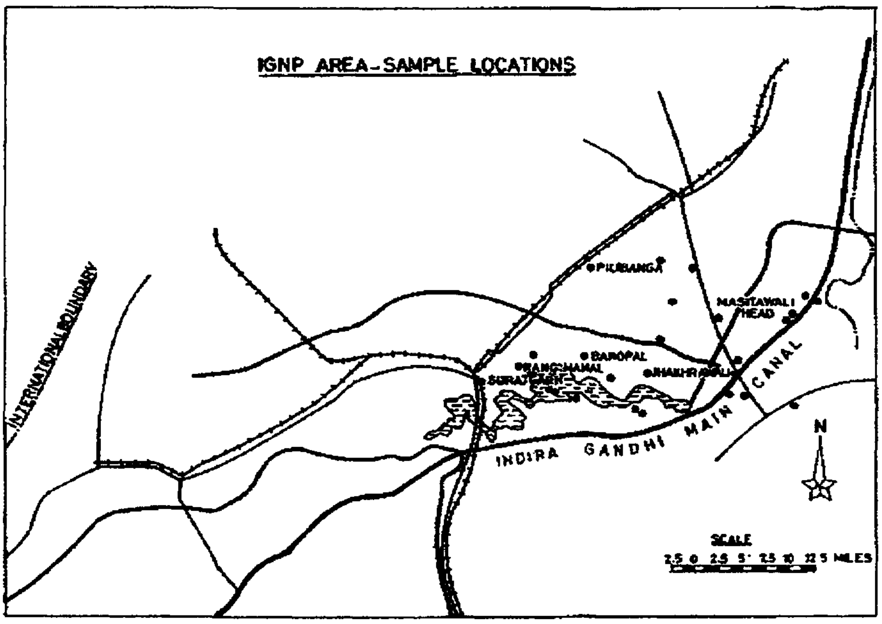

FIG. 6. IGNP study area with sample locations

Table 2(A). Samples collected from IGNP study area (Set-1)

ID No	Sample	Type	swl (m)	Cl (ppm)	^3H (TR)	δ^2H (‰)	$\delta^{18}O$ (‰)
1	Chaya	PM	7 5	10140	<5 0	-37	-4 9
2	ORD	CW	-	21	14 6	-83	-12 0
3	Masidawali Head	PM	1 5	-	-	-46	-7 7
4	Luni ka dani	PM1	1 4	1560	62 2	-55	-8 5
5	,,	PM2	1 4	7660	<5	-46	-6 3
6	Bharusari	PM	4 6	234	15 5	-52	-8 3
7	Jhakrawali	PM	0 7	2730	-	-42	-6 0
8	Baropal	PM	7 8	106	11 5	-30	-3 4
9	Manakteri	SW	-	24080	7 8	+10	+3 4
10	,,	PM	4 3	78	-	-38	-5 3
11	Rangmahal	PM	4 1	-	-	-31	-4 4
12	Ghaggar River	SW	-	-		-37	-5 0
13	Manaksar	PM	4 5	-	12 3	-70	-10 2
14	Birmana	PM	49 0	5640	18	-58	-8 7
15	Rajasar	TW	35 0	-	-	-54	-7 6
16	Lunkaransar	PM1	2 2	2760	14	-40	-5 9
17	,,	PM2	3 5	7070	<5 0	-13	-0 6
18	Lunkaransar Colony	PM	-	7060	-	-36	-5 2
19	Bikaner	CW	-	-	-	-77	-11 7
20	RD 838	TW1	50 0	-	8 8	-42	-5 8
21	,,	TW2	47 0	-	-	-54	-9 0
22	,,	PM1	0 9	-	-	-61	-9 8
23	,,	PM2	0 9	-	-	-48	-8 0
24	RD 837	CW	-	-	13 8	-73	-11 3
25	RD 961	PM	7 3	-	-	-61	-10 7
26	TW 1117	TW	12 0	-	-	-51	-9 0

Figure 7(A) shows the δ^2H-$\delta^{18}O$ plot for the first set of samples The results indicate the following

- Canal waters, which originate from the Himalayas, are depleted in stable isotope values compared to local precipitation and local groundwaters These fall in the group A on the plot Samples from tube wells and piezometers, from areas near the canal and its distributaries which are affected by canal water, fall in group B on the plot and are represented by the equation, $\delta^2H = 8\ 02\ \delta^{18}O + 15\ 69$
- Piezometer and tube well samples affected by return flow of irrigation and water logging fall in group C They show evaporation effect and fall on the regression line represented by the equation, $\delta^2H = 5\ 27\ \delta^{18}O - 10$ This group also includes surface water samples from Ghaggar flood plain, Manakteri brine as well as saline waters
- Tritium value of canal water is slightly higher than that of local precipitation Native saline waters show negligible tritium Some Piezometer samples showed high tritium values (>50 TR), indicating presence of trapped canal waters with bomb tritium from the early period

Table 2(B). Sample collected from IGNP area (Set-2)

ID No.	Sample	Type	swl#	EC (μS/cm)	pH	δ^2H (‰)	$\delta^{18}O$ (‰)	^3H (TR)	14C (pMC)
1	10/11 STB	TW	3.5	605	7.6	-46.0	-7.0	<5.0	81.5
2	S.B. Canal	SW	-	236	7.3	-50.0	-8.5	13.1	-
3	10/11 STB	PM	12.7	1150	8.2	-26.9	-4.0	<5.0	-
4	Water log	SW	-	27550	-	+5.1	+4.6	-	-
5	Rangmahal	PM	4.1	9450	8.7	-25.8	-3.5	8.6	70.5
6A	Hanuman T.	PM	15.5	437	9.2	6.8	+2.5	8.0	-
6B	,,	HP	-	343	7.5	+5.8	+1.9	<5.0	-
7	Saddle-8	SW	-	119	9.2	-52.0	-7.2	5.8	-
8	Manakteri	HP	3.6	824	8.4	-12.3	-1.7	13.8	76.7
9	Baropal	HP	3.4	720	7.5	-35.0	-4.1	<5.0	-
10	Daulatawali	PM	5.8	813	10.3	-57.0	-8.1	<5.0	-
10A	,,	SW	-	-	-	-36.8	-6.0	-	-
11	4NSWB	TW	-	4300	8.5	-48.8	-8.0	13.3	72.7
12	Kalibangan	PM	13.3	1608	7.9	-46.0	-7.0	15.9	-
13	20 SPD	PM	5.0	3640	7.8	-46.0	-7.0	<5.0	-
14	13 SPD	PM	1.7	7160	10.9	-39.7	-6.5	-	-
15	11 SPD	PM	6.9	2770	8.0	-44.0	-7.3	-	-
16	S.B. canal 2CS	SW	-	278	-	-55.0	-8.3	-	-
16A	2CS	PM	8.9	450	8.1	-53.2	-8.0	-	-
17	1CS	TW	-	4730	7.4	-52.6	-7.8	8.3	51.6
17A	1CS	HP	-	1655	6.6	-52.6	-7.9	23.0	-
18	Main canal	SW	-	270	7.2	-50.5	-8.0	-	-
19	5KWD	PM	2.0	670	7.2	-53.0	-7.6	<5.0	-
20	Lakhuwali	PM	1.2	6330	7.5	-58.0	-8.4	21.9	-
21	12 RP	TW	1.8	1260	7.2	-50.0	-7.8	<5.0	-
21A	12 RP	HP	-	2070	8.1	-48.4	-7.1	<5.0	-
22	14 NDR	HP	-	930	-	-55.0	-8.2	-	-
23	GFDC LH Rd.	HP	-	430	-	-40.0	-5.0	-	-
24	17 KSPSM	PM	11.4	2260	-	-50.0	-7.2	-	-
25	21 NDR	PM	7.7	4160	-	-46.0	-6.1	<5.0	-

SW: surface water; HP: hand pump; TW: tubewell; PM: piezometer; (#) static water level

At many locations the groundwater is a mixture of canal water and native groundwater. From end member compositions, it is possible to estimate their contributions. For e.g., The saline sample from Luni ki Dani (PM2), with low tritium content, may be considered to represent native saline water, having a $\delta^{18}O$ value of -6.3‰. Assuming $\delta^{18}O$ value of -11.7‰ for canal water, its contribution at Luni ki Dani (PM1) with $\delta^{18}O$ value of -8.5‰ may be estimated as

$$X = \frac{\delta^{18}\text{ of PM1} - \delta^{18}O\text{ of PM2}}{\delta^{18}O\text{ of canal} - \delta^{18}O\text{ of PM2}} = \frac{-8.5 + 6.3}{-11.7 + 6.3} = 0.41 \text{ or } 41\%$$

Using a similar approach, canal water contribution at Bharusari (6), Manaksar (13) and Birmana (14) may be estimated at 37%, 62% and 44% respectively.

Figure 7(B) is the δD - $\delta^{18}O$ plot for the second set of sample taken from the study area, but all are not from the same locations. The trend seen is similar. A few samples taken

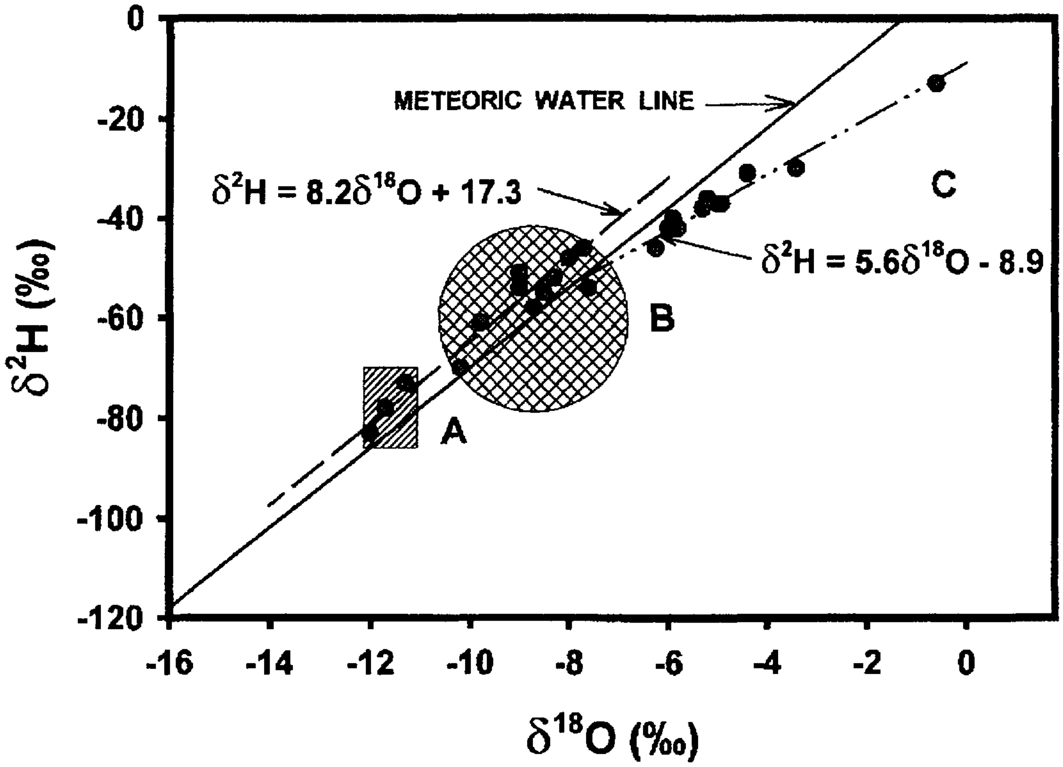

FIG. 7(A). δ^2H - $\delta^{18}O$ plot for samples, IGNP area, (set-1)

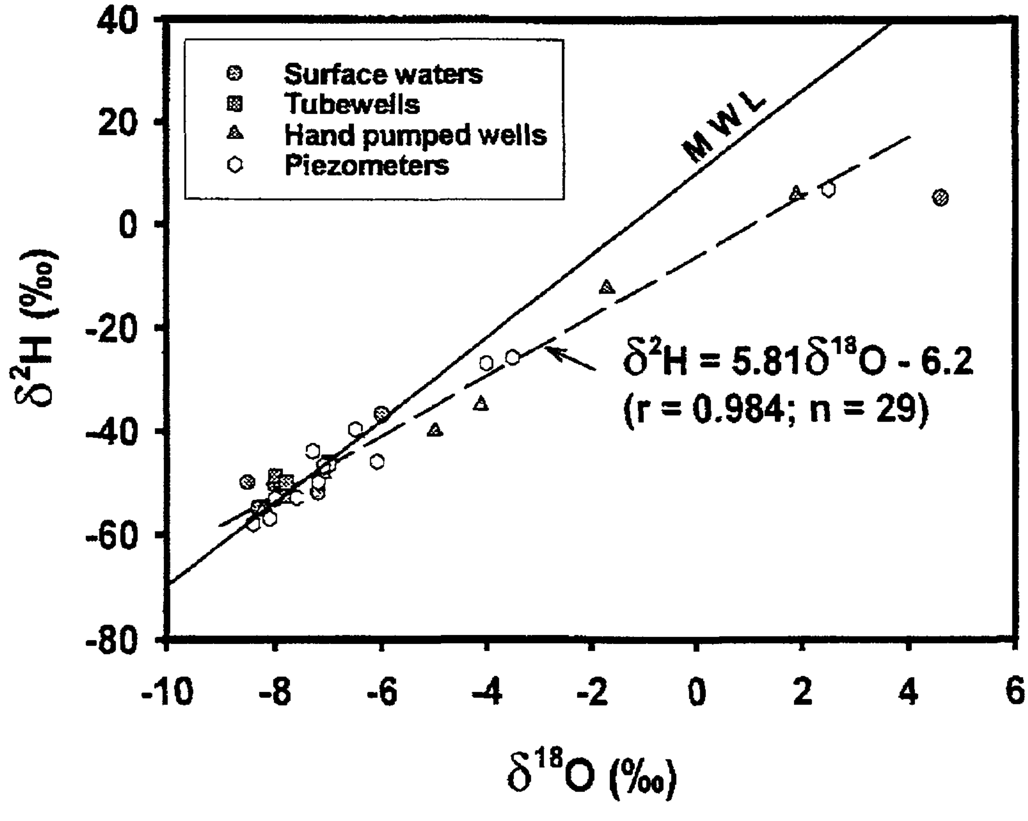

FIG. 7(B). δ^2H - $\delta^{18}O$ plot for samples, IGNP area, (set-2) from the area showed ^{14}C values in the range 52-82 pMC. These samples also have bomb tritium to indicate that they are mixture of old native water and canal water. Samples 8,12 and 23 (set 2) show enrichment in stable isotope values and have high tritium concentrations. They have EC values between 430 to 1600 μS/cm. These waters indicate presence irrigation return flows.

The limited study carried out shows that the groundwaters in the study area in general are extensively affected by canal water. At many locations canal water is seen mixed with native saline water. Evaporation from shallow groundwaters in the waterlogged regions also contributes to the observed high salinity.

2.3. RECHARGE STUDIES IN BARMER AND BIKANER DISTRICTS.

Barmer District lies in the southwestern part of the Rajasthan State. Figure 8 shows the study area and sample locations together with some geological information. The area receives a mean annual rainfall of ~280 mm. The Tertiary aquifer having fresh water is the most important one in the area. Lathi formation of Jurassic age is present in the northern side and Malani suite of igneous rock is present on other sides. Two lenticular outcrops of Tertiary sandstone, which are generally dry, are also found in the central part. In the middle portion comprising Nagurda, Bheemda and Bhadka, shallow aquifers are under phreatic condition while the deeper aquifers are under confined or semi-confined condition. Table 3 lists the samples collected from the study area together with analysis data. Shallow well samples are generally brackish and of Na-Cl type. Deep well samples, which are brackish, are also of Na-Cl type. The deep fresh groundwaters are of Na-HCO_3 type

Figure 9 shows the δD versus $\delta^{18}O$ plot for the samples. Deep groundwater samples, which are comparatively fresh, are depleted in stable isotope values and form group A along the MWL. A brackish water sample from Bhadka also falls in this group. Except the sample from Rajdhal, which is from the northern dunal part, other samples are

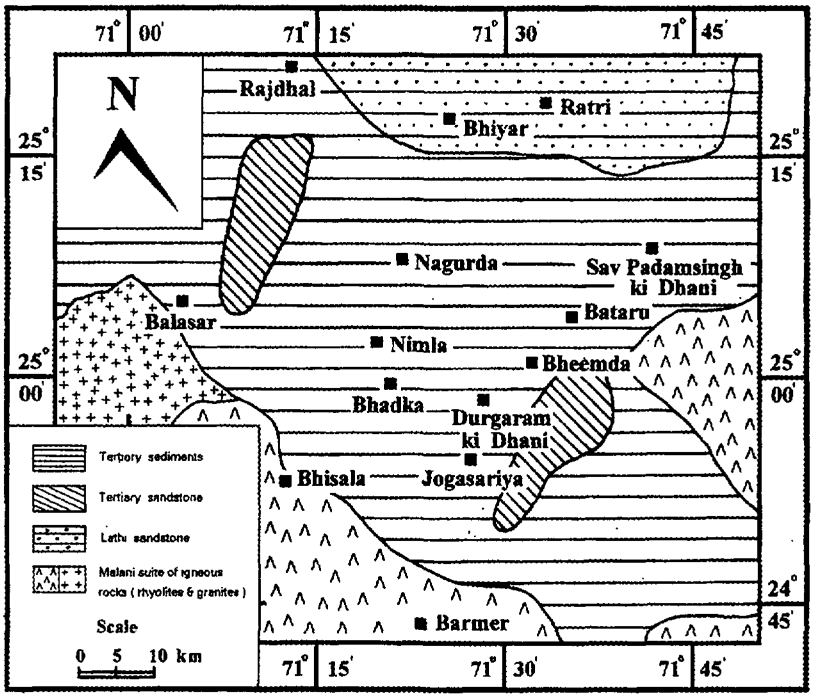

Figure 8. Study area showing sample locations, Barmer

Table 3 Isotope and relevant data for samples from Barmer, Rajasthan

ID No	Location	Depth(m)	EC ((μS/cm)	δ^2H (‰)	δ^{18}O (‰)	^{3}H (TR)	14C (pMC)
			Deep wells				
2	Bheemda	280	1830	-50 1	-7 3	<1 0	22
3	Jogasar	285	2450	-51 7	-7 7	1 4	25
4	Bhadka	200	4500	-51 5	-7 5	<1 0	42
5	Nımla	220	1560	-56 1	-8 0	1 0	50
6	D Ram kı Dhanı	100	3850	-43 2	-6 0	<1 0	23
7	Rajdhal	125	1380	-53 4	-8 1	1 7	-
9	Bhıyar	100	3000	-36 3	-4 5	-	-
10	Ratarı	100	1820	-35 9	-5 2	-	-
11	Nagurda	95	1710	-53 4	-8 0	-	-
			Shallow wells				
D1	Bheemda	-	6700	-40 8	-5 6	6 0	-
D2	Bhataru	-	5600	-34 1	-4 5	3 0	-
D3	D Ram kı Dhanı	-	4450	-45 1	-6 5	3 0	-
D4	Balasar	-	630	-20 3	-4 2	21 0	-
D5	S P Sıng kı Dhanı	70	3200	-38 9	-5 0	-	-
D6	Bhısala	40	4400	-26 9	-3 95	-	-

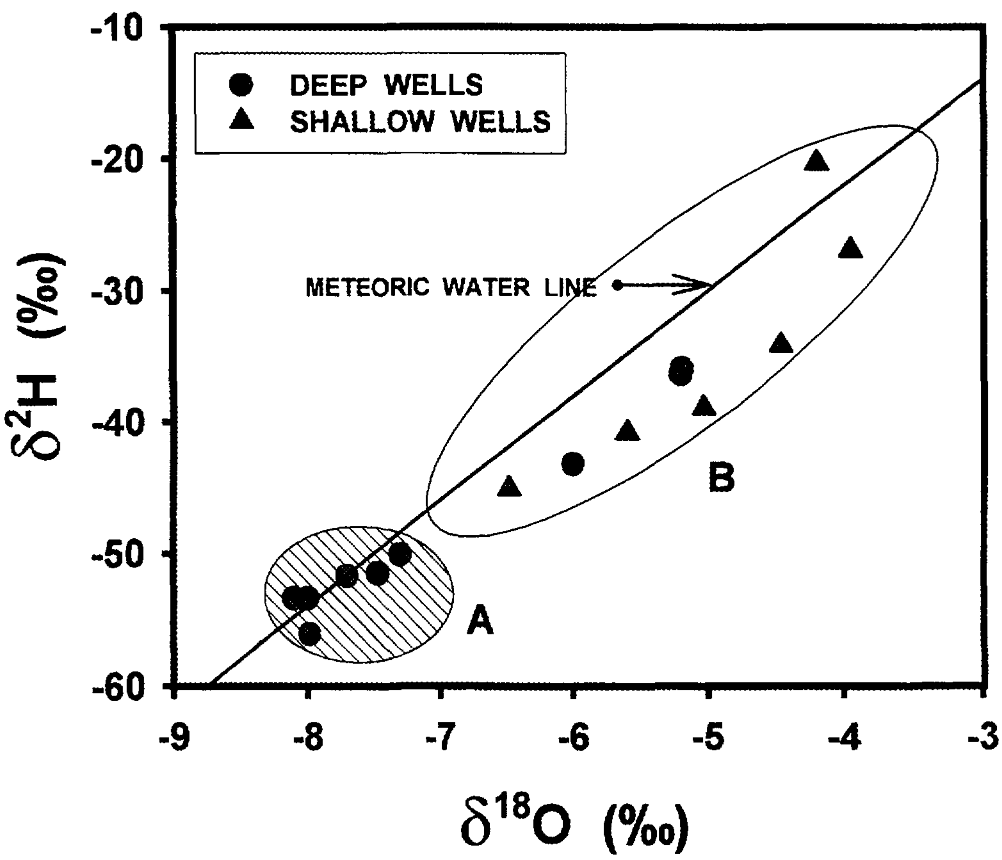

FIG 9 δ^2H - $\delta^{16}O$ plot for samples, Barmer area from the central portion of the study area. The shallow and deep well samples from Durgaram ki Dhani as well as other shallow well samples, which are brackish form the group B. Samples from the Lathi sandstone aquifer also are included in this group. These samples show evaporation effect in their stable isotope values. They contain measurable concentrations of tritium indicating components of recent recharge.

The higher electrical conductivity shown by the shallow well samples could be due to leaching of salts from the soil matrix or due to concentration of salts by evaporation. The shallow and deep well samples from Durgaram ki Dhani are seen as mixtures of deep and shallow groundwaters. Their similar tritium values also support this. A shallow sample from Balasar, which is fresh, has tritium content of 21 TR, which is high compared to present day precipitation value of about 10 TR. This well probably taps water from the weathered igneous rocks and is about two to three decades old. The deep fresh waters are depleted in stable isotope values and have negligible tritium. Their ^{14}C concentration ranges from 50-22 pMC with model ages (IAEA) 4300 to 9700 BP. These groundwaters appear to have recharged during the cooler and pluvial phases in the Holocene (9).

In a similar case (9), the shallow and deep well samples (depth >100m) from Bikaner have depleted δD and $\delta^{18}O$ values (Fig. 10) and have negligible tritium contents in them. Model radiocarbon ages vary from modern to 9500 BP. Similar δD and $\delta^{18}O$ values of the shallow and deep groundwaters and young waters encountered in some of the deep wells indicate mixing of the shallow and deep groundwaters, probably due to the heavy exploitation of the groundwater in the area.

3. CONCLUSIONS

The above studies indicate that in the southern part of arid Rajasthan, where precipitation received is higher compared to the northwestern region, shallow aquifers could receive recent recharge. The mechanism could be direct infiltration after intense

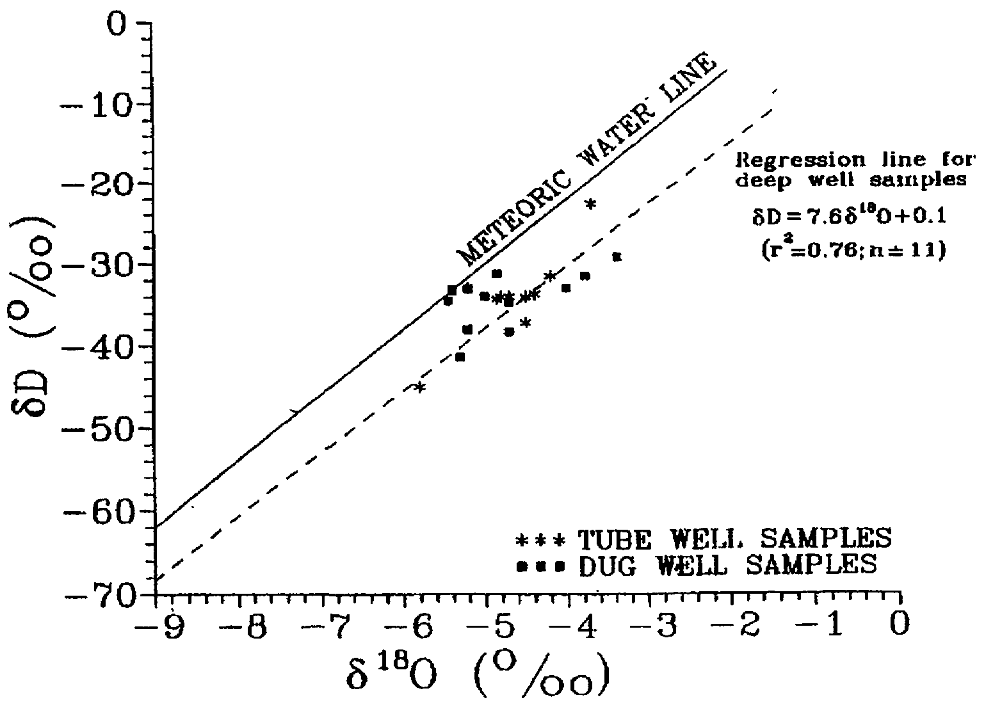

FIG. 10. δ^2H - $\delta^{16}O$ plot for samples, Bikaner area

episodic rain events followed by floods In the northwestern part, present day recharge is rare or negligible In many parts of the desert deep fresh groundwater is available, which were recharged in the past (as indicated by the low carbon-14 values), when the climatic condition prevalent were more favorable than the present Reconstruction of the past climate in the region from Palaeoclimatological and palaeontological studies (10,11), indicate that cooler and pluvial conditions in the Holocene were present in this region when recharge to these aquifers could have taken place However, the absence of modern recharge and evidence of over exploitation observed in many areas stress the need for a proper management of such scarce groundwater resources Isotope techniques can play an important role in such efforts

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ISOTOPE STUDY OF IMPACT OF CLIMATIC CHANGES ON HYDROLOGICAL CYCLE IN CENTRAL ASIAN AND CASPIAN ARID REGION

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Abstract

The problem of replenishment of groundwater and lakes in the Central Asian and Caspian arid region during the Late Pleistocene-Holocene transition time on the basis of isotope studies is discussed. Interpretation of the oxygen and carbon isotope record from the palaeogroundwaters and lake sediments shows that during climate cooling over the Eurasian continent its humid zone was extended towards the arid regions. In addition, voluminous glaciers were accumulated in the northern and southern mountain regions. Intensive melting of the glaciers during the transition time provided effective replenishment of the aquifers and lakes in the arid zone by fresh water.

1. INTRODUCTION

The natural phenomenon of the Earth aridity in a number of large regions appears in deficit of atmospheric moisture. This is because of specific conditions in moisture transfer over the regions. As a consequence of such conditions deficit of soil moisture appeared due to excess of evaporation relative to precipitation. The ratio of evaporation to precipitation is called index of aridity. The value of the index for arid regions is equal to $E/P>3$, and for semi-arid regions this value ranges in $1<E/P<3$ limits. The value of aridity index is characteristic for a region with positive mean annual temperature. But value of index $E/P>1$ is also observed for the regions with cold continental climate. Russian northeast Siberia and region of Yakutia in particular represent an example of such phenomenon.

It is well known that the main reservoirs of water resources in arid and semi-arid zones, which are groundwater, closed lakes and mountain glaciers, are replenished during humid climate periods. Current water of precipitation of amount of 50-200 mm/yr is lost by evaporation. In this connection the problem of impact of climate changes on hydrological cycle in arid and semi-arid regions is of great practical importance.

Isotope studies of palaeogroundwaters, glaciers and lake sediments in arid regions give unique information for solution of this problem. Environmental isotopes of oxygen, hydrogen, carbon and uranium series in climatology are mainly used for determination of palaewater temperature and the age of the climate events. Palaeoclimatic studies of the ocean carbonate shows also possibility to calculate the volume of the glaciers was accumulated in the polar and mountain regions using oxygen isotope data. In this paper we try to analyse the collected isotope data of groundwater and lake sediments in the Central Asian and Caspian arid region in order to identify the glacial-interglacial periods of replenishment of their water reservoirs.

2. OBSERVATIONS OF PALAEOGROUNDWATER

2.1. Humid Region

Let us consider a general picture of replenishment of groundwater within European and Asian Russia and in an arid region of Central Asia during the Pleistocene-Holocene transition time using the data obtained by the authors [1, 2].

During last glacial maximum 22-14 Kyr BP groundwaters within the central and northern regions of European Russia were not replenished. In accordance with our isotope data this process was completed 14-12 Kyr BP. First windows for the melted water infiltration were appeared along river and lakebeds. Intensive groundwater recharge in South Karelia is recorded during after-glacial optimum about 7-5 Kyr BP.

Analogous conditions of groundwater resources formation are typical for the Cambrian-Vendrian complex of the Baltic Sea in Estonia. Here intensive groundwater recharge through melting zones of riverbeds was favoured by low water pressure in the aquifers because of degradation of cryogenic strata. The prolonged frozen stage of the Cambrian-Vendrian complex most likely resulted in accumulation of ^{234}U in the crystalline lattices defects of minerals. The uranium isotopes entered into the liquid phase preferentially during development of the permafrost and were incorporated into the aquifers together with the melted water.

Degradation of the permafrost thickness in an aquifer is likely resulted in formation of zones with low water pressure are observed in Yakutia, which led to quick filling of aquifers with fresh water. Using the palaeoclimatic temperature gradient of about -0.6‰/^{0}C one can conclude that the mean annual temperature during the time of the glacier formation in the region under study was about 14^{0}C lower than modern temperature of 5^{0}C, i.e. -9^{0}C. The present similar temperatures are observed in Yakutia region (northeast of Siberia), where the mean annual isotopic composition of precipitation now is close to that in palaeowaters of Estonia.

The reconstruction of groundwater recharge and discharge for the central region of European Russia was done by using the radiocarbon age of freshwater carbonate sediments, which were formed at the discharge of groundwater into river valleys, and by water circulation in the carbonate rocks and tuffs of the Carboniferous age. Palaeotemperature studies of the carbonate sedimentation, which were carried out on the basis of oxygen isotope thermometry, demonstrate temperature values ranging from 1.5^{0}C to 14^{0}C. Higher temperatures correspond to decrease of age of the carbonate sediments. The wide range in temperature variation of the carbonate sedimentation reflects not only the impact of the Holocene climatic epoch, but also the effect of the seasonal variation in groundwater temperatures. Calcareous tuffs with an age greater than 10 Kyr were not found in Moscow region up to now after examination of 70 samples taken from 6 different sites. This fact indicates the absence of groundwater discharge into river valleys during the minimum stage of the Valday glaciation owing to the continuous formation of permafrost (18 Kyr BP). There are no tuffs with an age exceeding 25-30 Kyr, which is related most likely to their complete destruction by the glaciers.

No recharge of groundwaters in sediments of the Upper Devonian in the Central European region of Russia was found in the course of study on the exploration of groundwater occurrences in the south-western part of the Moscow artesian basin. The results obtained show that approximately 12-25 Kyr BP ago restrictions in recharge of the aquifers existed which can be related to the presence of permafrost. The isotopic composition of atmospheric precipitation during Valday glaciation 25-30

Kyr ago was similar to the modern values. According to the isotope gradient, the temperature in the regions studied during the seasons of the aquifer replenishment was only 1-1.5C lower than the modern temperature.

2.2. Semi-Arid Region

Within the southern part of west Siberian lowlands the determined radiocarbon age of groundwater of the Beshcheul series of the Lower Miocene is about 8 Kyr BP. The minimum δD and $\delta^{18}O$ measured values were -140‰ and-18‰ respectively. These values differ considerably from the mean annual isotopic composition of atmospheric precipitation (δD=-108‰ and $\delta^{18}O$=14.2‰), and correspond to average values for cold seasons of the year from October to May. The experimental data obtained lead to the conclusion that the beginning of the intensive groundwater recharge of the Beshcheul series at the site studied began not earlier than 8 Kyr ago after degradation of the permafrost rocks. The δD and $\delta^{18}O$ values obtained is evidence that mean annual temperatures in the south of the west Siberian lowlands were lower than modern values by about 6^0C. This conclusion proves independent stratigraphic and radiocarbon studies carried out in the southern part of the west Siberian lowlands [3]. Since the modern mean annual temperature in the region does not exceed 1^0C and 8 Kyr ago was -5^0C, at such low temperatures it is difficult to assume complete degradation of the frozen rocks and intensive recharge of groundwater. The groundwater isotopic composition most likely reflects the climatic conditions of the Late Pleistocene in the south Ural mountain ridges, where the glaciers which recharge the surface channel network of the south of the west Siberian lowlands were probably formed.

2.3. Arid Region

Isotope studies of the Yaskhan reservoir of fresh water in the central region of Preuzboy Kara-kum desert (west Turkmenia) showed that the majority of fresh water whose mineralization is less than 0.6 g/l are homogeneous in their ^{14}C content (17-22 pmc). Assuming that the underground reservoir was formed from infiltration of waters of the Pra-Amu Darya River (the reservoir is located near the dry bed of the Uzboy River), where the ^{14}C concentration was 100 pmc, the age of the reservoir water is about 13 Kyr BP. However, as our study of the modern rivers of Central Asia indicated, the ^{14}C content there did not exceed 90% of its modern content in the atmosphere. If this assumption is valid for the Late Holocene, the age of the reservoir waters will be about 12 Kyr.

The hydrogen and oxygen isotopic composition of the reservoir of fresh water and saline waters of the Kara-kum Stream below it differs considerably. In the first case, the average value of δD and $\delta^{18}O$ are -66 and -7.2‰, respectively, while for the second type they are -78 and-7.8‰. In waters of the surface part of the reservoir at depth of 4 m near Yaskhan Village, where the ^{14}C content was found to be related to the modern atmospheric recharge (the concentration of the ^{14}C was 65 pmc), the values of δD and $\delta^{18}O$ were -54 and 7.9‰ respectively.

The excess parameter **d** is 18.4 and -16.6‰ for fresh and saline waters, respectively, indicates the considerable transformation of atmospheric precipitation recharging groundwaters owing to non-equilibrium evaporation processes. For modern recharge waters **d**=9.2‰. The excess parameter value is close to the value which is typical of the majority of meteoric waters, for which **d**=10‰.

Isotope studies of the Yaskhan lens of fresh waters show that there was quick formation of the balk of fresh waters not earlier than 14 Kyr ago. According to deuterium concentrations, the climate in the Late Pleistocene-Early Holocene in the region of west Turkmenia was colder than modern climate. The mean annual temperatures were lower than modern ones by approximately 2-3^0C. In accordance with data obtained during the isotope studies of the Syr-Darya, Chusary and Illy artesian basins in south Kazakhstan, in the period of 30-14 Kyr the climate of that arid region was cooler than in modern times. Its worming occurred rather sharply about 14-12 Kyr and 12 Kyr ago the climate in the region became close to modern (Fig.1). This conclusion is in agreement with palaeohydrological data obtained by other researches in the regions with arid climate [4].

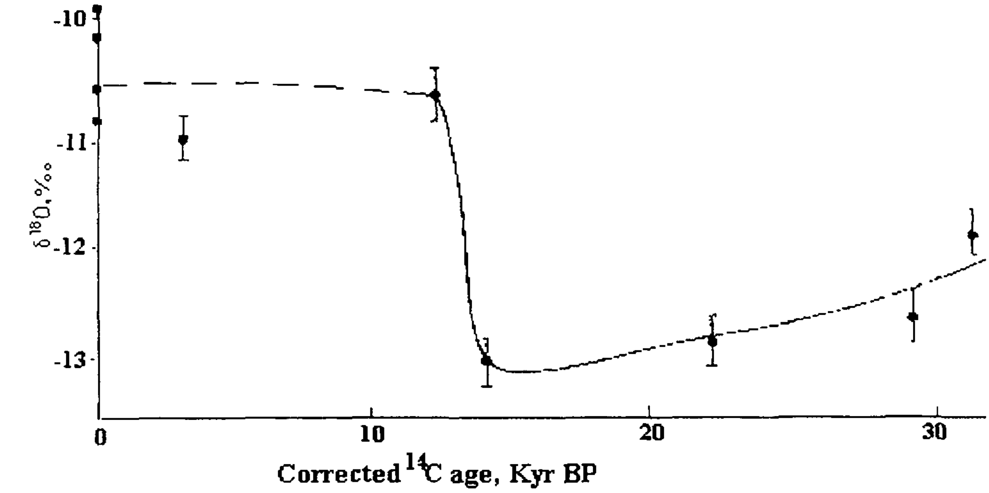

Fig. 1. Relationship between the corrected radiocarbon age and oxygen isotopic composition for groundwater in the Syr-Darya artesian basin.

A study of groundwater formation in the Syrian Desert in Upper Cretaceous sediments done by the authors and the data from a number of studies in the Middle East and the African continent carried out by other authors [5, 6, 7] complete the general picture of replenishment of groundwater in the considered arid region during the Pleistocene-Holocene transition time. Fig. 2 demonstrates the results obtained from the Syrian Desert. Having analysed the data we found that 20 Kyr ago and earlier the climate here was cooler than modern one by about 3^0C. The period from 20 to 11 Kyr is characterized by minimum of temperature when the annual average temperatures were lower than modern ones by about 6^0C. Climate wdrming and its transition to the modern arid phase started approximately 11 Kyr and ended 9 Kyr BP. Summary of the above stated data are presented in Table I.

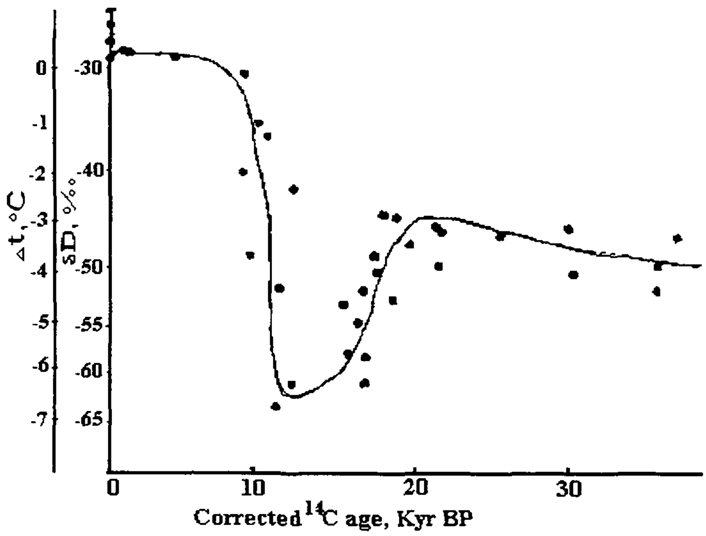

Fig. 2. Relationship between the corrected radiocarbon age and hydrogen isotopic composition for groundwater in the Syrian Desert. The temperature variation over time for the area studied using the temperature gradient «δD/dt = -5‰/°C is shown.

TABLE I. Studied palaeowaters within humid zone of the Eurasian continent.

Sampling place	Location	δD, ‰ SMOW	$\delta^{18}O$,‰ SMOW	^{14}C age Kyr BP	Δt, ^0C
Karelia	62N, 33E	-110	-13.8	5 – 6.5	-4
Baltic coast	59N, 25E	-172	-21	8 – 15	-14
Central Russia	55N, 36E	-88 – -96	-12.2 – -13	12 – 25	-1.5
South Ural and West Siberia	56N, 63E	-140	-18.1	8	-6
West Turkmenia	45N, 63E	-66 – -78	-7.2 – -7.8	12 – 13	-3
South Turkmenia	38N, 57E	-87	-11	12 – 14	-2.1
South Kasakhstan	45N, 63E	-92 – -104	-11.7 – -12.7	22 – 30	-3.7
Syrian Desert	34N, 37E	-63	-9.2	11 – 20	-3 – -6

According to the data of some authors [5, 6, 7], in the interval from 12 to 20 Kyr BP, a period of "intertropical aridity" was observed in the southern latitudes of both hemispheres, accompanied by formation of sandy dunes and drying lakes. This climate phase corresponds to the Late Pleistocene minimum of temperatures from 25 to 16 Kyr, when the humidity of the atmosphere was lower than in modern times, the amount of ice in glaciers increased by about 40 million km^3 and the ocean volume was reduced by about 4%.

On the basis of the above data and also of the results of published isotope studies of groundwater formation in a number of arid regions, it can be concluded that the coldest climate in the past in the present day arid regions does not always accompany pluvial periods of high humidity. It is obvious that the decisive role in the humidification or aridization of the climate was played by the change in atmospheric circulation, which transports the moisture. During the last temperature minimum the cooling by about 5-6^{0}C of the ocean surface in an area from the North and South Poles down to latitude of 40 degrees resulted in a sharp decrease in the evaporation rate by about 30-40%. This resulted in a reduction in moisture transportation to the Eurasian and African continents owing to the western circulation. Moisture prevailing in the Northern Hemisphere is transported to the south. In this connection, climate aridization is observed in the countries where moisture arrives from the Atlantic Ocean as a result of westward circulation. In the countries where the moisture regime is governed by a southern direction of transport, such as in the Arabian Peninsula, pluvial times were found.

3. INTERPRETATION OF THE CASPIAN SEA SEDIMENTS

Climatic record of lake sediments in arid regions gives useful information related to changes both in aridity-humidity regime in the catchment area and water replenishment of the lake itself. Two sediment cores of about 10 m long were taken from the southern and middle part of the Caspian Sea during French-Russian cruise in 1994 (Fig. 3) [8]. Isotopic composition of oxygen and carbon of the carbonates, radiocarbon age, lithology, salinity components, mineralogy, chemistry, granulometry, polinology and microfauna of the cores were analysed. Modern data of the above parameters of sediments and water are also available.

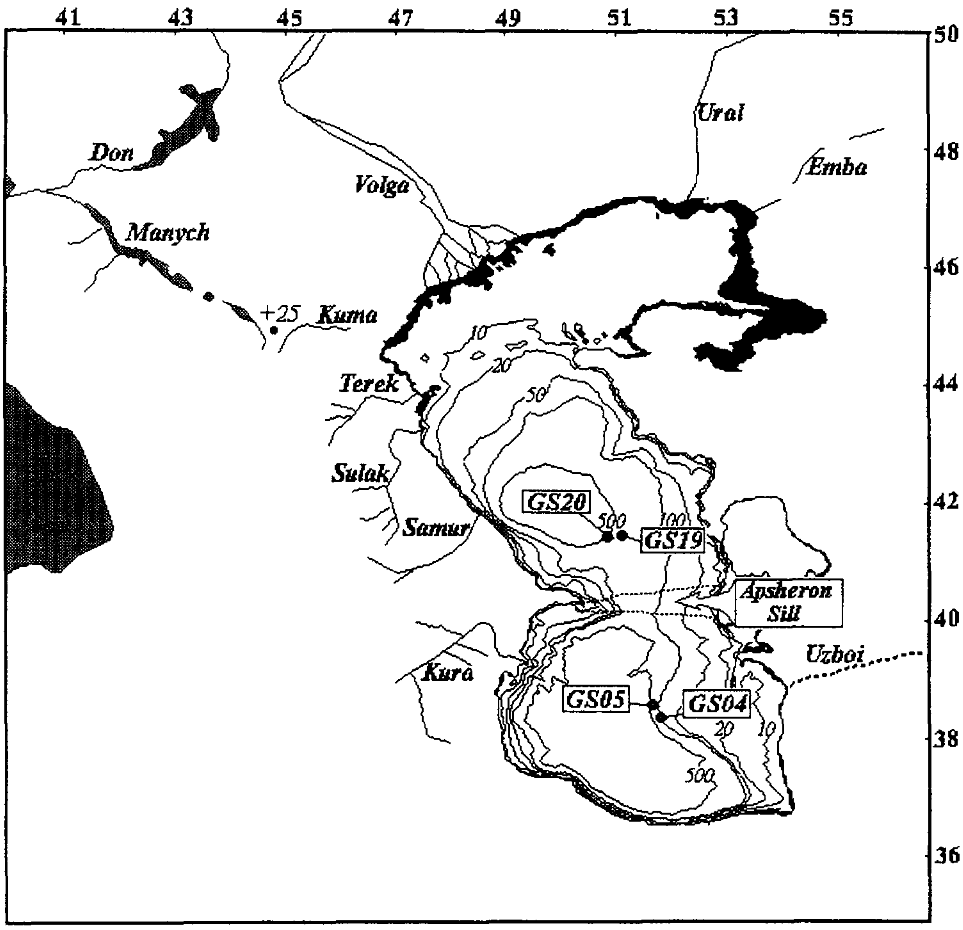

Fig. 3. Coring sites of the Middle (GS19) and Southern GS04) Caspian Sea.

3.1. Sedimentation of Carbonates and their Isotope Record

Fig. 4 presents isotope record in the carbonate minerals. High resolution of the record is guaranteed by continuous sampling every centimetre along both GS04 and GS19 cores. In order to provide basis for interpretation of the measured data, the conditions of sedimentation of the carbonates and their isotopic composition are under our consideration.

It is known that the index of the supersaturation of the Caspian Sea water by calcite is close to 3 [9]. This fact appears to be direct indication of supersaturation of water by Ca^{2+} and CO_3^{2-} ions leading to precipitation of chemogenic carbonates isotopically equilibrated with marine water. Supersaturation of water by calcites may happen in principle because of two reasons. First, this is due to concentration of salts in the surface water layer during evaporation. Secondly, the phenomenon occurs as result of change of the ion force and pH in the mixing zone of the river and marine water. Calculation of the ion force equilibrium made by our colleague G.Solomin who applied for this purpose computer program MIF-4 has shown that the abrupt supersaturation of Volga River water happens at its mixing with the marine water in proportion of 10:1 and at salinity about 1 ‰.

The content of carbonate minerals in the Caspian bottom sediments of quaternary age is varied from 10 to 70%. Those are mainly chemogenic and biogenic calcium carbonates. But many researchers assume that, in addition to the pelagic carbonates, which are formed in the water masses at isotopically equilibrium conditions, the bottom sediments contain terrigenic carbonate minerals delivered by river runoff and wind from the land. It is obvious that this part of the carbonate sediments is isotopically not equilibrated with the marine water.

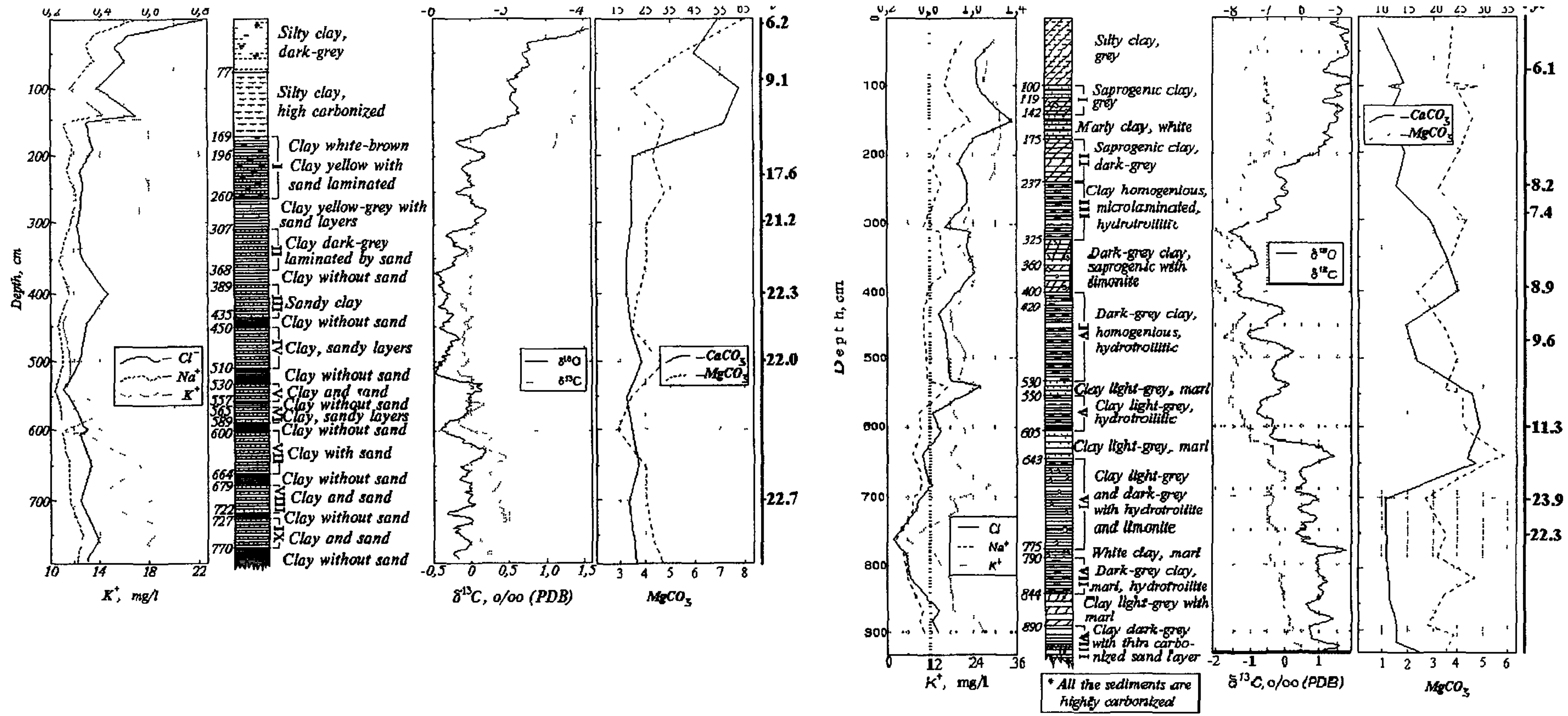

Fig. .4. Oxygen and carbon isotope record in bulk carbonates, lithology, contents of Cl⁻, Na⁺ and K⁺ ions, Ca, Mg values and ^{14}C dating results of measurement in GS04 (a) and GS19 (b) core sediments.

It follows from the theory of isotope thermometry that isotopic composition of oxygen of the carbonate sediments is the function of two variables which are temperature of water, where the carbonates precipitate, and isotopic composition of the water itself [10]. But palaeoclimatic studies of the Pleistocene glaciations evidenced that isotope record in marine carbonates reflects mainly changes in isotopic composition of water, which is enriched during glaciation due to accumulation of glaciers. The temperature of water is appeared to be a minor factor in formation of isotope ratios of the carbonate minerals [11].

Dependence of isotopic composition of chemogenic and organogenic carbonates mainly on isotope ratio of water, but not of the water temperature, is a characteristic feature of the Caspian Sea sediments. It is assumed that the isotopic composition of the seawater varied in the past. During transgressions the basin was recharged by 'light' river water of the melted glaciers. Through the regression episodes the marine water was enriched by heavy isotopes due to prevailing evaporation process in the water balance of the basin.

The carbon isotopes of the carbonate minerals are at the same picture. Such components as H_2CO_3, HCO_3 and CO_3^{2-} of the carbonate system should be enriched by ^{13}C in comparison with the dissolved in marine water carbonates.

The effect of changes in isotopic composition of water during glacial and interglacial episodes creates the basis for interpretation of palaeoclimatic events using chemogenic and organogenic carbonates in continental reservoirs. The roots of the effect are in variation in time and space of isotopic composition of atmospheric precipitation, which is the only source of water of the continental reservoirs and catchment basins of river systems. The variations of deuterium and oxygen-18 contents during climate change are analogous to the latitudinal effect and can be described by equations [12]

$$\Delta\delta^2H / \Delta t \cong (5.1 \pm 0.9)\ ‰/^oC,$$

$$\Delta\delta^{18}O / \Delta t \cong (0.62 \pm 0.1)\ ‰/^oC.$$

So, in the cold climatic periods the Caspian Sea was recharged by 'light' precipitation water and river runoff. But, because of the residence time of water in the Caspian Sea was not less that some hundred years, then the sea water has to be enriched due to kinetic fractionation of oxygen and hydrogen isotopes at evaporation and isotope exchange with atmospheric water vapour. The authors' results of water exchange study of Lakes Sevan in Armenia and Issyk Kul in Kyrghiz Republic prove the above statement [13].

The fact, that isotope enrichment of the Caspian Sea water by heavy isotopes through the exchange with atmospheric water vapour in the past took place, is also documented in our data of isotopic composition of hydrogen of pore water taken from core GS20 (Fig. 3). The samples were taken from the core, which was studied by our French colleagues. Fig. 5 shows the results, which demonstrate that during the studied time interval isotopic composition of hydrogen varied within -10 to -25 ‰ and never approached the present -90 ‰ value of Volga River water.

Thus, the conclusion is made that isotopic composition of the chemogenic carbonate minerals was formed in the zones of mixing of marine and river water and the river water plays the dominating role. The precipitated finely dispersed carbonate sediments was carried out by currents within the central and southern basins, The main part of such sediments was accumulated in the zones of slow water movement. Isotope record of the carbonate particles has to be kept safe because of isotope exchange in heterogenic system like solid sediment-water at the temperature below 400 K is inconvenient and the rate of the isotope exchange reaction by diffusion kinetics has a very low probability. In the case of sudden drop of river runoff, what is characteristic for the south-east Caspian Sea, dependence of isotopic composition of the chemogenic carbonate minerals from temperature of the marine water should appear.

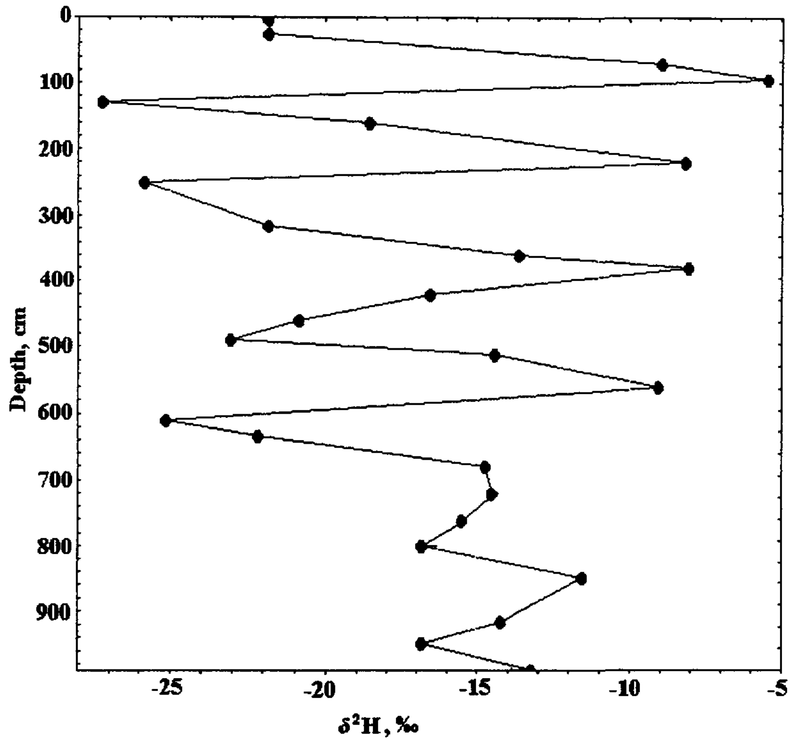

Fig. 5. Deuterium contents in pore water of GS20 (central basin) core sediments.

As it was mentioned above, terrigenic fraction in addition to the pelagic carbonates is presented in the sediments. This nonequilibrated with the marine water component distorts the palaeoclimatic record. Unfortunately, there is no reliable method for separation of the two components. But our French colleagues try to do this [14]. The studies show that the biogenic fraction in the form of microfauna and microflora, which was a priori in the equilibrium state with the marine water, presents in the studied cores in negligible amount not enough for the conventional mass-spectrometric measurement of oxygen and carbon isotopes. That is why in our work isotope palaeoclimatic interpretation is based on the study of bulk carbonate sediments.

In order to assess the degree of isotope equilibrium of carbonates in the measured samples, $\delta^{18}O$ and $\delta^{13}C$ in Cardium edule and Didacna trigonoides mollusc shells, in the adjacent sediment carbonates and in water was measured. The samples were taken in the southeast part of the sea near Ogurchinsky Island at 13-m depth of water. The measured shells, sediments and water were sampled from the upper 0-5 cm layer of the sediments. The other place of sampling for the same measurements was the dried lagoon in the southeast of Iranian shore. Both results are presented in Table II.

Calculation of temperature of the calcite formation near Ogurchinsky Island using Urey-Epstein equation gives the following results: the temperature of the shell growing is 20°C and the temperature of the carbonate precipitation was 24°C. Such values of temperature provide conditions for oxygen isotope equilibrium between the water and sediments. At the moment of sampling (17.08.94) the surface and bottom temperature of water was about the same and equalled to 28°C (pH=8.3, concentration of $[HCO_3^-]$=0.254 g/l, $[Ca^{2+}]$=0.343 g/l, S=13.2‰). The above data show that water was supersaturated with calcite by 1.5-2.0 times. The results demonstrate that in summer temperature hemogenic carbonates were in equilibrium with water. This was because precipitation of calcium carbonates was developed most intensive during active evaporation of water when the degree of its oversaturation was risen. The equilibrium temperature of creation of calcium carbonates of the shell was somewhat lower by 4.6°C in comparison with the hemogenic ones. Explanation of this is that growing of shells appears in more wide range of temperature variation. Carbon isotopes give

Table II. Oxygen and carbon isotopes in shells, bulk carbonates and water.

Sampling place	Sample	$\delta^{18}O$ (PDB)	$\delta^{13}C$ (PDB)
	Shells	-2.25	+0.98
Ogurchinsky Island	Carbonates	-3.27	+1.45
	Water (SMOW)	-1.32	-
	Shells	-2,1	+1.05
Southeast lagoon	Carbonates	-3.8	-1.0
	Water (SMOW)	-1.5	-

reverse picture. The shells are enriched by 0.5 ‰ in comparison with the hemogenic carbonates. The cause of this is not clear. Metabolic effect is one of the possible explanations of the observation. It is known that carbon of the body of living molluscs is depleted in ^{13}C on 15-20 ‰ relative to that of the carbonate components of water [13]. Enrichment of the carbonate sediments in ^{13}C in comparison with the shells was observed by Stuiver and Suss [15].

The values of $\delta^{18}O$ close to equilibrium at 26-28 °C are characteristic for the top 0-5 cm sediment layer from the southern basin of the sea where $\delta^{18}O$= -3.4 ‰ for the carbonates and $\delta^{18}O$=1.72‰ for the water. It means that modern climatological and hydrological conditions provide equilibrium state between marine water and formation of pelagic sediments in the southern Caspian Sea. Modern carbonate sediments from GS19 core demonstrate reverse picture: mean value of oxygen in carbonates is -4.7‰, but at the measured temperature 24.6°C of water and its $\delta^{18}O$=-1.89‰ the equilibrium value of oxygen should be -3.9‰. The only explanation on the observed difference is the presence of an impurity fraction in the sediments. It is assumed that the depleted in oxygen and carbon fraction of calcites was formed in Volga River waters where mean oxygen isotope value is varied between -8 and -12‰. If one accepts mean oxygen value for the river carbonates equals to −10‰ then the river calcite in the upper part of the core GS19 is amounted by about 15-16‰. The assumption of direct terrigenic origin of the impurity fraction has low probability because of carbonate rocks of marine genesis of the surrounded mountains have values of $\delta^{18}O$ and $\delta^{13}C$ close to 0. Discharge of carbonate material by rivers to the central Caspian Sea is fixed in modern bottom sediments by carbon isotopes which are depleted by 1.5 ‰ in comparison with the southern Caspian sediments (See Fig. 4). It worth to note that a number of authors applied carbonate minerals in bottom sediments of the continental lakes for palaeoclimatic reconstruction [16, 17].

The following practical conclusions can be made from this paragraph:

(a) Isotopic composition of oxygen and carbon of calcites in the sediments is governed by isotopic composition of water where the calcite precipitates;

(b) Periodic regressions and transgressions should considerably change isotopic composition of the Caspian Sea water due to variation of amount of the 'light' runoff water;

(c) Oxygen isotopes of the modern South-Caspian carbonate minerals keep equilibrium with the marine water, whereas some depletion of carbonate sediments in heavy isotopes in comparison with the equilibrium state for the central basin is observed;

(d) The above phenomenon is explained by recharge of depleted in ^{18}O carbonate minerals to the central basin where they precipitate in the mixing zone.

We can state now that the phase of the sea transgression is identified by the effect of depletion of the oxygen and carbon isotopes in comparison with those enriched during regression phase when equilibrium state with marine water and water vapour dominated.

3.2. Radiocarbon dating

The standard procedures were used for radiocarbon dating of the bulk carbon minerals. It was understood that, because of the presence of small terrigenic fraction in the measured bulk sediments, the calculated ages contain some error. There is no way to separate this fraction or to make direct correction of the results. In order to estimate amount of the detritus component our French colleagues applied X-ray analysis. It seems there is relationship between the sedimentation rate and contents of the terrigenic component. But in our case, for interpretation of the main palaeoclimatic events in the Caspian Sea basin, the first approximation of the sediment dating was applicable.

Table III presents results of the radiocarbon dating of GS04 and GS19 cores. The measurements were done by R.Petronius in Lithuanian Institute of Geology (Vilnius) and by M.Groening in the IAEA Isotope Hydrology Laboratory. The corrected French data are also presented in Table III.

Table III. Results of radiocarbon dating of GS04 and GS19 core sediments.

Core	Depth of sample (cm)	^{14}C activity [pmC]*	^{14}C age [yr]
	10	46.07	6230±370 **
	15	32.4	9053±540***
	80	32.19	9100±803**
	225	11.18	17600±700**
GS04	230	10.5	18104±540***
	295	7.14	21200±1130**
	400	6.2	22334±1100***
	500	6.5	21957±1050***
	700	5.9	22735±680***
	70	46.2	6100±140**
	245	36.23	8160±330**
	280	39.8	7400±590***
	395	33.18	8860±140**
GS19	410	33.6	8761±260***
	470	30.27	9600±280**
	600	24.5	11298±560***
	710	5.5	23905±890***
	750	6.2	22337±670***
	10	-	4190±100****
	45	-	7980±100****
	60	-	8720±120****
	65	-	9290±100****
	75	-	9670±160****
	85	-	9920±160****
GS05	95	-	10090±220****
	100	-	10330±380****
	105	-	10600±1360****
	110	-	11190±1310****
	115	-	11600±730****
	120	-	12180±690****

* Percent of modern ^{14}C activity. The ages of GS04 and GS19 core samples not corrected for detritus fraction;
** Done in the Lithuanian Institute of Geology, Vilnius;
*** Done in the IAEA Lab, Vienna;
**** Done in Paris University. The ages corrected relative detritus fraction [14].

3 3 Contents of carbonate minerals

Carbonates are the main component of the bottom sediments, which is the subject of the stable and radioactive isotope measurement and interpretation. The content of carbonate minerals in the Caspian Sea bottom sediments of quaternary age is varied from 10 to 70%. Those are mainly chemogenic and biogenic calcium carbonate minerals. But many researchers assume that, in addition to pelagic carbonate, which are formed in isotopically equilibrium with water masses conditions, the bottom sediments contain terrigenic carbonate component, delivered by river runoff and wind from the land. It is assumed that the isotopes of this part of the carbonate sediments are not in equilibrium state with the marine water.

The procedure of determination of the carbonate mineral content in the core sediments was made in this way. Sediment samples of about 1-3 g in weight were taken each 50 cm along the core. The samples were treated by hydrochloric acid for dissolution of the carbonate fraction. After that the content of calcium and magnesium was determined by the titration method. The results of bulk carbonate measurement in GS04 and GS19 cores are shown in Table IV and on Fig. 4.

Table IV. Contents of calcium and magnesium carbonates in two core sediments.

Depth of sample (cm)	Core GS04		Depth of sample (cm)	Core GS19	
	$CaCO_3$	$MgCO_3$		$CaCO_3$	$MgCO_3$
0	54 0	7 98	20	9 5	3 77
50	45 4	5 65	95	14 05	3 50
100	62 9	3 50	100	11 8	4 84
150	53 0	4 84	105	13 4	4 04
200	21 4	4 30	150	12 8	4 57
250	20 4	4 84	200	14 7	4 04
300	20 1	4 04	250	12 8	3 23
350	17 9	4 04	300	19 2	4 30
400	17 6	3 77	350	22 4	3 77
450	20 4	3 5	400	24 9	2 42
500	24 3	4 84	450	14 4	3 50
550	17 6	3 50	500	16 9	4 04
600	19 5	2 96	540	26 8	3 50
650	22 4	4 03	550	27 8	4 3
700	17 9	4 03	600	29 4	4 3
750	18 8	4 30	640	27 2	5 92
780	19 8	4 84	650	28 8	5 11
			700	11 2	2 7
			750	11 2	3 5
			780	11 5	3 23
			820	12 1	4 57
			840	12 5	3 5
			890	13 1	2 7
			915	13 1	3 77
			935	17 3	3 5

3.4. Isotopic Composition of Caspian Rivers

On the basis of the isotope and salinity data the conclusion follows that the analysed sediments cover a time interval longer than that, which was 20-16 Kyr and is named cold Upper Khvalinian. In accordance with vast literature the mean annual temperature at that time was by 6°C lower of modern in the Northern Hemisphere.

It is well known that isotopic composition of atmospheric precipitation and recharged surface and groundwaters is a function of the local mean annual temperature. Isotopic composition of the carbonate system of groundwater and carbonate sediments is also in first approximation a function of the mean annual temperature. The $\delta^{13}C$ values of the lake and river carbonates are increased for the warmer climate areas and vice versa. It seems to be connected with the rate of isotope exchange of the dissolved inorganic carbon with the atmospheric carbon dioxide, which is varied in a narrow limit between -7 and -8‰ PDB. The mean values of oxygen and carbon isotopes in river waters of the Caspian basin are presented in Table V. Those data are the summary of the authors' study of the discussed arid region.

From Table V one can see that isotopic composition of the southern rivers, especially of Pra-Amu Darya, it was the main source of the runoff to the Caspian Sea during the Valday period of minimum temperature, practically identical to the modern isotopic composition of Volga River water. It is also seen from Fig. 4 that isotopic composition of oxygen of calcium carbonates of the middle and southern basins within the depth of 630-787 cm (cold climatic epoch) and 20-200 cm (modern climatic epoch for the middle basin core) is identical. At that time the main source of the sea replenishment was southern rivers. Volga River's runoff is marked on the oxygen curve starting from the depth about 640 cm and upwards. The recharging waters practically do not affect on the isotopic and chemical composition of the southern basin waters. The oxygen and carbon isotope record of the carbonate sediments fixes this process.

Table 5. Oxygen and carbon isotope data of river water of the Caspian basin.

Rivers	Modern epoch			Cold Pleistocene epoch		
	δD, ‰	$\delta^{18}O$, ‰	$\delta^{13}C$, ‰	δD, ‰	$\delta^{18}O$, ‰	$\delta^{13}C$, ‰
Volga	-94.0	-13.0	-9.2	-124.0	-16.7	-14.0
Amu Darya	-78.0	-10.0	-6.2			
Pra-Amu Darya				-90.0	-13.4	-8.0
Caucasus rivers	-88.0	-11.8	-8.0	-119.0	-15.5	-12.0

4. INTERPRETATION OF PALAEOCLIMATIC EVENTS

It follows from Table I that the age of the sediments of GS04 and GS19 cores, taken in the southern and central part of the Caspian Sea, is covered by radiocarbon time interval of 24 Kyr. The main palaeoclimatic events and consequences within that period of time can be read on the basis of interpretation of the collected data.

4.1. Variation in sedimentation rate

Fig. 6 demonstrates the data of Table 3 of radiocarbon ages of GS04 and GS19 core sediments as function of their depth. The ratio of value of the depth interval of the sediments Δh to the time interval Δt is the rate of sedimentation. So, Fig. 6 presents the plot of sedimentation rate $v=\Delta h/\Delta t$ in the coring points of the southern and central basins of the Caspian Sea. One can observe from the graphs a reverse character of sedimentation rate in the two basins. Increase of the rate value for one basin is accompanied by decrease of the rate for another one. Within the time interval from 24 to 11 Kyr the mean value of sedimentation rate for the central basin was low and accounted by value of 0.12 mm/yr, whereas for the period from 11 to 6 Kyr that value increased up to 1.2 mm/yr. On the contrary, for the southern basin within the period of 23 to 17.8 Kyr mean value of sedimentation rate was 0.9 mm/yr, but for the time interval from 17.6 to 6 Kyr it dropped up to 0.19 mm/yr. Taking into account that volume of the river runoff is a function of the volume of sediments, then we can assume that the observed picture of sedimentation rates in the two basins is the consequence of changes of direction of the river runoff and of separation of the Caspian Sea into two basins in the past.

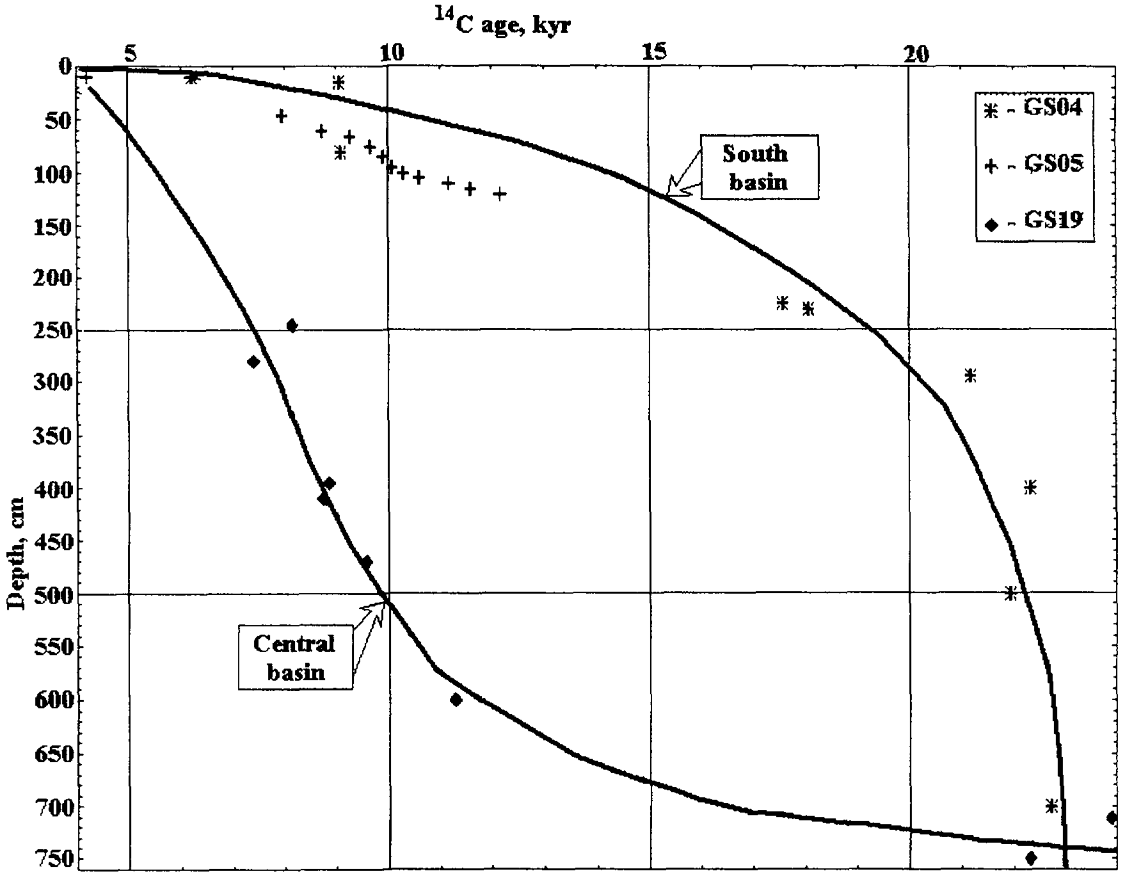

Fig. 6. Changes in sedimentation rate within period of 24 Kyr for GS04 and GS19 core sediments.

4.2. Periodic changes in direction of river runoff

In addition to the above discussed in 4.1, there are a number of facts, which proves the assumption that the main direction of the river runoff to the sea was reversed in the past. The data of salinity variation presented on Fig. 4 show that salinity of sediments within the depth interval of 5.4 to 1.5 m of core GS04 from the south basin was dropped in comparison with the central basin. This interval of sediments was formed since 22.5 to 17 Kyr. The river recharge of fresh water to the southern basin was possible occurred only due to runoff from the southern part of the catchment. In the mean time the depth interval of 7.5 to 2 m of core GS19 from the central basin shows higher salinity. Evidently that evaporation here prevails over the recharge to the basin. The corresponding period of time to that interval was 22.5 to 12 Kyr. A possible source of water discharge to the central basin at that time could be eastern part of the catchment area and overflow through the Apsheron Sill.

The salinity peak in the core of the central basin is fixed two times. First, it locates at the depth about 5.5 m and corresponds to salinity of 12-15‰ and to the age of 12-12.5 Kyr. In GS04 core of the southern basin salinity starts to rise from the depth of 5.4 m and riches its maximum value on the depth of 1.5 m at the age of 12 Kyr. But salinity here is accounted only by 6.5-8‰. This fact evidences about water discharge from the southern slope of the catchment area.

The second peak of higher salinity is fixed 5-6 Kyr on the core depth of 0.5 m for the southern basin and 6-6.5 Kyr on the depth of 1.5 m for the central one. The corresponding correlation between salinity and oxygen and carbon isotopes is observed.

The curves of oxygen and carbon isotopes of the carbonate minerals also prove the idea of the southern basin recharge from the southern slope at that period of time. The sediments here are characterised by the most negative values of $\delta^{18}O$ and $\delta^{13}C$. It worth to note that isotopic composition of river water at that time was the same as the modern Volga River water. This fact evidenced about shift of the humid European zone to the Central-Asian and Iranian-Caucasian region of the Caspian Sea catchment basin.

4.3. Periodic separation of the Caspian Sea

One more fact of periodic recharge of the Caspian Sea from the southern direction and separation of the sea into two lakes is the discovered riverbed in the Apsheron Sill. Fig. 7 presents a modern topography of the bottom in isobathes and three latitudinal sections of the sill. It is seen here that the sill has heave (~180 m) river channel washed by a water flow. The flow was reversal but because of the mouth is located on the central basin side, its main direction seems to be from the south to the north. The western slope of the upper (~80 m) more ancient part of the bed is steep due to action of the Coriolis' force and the eastern terrace is flat. Below 80 m the flow turned to the northeast, seems, because of more soft for washing sediments. A number of river terraces are observed along the bed slope.

One can assume that sometime in the beginning there were two lakes completely isolated by the Apsheron Sill. Because of the sea level rise and drop the sill was washed up to observed bottom. Complete separation or restricted hydraulic connection of the two basins is valid for each climatic cycle in the basin.

4.4. Variation of sea level

On the basis of the obtain data it is possible to determine a number of fixed positions of the sea water levels. It follows from the data of major ions of the pore water and taking into account density corrections, the lower salinity of the Caspian water was about 5-7‰. It was happened 22.5 Kyr ago and is fixed on the depth of 5.4 m and 7.5 m in the southern and central cores accordingly. This salinity is by 2-2.5-time lower of the modern one. The volume of water in the basin obviously should be estimated by figure of 200 000 km^3. Elementary calculation shows that the sea level at that time should be on 70 m higher of the modern one. It seems that the Caspian and Black Seas were in hydraulic connection through the Kuma-Manych watershed.

Positions of the main terraces of the riverbed in the Apsheron Sill are also reliable indication of the sea level. The main terrace is located on 80 m below the modern sea level. About 100 m, 150 m and bottom 180 m was the three more positions.

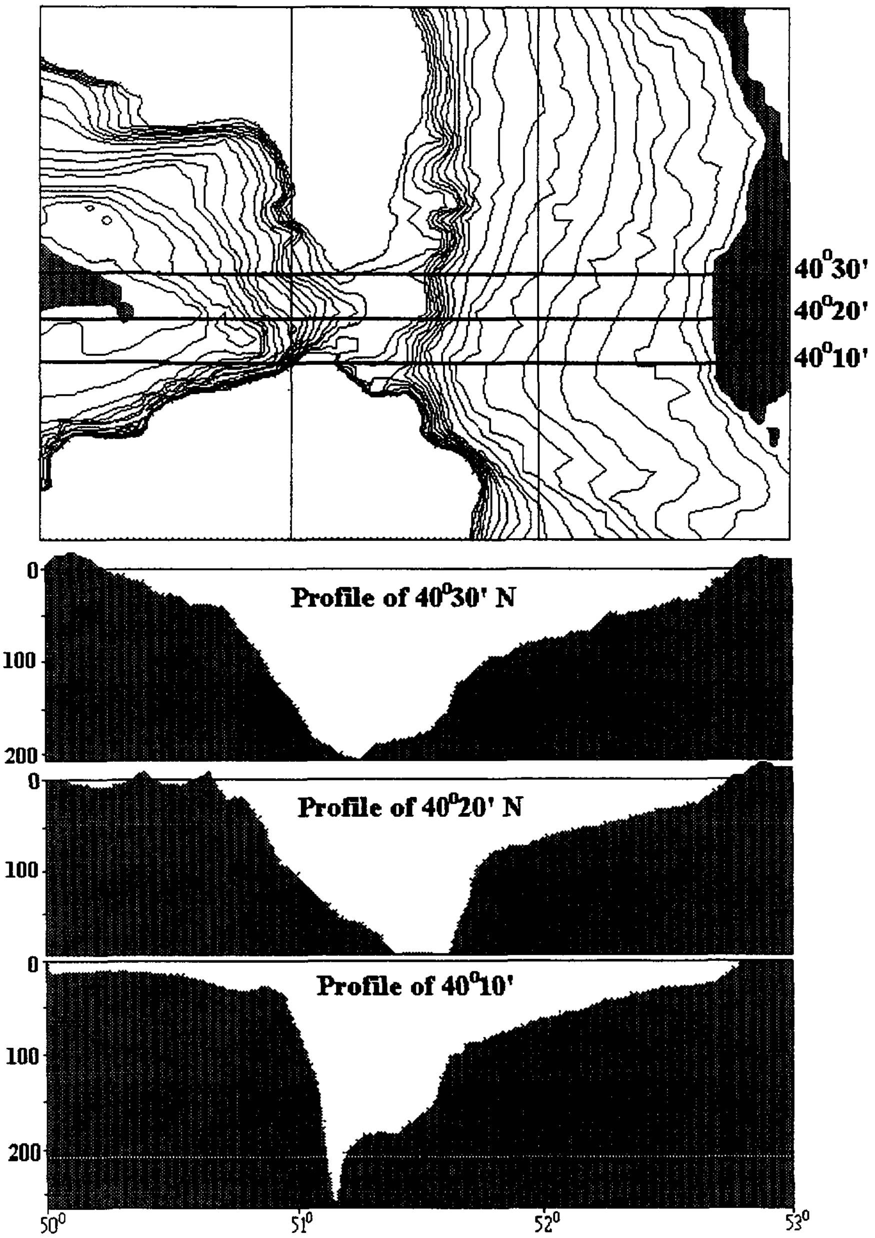

Fig. 7. Topography in isobathes and three latitudinal profiles along the Apsheron Sill.

5. CONCLUSION

Replenishment of groundwater and lakes during climate changes is the main source of water resources in arid regions. This statement is valid not only for glacial-interglacial epochs but also for current 'small' climatic variations. Recent vast drought in the Sahel region is a good example of such a 'small' climatic change. Prediction of short periodic climate changes based on interpretation of isotope and chemistry records in lake sediments and fossil groundwaters is an important goal of the arid zone hydrology.

ACKNOWLEDGEMENTS

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MECHANISMS, TIMING AND QUANTITIES OF RECHAGRE TO GROUNDWATER IN SEMI-ARID AND TROPICAL REGIONS

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Abstract

Groundwater being exploited in many arid and semi-arid regions at the present day was recharged during former humid episodes of the Pleistocene or Holocene and, in contrast, the amounts derived from modern recharge are small generally small and variable. Geochemical and isotopic techniques provide the most effective way to calculate modern recharge and to investigate recharge history, since physically- based water-balance methods are generally inapplicable in semi-arid regions. Examples from Africa (Senegal, Niger, Nigeria, Sudan as well as Cyprus) show that direct recharge rates may vary from zero to around 40% of mean rainfall, dependent primarily on the soil depth and the lithology. Spatial variability presents a real problem in any recharge investigation but results from Senegal show that unsaturated zone profiles may be extrapolated using the chemistry of shallow groundwater. Unsaturated-zone studies show that there are limiting conditions to direct recharge through soil, but that present day replenishment of aquifers takes place via wadis and channels. In the Butana area of central Sudan the regional groundwater was also recharged during a mid-Holocene wet phase and is now in decline. The only current recharge sources, which can be recognised distinctly using stable isotopes, are Nile baseflow and ephemeral wadi floods.

1. INTRODUCTION

Prior to human intervention, groundwater systems had evolved under near steady conditions reflecting hydrodynamic conditions that had remained stable possibly for several thousands of years under modern climatic regimes. Small climatic perturbations at the century todecadal scale such as the little ice age or the prolonged drought of the previous millennium (800-1000BP) whilst having a strong impact locally on water availability probably did not have any long term effects on aquifers. Many aquifers contain evidence of palaeowaters which were recharged during the early Holocene or Pleistocene when the global climates and recharge patterns were significantly different, coinciding with the late Pleistocene glaciation. In coastal regions groundwater movement was also enhanced by the lowering of sea level by up to 130m. With the end of the ice age and the rise to modern sea levels by around 7000 BP some extreme wet periods occurred in the mid-Holocene for example in Africa, which resulted in discrete groundwater recharge. Since that time greater aridity has characterised the modern era (about 4000 years) creating arid or semi-arid regions which may have been much wetter in former times. Well drilling has had the effect of penetrating aquifers which are naturally stratified both in age and in quality. Pumped sampling invariably results in mixed groundwaters.

The development of groundwater resources in semi-arid regions often proceeds without an understanding (or with an over-optimistic interpretation) of the recharge rates and processes. Some of the produced groundwater may therefore not represent that which has been recharged during the modern era. Falling water tables testify to over-development of groundwater, specifically that the rates of groundwater abstraction exceed the rates of natural replenishment from current rainfall or, that a transient condition is produced where water level decline is proportional to the hydraulic diffusivity (transmissivity/storage) of the aquifer (Custodio 1992). In many semi-arid areas the water resources are being mined from recharge from former humid episodes.

Recharge estimates based on empirical formulae are inadequate for low rainfall areas with high evapotranspiration (Gee and Hillel 1988; Allison et al. 1994). One way to overcome this inadequacy is to use the unsaturated zone as a rain gauge. The concentrations of rainfall-derived chloride and other conservative solutes in the unsaturated zone are proportional to the precipitation less evaporation and under favorable conditions may serve as a long term (decadal scale) estimate of recharge rates. The unsaturated zone may also preserve an archive of recharge rates and corresponding climatic events at the decadal scale or better, serving as the only part of the hydrological cycle, excepting ice cores, to provide this function. Inert tracers, especially chloride, can provide a record of oscillating recharge events during wetter or drier periods at time scales up to 500 years or more (Edmunds and Walton 1978; Allison and Hughes 1978; Edmunds et al 1992; Cook et al 1992). Much longer records may be preserved in the unsaturated zone of more arid regions (Allison and Hughes 1983; Phillips 1994; Tyler et al 1996)

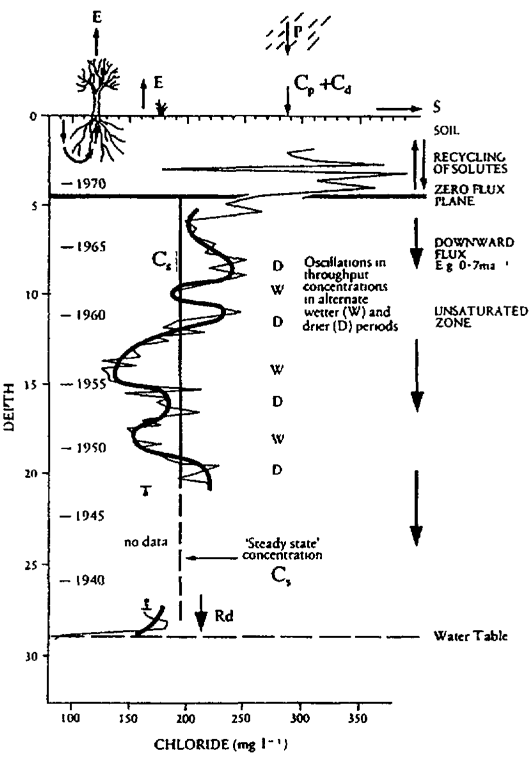
The objective of this present paper is to review recent work relating to arid zone recharge and to demonstrate how geochemical and isotopic methods may be used to measure the mechanisms, timing and amounts of recharge in arid and semi-arid regions. Results are illustrated using examples from three semi arid regions - the Mediterranean (southern Cyprus), west Africa (Senegal) and east Africa (Sudan).

2. METHODOLOGY

Geochemical techniques using chloride 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. Until recently tritium has been an important technique for unsaturated zone investigation but it cannot be used as a routine tool and its effectiveness is now limited due to radioactive decay. Tritium has been widely used in temperate zones and less commonly in arid zones (Edmunds and Walton 1980; Allison and Hughes 1978; Gaye and Edmunds 1996) to measure recharge. The position and shape of the tritium peak in unsaturated-zone moisture profiles has provided convincing evidence of the mechanisms of recharge as well as 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 basis of the method has been described elsewhere (Edmunds et al.1988) but a conceptual model and summary of the measurement of recharge and recharge history are given in Figure 1. 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 et al. (1994); in India:Sukhija et al.(1988); in southern Africa: Gieske et al.(1990) and in north America: Stone (1987), Phillips (1994), Wood and Sandford (1995).

Samples of moist sand are obtained by augering 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 elution with distilled water. Rainfall amounts and chemistry (total solute deposition) must be known. In the studies discussed in this paper, an average of the mean rainfall and weighted mean chloride concentrations typically have 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 (up to 25%) and an assumption must be made that the average atmospheric chloride flux has remained constant with time at a given location. It is also assumed that surface runoff is negligible and that homogeneous movement of solutes through the unsaturated zone by piston flow is taking place.



1) **Direct Recharge Estimation.** Assuming no surface runoff rainfall (P) containing a concentration of Cl (C_p) and any dry deposition (C_d) enters the soil. In the soil zone water is lost by evapotranspiration and chloride is recycled and concentrated. Below the "zero flux plane" water is transmitted with variable concentrations depending on the antecedent climatic conditions; the mean concentration (C_s) is proportional to the long term direct recharge (Rd):

Direct Recharge (mm) $\quad$ $\mathbf{Rd = P\,(C_p + C_d) / C_s}$

2) **Residence Time.** The drainage rate V_w in m yr^{-1} is given by

$$V_w = R_d / \rho . \theta_g$$

where θ_g is the gravimetric moisture content and ρ is the dry bulk density. This enables the transit (residence) time for the water in the unsaturated zone to be calculated.

Figure 1. The use of chloride in unsaturated zone profiles to measure recharge through soils and recharge history.

Groundwater at the water table may also be used to obtain information on recharge and in conjunction with the unsaturated-zone profiles, can provide estimates of the spatial variability of recharge in recent times (Edmunds and Gaye 1994). For the investigation of groundwater recharge to deeper systems, groundwater samples may be obtained from pumping wells. Sampling is restricted by the borehole network. Information on the depth stratification of water quality in aquifers is rare, and the probability is that most pumped samples are mixtures of water from different recharge episodes. It is with these qualifications that some information on the recharge history of palaeowaters may be obtained.

3. PRESENT DAY RECHARGE MEASUREMENT

The data from Cyprus are from the Akrotiri peninsular from Recent dune sediments, and the chloride profiles are shown together with tritium profiles (Figure 2) from the same percussion drilledborehole, and are described in detail in Edmunds et al.(1988). The chloride concentrations below the zero flux plane (around 2m 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 a^{-1}, using a three year mean rainfall concentration of 16.4 mm a^{-1} 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 a^{-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.

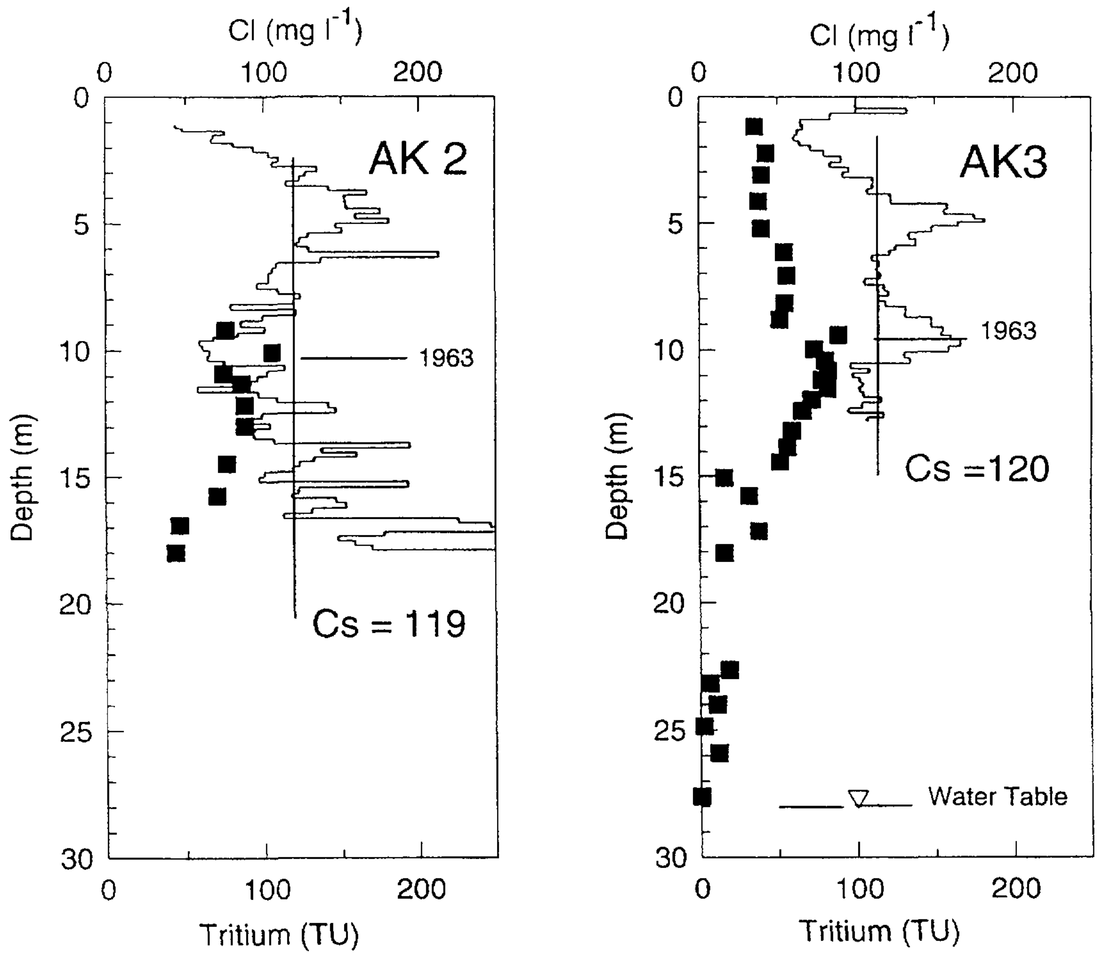


Figure 2. Two profiles (AK2 and AK3) of chloride and tritium in the unsaturated zone from Akrotiri, Cyprus showing the presence of the 1963 thermonuclear peak and the mean concentrations of chloride (C_S) in the unsaturated zone.

Four profiles of chloride from north-west Senegal (Figure 3) illustrate the spatial variability of recharge within one site (of area $0.1m^2$). All were obtained from Quaternary dune sands where the water table was at 35m and where the long term (100 year) rainfall is 356 mm a^{-1} (falling by 36% to 223 mm a^{-1} since 1969 during the Sahel drought). The mean concentrations of chloride (C_S) in these four profiles ranges from 28 to 81mg l^{-1} which correspond to a value for mean direct recharge from 10 to 25 mm a^{-1}; as in Cyprus a series of oscillations related to wet and dry years can be found . The average chloride concentration of 7 profiles at this site is 82 mg l^{-1} (13mm a^{-1}). Having established that all the Cl in this region is atmospherically derived, it is possible to extrapolate the unsaturated-zone data to determine the spatial variability of recharge at a regional scale using data from shallow dug wells. Over an area of 1600 km^2 120 shallow wells were used to calculate the distribution of recharge over this area of NW Senegal. The regional recharge varies from 20 to <1mm a^{-1}, corresponding to a renewable resource of between 13 000 and 1100 m^3 km^2 a^{-1} (Edmunds & Gaye 1994).

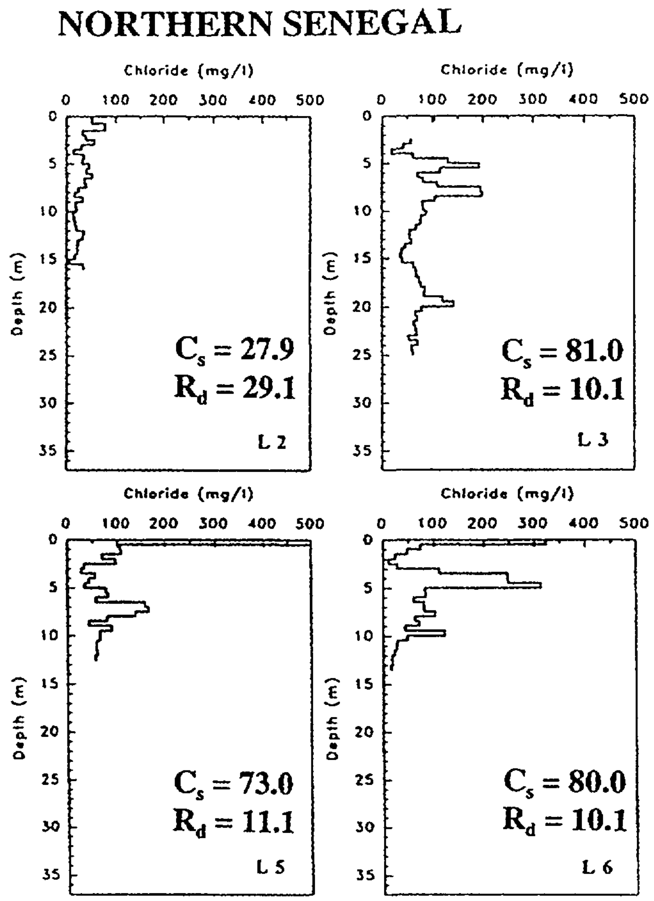


Figure 3. Four profiles (L2, L3, L5, L6) of chloride in the unsaturated zone at Louga, northern Senegal with mean chloride concentrations (C_s) and derived estimates of direct recharge (R_d).

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. The limiting rainfall value will vary widely depending on the local conditions. Under this condition the unsaturated zone will become saline and geochemical reactions will lead to the formation of minerals in the soil zone and the formation of indurated crusts. Data from Sudan (Figure 4) are from the Butana region, north east of Khartoum where, prior to 1969, the mean annual rainfall was 225 mm but for the following 15 years was only 154 mm (Darling et al 1991). 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 a^{-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 a. The shapes of the profiles are complex and suggest that in the top 3 m 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).

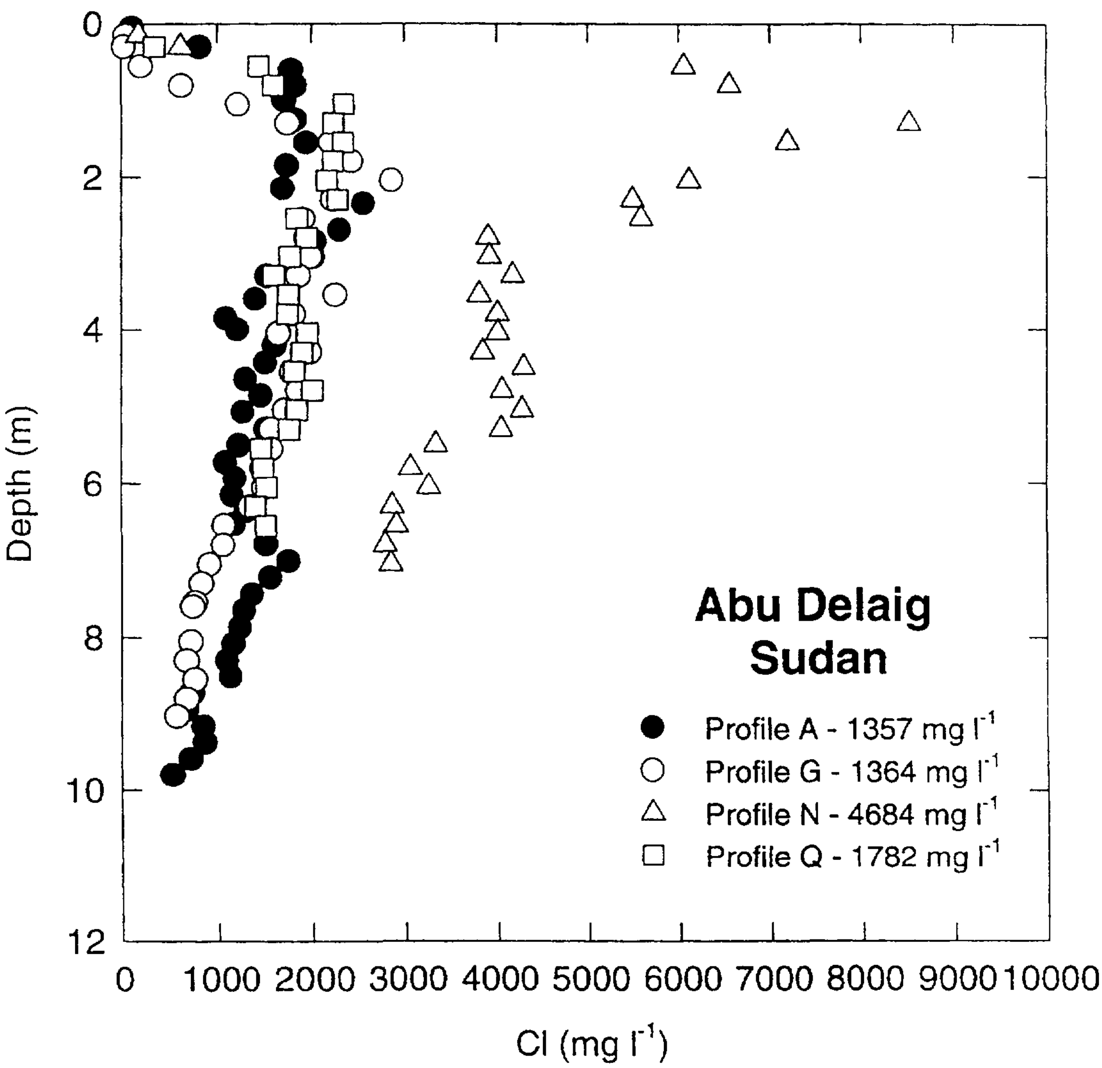


Figure 4. Four profiles of chloride in the unsaturated zone from Abu Delaig, Butana region, Sudan.

4. RECHARGE HISTORY OF PAST 500+ YEARS

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 diffusivetimescale. 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. Thus a 20-year event such as the recent Sahel drought should persist at a recharge rate of 10 mm a^{-1} 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.

Several profiles obtained from N Senegal have been interpreted (Edmunds et al 1992) as archives of recharge, climatic and environmental change for periods up to 500 years. Over the past 100 years, validation is provided by instrumental records for rainfall and river flow. In Figure 5, one profile (L3) has been calibrated using recharge rates and moisture contents. The profile record is 108 years, assuming that recharge over this period is representative of the 3-year average (2.8 mg a^{-1}) measured

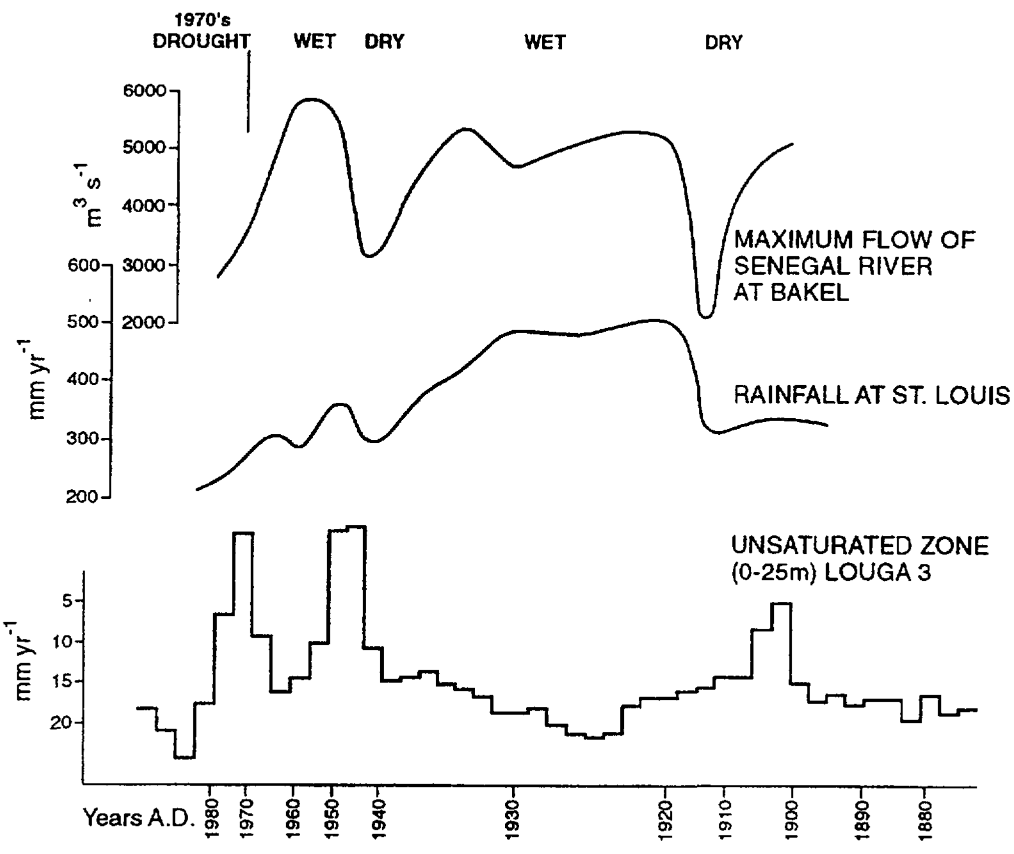


Figure 5. Comparison of the calibrated L3 profile with the climatic record of the last century as given by the rainfall record of St Louis and the flow of the Senegal River at Bakel.

in this study. Assuming that the piston flow model applies, the peaks in Cl at 4-6 m and 6-13 m should correspond to periods of drought from 1970 and also in the 1940's. Another peak in the 1900's also reflects a recorded drought period. The unsaturated-zone profile is compared (Figure 5) 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 much 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 a^{-1} 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.

5. RECHARGE DURING THE HOLOCENE

In north Africa and the Sahel region there is growing evidence from different archive materials (lake deposits, palaeoecology etc) that the early Holocene was characterised by one or more wet periods (Gasse et al 1991) although these were not necessarily synchronous. Evidence is also available from much of north Africa that these wet periods also gave rise to considerable recharge to groundwater which is recorded especially in the phreatic aquifers of arid areas (Edmunds and Wright 1979: Fontes et al. 1993).

In the mainly unconfined Miocene aquifer in central Libya a distinct body of very fresh groundwater (<50 mg l^{-1}) was found which cross-cuts the general NW-SE trend of salinity increase. This feature, around 10km in width may be traced in a roughly NE-SW direction for around 130 km, where the depth to the water table is currently around 30-50 m. Because of the good coverage of hydrocarbon exploration wells (water supply wells) in this region, a three-dimensional impression can be gained of the water quality. It is clear that this feature is a channel that must have been formed by recharge from a former ancient wadi system (Edmunds and Wright 1979). No obvious traces of this river channel were found in this area which had undergone significant erosion, although neolithic artefacts and other remains testified that this region had been settled in the Holocene. Further studies of the different groundwaters were made using stable isotopes (O, H and C) and radiocarbon as well as inorganic chemistry. Whereas the regional, more mineralised, groundwaters gave values of 0.7-5.4% modern carbon, the fresh waters gave values from 37.6-51.2% modern carbon and also were distinctive in their hydrogeochemistry. The younger waters gave 'ages' ranging from 5000-7800 years (uncorrected ages since it was argued that any reaction with the solid phase would have been with active carbonates in the soil zone or with calcretes). Evidence of former extensive soil and vegetation cover over this whole region is also given by the very high nitrate concentrations preserved in the mainly aerobic waters beneath the Libyan desert (Edmunds and Gaye 1997.

Clear evidence of regional replenishment of groundwaters during the Holocene is provided from the Butana area, Sudan (Darling et al 1987; Edmunds et al 1992), where direct recharge through the present day soils in an area with long term average rainfall of 225 mm is close to zero. A detailed study was made of the Wadi Hawad , a former tributary of the Nile and its region. This wadi flows intermittently at the present day yet seldom reaches the Nile, and it represents a good example of hydrological conditions at the boundary between arid and semi-arid conditions. Evidence from tritium shows that current recharge from the rainy season in the headwaters area moves laterally up to 1km from the wadi, but there is no evidence that recharge actually reaches the water table, although it is likely that this is the case. Stable isotopic and radioisotopic evidence together with chemical data provide a good characterisation of the different sources of groundwater (Figure 6).

Groundwater in the Nubian sandstone is abstracted from wide-diameter traditional wells which may be up to 100m deep, and also from boreholes of similar depth. The majority of these groundwaters give uncorrected radiocarbon ages mainly in the range 5500-10000 yr which are probably close to the true ages since active carbonate was probably involved in the formation of the total dissolved inorganic carbon (TDIC). These waters may be mixtures in which any age stratification may have been smoothed out, but they give a distinct mid-Holocene signature across the region. Waters with the youngest ages are found in the more humid southern part of the region, hinting that some modern recharge from the upper courses of the wadi system may be occurring. The regional groundwaters have distinctive light signatures (* ^{18}O of -9 to -10 1) which contrast with modern waters, including the river Nile. Intermediate waters with * ^{18}O of -7 to -5 1 may also indicate mixture with modern recharge. The distinctive isotopic signature also implies a different climatic pattern at the time of recharge, probably that the rainfall was derived from the Atlantic or from the Gulf of Guinea rather than from the Indian Ocean as at present (Fontes et al. 1993) who propose a northward shift of the ITCZ (Inter-tropical covergence zone) producing more intense rains to explain the presence of isotopically light rains (after correction for evaporation effects).

6. DISCUSSION AND CONCLUSIONS

The boundary between semi-arid and arid zones (approximately 250mm annual rainfall) is often viewed as the boundary between areas that receive recharge to aquifers and those that do not. An example from the work presented in this paper demonstrates that over the short timespan represented by the prolonged drought in the Sahel region (1969-1989 approx) with a 100 year mean rainfall of 400 mm, where a decrease in mean annual rainfall of up to 38% occurred, the recharge in an area covered by sandy soil decreased from 10mm to 4mm. There must therefore be a threshold value of rainfall for any given set of soil conditions below which infiltrating rainfall is lost entirely by the

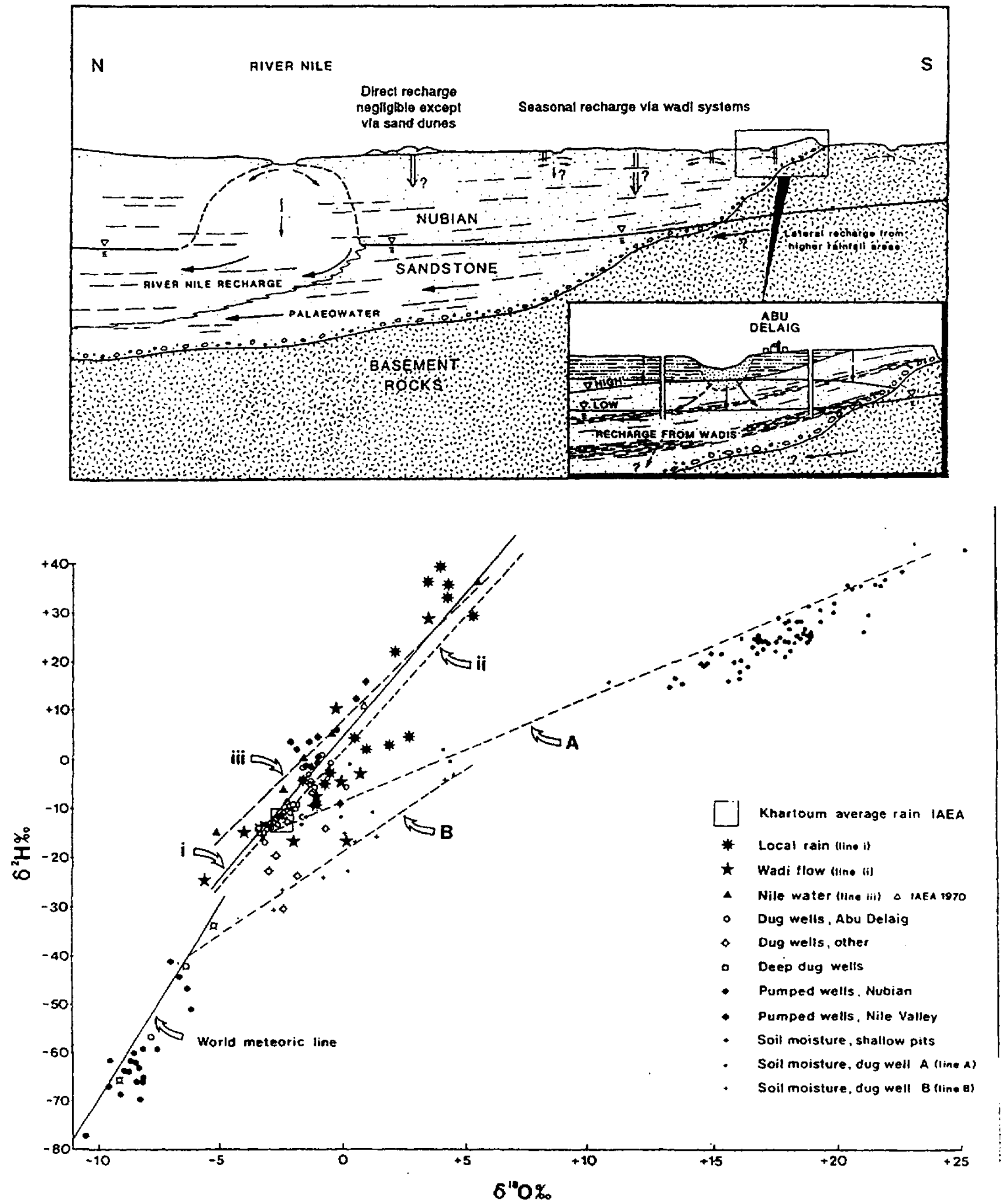


Figure 6. Conceptual model of the Butana region Sudan showing probable sources of recharge and isotopic signatures.

evapotranspiration process and where solutes accumulate giving rise to saline water accumulation and effectively zero movement through the unsaturated zone. This condition is demonstrated with the examples from Sudan, in the extreme situation in N Senegal and elsewhere such as Australia and SW USA.

The soil type and soil thickness are considered to be key variables in controlling recharge. Those semi-arid areas which are overlain by sands and sandy soils are highly favoured as recharge zones. It has been demonstrated at one extreme that sand dune-covered areas may receive significant direct recharge from heavy storms even where, as in Saudi Arabia (Dincer et al 1974), the mean annual rainfall may be as little as 80mm. Thus areas of present day sand dunes and sandy deserts in arid zones need to be closely studied in conjunction with the incidence and intensity of rainfall events to verify the possibility that regional recharge has occurred. In the example given from Senegal, the recharge studies have been carried out in Quaternary dune fields which are typical of much of the Sahel having formed during southward shifts of the arid margin and which now occur in higher rainfall areas. These areas, occurring at desert margins in many parts of the world, are of great importance at the present day since they occur in regions with relatively high populations, acting as buffer zones for migration during drought periods.

It has been shown from studies of the unsaturated zone in Australia discussed above that established vegetation coverage is highly efficient in water usage; on clearance recharge rates increase. This effect is also seen across climatic zones. In northern Senegal, where the mean annual rainfall is around 350 mm, the mean recharge rate is 13 mm (Gaye and Edmunds 1996), but in the south where the vegetation changes from Sahelian to Sudanian and mean annual rainfall increases to around 800 mm a^{-1}, the recharge rates in the same sandy lithology are essentially the same.

During the Holocene, semi-arid regions have witnessed intense changes in their water balance. Areas which at the present day receive 200-400 mm annual rainfall will have oscillated between arid periods when no recharge would have occurred and during which salinity accumulated in the aquifer. However, these same regions would also have undergone periods with active local (but not usually regional) replenishment giving higher water tables leading to spring discharges and lake formation. Further evidence of these changes should be present in the groundwater environment. Careful sampling of the deep unsaturated zones (up to 100 m possibly) for a range of geochemical indicators contained both in the moisture and possibly in the solid phase (resulting from contemporaneous water-rock interaction) should provide indicators of changes of inputs over 2000 a and possibly longer. With the miniaturisation of analytical techniques for isotopic and chemical analysis, notably AMS measurements of ^{14}C (Fontes & Edmunds 1989) it will be possible in well controlled hydrogeological investigations to determine with greater precision the undoubted age (and quality) stratification of unconfined groundwaters.

In terms of groundwater development in arid and semi-arid areas, the methodology described in the present paper, together with representative examples, provide an effective method to determine recharge and the sustainable yield of groundwater. The chloride balance approach is inexpensive to apply and gives results which are applicable to the rates of recharge that apply at the decade or century scale. This methodology is particularly appropriate to areas of desert and desert margins where unconsolidated Quaternary sediments, themselves the products of climate change, are widely-distributed. It is essential to establish a proper water balance before exploitation of a groundwater resource. In many cases this has not been done and the consequences of over-development are all too obvious. In such cases it is still desirable to establish the safe yield of the aquifer, either as a target for reduced but sustainable consumption, or to come to terms with the consequences of mining. In this context it is valuable to have a good understanding of recent variations in recharge history so that management options can include scenarios for any future abrupt climatic change.

ACKNOWLEDGMENTS

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SOME ISPTOPE HYDROLOGICAL STUDIES IN SOUTHERN AFRICA

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Abstract

Four case studies involving the use of the environmental isotopes ^{14}C and ^{3}H, in the arid to semi-arid Kalahari region of Southern Africa are described and general conclusions regarding the qualitative aspects of recharge and discharge characteristics of the systems are based on these measurements. In each of the studies, diffuse, local recharge was found to be the dominant recharge mechanism. Recharge via river beds was found to be limited at the regional scale. The balancing discharge mechanism for groundwater was found to be via evapotranspiration. Groundwater salinity and mineralisation as well as the regional hydrogeology are controlled by geological structure rather than lithologies or residence times and the absence of hypersaline groundwaters indicates that the aquifers are periodically flushed during pluvial periods, thus pointing to long-term hydroclimatic controls over the observed present-day hydrology.

Introduction

The Environmental Isotope Group at the Schonland Research Centre has been involved in ground water studies for the past 30 years and has pioneered and zone isotope hydrology in southern Africa. Some of the earlier studies were sponsored by the IAEA. More recently, the value of environmental isotope hydrology has become more generally realised and accepted. As central funding for research at Universities has been drastically reduced, sponsored research and commercial contracts have provided the basic funding for the group.

The four case studies presented here were conducted in the semi-arid to and Kalahari region and deal with three contrasting aspects of the hydrology of this thirstland. From this, some general conclusions can be derived for the region as a whole and other and zones.

Sources of recharge in Gordonia

The Gordonia area in South Africa forms the southernmost section of the sand-covered Kalahari thirstland. It is traversed by ephemeral river beds. Ground water yields and quality from the underlying hardrock aquifers are poor. Fresher ground water is found along the Kuruman River, and wells of higher yield drilled in the sand filling a palaeovalley, or trough, stretching some 40 km southwards from the river. The working hypothesis to be investigated was that, in the assumed absence of diffuse rain recharge, the fresh water in the trough is derived from bank infiltration during river flooding.

Radiocarbon measurements showed very recent water in the aquifers close to the river, sometimes with measurable trititun. Lower values were found in the trough, in the range of 33 - 77 pMC. Neither the ^{14}C values nor the hydrochemistry show consistent geographic trends away from the river. The stable isotope signal for ground water close to the river is much lighter than values observed further away in the trough. Isotopic and hydrochemical data therefore converge in showing that the river cannot be the source of ground water in the trough.

The range of ^{14}C values of ground water in the trough suggests active recharge. In the absence of clear regional influence of the river, diffuse rain recharge must occur. The question remains as to the stable isotope contrast observed. This is ascribed to the different types of rainfall occurring in the area. The river flows once every 10 - 15 years, during widespread monsoon-type rainfall periods, producing much above average rainfall for two to three years in succession.

During such periods, the vegetation becomes active and develops, thus largely consuming infiltrated water and preventing significant diffuse recharge. Rare localised convective rainfall events of extreme intensity, and different isotopic signal, falling during periods of vegetal dormancy, were postulated as being the source of the observed diffuse recharge. Such a model of and zone recharge has since become generally accepted.

In the extreme west of the area, where the mean annual rainfall drops to 200 mm, fairly shallow, highly saline and alkaline (up to 300 meq L^{-1}) ground water is encountered. Stable isotopes show that this water undergoes considerable evaporation before recharge. Carbon-14 values lie between 17 and 52 pMC, which, due to the extreme alkalinity, cease to reflect ground water residence time. The isotope signal and high mineralisation is interpreted as due to occasional widespread flooding of the area between the dunes, followed by evaporation and a concentration of solutes. Below the river bed, a fresh water lens is maintained by the occasional flooding, with high 14C, measurable tritium and lighter stable isotope signal. This again underlines the localised nature of infiltrated river water.

Kweneng province

A regional rest level gradient, directed northwards, suggests ground water flow from the piezometric high in the south, long accepted to be a recharge area. However, the ground water chemistry is heterogenous, showing no regional systematics, in both concentration and hydrochemical type.

The Kweneng province of Botswana lies some 300 km to the northeast of Gordonia. The Carboniferous to Jurassic sediments, capped by basalt, are covered by tens of metres of Kalahari sand. The two sandstone facies of this succession are almost everywhere good aquifers. The area is traversed by a fault, with its downthrown side on the north.To the south, the lower sandstone subcrops and dips below increasing thickness of mudstone northwards. To the north of the fault, the younger Ntane sandstone subcrops beneath the sand cover. Wells are usually sunk into the first aquifer sandstones encountered.

To the south of the faultline, the radiocarbon values average about 50 pMC. Immediately to the north, very low radiocarbon values are found below the thick layer of mudstone, where ground water is trapped. Further to the north, values are again around 50 pMC. These results are interpreted as being generated by diffuse rain recharge where the sandstone subcrops beneath the sand cover. At a mean residence time of some 4000 years, an aquifer porosity of 10 % and a depth of penetration into the saturated zone of 60 - 80 m, a mean annual recharge of the order of 1- 2 mm is obtained.

Jwaneng mine well field

This well field was established in the Kweneng just to the south of the fault line. The hydrogeological system tapped was interpreted as being a delta or alluvial fan of very coarse sandstone and a highly developed aquifer. As elsewhere in the area, the sandstone which subcrops beneath the Kalahari cover dips northwards below increasing thicknesses of mudstone, confining the ground water. The mudstone thickness increases rapidly north of the fault line. As in the rest of the area there was a slight natural piezometric gradient northwards, before exploitation started.

Wells are high yielding (up to 30 L s^{-1}). Initial estimates of drawdown had to be repeatedly updated as the wellfield was performing much better than predicted. The chemistry of the wellfield water is of the Ca,Mg - HCO_3 type, which suggests that ground water is actively recharged. In the surroundings, the chemical type is Na,Ca,Mg - Cl,HCO_3. However, on account of the 20m+ sand cover, it was postulated that recharge occurs some 50 km south of the wellfield, where the sand cover disappears.

Isotope data on the wellfield boreholes showed no measurable tritium. Radiocarbon values increase from around 50 pMC in the south-east to some 79 pMC in the north-west, i.e. where the ground water is most confined. Somewhat to the north of the wellfield, deep village boreholes tapping the same aquifer have vanishing ^{14}C values.

The only model which fits this apparently contradictory set of data is to assume diffuse recharge to the unconfined section of the aquifer. Boreholes increasingly intersect the shallow flow lines in a N-W direction, giving higher `C values. The deep boreholes to the north show that the flow has ceased there: water therefore has to enter the mudstone aquitard. During exploitation, some 107 M3 a-' at present, the cone of reduced pressure in the aquifer spreads and water in the aquitard will flow back into the aquifer. This may explain the apparent increase in the effective storage coefficient with progressive exploitation. Simple residence time calculations show long-term recharge of the order of 5 mm a^{-1}, which accounts for some 20% of present-day abstraction.

Toteng-Sehitwa grazing lands

The Toteng-Sehitwa Tribal Grazing Lands ranching area of the northern Kalahari some (7400 km^2 in extent, annual rainfall 350 to 450 mm) presents particular difficulties in geohydrological interpretation on account of i) the generally poor quality of the ground water and ii) the absence of clear regional rest level trends revealing ground water dynamics. It is sand-covered and extremely flat in the east, but rises in the west, where the underlying late Proterozoic sediments are exposed above the sand in isolated hills. In the west, ground water levels conform to the rising surface topography, gradients levelling out to 0.0002 in the Kalahari deposits. The regional piezometric baseline lies inside the study area, to the north west.

The aimlessness of the hydrological system is reflected in the observed isotope values and hydrochemical types, which show few regional trends. Somewhat more positive stable isotope values in the extreme north may reflect historical transgressions of the Boteti River. Much of the ground water of the area reflects a degree of evaporation before infiltration. This can be understood in terms of the few larger and numerous smaller pans or ephemeral playa lakes which characterise the area. Total dissolved solids range from 500 to 52 000 mg L^{-1}. The few cases of very low mineralisation are confined to the western rock outcrops.

The ^{14}C frequency distribution suggests that there is a continuum of mixtures between old and younger ground water, of unconfined (up to 85 pMC, sometimes with measurable tritium (0.5 - 2 TU)), to confined (~ 10 pMC) conditions, all in the thicker Kalahari deposits, where the $\delta^{13}C$ values become less negative and more uniform. Values > 90 pMC are found in rock outcrops. In general, there is no correlation of dissolved solid and radiocarbon concentration.

Environmental isotope and hydrochemical data show qualitatively that the area as a whole is receiving ongoing rain recharge much higher than the poor ground water quality and drainage would suggest. Recharge is however difficult to quantify, as the effective porosity of the aquifers is as yet poorly known.

These conclusions suggest that continued exploitation should improve ground water quality by removing salinity from the aquifer. The historical record of many supply boreholes showed an improvement of water quality with time, as predicted.

Conclusions on the arid-zone hydrology of the Kalahari

- In each of the studies, diffuse local recharge is found to be the major hydrological driving mechanism.

- The influence of surface features such as river beds is found to be very limited on a regional scale

- Regional sub-surface water movement is found to be at best a second-order effect, except where local structure enables limited lateral displacement

- Ground water mineralisation is a function largely of structure, rather than of lithology or residence time.

- The only balancing output mechanism is evapotranspirative losses from the saturated zone. Similar loss mechanisms have been invoked in north-west Africa for the existence of large scale depressions in the phreatic surface.

- With the exception of western Gordonia and parts of the Toteng-Sehitwa area, the absence of hypersalinity suggests that the aquifers are periodically flushed during "pluvial" episodes. The effectiveness of such resetting of the ground water mineralisation will be reflected in the present-day hydrology, which in turn is structurally controlled.

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SLOW AND PREFERENTIAL FLOW IN THE UNSATURATED ZONE AND ITS IMPACT ON STABLE ISOTOPE COMPOSITION

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Abstract

Stable isotope methods ($\delta^{18}O$ and $\delta^{2}H$) have been used investigate the importance of bypass flow in the unsaturated zone which leads to unproductive water loss during flood irrigation. Field experiments have been carried out in Jordan and Pakistan in order to determine the occurrence of bypass flow, its amount and its velocity compared to piston flow. Results show that there is not only an advective component of flow (bypass flow) but a diffusive tracer exchange between piston and bypass flow. Infiltration calculations and analysis of tracer distributions are used to show that at the research sites, bypass flow amounts to about 25% of water recharged during winter. This estimate is important as it provides an assessment of the amount of water that passes the root zone and directly recharges groundwater.

Introduction

Sediments may be homogeneous or inhomogeneous in granulometry and thus in pore size distribution. Pore sizes, however determine variations in hydraulic conductivities and flow in the unsaturated zone.

Typical examples of pore size distributions in terms of total porosity are shown in Figure 1. Inhomogeneous pore size distributions are mostly bimodal, causing a corresponding bimodal distribution of flow velocities with slow piston flow (a few metres per year) and quick bypass or preferential flow (a few metres a day). Piston flow is characterized by horizontal break-through fronts; bypass flow always has a fingered front (Figure 2). These flow components may alternate.

Bypass flow is limited to a transition zone between soil surface to a depth of 3.0 in. Due to suction heads in this transition zone preferential (bypass) flow is increasingly incorporated into piston flow and finally disappears. Below 3 in depth seepage flow becomes homogeneous and is exclusively piston flow in nature.

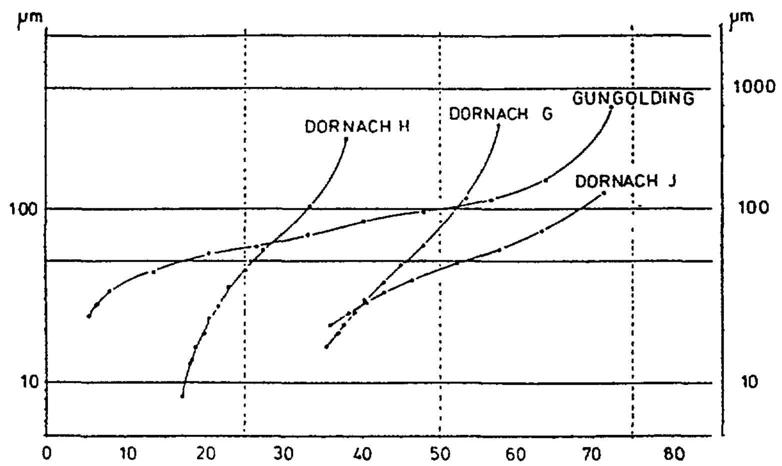

Figure 1: Pore sizes (μm) as a function of the available pore space (%)

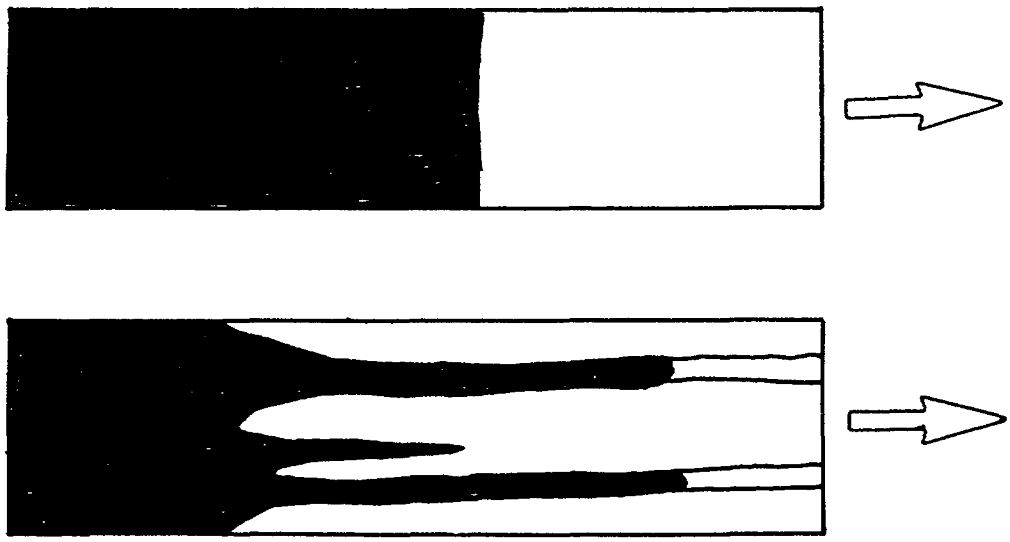

Figure 2: Fingered (bypass) and non fingered flow (piston flow) in the unsaturated zone

Water or tracer balance studies in the unsaturated zone mostly focus on near surface zones. Considering only water or tracer balance it is impossible to recognize equilibrated or non-equilibrated balances. To differentiate, tracer and water balances should be linked to infiltration rates; and a good knowledge of water contents before infiltration events.

From such investigations it can be established; (i) if and how much bypass flow occurs; (ii) if evaporation processes may change stable isotope information below the surface; and (iii) how bypass flow and piston flow interact.

Water balances and bypass flow in the unsaturated zone

Irrigation is commonly practiced in arid and semi-arid areas. Flood irrigation experiments have been conducted in order to study the importance of bypass flow in the unsaturated zone, which contributes to unproductive water losses. The tools for these studies are:

- coring before and repeatedly after flooding;
- the determination of changes in water contents;
- the extraction of water from cores to study time dependent changes of the concentrations of the non-reactive tracers (^{18}O, ^{2}H and Cl).

These experiments have been carried out in the Jordan valley, Jordan, and in the Punjab, Pakistan, applying:

- flood irrigation of 7.5 cm (75 mm/m^2);
- field sizes of 30 m x 30 m; and
- types of sediments in the unsaturated zone (Figure 3).

Fissured Lissan marls have also been selected in the Jordan valley (not reported in Figure 3) for irrigation experiments. On each field an experiment has been carried out at the end of the wet and during the dry season, respectively. No further flooding took place at the experimental site and its neighbouring fields following each experiment.

The quantities, isotopic and chemical composition of water:

- added to the field;
- pre-existing in the unsaturated zone; and
- changes following irrigation in the unsatured zone;

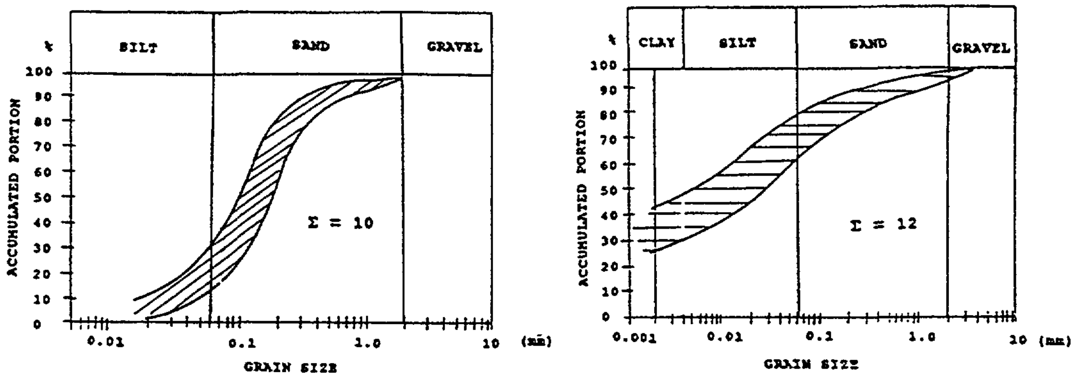

Figure 3: Rang of grain size distribution of some sediments used in irrigation experiments

have been measured over 2 m of depth. Water content was determined by gravity methods. For chemical and isotope analysis, water held in small core sections was diluted with Antarctic water, well mixed and extracted. From this data, flow rates and mixing have been determined in order:

- to prove the existence of bypass flow relative to infiltration quantities;
- to determine the amount of bypass flow;
- the importance of pre-existing suction heads for the origin of bypass flow; and
- the velocity of bypass flow as compared to piston flow.

The changes in water contents have been determined using:

$$\Delta M = \int_{x_a}^{x_i} \Theta_1 dz - \int_{x_{a1}}^{x_i} \Theta_2 dz$$

the changes in isotope as well as chloride concentrations have been used to calculate mixing ratios:

$$n = \frac{c_3 - c_2}{c_1 - c_2} \ .$$

M	quantity of water	θ	water content
z	depth	n	quantity ratio
c_1, c_2	pre-existing and added tracer concentration	c_3	final tracer concentration

Table 1 indicates the measured changes in water contents do not always reflect the calculated changes using Cl or ^{18}O-concentrations. Obviously there exists not only an advective change of water but also a diffusive tracer exchange between piston and bypass flow. This effect is most pronounced in the fissured Lissan marls, and changing its extent with season.

These results give a good explanation for e.g. the discrepancy in seepage velocities determined in the same gravels of southern Germany: (a) as a few metres a week (Seiler & Baker, 1985) by tracer tests; and (b) a few metres a year (Eichinger et al., 1984) by stable environmental isotopes. Tracer experiments determined the velocities of bypass flow. Environmental tracers determine the velocity of piston flow.

Table 1 Observed and calculated changes of water contents in the unsaturated zone in connection with irrigation experiments. shadowed during the dry season, unshadowed just after the wet season. nd = not determined

SEDIMENT	IRRIGATION QUANTITY IN l/m^2	INITIAL WATER CONTENT IN %	RESULTING WATER CONTENT IN %	STORED WATER QUANTITIES BASED ON CALCULATIONS OF CHANGES OF		
				WATER CONTENT	CL CONCENTRATION	^{18}O CONCENTRATION
SAND	190	10	15	38	53	53
SAND	150	6	12	58	nd	60
SANDY SILT	150	22	25	26	30	29
SANDY SILT	150	6	12	53	nd	68
LISAN MARLS	150	45	50	16	36	nd
LISAN MARLS	150	30	37	nd	34	36

Considering seepage recharge in the unsaturated zone of tertiary sediments during the winter months (November to April) results in infiltration quantities that should have completely exchanged the water contents in the first metre of the profile. Stable environmental isotope concentrations on the first metre of the profile, however, indicate that winter input is not reflected; the profile reflects a mixing between winter rains and the isotope composition of soil water from the previous summer (Fig. 4). This again is attributed to bypass flow and diffusive tracer exchange between bypass and piston flow. Both infiltration calculations and admixture of tracers from winter recharge are used to quantify bypass flow; in the area of research it amounts to about 25% of water recharged during winter.

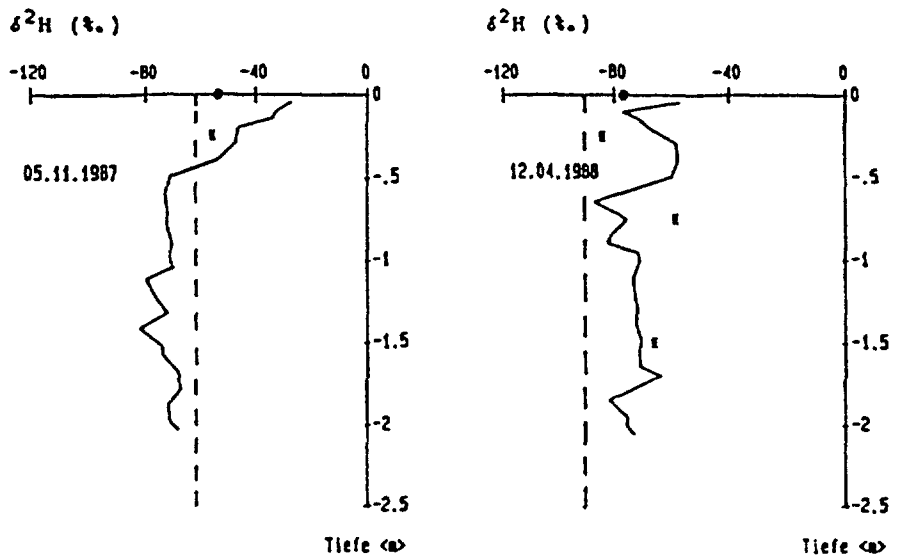

Figure 4: Stable isotope profils from the beginning (05-11-1987) and the end (12.04.1988) of the winter season. Broken line represents mean isotope concentration in precipitation, unbroken line samples from water extraction out of cores, point sampling by sucction cups. Samples from tertiary silty sand north of Munich

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