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Isotope field applications for groundwater studies in the Middle East

Proceedings of the final co-ordination meeting
of a regional technical co-operation project
held in Ankara, Turkey, 21–25 November 1994

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FOREWORD

Lack of freshwater for domestic, agricultural and industrial uses is presently hindering development in many parts of the world. Water scarcity is more acute in arid and semi-arid regions which cover almost one third of the Earth's land surface. Moreover, limited freshwater resources available in these regions are also threatened with deterioration in quality owing to human-induced hydrological changes. In recent years, the IAEA has placed emphasis on the use of isotope techniques over a wide spectrum of hydrological problems encountered in the assessment and management of water resources in arid and semi-arid regions.

A regional technical co-operation project entitled "Isotope Hydrology in the Middle East" (RER/8/002) was implemented by the IAEA during the period 1990-1994. Since available water resources in arid and semi-arid regions of the Middle East are often restricted to groundwater, the subject matter of the project was limited to isotope applications in hydrogeology. Applied isotope field investigations were carried out in selected major aquifer systems which are of immediate priority in the participating countries as a source of water. The Agency has contributed expert services, training and minor laboratory and field equipment according to the individual needs of the countries involved in the project. Isotopic analyses of the water samples were mainly undertaken by the Isotope Hydrology Laboratory of the Water Authority of Jordan, located in Amman. The isotope hydrology laboratory of the IAEA in Vienna has also provided analytical support to the implementation of the project.

The results obtained from applied isotope field investigations and the overall findings of the studies were presented and discussed at the final coordination meeting held in Ankara, Turkey, during 21-25 November 1994. This publication compiles the papers presented at this final meeting of the regional project. While these reports provide in-depth analyses of isotope results in the aquifer systems studied, they also provide background isotope data from the region as a basis for more effective planning of future isotope investigations.

Y. Yurtsever, Division of Physical and Chemical Sciences, was the IAEA Technical Officer for the project.

It is expected that the results and information provided in this publication will be useful guidance material to practitioners and scientists involved in water resources development activities in the Middle East region, as well as for those involved in isotope applications in arid and semi-arid zone hydrology.

EDITORIAL NOTE

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SUMMARY

This report summarizes the final meeting of the regional technical cooperation project entitled "Isotope Hydrology in the Middle East" (RER/8/002), implemented by the IAEA during the period 1990-1994.

In view of the severe shortage of available water resources in arid and semi-arid regions and potential contribution of isotope methods to solving hydrological and hydrogeological problems associated with water resources assessment and management in such water scarce areas, the IAEA has given special emphasis to isotope applications in arid zone hydrology during the last decade. The technical cooperation project was a part of this effort. Since available water resources in the Middle East region are often restricted to groundwater, the project was directed towards isotope field investigations related to various hydrogeological problems presently encountered in water resources assessment and development in the region. Eight Member countries in the region (Islamic Republic of Iran, Jordan, Lebanon, Kuwait, Saudi Arabia, the Syrian Arab Republic, Turkey and United Arab Emirates) have actively taken part in the project.

Results obtained from these isotope field investigations, and overall achievements of the project were discussed during the final coordination meeting held at the Civil Engineering Department of the Middle East Technical University (METU), Ankara, Turkey, during 21-25 November 1994 and are reported in this document.

The deliberations of the meeting indicated that the results of isotope studies conducted have substantially contributed to:

- Improved understanding of the sources and origin of water, mapping of palaeowaters and delineation of hydraulic interconnections between different aquifer units:
  Studies undertaken in Jordan, Kuwait, Lebanon and the Syrian Arab Republic on major aquifer systems aimed at identification of genesis of groundwater have enabled mapping of palaeo-subsurface water reserves which are not being replenished under present climatic conditions. Groundwater withdrawal from such reserves will be depleting of the existing reserves.

- Estimating rate of direct recharge to the groundwater from precipitation:
  Specific isotope studies conducted in the unsaturated zone of the selected representative sites of major aquifer systems in Saudi Arabia and the Syrian Arab Republic have enabled estimates to be made of replenishment rates to the underlying groundwater as a means of establishing allowable water extraction amounts without causing decline of the water table.

- Study of sources and processes of water salinization in coastal aquifers and identification of sources of pollutants and their transport dynamics:
  Methodologies based on natural isotopes were employed in Jordan, Lebanon and Turkey to identify the pathways of sea-water encroachment on coastal aquifers as a basis for proper engineering decisions to prevent groundwater salinization.

The meeting also considered further needs and requirements of the region in the field of isotope hydrology. Deliberations of the meeting in this regard indicated that the following topic-related problems associated with the impact of humans on water resources and isotope applications to existing problems of water management (particularly related to water pollution) will need to be given priority in future activities. These cover the following areas of specific interest to Member countries:

1) *Isotope applications for problems of groundwater pollution,*

2) *Study of human-induced changes to hydrology of groundwater systems,*

3) *Environmental isotopes for groundwater resources assessment in karst systems,*

4) *Estimate of direct recharge to the aquifers (from rainfall) through in-situ isotope studies in the unsaturated zone of selected major aquifer systems in the region,*

5) *Improved capability in the region for use of more advanced quantitative interpretation methodologies of isotope data in hydrology, particularly concerning numerical flow and transport modelling procedures in groundwater systems.*

The type of problems tackled in the field investigations conducted for the above purposes are common to all of the countries participating in the regional project. The methodologies used and results obtained provide a detailed assessment and illustration of isotope applications to a variety of problems encountered in groundwater systems under arid and semi-arid climatic conditions.

The deliberations of the final coordination meeting indicated that the regional project implemented by the IAEA during 1990-1994 has substantially contributed to the transfer of isotope techniques to the Member countries involved in the project. Final reports which summarize the results and findings of the isotope field investigations conducted on specific problems of the selected aquifer systems, are compiled in this publication. It is expected that the methodologies illustrated and results provided in the publication will serve as a guide for isotope applications in arid zone hydrology. In addition, this publication provides actual field data on the environmental isotope composition in major aquifer systems of the Middle East region which can serve as basic background data for planning and implementing future isotope hydrological applications in the region.

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PAPERS
PRESENTED AT THE MEETING

USE OF ISOTOPES TO STUDY GROUNDWATER RECHARGE THROUGH SAND DUNES IN QASIM AREA, SAUDI ARABIA

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Abstract

Long-Term Recharge monitoring is necessary in order to balance the scheme of groundwater in certain area. This study, conducted in Qasim region, considered recharge estimation for the unsaturated soils in Qasim area, particularly along the dune deposits near King Abdulaziz City for Science and Technology (KACST) Research Station, between Unaizah and Buraidah. Chemical tracers (Cl and H etc.) and the stable isotopes (the most successful in estimating groundwater recharge in dry regions) along with the physical methods were used to estimate the volume of water infiltrated through the sand dunes. The result showed undistributed recharge in a small scale belt. In SDB2 and SDB4 (Dune Site), the average recharge was estimated over 30 mm/y while in SDB1 and SDB3 (Swale Site), the average volume of water recharged (5mm/y) through the area was comparatively very low. On relative basis, the dune site received more recharge than the swale site. The difference in recharge between sites could be attributed to the lithological nature and processes subjected to the deposits. Overall, the swale site showed relatively more compacted material than the dune site.

INTRODUCTION

The development programs in Saudi Arabia during the last two or three decades have put tremendous pressure on the Kingdom's available water resources. The rising demands of municipal, agricultural and industrial sectors require better utilization of the country's surface and groundwater resources. Groundwater constitutes most of the available natural water resources in Saudi Arabia. The Ministry of Agriculture and Water (MAW) has conducted many general studies on aquifers in different parts of the country[1]. Efficient utilization of groundwater requires estimating recharge to aquifers (shallow and deep). The few studies of natural recharge to groundwater aquifer carried out so far give conflicting results and are not comprehensive in nature[1]. Most of the natural recharge to aquifers occurs either from floods in wadis or rainfall water penetrating directly to the aquifers. Vast areas of Saudi Arabia are covered with sand dunes and it is suspected that the aquifers below receive substantial amounts of recharge from the sand dunes above. Examples of these areas are Al-Dahna and Al-Nafud. Parts of the Saq aquifer occurs beneath Al-Nafud dunes. The Saq aquifer constitutes a very important part of the Qasim domestic and agricultural water supply reserves. Many well fields are located in the sand dunes covering Saq aquifer. The Saq Aquifer outcrop area is located west of the study area itself .The large areas of sand dunes receive substantial amounts of rain, it is likely that certain amount of that rain will reach the layers containing the aquifers below the dunes. This study was directed toward groundwater recharge through sand dunes to the aquifers existing below. The major objectives of the study were (1) a study of infiltration, and percolation processes in a sand-dune area; (2) investigations of characteristics of the formations and aquifers below sand dunes. However, the specific objectives at this stage of the study were:

1. To study quantitatively the processes of infiltration in a sand dune area.
2. To investigate variations of water content and water movement in the sand dune profile.

CLIMATE AND RAINFALL

The Arabian peninsula is characterized by a hot climate subject for the greater part of the year to northerly winds moving from the eastern Mediterranean towards the Arabian Gulf. Relative humidity is low except along the coastal zones where it reaches over 90%. The average annual temperature is 33.4°C in summer and 14°C winter. Rainfall in the upper two-thirds of Saudi Arabia is scanty, unpredictable and irregular. Variation between years is high and long periods may pass without rain. When rainfall occurs, it is very local and sometimes takes the form of violent storms of short duration. The intensity of the rainfall during such storms is far excess of the capacity of the land to absorb it. Thus, the high rate of runoff leads to rapid filling of wadi beds. Sometimes severe erosion and destruction may occur because of these floods. In general, the mean annual rainfall averages less than 100 mm most of it occurring in December-March and serving substantially for the development of range vegetation. Rainfall conditions in the Hejaz mountains and Asir Regions are completely different from the upper two-third of the country and there are two types of rainfall in that area: continental in winter and monsoon in summer. The rain in this area is well distributed throughout the year with peaks in spring and autumn. The annual rainfall exceeds 300 mm in the mountains. Rainfall diminishes from Taif and Jeddah to the North towards the Gulf of Aqaba. Snow seldom falls in the mountains but hail storms and winter frosts are common and the climate there is cool and dry: modified from Al-Khatib[1].

REVIEW OF LITERATURE

In general, there are quite few studies on modeling recharge in sand dunes and the factors that affect the recharge process. One of the old researches in sand dune area is the work of Prill[2]. He conducted the study in the sand-dune area of southwestern Kansas for a period of one year when precipitation was nearly the highest on record. He estimated the build-up of moisture under a sagebrush - grass and undergrass communities. Amounts of water depletion from soil were also evaluated. A similar work was done by Frank[3] in Clatsop plains in Oregon. He estimated the annual groundwater flow at different locations of the dune that have different permeabilities. Allison et al.[4] investigated the rates and mechanisms of local recharge in a semi-arid environment beneath two major landscape settings overlain by sand dunes in South Australia. It has been estimated that the annual recharge was about 100 mm.

A study of the effect of groundwater recharge on configuration of the water table beneath sand dunes was done by Winter[5]. The nature of this study was to examine water level fluctuations in about 30 observation wells and 5 lakes in the sand hills of Nebraska. It indicated that water-table configuration beneath-sand dunes in that area varied considerably, depending on the configuration of the topography of the dunes. The recharge beneath dunes was also affected by the dune configuration. A symposium was held in 1991 titled "Recharge in arid and semiarid regions". It covered various aspects of the recharge mechanisms and methods of measurements[6].

In Saudi Arabia, the early use of isotope for the study of water resources was done late in the 1960's when a team from IAEA experts came to collect samples for the purpose of dating the minjur aquifer, the main water supply for the capital city Riyadh. Since then many investigations were done either by the Ministry of Agriculture and Water (MAW) or by experts from local or foreign universities. Most of the studies were concentrated on dating the main aquifers of the Kingdom. A pioneering study on the unsaturated zone was done by Dincer et. al.[7] in 1974 on the sand dunes of Al-Dahna near Riyadh. They used temperature gradients, moisture content, grain size distribution and tritium, deuterium, oxygen - 18 content of the sand dune moisture, to determine possible infiltration. They concluded that a significant portion of an 80 mm rainfall was infiltrating through the sand dune.

The consulting companies, who were also clients to the Ministry of Agriculture and Water, were asked to collect Isotope samples from the shallow aquifers in various parts of the country. This was done within the framework of the general water and soils studies carried out by these consulting companies. Values of oxygen-18, Tritium and Deuterium in the rain water were reported as -0.02, 9, and 2.9 respectively by Hotzl et al.[8]. A review of the available data was done by Shampine et al.[9]. They reported that out of 137 wells sampled only 6 wells had a value of 15 tritium units or more, all in outcrop areas. A 1984 study by a consulting company for (MAW) reported a value of -9.8 for Oxygen - 18 and a value of -38.4 for deuterium[10]. The sample here represents a 100 m well which has less than 1 tritium unit.

MATERIALS AND METHODS

Site Location and Sampling

The sites chosen were at the top and at the base of sand dunes near King Abdulaziz City for Science and Technology (KACST), Research Station, Qasim area approximately 400 km North-West of Riyadh, where the mean annual precipitation is between 100 and 200 mmy-1[8].

The sand dune (SDB2) was approximately 10 m in elevation. The swale core(SDB1) was drilled toward the east and was in a small depression about 1 m lower than the immediate surrounding area. The two sites were approximately 700 m apart. In October 1993, two additional cores were drilled in the same area. The cores were labelled as SDB3 and SDB4 and were located within 10-20 meters from the previous two core sites (SDB1 & SDB2) in order to reproduce comparable results obtained in the first sampling. The analysis of samples collected from similar sites within close proximity of each other also allowed some preliminary evaluation of spacial variability and the effect of a drying season (summer) on the measurements performed earlier that year.

Drilling

Soil cores were drilled using a light, portable, hydraulically operated rig known as the "sand-drill". At site SDB1, samples were collected every 0.75-1.0 m interval to a depths of 27 and 14 meters, for the top and base of the sand dune, respectively where a hard gravel-type layer prevented further drilling on both times. The first 1.5 m was cored and sampled using a hand auger and a sleeve placed down the hole to minimize collapse. Samples were initially taken every meter between 100 and 200 mm of contaminant soil collapsing into the hole between samples. For each sample only the core from the bottom of the core barrel was used. Coring continued at 0.5 m intervals until, at a depth of 14 m, a hard gravelly layer was reached and no further drilling was possible. For the total depth of coring, samples were collected and where necessary bulked in 1 m intervals.

At site SDB2, the sand was wet at the surface. Drilling proceeded smoothly and a continuous record of samples was obtained upto a depth of 27 m where a hard layer prevented further drilling. A similar amount of collapse was seen as for the previous hole. Samples were divided and stored in the same manner as for the swale core. The time taken to sample the 27 m core was about 5.1/2 hours. The samples from the first two cores were put in honey glass gars. However, the samples from the second two cores were placed in 1000 ml aluminum cans and transported back to the laboratory for analyses. Water was extracted from the soil samples using azeotropic distillation[11]. Filter paper techniques as described by Greacen et al.[12] were used for the determination of soil suction. Data for all cores drilled are presented in tables 1-4.

RESULTS AND DISCUSSION

Mineralogical

Mineralogical analyses of soils from SDB3 and SDB4 sites indicated that the dominant elements were Silicon and Potassium followed by Calcium. These elements constitute sand, clay etc. For the dune site, SDB4, the clay contents increased with depth. Figure 1a shows relationship between mineralogical, water content and depth. The increase of water content with depth corresponds to the increase of clay dominant minerals with depth suggesting a higher retention of water in the clay. Similarly, for the swale site (SDB3), the clay contents were low near the surface (Fig 1b) but chloride concentration was higher thus indicating a low water content. Chloride concentration decreased with high contents of water because it dissolves and moves downward from the surface. This is an evidence of higher retention of water and suggests the presence of clay in the site.

Gravimetric Water Contents

Water content measurements for the swale site (Fig. 2a) and for the dune site (Fig. 2b) clearly showed the effect of evaporation during the hot dry summer. For the swale site, the sand about 3-4 meters below the soil surface showed similar trends in water content for the 2 sampling periods. There was, however, a reasonably consistent difference between the cores with the core collected after the summer having about 0.005 g of H_2O per g of sand less than core sampled earlier. It is difficult to determine whether this difference resulted either from evaporation or small-scale spatial variation in the sites. The sand above this depth has clearly undergone evaporation. Although water contents were not measured for all of this section (as the soil was too dry to core), it is likely that the average gravimetric water content would have been about 0.008 g of H_2O per g sand. Using this value, we estimated a net loss from the sand of at least 10 mm of water {(0.021 - 0.008) kg(H_2O)/kg(sand) * 40 dm * 1.5 kg(sand)/dm3 * 10 mm/dm} during the summer.

For the dune site, the water content measurements for the 2 sites were reasonably consistent upto 5 meters below the surface. Using calculations similar to those presented for the swale site, a net loss of ~ 12 mm evaporation was estimated. While there has been a net loss of water from the sand during the summer, it is possible that some recharge might have taken place at the dune site as a result of the large rainfall event in May. As seen from the results of the first cores, 13 mm of rainfall was sufficient to wet the soil upto 3 meters on the dune. Hence, it is possible that a further 57 mm in the following month, including 28 mm in one day, could have displaced soil-water to a depth below the zone of evaporation and hence allowed some recharge[13].

Chloride Concentration of Soil Water ([Cl] soil water)

In order to determine [Cl] soil water , the [Cl] soil and [Cl] water should be determined on the same soil sample. Colorimeteric and titration methods were used to estimate Cl in soil and water content (g_0) in the soil (Table 5). The following equation was used to determine [Cl] soilwater from the chloride concentration of soil water.

$$[Cl]soilwater = [Cl]soil/g_0$$

The chloride concentration of the soil water was considerably higher in the Swale site than the dune site thus indicating a lower rate of recharge on the swale site. In swale site, the concentration of soil water increased with depth than the surface where recent rains were obviously still present to a depth of 2-3 m. From this depth, a plateau chloride value is maintained at about 1000 mg/L to a depth of about 9 m. From 9 m depth to the end of the sampling intervals, there was a monotonic increase in the chloride concentration of the soil water.

Suction (Water Potential)

Filter Paper techniques described by Greacen et al.[12] were used for determination of soil suction.

Soil water potential measurements for the swale sites were high for all the data except samples collected after rain for the first period (Fig. 3a). These results indicated that there was no recharge resulting from the rainfall event immediately prior to the first sampling period and also there was no evidence from this profile of any significant recharge.

The results for soil water potential measurements on the dune samples were much lower than those for the swale ranging in general from ~10 - 100 kPa (Fig.3b). An exception to this was the surface five meters for the second sampling period where soil water potential was considerably higher. This data reinforces the suggestion that, if there was any recharge between the first and second sampling periods, it might have occurred soon after the rainfall event in May. By the time of the second sampling, the soil water potential for the top 5 meters of sand was very high. However, low soil water potential observed for both the cores for 10 to 20 m interval, suggests relatively recent recharge at least in the range of years or decades.

Another exception to the general trend of low soil water potential for these cores can be seen at the bottom of core SDB4 and to a lesser extent at about 15-16 m for both dune cores. These high values were most likely associated with periods of low recharge with an intervening period or periods of higher recharge resulting in soil water potential approaching field capacity. It is probable that this type of pattern for soil water potential and other parameters (see later) is indicative of sporadic recharge which is typical in arid areas. The 2 troughs of low soil water potential indicate at least 2 significant rainfall events where infiltration was deep enough and could not be evaporated over the following dry season or seasons[13].

Tritium

The tritium concentration at swale site, when plotted against depth, showed two peaks of similar magnitude at 0-1 m and at 4-5 m (Fig 4a). Both peaks were similar in magnitude at around 50 TU.

This profile was remarkably similar to that presented by Dincer et al.[7] from a sand dune cored in the Al-Dahna sand dunes (collected 1972). If allowance is made for radioactive decay, the tritium profile presented by Dincer et. al[7] not only has the same shape but also has the same magnitude to that seen in this study at the swale site.

Dincer et al. [7] suggested that clearly, infiltration had proceeded to displace the bomb-peak tritium to a depth of about 4 meters in less than 10 years from the time when tritium concentration in rainfall was at peak. He suggested that perhaps about 20 mm of recharge would result from this infiltration.

Profiles with two tritium peaks, the first located at or near the surface and the other displaced down the profile, have been reported by several researchers [14]. Dincer et. al. [7] suggested that, for the Dahna sand dune study, this type of profile is likely to be the result of varying tritium input in rainfall (eg. low tritium in 1969 rainfall).

The tritium profile for SDB2 displayed a trend of increasing tritium concentration with increasing depth (Fig. 4b). The maximum tritium concentration measured was about 50 TU located at the bottom of the profile. It was interesting to note that this value was the same as that seen in SDB1 and, if radioactive decay is considered, also the same as that reported by Dincer et al.[7]. Unfortunately, as the maximum tritium concentration was found at the bottom of the core, it is possible that (a) the peak is actually located somewhere below the bottom of the hole and (b) the peak tritium value is greater than 50 TU.

However, results from the chloride data suggest that the tritium peak is likely to occur near to the end of the hole and the following discussion assumes the tritium peak to be at 26 m. Apart from the general trend in tritium concentration with depth, local maximum tritium concentrations were seen for the samples at 3.0-3.75 m and to a lesser degree at 13.5 -15.75 m.

The local tritium maximum at 3.0 - 3.75 m is clearly still in the zone of evapo-transpiration and, like the peak seen for the swale site, is trapped there until a sufficiently large rainfall event displaces it beyond this zone.

The other local maximum occurs at a depth of about 13.5 - 15.75 m and is about 10 TU greater than core samples immediately before and after this depth. It is interesting that this local maximum value for tritium concentration occurs at about the same depth as the local maximum soil potential for SDB2.

As is the case with the deeper local tritium maximum, the enriched tritium levels probably result from residue bomb-peak tritium and not recent rain-fall. If this is so, then an estimate of recharge may only be made from the maximum depth of enriched tritium in the soil-water. Interpreting these peaks as remnant peaks in the tritium input function or historical high rainfall periods may, in this case, be erroneous[13].

Recharge Estimation From Tritium, Chloride and Stable Isotopes data

Unfortunately, the core was not deep enough to define the tritium profile in this case and hence, an estimate of the position of the tritium maximum rather than the tritium center of mass was used for recharge estimation. If a plot is made of tritium concentration as a function of cumulative water rather than depth, the amount of water (in mm) above the tritium peak can be easily obtained. Hence, the amount of water in the profile above the tritium peak was defined as follows [15].

$$\text{Amount of water (mm)} = \int_0^{z_m} \theta(z)\,dz$$

where z_m is the depth at which the maximum tritium concentration is located.

For SDB2, z_m is at 26 m or greater and the amount of water in the profile to this depth was about 930 mm (Fig. 5a). Assuming that the year of maximum tritium concentration in rainfall was 1963 and hence 30 years has elapsed since this precipitation infiltrated the dune, average recharge for this time interval was estimated at just over 30 mmy-1. This should be considered an estimate only because:

A. The peak may be lower than this depth. (It is encouraging, however, that the maximum tritium concentration for SDB2 was the same as that for SDB1 and perhaps, it was close to the peak value).

B. The recharge mechanism is not via piston flow and hence the tritium center of mass and not the peak tritium value should be used.

For SDB1, z_m is at 140 mm (Fig. 5b) which would translate to an average recharge rate of about 5 mmy-1 , where it is not because this peak is located in the zone of evapo-transpiration. As discussed above, it is likely that recharge for the swale site was close to zero and hence, this method for recharge estimation will only work if the tritium peak has progressed beyond the depth of evapo-transpiration. It is interesting to note that the corresponding peak in SDB2 was located at a similar position falls ($\sim$150 mm of water). It is also worth noting that the magnitude of this peak was $\sim$20 TU less than that seen for SDB1 as bomb-peak tritium might have been exported (recharged) to a depth beyond the zone of evapo-transpiration.

Chloride

Chloride profiles for the 2 cores from the swale site were significantly different (Fig 6a). The SDB1 core, collected soon after rain in April 1993, showed low chloride concentration to a depth of about 2 meters. From 2-7 meters, the chloride concentration was constant at about 1300 mgL-1 after which the chloride concentrations increased rapidly to the bottom of the core.

The other core, taken after the dry summer displayed the characteristic evaporation profile with increased chloride concentration toward the soil surface commencing at a depth of at least 6 meters. The minimum chloride concentrations for this core were around 500 mgL-1 at a depth of 8-10 meters. Below this depth, the chloride concentrations increased rapidly in a similar way to that of SDB1. The difference between these cores is primarily a result of small scale spatial heterogeneity with SDB3 displaying a greater potential for recharge than SDB1. Overlaying this, of-course, is the evaporation effect of a drying season.

Chloride concentration profiles for the dune core were also quite different from each other (Fig. 6b). As with the swale site, there was an evidence of evaporation to a depth of somewhere between 5 and 10 meters. From the bottom of the zone effected by evaporation to a depth of about 12-13 meters, the 2 profiles had similar chloride concentrations. Below this depth, however, SDB2 continues to have low chloride soil-water while the soil-water in SDB4 shows a similar trend to the 2 swale sites.

Small-scale spacial variations in recharge have been reported in semi-arid environments with sandy soils[15]. Despite the attempts to duplicate the sampling sites in this study, all the sites displayed different recharge rates with the highest recharge occurring at SDB2 followed by SDB4, SDB3 and finally SDB1 possibly having no obvious recharge for at least in the last 3 decades. The core SDB4 is interesting in that it contains information on at least 2 low recharge (high chloride) and at least 2 high recharge (low chloride) intervals. The largest low recharge period is reflected in the chloride data for the core at a depth of 16-24 m. Chloride concentration of the soil-water reached a maximum of about 16,000 mgL-1 at this depth. Another smaller chloride peak was seen at a depth of about 25-26 m. The depth interval between the high chloride values may give some indication of the frequency of recharge producing events. The variations in chloride did not correspond to changes in soil-water potential for the cores. It is interesting to note that the agreement was much better between the "paired" cores for the soil moisture determination than for chloride analyses. Understanding to this phenomenon may help in further evaluating the mechanism and time frame for recharge in this area. Another way of looking at the chloride data is to look at cumulative or total chloride as a function of depth (Figs. 7a) or cumulative water (Figs. 7b). For the dune sites, the chloride concentration profiles of the soil were same to a depth of about 15 meters after which there was a large increase in the chloride concentration at SDB4 while that at SDB2 only increased marginally to the bottom of the hole. This data suggests that while recharge conditions may be similar now for the 2 sites, at some stage in the past recharge at SDB4 was restricted. It is also possible to see a period of high recharge associated with low chloride content in the sand at depths greater than 21 meters for SDB4. Results of tritium analyses between depths 15 and 26 meters should be particularly enlightening for core SDB4. However, the tritium results were not available at the time when this report was preparing.

Deuterium and Oxygen-18

The stable isotope profiles of the soil-water extracted from the 2 cores were very different. This is not surprising given that they represented water for the very different time frames and recharged at very different rates. When plotted in deuterium vs Oxygen-18 space the results are interesting (Fig. 8). All data, barring the most recent rainfall near the surface of SDB2, plot on a slope of about 8 but are displaced from the Global Meteoric Water Line by about 20-35 for SDB1 and by about 20-30 for SDB2 (i.e. the deuterium deficit for the dune site is only slightly less than that for the swale site). The data for SDB4 show the same trend except the deplation of deuterium is more pronounced than the other two sites, SDB1 & SDB2, (Fig. 8). The available information for the isotopic composition of precipitation in inland areas in the middle east suggests that it is extremely unlikely that major rainfall events would be displaced by more than a few per millie from the meteoric line. Hence, it is unlikely that the soil-water has not been fractionated. When plotted against depth, the isotopic composition of soil-water for SDB1 shows a reasonably constant value from about 6-11 meters and a steady decline below that depth (Fig. 9a). This is quite different from the profile at SDB2 where all data lies in a narrow deuterium and O-18 range. A similar profile is seen for the Oxygen-18 composition variations with depth (Fig. 9b). When oxygen-18 and deuterium composition is plotted against depth for SDB4, generally, the decrease of isotope composition with depth is quite clear. The shift of deuterium and oxygen-18 composition with depth is probobly due to a long period of rainfall absence which caused downward percolation and hence the gap between the recent rainfall and the old one (Fig. 10a. b).

Clay Contents and Recharge

A very good summary of a decade of recharge studies in a 6,000 km2 semi-arid region in south-east of South Australia attempted to quantify the factors affecting recharge in that environment. While the average precipitation in the Australian study (250-400 mmy-1) is considerably higher than that for this study (120 mm y-1). Perhaps the most interesting conclusion arising from this study was the relationship between recharge and percentage clay content in the top 2 meters of the soil . The depth chosen for the clay content was 2 meters, commonly believed to be the maximum depth from which evapotranspiration can take place in this environment. The presence of clay in the top 2 meters of surface soil greatly reduced the recharge as it retarded the infiltration of water in the zone of evapo-transpiration and is evapo-transpired rather than being available for recharge [15].

A similar relationship between recharge and clay content may be expected for the study sites in the Saudi Arabia. However, as a result of the increased potential evaporation and the prolonged periods between rainfall events the zone of evaporation is considerably deeper than that experienced in the Australian study. Evaporation of soil-water to a depth of at least 5 meters was clearly evident from the changes in the soil-water potential profiles before and after the summer [14]. If this is the case, then the proposed study on the Al-Dahna dunes within the framework of the ongoing studies on sand dunes in Saudi Arabia should be very interesting. The Al-Dahna dunes are situated in an area with a mean annual rainfall about 80 mmy-1, significantly less than that for the Al-Qasim area. However, these dunes are believed to have less clay in the soil profile than those at Al-Qasim. This belief is supported by an inter-comparison of infiltration rates at the 2 sites with the rate at the Al-Dahna dune 2-3 times that of the Al-Qasim dune[16].

Summary

The use of tritium analyses on soil-water extracted from the unsaturated zone, provided an estimate of mean recharge for the last 3 decades to the deep unsaturated zone and , probably, the unconfined water table. In addition, combining the results from the tritium analyses with analyses for stable isotope composition, soil-water potential, soil-water chloride concentration and water content has resulted in a better understanding of the processes involved and extended the time frame, at least qualitatively, to beyond that commonly employed by the use of "bomb-peak" tritium alone. Recharge rates for the 4 cores collected to-date ranged from <5 mmy-1 (may be no recharge) at SDB1 to >30 mmy-1 at SDB2. While tritium and stable isotope analyses are not yet available for SDB3 and SDB4, the chloride data suggests that the recharge rate for SDB3 is similar or may be slightly greater than at SDB1 while that for SDB4 is almost as high as that at SDB2.

Text cont on p. 31.

TABLE 1. ALL ANALYSES FOR SDB1

		KACST					CSIRO	IAEA	IAEA	
Sample	Wat. Con	Cum Wat	[Cl]soil	[Cl]soilwater	[Cl]soil	[Cl]soilwat	Deuterium	Deuterium	Oxygen 18	Tritium
Depth (m)		(mm)	mg/kg	mg/l	mg/kg	mg/l	% SMOW	% SMOW	% SMOW	TU
0-1	0 0279	21	5 72	205	9 8	351	13 4	5 4	1 7	50 3
1 2	0 026	60	15 43	593	11 4	438	1 5	-4 8	2.14	13 4
2-3	0 02	90	29 04	1452	27 3	1365	8 8	5 7	3 08	25 2
3-4	0 0154	113	18 18	1181	21 2	1377	10 2	8.9	3 28	28 5
4-5	0 0146	135	14 8	1014	17 9	1226	2	5 7	1 9	47 8
5-6	0 0132	155	15 18	1150	15 9	1205	-2 8	9 6	1 19	
6-7	0 0142	175	13 55	954	17	1197	-4 1	-12 6	-0 3	15 6
7-8	0 0173	202	19 09	1103	22.3	1289	-6	12.8	0 16	
8-9	0 0241	238	28 33	1176	34 6	1436		14 2	0 23	8
9-10	0 0204	269	32 94	1615	38 9	1907	10 3	17	-0 44	
10-11	0 0213	301	50 73	2382	58 2	2732		14 7	0 17	4
11 12	0 0287	344	85	2962	87 2	3038	15 9	20 2	-0 28	
12 13	0 0349	396	132 22	3789	126 5	3625		28	1 98	
13-14	0 0311	443	152 18	4893	142.1	4569	23 8	34	3 06	13 6

TABLE 2. ALL ANALYSES FOR SDB2

			Kacst				Csiro				CSIR	IAEA	IAEA		
Sampl	Wat C	Cum	[Cl] so	[Cl]soil	Cumcl	[Cl]so	[Cl]soil	Cumcl	Suctio	+/-st d	Deuteri	Deuteri	Oxyge	Tritium	Cum tr
Depth		(mm	mg/kg	mg/	mg/dm	mg/	mg/l	mg/dm	kPa		% SM	% SM	% SM	TU	TU
0 0-0 7	0 028	15	5 85	211	47 18	8 5	307	47 2	4 4	0 5	38	31	3 14	13 7	0 2
0 75-1	0 037	57	5 81	157	85 5	7 6	205	132 7	4 6	0 7	8 3	1 3	0 03		0 8
1 5-2 2	0 037	98	6 94	187	102 9	9 4	253	235 6	4 3	0 1	6 4	4 3	2 08	14 6	1 4
2 25-3	0 036	138	9 79	272	109 1	9 7	269	344 7	4 6	0 8	18 6	11 6	3 96		2 3
3 00-3	0 016	158	6 65	413	87 6	7 3	453	432 3	15 3	1 1	11 8	6 4	2 42	28 7	2 8
3 75-4	0 018	177	7 72	422	109 2	10 4	568	543 5	18 4	1 1	10 8	4	2 16		3 3
4 50-5	0 015	195	6 47	423	105 6	8 8	575	647 1	13 3	0 9	9 2	3 4	2 27	23 5	3 8
5 25-6	0 017	213	6 52	386	67 2	6 4	379	714 3	15 3	2 1	7 6	5 2	2 05		4 1
6 00-6	0 016	232	5 3	335	78	6 5	411	792 3	11 1	0 6		1 2	1 89	15 7	4 4
6 75-7	0 016	244	5 12	312	47 25	6 3	384	839 6	12 3	1 1	8 5	1 8	1 61		4 6
7 5-8 2	0 016	268	6 77	420	126	8 4	522	965 6	9 9	0 3		-1 5	1 22	17 7	5 0
8 25-9	0 017	286		0		19 9	1199	1175	12 5	0 8	5 7	-1 7	1 13	19 3	5 4
9 00-9	0 018	307	0	0		6 2	350	1249	8 2	0 7			-1 98		5 8
9 75-1	0 021	329		0		7 3	349	1326	8	1 4	5 6	0	1 56		6 2
10 50-	0 02	352		0		10	510	1446	7 6	0 4		-2 8	0 81	19 4	6 7
11 25-	0 025	378		0		9 6	389	1546	6 2	0 7					7 2
12 00-	0 023	405		0		18 4	818	1767	6	0 4	5 6	0 1	1 05	22 8	7 8
12 75-	0 024	430		0		6	252	1830	7 3	1 3		-2 9	0 88		8 5
13 50-	0 02	541		0		6 1	305	1894	7 2	0 4		-1 2	0 9	31 3	9 2
14 25-	0 035	493		0		8 9	256	2001	21 8	1	3 7	-6 8	0 47		10 5
15 00-	0 041	542		0		12 8	316	2155	161 1	15 3		-4 6	0 93	32 4	12 1
15 75-	0 04	584		0		7 9	197	2238	48	2 7		-0 5	0 4		13 2
16 5-1	0 033	623		0		5 7	174	2306	32 2	1 9	6 3	-6 1	0 64	19 5	13 9
17 25-	0 027	651		0		8 7	325	2397	20	1		-1 6	1 47		14 7
18 00-	0 028	685		0		6 4	231	2474	20	1		-5	1 11	39 6	16 1
18 75-	0 029	714		0		7 5	263	2553	20 4	1	6	-5 8	0 76		17 1
19 50-	0 029	749		0		7 9	273	2648	18 5	0 3		-3 5	1	31 7	18 2
20 25-	0 032	742		0		6 9	218	2720	22 6	0 8		-5 2	0 65		19 5
21 00-	0 024	811		0		4 2	179	2771	11 1	0 5	8 3	-2 9	1 27	43 1	20 7
21 75-	0 029	841		0		8 7	304	2862	10 5	0 5		-1 8	1 43		22 2
22 50-	0 028	870		0		6 7	238	2932	10 6	0 6				34 9	23 2
23 25	0 027	903		0		4 4	161	2985	13 2	1 2	9 3	-0 5	1 97		24 6
24 00-	0 023	930		0		3 8	168	3031	18 9	1 3		-0 7	2 17	50 4	26 0
24 75-	0 047	979		0		5 3	114	3086	23 3	1 6	7 8	-2 7	1 64		

TABLE 3. ALL ANALYSES FOR SDB3

Sample	Depth	Watercon	K	Ca	Cumwat	Clsoil	Clsoilwat	Cumcl	Suction	+/- 1s d	O-18(AV)	DELTA-D
	m	%	%	%	mm	mg/kg	mg/l	mg/dm^2	kPa			
1	-3	0.00701	2.34	0.65	31.55	4.13	589	371.7	35293	35293		-29.5
2	-4	0.00986	1.79	0.46	46.33	15.13	1534	825.6	20008	20008.7		
3	-5	0.0089	1.4	0.55	59.69	9.5	1067	1110.6	15943	15943.1		-35.6
4	-6	0.01066	2.28	0.84	75.68	5.63	528	1279.5	13356	13356.7		24.5
5	-7	0.00921	2.52	0.93	89.5	6.25	679	1467	33478	33478		-8.3
6	-8	0.02154	3.1	0.22	121.8	5.13	238	1620.9	3905	3905.3	-2.5	-35.7
7	-9	0.01679	10.55	1.62	147	3.13	186	1714.8	5269	5269.6	-0.5	-12.6
8	-10	0.01568	3.6	1.39	170.5	3.75	239	1827.3	5555	130413.5	-0.58	
9	-11	0.01378	3.16	1.14	191.2	2.5	181	1902.3	2347	8032.2		-17.6
10	-12	0.02254	3.29	2.48	225	11.25	499	2239.8	2437	2437.1	-0.34	-23.3
11	-13	0.01854	3.44	1.38	252.8	12	647	2599.8	3735	3735.5	-0.5	
12	-13.5	0.02391	2.56	0.91	271	18.5	774	2877.3	3058	3058.6	-3.12	
13	-14	0.0204	2.46	1.02	286	18.63	913	3156.75	4022	4022.1	-4.51	

TABLE 4. ALL ANALYSES FOR SDB4

Sample	Depth	Water Con.	K	Ca	Cum wat.	Clsiol	Clsiolwat	Cumcl	Suction	+/- 1s d	O-18(AV)	Delta D
	m	%	%	%	mm	mg/kg	mg/l	mg/dm^2	Kpa			
1	-2	0.00972	2.13	0.43	29	1.5	154	90	494	229.1		25.4
2	-3	0.00485	2.59	1.14	36	0.75	155	112.5	14131	6062		18.2
3	-4	0.00839	2.5	1.53	49	1.06	126	144.3	3041	1795.7		-1.4
4	-4.5	0.00901	2.6	1.77	56	4.13	458	206	1647	394.9		2.4
5	-5	0.01375	3.09	2.44	66	2.25	164	240	87	2		8.4
6	-6	0.01519	2.21	1.54	89	1.5	99	285	250	291.1	3.51	8.9
7	-7	0.01767	3.51	1.74	115	1.88	106	341	55	7.5	5.23	6.8
8	-7.5	0.01816	2.32	1.63	129	1.4	77	362	37	14.7	3.77	-2.5
9	-8	0.01383	3.01	2.04	139	2.75	199	403.6	31	6.1	3.8	8.2
10	-8.5	0.01361	2.08	1.27	150	1.25	92	422	28	1.6	1.47	
11	-9	0.01604	2.25	1.03	162	1.13	70	439	23	1.7	4.95	7.5
12	-9.5	0.01676	2.92	1.55	174	0.88	53	452.5	15	2.4	3.2	-54.3
13	-10	0.01703	2.72	1.69	187	1.25	73	471	16	3.5	2.85	-4.9
14	-11	0.0133	2.59	1.19	207	2.63	198	550	16	1.7	0.98	-34.1
15	-12	0.02574	6.91	2.25	246	4.5	175	685	9	2.4	3.58	7.9
16	-13	0.02403	2.09	0.92	282	5.88	245	861.6	6	1.8	3.64	15.4
17	-14	0.01893	1.9	1.3	310	10	528	1161.6	9	1.4	1.51	1.2
18	-15	0.01914	2.03	1	339	13.63	712	1570.5	12	3.2	4.91	29.5
19	-16	0.03862	3.5	1.59	397	18.63	482	2129	60	2.8	0.76	-6.8
20	-17	0.03163	3.12	1.83	444	50.88	1609	3655	47	5.5	-0.93	-12.6
21	-18	0.03511	3.85	3.19	497	130.13	3706	7559.7	27	5.3	3.67	-17
22	-18.5	0.03163	3.84	1.57	520	161.88	5118	9987.9	26	1.7	-0.73	-22
23	-19	0.03679	4.97	2.63	548	237.75	6462	13554	27	3	-5.09	-41
24	-20	0.03581	3.97	2.23	602	284	7931	22074	32	4.1	-3.12	-33.4
25	-20.5	0.03389	4.25	1.93	627	276.88	8170	26227	32	3.6	-3.98	-36.5
26	-21	0.03281	3.34	2.34	652	270.25	8237	30281	18	3.2	-4.64	-49.5
27	-22	0.02561	2.13	0.79	690	171.25	6687	35418.6	14	3	-4.97	-44.7
28	-23	0.01352	2.66	1.18	710	65.63	4854	37387.5	1969	986.6	-5.27	-75.5
29	-24	0.01427	2.84	0.67	732	46.75	3276	38790	2513	826.3	-5.52	-51.9
30	-25	0.01503	2.86	0.82	754	35.75	2379	39862.5	3143	725	-4.15	-55.2
31	-25.5	0.01288	2.31	0.92	764	58.63	4552	40742	700	188.5	-5.83	-52
32	-26	0.01518	3.4	1.45	775	25.25	1663	41120.7	10936	2090	-0.36	-39.3

TABLE 5. COMPARISON OF CHLORIDE ANALYSES FOR SDB4 USING DIFFERENT ANALYSIS TECHNIQUES

sample no	Depth(m)	wat.con	Clsoilsub	Cl soil	Cl s'water	cl(Titration)			cl (Repet.)		CSIRO	
			extract	mgCl/kgsoil	mgCl/Lwat				feb/20/94			
1	2	0 00972	1 5	3	308 64198	10 65	637 86008	2191 358			4 7	967 07819
2	3	0 00485	0 75	1 5	309 27835	10 65	896 90722	4391 7526			3 6	1484 5361
3	-4	0 00839	1 06	2 12	252 68176	10 65	698 45054	2538 7366			4 8	1144 2193
4	-4 5	0 00901	4 13	8 26	916 75916	10 65	980 0222	2364 04			4 7	1043 2852
5	5	0 01375	2.25	4 5	327 27273	10 65	476 36364	1549 0909			4 3	625 45455
6	-6	0 01519	1 5	3	197 49835	14 2	500 32916	1869 6511			6 1	803 15997
7	7	0 01767	1 88	3 76	212 79004	10 65	310 13016	1205 4329			3 6	407 47029
8	7 5	0 01816	1 4	2 8	154 18502	14 2	126 65198	1563 8767			0 9	99 118943
9	8	0 01383	2 75	5 5	397 68619	14 2	227 76573	2053 5069			0 4	57 845264
10	8 5	0 01361	1 25	2.5	183 68846	10 65	341 66054	1565 0257			3 4	499 63262
11	9	0 01604	1 13	2 26	140 89776	14 2	126 5586	1770 5736			0 9	112 21945
12	9 5	0 01676	0 88	1 76	105 01193	10 65	130 0716	1270 8831			1 3	155 13126
13	10	0 01703	1 25	2 5	146 79977	7 1	220 19965	833 82267			2 5	293 59953
14	-11	0 0133	2 63	5 26	395 48872	10 65	468 42105	1601 5038			3 6	541 35338
15	-12	0 02574	4 5	9	349 65035	7 1	213 67521	551 67055			1	77 700078
16	13	0 02403	5 88	11 76	489 38826	10 65	423 63712	886 39201			4 3	357 88598
17	-14	0 01893	10	20	1056 524	14 2	1500 2	1500 2641			0 8	84 521923
18	-15	0 01914	13 63	27 26	1424 2424	17 75	1854 8	1854 7544	6 4	668 75653		
19	16	0 03862	18 63	37 26	964 78509	21 3	1103	1103 0554	13 188	682 9622		
20	17	0 03163	50 88	101 76	3217 1989	63 9	4040	4040 4679	48 63	3074 9289		
21	18	0 03511	130 13	260 26	7412 7029	142	8088	8088 8636	126 25	7191 6833		
22	-18 5	0 03163	161 88	323 76	10235 852	188 15	11896	11896 933	169 25	10701 865		
23	-19	0 03679	237 75	475 5	12924 708	266 2	14471	14471 324	212 63	11559 119		
24	20	0 03581	284	568	15861 491	326 4	18229	18229 545	284 75	15903 379		
25	-20 5	0 03389	276 88	553 76	16339 923	298 2	17598	17598 112	224	13219 239		
26	21	0 03281	270 25	540 5	16473 636	326 6	19908	19908 564	224 38	13677 537		
27	-22	0 02561	171 25	342 5	13373 682	231	18039	18039 828	178 75	13959 391		
28	-23	0 01352	65 63	131 26	9708 5799	74 5	11020	11020 71	54 5	8062 1302		
29	24	0 04127	46 75	93 5	2265 5682	66 15	3205	3205 7184	36 25	1756 724		
30	25	0 01503	35 75	71 5	4757 1524	42 6	5668	5668 6627	31 75	4224 8836		
31	-25 5	0 01288	58 63	117 26	9104 0373	67 45	10474	10473 602	49 75	7725 1553		
32	26	0 01518	25 25	50 5	3326 7457				30 78	4055 336		

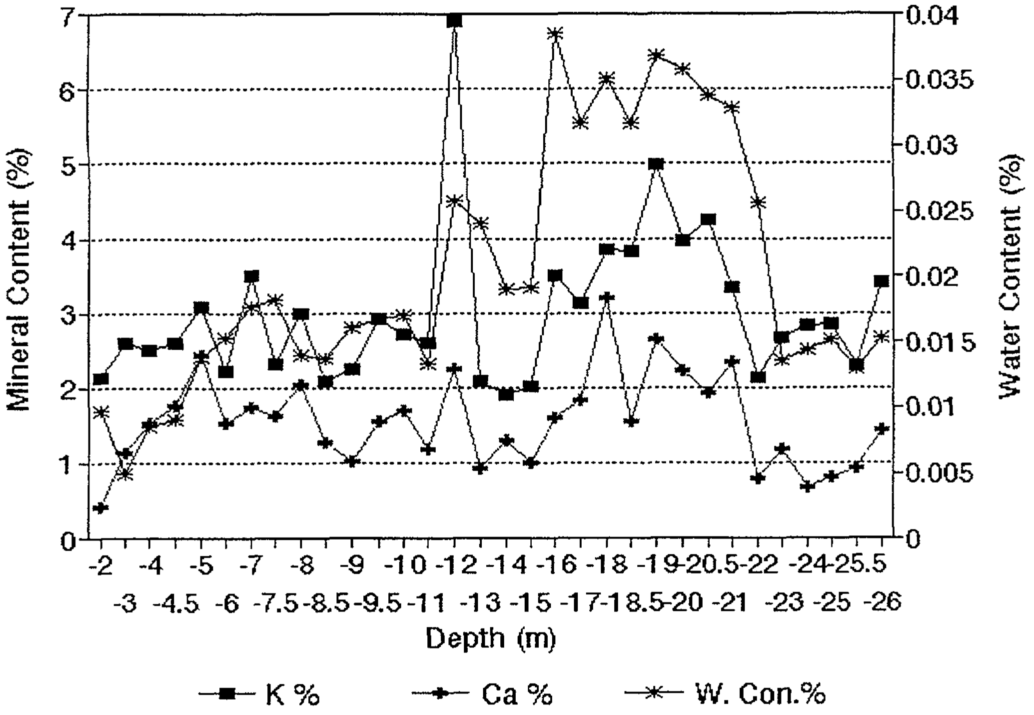

FIG. 1a. Mineral Content Vs. Depth (SDB3-Swale).

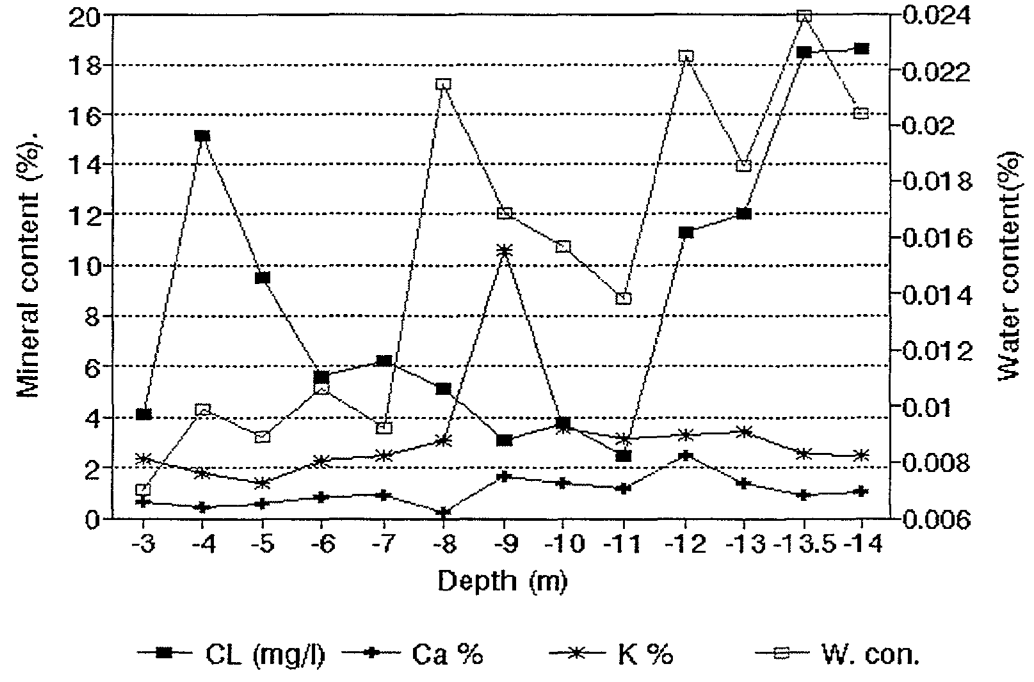

FIG. 1b. Mineral Content Vs. Depth (SDB4-Dune).

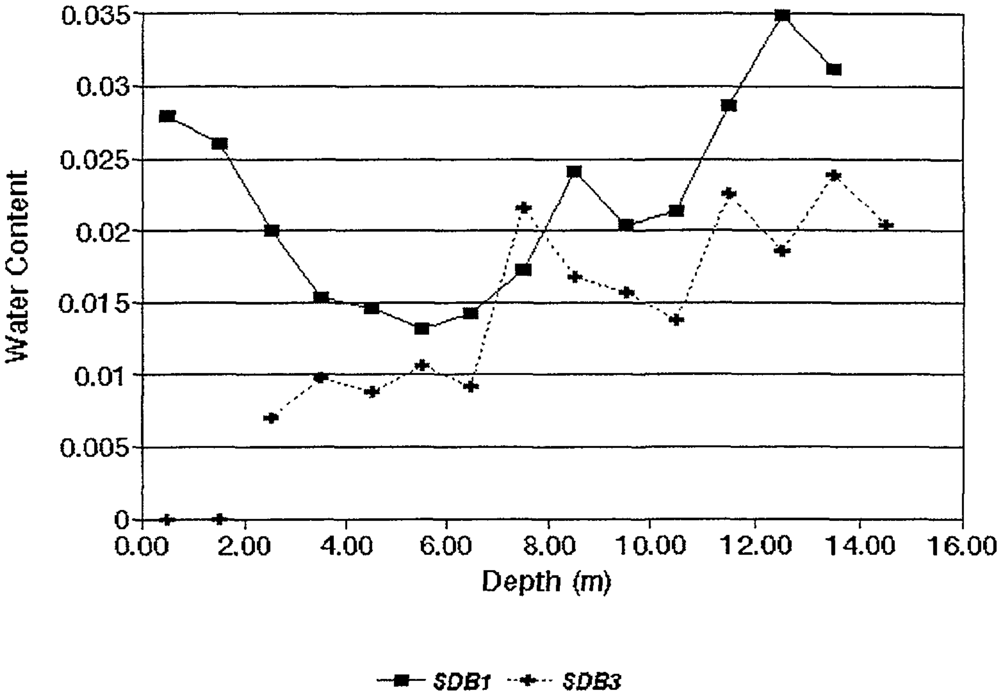

FIG. 2a. Water Content Vs. Depth (SDB1 and SDB3; Swale).

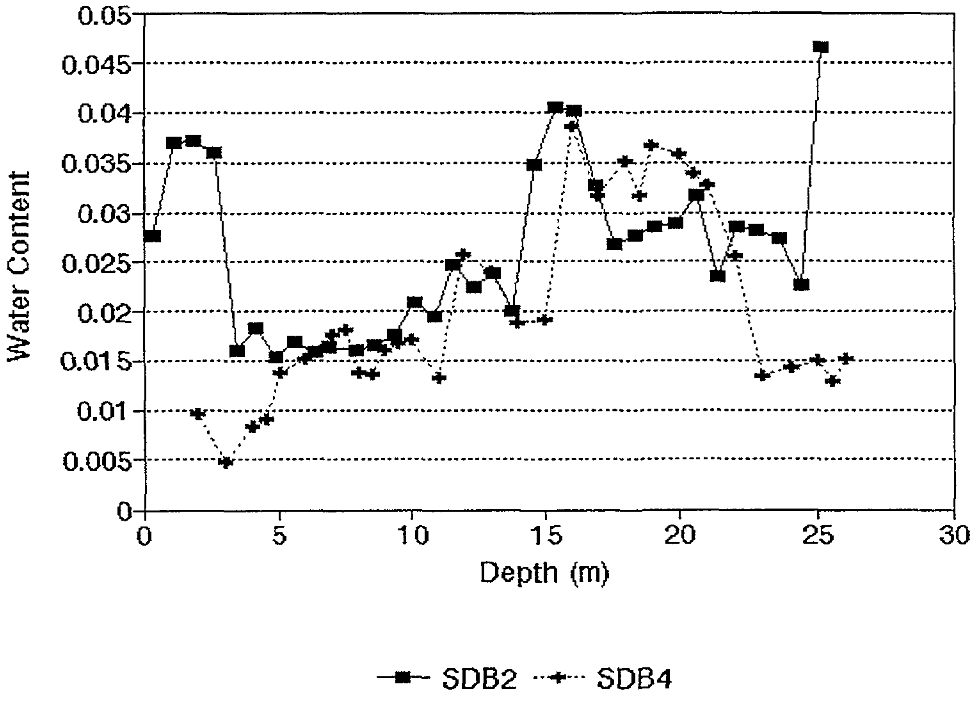

FIG. 2b. Water Content Vs. Depth (SDB2 and SDB4; Dune).

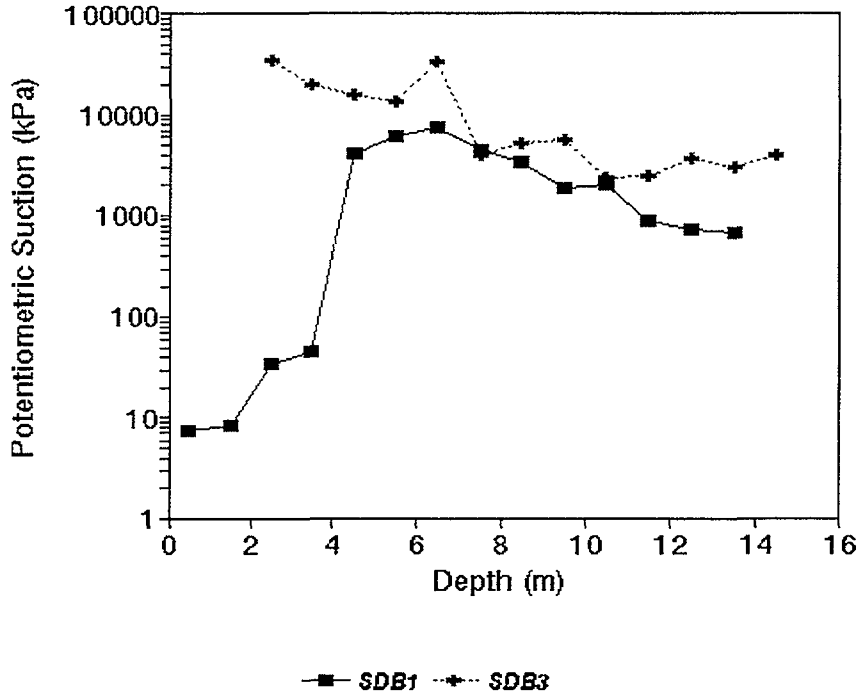

FIG. 3a. Soil-Water Potential Vs. Depth (SDB1 & SDB3; Swale).

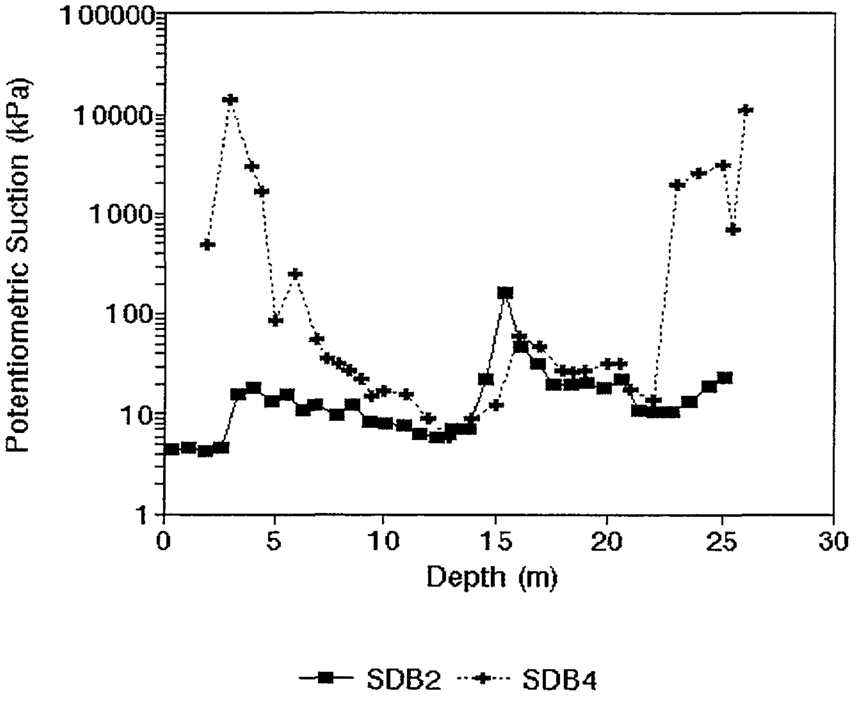

FIG. 3b. Soil-Water Potential Vs. Depth (SDB2 & SDB4; Dune).

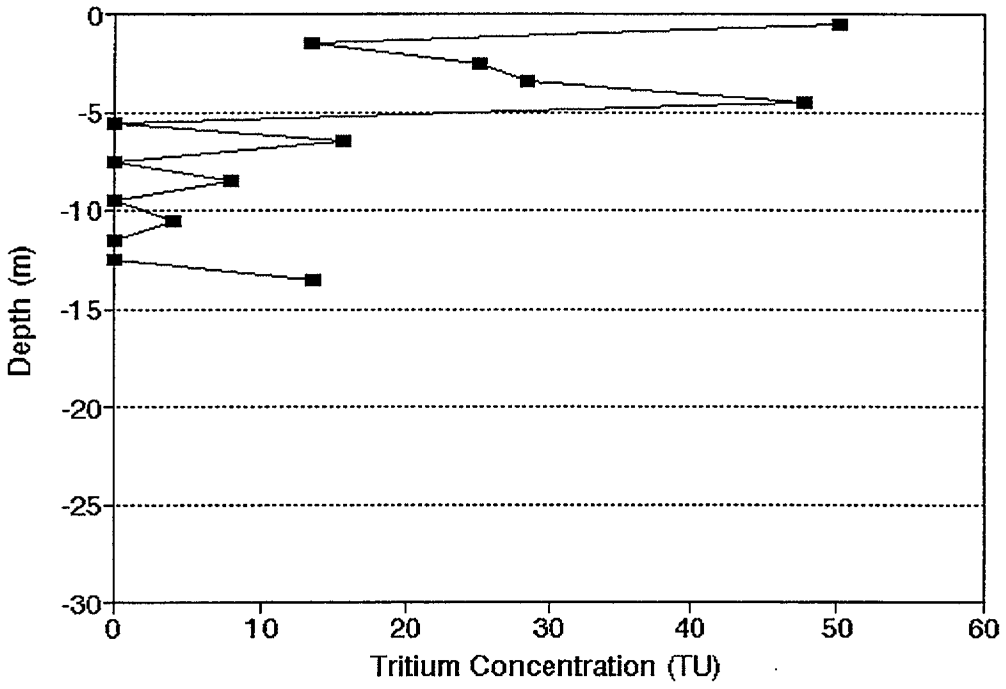

FIG. 4a. Tritium Concentration Vs. Depth (SDB1; Swale).

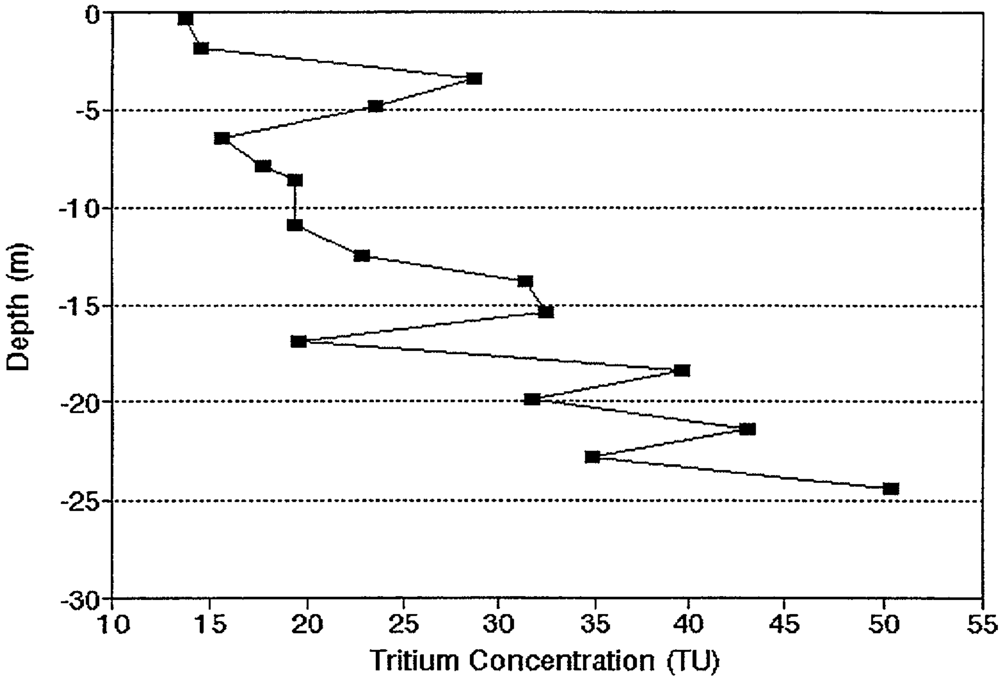

FIG. 4b. Tritium Concentration Vs. Depth (SDB2; Dune).

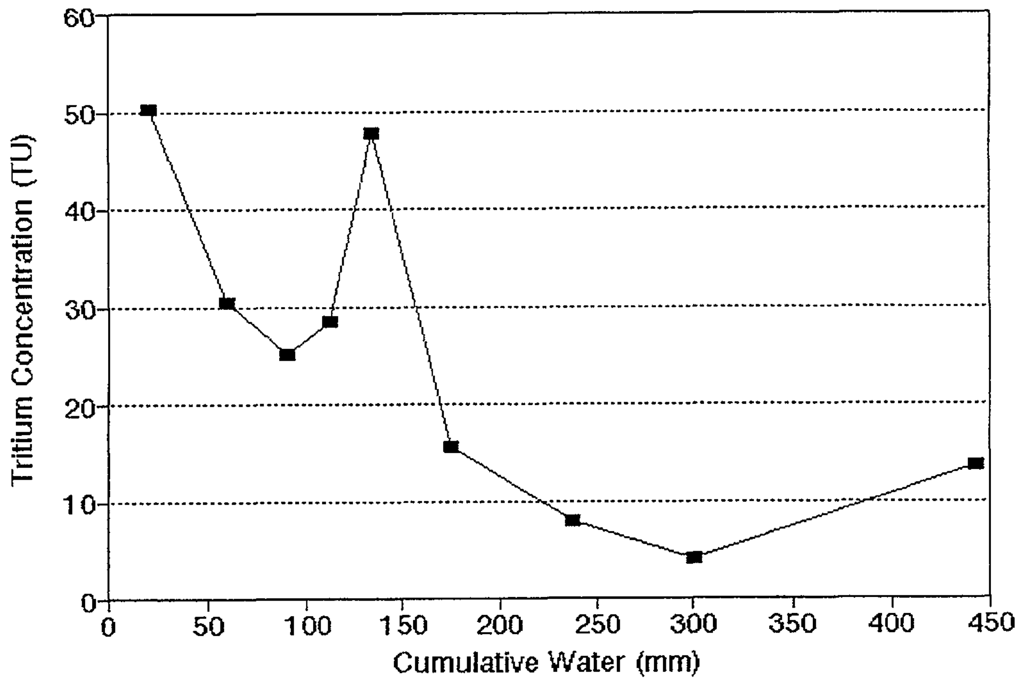

FIG. 5a. Cumulative water Vs. Tritium Content (SDB2; Dune).

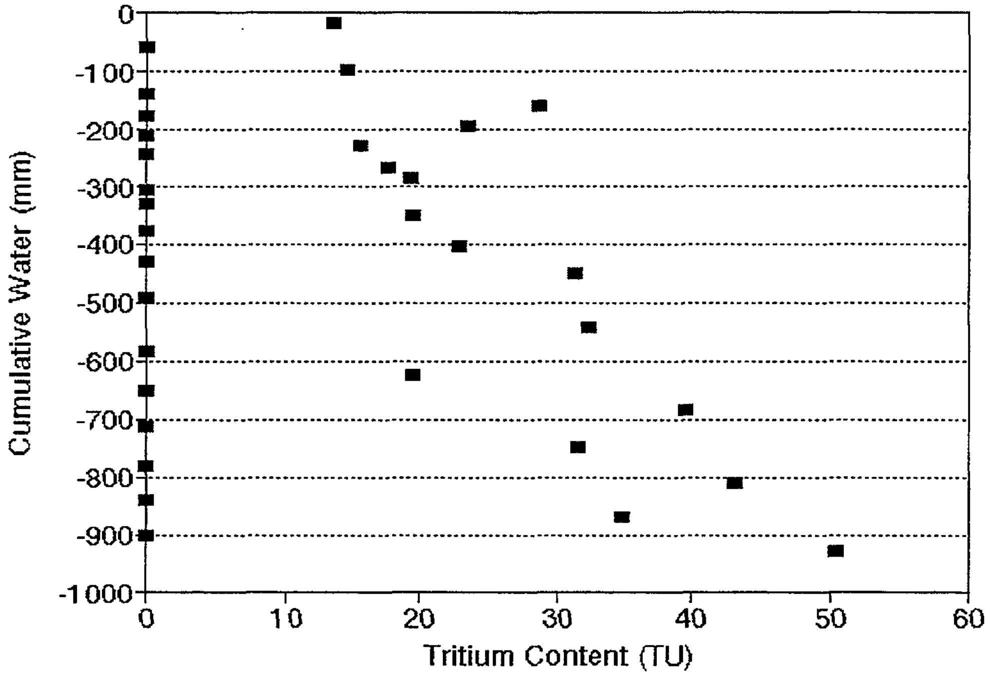

FIG. 5b. Tritium Concentration Vs. Cumulative Water (SBD1; Swale).

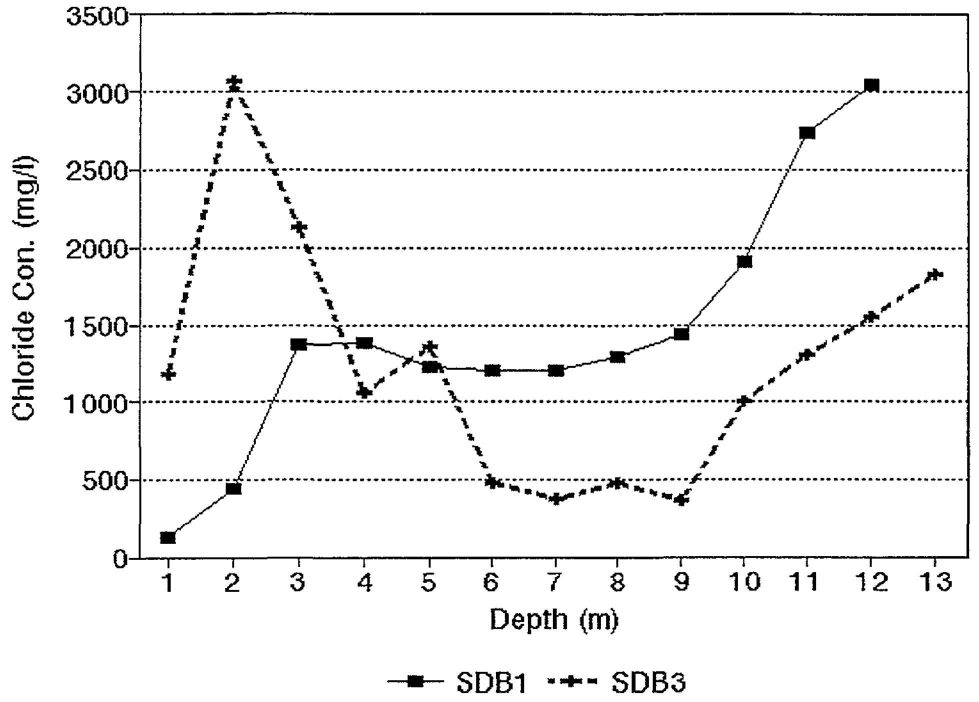

FIG. 6a. Chloride Concentration of Soil-Water Vs. Depth (SDB1 & SDB3; Swale).

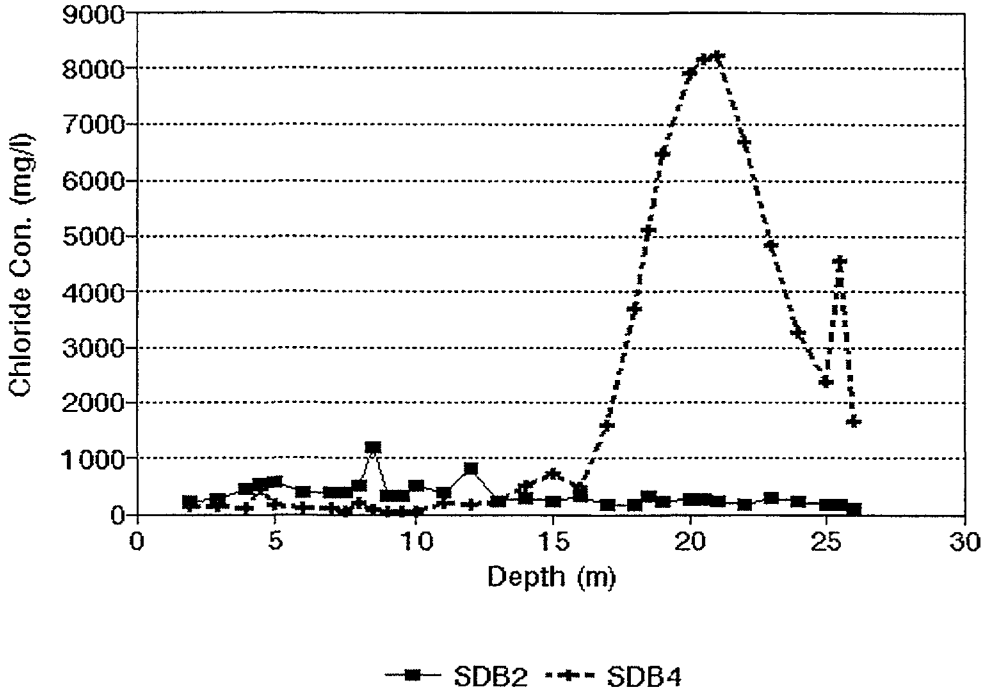

FIG. 6b. Chloride Concentration of Soil-Water Vs. Depth (SDB2 & SDB4; Dune).

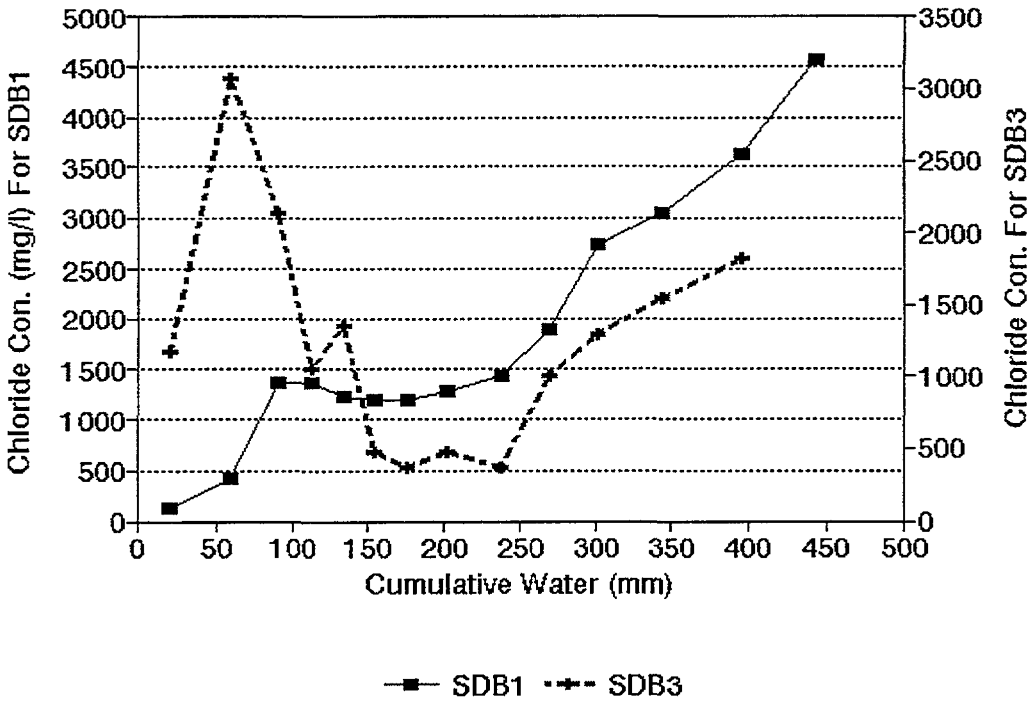

FIG. 7a. Chloride Concentration of Soil-Water Vs. Cumulative Water (SDB1 & SDB3; Swale).

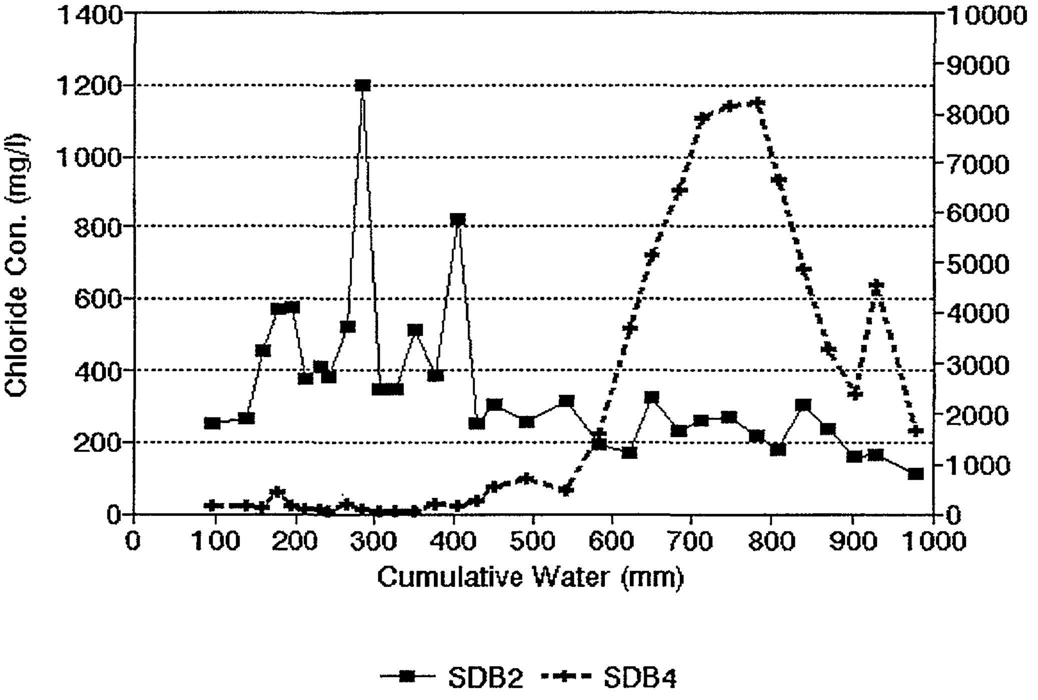

FIG. 7b. Chloride Concentration of Soil-Water Vs. Cumulative Water (SDB2 & SDB4; Dune).

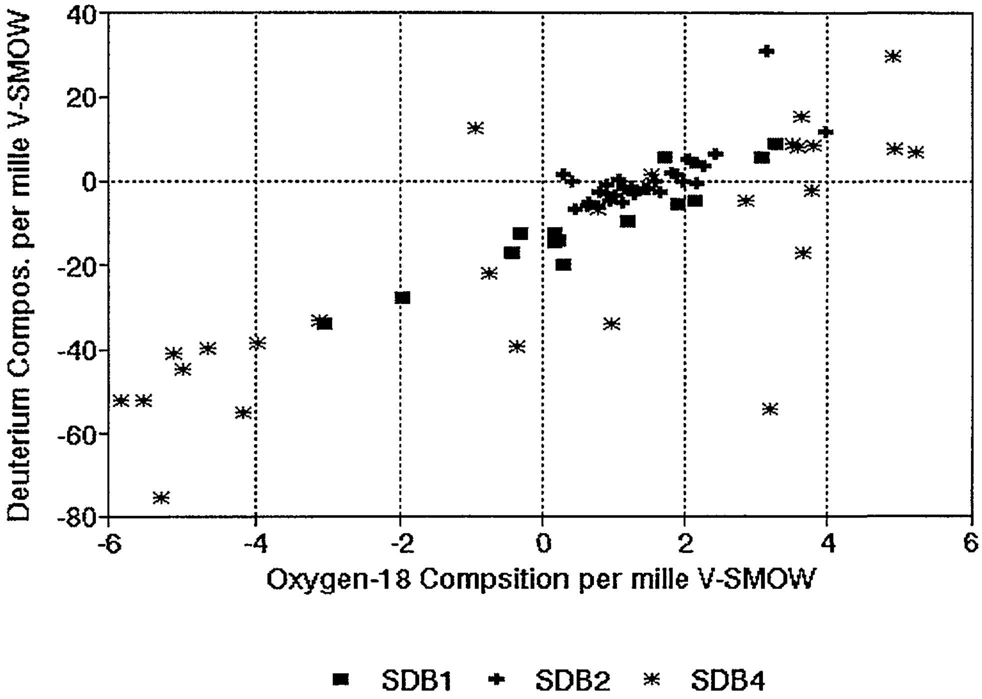

FIG. 8. Deuterium Vs. O-18 Composition (SDB1, SDB2 & SDB4).

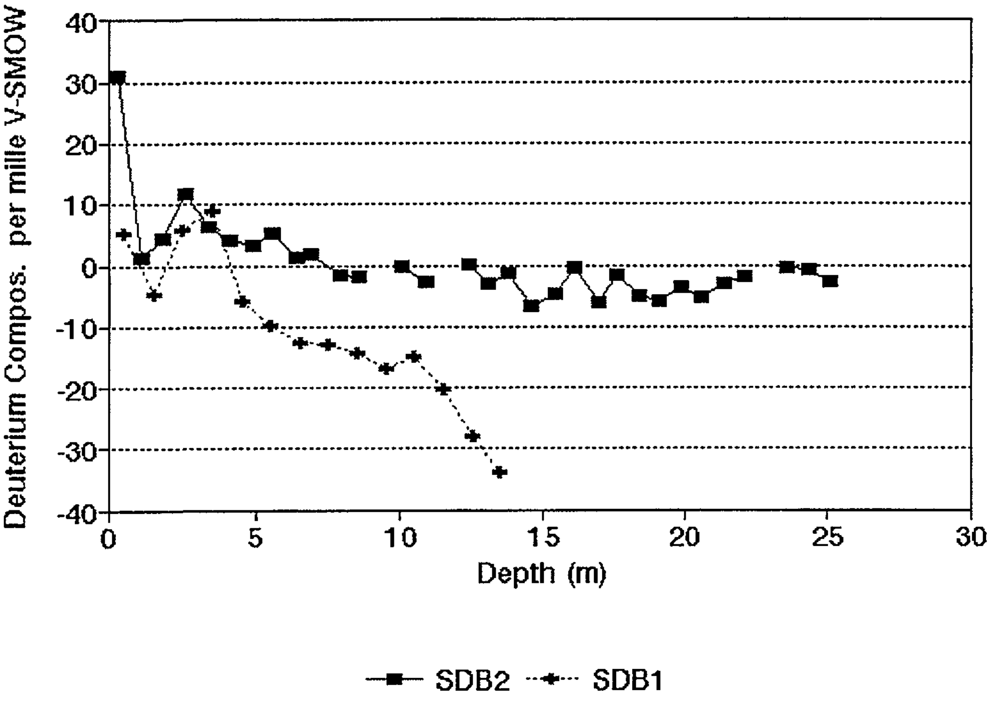

FIG. 9a. Deuterium Composition Vs. Depth (SDB1 & SDB2).

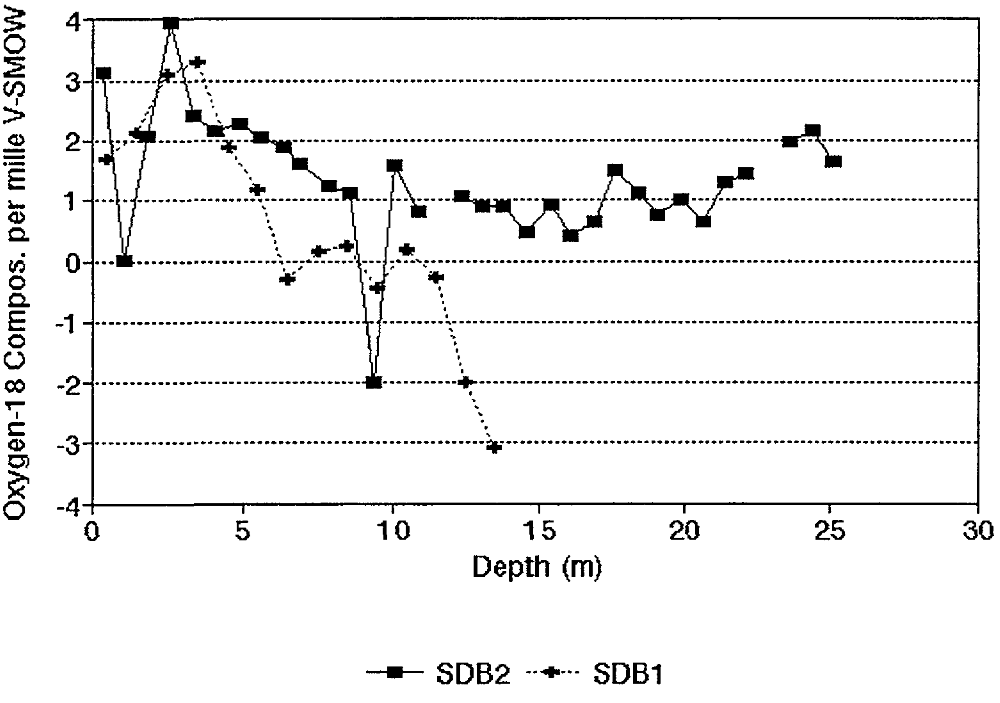

FIG. 9b. O-18 Composition Vs. Depth (SDB1 & SDB2).

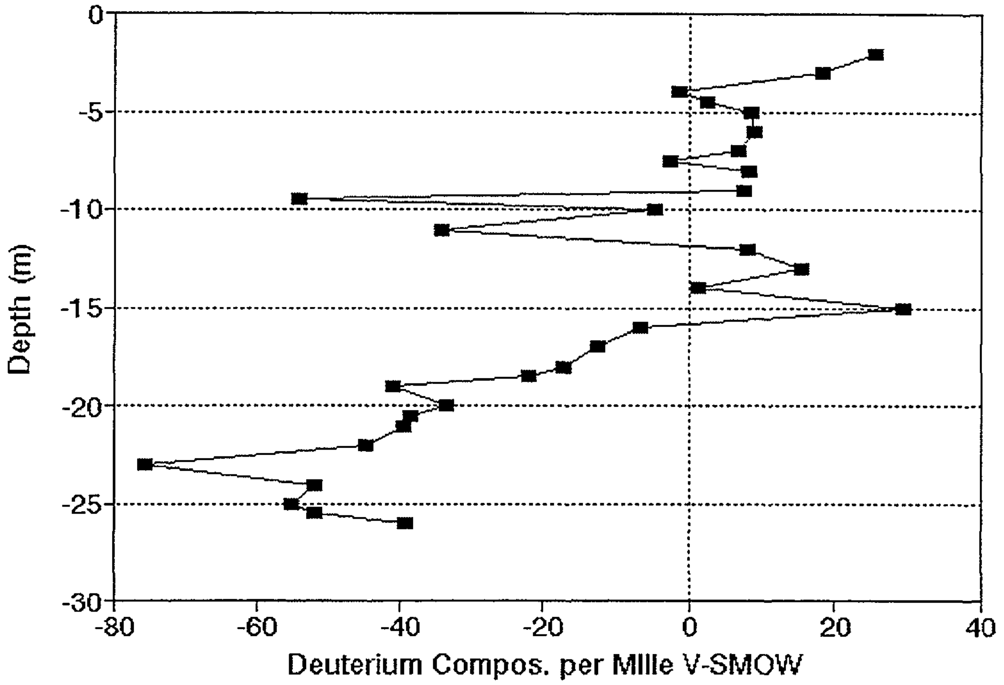

FIG. 10a. O-18 Vs. Depth for SDB4.

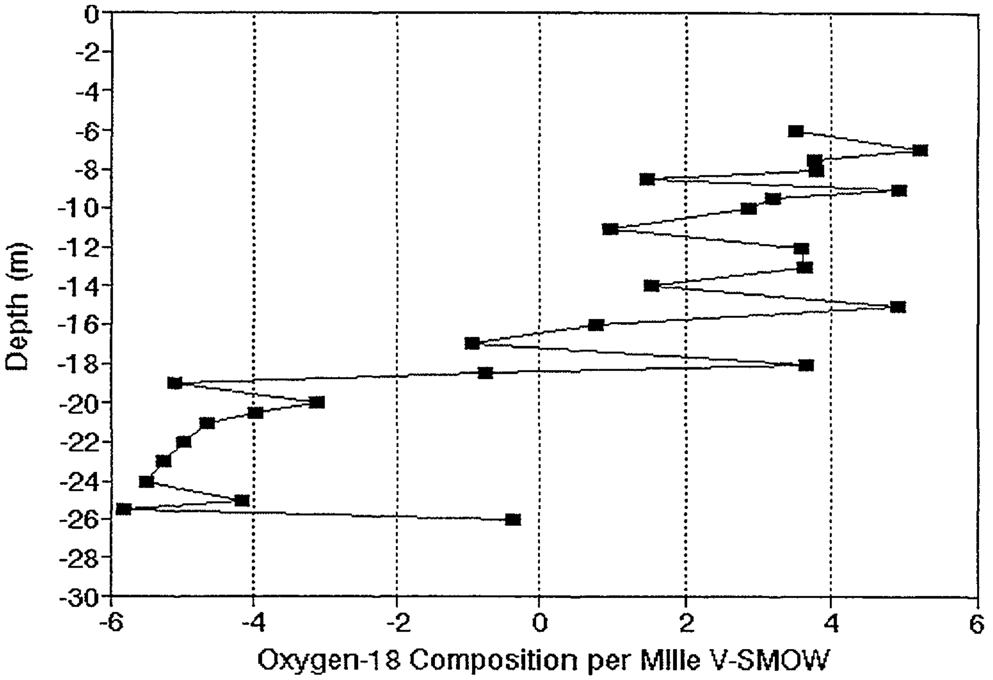

FIG. 10b. Deuterium Vs. Depth for SDB4.

The core at SDB4 is particularly interesting in that it appears to contain data related to at least 3 recharge events. If the suggested rates of recharge for these sites are as proposed, then the question arises as to why there is such variation over such a small area and the recharge rates for the dune sites are much higher than the swale site.

One would imagine that, assuming all other parameters equal, the recharge for the swale or inter-dune areas would be higher given the potential for run-off during the highest intensity storms. Clearly, recharge is lower at these sites and so other parameters related to recharge must be important in this environment. In particular, the following conclusions can be made:

i) The recharge rate for the dune site is much greater than that at the swale site. Recharge rate for the dune site is estimated at ~ 30 mmY-1 while that for the swale site is less than 5 mmY-1.

ii) The differences seen in the recharge may be due to the difference in the clay contents of the soil for the depth interval affected by evaporation.

iii) There is evidence for at least 3 episodic periods of recharge from the chloride and stable isotope data.

Evaluation and Recommendations

The use of the "Sand-drill" to sample the unsaturated zone in this type of soil has proven successful. There appears to be very little mixing of the sample within the core barrel and, although some soil does fall in during the process of extracting the core stem, the contaminated soil is easily removed from the sample.The speed of drilling is adequate for most purposes and , because of the light-weight design of the equipment, access to most sandy sites would be possible.

All of the soil-water below the zone of evapotranspiration at SDB2 has a similar deuterium and 18O signature which suggests a single recharge event or more than one recharge events having the same input isotope concentration. Given that 1,000 mm of water is present in the profile, it is virtually impossible that this originates from a single recharge event. It is also unlikely, given the extreme variation in the isotopic composition of rainfall in arid environments, that numerous rainfall events would have almost identical isotopic input compositions. This inconsistency needs to be studied further[14].

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STUDY OF RECHARGE AND EVAPORATION PROCESS IN THE UNSATURATED ZONE OF DAMASCUS BASIN, SYRIA

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Abstract

The study of unsaturated zone is necessary for the understanding of the flow movement through percolation. The isotopic method is a useful approach to determine the infiltration and evaporation in the studied zone.

The isotopic method was applied in the study of Damascus depression (Damascus oasis) which is cosidered one of the most important aquifer in Syria, in order to evaluate quantitatively the current elements such as the infiltation and evaporation, controlling the water balance in the system.

1- Introduction.

Damascus oasis, which extends over 1200 km^2 to the south of Damascus city, it plays a main economical role, especialy in the agricultural production. Many hydrological and hydrogeological studies were conducted to determine the sources of the surface water, in one hand, and to study the yield of aquifer to supply the groundwater in the other. However, determinations of water balance in the oasis has not been very accurate. This is attributed to the difficulties in applying the conventional methodes in arid and semi arid zones [1].

The main purpose of this study in unsaturated zone is to investigate the mechanical movement of water and to estimate the infiltration and evaporation processes. Therefore, several soil profiles using auger were performed and granulometrical, mineralogical, chemical and isotopic analysis (^{18}O, ^2H and ^3H) were conducted.

This study was done in co-operation with in IAEA project entiteled "Isotope Hydrology In The Middel East" n° RER/8/002.

2- General context.

2-1- Location.

Damascus oasis which is called "Ghouta" is located in the south western part of Syria (Fig. 1). To the north and north-west of it, there is Kassion mountain (1150 m). To the south and south-west there is Al-Maneh mountain (950 m), Badieh plate forms the eastern and south-eastern borders. The oasis has mean altitude about 650 m and varies from 600 m near Oteibeh lake to 720 m in Al-Mazzeh. This oasis represents the lower part of Barada and Awaj basin which has its upper parts lies in the Anti-libanon and Haramoun mountain (2814 m) in the north-west.

Barada and Awaj rivers represent the main rivers in the hydrographic system where Barada is fed from several karstic springs located on high mountains, in particular Barada spring with average discharge (3.12 m^3/s) and Figeh spring (7.7 m^3/s) which is used for supplying purposes in Damascus city. Whereas, the sources of Awaj river its are located in the Haramoun mountain. Barada and Awaj rivers are terminated in Oteibeh and Hyjaneh lakes, respectively, situated in the east and south eastern part of the oasis depression. However, these rivers reach the lakes during flood periods only.

2-2- Geological setting.

Damascus oasis consists of :

1)- Cretaceous - Neogene formations :

This formations represent the basal parts of Damascus oasis depression.

- In the middle of Kassion mountain anticline, the (Turonean - Campanian) limestone and calco-dolomite rocks expose (Fig. 1, 2). The eastern side of the anticline was effected by vertical fault (NE-SW) which is of a regional importance. Its slopes ranges between 20° to 30° in the NW and 70° to 80° in the SE.

- The Paleogene formations are exposed on the border of the anticline represented by limestone, marly limestone and marls.

- The Neogene is characterized by continental rock debris consisting of conglomerate, sand fine, sandy marl and silt covering the depression of Deemas desert reaching the western part of Damascus, (Fig. 1).

2)- Quaternary formation :

Quaternary rock debris fill in Damascus depression, represented by proluvial and alluvial deposits with gravels and big sized sands. Eastwards sediments grain size decrease to become clayey, sandy and fine loamy lacustrine near Oteibeh lake representing the most recent quaternary [2].

To the south and south-eastern rims of the basin, Neogene and Quaternary basalt outcrops.

2-3- The hydrogeology.

In Damascus depression, the quaternary formations have very important aquifer invested by 6000 wells.The depth of this aquifer varies from 1 - 6 m in the western part of depression and reachs 35 - 50 m depth in the eastern part of it. It forms two pesometric depression resulting from extensive investment (Fig. 3).

The transmisivity is relatively very high near Damascus and it decreases progressively towards the east. The water flow is homogenous in the aquifer but velocity decreases when the clay content increases in sediments. This could be the reason for the existance of several springs along north-south zone passing Karrabo area; i.e. Der Al-Assfir spring. In addition, the aquifer in this area is invested by "Fougara" system. This aquifer is mainly fed by infiltration of surface water. Towards the east of oasis plane, the water of Barada and Awaj disapear slowly, but in flood periods the runoff reachs the middle part of the depression. The second source in feeding the aquifer is the groundwater flows. In another hand, the pesometric seasonal variations show that rainfall shares directly or indirectly in feeding the aquifer.

2-4- The climate.

The area is located in arid and semi arid zone of mediterranean type which is generally characterized by irrigular and variable precipitation, distributed through 8 months in the year (Oct.-May). 20% of precipitation falls during Oct., April and May, whereas 80% falls during the period of Nov. to March (Fig. 4).

The mean annual precipitation is 221 mm/y in Al-Mazzeh, 167 mm/y in Karrabo and 136 mm/y at Damascus airport [3]. The meteoric line of 200 mm goes to the east of Al-Mazzeh to NE-SW direction. While the line of 150 mm goes to west of the airport and the east of Karrabo in the same direction (Fig.3).

The intensity of rainfall value reachs more than 50 mm/h, seperated by dry periodes about 40 days in average with a maximum of 105 days.

The evaporation "Piche" which is measured by "Lambrecht" method evaluated between 1326 mm and 2312 mm (Fig. 5). The mean annual evaporation from the soil surface is 240 mm in Al-Mazzeh, 150 mm at airoport and 146 mm in karrabo [4].

The potential evaporation in Karrabo, calculated by Pennman, Planky-Cridle, and Evanof method, is about 1554 mm, 1339.2 mm, and 1305.9 mm respectively [5]. 80% of evaporation process happens between April and October, however, we have less evaporation rate in January.

The mean annual temperature is 17.5 °C in Al-Mazzeh, 16.5 °C at l'airport and 15.8 °C in Karrabo. During hot months, these values reache 24.9 °C, 26.2 °C for July and August. However, during cold months it reaches 6.1 °C for January. The absolute maximum temperature value is between 22 °C in winter and 44 °C in August, when the minimum temperature value is between -18.5 °C in January and 11.6 °C in August (Fig. 6).

The year is divided to three parts : - Cold period : the temperature is < 10 °C (D, J, F). - Temperate period : temperature is between 10 and 15 °C (N, M, A). - Hot period : temperature is > 15 °C (M, J, J, A, S, O).

On regional scale, the temperature increases from the west and north-west towards the east and south-east.

The air relative humidity is 50 % in Al-Mazzeh, 57 % at airport and 60 % in Karrabo (Fig. 7). The maximum is 70 - 77 % in December and January, when the minimum is 34 - 48 % in June. The average relative humidity is less than 30 % in 200 days annually.

In cold winter, winds from Sybiryan depression have the N-NE direction.While winds from western humide depressions have the W SW-NW direction.

2-5- The isotopic characterisation of precipitations.

The isotopic contents of precipitation in Damascus city between 1989 - 1990 is given by the following :

	P mm	^{18}O ‰	^{2}H ‰	^{3}H (UT)
D 89	4.8	-7.32	-47.8	5.5
J 90	14.9	-9.64	-62.6	9.0
F 90	30.6	-7.18	-35.5	8.6
M 90	28.2	-6.46	-37.9	7.0
A 90	8.4	-9.44	-71.7	13.7

The meteoric line for 11 station in Syria for the same period is given by this equation [6] :

$$\delta\, ^{2}H = 8.26 \pm 0.37\ \delta\, ^{18}O + 19.3 \pm 2.7 \qquad 1$$

The isotopic gradian with altitude for all stations is - 0.23 ‰ / 100 m for ^{18}O and - 1.65 ‰ / 100 m for ^{2}H.

3- Field work.

During Jan. and Feb. 1993, four profiles were obtained using manual auger for soil samples every 50 cm. These samples were kept in airtight containers. Two profiles (H and D) were chosen from irrigated zones, whereas the other two (M and G) were from unirrigated ones in order to well represent the basin taking into consideration both the depth of the aquifer and the lateral lithological variations.

4- Laboratory work.

In laboratory the following measurements were performed :

- extraction of water from soil samples by distillation under vacum conditions,
- granulometrical and mineralogical analyses of sediments,
- chemical analyses of extracted water from dry sediments,
- isotopic analyses (^{18}O, ^{2}H and ^{3}H).

4-1- Water extraction from soil samples.

Water extration from soil samples was performed under vacum conditions [7], [8], [9], [10][11], [12][13], [14][15]. In addition to isotopic analyses (^{18}O, ^{2}H and ^{3}H), this part of project was performed in IAEA laboratories - Vienna. While the chemical analyses were done in Syrian AEC - Damascus.

4-2- Granulometry.

The results of granulometry analyses (Fig. 8, 9) indicate that there was, in average, 44 % clay, 40.6 % loam and 17 % sand in profile G. In profile M, there was 34 %, 37.2 % and 19.8% respectively. Generally, these values are similar in both profiles. Thus, the sediments in these profiles consist of 75 % fine sandy clay. However, in some samples in profile M, the percentage of sand reaches 85.

4-3- Mineralogy.

The mineralogical analyses were under taken using X-ray in the geochemical laboratories in the Syrian AEC. The results of profile M show that the quantity of calcite varies from 25 to 90 % with an average of 70 % and the quantity of quartz varies from 10 to 30 % generally (in some samples 65 %) with an average of 23 %. Clay minerals are rarely found in this profile, it varies from 0.1 to 2.5 % with an average of 1% (in one sample 18.18 %).

4-4- Chemical analyses.

Elution solutions of sediments were prepared for these analyses by adding a destillated water to the sediments and shaking for 45 minutes followed by filtration of, these mixtures using filter paper, [9], [12], [14], [1][10], [16].

For the results of this analyses the chemical balance is given as following :

$$M_w * C_i = Q * C_q \quad \Rightarrow \quad C_i = (Q * C_q) / M_w \qquad 2$$

where
Q : Elution water quantity,
C_q : Concentration of elution water,
C_i : Initial solution concentration in the soil,
M_w : Water mass in the soil,

- The conductivity C.

Variations of conductivity with depth in profile M (Fig. 10) indicate that there is an increase of conductivity values from 2000 µs/cm at 4.5 m depth to 6000 µs/cm at 2.5 m. This corresponds with effect of evaporation zone. The conductivity show minor variation from 4.5 m depth with an average value of 1500 µs/cm.

In profile G (Fig. 11) the conductivity values are approximately stable (around 400 µs/cm from the bottom to 2 m depth), then it increases from 2 m depth towards the surface where it reaches 1200 µs/cm corresponding with evaporation zone.

- The chloride content in porous media.

The chloride analysis was done by calibration method. The relationship between the chloride content verses depth indicates that this content increases progressively from 4 m depth in profile M (Fig. 12), and from 2 m depth in profile G (Fig. 13) towards the soil surface. However, these contents are quite constant towards the bottom of the profiles.

We tried to estimate the efficient infiltration value considering that C_i = 780 mg/l in profile G, which is the mean concentration value of chloride in the lower part of the profile correspending with permanent infiltration conditions (after Aranyossy, 1991).

The chemical balance is given as following :

$$P * C_p = I * C_i \qquad 3$$

where
P : precipitation quantity,
C_p : concentration of precipitation,
I : infiltrated water quantity,
C_i : concentration of infiltrated water,

Considering the average annual precipitation in Damascus is 221 mm/y, and the mean chloride concentration in precipitation is 6 mg/l, we found the averge yearly quantity of efficient infiltrated water to be 1.7 mm/y which varies between 3 mm/y and 0.5 mm/y during wet seasons (360 mm/y) and dry seasons (60 mm/y) respectively.

For comparison, Edmonds and Walton, (1980) [17][18] estimated the efficient infiltration in Cyprus to be 52 mm/y where the precipitation was 420 mm/y. While, Zouari, (1983) [12] found that efficient infiltration value to be 5 mm/y in Tunisa under dry climate where the average annual precipitation was 186 mm/y, over soil consisting of 70 % sand.

5- Isotopic profiles.

There are three main phenomena that control the isotopic content of water in unsaturated zone under the effect of evaporation [19][20], [21], [22] :

- isotopic enrichement related to temperature, relative humidity of air, isotopic composition of atmospheric vapour and isotopic composition of water feeding the system.

- diffusion of water vapour in the upper part of profile where the vapour movement is dominant.

- distribution by diffusion of heavy isotopes towards the lower part of profile where the movement in liquid phase is dominant.

These phenomena, in whole permit the establishment of the evaporation profile [23], [24][25][26].

During his experiments in Bilma-NIGER, Aranyossy (1991) [27][28] tested the effect of various parameters, which effect the adjustment of experimental isotopic profiles, on calculated evaporation flux. In lower parts of profiles where liquid movement is dominant, Aranyossy gave an importance for the followings parametres :

- Temperature.
- The isotopic composition value of peak δ_{ef}.
- The isotopic composition of reservoir δ_{re}.
- Tortuosity τ .
- Humide density and volumic humidity of soil.

Whereas in the upper parts of profile where the movement of gazeous phase is dominant, the important parametres were :

- The depth of isotopic enrichement of peak z_{ef}.
- Atmospheric relative humidity.
- Temperature.
- Porosity.

5-1- Profile M.

5-1-1- Lithology and soil humidity.

The lithological variations are very obvious in profile M (Fig. 14). It should be noted that the sediments near the Otaibeh lake become very fine.

From surface to bottom in lithological profile, we have agricultural soil layer with 1.5 m thickness, black clay from lacustine origin with interlayer of brown clay. Between 3 and 5 m depth there is a sequence of clay and loam which becomes pure clay, followed by orangy sandy layer of 1 m thickness. Then, there is a sequence of fine and humide silty clay of 2 m thickness followed by 1 m of pure sand. Between 9 and 18 m, we have an alternation of humide brown clay with less humide orangy silty levels. Towards the bottom, this alternation becomes more clayey and the humidity increases progressively. The water table is found at 18 m depth.

The humidity variations reflect the lithological variations of sediments. In the upper part of this profile, the humidity increases to reach more than 25 % with parallel clay exsistance in the sediments, then it decreases till 5 % in the sandy layers. Towards the bottom, the alternation of clay and sandy layers reflect the variations of humidity. But in general the humidity increases progressively till the saturation zone at 18 m depth.

5-1-2- Isotopic profiles of ^{18}O and ^{2}H.

The variations of stable isotope contents (^{18}O and ^{2}H) in extracted water of sediments verses depth (Fig. 15) indicate :

- At 2 - 0.5 m depth, there is significant enrichement of ^{18}O from -7 ‰ to -4 ‰ respectively, with a peak between 0 and 0.5 m depth. Our profile represents the lower part of evaporation profile, where the zone of liquid transfer is dominant.

- Depleted value of heavy isotopes at 2.5 m depth is remarkable in all profiles.

- At 3 -14 m depth, the isotopic variations are influenced by lithological variations We noticed that sandy levels have relatively more enriched values of heavy isotopes in water. However, the clay levels have more depleted values. Generally, these values are stable around -7 ‰ of ^{18}O contents and -45 ‰ of ^{2}H contents.

- At 14 - 18 m depth, isotopic contents decrease progressively towards groundwater (-9.02 ‰ ^{18}O and -55 ‰ ^{2}H).

We noticed that variations of isotopic contents of ^{18}O, ^{2}H with depth are parallel.

The interpretation of isotopic results in profile M will be as following :

- Isotopic enrichment between 2 - 0.5 m depth is effected by influence of evaporation, but the thickness of this zone is the consequence of clay existance in sediments. In Tunisia this zone is between 0 - 7 m depth in areas formed of 70 % of sand [12].

- At 3 - 14 m depth zone, we have the following :

1- Existance of the secondary and thirdly peaks which are separeted by very cold periodes of condensation.

2- Influence of lithological variations on the isotopic composition which may be due to high liquid diffusion through clay layers (high humidity) which have relatively depleted values of heavey isotopes. However, in sandy layers which is less saturated (low humidity), we have vapour diffusion (in situ) in unsaturated media leading to relative enrichment in the remaining parts. in addition, the nonisothermic conditions in the sediments along the profile may have an important role.

- At 14 - 18 m depth, the decrease of isotopic contents may be due to capillary effect. This zone is isotopically diffrent from the aquifer, that indicates the recharge of groundwater does not take place through unsaturated zone, it could have an underground recharge.

5-1-3- Relationship between ^{18}O and ^{2}H.

In Fig. 16, we find most of data points located around the meteoric water line with slope value of 8. While, the points of surface evaporation zone are located at 2.9 slope which indicates to the existance of extensive evaporation. The equation of this line is given by :

$$\delta\, ^{2}H = 2.9\ \delta\, ^{18}O - 30.51 \qquad \text{with} \qquad r^2 = 0.84 \qquad 4$$

This equation permits to evaluate the mean ^{18}O value of infiltrated precipitation to be around -8 ‰ (d = 10 ‰). This value differs from the value of the aquifer.

5-1-4- d-exess (d = $\delta\, ^{2}H - 8\ \delta\, ^{18}O$ ‰).

Variation of d exess verses depth (Fig. 17) indicates the following :

- Increases from -10 ‰ at 0.5 m depth, to 5 ‰ at 2 m. This shows that this zone was influanced by kinetic evaporation ($d \leq 2$ ‰).

- Small increase from 5 ‰ to 10 ‰ where water evaporation was less.

- Towards the bottom of profile M, d-exess values reach 15 ‰ but the mean values reach 10 ‰, corressponding with nonevaporation water.

We can distinguish in this graph the superimpostion of secondary and thirdly evaporation peaks separated by cold periods.

5-2- Profil G.

5-2-1- Lithology and soil humidity.

The depth of profile G is 6 m. Fig. 18 shows an agricultural layer with 1 m thickness, followed by clayey layer, then sandy layer. From 2 to 4 m, there is a sequence of fine sandy clay at the top that becomes marl and gravel at the bottom. Then at 4-6 m depth, we have a sequence of marly clayey layer that becomes gravel at the bottom where we find the aquifer at 6 m depth.

5-2-2- Isotopic profile (^{2}H and ^{18}O).

The isotopic contents change with depth (Fig. 19) leading to the following observations :

- Enrichment of isotopes from 0.5 to 2 m depth.

- Relative depletion of isotopic contents at 2.5 m depth.

- Isotope contents at 3 - 6 m depth are approximately constant with a value of -7 ‰ for ^{18}O and -48 ‰ for ^{2}H.

We can interpret these changes as following :

- Evaporation influence zone is found at 0.5 - 2 m depth whereas the evaporation peak is located between 0 - 0.5 m depth. This profile represents the lower part of evaporation profile especially the zone of liquid tranfere is dominant.

We notice that there are similar depths of evaporation effect in both M and G profiles.

- The depleted values of isotopic content in M and G profiles can be explained by :

1- Recondensation of water vapour which has more depleted value of stable isotope contents.

2- Irrigation with water has depleted value.

3- Alternation of dry and wet seasons.

5-2-3- The relationship between ^{18}O and ^{2}H contents.

Fig. 20 shows that all of the data points are located around the meteoric water line which has the slope of 8. While the points of evaporation zone are situated at a line of 4.15 slope following this equation :

$$\delta\,^{2}H = 4.15\,\delta\,^{18}O - 19.62 \qquad \text{with} \qquad r^2 = 0.87 \qquad 5$$

We can estimate the mean isotopic content of the infiltrated precipitation by intersection of this line with the meteoric world water line where $\delta\,^{18}O = -7.7$ ‰ and $\delta\,^{2}H = -51.5$ ‰, (d = 10 ‰) which is not greatly different from the value of aquifer.

5-2-4- Relationship between the d-exess and depth.

We distinguish from Fig. 21 the following :

- From 0 to 2 m depth, d-exess value is less than 10 ‰ (as the mean value of d-exess, in meteoric water in areas under oceanic effect, is 10 ‰ which is defined by Graig, 1961 [12]). This indicates that water of this zone has kinetic evaporation.

- From 2-6 m depth, where we do not have any evaporation process ($d \approx 10$ ‰).

5-2-5- Estimation of evaporation rate.

In the liquid movement dominant zone, the evaluation of isotopic composition along the profile is described by Barnes and Allison, 1983, [24][25][26] as following :

$(\delta_i - \delta_{res}) = (\delta_{ef} - \delta_{res}) \exp[-f(z)/\hat{z}_i]$ where : 6

$f(z)$ = Depth fonction : $f(z) = \bar{\Theta} \int_{z_{ef}}^{z} dz/\Theta$ 7

$\hat{z}_i$ = Caracteristic depth : $\hat{z}_i = \bar{\Theta}\tau D_i/E$ 8

$-1/\hat{z}_i$ = Slope of the linear correlation : $\ln(\delta_i - \delta_{res})/(\delta_{ef} - \delta_{res})$ vs $f(z)$

δ_i = Isotopic content at depth z
δ_{res} = Isotopic content of groundwater (reservoir)
δ_{ef} = Isotopic content of evaporation front (peak)
τ = Tortuosity
Θ = Water content (by volume)
Di = Isotopic diffusivity in the liquid phase
E = Evaporation rate

The application of this model on the profile G in whole, permits to estimate evaporation rate 2.4 mm/y from 6 m depth where the aquifer is found (Fig. 22). However this adjucement is not very satisfying. We think that isotopic content at 3 m to 6 m depth is effected by seasonal groundwater level variations.

The application of this model on the upper part of profile (0-3 m depth) gives evaporation rate of 18.1 mm/y (Fig.23).

6- General conclusion.

From chemical and isotopic results we have the following resultes:

- The evaporation front is located between 0 and 2 m depth in each profile.

- In profile M, the variation of isotopic contents is probably due to alternation between wet and dry years where there is both infiltration and evaporation.process

- In profile M, the small difference between the isotopic contents in the unsaturated zone and in groundwater, indicates that the recharge of groundwater does ont completly take place through unsaturated zone, it could have an underground recharge.

Text cont. on p. 56.

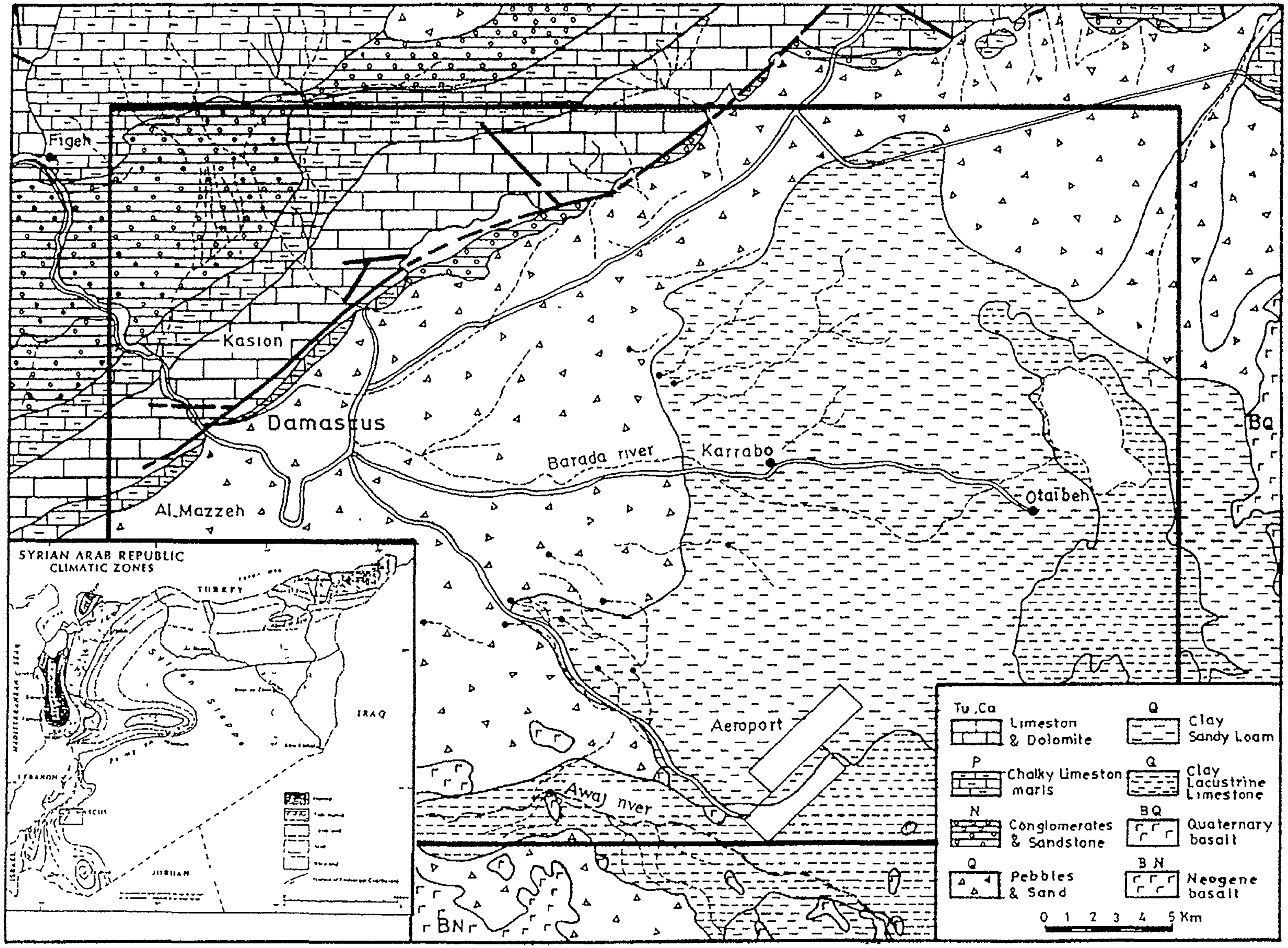

Fig. 1 : Geological map of studied area

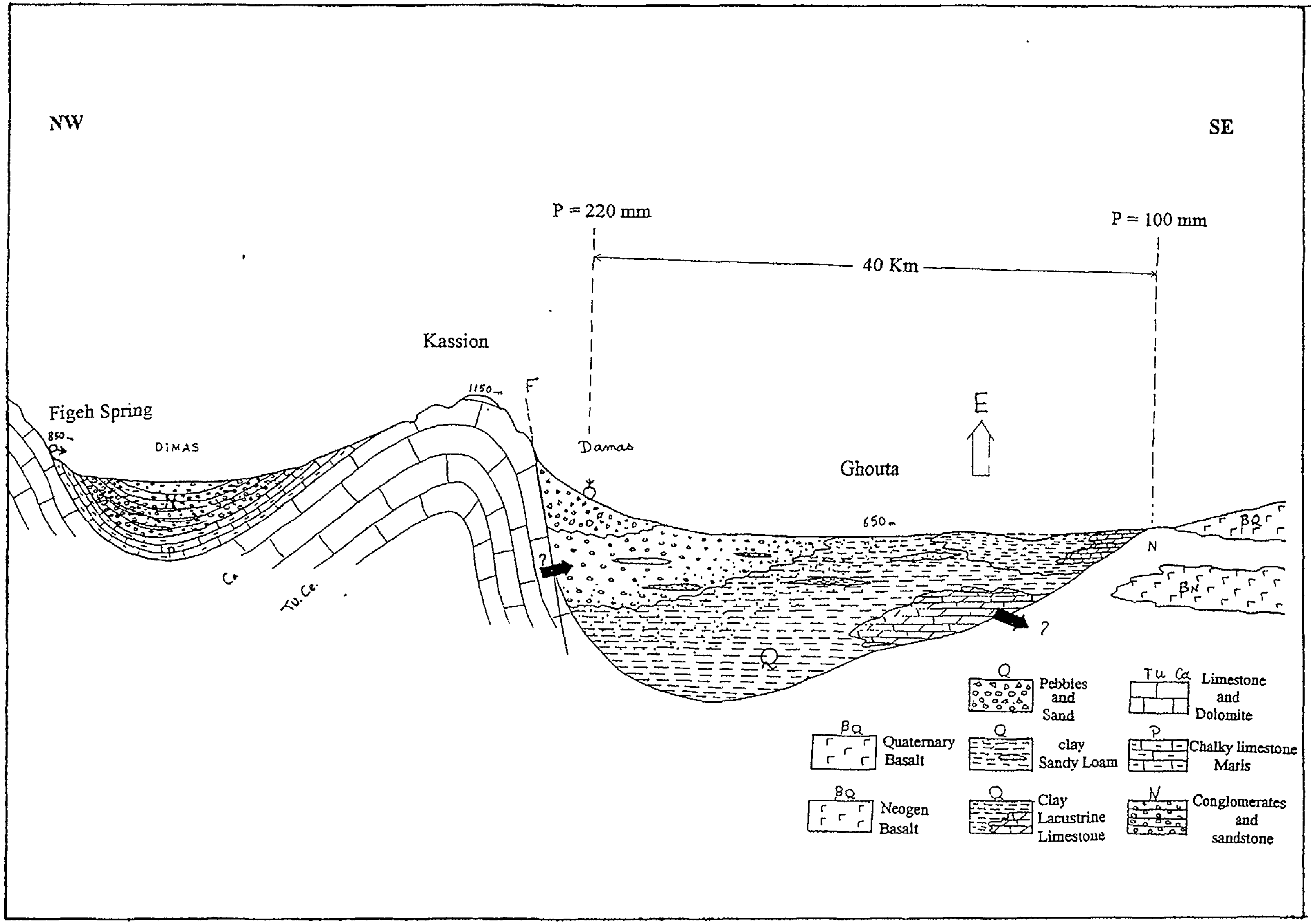

Fig. 2 : Cross section of studied area

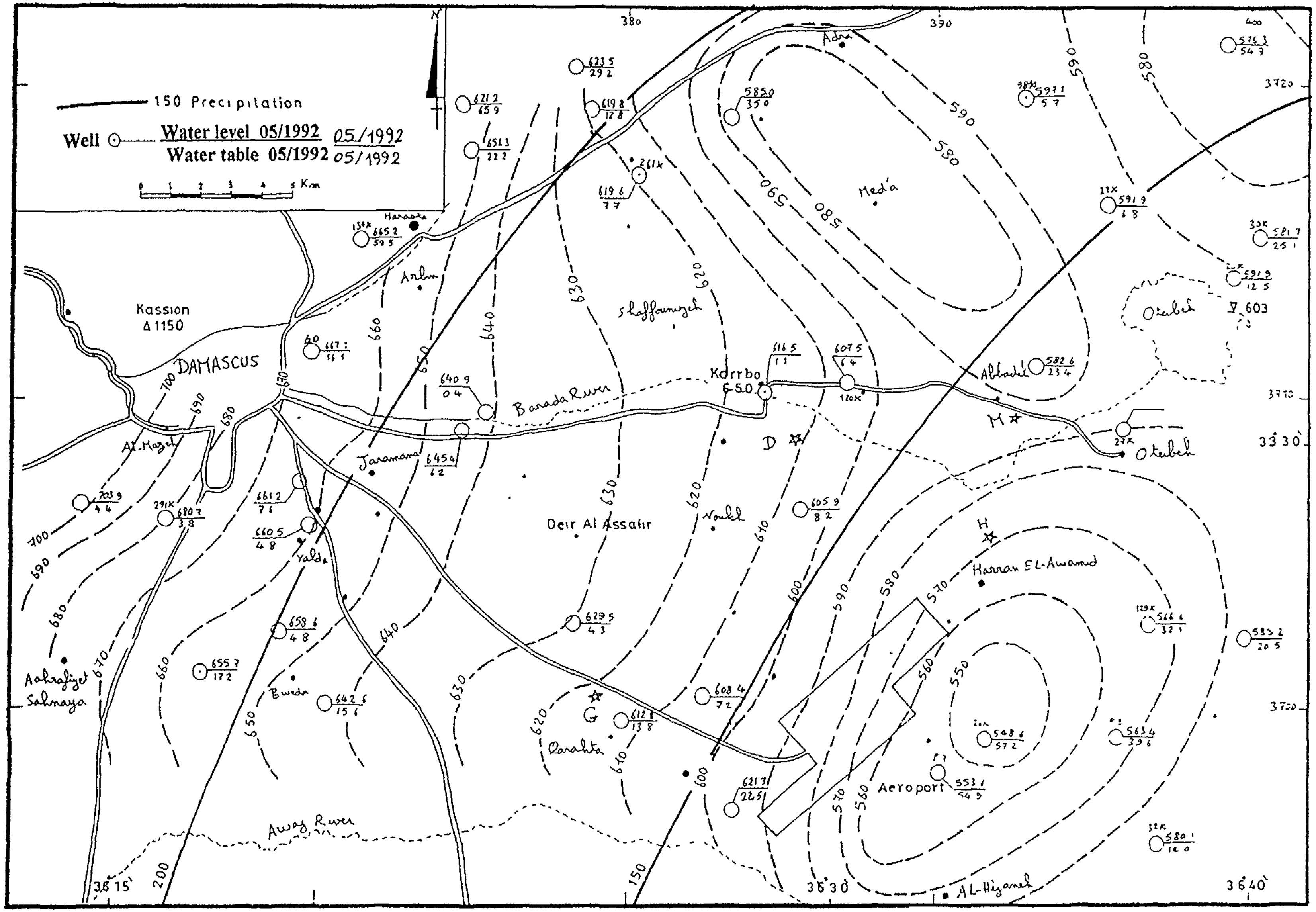

Fig. 3 – Pesometric Map
Damascus Basin

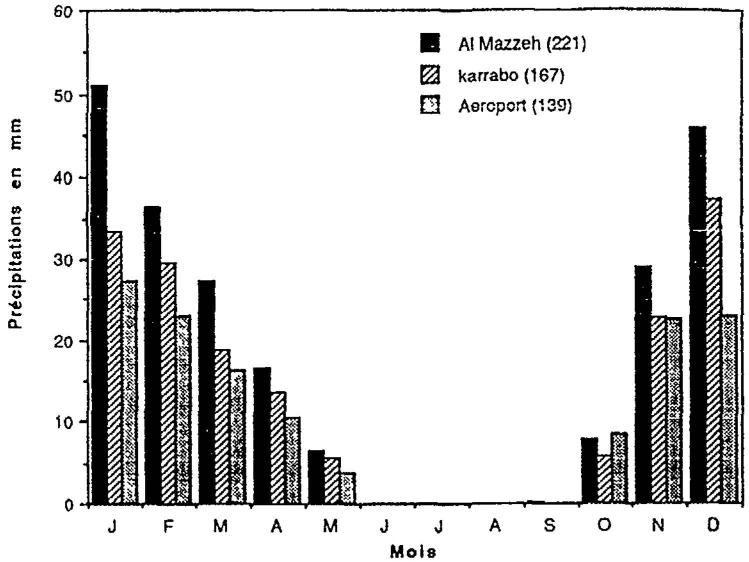

Fig. 4- Mean annual precipitation registered in the three stations.

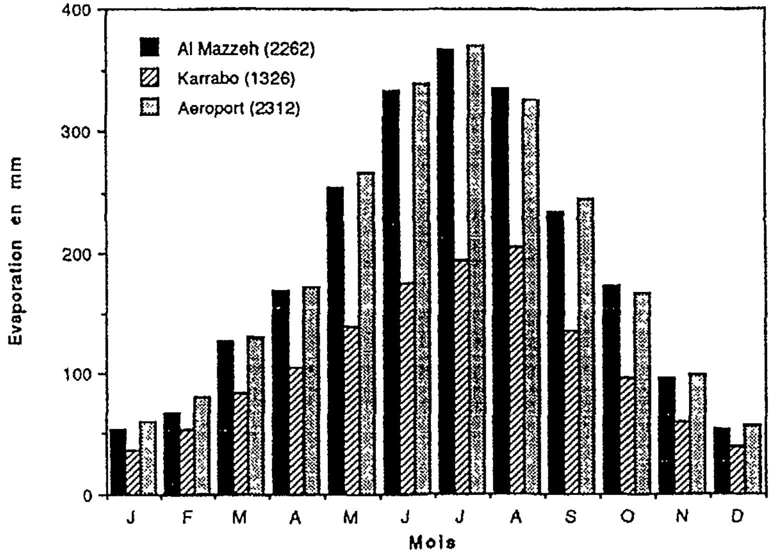

Fig. 5 - Evaporation registered in the three stations, (Lambrechete).

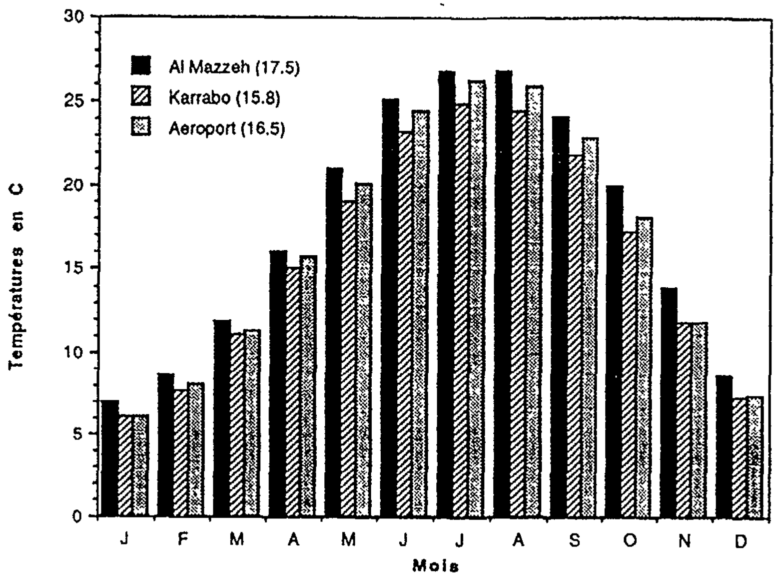

Fig. 6 - Variations of mean annual temperatures in the three stations.

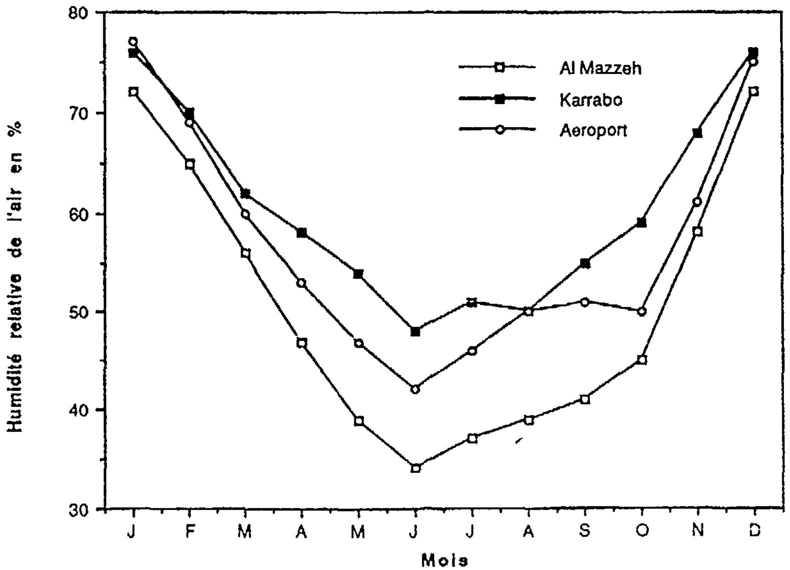

Fig. 7- Mean annual relative air humidity in three stations.

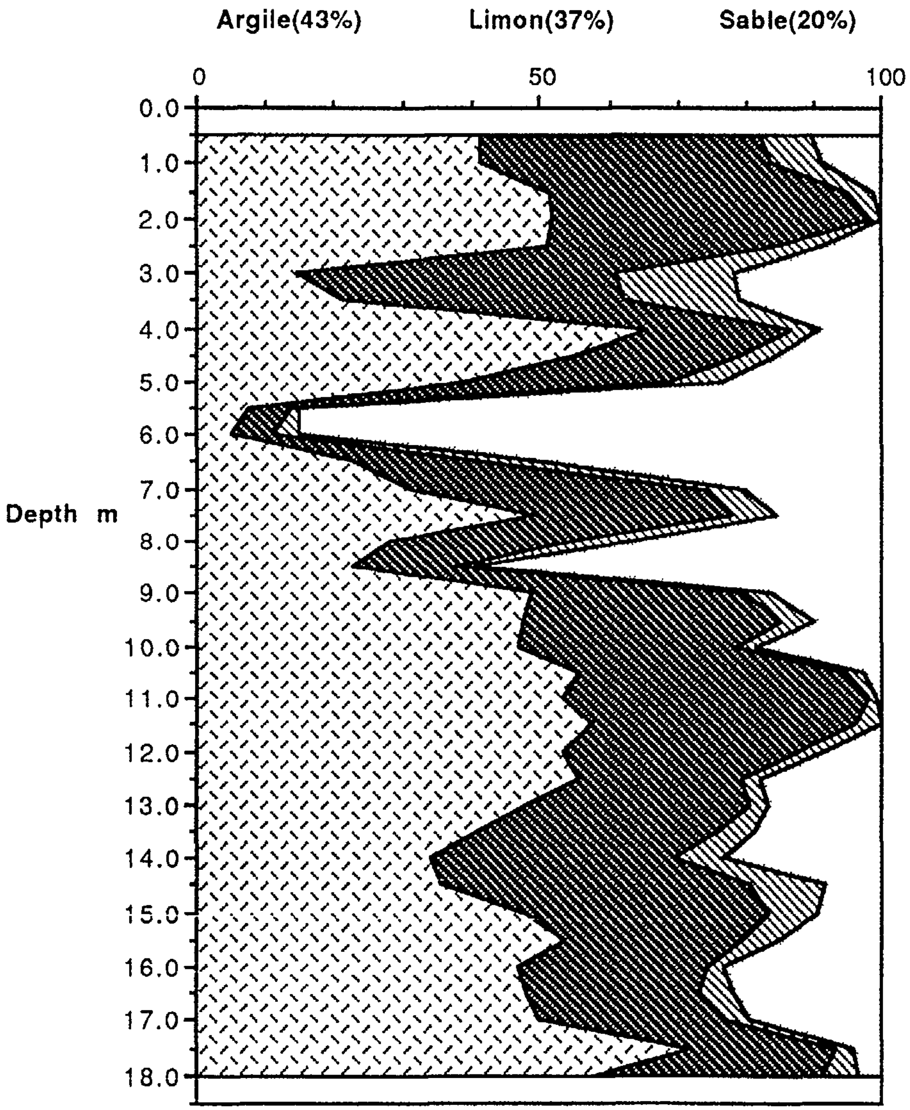

Fig. 8- Granulomitry : Profile (M)

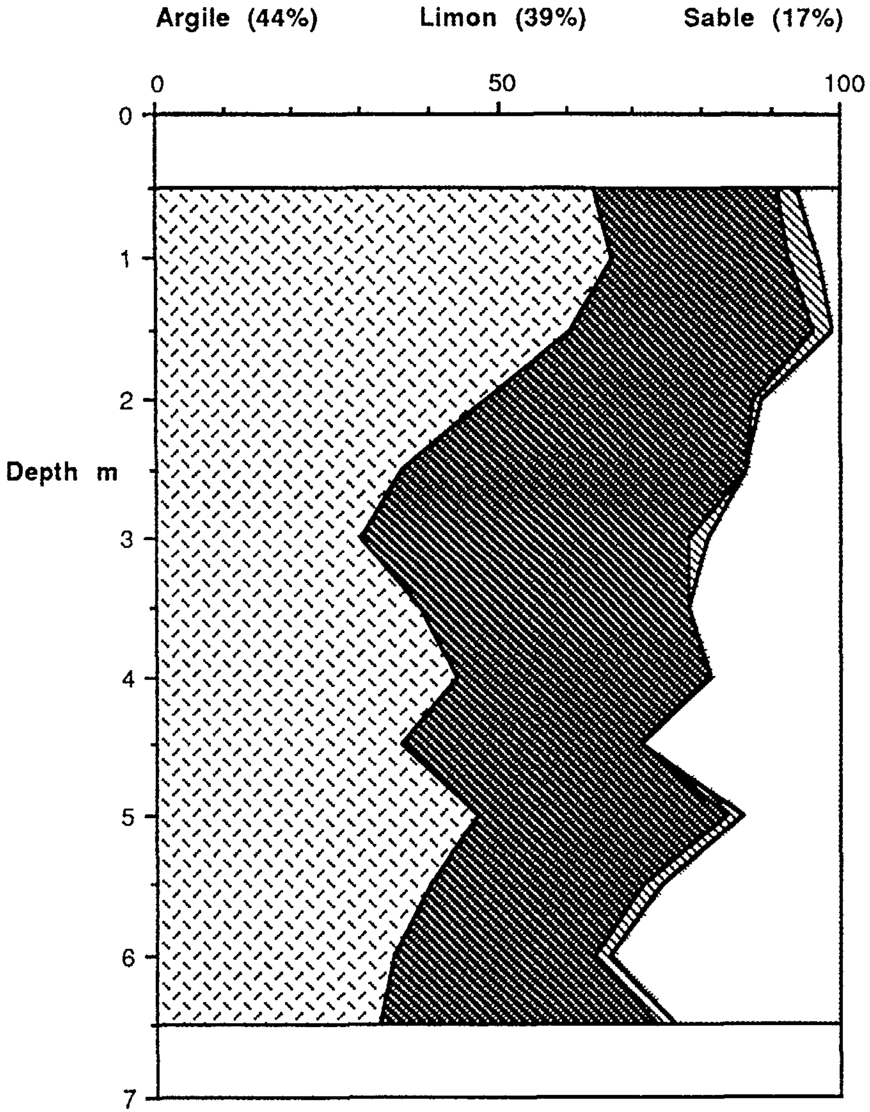

Fig. 9- Granulomitry : Porfile (G)

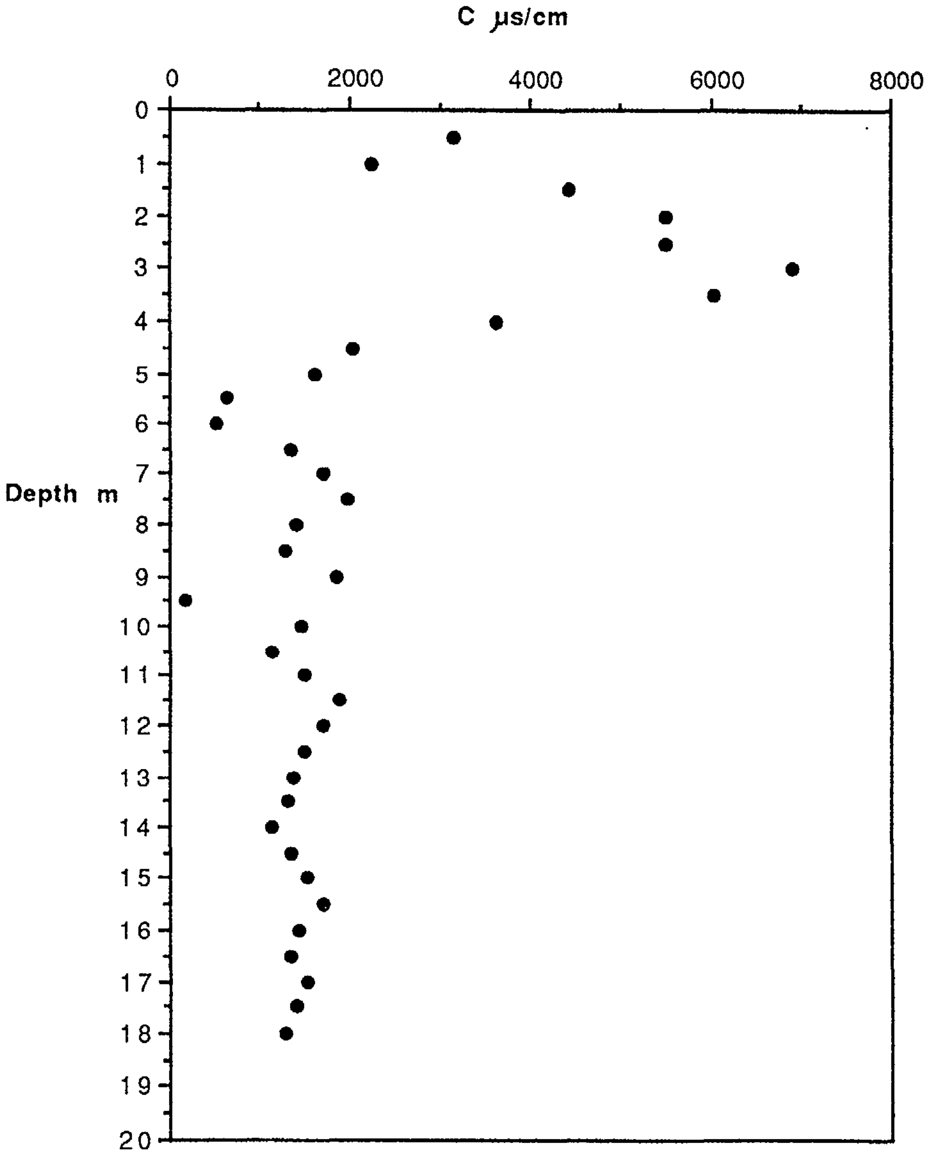

Fig. 10- Relationship between Conductivity and depth (profile M)

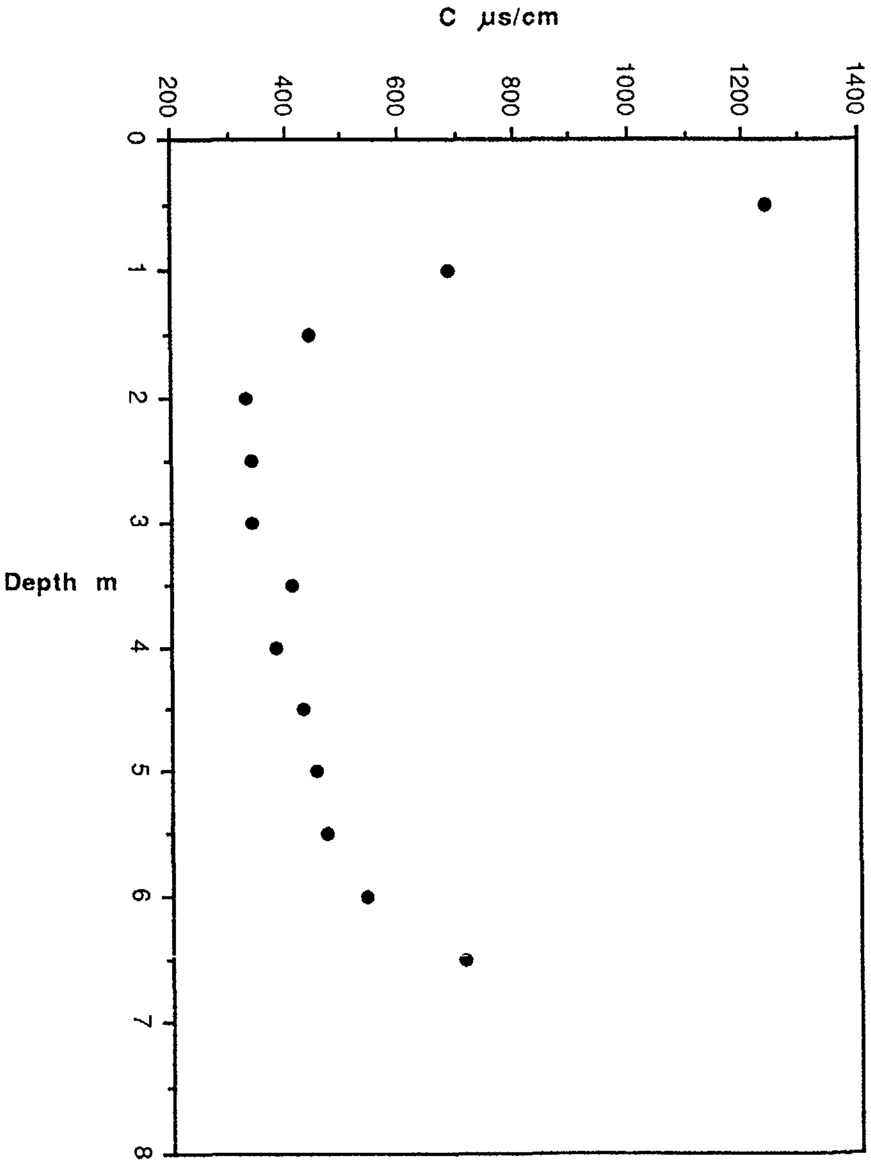

Fig. 11- Relationship between Conductivity and depth (profile G)

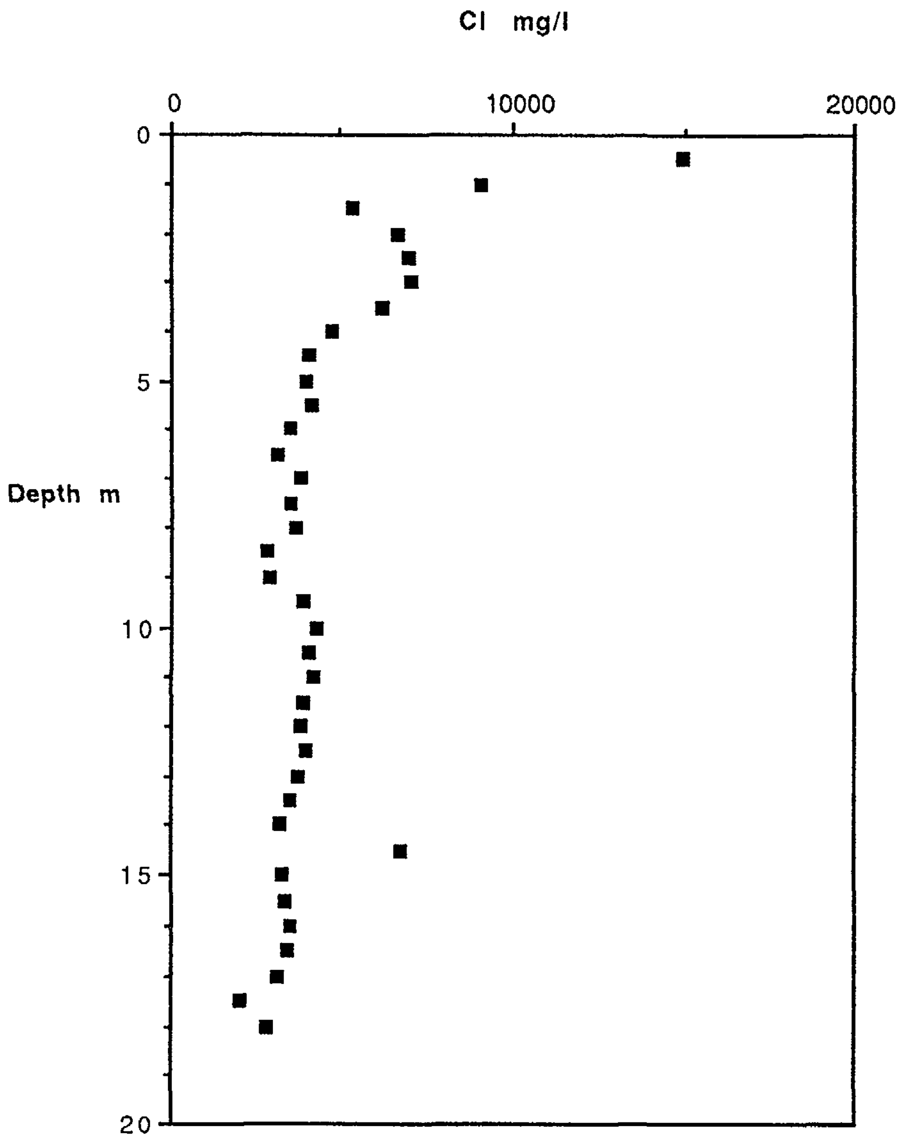

Fig. 12- Relationship between Chloride contents and depth (profile M)

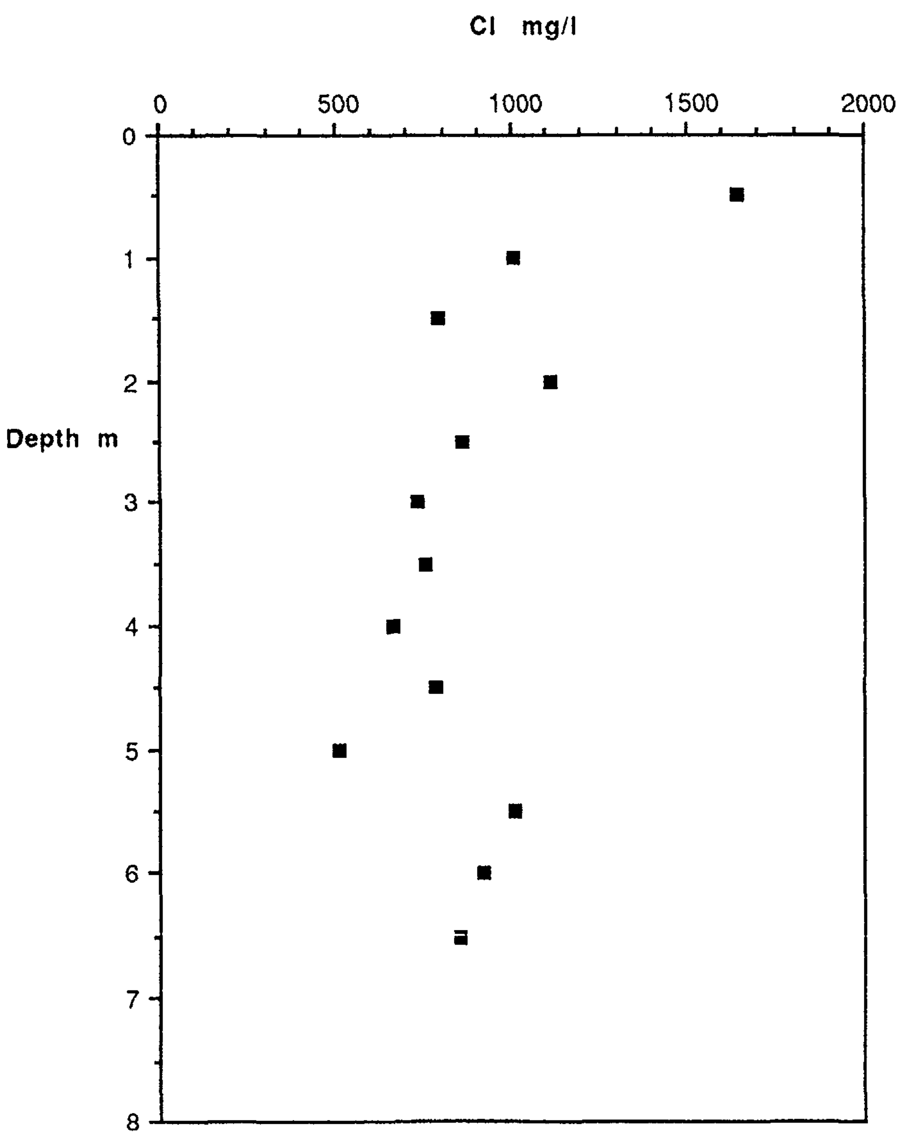

Fig.13- Relationship between Chloride contents and depth (Profil G)

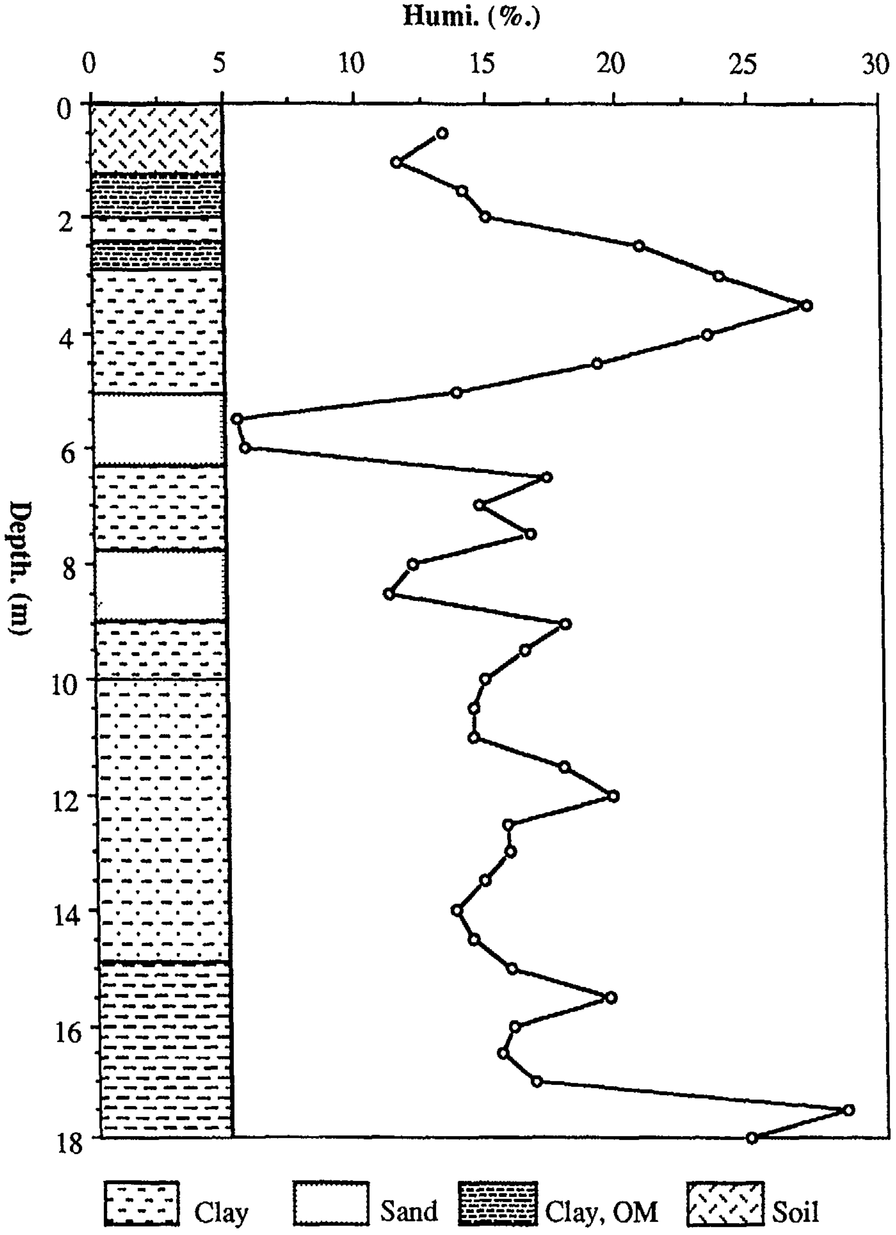

Fig. 14- Lithological profile and weighted humidity (Profile M).

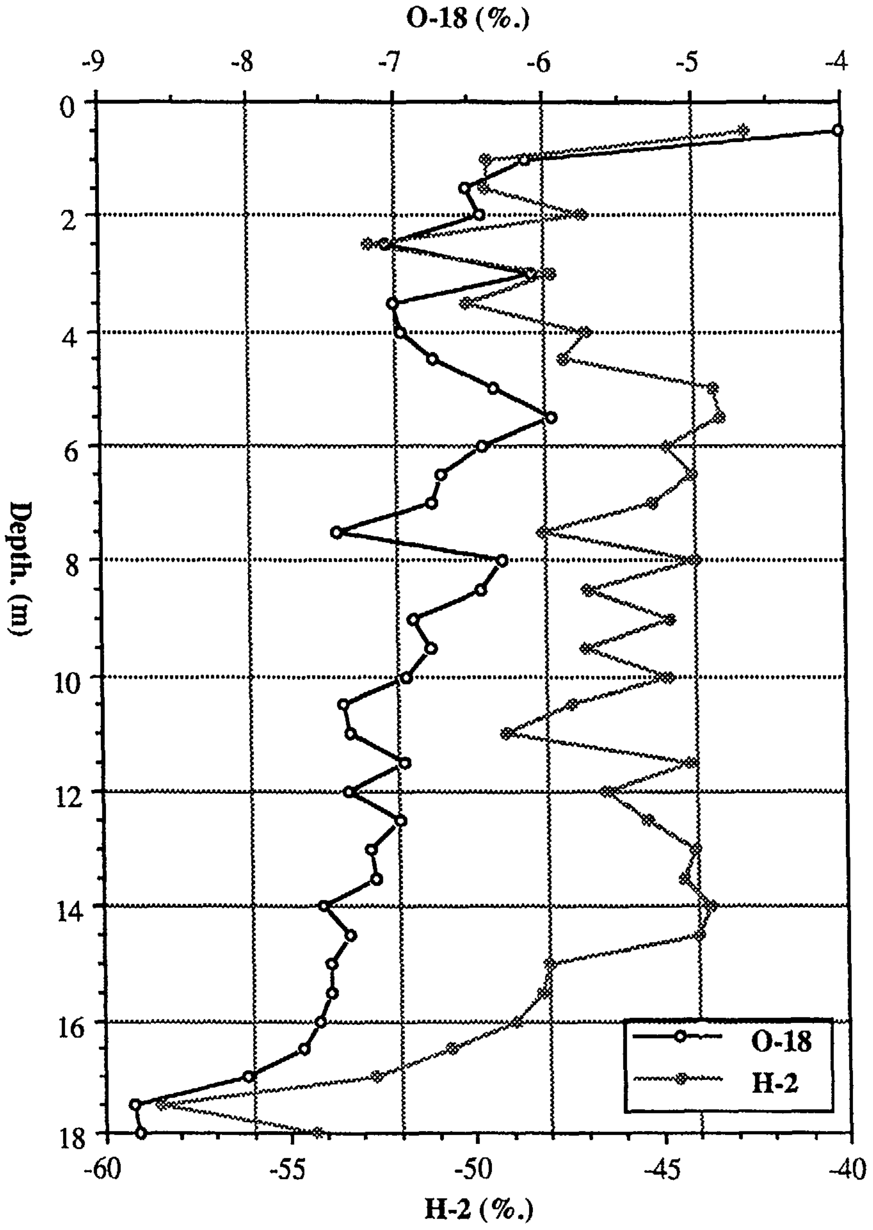

Fig. 15- Relationship between stable isotopes and depth (Profile M).

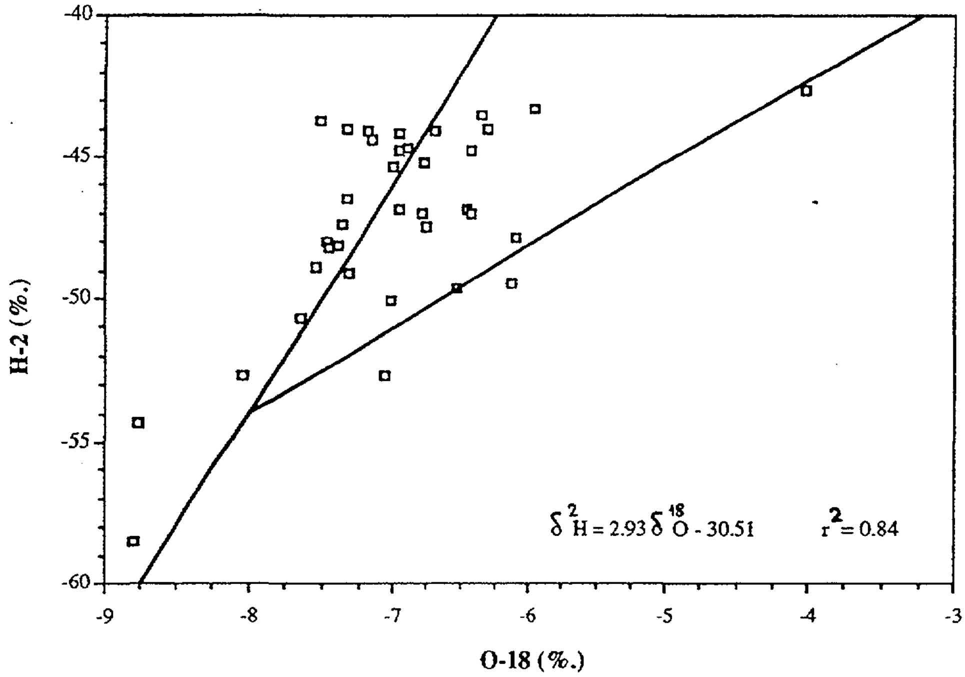

Fig. 16- Relationship between O-18 and H-2 in profile M.

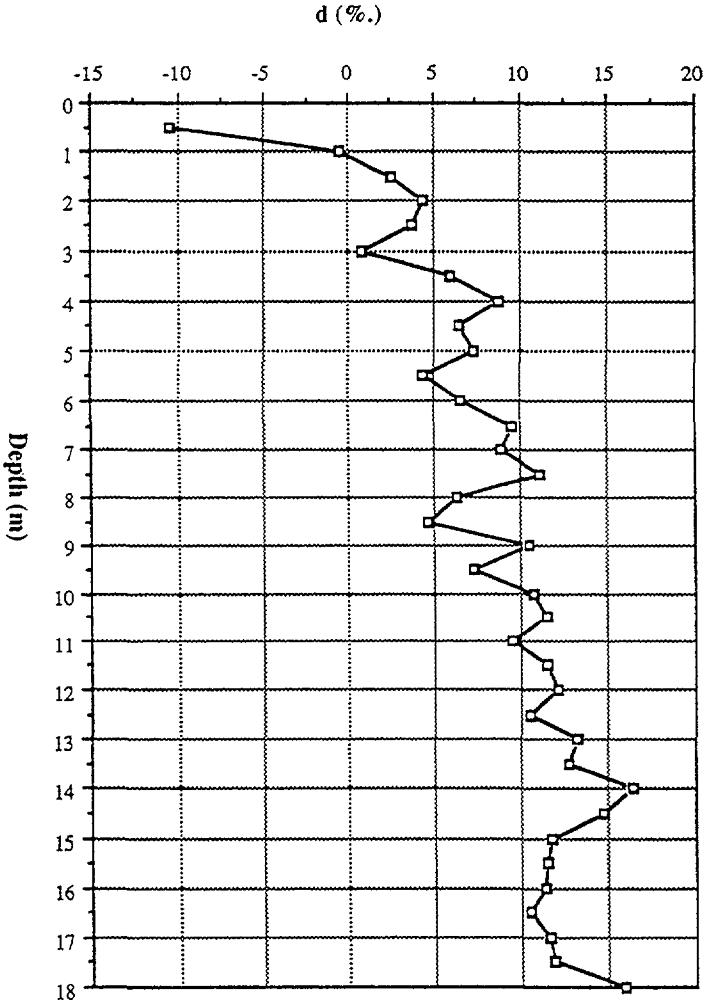

Fig. 17- Relationship between deuterium excess (d) and depth in profile M.

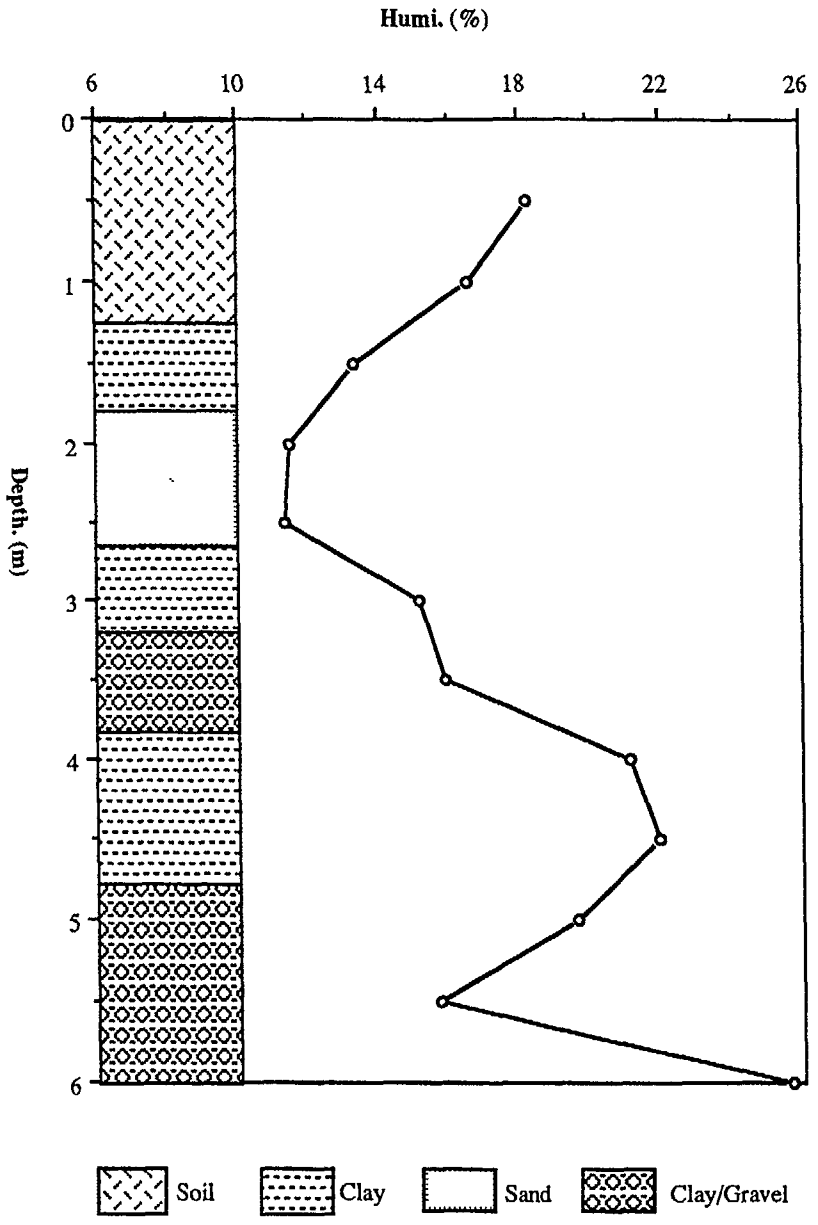

Fig. 18- Lithological profile and weighted humidity (Profile G).

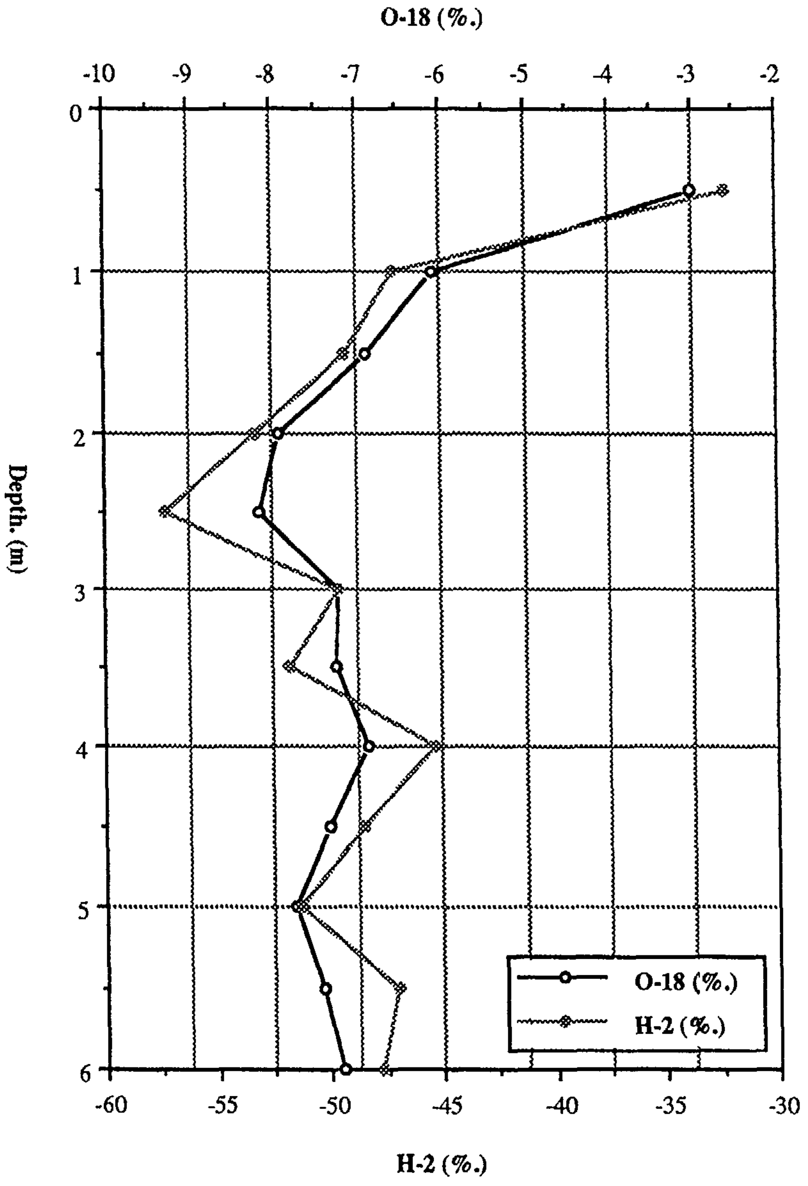

Fig. 19- Relationship between stable isotopes and depth (Profile G).

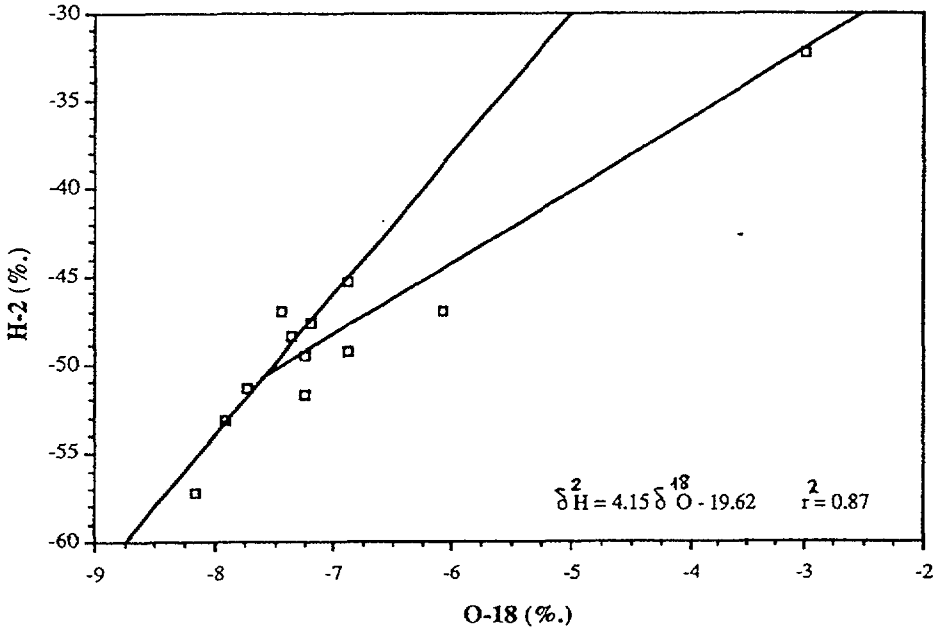

Fig. 20- Relationship between O-18 and H-2 in profile G.

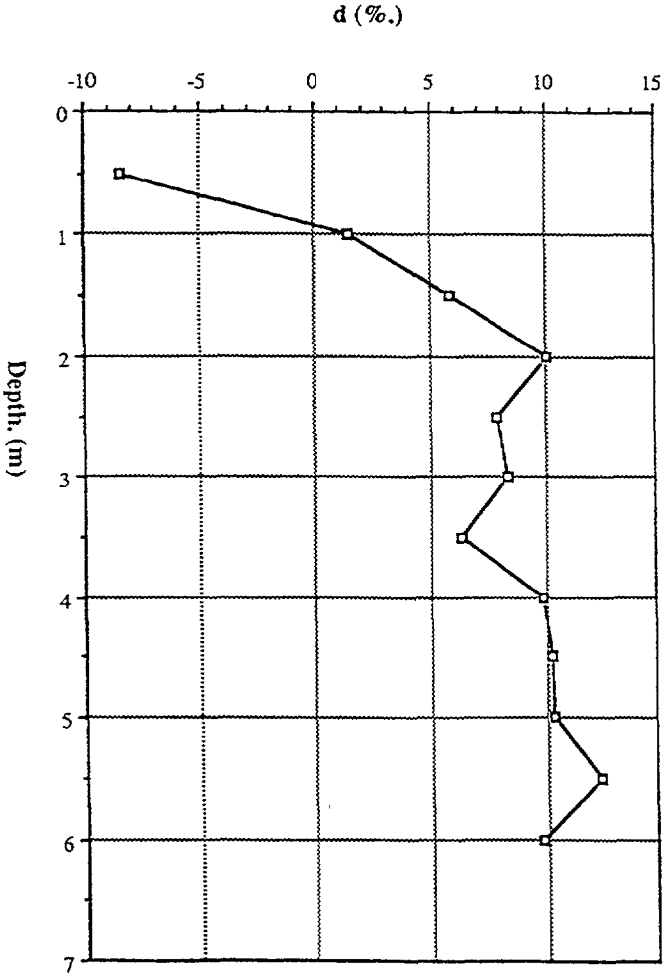

Fig. 21- Relationship between deuterium excess (d) and depth in profile G.

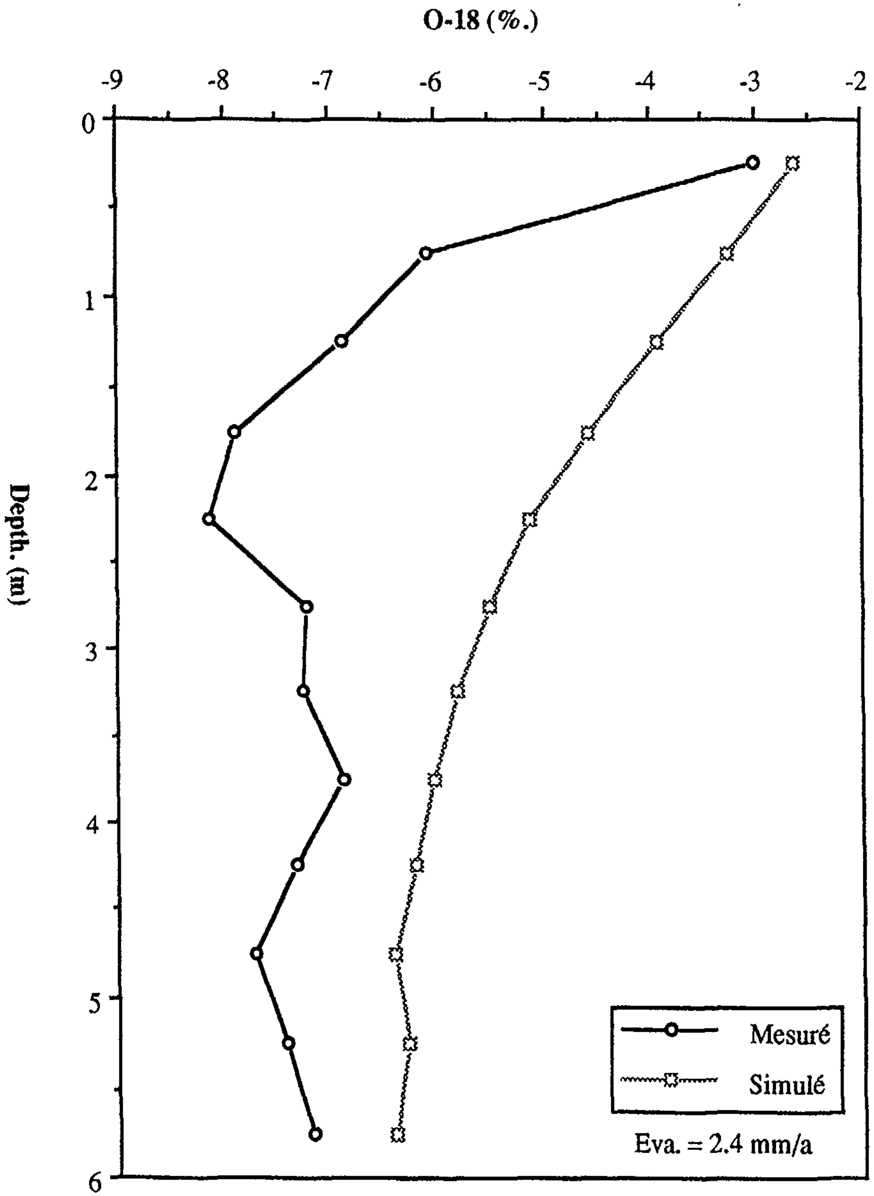

Fig. 22- Evaporation model for the profile G at 6 m depth.

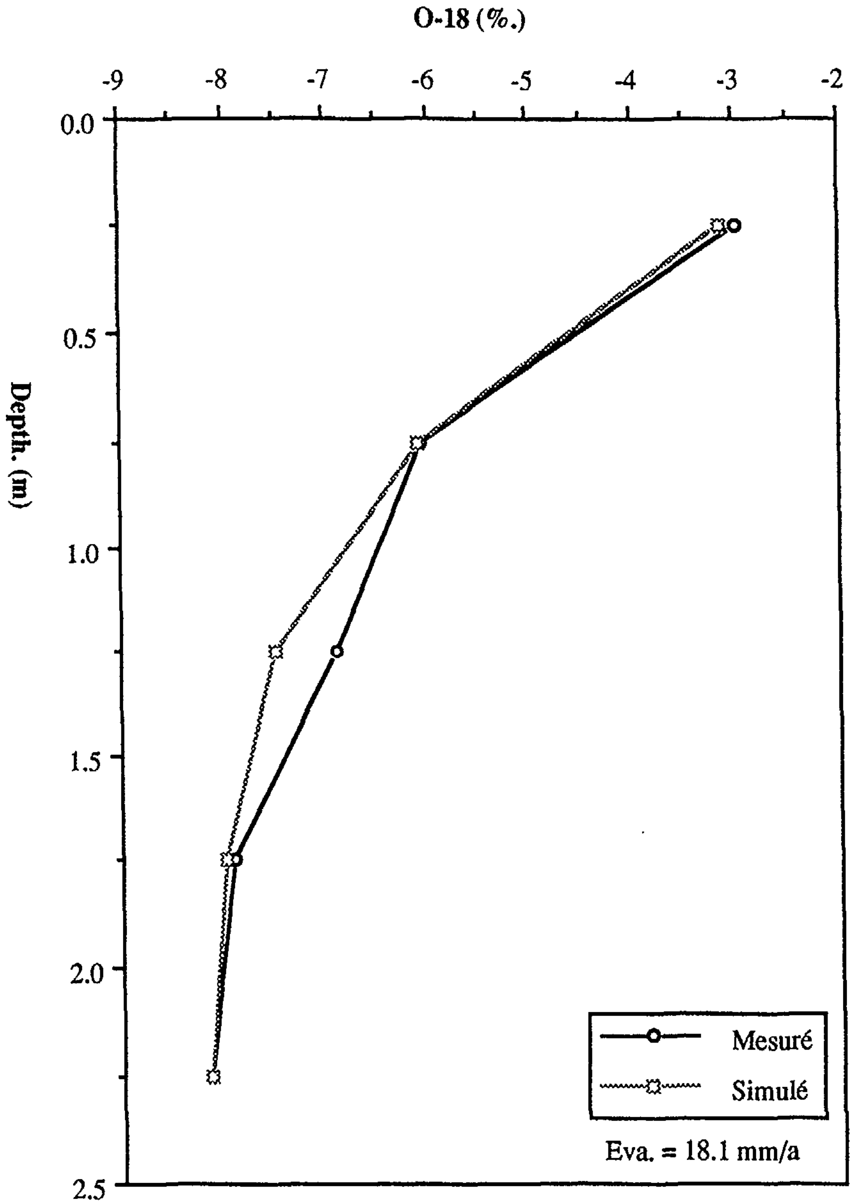

Fig. 23- Evaporation model for the profile G at 3 m depth.

- The depleted value of isotopic contents at 2.5 m depth in each profile may be due to :

1 - Recondensation of water vapour during its upwards flow.

2 - Irrigation with water which has more depleted values of isotope contents .

3 - Or precipitation in cold seasons for short time between two dry seasons.

- The study of salt movement in the unsaturated zone indicates that salt react the same way as the heavy isotopes which increase with evaporation effect.

- the chimical balance using chloride amount indicates the average direct recharge is about 2 mm/y.

- The evaporation rate calculated by Barnes and Allison model in profile G changes depending on the depth of groundwater that is between 18.1 mm/y in 3 m depth and 2.4 mm/y in 6 m depth.

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HYDROCHEMISTRY AND ISOTOPIC COMPOSITION OF THE NUBIAN SANDSTONE AQUIFERS OF DISI-MUDAWWARA AREA, SOUTH JORDAN

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Abstract

The Nubian sandstones of Cambro-Ordovician age crop out in the southern desert of Jordan. It comprises varicolored fine grained sandstones, siltstones and shales. The water bearing strata consist of two groups. The Khreim group of Ordovician-Silurian age overlies one of the most important fresh water resource in the country, which is Rum group. The Rum group is of Cambro-Ordovician age and consisting mainly of white medium grained sandstone. Any future development of the Rum group might accelerate the vertical leakage of the poor water quality from the Khreim group (upper aquifer) towards the Rum group (lower aquifer). Investigating and studying the origin and behavior of the Khreim group is of great importance to deal with the vertical leakage of the upper aquifer. Therefore, the hydrochemical and isotopic compositions of the Khreim water have been investigated as well as that of the Rum. The water types and geneses of both aquifers have been identified, by using complete hydrochemical analyses and the T, D, and O^{18} analyses. However, the average tritium content indicates that the water of both aquifers is not recent. Saturation indices and species of the waters of the waters of the two aquifers, were calculated by using the program PHREEQE. In order to identify the origin of the Khreim water a mixing model between the water of the lower aquifer and that of the Khreim was applied to demonstrate the potential risk of leakage from the Khreim group.

1. Introduction

The Cambro-Ordovician sandstones and Ordovician-Silurian sediments are extensively covering the southern part of the Arabian Peninsula and the northeastern part of Africa. In the southern desert of Jordan the sediments of the Cambro-Ordovician-silurian crop out and cover most of the southern part at various depths (Fig. 1).

The work of Lloyd (1969) was the first major contribution to the hydrogeological investigation of the sandstone aquifer in the southern desert of Jordan, with recognition of the Rum Group (Cambro-Ordovician). The stratigraphic subdivision was further developed by Selly (1972) on the depositional analysis of sandstone outcrops. Type localities for lithostratigraphic units were defined for the now termed Rum and Khreim groups. Powell et al. (1989) in cooperation with the Natural Resources Authority of Jordan have undertaken a comprehensive stratigraphic and sedimentological study of the Rum and Khreim groups. More recently Andrews (1991) and by using geophysical data from deep boreholes has introduced alternative nomenclature to describe Rum and Khreim groups. Extensive groundwater modelling work was carried out by

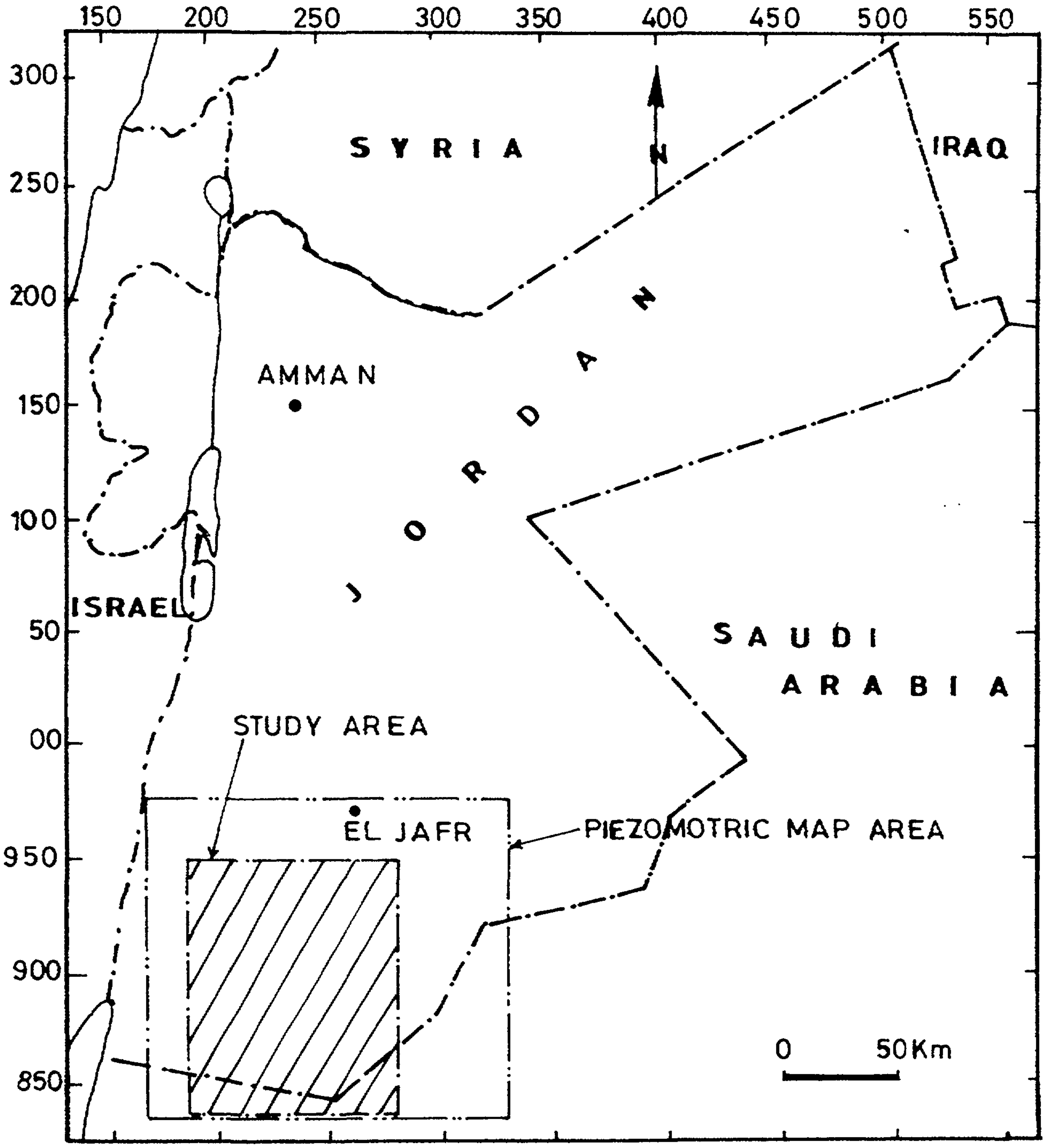

Figure (1): Location map of the study area

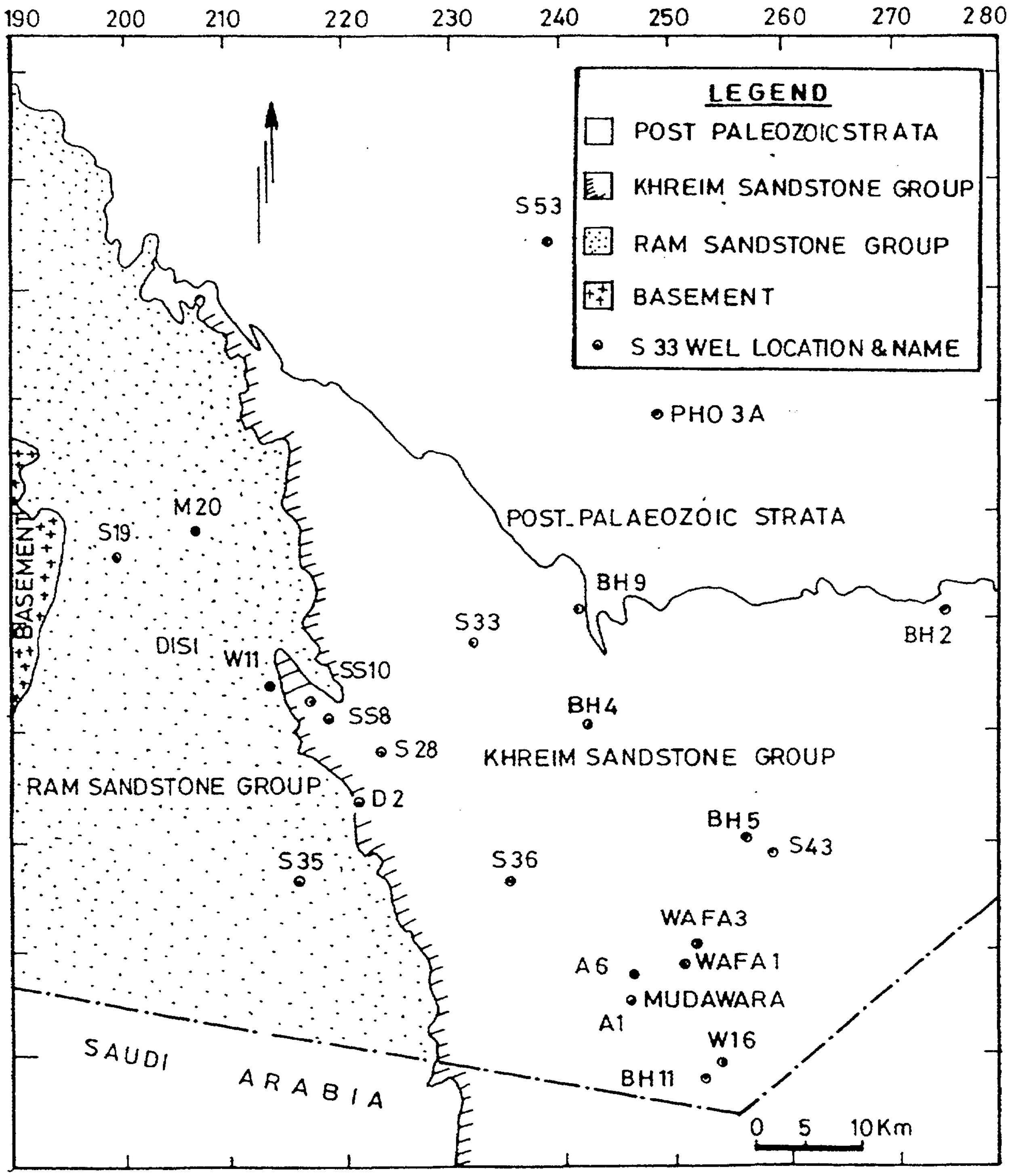

Figure (2): Location map of major stratigraphic group boundaries

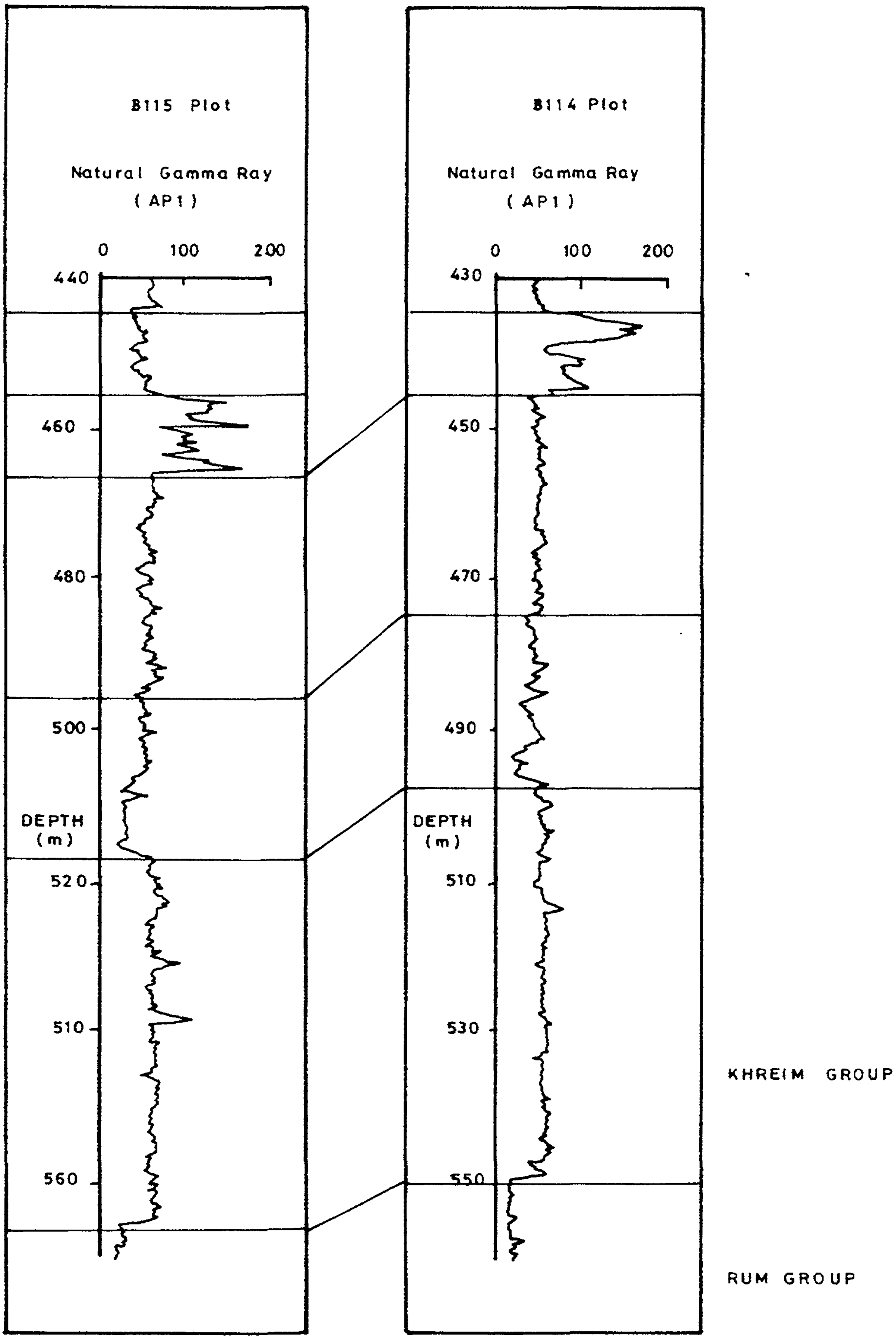

Figure (3): Geophysical log showing base of Khreim group

Howard Humphreys (1986). Subsequent work carried out by HSI (1990) has provided a comprehensive summary of all the hydrogeological studies of the Rum (then Disi) sandstone aquifer. BGR (1991) has presented a comprehensive report on southern Jordan with the main emphasis on the collection of a considerable amount of data. The most recent study is a UK ODA/WAJ-financed study carrying out by Scott Willson Kirkpatrick (SWK) & WAJ (1991-1994) to investigate the groundwater resources of the sandstone aquifer by drilling deep wells in the northeastern part of the aquifer.

2. Hydrogeology and Hydraulic Characteristics

The outcrops of the Rum and Khreim groups are shown in Figure 2. The Rum aquifer covers about 3,000 km^2 and has uniform lithology over a large area. At outcrops, the Rum aquifer has a thickness of 500 m, but as the group dips northwards, its thickness increases up to 2,000 m. The Khreim group overlies the Rum group with thicknesses ranging between zero and 1200 m in the northeastern part of the area. The geological contacts as well as the formations of the Rum and Khreim groups can be easily recognized as shown by the geophysical data (Figure 3, WAJ open files).

Analysis of data from borehole cores in the Rum aquifer give total porosities in the range of 15 to 25% suggesting an average value for the Rum aquifer of 20%. The porosity values of the Khreim group are in the range of 15-20%. The K values for the Rum aquifer are between 0.5 and 3 m/d. The permeability of the Khreim group ranges from 0.001 to 0.08 m/d. The transmissivity of the confined section of the Rum aquifer has a value of 1000-1600 m^2/d and a storativity of 3-5 x 10^{-3}. The storativity of the Khreim group is about 1 x 10^{-4} (SWK & WAJ, 1994).

Leakance analysis conducted by SWK & WAJ (1994) suggests a maximum value of leakage from the Khreim group to the Rum group of 1-3% for a 50-years production scenario. The maximum limit of leakage may be determined by use of the Papadopulos double layered aquifer method (1966) and others described in Kruseman and De Ridder (1990).If the influence of the Hiswah Shale (Fig.3) is ignored then the Khreim sandstone immediately above the Hiswah Shale may be considered as in complete hydraulic connection with the Rum Group. Hence the drawdown in the Khreim is the same as in the Rum Group. The discharge Q2 derived from the Khreim sandstone has the same ratio to the Rum Aquifer discharge Q1 as their respective transmissivities, T2 and T1. The transmissivity of the Rum Aquifer is 1000-2000 m^2d-1. The permeability from plug data of the Khreim sandstones are a maximum of 0.1 m/d. The permeability of 1 m/d observed in the Rum aquifer must therefore be the notional maximum. Therefore applying the Khreim sandstone and Rum aquifer transmissivity ratios gives:

$$Q2=Q1*(1*100)/(1000 \text{ to } 2000)=5 \text{ to } 10\% \text{ of } Q1.$$

Since the Hiswah Shale is an aquitard, 5-10% must therefore be considered a notional maximum leakage limit which can not be exceeded . However the Hiswash Shale can be expected to have a low permeability and will reduce drawdowns in the Khreim sandstone substantially restricting the ability of the Khreim sandstone to transmit leakage water. The slug test estimates of the Khreim K value, which are the best available values give K's of 0.01-0.06 m/d and suggest a maximum permeability of 0.1 m/d, which corresponds to a maximum of 1% leakage using the Papadopulos double layer aquifer scenario. This value is confirmed by the values obtained from the BH4 pumping test. Allowing for heterogeneity, 1-3% maximum leakage for the 50 year predictive scenario seems probable.

In the western part of the study area the Rum group is under unconfined conditions. However, the Rum aquifer gradually becomes confined towards the east where the Khreim group overlies the Rum group. The depth to the groundwater table in the unconfined section of the aquifer is about 80 - 100 m b.g.l. In the confined section, the groundwater potential ranges from artesian outflow in some

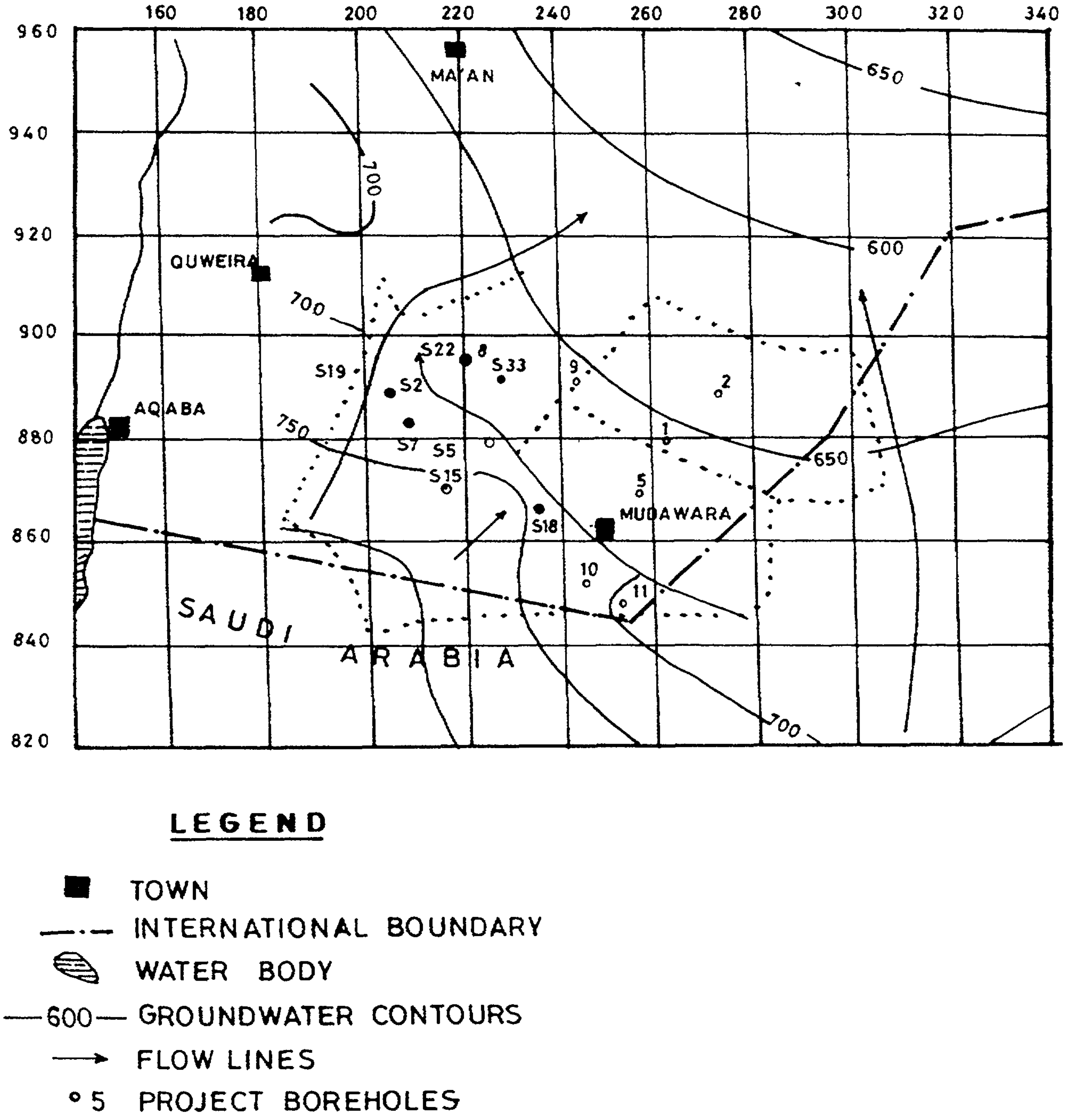

Figure (4): Groundwater flow map of Rum group wells to about 170 m b.g. Whereas, towards the north, the groundwater depth is much deeper where it reaches 250 m b.g.

Figure 4 shows the groundwater flow map of the Rum aquifer as well as the locations of the boreholes. Generally, the groundwater flow is from the south to the northeast. In the vicinity of the Khrewi dyke, the flow converges partially towards the southeast.

3. Hydrochemistry

The groundwater of the Rum group is of good quality, suitable for potable use with a range of salinity of 200-300 mg/l (Fig. 5) in the unconfined section increasing slightly in the confined section to 300-400 mg/l. The overlying Khreim group, of marine origin, contains groundwater of significantly greater salinity ranging from 900 to 9000 mg/l.

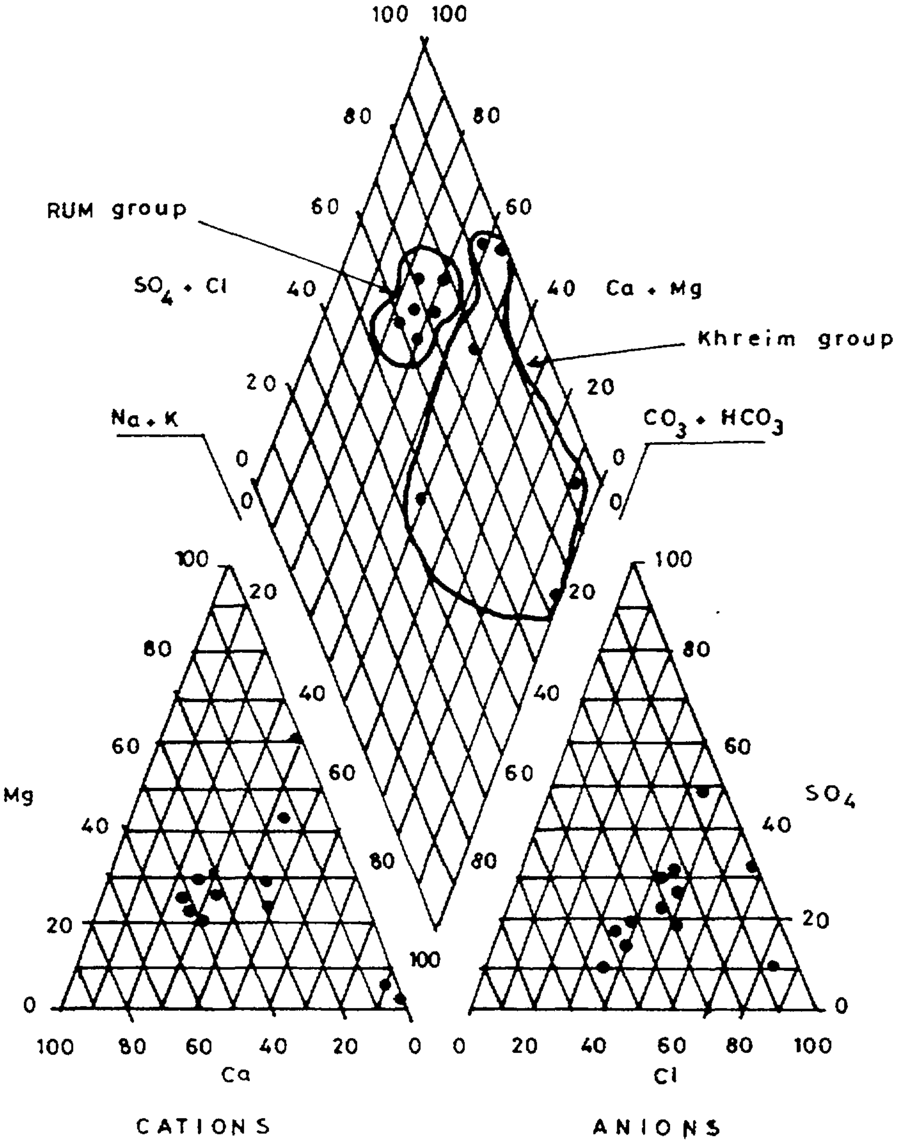

Fig.(5): Trilinear plot of the major ions of Rum and Khreim groups

The milliequivalent ratios of the chemical constituents of the Rum group follow Ca > Na > Mg and Cl > HCO_3 > SO_4. In the areas of recent recharge HCO_3 > CL > SO_4.

The milliequivalent ratios of the Khreim group follow Na > Mg > Ca and Cl > SO_4 > HCO_3.

The Piper diagram (Figure 5) shows the hydrochemical plot of the water quality of some selected samples from both the Rum and Khreim groups. According to Langguth's (1966) classification the water quality of the Rum group is classified as earth alkaline water with increased portion of alkalies and prevailing chloride. The Khreim group has several water types, which demonstrates the various kinds of genesis. The first water type is the same type as the Rum group, which means that the origin of the Khreim water at certain localities is originated from the Rum aquifer through upward leakage. The Khreim samples of alkaline waters with prevailing chloride (Fig. 5), represent old formation waters partially subjected to evaporation and with long residence time. The Khreim samples that have earth alkaline water with increased portion of alkalies and prevailing bicarbonate type, might be related to the recharge of the Khreim group through wadi floods during the winter season. Wadi flood flows long distances to areas with considerable amount of bicarbonate content.

3.1 Hydrogeochemical Modelling

Although the evidence for leakage from the Khreim Group is not conclusive with the present level of data, it has been judged that an investigation of potential leakage on water quality in the Rum Aquifer would be of benefit to the assessment of groundwater resources. According to the analyzed water quality samples the salinity of the Khreim group at two sites (BH5 & BH4) ranges between 4000 to 9000 mg/l, while the salinity of the Rum group ranges between 200-300 mg/l. By using simulation techniques a hypothetical mixing model at each site has been applied to investigate the leakage effect.

Hydrogeochemical modelling is of great importance in identifying a single set of phases that account for the observed water chemistry and in simulating the possible mixing ratios of different water bodies.

A downward leakage from the Khreim Group to the Lower aquifer (Rum) might be taking place. The only way to investigate the effect of the leakage on the quality of the Rum aquifer is by using hypothetical geochemical models which represent the mixing ratios of the two water bodies under certain plausible mineral phases. The selection of these phases is based on mineralogical and geological data, which have been collected from various sources. However, the principal mineralogical phases of the Khreim aquitard are quartz and kaolinite. The principal mineralogical phase of the Rum group is mainly quartz.

In order to determine the mixing ratios between the Khreim group and Rum group, as well as the thermodynamics of the two aquifers, the hypothetical hydrogeochemical models were applied for two cases. A mixing model of 2% of Khreim water with 98% of Rum water represents the average value of the calculated leakage (1-3%). The other case of 10% leakage from the Khreim group and 90% of Rum group has been calculated. The 10% case was selected to demonstrate the maximum value of leakage that makes the water of the Rum group undrinkable. However, the 10% mixing model is five times greater than the calculated value of leakage after 50 years of production.

Because of the complexity of the calculations required in simulating the chemical evolution of the reacting water-rock system, the simulations are performed using the computer code PHREEQE (Parkhurst et al., 1980). PHREEQE is a geochemical reaction model based on an ion pairing aqueous model. This code is capable of evaluating mixing and calculating the assumed mineral reactants and products that must dissolve and/or precipitate between the selected initial and final solution points (mass balance). In addition PHREEQE determined the composition of the solutions and the stage of equilibrium with multiple phases, and their pH and redox potential values.

The initial water quality values that have been incorporated into the model are shown in Table 1.

The results of the two hypothetical hydrogeochemical simulations at each site are given in Table 2. The results of the simulations and the initial water quality concentrations are given, for comparison purposes, in ppm in Table 2. As can be seen from the results of the mixing models, the water quality of the Rum group does not change considerably with a mixing ratio of 2%, which should represent the actual future leakage. Even with an extreme leakage of 10% the water quality of the Rum at the Bh4 site is still within the standard of drinking water, while the Bh5 site is slightly above the WHO recommended TDS.

Table (1): Initial water quality of the different wells

Well Name Parameter	BH5	BH5A	BH4	BH4A
Date	7.3.94	6.3.94	4.2.94	16.2.94
Depth	1450	304	328	285
Aquifer	Rum	Khreim	Rum	Khreim
Ec (uS/cm)	373	12930	328	5600
pH	7.42	7.73	7.18	7.4
T (oC)	42	25	38	25
Ca (mmol/l)	0.85	11.07	0.86	5.17
Mg (mmol/l)	0.3	24.8	0.25	13.4
Na (mmol/l)	1.18	83.0	0.96	30.8
K (mmol/l)	0.04	0.99	0.03	0.5
Cl (mmol/l)	1.38	90.29	1.11	25.3
SO4 (mmol/l)	0.42	30.14	0.26	18.4
HCO3 (mmol/l)	1.38	4.86	1.53	5.62
TDS (mg/l)	243.4	9380.1	221.3	4270.2

Table (2): Water quality simulation for different mixing ratios

Well Parameter	BH5 (2%)	BH5 (10%)	BH4 (2%)	BH4 (10%)
pH	7.42	7.47	7.19	7.22
T (oC)	41.7	40.3	37.7	36.7
Ca (mmol/l)	1.06	1.88	0.95	1.29
Mg (mmol/l)	0.79	2.77	0.51	1.57
Na (mmol/l)	2.83	9.44	1.56	3.94
K (mmol/l)	0.06	0.136	0.041	0.078
Cl (mmol/l)	3.17	10.3	1.59	3.54
SO_4 (mmol/l)	1.02	3.42	0.53	2.08
HCO_3 (mmol/l)	1.45	1.73	1.61	1.94
SiO_2 (mmol/l)	0.173	0.165	0.152	0.147
Initial TDS (mg/l)	243.4	243.4	221.3	221.3
TDS after Mixing	427.7	1164	293.4	626.9

Table (3): Saturation indices (SI) of different mineral phases of Bh4 and Bh5 sites at 2 and 10 % mixing ratio

PHASE	SI (2% Model) (Bh4 Site)	SI (10% Model) (Bh4 Site)	SI (2% Model) (Bh5 Site)	SI (10% Model) (Bh5 Site)
CALCITE	-.5565	-.4125	-.2869	-.0792
DOLOMITE	-1.2526	-.6267	-.5671	.1478
GYPSUM	-2.0113	-1.5210	-1.8248	-1.2940
CHALCEDY	-.4348	-0.4386	-.4207	-.4256
QUARTZ	.0000	.0000	.0000	.0000
GIBBSITE	-1.9423	-1.9397	-1.9517	-1.9485
KAOLINIT	-3.2609	-3.2626	-3.2289	-3.2349
SEPIOLIT	-4.7353	-3.8909	-3.0829	-2.1784
PCO_2	-2.1641	-2.1408	-2.4004	-2.4065

In order to check the saturation indices (SI) of the aquifer water chemistry with respect to other mineral phases, the saturation indices of various mineral phases are given for each mixing model.

Table 3 summarizes the saturation indices of the mineral phases. As it can be seen the mixed Rum water is undersaturated with respect to all the mineral phases. Increasing the mixing ratio from the Khreim group causes the saturation index of dolomite and probably calcite to convert from unsaturated to oversaturated. This might cause scale problems (precipitation of calcium carbonates) to occur.

4. Isotopic Composition

Samples from the groundwater boreholes of the study area representing the two groups were collected for the analysis of deuterium (D), O^{18} (Table 4) and Tritium. The isotope samples were analyzed in the Isotopes Labs of the Water Authority of Jordan. The isotope samples were clustered in four groups. All analyzed samples

Table (4): Isotopic composition of the groundwater sample

Well Name	Date	EC (uS/CM)	O-18 (%.)	D (%.)	T (oC)	d-PARAMETER*	CLUSTER
MW9	10/89	370	-6.91	-42.80	15.02	12.48	2
MW9	03/88	330	-7.28	-41.20	13.92	17.04	1
MW8	10/88	380	-7.03	-44.10	14.66	12.14	2
MW8	06/87	380	-6.64	-41.70	15.82	11.42	2
MW6	10/89	350	-7.01	-43.30	14.72	12.78	2
MW5	10/89	380	-6.92	-43.40	14.99	11.96	2
MW3	06/87	320	-6.46	-41.60	16.35	10.08	1
W16	06/87	350	-6.00	-34.30	17.71	13.70	2
MW11	03/88	340	-7.05	-40.00	14.60	16.40	1
G6	10/89	330	-5.73	-33.80	18.51	12.04	1
G5	10/89	310	-5.61	-33.80	18.86	11.08	1
G4	10/89	400	-5.74	-34.50	18.48	11.42	2
G3	10/89	340	-5.71	-34.30	18.57	11.38	1
G2	03/88	340	-5.76	-32.40	18.42	13.68	1
G1	10/89	330	-5.69	-34.20	18.63	11.32	1
A2	10/89	340	-5.75	-35.20	18.45	10.80	1
SS8	10/89	340	-6.36	-40.20	16.64	10.68	1
SS5	03/88	330	-6.61	-40.20	15.90	12.68	1
SS2	10/89	340	-6.42	-41.70	16.47	9.66	1
SS11	10/89	440	-6.32	-40.30	16.76	10.26	3
SS11	03/88	350	-6.44	-37.60	16.41	13.92	1
SS1	10/89	340	-6.32	-41.30	16.76	9.26	4
S7	06/87	360	-6.67	-38.50	15.73	14.86	2
S4	10/89	350	-6.35	-41.10	16.67	9.70	2
S2	10/89	490	-6.68	-42.40	15.70	11.04	3
S2	03/88	420	-6.84	-40.30	15.22	14.42	3
S19	03/88	400	-6.21	-34.80	17.09	14.88	2
S19	06/88	380	-5.74	-33.00	18.48	12.92	2
S19	10/89	500	-6.01	-38.90	17.68	9.18	3
MANSH.	06/87	420	-6.46	-40.90	16.35	10.78	3
M9	03/88	360	-6.97	-39.00	14.84	16.76	2
M7A	10/89	300	-6.61	-39.90	15.90	13.08	1
M6	10/89	330	-6.73	-42.60	15.55	11.24	1
M3A	06/93	300	-6.52	-39.40	16.17	12.76	1
QD6	06/93	350	-6.26	-40.30	16.94	9.78	2
M8	06/93	366	-6.75	-41.30	15.49	12.70	2
S7	06/93	430	-6.66	-38.60	15.76	14.68	3
M3	06/93	313	-6.67	-39.30	15.73	14.06	1
WF5	06/93	327	-6.42	-36.80	16.47	14.56	1
S19	06/93	469	-6.72	-33.90	15.58	19.86	3
M6	06/93	338	-6.97	-42.50	14.84	13.26	1
M2	06/93	548	-6.45	-38.50	16.38	13.10	3
W11	06/93	336	-6.46	-38.60	16.35	13.08	1
G4	06/93	362	-5.52	-32.20	19.13	11.96	2
WF3	06/93	344	-5.76	-32.80	18.42	13.28	1
SS23	06/93	352	-5.2	-36.00	20.08	5.60	2
G10	06/93	364	-5.51	-31.70	19.16	12.38	2
SS22	06/93	361	-6.27	-38.60	16.91	11.56	2
WF4	06/93	359	-6.86	-33.60	15.16	21.28	2
SS20	06/93	381	-6.27	-39.70	16.91	10.46	2
WF2	06/93	360	-5.63	-32.30	18.81	12.74	2
BH4	06/93	334	-6.00	-35.70	17.71	12.50	1
G10A/5	06/93	1159	-5.90	-33.70	18.01	13.50	4
G10A/35	06/93	1189	-5.71	-34.50	18.57	11.18	4
A1/OBS	06/93	355	-5.63	-34.60	18.81	10.44	2

Table (5): Isotopic composition of groundwater samples

Cluster No.	No. of Samples	EC (uS/cm) (Mean)	O-18 (%.) (Mean)	D (%.) (Mean)	T-WT (Mean)	d-PARAMETER (Mean)
I	21	329.6	-6.313	-37.900	16.784	12.603
II	24	365.4	-6.285	-37.904	16.865	12.379
III	8	464.6	-6.517	-39.225	16.178	12.915
IV	2	1174.0	-5.805	-34.100	18.287	12.340

* d-Parameter = Delta D - 8 Delta O-18

have tritium contents below detection limit, which means that the water of that area is more than about fifty years old. Table 5 gives the number of samples in each cluster as well as the mean value of the different parameters for each group.

Group I (Table 4) represents most probably the youngest groundwaters in the upper most part of the aquifer's water. This type of water is discharged with artesian outflow in some of the wells in Mudawwara area. Table (4) gives the names of the groundwater wells of this type.

Group II comprises groundwaters of probable higher age. This type of water has been found in wells that are pumping water for a long time. It is assumed that the water pumped of the cone of depression has paleo origin. Along the flow line in the vicinity of Mudawwara area, Group I changes to Group II towards the northeast where the groundwater becomes deeper. Typical groundwaters of this type are given in Table 4. The groundwater of both groups has the same stable isotope composition.

Group III comprises groundwaters which is isotopically enriched. Representative areas of this type are found near the recharge areas (i.e., south of Ras En Naqab area). The waters of this group had the highest deterium excess (d-Parameter).

Group IV has different characteristics from all the above mentioned groups. The waters of this type represent the Khreim group, which has relatively high TDS. The isotopic composition of this group indicates evaporation water origin. Hydrogeologically, the Khreim group is partially recharged by flood water and rainfall events every 4-5 years. However, large amounts of these waters do evaporate to the atmosphere, which enriched the isotopic composition of the recharged water to this group. Table 4 shows typical groundwater wells of this type.

Because of the limited isotope samples of the Khreim group, it was difficult to give conclusions about the hydrodynamic relation between the waters of the two groups.

Conclusions

The water quality of the Rum group is excellent for any use. The water is classified as earth alkaline water with increased portion of alkalies and prevailing chloride. The Khreim group has a poor water quality and has more than one water type, which demonstrates the various sources of recharge to this group. The first water type is the same type as of the Rum group, which means that the origin of the Khreim water at certain localities is originated from the Rum aquifer through upward leakage. The Khreim samples of alkaline waters with prevailing chloride represent older formation waters partially subjected to evaporation and with long residence time. The Khreim samples that have alkaline earth water with increased portion of alkalies and prevailing bicarbonate type, might be related to the recharge of the Khreim group through wadi floods during winter season. Wadi flood flow long distances to that area with considerable amount of bicarbonate contents and evaporation processes.

The hydrogeochemical mixing models have shown a low leakage risk from the Khreim group to the Rum group (at 2% of mixing ratio), which represents the actual leakance factor. Even by multiplying the calculated leakance factor by five times the Rum aquifer, the water is still drinkable at certain localities.

The isotopic composition of the isotope samples of both the Rum and Khreim groups have shown four types of water. The first group of groundwaters is in upper most part of the aquifer. This type of water is discharged artisan from the wells in Mudawwara area.
The second group has been found in wells that are pumping water for a long time. It represents deep water possibly of paleo origin.
Group three comprises groundwaters which is pumped after a long time of recovery and is isotopically enriched. Representative areas of this type are found near the recharge areas. This type of water is more recent than that of group one.
The last group of waters represents the Khreim group, which has relatively high TDS. It is isotopically most enriched with respect to the other groups. Hydrogeologically, the Khreim group is partially recharged by flood water and rainfall events every 4-5 years. However, large amounts of these waters do evaporate to the atmosphere, which enriches the isotopic composition of the recharged water to this group.

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ENVIRONMENTAL ISOTOPE AND HYDROCHEMICAL STUDY OF THE SHALLOW AND DEEP GROUNDWATER IN THE AZRAQ BASIN, JORDAN

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Abstract

Since the country depends mostly on ground water resources especially for domestic water supply, investigation, development and management of the limited water resources takes importance and priority on governmental level as well as for the decision makers in the water Authority of Jordan. Azraq basin took importance in the whole water policy of the country, since the ground water abstraction for different water uses influances the natural environment of the Azraq Oasis. One of the aims of the study is to define the origin and source of recharge of AWSA water supply well field and the interrelationship between the Azraq depression and the situation in northern Azraq basin. Also quantitative and qualitative identification of the interrelationship between the upper and the deep aquifers becomes necessary. Many springs and wells in the Azraq area have been sampled for isotope analyses during the past 30 years by independent projects. The isotope analyses for the present project have been carried out by the Isotope Laboratory of the Water Authority of Jordan. This is existed within the frame work of the IAEA Regional Technical Cooperation Project entitled "Isotope Hydrology in the Middle East". Some hydrological and hydrogeological data from the Water Resources Studies Department of the Water Authority of Jordan have been used in the interpretation and evaluation. The overall evaluation of the environmental isotope data for both upper and deep aquifer systems in Azraq basin is presented in this study.

1. INTRODUCTION

Azraq Oasis is located about 85 km east-southeast of Amman. The total area of the basin covers approximately 12,710 km^2. About 94 % of it belongs to Jordan, 6 % to Syria.

The Azraq drainage basin (Figure 1) is irregular in shape and forms morphological depression with Sabkah (Qa'a Azraq) in its center which is bordered by the Azraq springs with an average discharge of about 10.6 million m3/year before 1981.

Two groups of spring exist at the border of the Azraq Sabkah, the Drouze springs (north of Azraq) and the Shishan springs (south of Azraq). They are 4 km distant from one another and several kilometers distant to the Sabkah forming the discharge area for all ground waters. Under undisturbed conditions the discharge of these springs (10.6 million m3/year) was considered in equilibrium with the actual water balance. Thus also the interface between fresh and saline waters in the deep underground has been established in a steady-state system. Therefore this ground water resource has been explored and is widely used today.

In 1981 the Water Authority of Jordan completed the drilling of 15 wells (AWSA wells), 3 to 8 km north of the Drouze springs, for drinking water supply of Amman. In addition many dug wells have been drilled for farming. At present about 40 million m3/year (1.3 m3/s) of ground water is abstracted from Azraq area; as a consequence the discharge of the springs around Azraq have seriously been affected.

Drouze springs completely dried in 1986 and the discharge of the Shishan springs reduced to about 20 % of the original. Under these conditions there was need:

- for a precise estimate of the amount of the actual recharge.
- to establish and verify former hydrodynamic conditions in steady state conditions and
- to study dynamics of the salt/fresh water interface in the underground due to increased withdrawal and predict its future behavior.

To answer these questions an isotope study together with hydrodynamic and hydrochemical studies was initiated. Results of these investigations will be presented in this report.

2. MORPHOLOGY, GEOLOGY AND CLIMATE

The entire Azraq basin is dissected by a dense network of wadis that acted during Pleistocene as permanent discharge system and serves today as dicharge systems for the scarce wadi floods.

The temperature regime in the study area is typical for arid to semi-arid zones. The precipitation ranges from 50 mm/a in the Azraq Oasis to 500 mm/a in the Jebel Arab. For the entire basin an average precipitation of 87 mm/a has been calculated. Most of it occurs as storms within January through March.

The Azraq Sabkah is actually fed by the very erratic muddy flood flows produced by storm events and also fed by natural ground water discharges represented mainly by the two Azraq springs.

The soils in the center of the Azraq basin are mostly saline due to evaporation processes at those actual land surfaces being in close contact to the ground water table.

At the surface of the Azraq basin the north-eastern half is dominated by basalts of Miocene/Oligocene age (Figure 2). The basalts reach a thickness of more than 1,500 m in the area of Jebel Arab. The landscape south of the basalt outcrop is dominated by Paleocene and Eocene limestones, chalks and chalky limestones of the B4 formation (Figure 2) that is covered in the center of the Azraq basin by Quaternary sediments.

The B4 formation is underlain by the Muwaqqar formation (B3) of Maastrichtian age; it consists of marls and marly limestones with some evaporites and is considered as aquitard. It is followed by the B2/A7 formation of Campanian and Turonian age that consists mainly of cherts and limestones. This formation outcrops mostly at the western border of the catchment area.

The basalts cover a pre-existing land surface. Depending on topography and tectonics they may therefore be in contact with the B4 and B2/A7 aquifers and recharge it directly.

The upper aquifers (B4, basalts and the quaternary deposits in the center of the Azraq basin) represent the main discharge system in the study area. It is unconfined and discharges almost radial to the Azraq Oasis (Figure 6). Depth to the ground water table ranges from a few meters in the center of the Oasis to about 400 m in the northern catchment area.

The deep B2/A7 aquifer is confined aquifer in most parts of the study area starting from the center of the basin. It becomes unconfined aquifer mainly in the western and southwestern edge of Azraq catchment. Depth to the bottom of the confining layer (B3) range from 260 m in NDW6 well to 720 m in NDW1 where, depth to static water level range from 34 m in NDW7 well to 236 m in NDW10.

3. TOOLS OF INVESTIGATION

Hydrological and Hydrogeological information as well as ground water monitoring data are available. They have been used and considered as main input to clarify the upper B4 and deep (B2/A7) ground water systems.

Long term environmental isotope data for the upper aquifer have been gathered from the previous researches of Azraq basin.

Actual precipitation have been sampled from 10 different stations (Figure 1) for chemical as well as isotope analyses.

Concerning this study,the upper aquifer has been sampled for stable isotope and Tritium for several sampling campaigns since 1988 until 1994. The sampling from the upper aquifer mainly concentrated on the wells located in the upper Azraq basin (Northern Azraq basin) and AWSA well field. The isotope sampling from the deep (B2/A7) aquifer has been existed during the pumping tests of NDW investigation wells in 1993,it includes stable isotopes (O-18 and Deuterium) and radioactive isotopes (Tritium and C-14). This is existed within the framework of the technical cooperation project with the IAEA entitled " Isotope Hydrology in the middle east".

For long-term information chemical components as well as radioactive and stable environmental isotopes are used as tracers in the ground water. The distinction between both tracers is due to the fact that environmental isotopes behave predominantly non reactive in the underground as compared to most of the chemical components that often undergo changes in concentrations due to physical and chemical reactions.

4. RESULTS

4.1 Isotopic composition of rains

Monthly precipitation have been sampled from October 1987 to March 1993. This time span is sufficient in an arid to semi-arid climate to get representative values.

In precipitation pH overpasses 7 and Total Dissolved Solids is high . Obviously neutralization of acids in the atmosphere (CO_2 and man made acids) already takes place in the atmosphere among buffering particles and protons. These reactions increase the TDS.

The weighted means of H-2 and O-18 in precipitation follow as expected the East Mediterranean Water Line (Figure 7)

$$^{2}H = 8\,{}^{18}O + 22$$

Available data on stable isotopes in precipitation prove a good relation to the altitude of the precipitation station (Figures 8 and 9). The slope of the regression line results in a decrease of 0.26 ‰ of O-18 and 1.3 ‰ of H-2,respectively, with an increase of 100 m in altitude. These values are known in the same order of magnitude all over the world and will allow to judge the role of Jebel Arab as compared to the flat desert area of Jordan for the ground water recharge.

4.2 Groundwater flow

Ground water contour maps have been drawn for both the upper (shallow) and deep aquifers (Figures 4 and 5). They prove that the shallow as well as the deep ground waters discharge almost radially to the

Azraq springs and sabkah. Obviously this area is to some extend important for regional ground water flow.

The slope of the water tables in figures 3 , 4 represents only a trend because it results from measurements of ground water tables in wells of different depth in a discharge area.

The regression line of depth-temperature of the deep (B2/A7) aquifer (Figure 10), refers that the geothermal gradient of the deep ground water system is 0.035 with the following equation:

$$T = (0.035 \pm 0.006)\, D + (16.7 \pm 5.49) \quad n=12 \text{ and } r2 = 0.74 \text{ where,}$$

T is the temperature and D is the total depth of the well. Actually this figure is in agreement with the normal geothermal gradient well known all over the world.

4.3 Chlorides in ground waters of the study area

In the shallow ground waters chlorides average at 1.3 meq/l with few exceptions to higher or lower concentrations. Assuming a chloride concentration of 1.5 mg/l in precipitation with considering the average chloride content in the shallow ground water allows probably, to estimate the recharge as far as no other chloride source exists except the atmospheric one. From

$$c_P\, P = c_R\, R$$

with c_P = chloride concentration in precipitation (P) and
c_R = chloride concentration in recharge (R)

a 3.3 % or 2.8 mm/a recharge from average precipitation (87 mm/a) in the study area is deduced. With respect to the area of the catchment it results an actually sustained recharge of 1.1 m^3/s or 35.6 million m3/year. These values are in very close agreement with recent considerations of WAJ (Water Authority of Jordan) and meteorological water balances for the same area of 12,700 km2.

The ground water abstraction from this area amounts to 40 million m3/year, thus actually exceeding the available recharge and causing a general drawdown of hydraulic heads in the area. This actual drawdown is desirable inorder to create a regional pumping depression that avoids losses of ground waters through discharges of springs and evaporation from soils. On a long-term, however, man made discharge should be reduced, in order to avoid permanent ground water mining. To which extend it should be reduced is still in question and will primarily depend on ground water quality aims.(see chapter 4.4.)

With respect to the 10.6 million m3/year of spring discharges before ground water abstraction was initiated it gets obvious that the discharge system was and still is under non-steady state (transient) conditions. This is very common for wide basins in arid, semiarid and even humid zones. These transient conditions are also of importance for the movement of the salt/fresh water interface.

4.4 Chloride and Deuterium in ground waters

Considering chloride and H-2 concentrations in ground waters out of deep wells (Figure 18) it is obvious that increasing chloride concentrations are closely correlated to decreasing H-2 concentrations. Due to the general geometry of ground water flow field a decrease of O-18 with depth was expected supposing a homogeneous flow field.

The change of chlorides with depth, however, seems not to be very clearly correlated (Figure 17). As can be seen, some wells (9, 10, 11, 12 and 2) deviate from a linear increase of chlorides with depth.

These wells occur geographically along a line stretching from the south to the north (Figure 6). Along this line it is assumed that saline ground waters intrude preferentially into the deep aquifer. The interface salt/fresh water therefore is up- and downwelming in the study area. As a rule the interface is sharp and occurs at about 1000 m below floor.

A confirmation for such local intrusions of ground waters into the deep aquifer is deduced from the following observations. In most of the deep wells pumping tests have been executed and in many wells sampling was done at different times during the pumping tests. These results indicate that all wells with unusual high chloride concentrations decrease in chlorides (e.g. as in NDW7 well from 2468 meq/l Cl to 250 meq/l Cl), because they are situated upon a salt water intrusion zone with low yield and therefore fresh waters substitute salt waters. In some zones away from salt water intrusions chloride concentrations.

- keep either constant as far as the well is situated far away from intrusion zones or
- the waters from wells increase slightly in chloride concentrations as far as it is situated in the vicinity of a salt water intrusion zone.

The highest chloride concentration known up till now in this area reaches 86 g/l ;it is correlated to an equivalent sodium concentration and is more enriched than ocean waters. (Figure 11) is the concentration composition diagram of the brine water in the well of NDW.7 located in the center of Azraq basin. This indicates either connate waters or diagenetic processes that enriched waters in NaCl. The possible origin of these waters will be discussed in chapter 4.5.

4.5 Deuterium and O-18 in groundwaters

The existing study refers that the distribution of O-18 versus Deuterium of the northern Azraq basin ground water (upper aquifer) fall on the local meteoric water line with an average deuterium excess of 20.4‰ (Figure 13). This indicates that no significant evaporation occurred before or during infiltration suggesting fast infiltration through fractured lavas.

Concerning the AWSA well field (upper aquifer) the plot of O-18 versus Deuterium and the regression lines of EMWL and GMWL (Figure 14) indicates that samples fall on the Local meteoric water Line with Deuterium excess parameter ranging from 18-20.3 ‰ as an average of 19 ‰.

Ground waters from the shallow aquifer group in their H-2 and O-18 concentrations closer to the East Mediterranean Water Line (EMWL) with deuterium excess around 18 ‰ as well as along an evaporation line. Evaporated waters out of dug wells belong either to ground waters near to the surface or to waters out of ponds (Figure 15).

Determination of the stable isotope composition of the ground water provides an indication for the mean elevation at which this water was recharged. The mean stable isotopic composition of the ground water of AWSA well field and northern Azraq basin is -6.4 ‰ for O-18 and -31.3 ‰ for deuterium. This indicates that ground water has a mean recharge altitude of around 950m.

Generally speaking the mean O-18 concentration in shallow ground waters of the study area amounts to -6 ‰. With respect to figure 5 this corresponds to a mean recharge altitude of 800 m a.s.l. which represents roughly the weighted mean altitude of whole the Azraq basin. This result suggests that ground water recharge takes place all over the research area and not preferentially in the Jebel Arab.

Deep ground water group (Figure 16) also along the EMWL with deuterium excess ranging between 18-22 ‰. The scattering of samples to more enriched stable isotope concentrations, however, can not be attributed to evaporation. It may be caused by mixture of deep ground waters with

- oil brine waters
- connate waters
- paleowaters.

At the actual stage of study connate waters with a stable isotope concentration close to ocean waters can be excluded (Figure 16). A mixture with paleowaters seems to be unprobable because its stable isotope concentrations should be lower than actual. Oil brine waters can therefore not be excluded. Near to the Azraq basin some small oil fields are known. Due to the formation of the Jordan graben the hydrodynamic system, especially hydraulic heads have been lowered. This may have led also to the migration of hydrocarbon resources and its surrounding brine waters that not yet stopped in the existing transient flow system. For a better prove of this idea the determination of sulphur and methane in the respective wells is suggested.

4.6 Radioactive environmental isotopes

Tritium has been measured once in several shallow wells. It amounts in shallow ground water mostly non detectable concentrations. Only in ground waters of some dug wells near Wadis Tritium from actual ground water recharge may reach 6 to 23 TU. All these data, however, represent only local information on mean residence times and therefore have not be evaluated in detail. The water in the springs is not tritiated except Druze springs where two values of 2 and 5 T.U have been recorded.

Figure 12 shows the time dependent distribution of the stable and radioactive isotopes content in Aura spring (Druze). It shows that there is enrichment of the stable isotopes during flood storm events which refers that there is contribution of the evaporative floods to the spring waters.

Carbon-14 data from some shallow ground waters in the area of research amount to 3.7 to 80 pmc. No detectable concentrations have not been reported. It must be noticed that repeated sampling in e.g. well AZ 8 showed variations of C-14 from 9.3 pmc in Dec/1979 to 15.9 pmc in Oct/1985 and in well ABU GHALYON from 31.6 pmc in Sep/1980 to 42.1 pmc in May/1983; in both stations tritium concentrations are below detection limit. From this examples it seems to early to translate C-14 concentrations into ground water ages. because possible mixing of individual components or some analytical errors can not be excluded. It is however for sure that old ground waters dominate. In deep ground waters of the study area no tritium and no C-14 is detectable. These ground waters overpass ages of 30,000 years.

5. CONCLUSIONS AND RECOMMENDATIONS

The ground water in the upper Azraq basin and AWSA well field is very old, where the stable isotopic composition of this aquifer lies on the eastern mediterranean water line [EMWL] so, abstraction of large amount of water from the aquifer system leads to a gradual decline of the water table on the long run, this will cause a negative effect on the ground water availability in Azraq depression.

There is salt/fresh water interface and local intrusion zones of ground water into the deep aquifer. This is situated mainly in the center and in the area close to Azraq depression.

Concerning of the deep (B2/A7) aquifer of the study area, the ground waters overpass ages of 30.000 years. The possible origin of these waters have been discussed in the data evaluation.

Since no tritium and no C-14 is detectable in the deep (B2/A7) aquifer,the chloride-36 method should be applied for research purposes.
Inorder to study the influence of future exploitation of the deep (B2/A7) aquifer, preparation of water quality models of the shallow and deep aquifers are necessary.

Text cont. on p. 101.

TABLE 1. ISOTOPIC AND CHEMICAL COMPOSITION OF AWSA WELL FIELD AND NORTHERN AZRAQ, JORDAN

WELL NO.	NAME	SAMPLING DATE	OXYGEN-18 (o/oo) ± 0.2	DEUTERIUM (o/oo) ± 1.0	D-EXCESS (o/oo)	TRITIUM (T.U.) ± 1.0	E.C. [µS/cm]	pH	Ca++ [meq/l]	Mg++ [meq/l]	Na+ [meq/l]	K+ [meq/l]	Cl- [meq/l]	SO4= [meq/l]	CO3= [meq/l]	HCO3- [meq/l]	NO3- [meq/l]	SIO2 [meq/l]
1	Sabha well	JAN/87	-6.25	---	----	3.0												
1	Sabha well	APR/87	-5.90	---	----	< 1												
1	Sabha well	MAY/90	-6.24	-28.7	21.2	----	410	7.28	0.72	0.76	2.40	0.14	1.23	0.29	0.00	2.14	0.23	0.75
2	Hamada Fawaz	MAY/90	-6.39	-29.4	21.7	< 1	390	8.26	0.62	0.61	2.40	0.16	1.19	0.18	0.00	2.06	0.19	0.68
3	Arab Khazar		-6.31	-30.8	19.7	----												
4	Affash Kataan	MAY/90	-6.28	-29.3	20.9	< 1	420	8.17	0.72	0.61	2.60	0.21	1.37	0.37	0.00	2.01	0.21	0.70
5	Aref Ghasab	MAY/90	-5.73	-28.1	17.7	----	510	8.26	0.68	0.84	3.50	0.17	0.77	0.64	0.00	2.14	0.28	0.66
6	Ghasi Hamad	MAY/90	-6.17	-29.1	20.3	< 1	360	8.25	0.63	1.10	1.60	0.16	0.85	0.20	0.00	2.14	0.16	0.68
7A	Mukefteh1 *	JUL/90	-6.16	-28.5	20.8	< 1												
7A	Mukefteh1 *	JUL/90	-6.30	-29.5	20.9	< 1												
7B	Mukefteh2 *	MAR/92	-6.20															
7B	Mukefteh2 *	MAR/92	-6.24															
7A/B	Mukefteh1,2	JAN/93	-6.14			< 1	380	8.03	0.68	1.10	1.68	0.14	0.96	0.35	0.00	2.05	0.17	
7A/B	Mukefteh1,2	FEB/93	-6.33															
8	Km. 101	APR/90	-6.48	-29.3	22.5	----	390	8.42	0.45	0.74			1.06	0.26	0.10	2.12	0.17	
9	Km. 104	APR/89	-6.32	-30.7	19.9	< 1	380	8.33	0.41	1.12			1.02	0.36	0.05	2.07	0.17	
10	Km. 106	APR/89	-6.26	-30.1	20.0	< 1	370	8.30	0.41	1.14			1.09	0.39	0.05	1.99	0.17	
10	Km. 106	APR/90	-6.18	-29.9	19.5	< 1	370	8.11	0.57	1.07	2.10	0.13	1.12	0.47	0.00	2.00	0.18	
11	Km. 109	JUN/90	-6.26	-30.1	20.0	< 1	360	8.40	1.00	1.00	1.50	0.20	1.00	0.00	0.00	2.00	0.14	
11	Km. 109	MAR/92	-6.21			< 1												
12	Km. 111	FEB/89	-6.45	-30.6	21.0	< 1												
12	Km. 111	APR/90	-6.23	-29.4	20.4	< 1	350	8.12	0.66	1.06	1.70	0.13	1.07	0.41	0.00	1.84	0.17	
12	Km. 111	MAR/91	-5.95	-29.8	17.8	< 1												
12	Km. 111 **	MAR/92	-6.28			< 1	380	8.24	0.71	1.10	1.73	0.14	1.11	0.52	0.00	1.99	0.18	
12	Km. 111 **	JAN/93	-6.42			< 1	370	8.16	0.80	0.80	1.70	0.14	1.12	0.45	0.00	1.71	0.20	
13	Km. 112	APR/89	-6.56	-30.4	22.1	< 1	330	8.31	0.45	1.04			0.82	0.32	0.05	1.89	0.17	
13	Km. 112	APR/90	-6.18	-29.9	19.5	< 1	340	8.11	0.70	0.86	1.60	0.13	0.92	0.72	0.00	1.80	0.19	
13	Km. 112	MAR/91	-6.38	-30.7	20.3	< 1												
14	Km. 114	APR/89	-6.56	-30.4	22.1	< 1	310	8.67	0.45	0.72			0.92	0.39	0.15	1.50	0.04	
14	Km. 114	APR/90	-6.23	-30.4	19.4	< 1	380	8.10	0.70	1.15	1.90	0.14	1.27	0.55	0.00	1.68	0.21	
14	Km. 114	MAR/91	-6.16	-30.3	19.0	< 1												
15	Km. 124	APR/90	-6.88	-32.6	22.4	< 1	290	8.23	0.51	0.58	1.70	0.10	0.84	0.25	0.00	1.50	0.15	
15	Km. 124	MAR/92	-6.67			< 1	300	8.38	0.61	0.40	1.61	0.09	0.75	0.40	0.29	1.40	0.13	
15	Km. 124	JAN/93	-6.82			< 1	290	8.31	0.51	0.60	1.72	0.10	0.88	0.35	0.12	1.50	0.13	
16	Km. 134	FEB/89	-6.39	-31.9	19.2	< 1												

TABLE 1 (cont.)

WELL NO.	NAME	SAMPLING DATE	OXYGEN-18 (o/oo) ± 0.2	DEUTERIUM (o/oo) ± 1.0	D-EXCESS (o/oo)	TRITIUM (T.U.) ± 1.0	E.C. [µS/cm]	pH	Ca++ [meq/l]	Mg++ [meq/l]	Na+ [meq/l]	K+ [meq/l]	Cl- [meq/l]	SO4= [meq/l]	CO3= [meq/l]	HCO3- [meq/l]	NO3- [meq/l]	SIO2 [meq/l]
16	Km. 134	APR/90	-6.31	-32.0	18.5	1.6	500	8.20	0.76	0.59	3.40	0.12	1.90	0.92	0.00	1.75	0.19	
16	Km. 134	MAR/91	-6.27	-30.9	19.3	< 1												
16	Km. 134	MAR/92	-6.28			< 1	540	8.33	0.71	0.60	3.27	0.17	1.96	1.01	0.15	1.57	0.19	
16	Km. 134	JAN/93	-6.57			< 1												
16	Km. 134	JAN/93	-6.25			< 1	560	8.14	0.70	0.60	3.64	0.16	2.14	1.24	0.00	1.71	0.19	
16	Km. 134	FEB/93	-6.40															
16A	Km. 136	MAR/92	-6.27			< 1	450	8.42	0.40	0.30	3.10	0.14	1.21	0.90	0.15	1.68		
16A	Km. 136	JAN/93	-6.56			< 1												
16A	Km. 136	JAN/93	-6.45			< 1	430	8.30	0.37	0.40	3.26	0.13	1.31	0.96	0.12	1.66	0.17	
16A	KM. 136	JAN/93	-6.35															
16A	Km. 136	FEB/93	-6.54															
17	DE 3		---	---	----	----	480	8.49	0.56	0.41	3.60	0.11	1.45	1.20	0.15	1.80	0.20	
18	AWSA - 1	MAR/89	-6.55	-35.5	16.9	< 1	510	7.93	0.79	0.97			1.98	0.87	0.00	1.96	0.08	
18	AWSA - 1	NOV/89	-6.44	-36.0	15.5	----	640	8.15	0.89	0.73			2.18	0.59	0.00	1.99	0.08	
18	AWSA - 1	APR/90	-6.23	-32.4	17.4	----	540	8.05	0.86	0.90	3.40	0.10	2.23	0.75	0.00	2.05	0.08	0.47
18	AWSA - 1	MAY/91	-6.70	-31.7	21.9	< 1												
18	AWSA - 1	OCT/92	-6.33				650	8.08	0.95	0.90	3.76	0.16	3.02	0.71	0.00	2.13	0.08	
19	AWSA - 2	JAN/87	-6.27	---	----	1.4												
19	AWSA - 2	MAY/87	-6.49	---	----	< 1												
19	AWSA - 2	NOV/89	-6.45	-35.0	16.6	----	530	8.24	0.70	0.97	3.50	0.12	2.02	1.02	0.00	2.11	0.08	
19	AWSA - 2	APR/90	-6.33	-32.2	18.4	----	540	8.08	0.77	0.74	3.60	0.11	2.05	0.84	0.00	2.12	0.07	0.48
19	AWSA - 2	MAY/91	-6.57	-32.5	20.1	< 1												
19	AWSA - 2	OCT/92	-6.45				580	8.14	0.85	0.70	3.68	0.15	2.40	0.69	0.00	2.12	0.09	
20	AWSA - 3	MAR/89	-6.46	-34.0	17.7	< 1	580	8.00	0.79	1.04			2.51	1.04	0.00	2.02	0.08	
20	AWSA - 3	NOV/89	-6.44	-35.0	16.5	----												
20	AWSA - 3	APR/90	-6.44	-32.0	19.5	----												
20	AWSA - 3	MAY/91	-6.44	-31.5	20.0	< 1												
20	AWSA - 3	OCT/92	-6.54				660	8.06	1.00	0.90	3.97	0.16	3.03	1.00	0.00	1.99	0.11	
21	AWSA - 4	APR/90	-6.44	-32.3	19.2	< 1	510	8.03	0.88	0.71	3.20	0.11	1.83	0.84	0.00	2.02	0.08	0.48
21	AWSA - 4	OCT/92	-6.44				480	8.06	0.79	0.70	2.86	0.13	1.73	0.61	0.00	2.07	0.08	
23	AWSA - 6	NOV/89	-6.52	-34.2	18.0	----	400	8.20	0.77	0.63			1.28	0.35	0.00	2.01	0.06	
23	AWSA - 6	APR/90	-6.63	-32.2	20.8	< 1	400	8.06	0.86	0.61	2.50	0.15	1.21	0.63	0.00	2.08	0.06	0.46
23	AWSA - 6	MAY/91	-6.64	-33.1	20.0	< 1												
23	AWSA - 6	OCT/92	-6.57				400	8.03	1.00	0.50	2.21	0.10	1.20	0.50	0.00	2.10	0.07	
24	AWSA - 7	APR/90	-6.51	-32.3	19.8	----	560	8.18	0.65	0.66	3.80	0.16	1.98	1.00	0.00	2.08	0.12	0.52

TABLE 1 (cont.)

WELL NO.	NAME	SAMPLING DATE	OXYGEN-18 (o/oo) ± 0.2	DEUTERIUM (o/oo) ± 1.0	D-EXCESS (o/oo)	TRITIUM (T.U.) ± 1.0	E.C. [µS/cm]	pH	Ca++ [meq/l]	Mg++ [meq/l]	Na+ [meq/l]	K+ [meq/l]	Cl- [meq/l]	SO4= [meq/l]	CO3= [meq/l]	HCO3- [meq/l]	NO3- [meq/l]	SIO2 [meq/l]
24	AWSA - 7	MAY/91	-6.40	-31.3	19.9	< 1												
24	AWSA - 7	OCT/92	-6.46				540	8.15	0.65	0.60	3.74	0.14	1.97	0.91	0.00	2.12	0.13	
25	AWSA - 8	MAR/89	-6.41	-31.9	19.4	< 1	490	8.00	0.62	0.83			1.77	0.91	0.00	1.73	0.17	
25	AWSA - 8	NOV/89	-6.32	-34.1	16.5	----	530	8.35	0.65	0.85			1.95	0.75	0.12	1.76	0.26	
25	AWSA - 8	APR/90	-6.28	-31.5	18.7	----	510	8.17	0.63	0.82	3.40	0.16	1.86	0.89	0.00	1.88	0.20	0.49
25	AWSA - 8	MAY/91	-6.41	-30.6	20.7	< 1												
25	AWSA - 8	OCT/92	-6.24				500	8.19	0.59	0.80	3.04	0.12	1.82	0.72	0.00	1.85	0.20	
26	AWSA - 9	APR/90	-6.45	-32.9	18.7	< 1	890	8.00	1.12	0.84	6.20	0.22	4.32	1.62	0.00	2.20	0.06	0.51
27	AWSA - 10	APR/90	-6.48	-32.5	19.3	< 1	640	8.09	0.79	0.80	4.50	0.17	2.63	1.23	0.00	2.16	0.07	0.49
27	AWSA - 10	MAY/91	-6.59	-32.9	19.8	< 1												
27	AWSA - 10	OCT/92	-6.49				670	8.00	0.87	0.60	4.33	0.16	2.85	1.00	0.00	2.12	0.08	
28	AWSA - 11	MAY/87	---	---	----	< 1												
28	AWSA - 11	MAR/88	-6.36	-32.5	18.3	< 1												
28	AWSA - 11	MAR/89	-6.27	-32.6	17.6	1.1	670	8.05	0.85	1.08			2.91	1.24	0.00	1.94	0.15	
28	AWSA - 11	NOV/89	-6.40	-33.9	17.3	----	620	8.15	0.81	0.82	4.10	0.13	2.45	1.12	0.00	2.05	0.15	
28	AWSA - 11	APR/90	-6.54	-31.7	20.6	< 1												
28	AWSA - 11	MAY/91	-6.11	-31.2	17.7	< 1												
28	AWSA - 11	OCT/92	-6.43				570	8.11	0.83	0.60	3.65	0.15	2.20	0.89	0.00	1.99	0.17	
29	AWSA - 12	APR/90	-6.30	-30.9	19.5	< 1	450	8.21	0.51	0.57	3.20	0.15	1.43	0.70	0.00	2.00	0.16	0.51
29	AWSA - 12	MAY/91	-6.09	-31.0	17.7	< 1												
29	AWSA - 12	OCT/92	-6.46				480	8.20	0.55	0.70	3.10	0.14	1.55	0.63	0.00	1.93	0.17	
30	AWSA - 13	JAN/87	-6.64	---	----	< 1												
30	AWSA - 13	MAY/87	-6.65	---	----	< 1												
30	AWSA - 13	MAR/88	-6.42	-33.6	17.8	< 1												
30	AWSA - 13	MAR/89	-6.62	-32.4	20.6	< 1	960	7.88	1.04	1.60			4.33	3.05	0.00	2.20	0.08	
30	AWSA - 13	APR/90	-6.70	-31.5	22.1	----	940	7.95	1.18	1.13	6.20	0.40	4.20	2.25	0.00	2.38	0.08	0.45
30	AWSA - 13	MAY/91	-6.55	-31.8	20.6	< 1												
30	AWSA - 13	OCT/92	-6.41				870	8.12	1.09	1.00	5.61	0.37	3.93	1.84	0.00	2.23	0.09	
32	AWSA - 15	MAR/89	-6.23	-31.0	18.8	< 1	470	7.90	0.47	0.63			1.63	0.70	0.00	1.89	0.19	
32	AWSA - 15	MAY/91	-6.08	-31.0	17.6	< 1												
32	AWSA - 15	OCT/92	-6.37				520	8.16	0.55	0.90	3.22	0.13	1.86	0.71	0.00	1.93	0.2	

* = samples from pumping test

** = samples from pumping station

TABLE 2. ISOTOPIC COMPOSITION OF THE SHALLOW GROUND WATER IN AZRAQ DEPRESSION, JORDAN

WELL NO.	NAME	SAMPLING DATE	OXYGEN-18 (o/oo)	DEUTERIUM (o/oo)	C-13 (o/oo)	C-14 (pmc)	TRITIUM (T.U.)	E.C. (µs/cm)
EASTERN AREA								
A	ASFOUR & NAHHAS	SEP/80	-4.7	-28.3	-9.3	3.7	0	1554
		MAY/83	-4.43	-30.8				
B	ABDEL-KARIM ERTAMAH 1	SEP/80	-4.15	-26.2			0	1579
	ABDEL-KARIM ERTAMAH	JUN/82	-4.3	-26.2	-7.3		0.3	
	ABDEL-KARIM ERTAMEH	MAY/83	-4.42	-29.4				
C	ABDEL-KARIM ERTAMAH 2	SEP/80	-4.35	-27.2			0.6	1794
D	NAYEF KHRASHA	SEP/80	-4.5	-28.7	-9.4	9.8	0	2253
		JUN/82	-4.65	-27.6	-10		0.3	
E	ABU-GHALYON	SEP/80	-3.3	-20	-6.3	31.6	0	2493
		MAY/83	-4.54	-22.9	-7	42.1	0.6	
F	Z-32	OCT/85	-4.65	-34.1	-7.2			
	Z-32	JUN/86	-4.47	-33.6	-8.3			
G	KIWAR WELL	SEP/80	-3.2	-25.4			0.1	884
G	BAZ KIWAR	MAY/83	-6	-34				
H	KHALIL EL-MOR	SEP/80	-5.7	-31.9			0.6	1955
I	NATHMAN SAMREIN	SEP/80	-5.5	-30.8			0.6	1182
	SURFACE PONDS	APR/90	2.6	25.4			12.4	
		APR/90	3.46	26.9				9500
MEDIAL AREA								
J	ADEL KONTAR	SEP/80	-5.6	-29.8	-8.3	80.1	1.6	2363
		JUN/82	-5.65	-28.6			2.4	
K	JAD HUSEIN	SEP/80	-6.08	-30.2	-9.7	41.5	1.1	1214
		APR/80	-6.32	-31.4	-10.8		0.5	
		MAY/83	-6.06	-33.7				
L	MOHAMMAD SALEH	SEP/80	-5.6	-28.3			18	746
		JUNE/82	-5.3	-24.6			22.5	
		MAY/83	-4.89	-27	-10			
M	MOSTAFA SAKET	SEP/80	-5.35	-31.5			0.5	1182
N	ELAYAN AKHO ALWA	SEP/80	-6	-32.8			0	1213
O	ALI MFADHI	SEP/80	-5.8	-31.5			0.8	1380
		JUN/82	-5.9	-29.7			1.5	
P	MOH,D RASOUL	SEP/80	-5.8	-31.7	-8.4	51.5	17.8	1982
		JUN/82	-5.8	-30.6	-9		8.9	
		MAR/88	-5.87	-31.78			7.7	
Q	FALAH ES-AYID	SEP/80	-6.1	-30.5			0	990
R	MAHMOUD LIDANI	SEP/80	-5.72	-30.1	-9.3	57.8	0	2069
		JUN/82	-5.53	-28.4			4.4	
S	AHMAD ABU-ESBA,A	JUN/82	-4.2	-23.5				
T	AZ-8	DEC/79	-6.27	-30.7	-12.5	9.3	0	
	AZ-8	OCT/85	-7.74	-32.2	-10.6	15.9		
	AZ-8	JUL/86	-5.71	-36.2	-9.7	14.2		
	AZ-8	MAR/88	-6.23	-32.29			0.5	
		APR/90	-6.2	-32.7			0.7	
U	AZ-11	MAY/83	-6.1	-30.9	-11			
SOUTH & SOUTHWEST AREA								
V	AHMAD SHAWKI	SEP/80	-5.75	-30.1			8	2704
		JUN/82	-5.85	-28.7			6.1	
		MAY/83	-5.83	-33.1				
W	ABDEL-RAHMAN	SEP/80	-3.88	-27.1			0.7	1152
		JUN/82	-6.13	-31.9			1.2	
		SEP/80	-6.8	-37.2	-8.6			
		JUN/82	-6.5	-35.2	-9.1			
		OCT/85	-6.39	-26.3	-6.7			
		JUN/86	-6.42	-42.5	-9			
X	AUMARI-2	MAY/83	-6.55	-37.2	-9			
X	SHOMARI	SEP/80	-6.54	-35.5	-7.3	14.1	0.3	2470
		JUN/82	-6.6	-34.3	-8.2	27.7	0.9	
		MAY/83	-6.45	-33.9	-8	10.8	1	
		JUN/87	-5.74	-34.56			0.3	
Y	ABU TOZIH	SEP/80	-6.56	-35.4			0.2	1864
Z	SOLAR ENERGY/UMARI	JUN/87	-6.31	-37.52				
Z1	WADI GHADAF	JUN/87	-6.12	-33.43				

TABLE 3. ISOTOPIC AND CHEMICAL COMPOSITION OF THE DEEP (B2/A7) AQUIFER, AZRAQ BASIN, JORDAN

NAME	SAMPLING DATE	OXYGEN-18 (o/oo) ± 0.2	DEUTERIUM (o/oo) ± 1.0	D-EXCESS (o/oo)	TRITIUM (T.U.) ± 1.0	E.C. [µS/cm]	pH	Ca++ [meq/l]	Mg++ [meq/l]	Na+ [meq/l]	K+ [meq/l]	Cl- [meq/l]	SO4= [meq/l]	CO3= [meq/l]	HCO3- [meq/l]	NO3- [meq/l]	TEMP C	TIME hours
NDW1	AUG/93	—	—	—	< 1	1011	7.78	2.54	1.70	5.04	0.62	3.90	1.40	0.00	4.63	0.13	62.00	
NDW1	SEP/93	—	—	—		1017	7.03	2.35	1.80	5.21	0.60	3.79	2.16	0.00	3.85	0.02		42.00
NDW1	SEP/93	-3.82	-27.30	3.26														0.25
NDW1	SEP/93	-4.85	-31.60	7.20														6.00
NDW1	SEP/93	-5.29	-33.60	8.72														27.00
NDW1	SEP/93	-5.31	-32.50	9.98														39.00
NDW1	SEP/93	-5.49	-33.40	10.52														54.00
NDW1	SEP/93	-5.37	-33.40	9.56														78.00
NDW1	SEP/93	-5.27	-33.40	8.76														96.00
NDW2	JUN/93	-7.08	-39.90	16.74	< 1												6.00	
NDW2	JUN/93	-7.22	-40.50	17.26													30.00	
NDW2	JUN/93	-7.30	-40.20	18.20		2800	6.96	8.16	6.40	13.65	0.25	16.69	5.97	0.00	5.64	0.01	32.00	49.00
NDW3	FEB/93	-6.35	-31.70	19.10	< 1	360	8.27	0.87	0.70	1.88	0.13	0.93	0.53	0.00	1.88	0.17	32.90	START
NDW3	FEB/93	-6.45	-31.80	19.80														
NDW3	FEB/93	-6.09	-31.00	17.72	< 1	330	8.09	0.69	0.60	1.87	0.11	0.93	0.42	0.00	1.82	0.14		33.00
NDW4	AUG/93	-5.68	-31.50	13.94	< 1	816	7.84	1.65	1.40	4.50	0.28	3.46	1.46	0.00	2.81	0.02	38.00	
NDW4	SEP/93	-5.65	-31.40	13.80														12.00
NDW4	SEP/93	-5.63	-31.10	13.94		814	7.71	1.65	1.30	4.40	0.30	3.45	1.43	0.00	2.85	0.05		13.00
NDW5	MAY/93	-5.50	-35.90	8.10	< 1												39.30	START
NDW5	MAY/93	-5.63	-35.60	9.44														48.00
NDW6	OCT/92					530	7.80	1.19	0.90	2.70	0.11	1.93	0.81	0.00	2.37	0.01	32.60	
NDW7						240000	7.24	49.12	156.90	2485.00	80.00	2468.00	288.00	0.00	2.32	0.14		
NDW7						213000	6.90	48.72	105.60	1688.00	52.00	1812.80	79.17	0.00	3.44	0.07		
NDW7	MAY/93	-6.31	-34.60	15.88														0.05
NDW7	MAY/93	-6.35	-34.70	16.10	< 1													1.00
NDW7	MAY/93	-6.17	-34.20	15.16														4.00
NDW7	MAY/93	-6.11	-34.40	14.48														8.00
NDW7	MAY/93	-6.29	-34.20	16.12		23500	6.93	13.65	16.00	217.50	8.00	228.50	22.91	0.00	5.63	0.09	45.00	15.00
NDW7	MAY/93	-6.79	-35.20	19.12		23800	6.99	16.58	16.60	221.50	8.00	230.00	25.35	0.00	5.74	0.08		16.00
NDW7	MAY/93	-6.22	-34.80	14.96		23400	7.02	11.46	18.10	222.00	8.00	229.50	21.40	0.00	5.26	0.06		24.00
NDW7	MAY/93	-6.07	-35.20	13.36		23500	7.05	11.32	17.90	225.00	8.00	231.70	21.20	0.00	5.45	0.05		32.00
NDW7	MAY/93	-5.39	-33.40	9.72		24400	7.06	11.86	18.30	236.50	8.00	234.50	23.40	0.00	5.55	0.07		38.00
NDW7	MAY/93	-6.10	-33.80	15.00		23400	7.06	11.80	20.40	251.50	8.50	259.30	23.04	0.00	5.53	0.05		48.00

TABLE 3 (cont.)

NAME	SAMPLING DATE	OXYGEN-18 (o/oo) ± 0.2	DEUTERIUM (o/oo) ± 1.0	D-EXCESS (o/oo)	TRITIUM (T.U.) ± 1.0	E.C. [µS/cm]	pH	Ca++ [meq/l]	Mg++ [meq/l]	Na+ [meq/l]	K+ [meq/l]	Cl- [meq/l]	SO4= [meq/l]	CO3= [meq/l]	HCO3- [meq/l]	NO3- [meq/l]	TEMP C	TIME hours
NDW7	MAY/93					24500	7.00	11.37	17.70	234.50	8.50	239.70	22.84	0.00	5.46	0.09		
NDW8	AUG/93	-6.55	-31.20	21.20	< 1													4.00
NDW8	AUG/93	-6.15	-31.30	17.90														20.00
NDW8	AUG/93	-5.98	-31.30	16.54		872	7.80	3.71	2.60	2.43	0.07	2.71	2.28	0.00	3.71	0.01	43.40	44.00
NDW8	AUG/93	-6.11	-32.30	16.58														72.00
NDW8	AUG/93	-5.85	-31.20	15.60														96.00
NDW9	JUL/93	-6.89	-35.00	20.12	< 1													21.00
NDW9	JUL/93	-6.95	-35.50	20.10		1891	6.85	7.04	4.70	7.60	0.25	9.18	5.00	0.00	5.21	0.05	59.00	43.00
NDW9	JUL/93	-7.31	-34.50	23.98														72.00
NDW9	JUL/93	-6.82	-35.20	19.36														96.00
NDW10	JUL/93	-6.93	-34.70	20.74	< 1	1916	6.82	6.64	4.40	7.90	0.20	8.43	5.95	0.00	4.58	0.01	49.50	1.00
NDW10	JUL/93	-6.75	-34.80	19.20														2.00
NDW10	JUL/93	-6.99	-34.80	21.12														4.00
NDW10	JUL/93	-6.83	-35.00	19.64														7.00
NDW10	JUL/93	-6.70	-34.60	19.00														6.00
NDW10	SEP/93	-6.81	-35.00	19.48		1880	7.26	6.46	4.30	7.77	0.27	8.60	5.73	0.00	4.37	0.01		24.00
NDW11	JUL/93	-7.52	-47.00	13.16	< 1	3380	6.84	13.61	10.50	14.40	0.80	12.54	21.45	0.00	5.20	0.02	38.00	14.00
NDW11	JUL/93	-8.23	-46.60	19.24														16.00
NDW11	JUL/93	-7.69	-46.40	15.12														24.00
NDW11	JUL/93	-7.54	-44.90	15.42		2630	6.88	12.32	10.48	13.25	0.70	12.29	17.96	0.00	5.97	0.01	38.50	48.00
NDW12	JUN/93	-6.82	-35.60	18.96	< 1												34.50	START
NDW12	JUN/93	-6.91	-36.60	18.68														14.00
NDW12	JUN/93	-6.88	-36.90	18.14		2510	6.15	8.56	5.80	10.43	0.23	12.76	6.79	0.00	5.13	0.18	35.10	24.00
NDW12	JUN/93	-6.84	-35.60	19.12														38.00
NDW12	JUN/93	-7.26	-36.70	21.38														40.00
NDW12	JUN/93	-7.11	-35.70	21.18														45.00
NDW-J	OCT/93	-7.05	-32.10	24.30	< 1													
NDW-J	OCT/93	-6.47	-32.50	19.26		857	7.15	4.44	2.50	1.82	0.04	2.16	0.56	0.00	6.20	0.01		

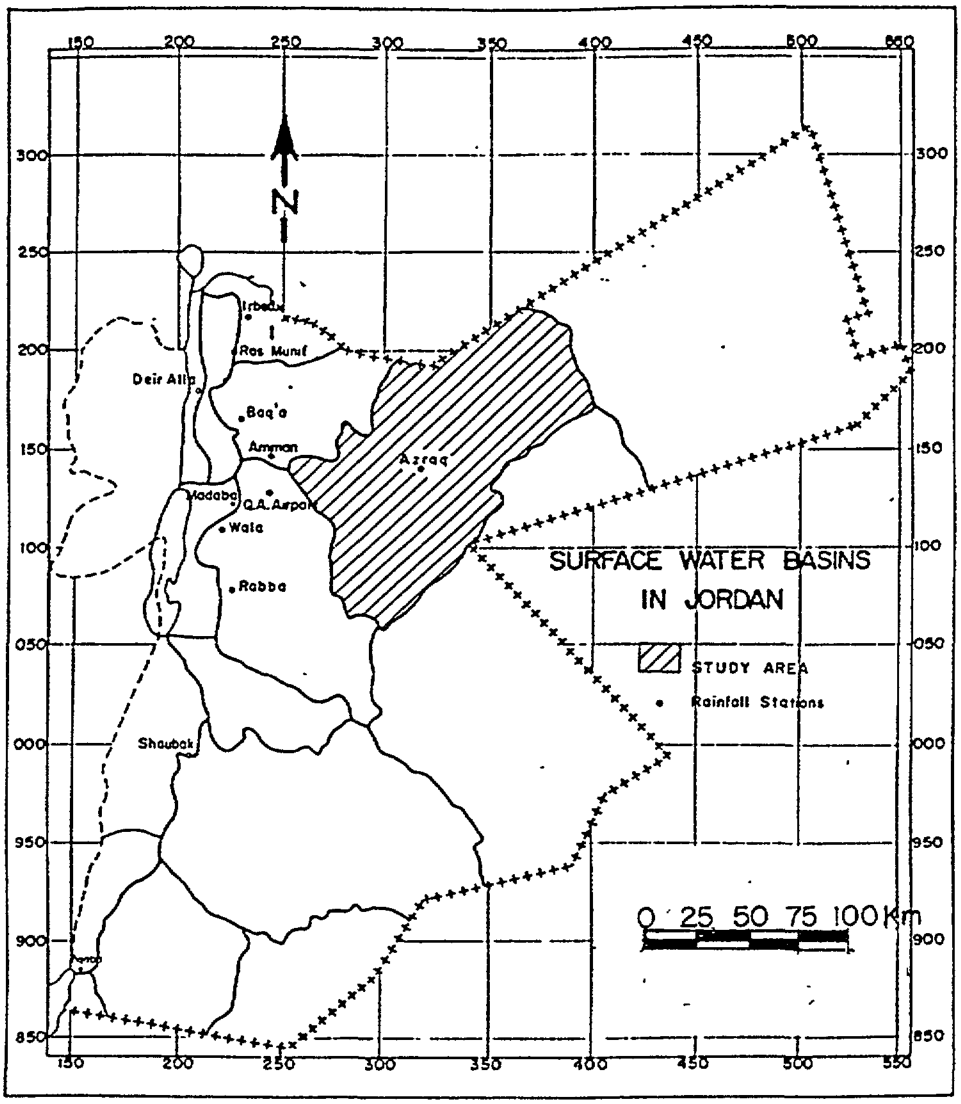

FIG. 1. Location map of the study area and the precipitation gauge stations.

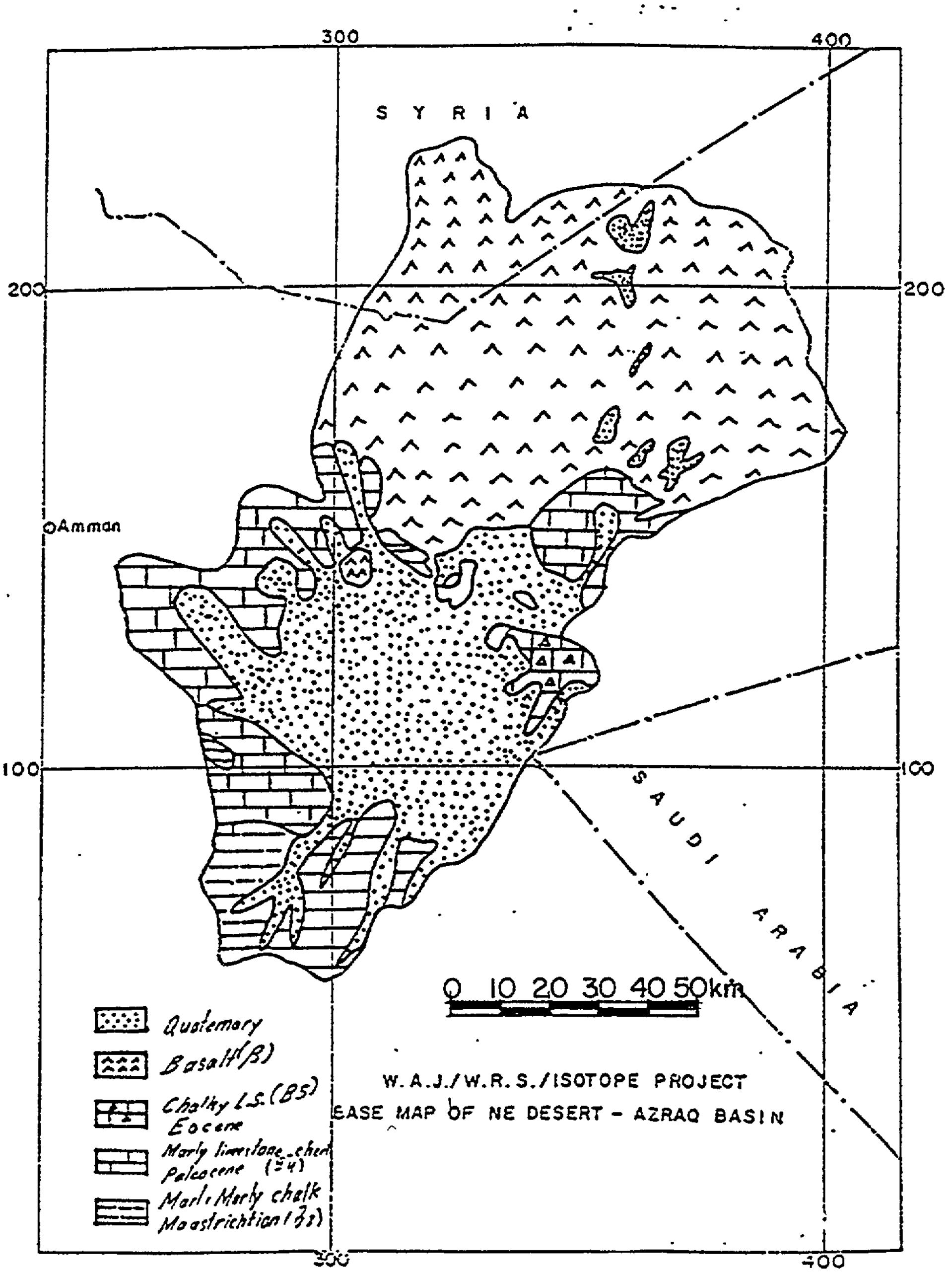

FIG. 2. Simplified geology of the drainage basin.

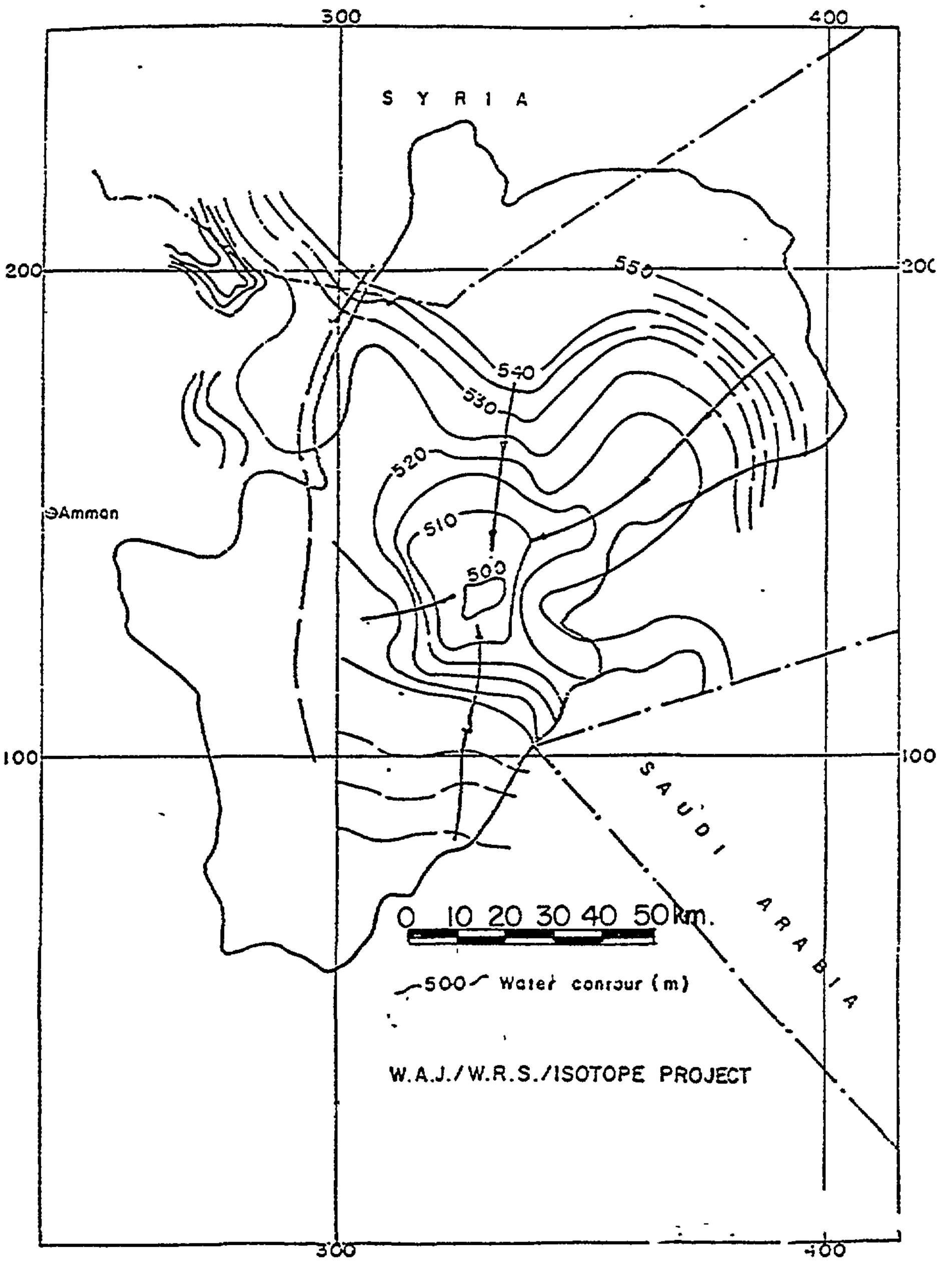

FIG. 3. Water table contour map for the upper aquifer (shallow aquifer).

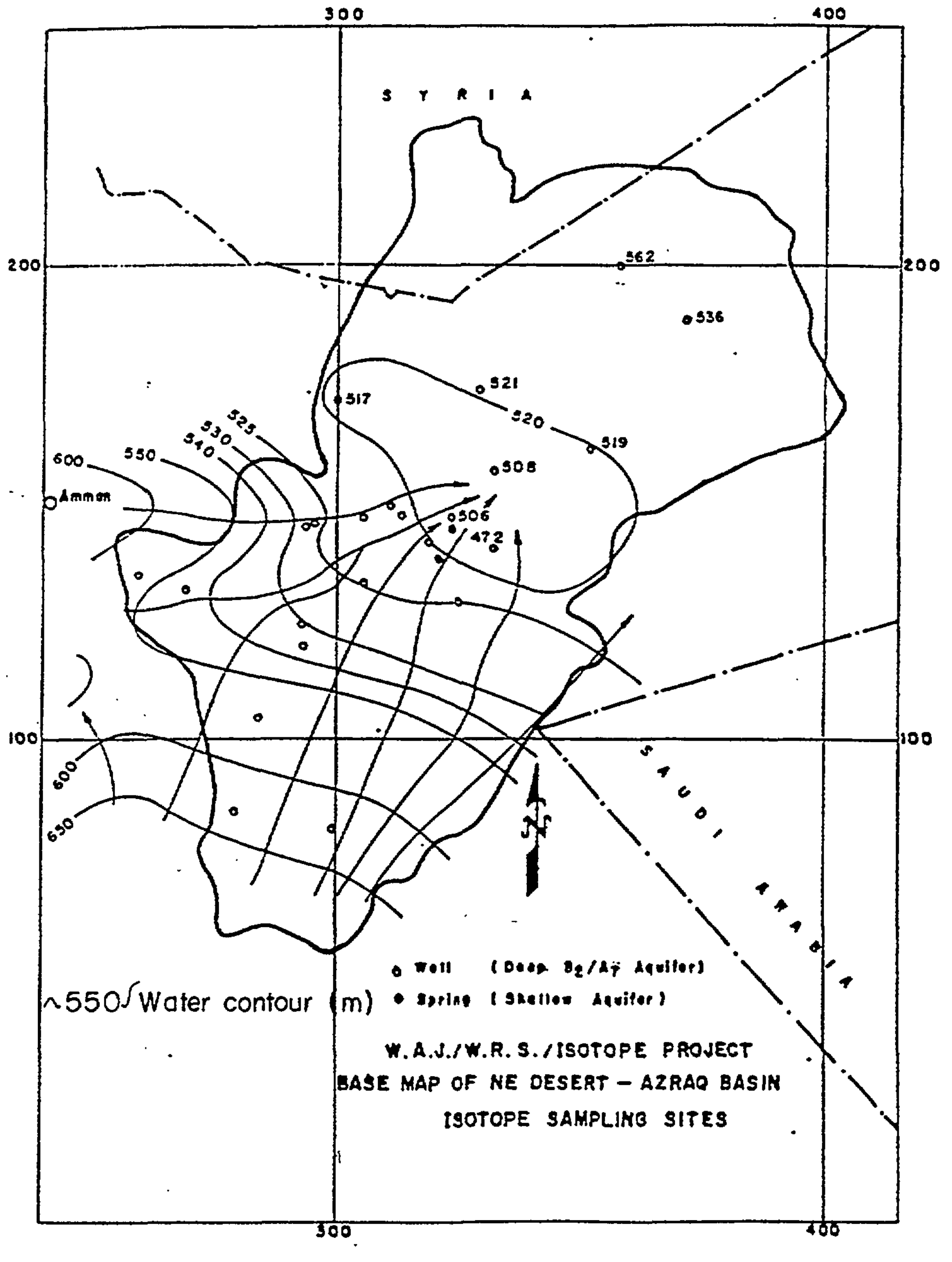

FIG. 4. Equipotential contour map for the deep (B2/A7) aquifer.

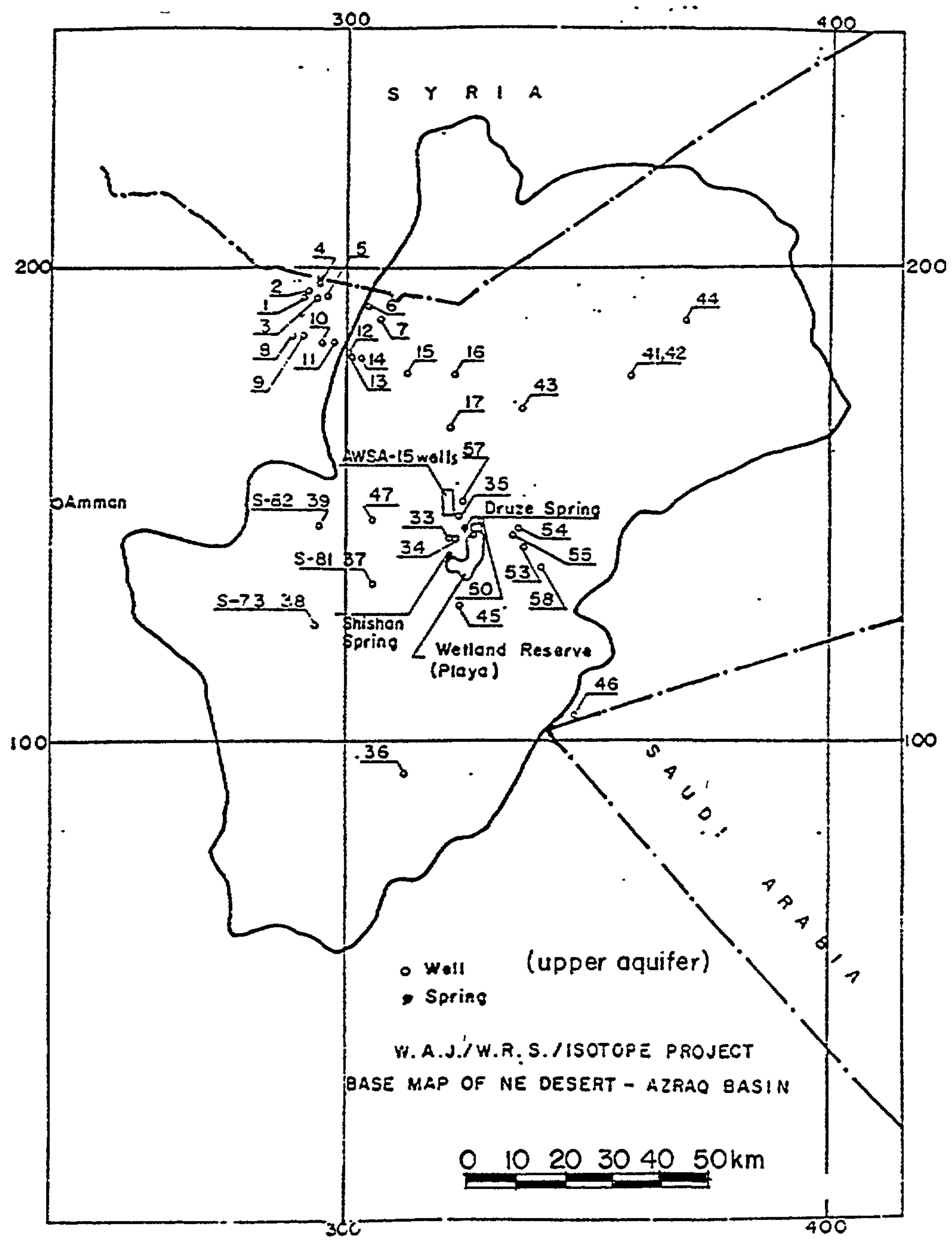

FIG. 5. Isotope sampling sites of the upper aquifer.

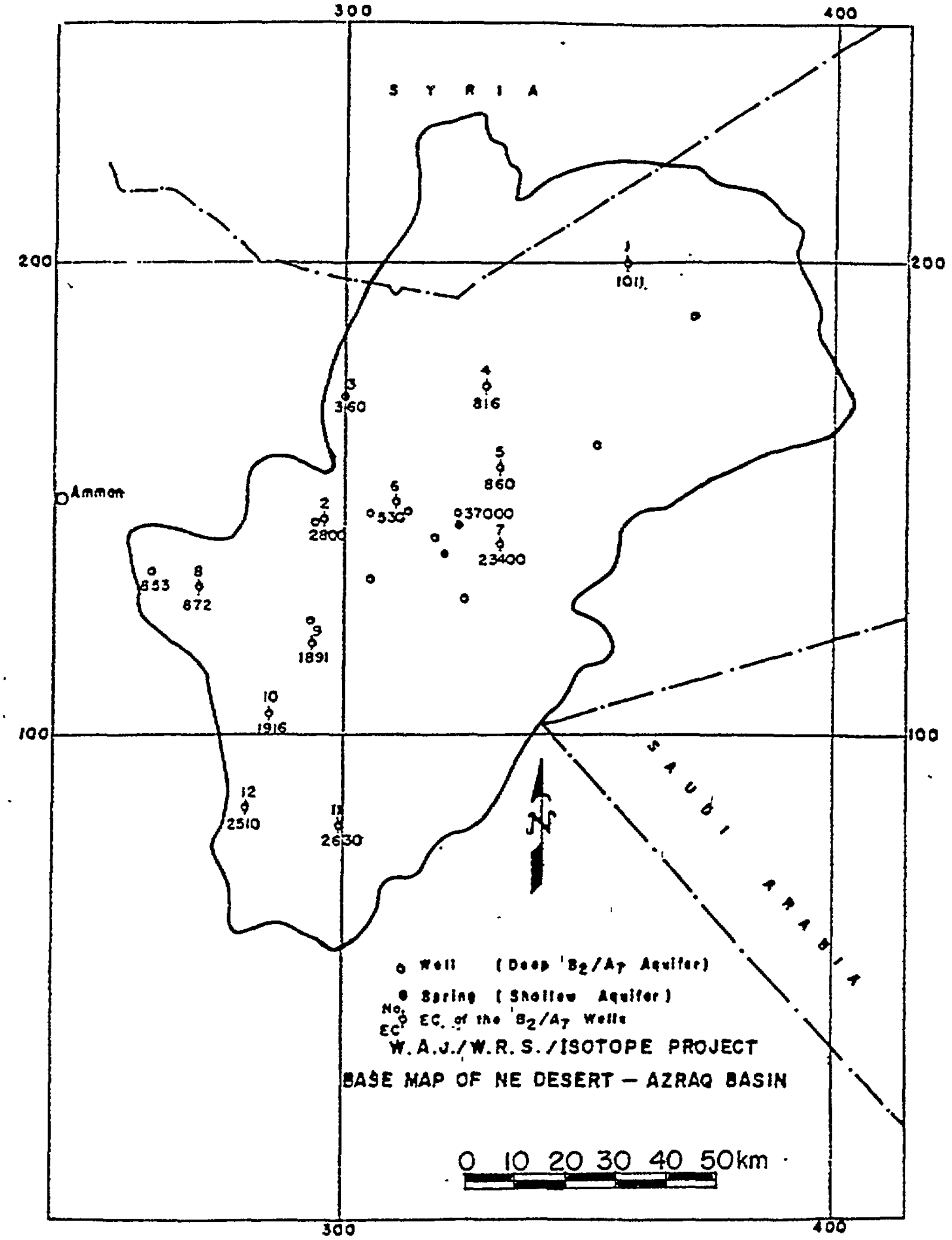

FIG. 6. Isotope sampling sites of the deep (B2/A7) aquifer.

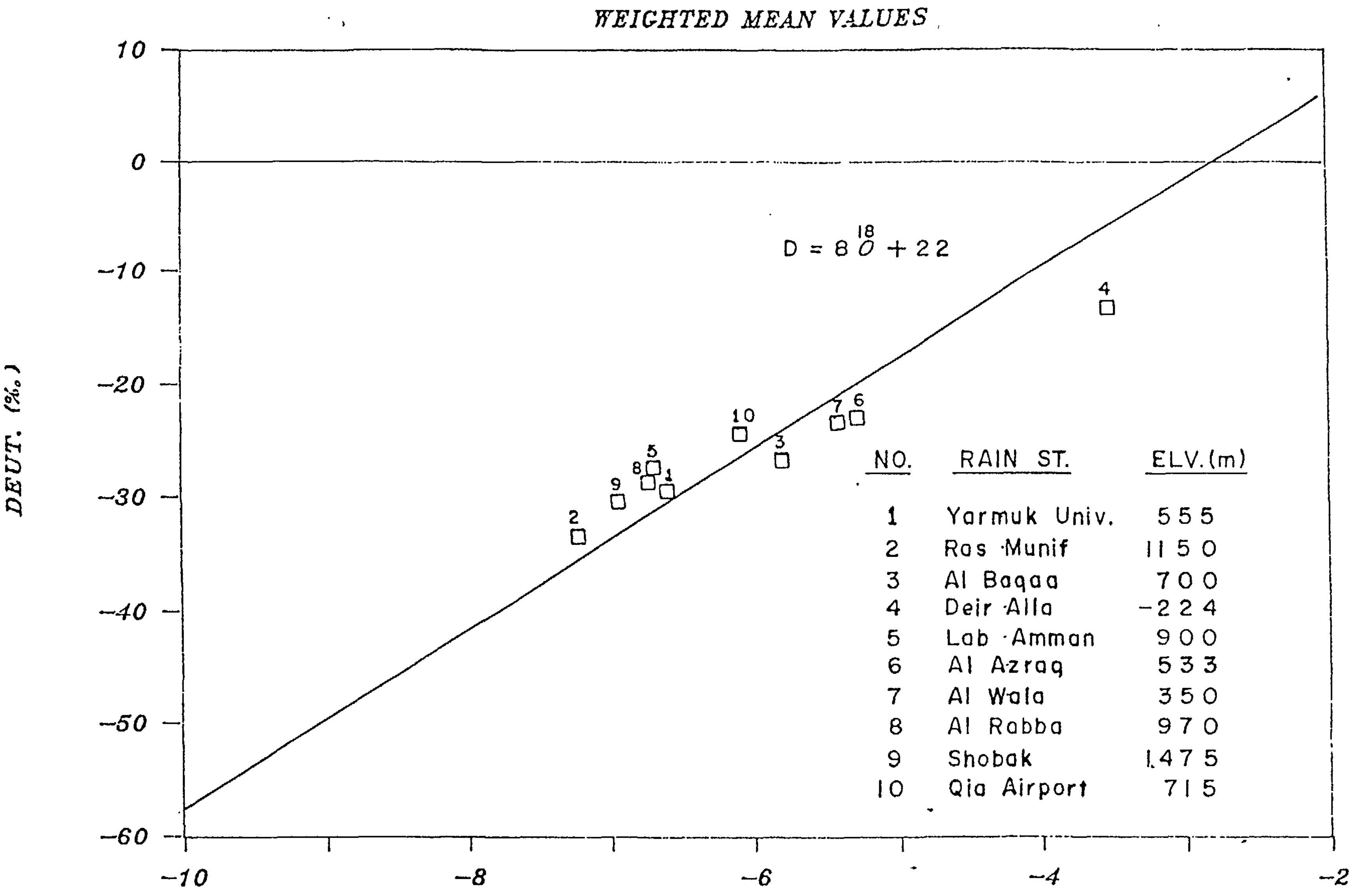

FIG. 7. Diagram of O-18 & Deuterium of precipitation stations.

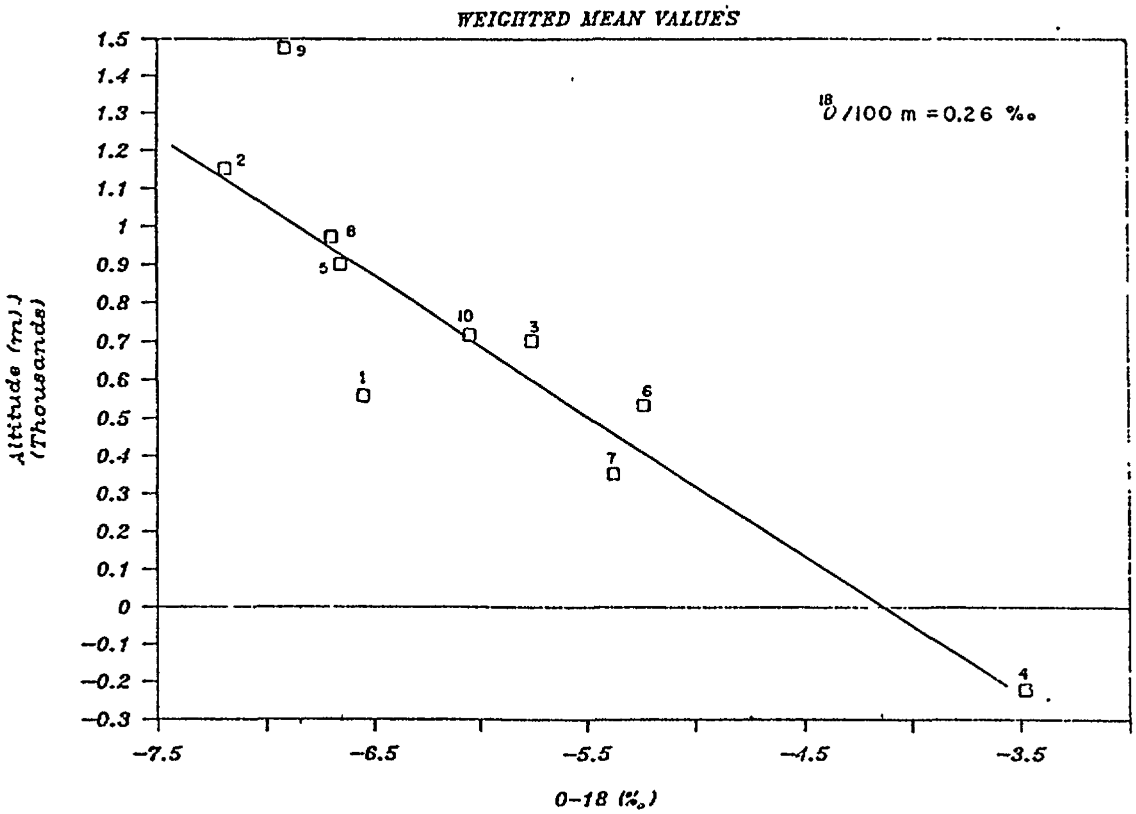

FIG. 8. Regression line of O-18 & altitude of precipitation stations.

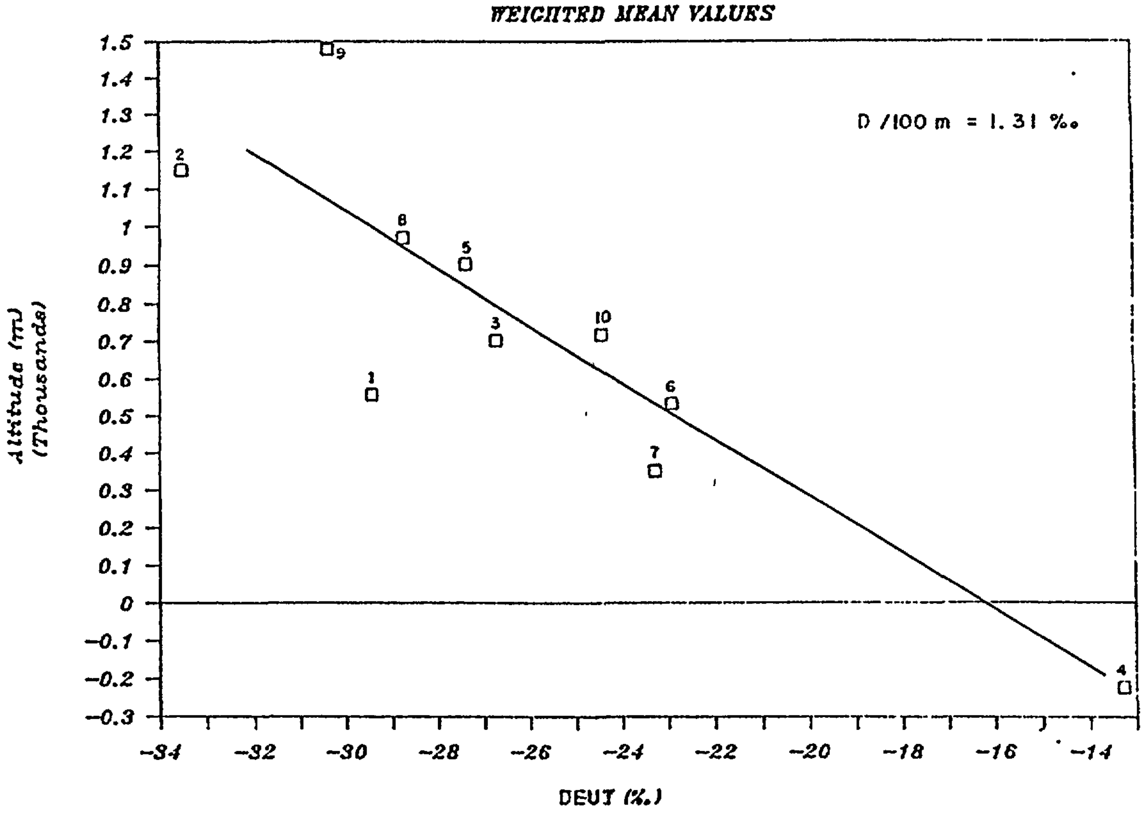

FIG. 9. Regression line of Deuterium & altitude of precipitation stations.

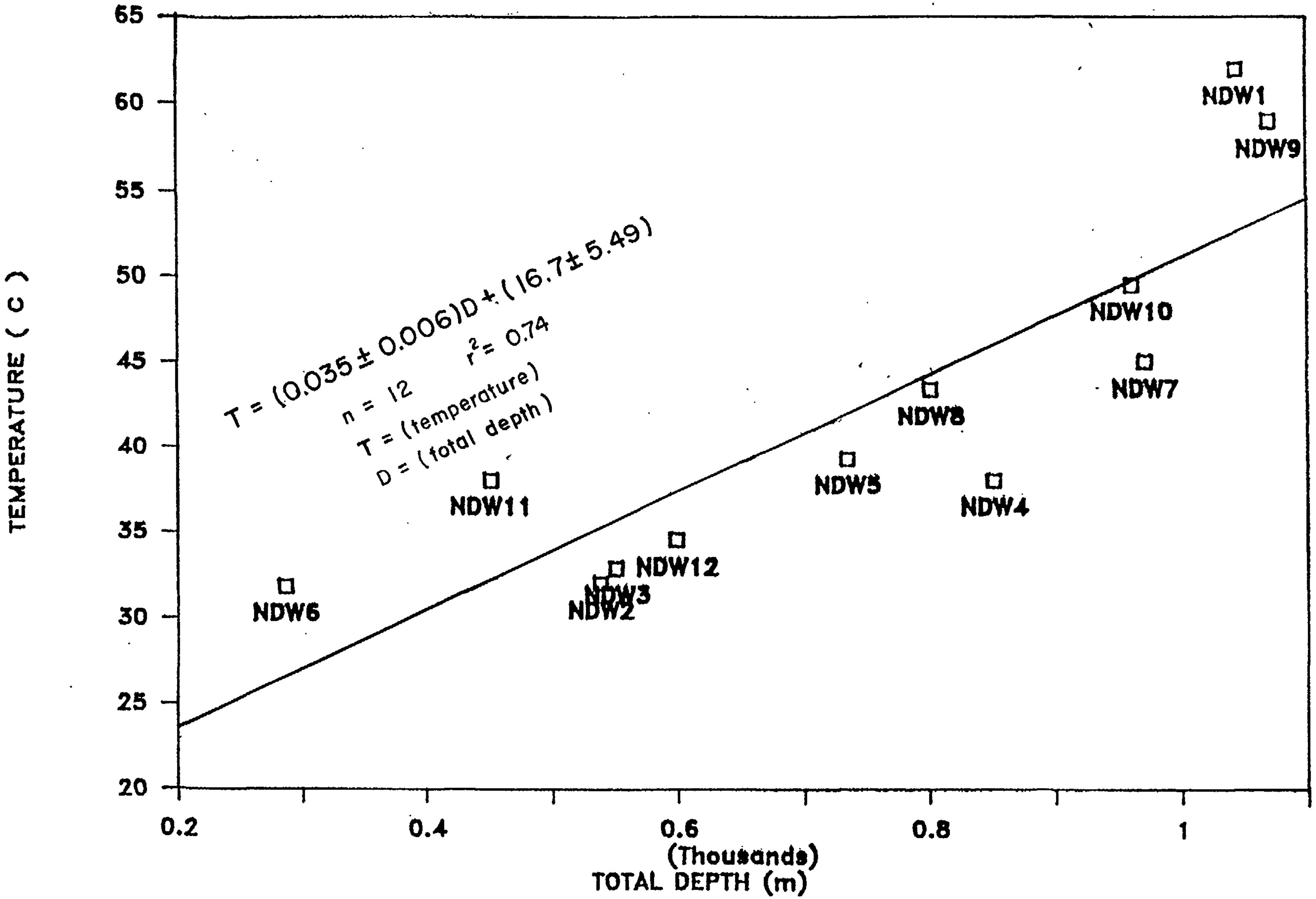

FIG. 10. Regression line of depth & temperature for NDW wells of the deep (B2/A7) aquifer.

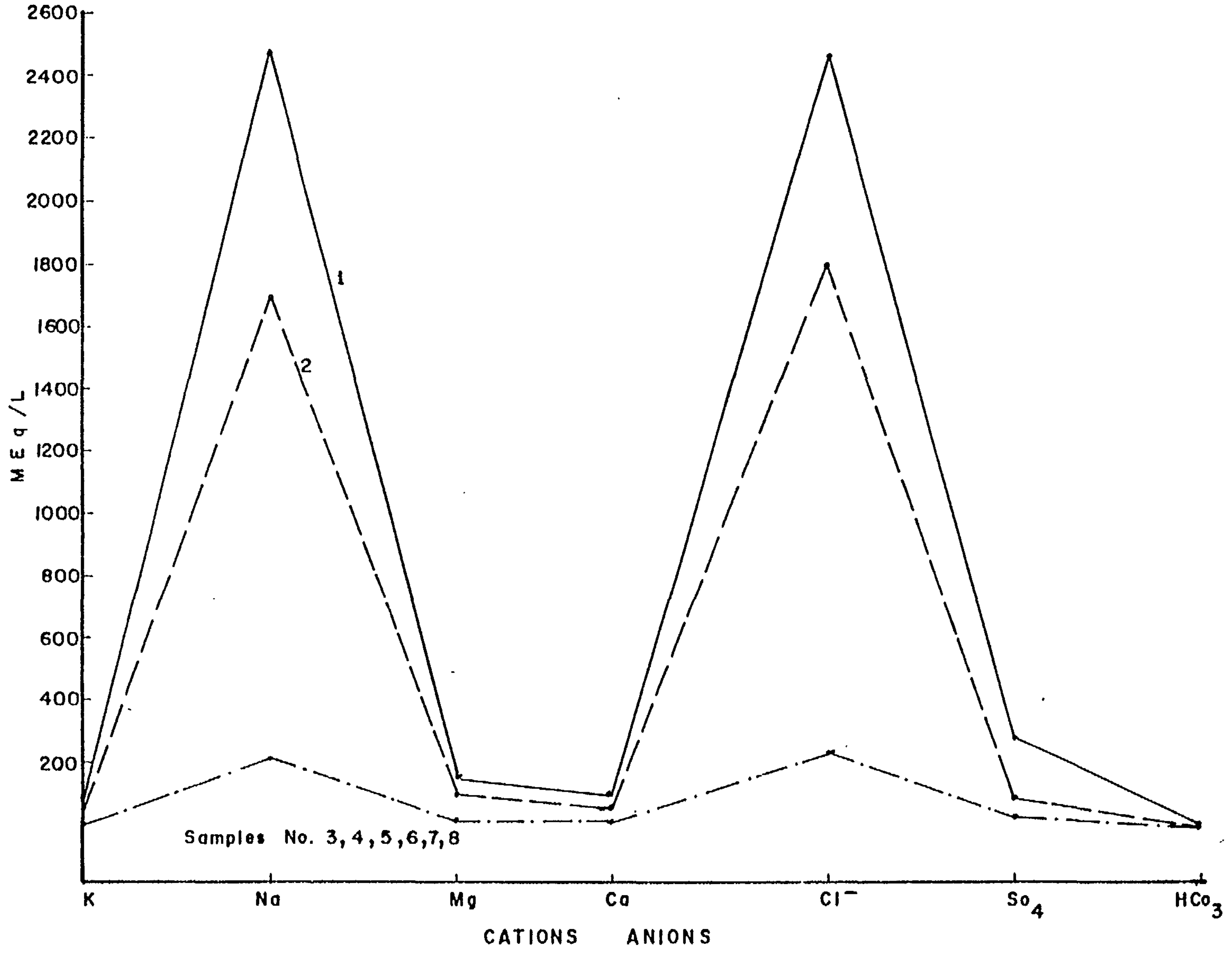

FIG. 11. Concentration composition diagram of NDW7 well tapping the deep (B/2A7) aquifer.

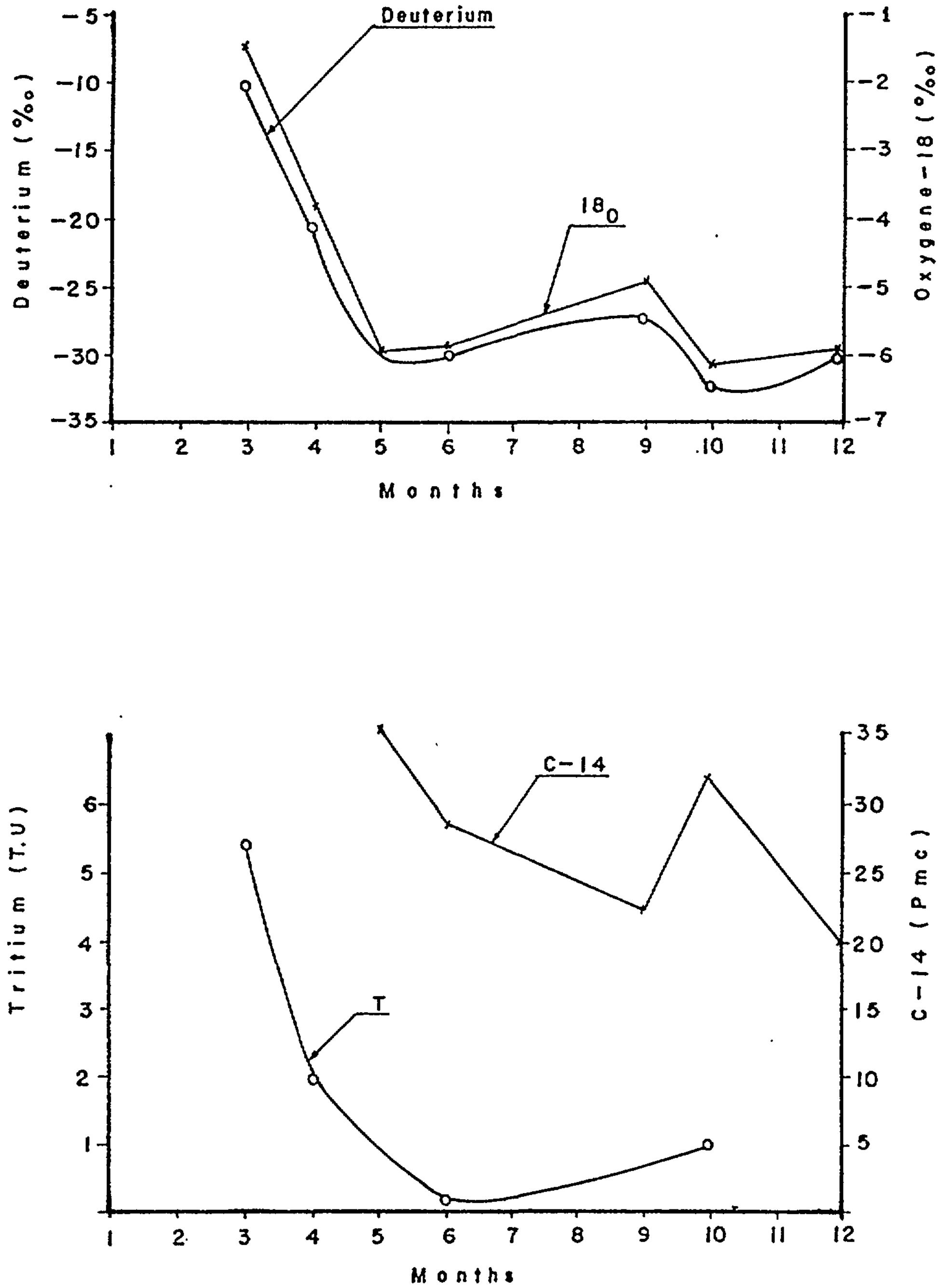

FIG. 12. Diagrams of stable and radioactive isotopes content in Aura (Druze) springs with time.

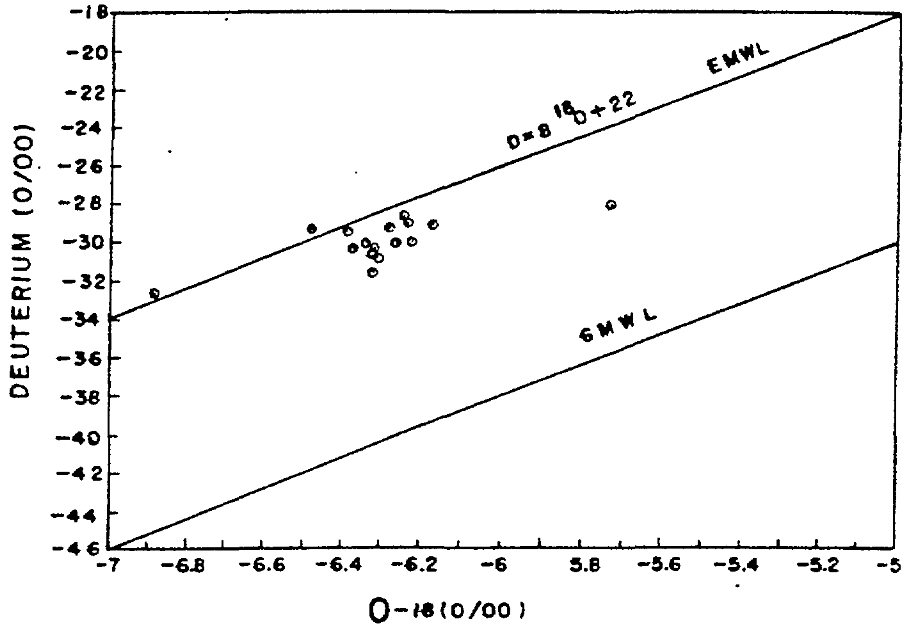

FIG. 13. Diagram of mean values of O-18 & Deuterium in upper Azraq basin wells (norhern Azraq).

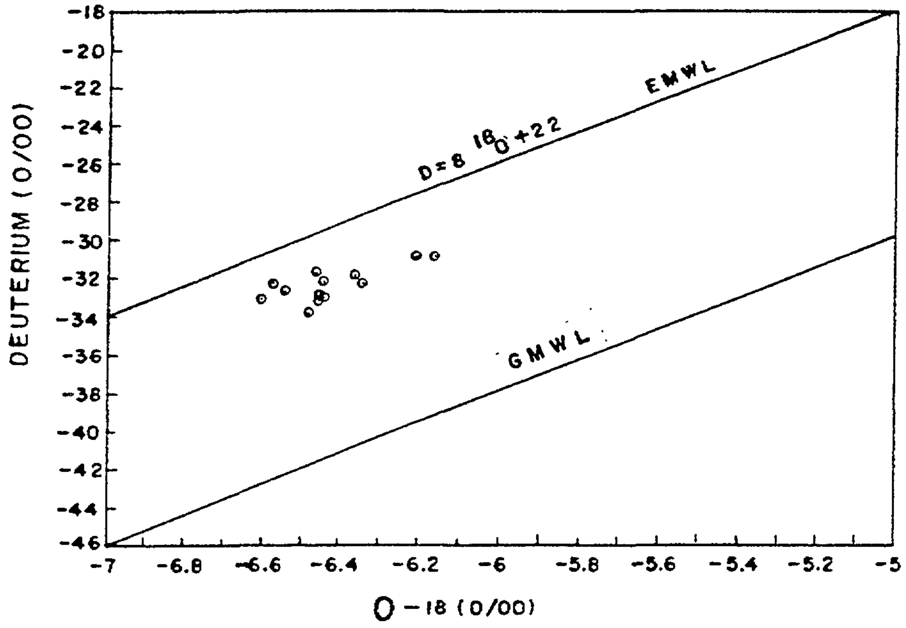

FIG. 14 Diagram of mean values of O-18 &Deuterium of AWSA *well field ground water.*

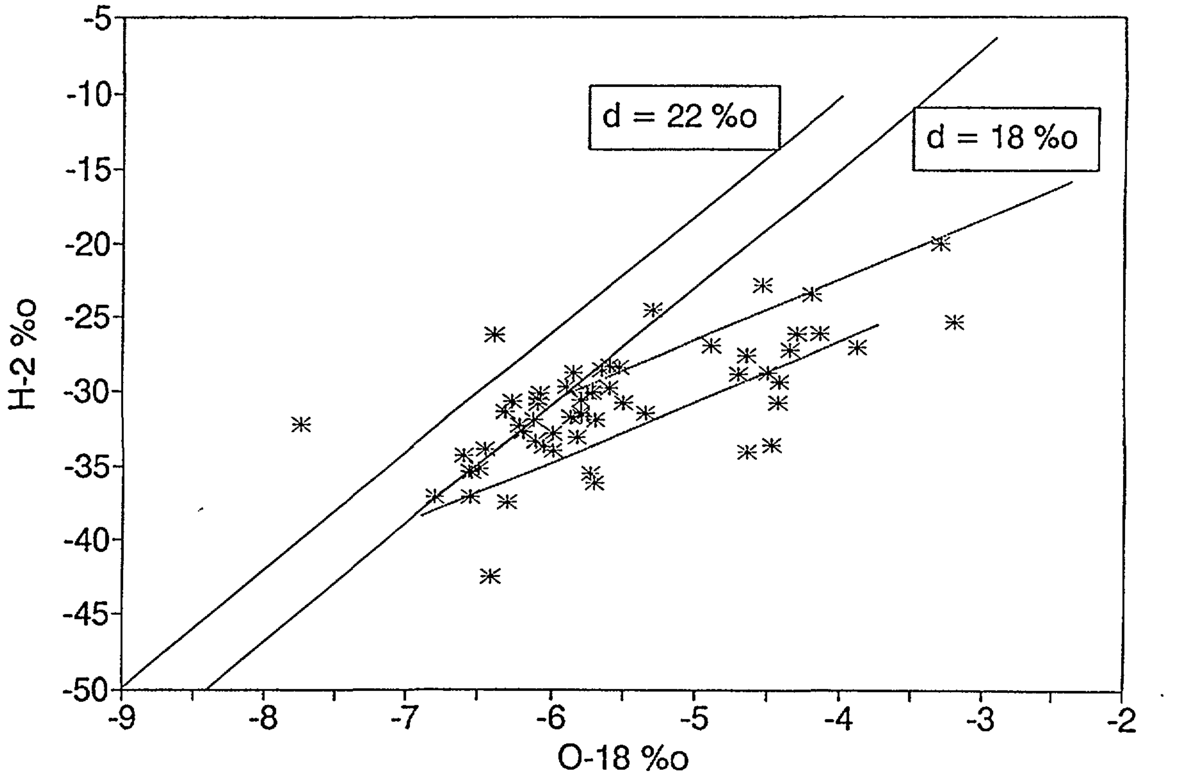

FIG. 15. H-2 & O-18 diagram for shallow ground water in the Azraq area.

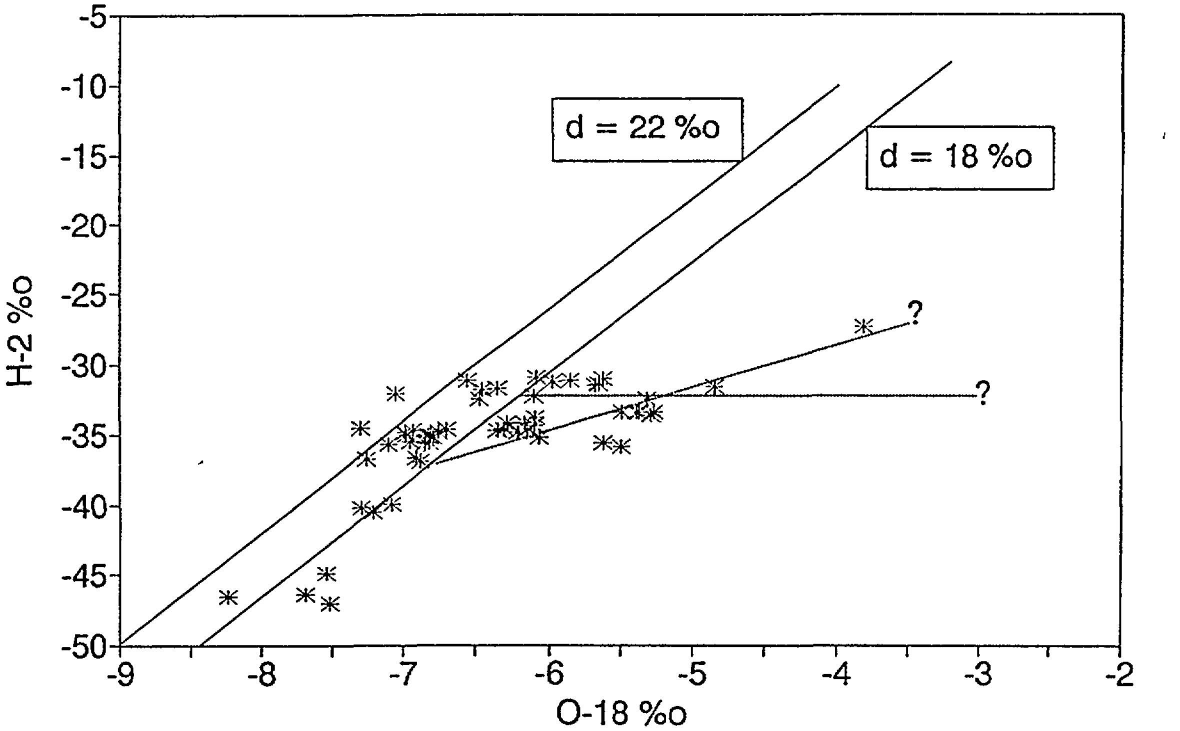

FIG. 16. H-2 & O-18 diagram for the deep ground water (B2/A7) aquifer in the Azraq area.

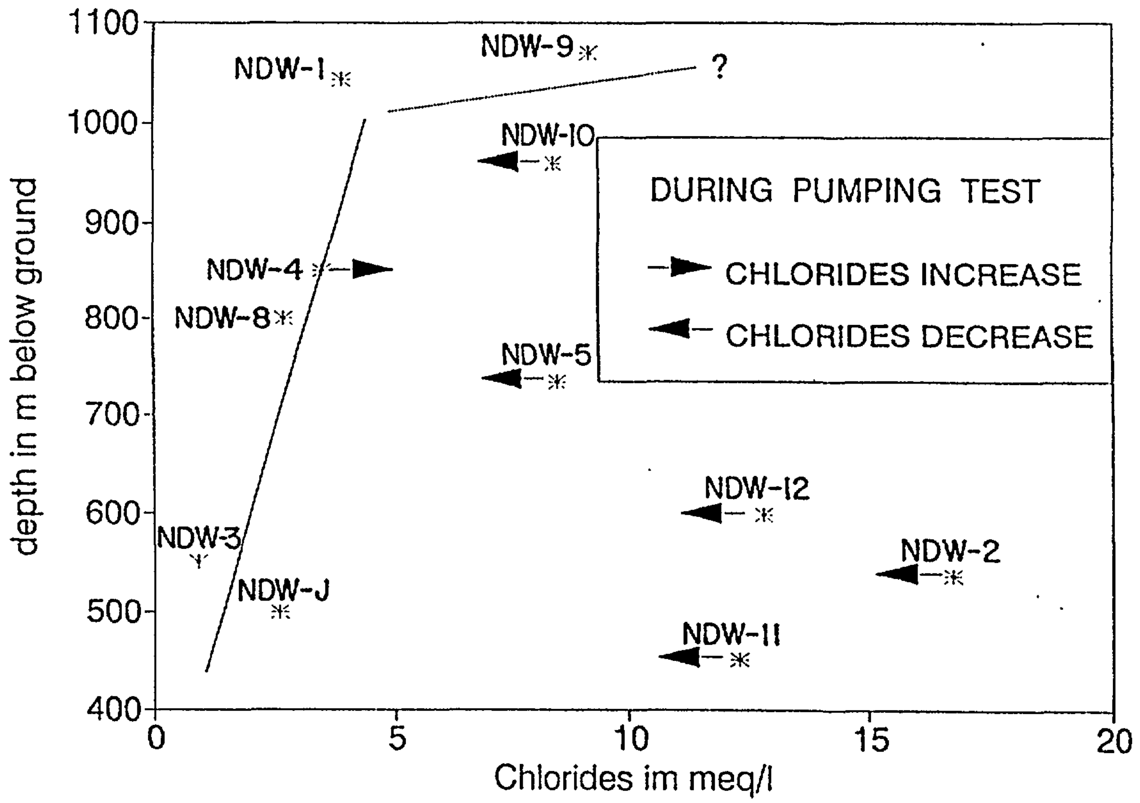

FIG. 17. Chloride-depth diagram of the deep ground water (B2/A7) aquifer in the Azraq area.

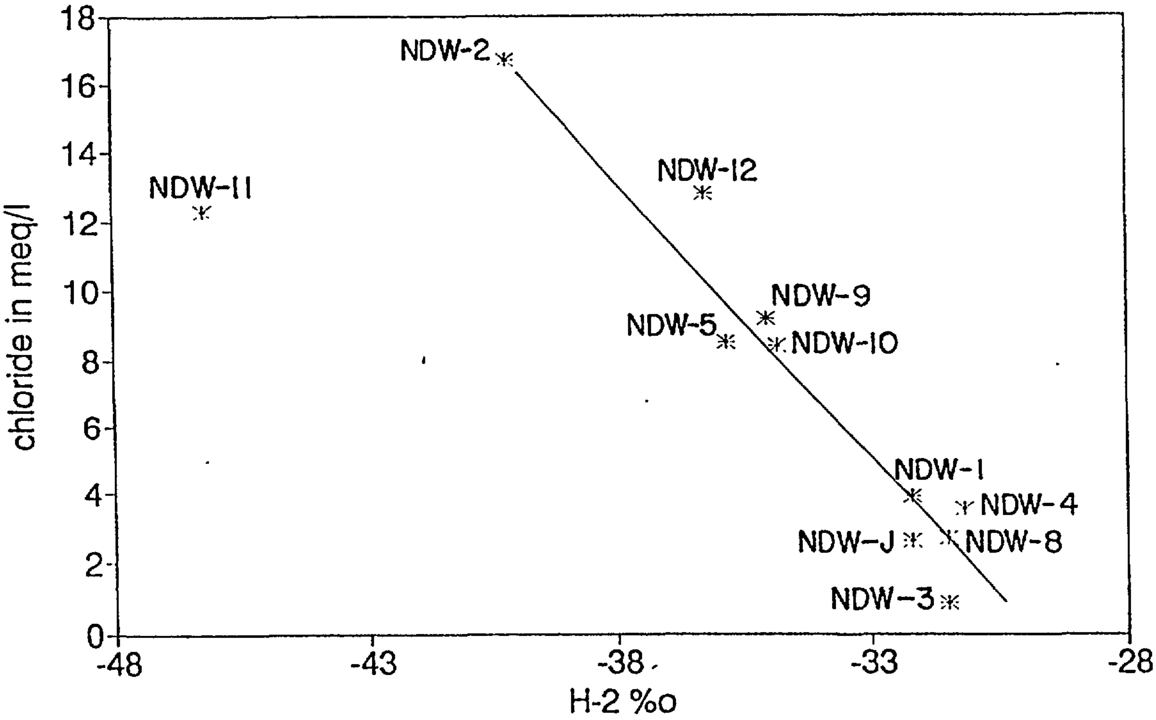

FIG. 18. H-2 & chloride diagram of the deep ground water (B2/A7) aquifer in the Azraq area.

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This study has been conducted within the frame of the cooperation project with IAEA "ISOTOPE HYDROLOGY IN THE MIDDLE EAST".

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F.Rshedat	Isotope laboratory
J.Jawawdeh	Carbon-14 unit
H.Attar	Tritium unit
I.Sallam	Isotope laboratory

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HYDROCHEMICAL PROPERTIES AND ENVIRONMENTAL ISOTOPES OF GROUNDWATER OF THE MIDDLE AQUIFER IN THE YARMOUK BASIN, JORDAN

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Amman, Jordan

Abstract

The middle aquifer (B2/A7) of Yarmouk Basin is found to be rechargeable in the side - Wadis south of Wadi-Arab; recharge is found isotopically affected by intensity of rain and basically on the altitude of recharge, the rest of the basin was recharged a long time before 1952.

The stable isotopic composition of Yarmouk groundwater clusters close to the east Mediterranean meteoric water line and majority of the samples have deuterium excess between 18-22 that signal similar recharge conditions and range of altitudes as prevailing in the present time. The two wells of Haji and Suwelmeh have an exceptionally low deuterium excess and lie close to GML (Figure 10).

Wadi Arab and Mukheiba well fields belong to two different sources of water. Hydrochemical analysis indicates $CaHCO_3$ type of water in the recharge area, where NaCl type is more prevailing in Ramtha and discharge area near the Yarmouk river.

Introduction

The Yarmouk Basin is bordered by the Golan plains (Syria) in the north-west, the desert areas of both Syria and Jordan in the east, the Ajlun mountains in the south and the Jordan graben in the west (Figure 1). It comprises an area of about 6,700 km^2, 25% is located in Jordan and represents the study area; the Syrian part of the basin has been studied by A. Droubi from the Arab Center for the Study of Arid Zones and Dry Lands (ACSAD).

The mostly used aquifers in the study area are the Balqa limestone (B2) of Campanian age and the Ajlun limestone (A7) of Turonian age. Both aquifers crop out in the Ajlun mountains as well as in the Nuaymeh area and dip below younger beds towards the Jordan graben. The two aquifers are partly unconfined and become confined towards Yarmouk river and Jordan graben.

The main objective of the study is to get information on groundwater origin dynamics and recharge.

Morphology, Discharge and Climate

The highest altitude in the study area is about 1150 m a.s.l. in Ras-Munif, the deepest point is situated in the Jordan valley at 200 m b.s.l. The highest point in the whole Yarmouk Basin reaches 2200 m a.s.l. in the Golan mountains. The discharges of the wadis contributing to the Yarmouk basin in Syria are estimated to 5.45 m^3/s; it is, however, not continuous because most Wadis get dry in summer. The discharge of 5.45 m^3/s out of the Syrian area corresponds to a specific discharge of 0.8 l/s per km^2).

The study area comprises the transition zone between Mediterranean and arid climates. It is characterized by cool winters and temperate as well as hot summers, with two transitional periods in spring and autumn. Rainfall occurs predominantly from October to May, with about 80% of the precipitation happening during December through March. Mean annual precipitation ranges from 50 mm in the east to 600 mm at the hilly areas of Ajlun dome. The potential evaporation is calculated to about 2500 mm/a, thus exceeds the yearly amount of rain. With this data it is obvious that rain intensities must play an important role for the infiltration of precipitation and thus for groundwater recharge.

Geology and Hydrogeology

The age of the outcropping formations in the whole Yarmouk and Northern rift side wadis ranges from lower Cretaceous to Eocene, the Jurassic sedimentary rocks underlay the Cenozoic basalt in southern Hermon mountains inside Syrian territory.

The formation of the main aquifer which is locally called B2/A7 (chert, limestone and dolomatic limestone) outcrops at the recharge area of Ajlune mountains and Nuaymeh area, where the younger formations overlying are exposed in sequence towards northeast. Some of them, namely the B3 (bituminous marl) and the B4/B5 (chalky and marly limestone with chert intercalations) reach their full thickness at Wadi-Shallala (Figure 2).

The volcanic activities formed basaltic rocks during the Miocene and Pleistocene age especially in Huran and Arab mountains including northeastern desert of Jordan.

The structural features of the study area indicate that the tectonic forces (horizontal and vertical) affected the sedimentary rocks after Oligocene forming anticlines, synclines and faults with different trends. The B4 aquifer is recharged locally through semi permeable strata in the north and Irbid and Ramtha area towards Yarmouk river. B4 aquifer discharges as springs (4.2 MCM/year); most of them are contact springs.

B2/A7 is the main aquifer in the study area and it is present in all Yarmouk Basin. The recharge of B2/A7 aquifer comes through the following three sources:

1. Ajlune mountains and Nuaymeh area inside Jordan.
2. The inflow from Northern desert towards Yarmouk Basin at Um-Essurab area.
3. The underflow moving towards Yarmouk river from Syrian territory at Muzerib area.

Ajlune major anticline acts as groundwater divide where water moves in two directions (Figure 3):

1. Northeast towards Yarmouk river.
2. West and northwest towards Northern rift side wadis especially towards Wadi-Ziqlab and Wadi-Arab.

Depth to groundwater level ranges from 50-300 m and becomes flowing above ground level at Mukheiba and Wadi-Arab due to the steep land slope at Yarmouk river and Jordan Valley.

In the low areas bordering the Jordan Valley most of the wells penetrating the B2/A7 aquifer system flow under high pressure reaches 292 psi. Due to such high pressure, the lower portions of B3 formation (marl and marly LST) is always found saturated due to upward leakage near the discharge area of Mukheiba and Wadi-Arab.

North of Tabqat-Fahel a lithofacies change is found to alter the A5/6 aquitard otherwise into a permeable formation connecting A4 formation with the main aquifer of B2/A7 to act as one groundwater system. The groundwater flows from Hawran Plain and Jabal Druze in Syria towards Yarmouk river and from Ajlune recharge area to the north and northwest resulting in a converged flow toward the river.

The NS: fault systems which are mostly normal faults associated with the main rift structure and are at angles with the groundwater movement where they cause some springs to occur along the fault trace as in Tabqat-Fahel spring.

The E-W: fault system is parallel with the groundwater movement and formed permeable conduits for the groundwater as in the case of Yarmouk river course.

Tools of Investigations

According to the aim of the study, instantaneous information out of the groundwater has been gathered as well as long-term information using tracer methods. Chemical components as well as environmental isotopes represent tracers in the groundwater. The distinction between both tracers is due to the fact that environmental isotopes behave predominantly as non-reactive in the groundwater as compared to chemical components that mostly undergo changes in concentration due to physical and chemical reactions in groundwater.

In order to restrict the number of sampled wells and springs, two general flow paths have been selected according to the groundwater contour map of the study area (Figure 3).

These wells and springs (Figure 4) have been sampled at least twice a year. The first flow path stretches approximately from south-east to north-west between Ajlun mountains and the Jordan graben, the second approximately from north-east to south-west from the Syrian border to the Jordan graben as well.

Samples taken from about 34 wells, three springs and the Yarmouk river at Maqarin and Mukheiba. Main chemical components and the environmental isotopes H-2, H-3, C-13, C-14 and O-18 have been analysed. Some of the results are still lacking for technical reasons.

As a reference to groundwater, actual precipitation has been sampled from 10 different stations (Figure 5) for chemical as well as isotopic analyses.

Results

1. Isotopic Composition of Rains

Monthly rains have been sampled from October 1987 to March 1993. This time span is sufficient in an arid climate to get good approximations to representative values. In precipitation pH overpasses 7 and the rain has a relatively high TDS concentration caused by the presence of dust in the atmosphere originating from different sources. The weighted means of H-2 and O-18 follow as expected the East Mediterranean Water Line (Figure 6)

$$\delta^{2}H = 8\delta^{18}O + 22$$

Data of stable isotopes in precipitation correlate well with the altitude of the precipitation station (Figure 7). The slope of the regression line results in a decrease of 0.26‰ of O-18 and 1.3‰ of H-2, respectively, with an increase of 100 m in altitude.

These values are known in the same order of magnitude all over the world. This correlation will permit to judge the role of Golan, Ajlun mountains and the Jordan Valley as areas of groundwater recharge.

2. Electrical Conductivity (salinity of groundwater)

Electrical conductivity of groundwaters in the unconfined aquifers of B2/A7 range (as expected in limestone with few soil covers) between 300 to 500 mS/cm an increase up to 800 mS/cm towards the confined aquifer (Figure 8). The 500 mS/cm line follows approximately the border line between the unconfined and confined areas of the aquifer (Figure 3).

The increase of salinity towards the discharge area may not only be attributed to a change in residence times of water favouring chemical reactions with low kinetics. It is thought that this increase results also from the admixture of groundwater arising from below the B2/A7 in order to discharge to the Jordan valley; it thus reflects a similar mechanism as the rise of highly saline waters in the Ramtha-Mafraq area.

Figure 8 also shows that salinity domes exist in the confined aquifers around Ramtha and to some extent also south of Irbid and north of Mafraq. The salinity domes between Ramtha and Mafraq correspond quite well with a tectonic alignment stretching from south east to north west (Figure 9). It is suggested that this alignment interconnects different aquifers allowing an uprise of more saline groundwater from depth (see sections 4, 5).

3. Stable Isotopes in Groundwater

Stable isotopes in the groundwater of the area follow the East Mediterranean Water Line (EMWL) with deuterium excesses between 18 and 22‰ (Figure 10). Two samples, however, deviate from this relation (Haji, Suwelmeh). This may be attributed to:

- a geothermal enrichment of 0-18;
- an evaporation since infiltration; or
- paleowaters with a deuterium excess of about 12.

With respect to temperature and chemical composition of both locations, no geothermal evidence exists. The correlation between stable isotopes and groundwater temperature results even in a decrease of 0-18 concentrations with increasing temperatures (Figure 11).

The two types of water deviating from EMWL belong to the zone with salinity domes in the confined B2/A7 aquifers (see section 2). The neighbouring wells, however, being also affected by admixtures of chlorinated water do not deviate from EMWL. Therefore, it is suggested that the waters of Haji and Suwelmeh have been evaporated.

The general enrichment of stable isotopes (deuterium excess between 18 and 22‰) is attributed to evaporation processes at the soil surface. The O-18 values group between -5 and -6.4‰. This indicates (Figure 7) mean recharge areas between 300 and 820 m a.s.l.; thus the floor and slope of the Jordan valley are excluded for groundwater the recharge as well as most of the Golan Heights of Syria. Considering the distribution of sampling points and the steady distribution of 0-18 values (Figure 12) it appears that recharge is not restricted to special areas within the 300 to 820 m a.s.l. areas. Groundwater in the recharge area of Nauymeh has a big variation in isotopes due to seasonality, fluctuation in intensity of rain, local altitude of recharge and other factors.

4. Chlorides and Sodium in Groundwater

The chloride concentration ranges between 0.3 and 5.5 meq/l. This cannot only be attributed to evaporative enrichment of chlorides; therefore an additional chloride source in the underground can be supposed. Considering the chloride concentrations above 2 meq/l, it is evident that all these waters occur in the area north of Mafraq and Ramtha as well as along the graben fault of the Jordan valley (Figure 13). In both zones an intrusion of saline waters from deep aquifer is supposed to contribute to the groundwater of the B2/A7 aquifers. This contribution must be of the NaCl-type.

Considering that all values surpassing 2 meq Cl/l represent mixed water results in the statement that water with lower Cl concentrations should belong to unmixed groundwater recharged by precipitation. This non-mixed groundwater is of recent origin in the unconfined aquifer (see section 5).

Chloride behaves as a conservative tracer in the environment. Away from coastal zones it occurs in precipitations in concentrations of about 1.5 mg/l and becomes enriched by evaporation processes out of the soil. As far as no other chloride source in the underground changes the recharge information it can be used to calculate groundwater recharge.

By means of mass conservation the amount of chloride entering the system (A) must equal the amount leaving the system (B):

$$A = B$$
$$C_p P = C_r R$$
$$R = (C_p/C_r)P$$

with C_p = chloride concentration in precipitation (P)
C_r = chloride concentration in recharge (R).

The mean chloride concentration in the undisturbed and unconfined aquifer is about 1.1 meq/l corresponding to about 40 mg Cl/l; with respect to 1.5 mg Cl/l rain, a 3.8‰ portion of rain is calculated as recharge. With respect to 500 mm/a of precipitation groundwater recharge amounts to 19 mm/a or 0.6 l/sec./km^2. At the actual state this is judged as a maximum value, because it ignores direct runoff produced by rain events.

This recharge agrees fairly well with the specific discharge of 0.8 l/sec./km^2 in the Syrian part of the Yarmouk Basin (see chapter 3).

Considering the distribution of groundwater recharge in the area without intrusion of deep groundwater to the B2/A7 aquifers it is of interest to notice that the calculated recharge protion does not change appreciably all over the area although the confined aquifers are out of actual recharge and have elevated ages (see section 5). This is interpreted in two ways:

- there exists a limited recharge caused by the outcrop area of B2/A7 aquifers;
- no significant changes in groundwater recharge occurred within the time span covered by the ages of the groundwater (see section 5).

5. Radioactive Environmental Isotopes

The actual tritium concentrations in local precipitations range between 6 and 18 TU. In groundwater such tritium concentrations are only found in the unconfined aquifer around Nauymeh 1, Nauymeh 2, Farhan H., and the southern side wadi area as clearly represented by Abu-Said wells, Tabqat-Fahel spring, Jdeita and Deir-Yusef wells. The first three wells have also high C-14 values (63 pmc) that range most probably at initial C-14 concentrations and don't seem to be influenced by intrusion of chlorinated groundwater (see sections 1, 3) from deep aquifers (Figure 16).

Mean residence times from tritium in the respective area of the unconfined aquifer may range between a few and less than 10 years and probably represent more seepage than groundwater turnover time. Downstream the unconfined aquifer, the C-14 concentrations decrease within the confined sector to 15 and 17 pmc, at distances of 25 and 35 km, respectively; from these data a flow velocity of 2 m/a is estimated.

In the area between Mafraq and Ramtha chloride intrusion is taking place from a deep aquifer; no tritium was detected and the available C-14 concentrations range between non-detectable and 10 pmc. These groundwaters belong to the same unconfined aquifer south of Ramtha and Irbid. They must represent a mixture of old and young groundwaters. With the available data, however, the mixing ratio can only be approximated using 10 TU and 63 pcm C-14 for recent groundwaters.

$$C_oQ_o + C_yQ_y = C(Q_o + Q_y)$$

$$n = Q_o/(Q_o + Q_y)$$

and $$1 - n = Q_y/(Q_o + Q_y)$$

$$C_on + C_y(1 - n) = C$$

(C = concentration, Q = discharge, index o = old, index y = young)

Taking the concentration of the old component as 0 pmc of C-14 and no detectable H-3, and the concentration of the young component as 63 pmc of C-14 and 10 TU of H-3, results in $>85\%$ old and $<15\%$ young groundwaters mixing in that zone. With respect to chlorides it seems that the deep groundwaters rising to shallow aquifers are not uniform in their Cl concentrations.

6. Chemical Composition of the B2/A7 Groundwater

The groundwater of the B2/A7 aquifers are of calcium-bicarbonate-type (Figure 14). Locally they have elevated sulfate concentrations (e.g. in Samara and Mukheiba deep) therefore carbonates and sulfates are represented together in Figure 14. The respective milliequivalents fit very well. In some cases the earth alkalies are a little depleted; this, however, is compensated by increased sodium concentrations forming sodium hydrogen carbonate waters.

Figure 15 shows $CaHCO_3$ type of water in the side wadis and recharge area of Nuaymeh. Decrease in HCO_3 and increase in Na and Cl ions are noticed primarily as going towards Ramtha and North-East Desert area and to a less extent in Mukheiba area.

Mg cation is more or less stable in Yarmouk Basin while it is found in relatively higher values in Ramtha and Mukheiba area.

TABLE 1. CHEMICAL & ISOTOPIC COMPOSITION OF GROUNDWATER SAMPLES COLLECTED FROM YARMOUK BASIN (1987-1994)

Code No.	Samples	O-18 o/oo	Deut. o/oo	D.Ex	Triti TU	C-14 PMC	C13 o/oo	EC Ms/Cm	TDS Meq/L	PH	Ca Meq/L	Mg Meq/L	Na Meq/L	K Meq/L	Cl Meq/L	SO4 Meq/L	CO3 Meq/L	HCO3 Meq/L	NO3 Meq/L
1	Nauymeh 1	-6.02	-29.6	18.5	6_4.5	60.0	-11.0	0.56	11.46	7.46	3.32	1.51	0.80	0.07	0.90	0.30		4.24	0.32
2	Nauymeh 2	-6.32	-30.1	20.5	8-7			0.61	12.22	7.31	3.25	1.83	0.90	0.08	1.03	0.32		4.23	0.58
3	Farhan, H.	-6.34	-29.6	21.1	10_2.3	63.0		0.57	11.38	7.40	3.23	1.73	0.70	0.07	0.90	0.11		4.27	0.37
4	Haji, M.	-4.59	-24.7	12.0	1_0	9.8		1.08	22.17	7.15	4.06	3.19	3.90	0.09	4.50	1.06		5.35	0.02
5	Mahasi D.	-5.83	-29.7	16.9	0	3.0	-10.3	0.77	16.31	7.55	2.83	2.63	2.70	0.04	2.87	0.73		4.50	0.01
6	Samara,A.1	-6.25	-33.8	16.2	0	6.0		1.32	28.88	6.83	6.20	4.30	3.90	0.10	3.46	3.50		7.39	0.03
7	Samara,A.2	-5.98	-30.4	17.4	1_0	2.0	-13.6	1.00	22.21	7.11	4.83	2.94	3.30	0.08	2.97	1.38		6.70	0.01
8	Tabba,K.2	-6.41	-34.2	17.1	1_0.4	1.0	-11.5	1.11	23.66	7.06	5.35	3.47	3.00	0.04	2.85	2.30		6.65	NR
9	Jahman, M.	-6.16	-29.2	20.1	0			0.77	15.42	7.55	1.71	2.02	3.90	0.11	2.90	1.21		3.54	0.03
10	Suwelmeh	-5.51	-31.1	13.0	0	2.4	-9.9	0.83	16.98	7.21	3.13	2.30	3.00	0.07	2.90	0.74		4.84	0.00
11	Masri,Taleb	-6.40	-32.0	19.2	0	3.3	-9.1	0.97	20.19	7.35	2.83	2.84	4.20	0.17	3.80	0.96		5.39	0.00
12	Ojan,Qasem	-6.33	-29.9	20.7	0			0.76	15.01	7.70	1.51	1.86	4.00	0.12	3.00	1.03		3.34	0.15
13	Ijiyan,Ali	-6.18	-30.3	19.2	1_0.6	<2.8	-10.5	0.89	16.97	7.78	1.31	1.94	5.00	0.13	4.28	1.12		3.01	0.18
14	Saket,Grem	-5.94	-28.4	19.1	1_0.5			0.78	14.95	8.07	1.16	1.80	4.40	0.17	3.40	1.10		2.70	0.22
15	Zayd,A.2	-6.12	-29.2	19.8	0	10.1	-9.3	0.89	17.19	7.90	1.17	2.54	4.70	0.14	4.51	1.29		2.52	0.32
16	Jalad,M.	-6.08	-29.9	18.7	0			0.85	16.18	8.05	1.11	2.23	4.70	0.12	3.95	1.37		2.38	0.32
17	Abu-Said 1	-6.06	-27.2	21.3	4_3.7	42.0	-13.7	0.82	17.61	6.90	5.37	2.37	1.00	0.09	1.06	0.66		6.79	0.27
18	Abu-Said 2	-6.10	-28.0	20.8	5			0.82	17.70	6.91	6.13	1.86	0.80	0.05	1.07	0.77		6.91	0.11
19	Tabget F.Sp	-6.00	-28.0	20.0	9.8			0.86	18.74	7.02	4.83	2.62	1.80	0.12	1.85	0.91		6.38	0.23
20	Jdata	-5.89	-26.3	20.8	7_5.2	63.8	-11.9	0.71	14.60	7.23	4.12	2.31	1.10	0.06	1.15	0.32		5.54	NR
21	Deir-Yusif	-6.10	-29.0	19.8	10	63.0	-10.4	0.43	9.12	7.77	2.90	1.10	0.40	0.11	0.36	0.10		3.72	0.43
22	Kfr-Yuba	-5.65	-22.0	23.2	4	45.6	-9.9	0.49	10.27	7.80	2.87	1.75	0.60	0.05	0.70	0.31		3.99	NR
23	Wali,M.Abd.	-5.47	-22.9	20.9	0_0.1			0.91	18.32	6.96	6.10	2.20	1.00	0.13	1.42	1.64		5.80	0.03
24	Khazer,M.	-5.70	-25.6	20.1	0_5.2			0.99	21.21	7.04	5.54	3.26	1.80	0.10	1.76	1.54		7.14	0.07
25	W.Arab 1	-5.34	-22.8	19.9	0	11.6	-13.1	0.88	19.38	7.06	5.30	3.30	1.10	0.07	1.06	1.62		6.92	0.01
26	W.Arab 2	-5.28	-22.8	19.5	0	16.7		0.84	18.46	7.20	5.43	2.79	1.00	0.08	1.02	1.08		7.04	0.02
27	W.Arab 3	-5.32	-22.4	20.1	0	11.0	-13.5	0.85	18.70	7.06	5.31	2.91	1.10	0.08	1.03	1.17		7.08	0.02
28	W.Arab 4	-5.11	-22.5	18.4	0	11.9		0.98	22.50	7.00	6.00	3.20	1.90	0.14	1.24	2.94		7.06	0.02
29	W.Arab 5	-5.35	-24.4	18.4	0	35.0		0.76	16.49	7.10	4.62	2.65	0.90	0.08	1.07	0.46		6.50	0.21
30	Shuneh Hot	-5.73	-26.0	19.8	0	8.0		1.02	21.42	6.85	3.90	3.50	3.10	0.12	2.85	1.62		6.28	0.05
31	Mukheiba 1	-5.87	-27.1	19.9	0	16.9	-12.9	0.82	18.40	7.35	4.85	2.58	1.80	0.06	1.68	1.26		6.16	0.01
32	Mukheiba 2	-5.97	-27.4	20.4	1.1	18.0	-11.6	0.74	16.42	7.23	3.97	2.15	1.90	0.10	1.63	0.67		5.94	0.06
33	Mukheiba 3	-5.91	-27.1	20.2	0.1_0			0.70	16.73	7.52	3.77	3.14	1.90	0.10	1.61	0.28		5.90	0.03
34	Mukheiba 5	-5.50	-25.3	18.7	0.9_0	3.6	-12.8	0.87	19.34	6.95	3.96	3.76	1.90	0.09	1.70	0.86		7.02	0.05
35	Mukh.Deep	-6.57	-31.7	20.8	0	5.4	-9.4	1.50	31.27	7.01	6.13	3.52	5.70	0.32	5.54	4.48		5.52	0.06
36	Balsam Sp.	-5.96	-28.5	19.2	1.4_?			0.98	22.92	6.97	4.30	3.10	3.90	0.13	3.84	2.00		5.64	0.01
37	Maqla Sp.	-6.30	-31.4	19.1	1.6_0	16.6	-9.6	1.41	29.19	7.27	5.88	3.02	5.40	0.36	5.55	3.50		5.48	NR
38	Yar.Maq.	-5.90	-27.0	20.2	1.3			0.70	13.90	8.42	1.26	2.20	3.30	0.19	2.26	1.52	0.20	2.98	0.19
39	Yar.Mukh.	-5.64	-32.0	13.1	1.5			0.74	14.53	8.26	1.24	2.31	3.70	0.14	2.49	1.32		5.31	0.33

Notes:
1-Yar.Maq.= Sample Collected From Yarmouk river at Maqarin on 24.11.1988
2-Yar.Maq.= Sample Collected From Yarmouk river at Mukheiba on 24.11.1988
3- O18 & Deuterium are Mean Values.
4- 0 Tritium= Below detection limit

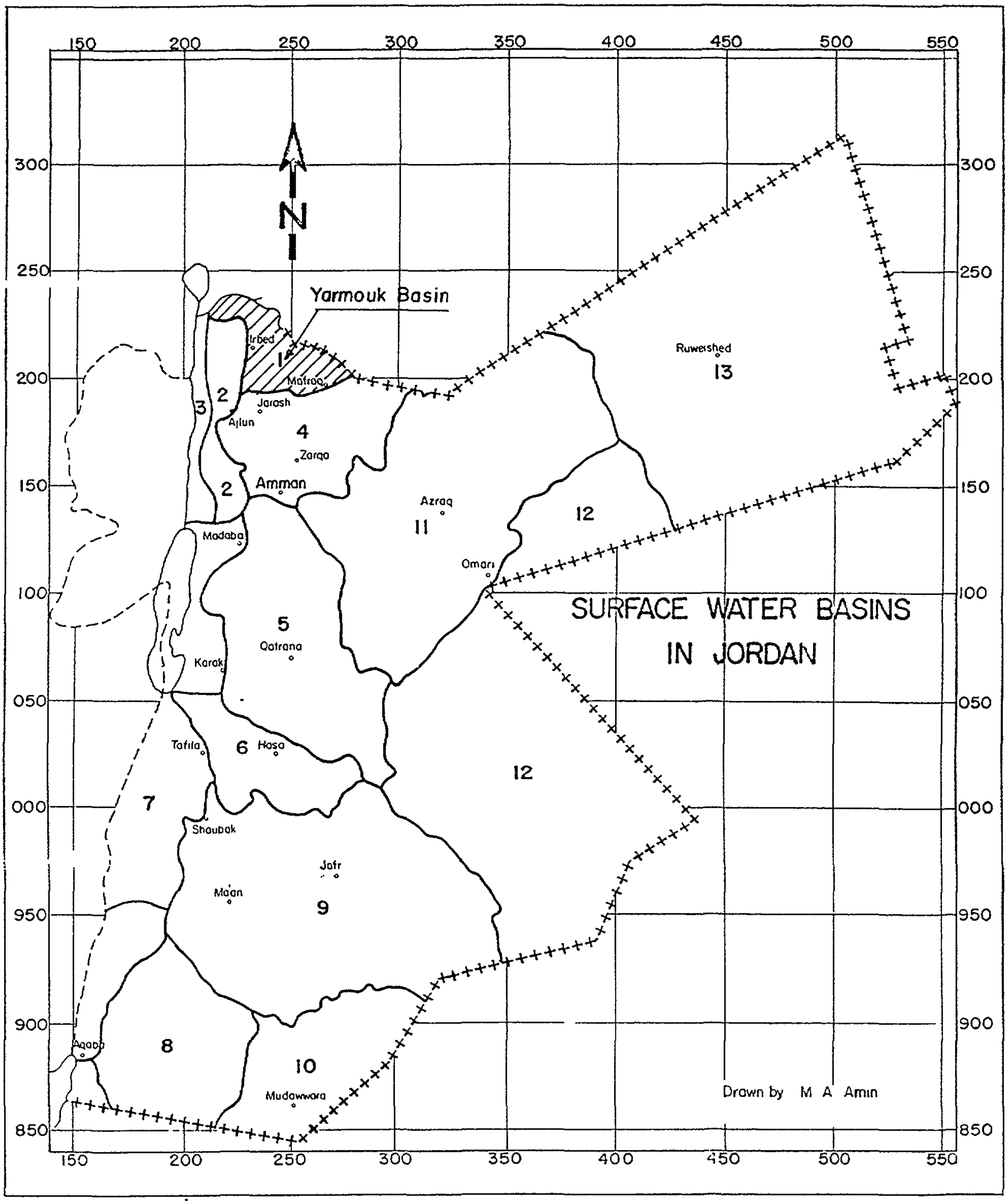

FIG.1. Lcation map.

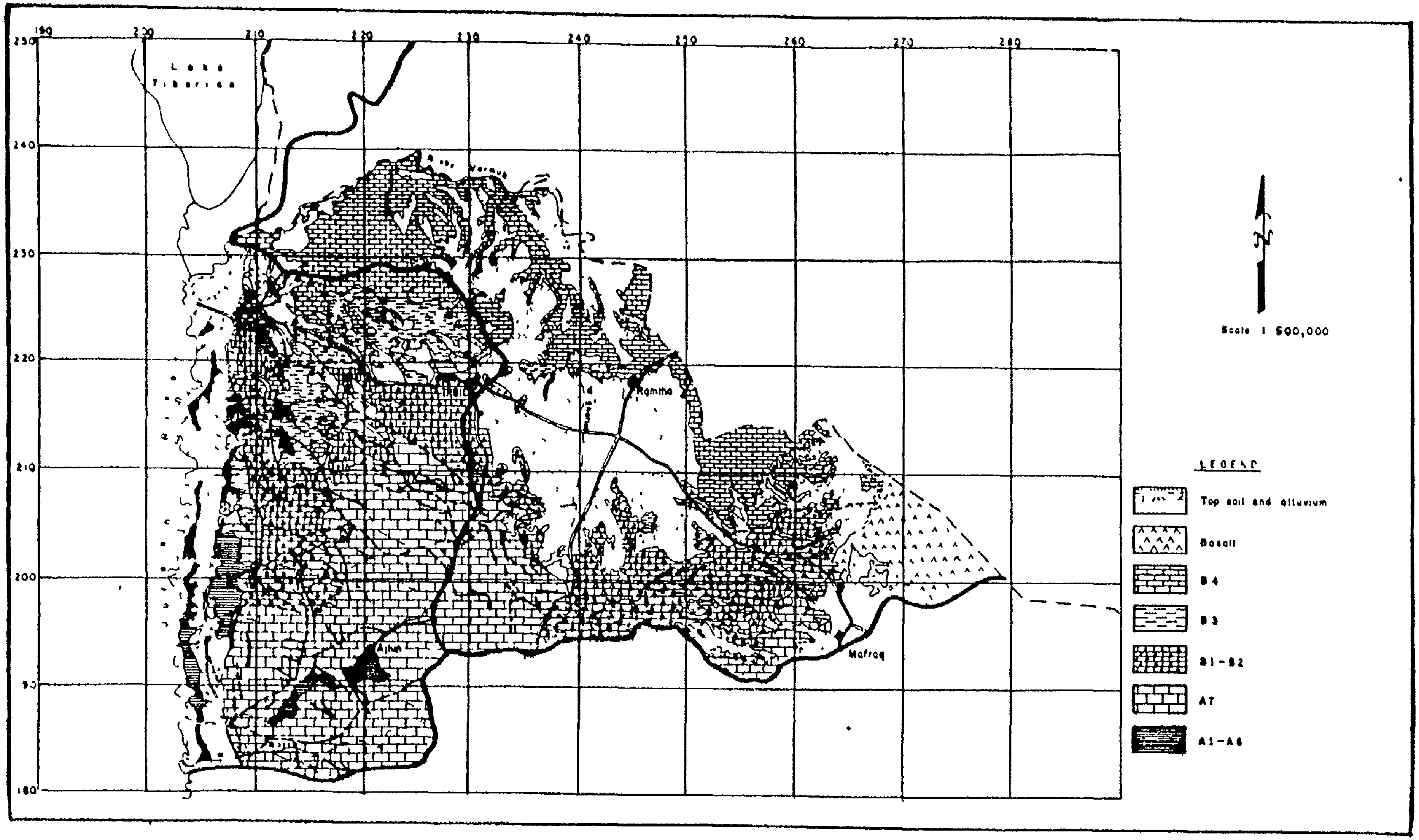

FIG. 2. Geological map of Yarmuk basin and northern rift side wadis.

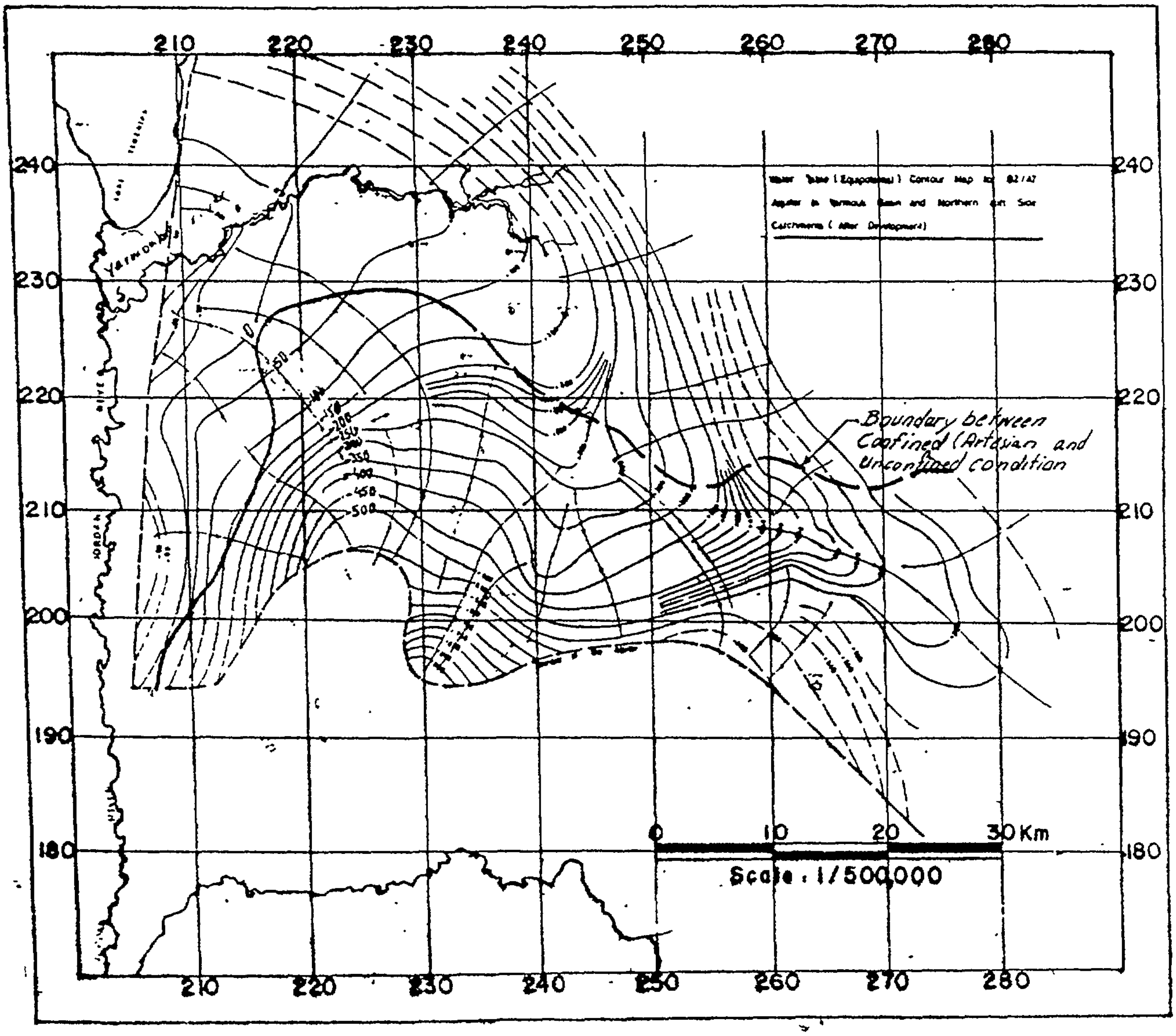

FIG. 3. Equipotential groundwater map.

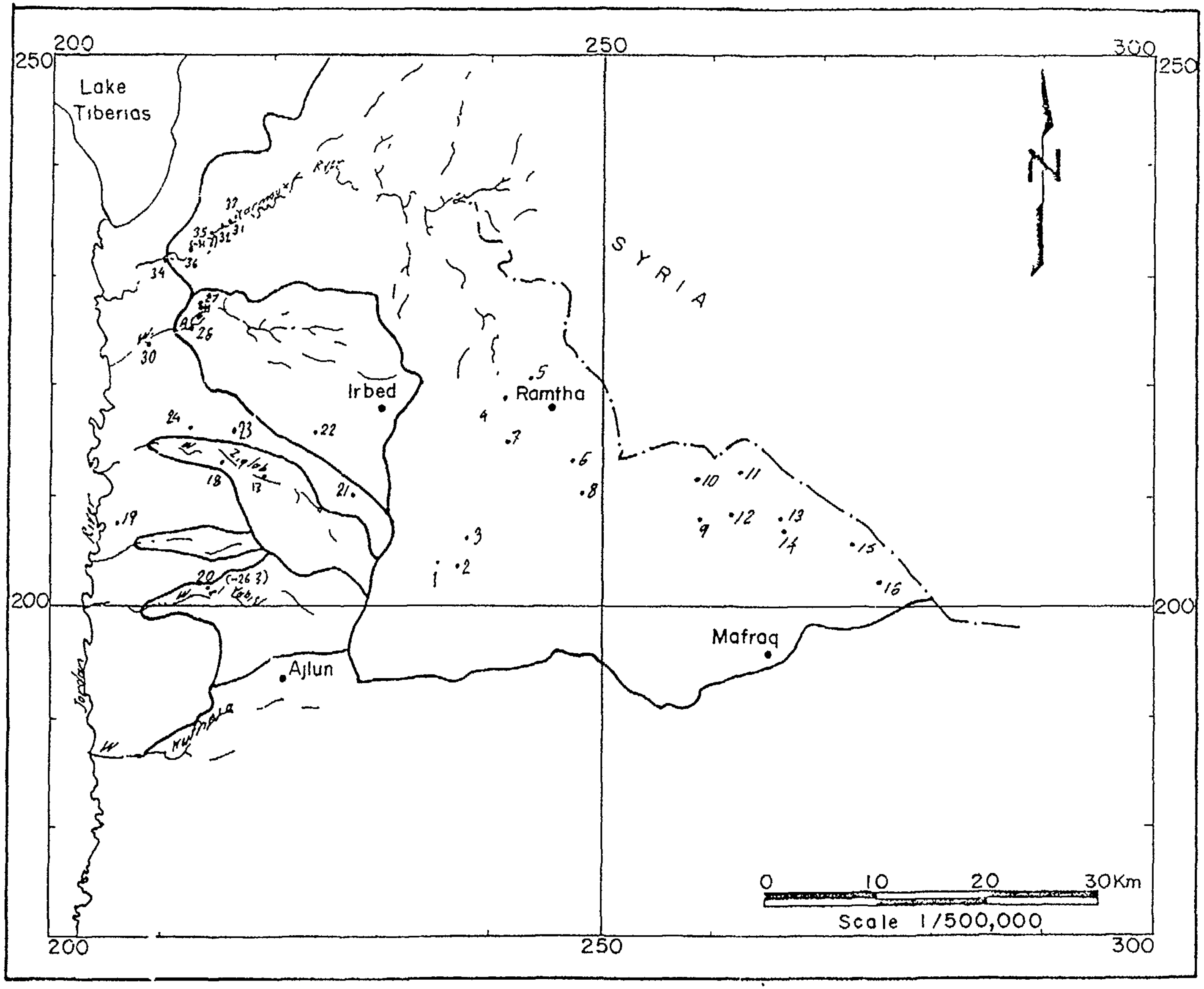

FIG. 4. Sample location map.

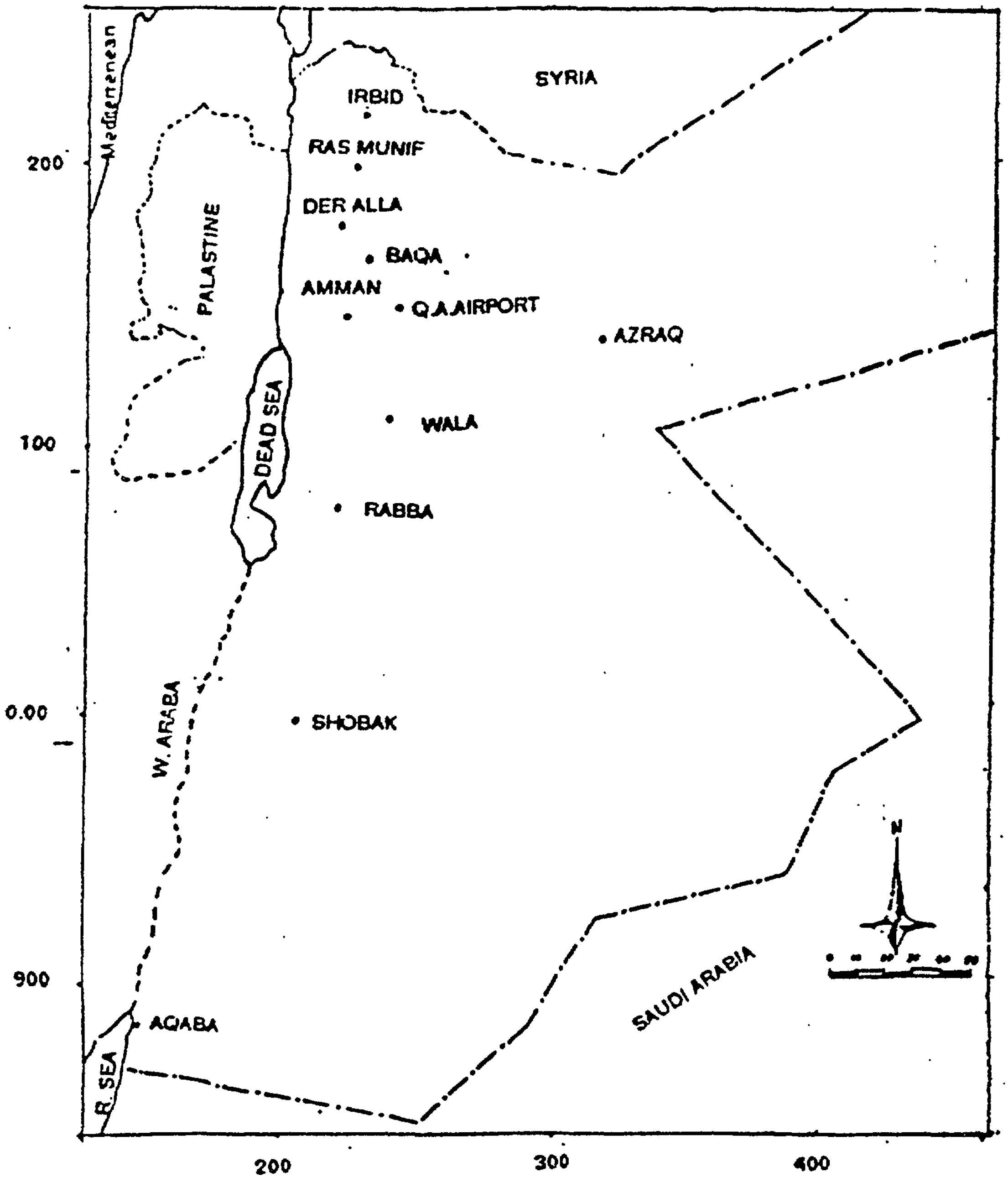

FIG. 5. Location map of the rainfall gauge stations.

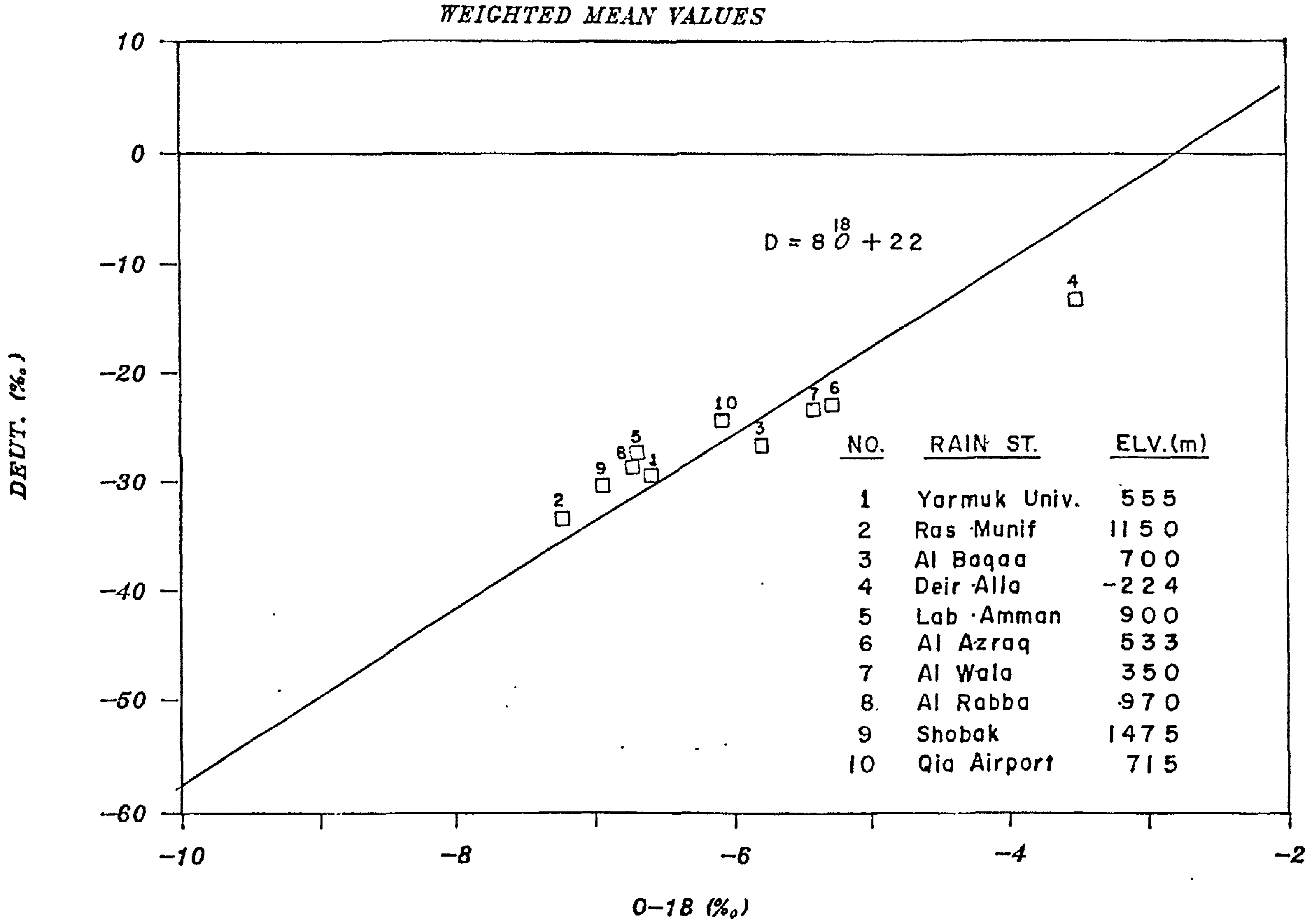

FIG. 6. Reg. Line of O-18/Deut for precipitation.

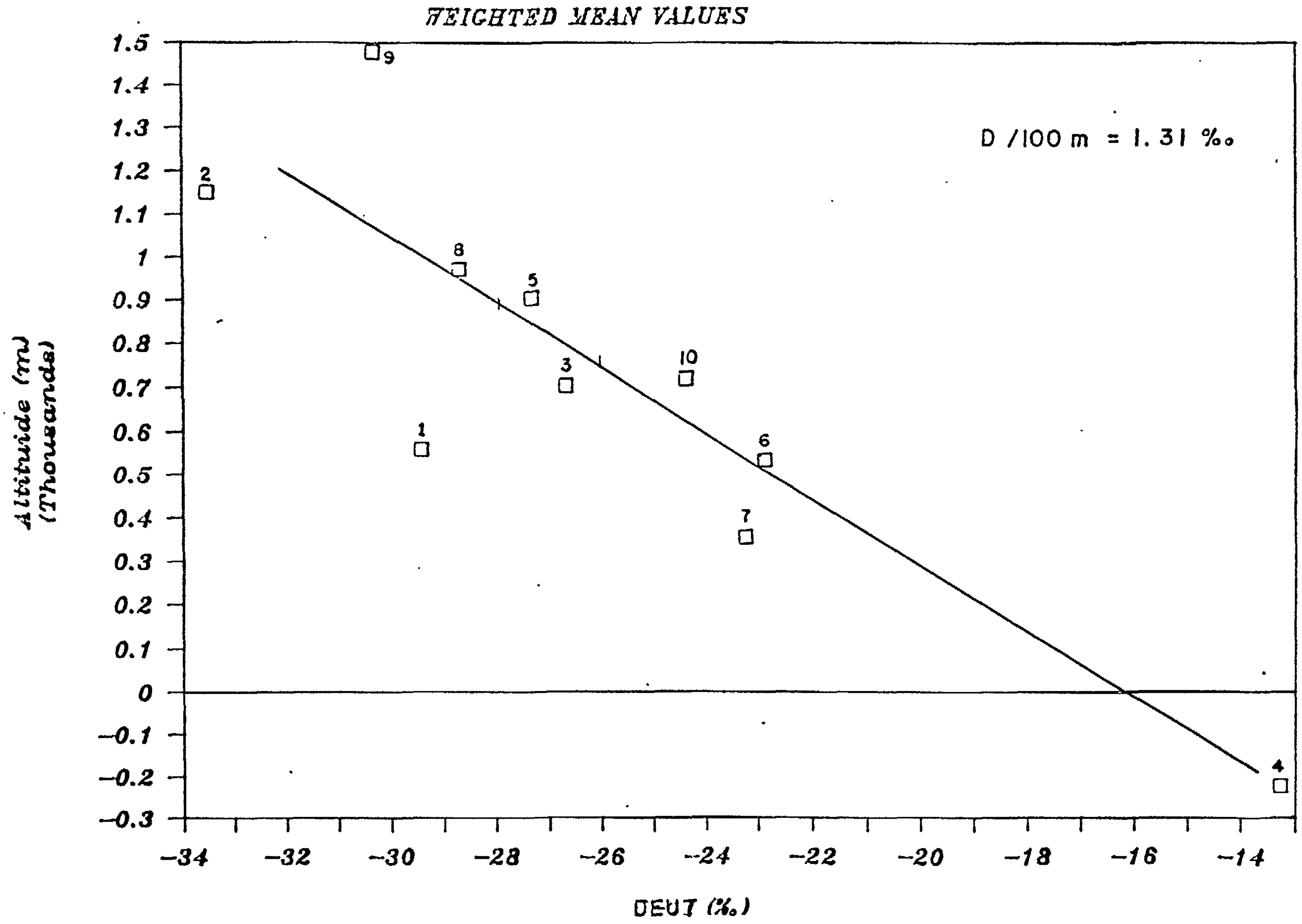

FIG. 7a. Deut./altitude relationship.

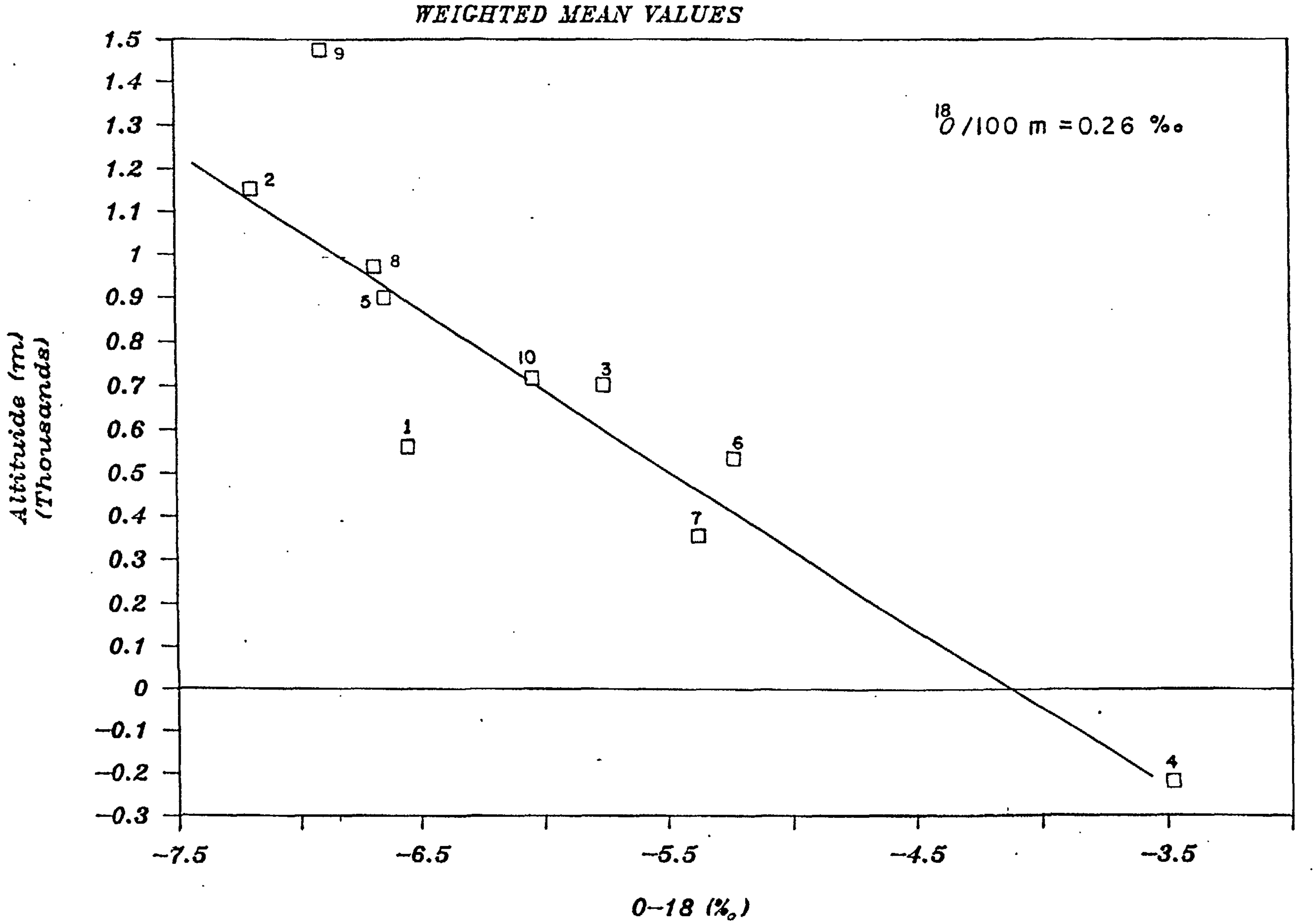

Fig. 7b. O-18/altitude relationship.

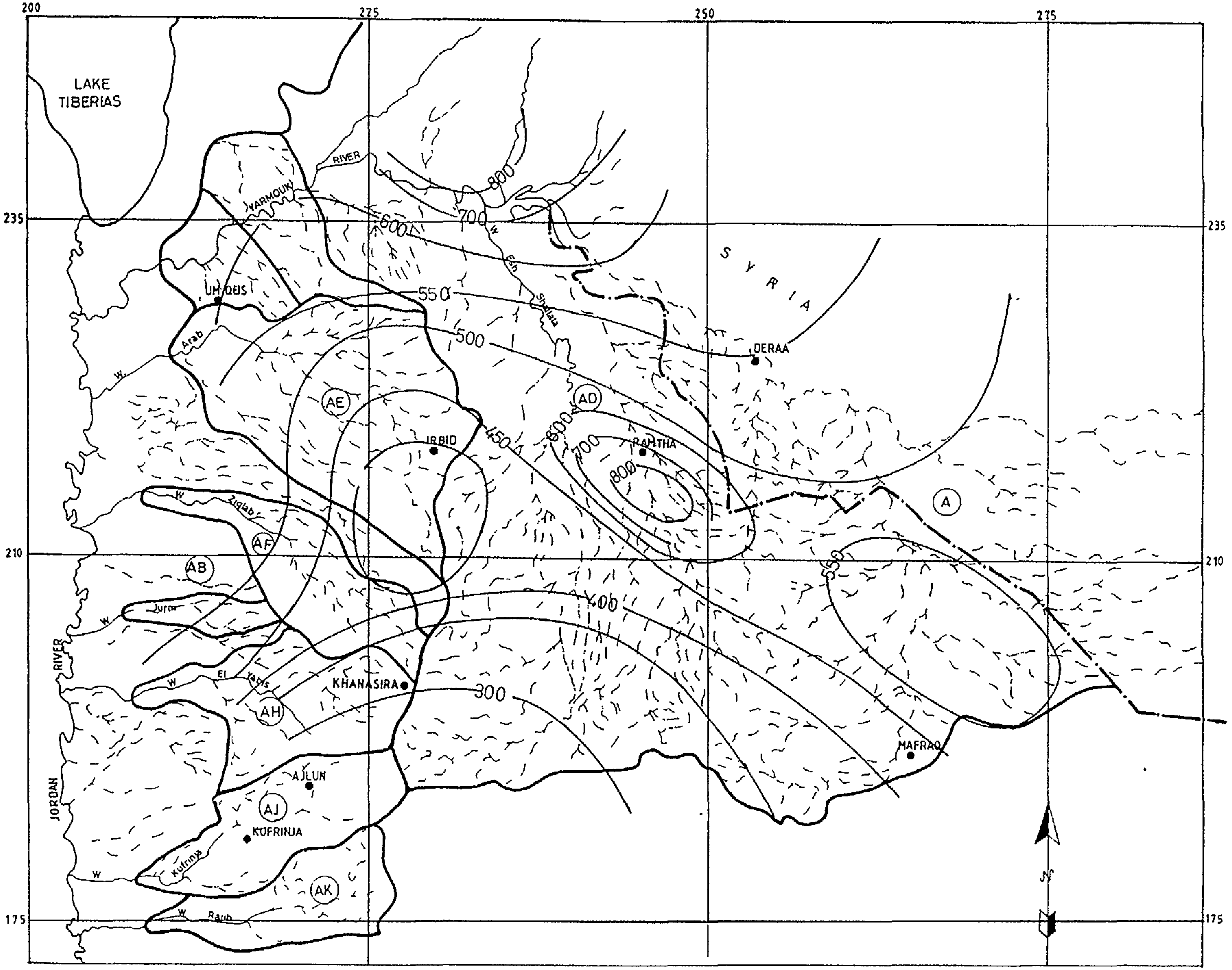

FIG. 8. Iso-salinity map. Yarmouk basin.

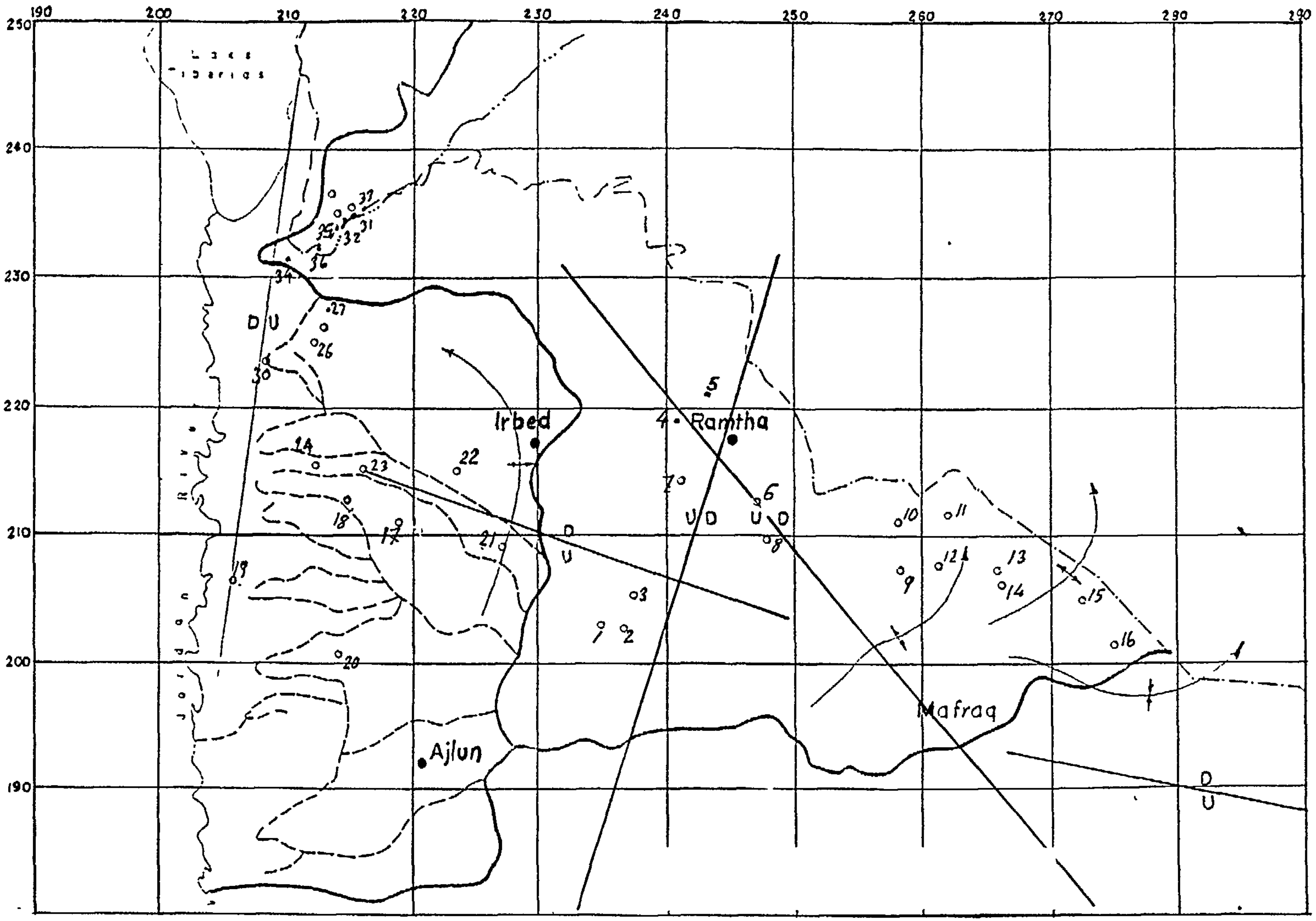

FIG. 9. Main linements and structures in the study area.

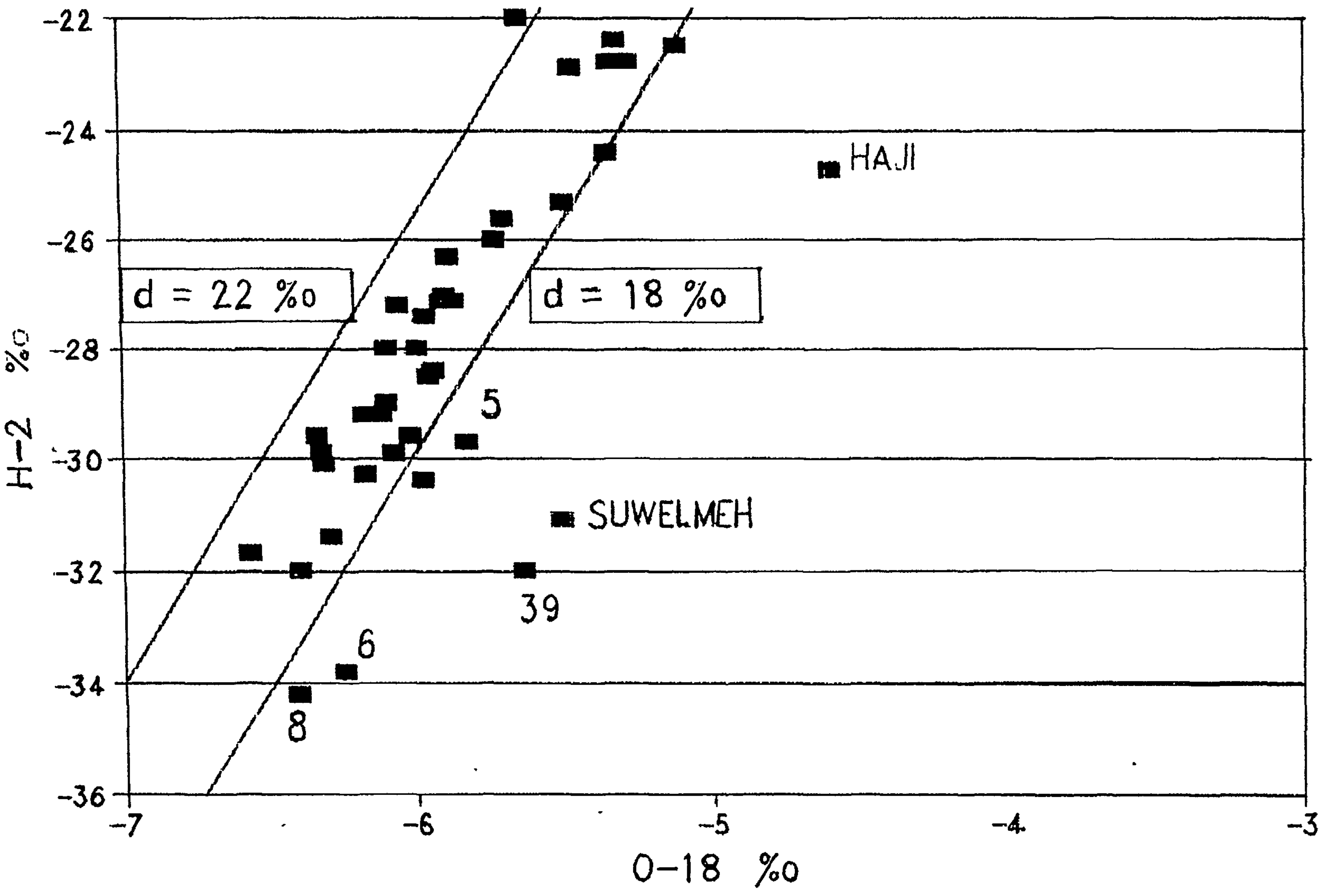

FIG. 10. Deut. Vs. O-18.

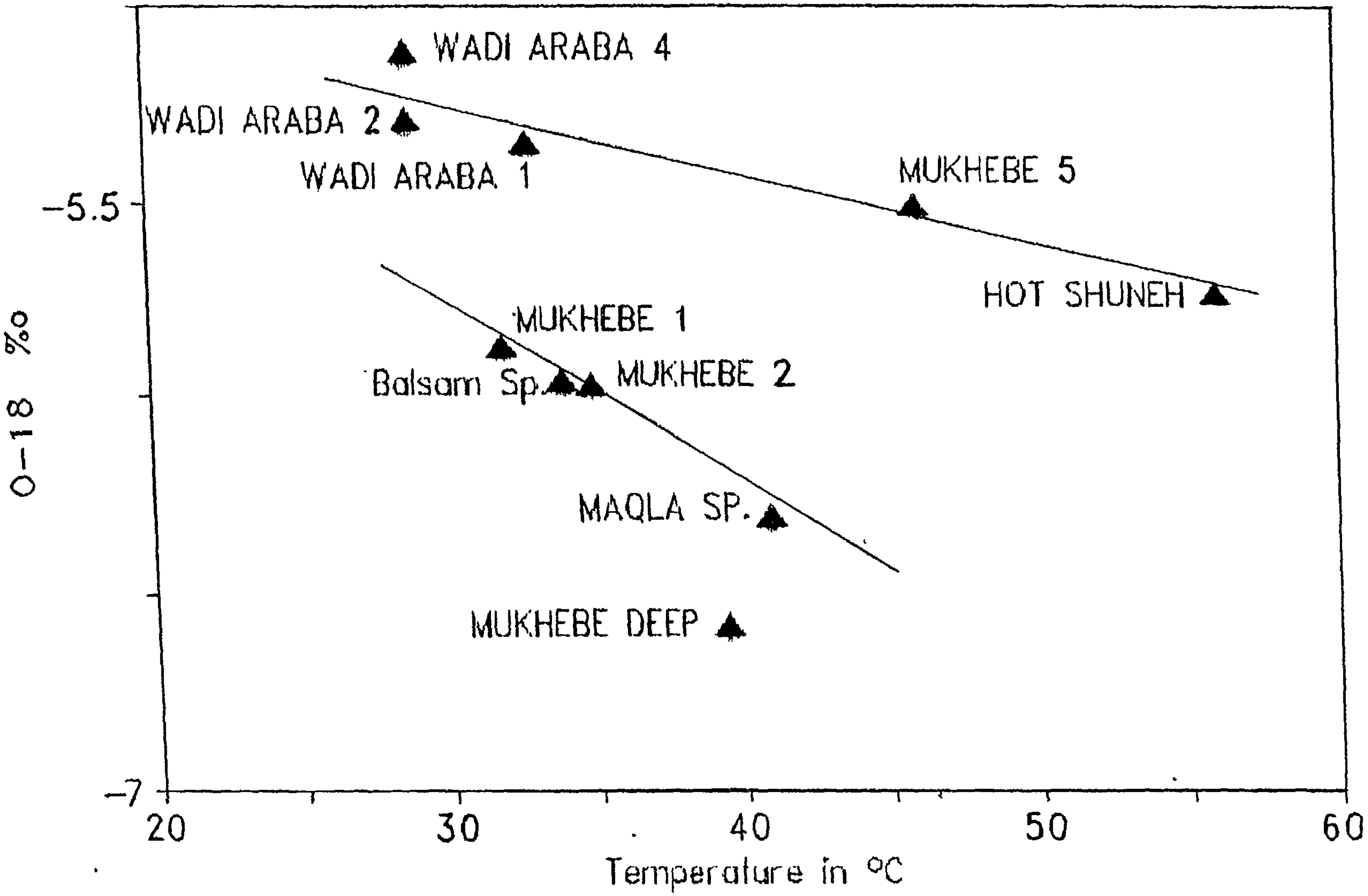

FIG. 11. Temperature - O-18 - diagram.

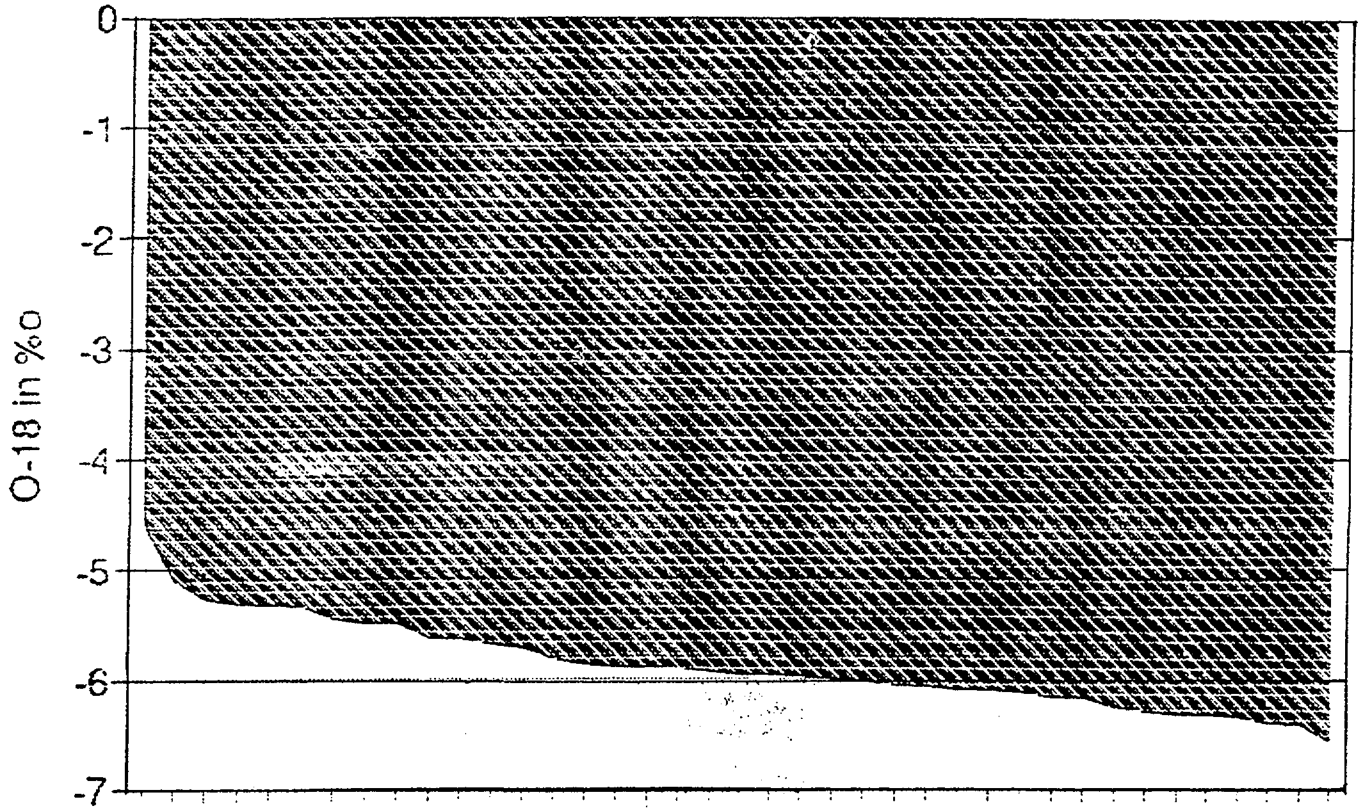

FIG. 12. Frequency distribution of O-18.

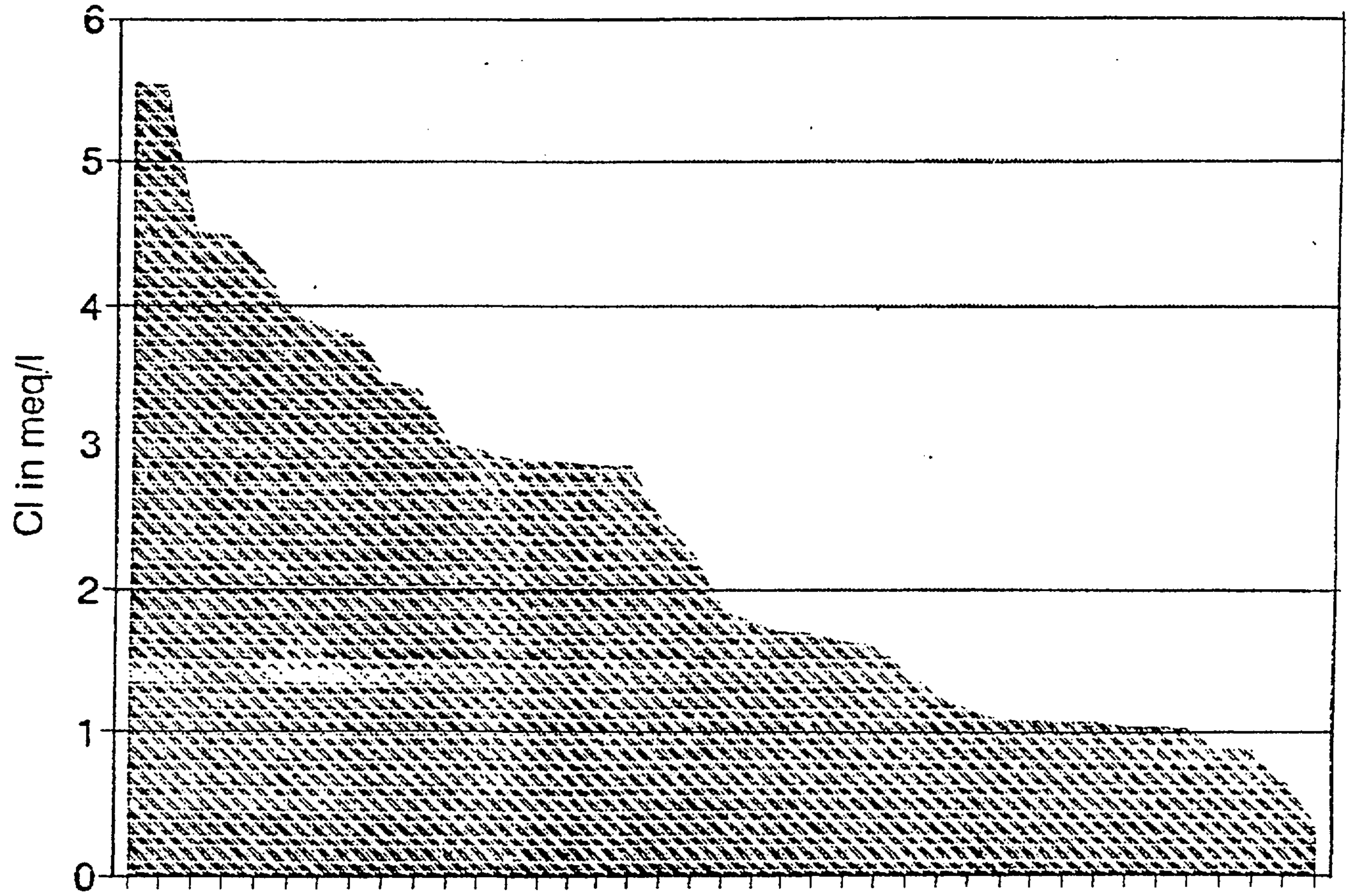

FIG. 13. Frequency distributuin of Cl.

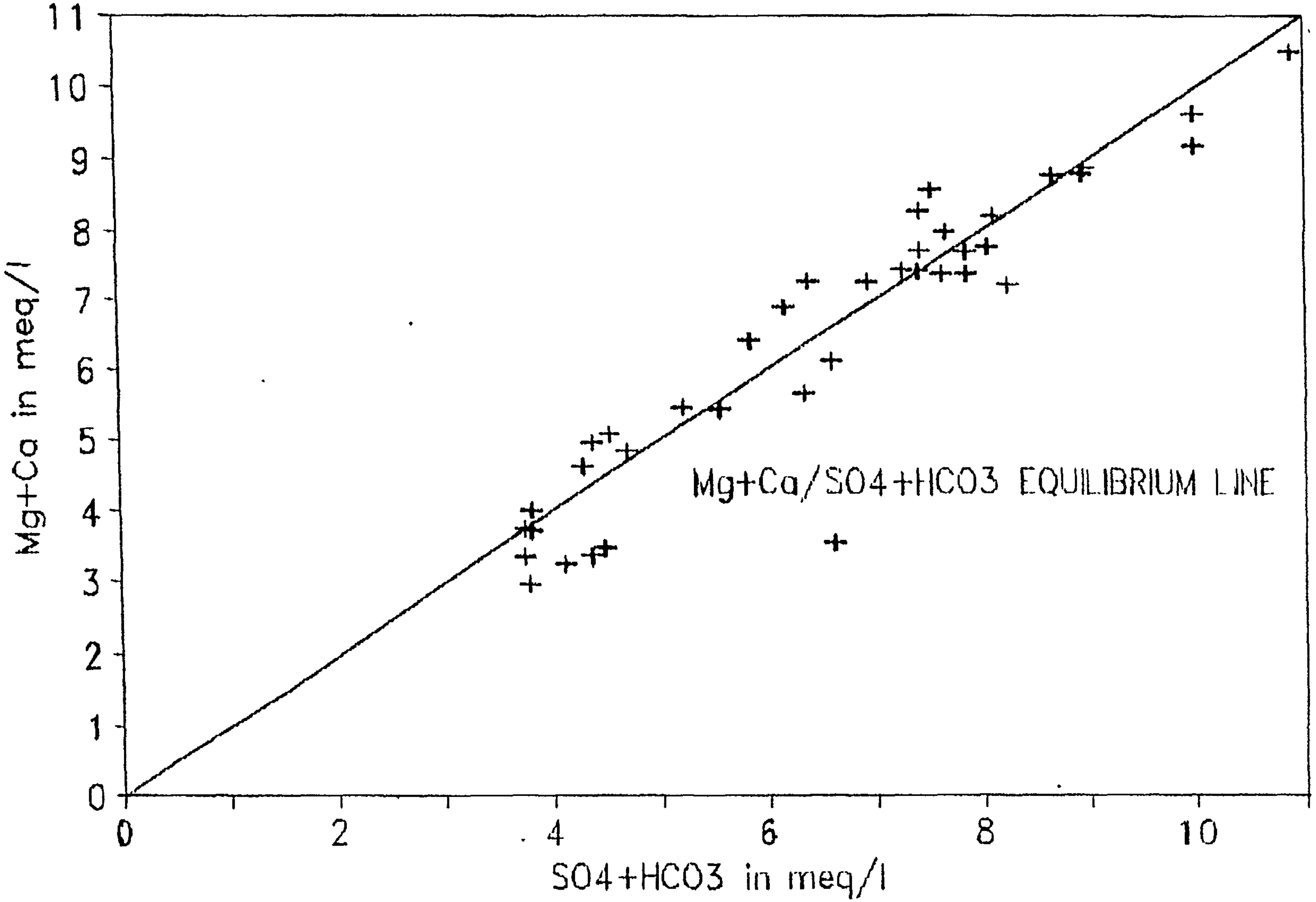

FIG. 14. $Ca + Mg/SO_4 + HCO_3$ - diagram.

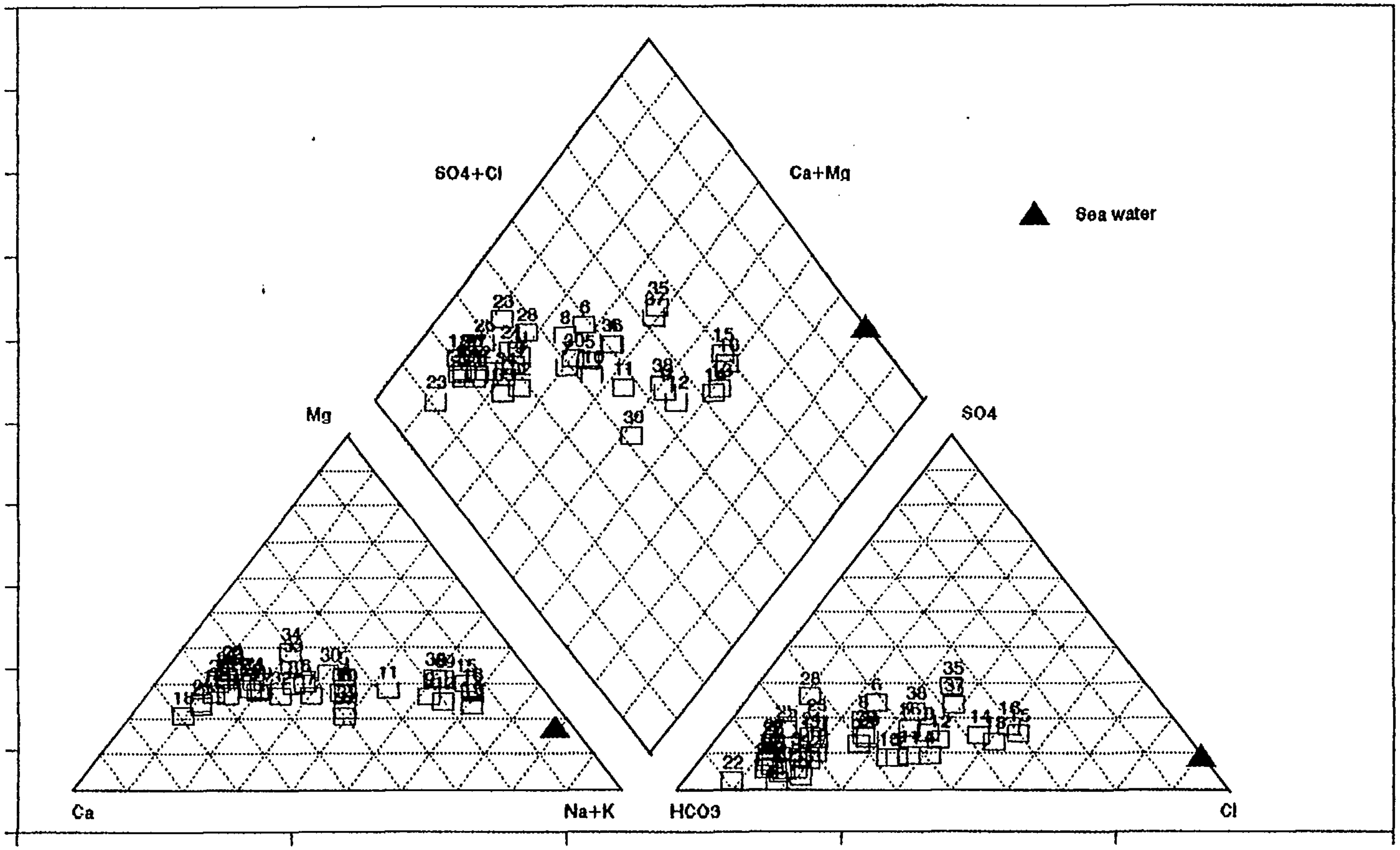

FIG. 15. Yarmouk basin.

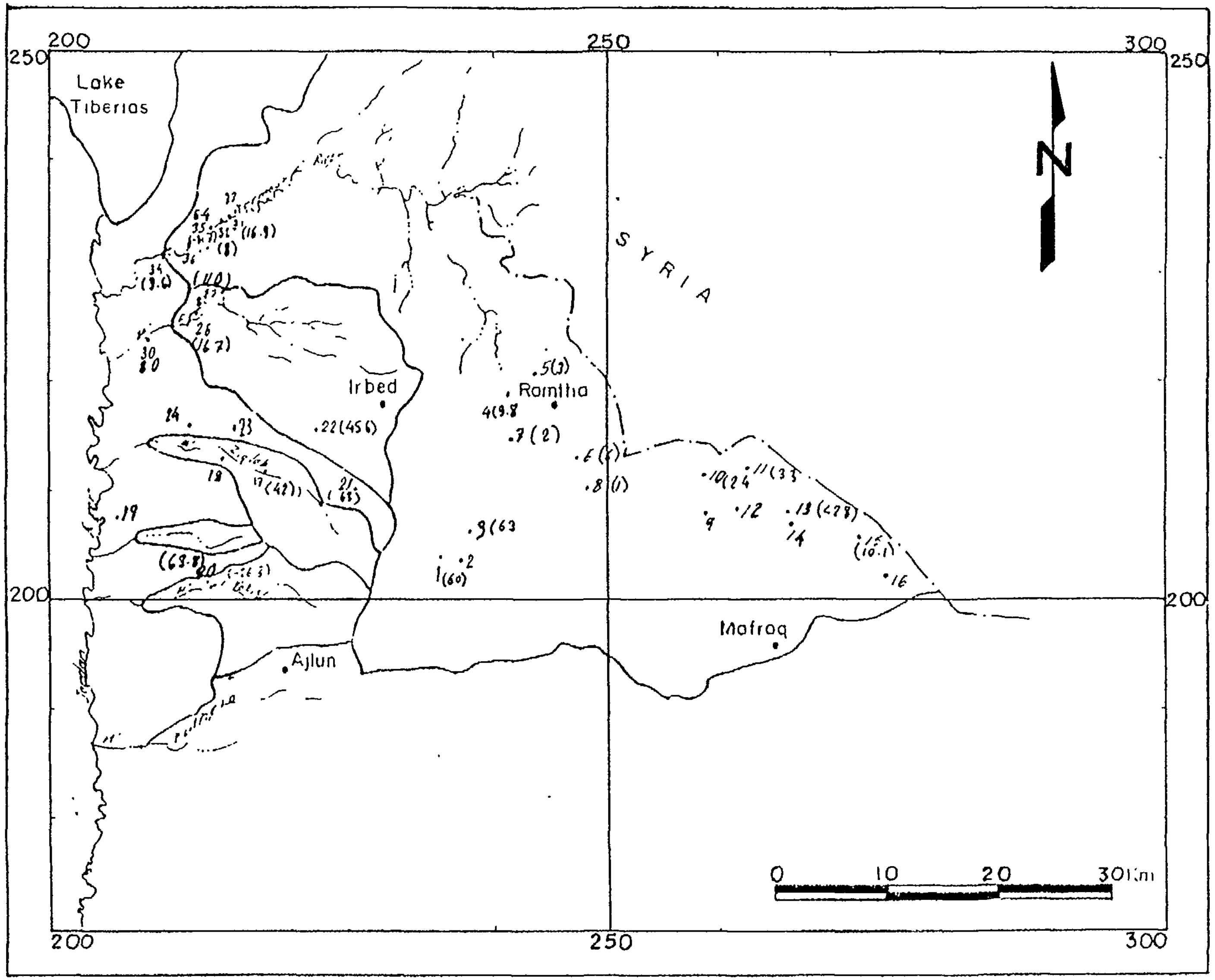

FIG. 16. Carbon-14 distribution (uncor.).

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ENVIRONMENTAL ISOTOPE STUDY OF THE MAJOR KARST SPRINGS IN DAMASCUS LIMESTONE AQUIFER SYSTEMS: CASE OF THE FIGEH AND BARADA SPRINGS

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Abstract

The groundwaters of major karst springs and several piezometers and wells in the Damascus limestone aquifer systems have been investigated using chemical and environmental isotope techniques. The groundwater bodies from different aquifer systems can be differentiated by their chemical and isotopic compositions. The groundwaters emerging from the Cenomanian-Turonian aquifers have lower stable isotope concentrations than those emerging from the Jurassic aquifers. Stable isotopes show that the elevation of the recharge zones of Figeh main spring (2600 m.a.s.l.) is higher than that for Figeh side spring (2100 m.a.s.l). The recharge zones for Harouch and Barada springs have somewhat similar elevation (1700 m.a.s.l). The temporal evolution of stable isotope concentrations shows also the existence of an interconnection between the aquifers of Figeh main spring and Figeh side spring, especially during flood period. The mean residence time of groundwater in Figeh main spring was evaluated to be 50 years in adopting model with exponential time distribution. On a basis of this evaluation, value of about 3.9 billion cubic meters was obtained for the maximum groundwater reservoir size.

1. INTRODUCTION

Environmental isotope techniques in hydrological investigations have been increasingly applied in the overall domain of water resources development and management [1 & 2]. In the case of application in arid and semi-arid zones, where the available water resources are often limited to groundwater, these techniques offer, therefore, a powerful tool in solving the envisaged problems [3].

The hydrogeological investigations using environmental isotope technique for the study of the major karst springs in Damascus limestone aquifer systems were initiated within the framework of the ongoing IAEA Regional Technical Co-operation Project entitled "Isotope Hydrology in the Middle-East (RER/8/002)".

The importance of this study came from the fact that Damascus limestone aquifer systems represent the major resources of water, especially for water supply to Damascus city.

The purpose of this study was, therefore, to assure proper management and development of these aquifer systems on a basis of good assessment of the recharge areas, replenishment rates, groundwater flows, flow directions, mean residence time and storage capacity, as well as to understand the interconnection between aquifer systems.

2. GENERAL CHARACTERISTIC Of THE STUDY AREA

The selected area for this study is situated in the south-western part of Syria, and located between 32° 43' and 33° 55' of latitude N. and 35° 48' and 37° 05' of longitude E. (Fig. 1). This area covers approximately about 8060 km^2.

2.1. TOPOGRAPHY

The topography of the study area is dominated mainly by the fold mountain structure of the Anti-Lebanon, Hermon (Es-sheikh) and Palmyrides and the flat area, so-called Damascus depression, situated in the south-eastern part of the territory. The highest elevation is up to 2814 m.a.s.l. (Mt. Hermon), while the minimum absolute elevation is about 597 m.a.s.l. (Ateibeh Lake). The average elevation of the study area is about 866 m.a.s.l.

2.2. CLIMATE

The climate of the study area is of Mediterranean type characterized by a cool winter and a dry summer with two transitional periods in spring and autumn [4 & 5]. The mean annual air temperature varies between 4.5 °C (elevation of 2800 m.a.s.l.) and 17 °C (elevation of 1000 m.a.s.l.). The climatic zones in the country are shown in figure 2.

2.3. PRECIPITATION

The precipitation patterns over the study area are influenced mainly by the presence of the mountain belts situated in the western part of the region. The average long-term precipitation, which occurs mostly in its liquid form, varies from 90 mm/year in the south-eastern part of the area and 1800 mm/year at the upper parts of Mt. Hermon. The total amount of moisture of condensation estimated for this area is equal to 2 % of the mean annual precipitation [5].

2.4. EVAPORATION AND EVAPOTRANSPIRATION

The long-term average annual evaporation varies from 1500 mm/year in the flat-land region to 1100 mm/year in the mountains, while the evapotranspiration in mountainous area is about 300-400 mm/year and in flat-land region it is close to precipitation (100 mm/year).

2.5. GEOLOGY

The rock exposures in the study area are represented by sedimentary and volcanogenic formations of Jurassic, Cretaceous, Paleogene, Neogene and Quaternary ages [4 & 5].

- The Jurassic deposits reported from Mts. Hermon and Anti-Lebanon are represented mainly by thin layers of limestone, dolomitic limestone and gray dolomite.

- The Cretaceous outcrops known mostly within Anti-Lebanon are characterized by the presence of limestone, marls, dolomite, cherts, sandstone, clay and basalt.

- The Paleogene sediments are represented by carbonate rocks with intercalation of chert-clay and basalt, while the Neogene formation occurs in Zabadani and north-eastern side of Damascus depression is represented by various series of conglomerate, clay, sandstone, gravel, limestone and basalt.

- The Quaternary formations developed mostly in the depressions and the stream's valleys are represented by alluvial-lacustrine and lacustrine-alluvial deposits.

2.6. HYDROGEOLOGY

From hydrogeological point of view, the following major water-bearing systems can be distinguished [4 & 5]:

i- The Cenomanian-Turonian Complex

This complex is widely developed in the fold mountain area and made up of a thick bedded strata (400-1000 m) of dolomite, dolomitic limestone and limestone. It is characterized by the occurrence of fissured and karstified layers with high transmissibility, which show up in the issue of the large springs, among which the most remarkable one, is the Figeh spring. The long-term discharge of this spring ranges from 1.4 m^3/s (dry year) up to 28.3 m^3/s during flood period. The average long-term yield is about 7.7 m^3/s. The massif karstified layers widespread in this complex contribute to intensive infiltration and inflow of atmospheric precipitation. The waters in this aquifer are very fresh (TDS varies from 0.2 to 0.6 g/L) and the water quality is characterized by a calcium-magnesium and bicarbonate type.

ii- Water-Bearing of Lower Jurassic Strata

This aquifer made up of a thick strata of intensively karstified limestone (2000-2200 m) with interbeds of dolomite, limestone is outcropping only in the western part of the study area. The Barada spring, which has a mean long-term yield of about 3.1 m^3/s is the largest spring issuing from this aquifer.

iii- The Alluvial-Proluvial Aquifer

This aquifer composed mostly of Paleogene marine sediments, continental Neogene and Quaternary is characterized by high transmissibility (100-1000 m^2/d) and a maximum thickness of about 93 m. This aquifer is extremely important for agricultural development in Damascus Oasis (Ghotta).

2.7. HYDROLOGY

The drainage network of the study area is controlled mainly by two important streams: the Barada and the Aawaj rivers. The most dense drainage network is found on the slopes of the Anti-Lebanon and Mt. Hermon ridges, where Barada and Aawaj rivers take their resources. The Barada river with a catchment area of about 1380 km^2 is the largest stream in this region. It takes its resources from Barada spring and receives part of its flow from Figeh spring, situated on the left bank of its course. Emerging to the Damascus Ghotta (Oasis), Barada river is subdivided into several irrigation canals. This river reaches Ateibeh Lake only during spring and flood period.

The second important stream is Aawaj river, which take its resources from Mt. Hermon ridges. This stream has a catchment area of about 1120 km^2. Both Barada and Aawaj rivers are fed almost by groundwater.

3. CHEMICAL AND ISOTOPIC CHARACTERISTICS

Several earlier environmental isotope studies were devoted to natural water resources in Damascus region [5, 6, 7, 8 & 9]. Because of the importance of Figeh spring as the major potential reservoir of fresh water being used, especially, for water supply to Damascus city, most of these studies were concentrated on this spring.

3.1. SAMPLING AND ANALYSES

The hydrogeological investigations using environmental isotope techniques were started on June 1989, within the framework of the ongoing IAEA Regional Technical Co-operation Project (RER/8/002). As regards these investigations, two campaigns of sampling were undertaken in this area.

The first campaign of sampling was started on 29/6/1989, during which one sample per month was taken from the major springs (Figeh main spring, Figeh side spring, Harouch and Barada springs) and from Barada river till the end of 1990. Moreover, two samples per month were collected from these sites during flood period.

In the second campaign, which started also at the same time, we tried to sample only twice (during the rainy and the dry seasons) some selected springs, wells and piezometers belonging to the catchment area. The total number of samples collected during these two campaigns is about 130. The groundwater sampling sites in the study area are shown in figure 3.

The water samples were collected in three bottles for the isotopic and chemical analyses. The isotopes being determined in this case study include ^{18}O, ^{2}H and tritium of which the analyses were performed in the Laboratory of Amman/JORDAN. It is also to be noted, that a number of duplicated samples have been sent to the IAEA Laboratory in Vienna in order to carry out intercomparison between isotope concentrations. The chemical analyses of all the groundwater samples were carried out in the Laboratory of Ain El-Figeh Establishment in Damascus. The temperature, electrical conductivity and pH of water samples were taken in the field during sampling.

3.2. GROUNDWATER CHEMISTRY

The chemistry of surface and subsurface waters is a reflection of the interaction between meteoric water and rocks [10].

The mean chemical compositions of water samples collected from the area under investigation are reported in Table I. According to these hydrochemical data, we can note first, that the chemistry of groundwaters belonging to the mountainous regions is characterized by low solute content (< 0.3 g/L). However, the springs emerging from Cenomanian-Turonian aquifers such as Hourirah and Figeh springs are less enriched with solute content than those emerging from Jurassic aquifer (Sarada and Barada springs).

The average temperature of water samples from Figeh main spring (13.7 °C) is lower than that for Figeh side spring (14.7 °C) and Harouch spring (15.9 °C). In all cases, the water temperatures of wells are higher than those of springs. The pH value of water samples in the study area ranges from 6.92 (well no. 4) up to 8.39 in Ain Nsour spring water (no. 16) situated at 2240 m.a.s.l. As can be seen in figure 4, the spatial evolution of total dissolved solids (TDS) shows a progressive increase from the mountainous area towards Damascus depression.

The results of water analyses covering all the investigated aquifers are represented in Piper diagram (Fig. 5). The water chemistry of the majority of groundwater is characterized by a calcium-magnesium and bicarbonate type, with the following ionic sequences: $rHCO_3 > rCl > rSO_4$. In all the cases, the average concentration of Ca^{++} and Mg^{++} exceed that of Na^{+} and K^{+}. This water type is, in fact, a reflection of the predominant rock type in the investigated area, where limestone and dolomite are the most predominant formations. On the other hand, we can observe that groundwaters emerging from Sarada and Ain Hour springs and from Zabadani wells are the only waters characterized by calcium-sulfate type. The high concentration of SO_4^{--} in this aquifer may be explained by the dissolution of gypsum, or by the presence of pyrite in the iron deposits, relatively abundant in this area.

The rMg/rCa ratio of water samples within the study area range from 0.16 in Hourirah spring to 0.79 in Ain Hour spring and Zibdeen well. This ratio is of about 0.6 in Figeh main spring and Figeh piezometers and decrease progressively to 0.44 in Figeh side spring and to 0.40 in Harouch spring.

The temporal evolution of calcium and magnesium concentrations in Figeh side spring, Harouch, Barada river and Barada spring during the sampling period are represented in figure 6, while those for Figeh main spring can be seen in figure 7. The variation of Ca^{++} in Barada spring is rather small, around a value of about 60 mg/L. In the contrary, the Ca^{++} variations in Barada river, Harouch spring and Figeh side spring are more important and decrease more quickly during flood period. As regards Mg^{++} evolution, we observe similar trends to that of Ca^{++} for all of these sites. The evolution of Ca^{++} concentration in Figeh main spring water shows slightly low fluctuations around 40 mg/L, and no decrease during flood period. However, we can observe as Droubi, 1988 [9] an inverse evolution between calcium and magnesium during flood period. This evolution may be explained by the hypothesis given by Droubi, 1988 [9], who considered that the lower part of the groundwater reservoir of Figeh main spring could be made up of rocks, similar to those of water bearing aquifer of Ain Hour (rMg/rCa = 0.76). This part of the total reservoir contributes predominantly, in terms of discharge during dry season and becomes less active during rainy season, where a part of groundwater is emerging from karstified limestone.

3.3. ENVIRONMENTAL ISOTOPES IN GROUNDWATER

The average values of the environmental isotope contents of the groundwater samples collected at different sites of the investigated area are reported in Table II. These data show that springs and wells emerging from the limestone and the dolomitic limestone of Cenomanian-Turonian Complex (Figeh main and side springs and Harouch spring), tend to have lower stable isotope concentrations than those emerging from the Jurassic aquifer such as Barada and Rawda springs and Zabadani wells (Fig. 8 & 9).

The averages of tritium contents in groundwater range from 9.3 TU in Boukeen spring up to 20.2 TU in Ifrah spring. The tritium contents in the discharge springs of Figeh (Figeh main and side springs and Harouch spring), fall in the range from 9.6 to 10.9 TU, while the average of tritium content in Barada spring (13.2 TU) is significantly higher than those of the Figeh discharge springs.

The averages of deuterium excess of the majority of groundwater vary very slightly from 20 ‰. However, we can observe that the deuterium excess is relatively higher in Hourirah and Boukeen springs (d = 23 to 24 ‰), and lower in Zabadani well (1), where d = 13 ‰. The low deuterium excess in Zabadani well indicates probably an enrichment by evaporation. According to these observations, we can conclude that the origin of groundwater emerging from Barada spring is different from that in the Figeh discharge springs. Furthermore, the high contents of tritium in Barada spring could be taken as an indication that groundwater in this spring is younger than that of Figeh discharge springs. The high tritium contents in Hourirah and Boukeen may be due to short turnover time of groundwater or to direct inflow from atmospheric precipitation, where the recharge zones are very close to the springs.

The temporal evolutions of environmental isotope concentrations of groundwater collected from Figeh springs, Barada river and Barada spring are shown in figures 10, 11 & 12. The variations of stable isotope concentrations in Figeh springs indicate distinct independent groundwater bodies to be associated with these two springs, while the stable isotope concentrations are similar during flood period. This indicates, in fact, a mixing of the two groundwater bodies and also a connection between the two water-bearing aquifers, particularly during flood period. The variation of the stable isotope concentrations in Harouch spring, which is different from those in Figeh main and side springs, may indicates a different origin of groundwater. Also, we can note that the fluctuation of stable isotope concentrations in Barada spring is an evidence for other recharge zones than those of Figeh discharge springs. The temporal evolution of stable isotope concentrations and tritium values in Barada river are similar to those of Harouch and Figeh springs, which could be explained by the hypothesis that Barada river is mostly fed by groundwater emerging from the same aquifers. The tritium variations in the Figeh springs have approximately the same trends, indicating probably a similar transit time of groundwater.

In order to study the spatial evolution of environmental isotope concentrations in groundwater bodies, we tried to plot the contour lines of the isotopic values within the study area (Fig. 13, 14 & 15). The contour lines of oxygen-18 values show that the areas where the oxygen-18 is the most depleted, are located in the elevated area expanded towards north-eastern part of the study area. This area corresponds topographically to the Anti-Lebanon fold mountain, where the Figeh discharge springs are emerging. On the other hand, the oxygen-18 contour lines having the same concentration of Barada spring are located in the western part of the study area, and could be expanded towards Lebanon territory. The spatial evolution of stable isotope concentrations towards Damascus depression is shown by a progressive enrichment in the isotopic concentrations, comparable to that of TDS. This evolution could indicate that the groundwaters in Damascus depression are undergone to progressive evaporation process by the increasing distance from the sources. The contour lines of tritium in the investigated area show, also, that the highest tritium values are located in the elevated area, where the stable isotope concentrations are very depleted.

On a basis of the relationship between oxygen-18 and altitude in rain water [11], we tried to estimate the mean elevation of recharge zones of groundwater in the study area. As can be seen in figure 16, a regression line with a depletion for δoxygen-18 of -0.23 ‰ can be plotted to envelop all the sampling points. According to this diagram, the mean elevation of recharge zone of groundwater in Figeh main spring and Figeh piezometers could be of 2600 m.a.s.l. The mean elevation of recharge zones of groundwater in Figeh side spring and Harouch spring are 2100 and 1700 m.a.s.l, respectively. The groundwater in Barada spring seems to be infiltrated from recharge zone having a mean elevation of about 1700 m.a.s.l. Although, the above estimations correspond more or less to the natural topographic situation in the study area, the elevation of recharge zone of groundwater of Figeh main spring seems to be a little bit over estimated, because the areas which should have such an altitude are rather limited to give such flow.

4. TURNOVER TIME OF GROUNDWATER IN FIGEH MAIN SPRING

Attempts have been made to estimate the mean turnover time of groundwater in Figeh main spring. In fact, several models of different transit time distribution have been suggested for the use of tritium in the estimation of mean turnover time of groundwater [12, 13 & 14].

In this study, we adopted model with exponential transit time distribution [14]. This model has proved to be satisfactory for groundwaters in fractured and karst aquifers [14]. The mean residence time calculated by this model is the maximum as compared to other models with different transit time distribution functions.

The tritium input function required for such an evaluation is adopted from the available records of the station of Bet-Dagan, which is the closest IAEA network station to the study area [15] and also from the tritium records obtained during our investigation from 1989 to 1990 [11]. Thus, the earlier missing tritium values for Bet-Dagan were estimated from the correlation with Ottawa data [15].

The tritium output curves were calculated using the convolution integral expressed by the following formula:

$$C_0 = \sum_{\tau=0}^{\infty} C(t-\tau).h(\tau).e^{-\lambda} \qquad [1]$$

where: $$h(\tau) = \frac{1}{\tau_0}.e^{-(1/\tau_0)t} \qquad [2]$$

and $$\tau_0 = \frac{V}{Q} = \frac{\text{volume}}{\text{discharge}} \qquad [3]$$

λ is the radioactive decay constant, and τ_0 is the turnover time of the system.

The calculations of tritium output curves were performed using the program MODEL written in GWBASIC by Y. Yurtsever, IAEA staff member.

The tritium data available from Figeh main spring since 1970, which published by Sogreah [6, 7 & 8] and by Droubi, 1988 [9] has been used together with our tritium data [11] to estimate the mean turnover time (residence time) of the water discharge at the spring.

The discharge hydrograph of the Figeh main spring during the period from June 1989 to November 1990 is given in figure 17. This hydrograph shows that the discharge increases from March to May, and that the maximum of discharge reaches a value of 12.7 m^3/s. The discharge during base flow (dry period) varies between 1 and 3 m^3/s.

The tritium output curves for different values of mean residence time going from 10 to 50 years, can be seen together with the observed mean monthly tritium values during the period from 1970 to 1990 in figures 18 & 19.

The comparison of the observed mean monthly tritium values with the output curves indicates the following:

i- The observed tritium values during the period from 1970 to 1974 show more variation than those observed during the period from 1982 to 1990. This may by due to the contribution of two flow components: fast flow (runoff) with high tritium content (younger water) and base flow with low tritium content (older water). The tritium input during the 1970's having more pronounced variation should be the cause of the observed oscillation at the spring.

ii- Based on the tritium observations available during the period from 1970 to 1990, groundwater emerging in the form of base flow during dry season fall in the range of mean residence time between 40 to 50 years.

In the same way, we tried to compare the output curves with the observed mean annual tritium values during the same period. As can be seen in figures 20 and 21 the mean annual tritium values for the period from 1970 to 1984 fall on the curves between 20 to 40 years, while those after 1985 are situated very close to the curve of 50 years. In fact, we know from the Authority of Ain El-Figeh that the groundwater from this spring was pumped for water supply since 1985, while before that time the groundwater taken from the spring was in its natural flow conditions. This may explain why we could find this increase in the water residence time. In other words, the pumping of groundwater from the spring site has resulted in exploration of mine older water from the groundwater reservoir.

If we consider that the mean discharge of the spring in the form of base flow during the time of investigation was equal to 2.5 m^3/s, the groundwater reservoir size, being involved in providing the base flow, would be about 3.9 billion cubic meters. This estimate of the groundwater reservoir volume is based on a value of mean residence time of 50 years, which signifies the upper limit of the groundwater reservoir size that can be associated with the Figeh main spring.

5. CONCLUSIONS

In conclusion it may be said that the use of chemical and environmental isotope techniques in the investigation of major karst springs in Damascus limestone aquifer systems has proved to be a useful tool in understanding a variety of problems, which could not be solved with conventional methods.

The groundwater bodies from different aquifer systems of Damascus Basin can be differentiated by their chemical and isotopic contents. The groundwaters emerging from Cenomanian-Turonian aquifers have low stable isotope concentrations as well as low solute content. The groundwater emerging from Jurassic aquifer have higher solute content and higher stable isotope concentrations than those of the Cenomanian-Turonian aquifers. The aquifers of Figeh main spring and Figeh side spring are interconnected, especially during flood period.

The elevation of the recharge zones for the Cenomanian-Turonian aquifer systems ranges from 1700 m.a.s.l (Harouch spring) to 2600 m.a.s.l. (Figeh main spring). The elevation of recharge zones for Figeh side spring (2100 m.a.s.l) is lower than that for Figeh main spring. The elevation of the recharge zones for the Jurassic aquifer is of about 1700 m.a.s.l.

The mean residence time of groundwater in Figeh main spring varies within the range from 20 to 50 years in adopting model with exponential time distribution. The residence time of groundwater taken after 1985 has increased as a result of pumping mine older water.

The maximum groundwater reservoir size of Figeh main spring reaches a value of about 3.9 billion cubic meters, based on a value of mean residence time of 50 years and a value of base flow of 2.5 m^3/s.

Table I. Mean chemical composition of groundwater samples collected in the Damascus aquifer systems during 1989-1990

No	Location	Type	Sample size	T (°C)	pH	E.C (μS/cm)	Ca^{++} (mg/L)	Mg^{++} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^- (mg/L)	SO_4^{--} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	TDS (mg/L)
1	Tichreen	W	1	18.0	7.27	516	88	20.0	10.0	1.0	317	20.0	20.0	17.0	335
2	Mazraa	W	1	12.5	7.32	660	84	29.0	18.0	2.0	317	22.0	40.0	36.0	390
3	Ghotta	W	1	17.5	7.28	640	92	44.0	29.0	1.0	354	30.0	92.0	32.0	500
4	Zibdeen	W	1	16.0	6.92	861	116	32.0	40.0	3.0	439	30.0	70.0	22.0	535
5	Ifrah	S	2	13.8	7.98	260	44	10.0	5.5	3.3	128	20.5	13.0	16.5	177
6	Bidda	S	2	11.5	7.76	248	48	7.5	2.5	0.8	147	14.5	7.0	8.0	162
7	Hourirah	S	2	14.3	8.19	178	38	3.5	2.5	0.5	110	6.5	7.0	8.5	122
8	Boukeen	S	2	12.5	7.99	262	40	16.0	2.5	0.8	183	3.5	6.0	8.5	169
9	Abou-Zad	S	2	11.8	7.99	265	48	9.5	4.0	0.5	159	7.5	7.0	14.5	170
10	Sarada	S	2	13.5	7.58	473	80	17.0	4.5	2.0	146	130.0	10.0	14.5	331
11	Rawda	W	2	16.0	7.63	344	70	7.0	4.5	0.8	214	12.0	11.0	11.0	223
12	Zabadani (1)	W	2	17.3	7.35	792	108	34.0	15.5	2.8	403	34.0	30.0	37.5	463
13	Zabadani (2)	W	1	16.0	7.00	713	132	17.0	13.0	2.0	378	40 0	30.0	39.0	465
14	Der Mokaren	W	2	20.3	7.77	321	44	20.0	5.0	1.0	207	8.0	10.0	10.0	200
15	Al-Dawlah	W	1	11.5	7.94	284	52	2.0	3.0	0.5	146	5.0	6.0	9.0	155
16	Ain Nsour	S	2	11.5	8.39	241	48	4.5	3.0	0.5	140	5.0	6.0	10.5	150
17	Ain Aourk	S	2	14.5	8.39	249	42	12.0	3.0	0.5	165	13.5	9.0	8.0	171
18	Ain Hour	S	1	12.5	8.05	275	36	17.0	2.5	0.5	134	37.0	6.0	8.0	174
19	Figeh m.s	S	20	13.7	7.91	253	40	14.5	2.2	0.7	173	4.6	6.0	9.3	164
20	Figeh s.s	S	20	14.7	7.62	339	57	15.3	3.5	0.9	220	10.6	8.2	9.7	217
21	Figeh x45	P	1	13.6	7.92	295	40	15.0	3.0	0.5	183	6.0	6.0	9.0	170
22	Figeh x43	P	1	15.0	7.80	295	40	15.0	3.0	0.5	183	6.0	6.0	9.0	170
23	Figeh x14	P	1	15.0	7.92	288	40	15.0	3.0	0.5	183	6.0	6.0	9.0	170
24	Harouch	S	20	15.9	7.45	404	71	17.1	3.1	1.6	261	17.1	10.0	10.4	263
25	Barada	S	20	15.1	7.59	313	60	10.5	3.2	0.6	209	7.4	7.3	8.6	202
26	Barada	R	18	16.4	7.76	484	78	17.5	13.1	2.7	286	23.3	21.6	9.6	309

Where: W, well; S, spring; P, piezometer; R, river; m.s, main spring and s.s, side spring. Samples from Barada River were collected at Chadirwan site.

Table II. Mean isotopic composition of groundwater samples collected in the Damascus Aquifer Systems during 1989-1990

No	Location	Type	Sample size	T (°C)	pH	E.C (μS/cm)	Depth (m)	Altitude (m.a.s.l)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	d (‰)
1	Tichreen	W	1	18.0	7.27	516	15	710	-8.26	-45.3	11.2	20.8
2	Mazraa	W	1	12.5	7.32	660	80	710	-8.43	-46.5	11.7	20.9
3	Ghotta	W	1	17.5	7.28	640	80	640	-7.93	-44.3	11.8	19.1
4	Zibdeen	W	1	16.0	6.92	861	20	640	-8.16	-45.3	12.9	20.0
5	Ifrah	S	2	13.8	7.98	260		1460	-8.22	-44.4	20.2	21.4
6	Bidda	S	2	11.5	7.76	248		1720	-8.13	-43.5	24.4	21.5
7	Hourirah	S	2	14.3	8.19	178		1500	-8.84	-46.6	16.9	24.1
8	Boukeen	S	2	12.5	7.99	262		1260	-8.77	-46.7	9.3	23.5
9	Abou-Zad	S	2	11.8	7.99	265		1600	-8.26	-46.4	17.0	19.7
10	Sarada	S	2	13.5	7.58	473		1380	-8.35	-45.7	15.2	21.1
11	Rawda	W	2	16.0	7.63	344	265	1280	-7.83	-42.0	15.4	20.6
12	Zabadani (1)	W	2	17.3	7.35	792	70	1115	-6.64	-41.4	8.8	13.3
13	Zabadani (2)	W	1	16.0	7.00	713	60	1160	-7.68	-41.0	13.0	20.4
14	Der Mokaren	W	2	20.3	7.77	321	220	980	-8.34	-47.1	5.0	19.6
15	Al-Dawlah	W	1	11.5	7.94	284	60	1660	-8.35	-45.4	17.2	21.4
16	Ain Nsour	S	2	11.5	8.39	241		2240	-8.45	-46.4	13.8	21.2
17	Ain Aourk	S	2	14.5	8.39	249		1280	-8.53	-45.9	11.5	22.3
18	Ain Hour	S	1	12.5	8.05	275		1450	-8.50	-46.3	14.3	21.7
19	Figeh m.s	S	20	13.7	7.91	253		860	-9.00	-51.9	9.7	20.1
20	Figeh s.s	S	20	14.7	7.62	339		860	-8.50	-47.8	9.6	20.2
21	Figeh x45	P	1	13.6	7.92	295	20	860	-9.03	-51.6	10.9	20.6
22	Figeh x43	P	1	15.0	7.80	295	20	860	-9.07	-52.2	10.8	20.4
23	Figeh x14	P	1	15.0	7.92	288	20	860	-8.90	-51.2	9.9	20.0
24	Harouch	S	20	15.9	7.45	404		860	-8.02	-43.9	10.4	20.3
25	Barada	S	20	15.1	7.59	313		1100	-7.90	-41.7	13.2	21.5
26	Barada	R	18	16.4	7.76	484		840	-8.00	-44.4	10.5	19.6

Where: W, well; S, spring; P, piezometer; R, river; m.s, main spring and s.s, side spring. Samples from Barada River were collected at Chadirwan site.

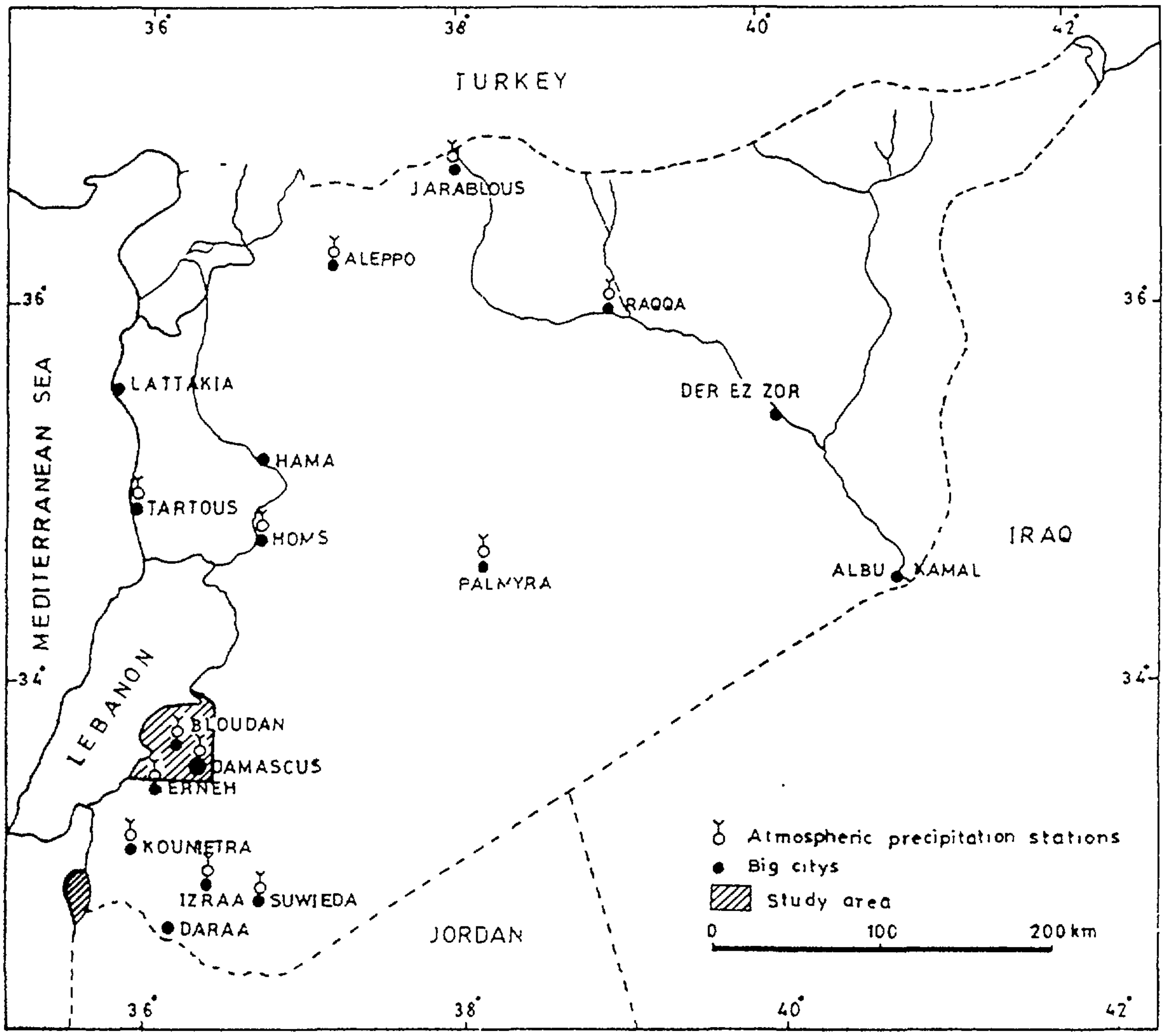

Fig. 1. Location map of the area under investigation showing the network of precipitation sampling sites in Syria

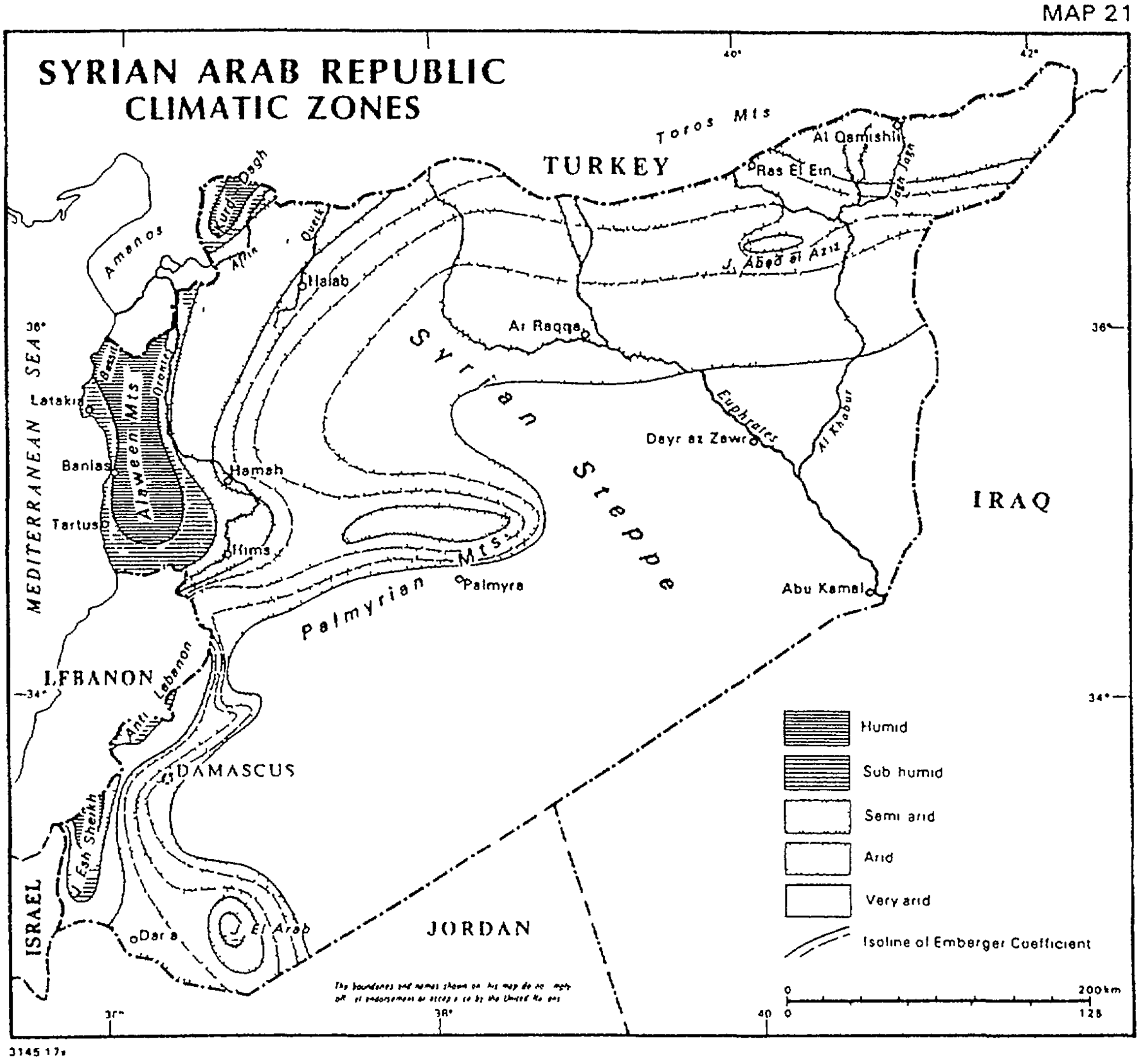

Fig. 2. Map of the climatic zones in Syrian Arab Republic [4]

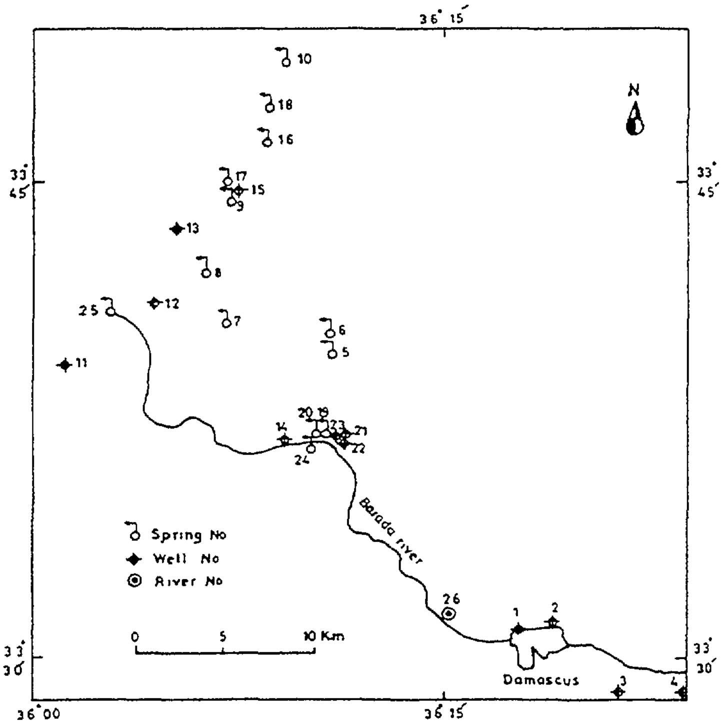

Fig. 3. Location map showing the water sampling sites in the study area

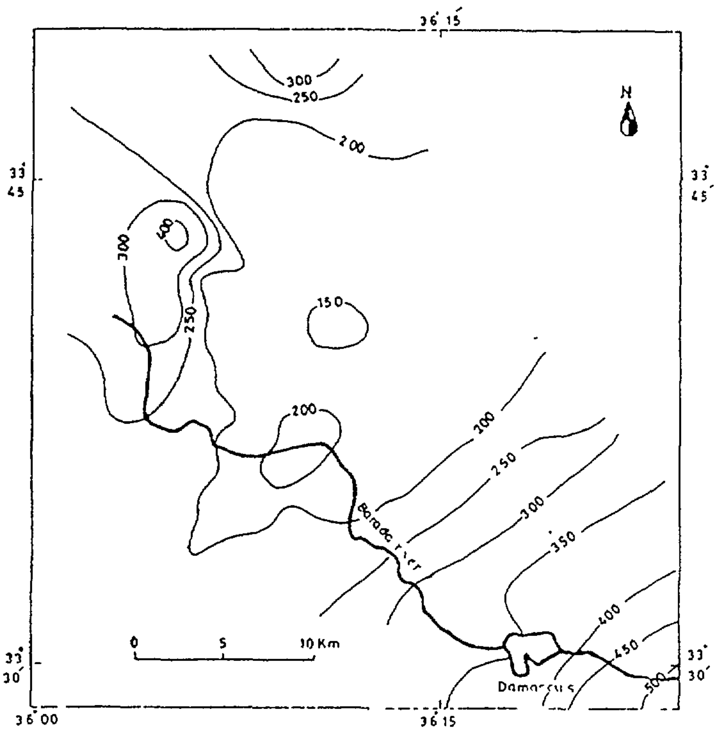

Fig. 4. Spatial distribution of the TDS content (mg/L) of the groundwater in the study area

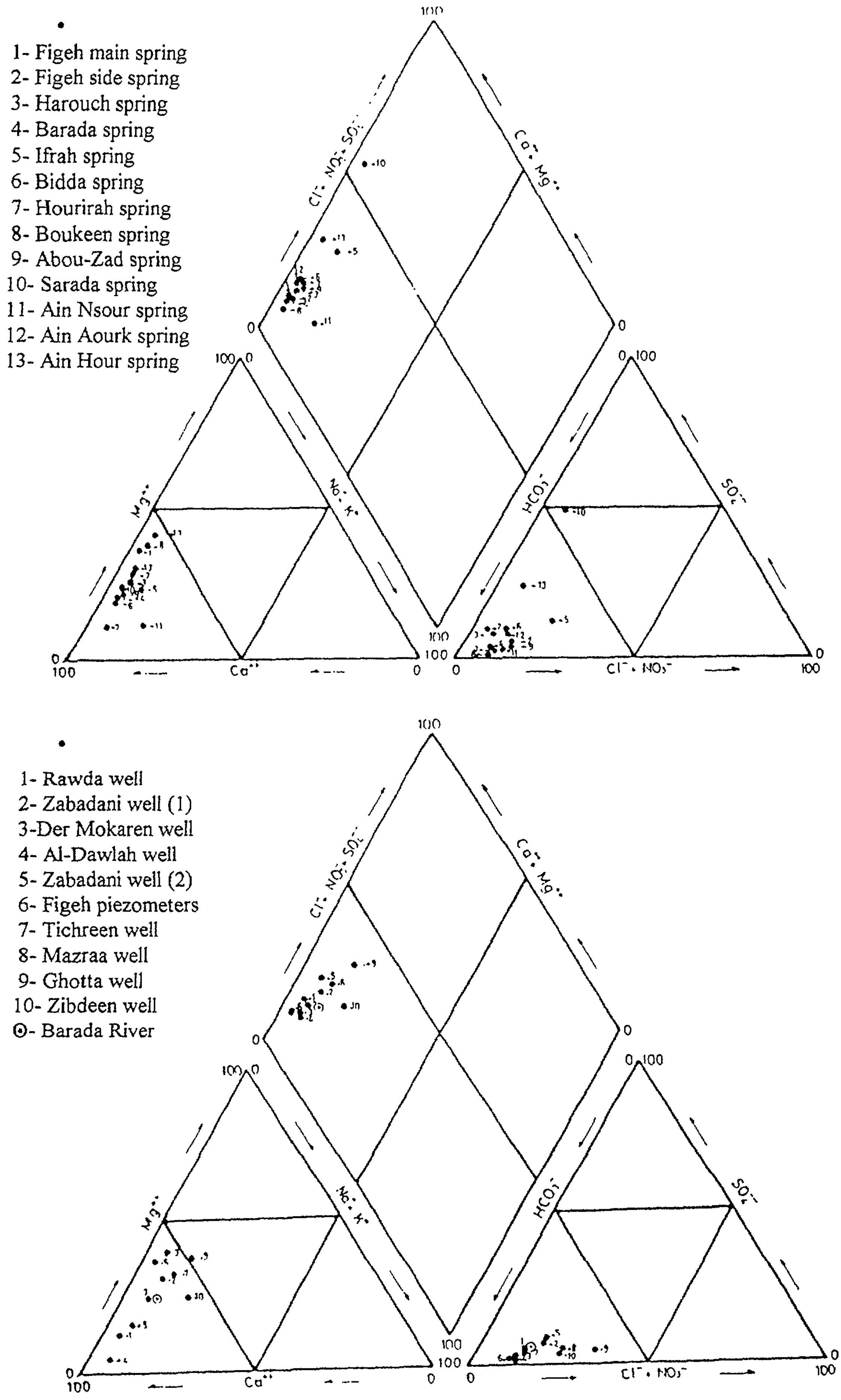

Fig. 5. Piper diagram of the chemical composition of groundwater samples collected from the study area

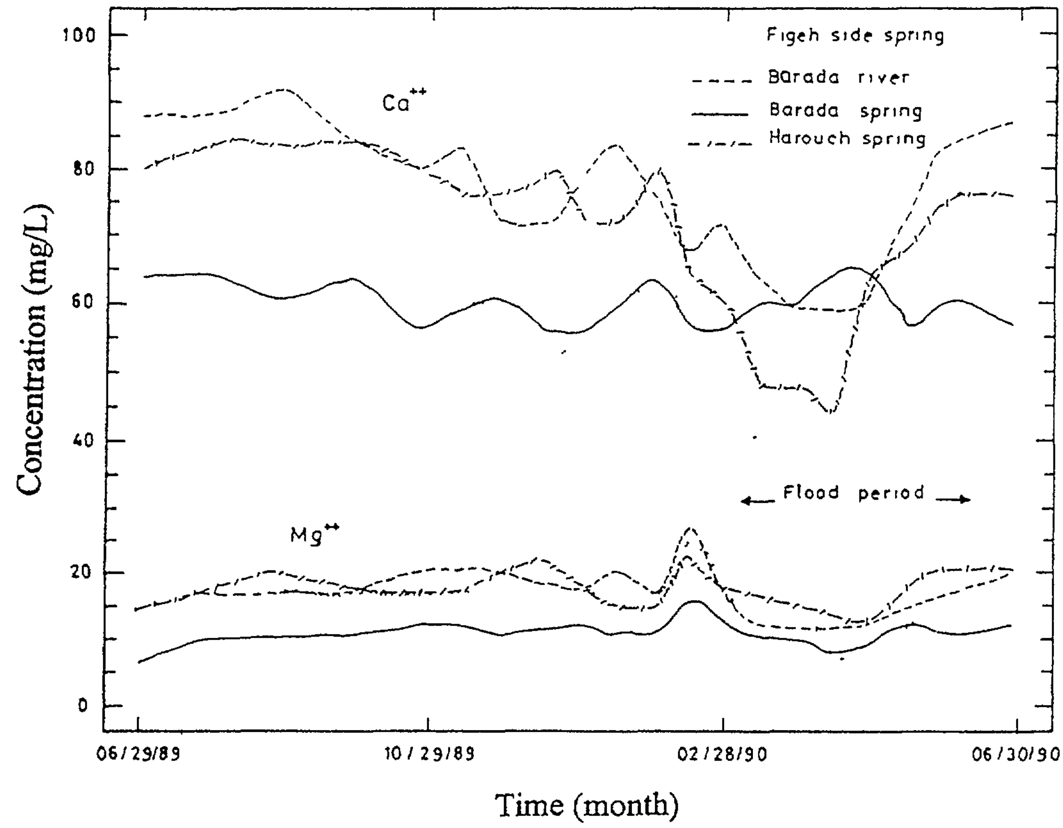

Fig. 6. Temporal evolution of Ca^{++} and Mg^{++} concentrations of the groundwater collected from different sites in the study area

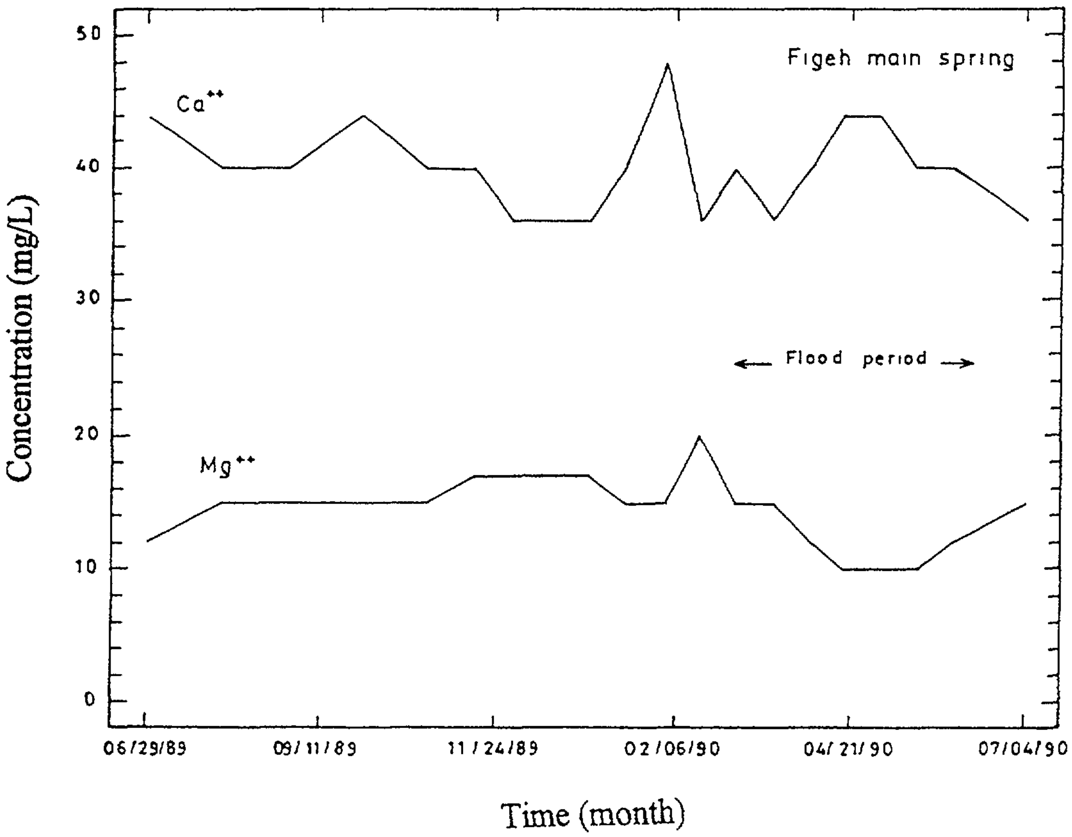

Fig. 7. Temporal evolution of Ca^{++} and Mg^{++} concentrations of the groundwater collected from Figeh main spring

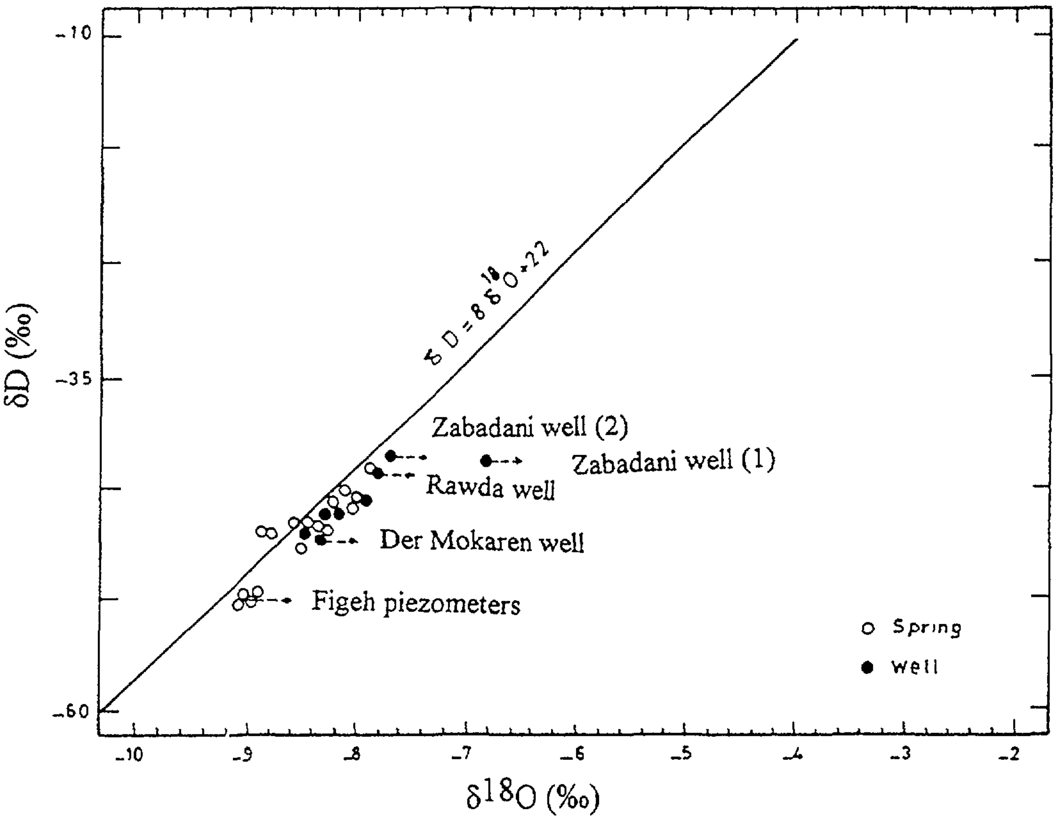

Fig. 8. Relationship between $\delta^{18}O$ and δD values of the groundwater samples collected from different sites in the study area

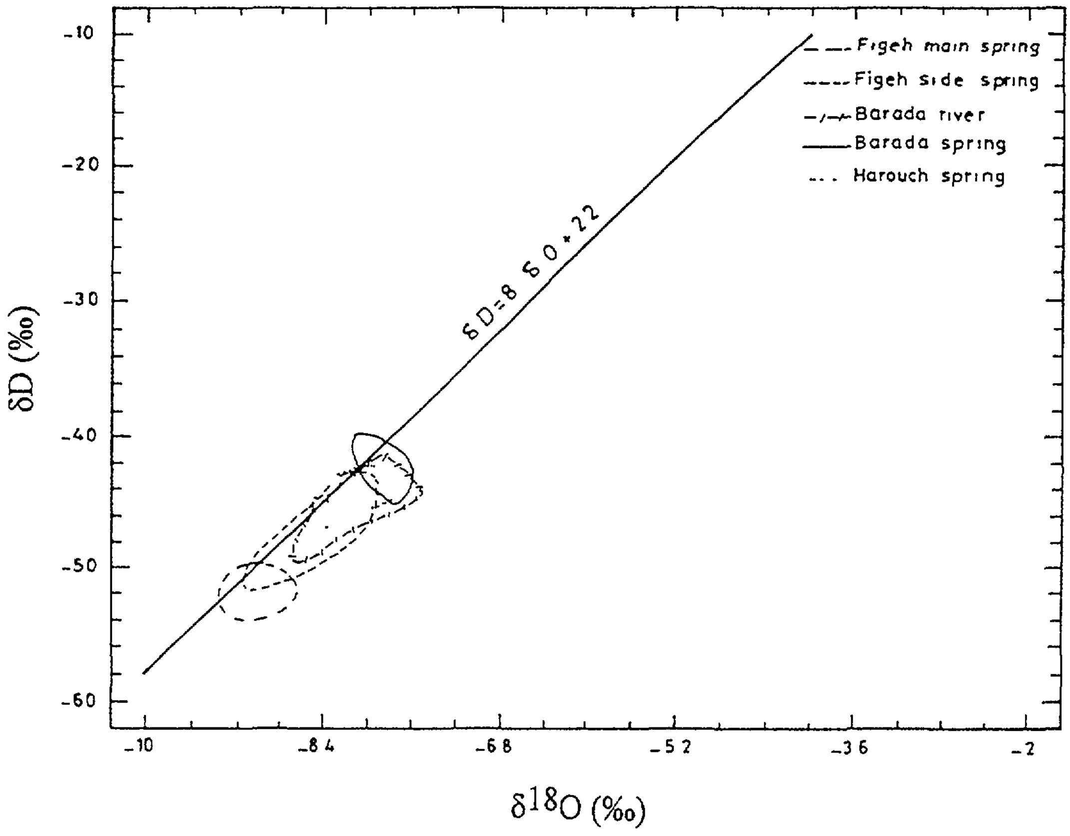

Fig. 9. Relationship between $\delta^{18}O$ and δD values of the groundwater samples collected from different sites in the study area

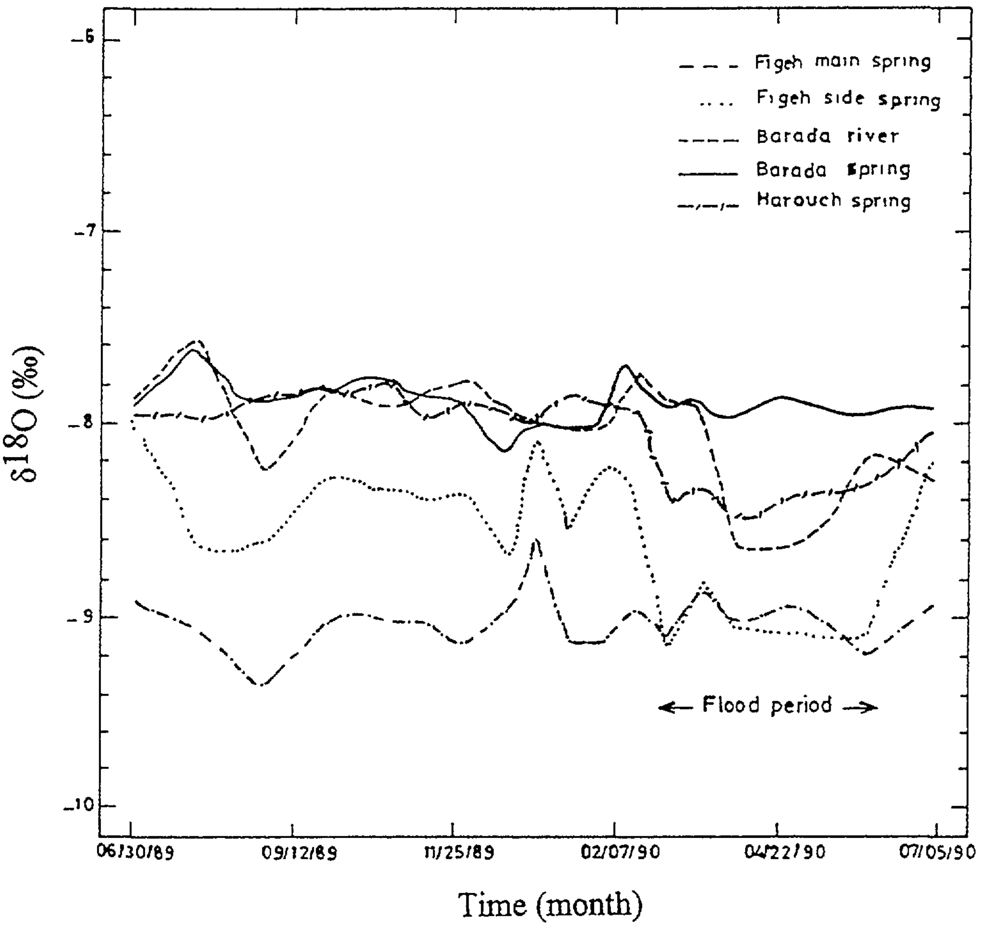

Fig. 10. Temporal evolution of $\delta^{18}O$ values of the groundwater collected from different sites in the study area

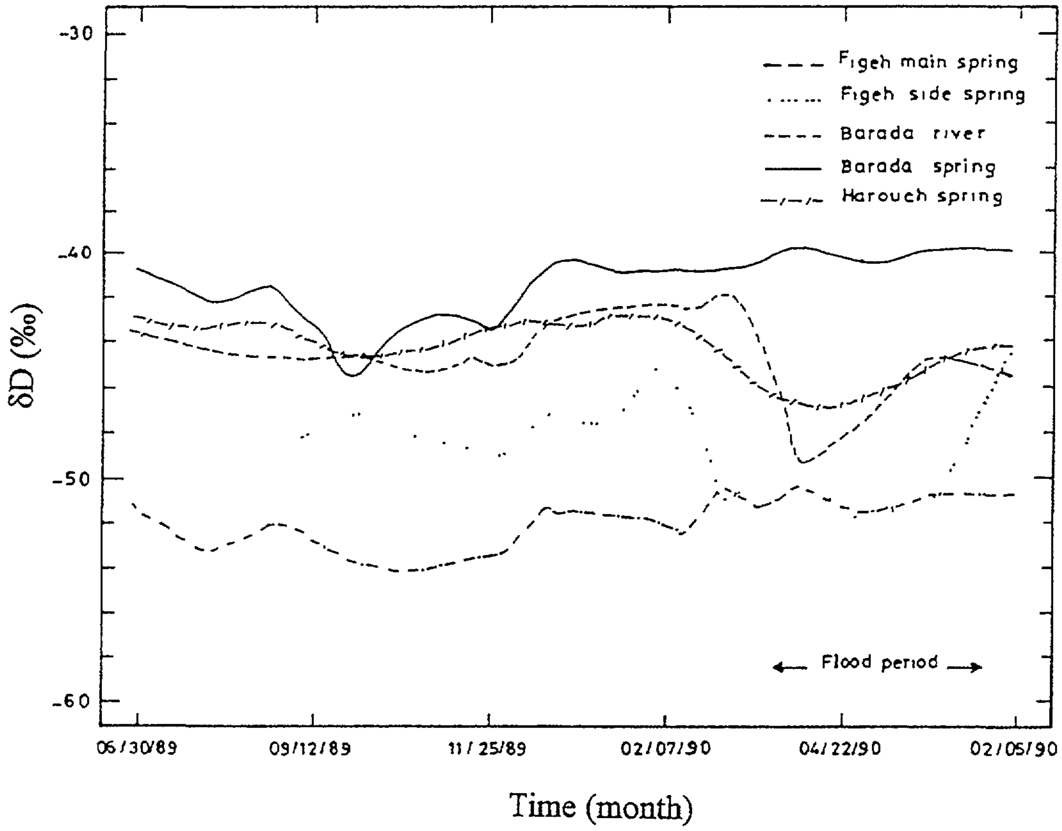

Fig. 11. Temporal evolution of δD values of the groundwater collected from different sites in the study area

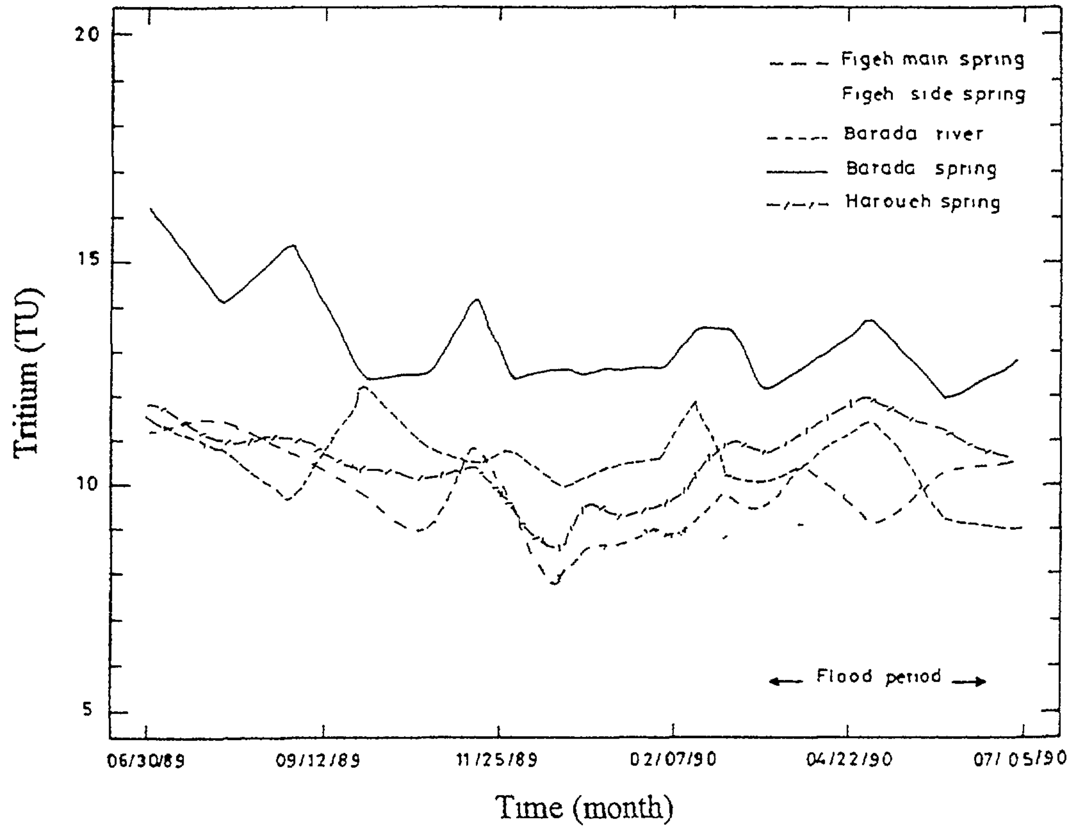

Fig. 12. Temporal evolution of tritium values of the groundwater collected from different sites in the study area

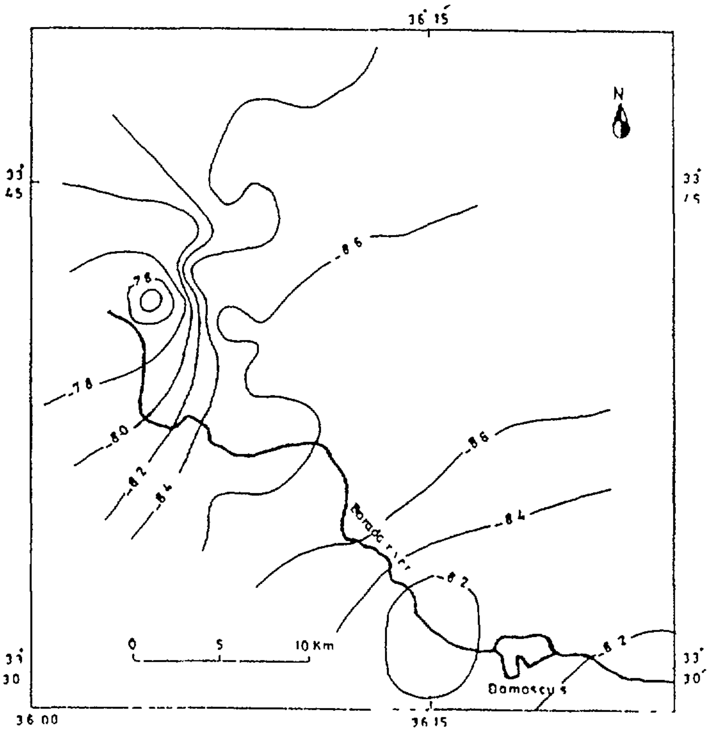

Fig. 13. Spatial distribution of the $\delta^{18}O$ values of the groundwater in the study area

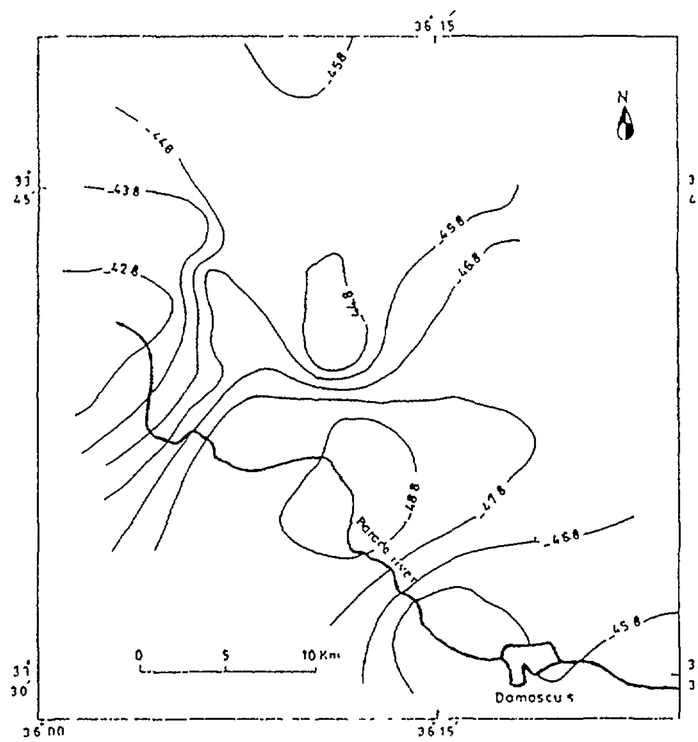

Fig. 14. Spatial distribution of the δD values of the groundwater in the study area

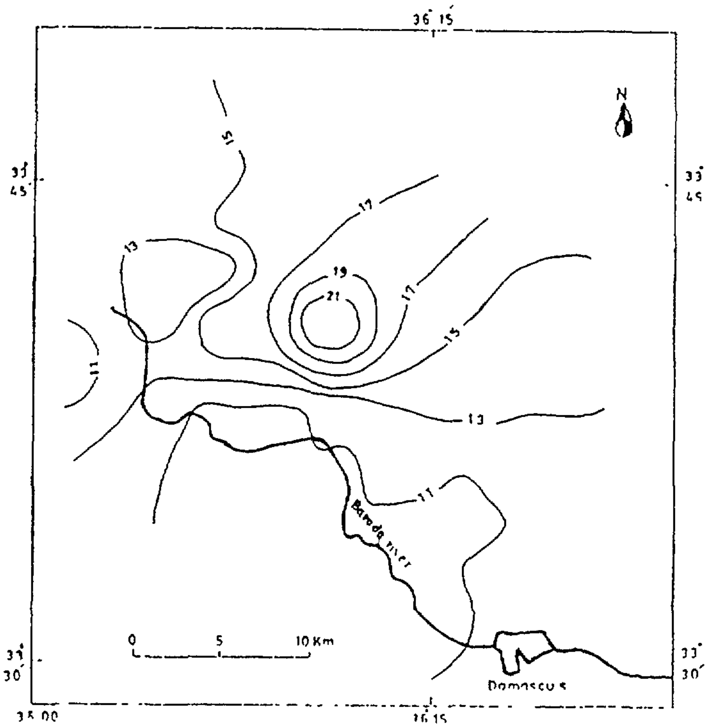

Fig. 15. Spatial distribution of the tritium values of the groundwater in the study area

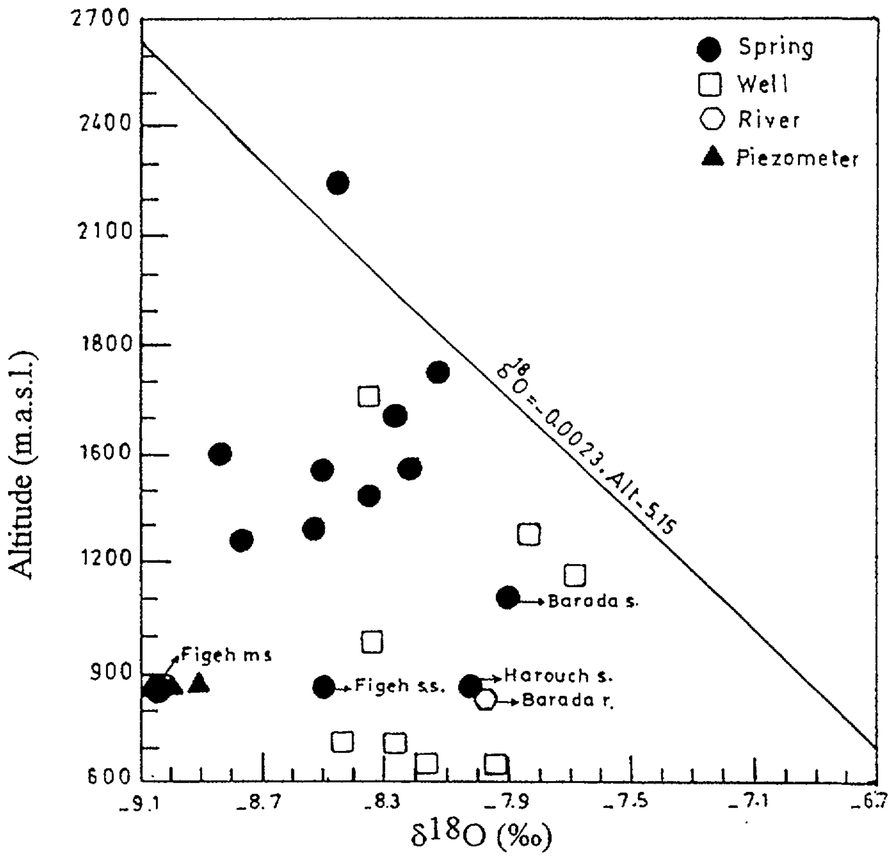

Fig. 16. Relationship between δ^{18}O values and the altitude for the groundwater samples collected from different sites in the study area

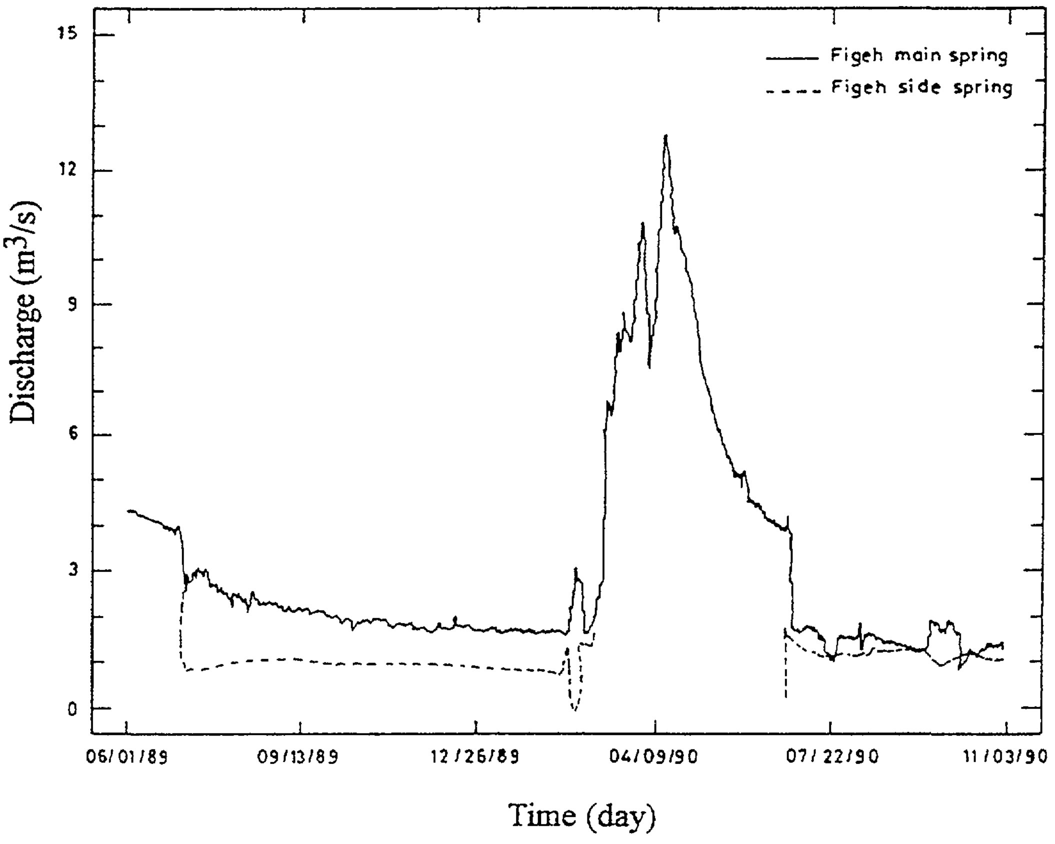

Fig. 17. Temporal evolution of discharge values of Figeh main spring and Figeh side spring during the period of study

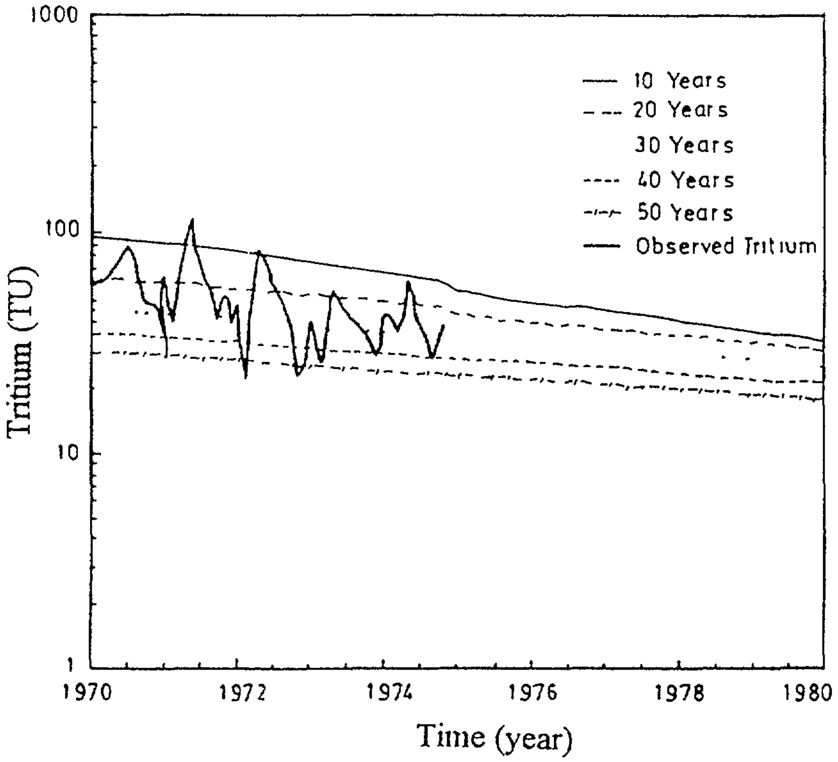

Fig. 18. Calculated tritium output curves for different turnover times and the mean monthly observed tritium values in Figeh main spring from 1970 to 1980

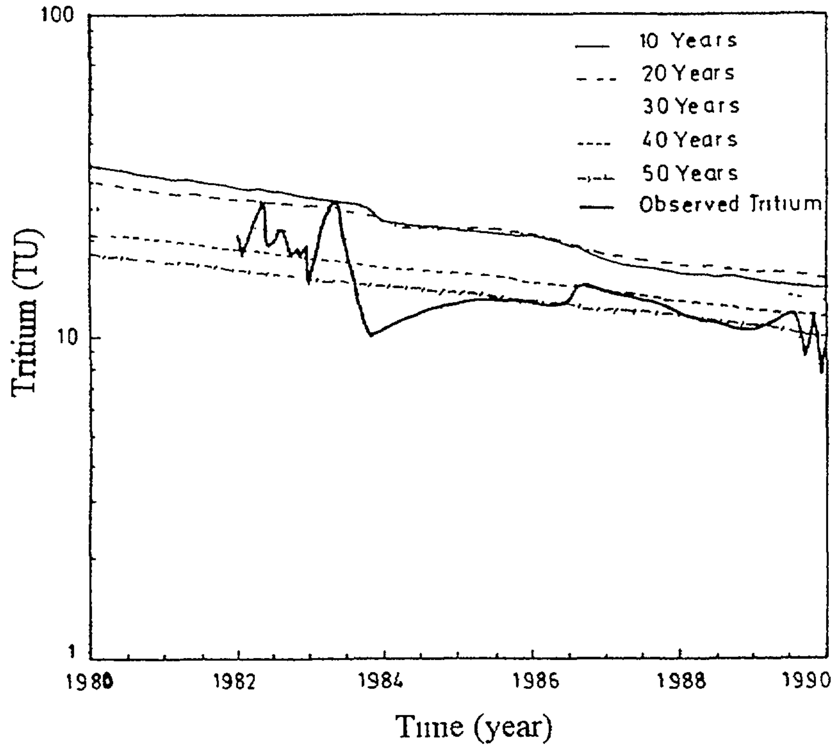

Fig. 19. Calculated tritium output curves for different turnover times and the mean monthly observed tritium values in Figeh main spring from 1980 to 1990

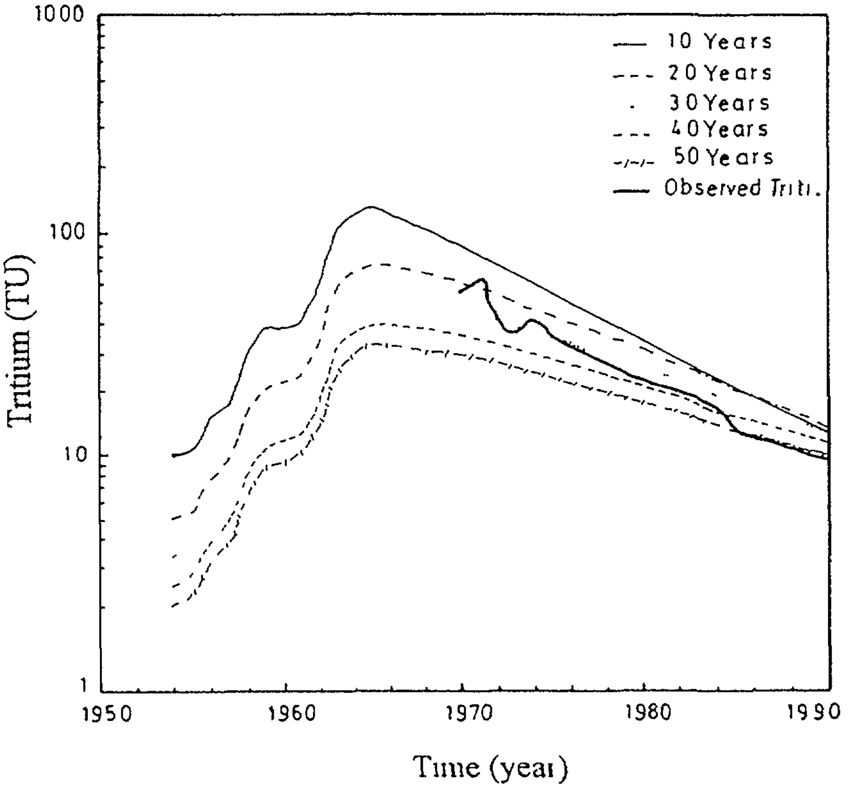

Fig. 20. Calculated tritium output curves for different turnover times and the mean annual observed tritium values in Figeh main spring from 1950 to 1990

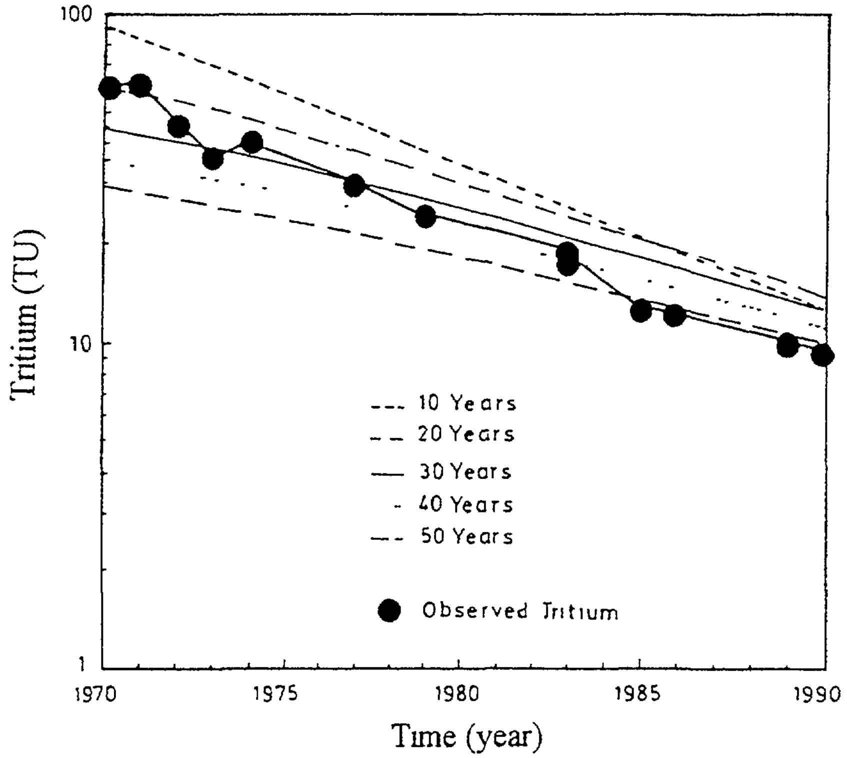

Fig. 21. Calculated tritium output curves for different turnover times and the mean annual observed tritium values in Figeh main spring from 1970 to 1990

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CHEMICAL AND ENVIRONMENTAL ISOTOPE STUDY OF THE FISSURED BASALTIC AQUIFER SYSTEMS OF YARMOUK BASIN, SYRIA

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Abstract

The water in the fissured basaltic aquifer systems and the Upper Jurassic aquifer of the Yarmouk Basin have been investigated using chemical and environmental isotope techniques. The groundwaters flowing through the different aquifers are differentiated by their chemical ratios and their isotopic compositions. The evolution of chemical facies of groundwater from the recharge area towards the basin outlet is characterized by increasing of sodium and magnesium contents as a result of silicate leaching. The stable isotope compositions of spring waters match the Mediterranean Meteoric Water Line, while the groundwaters from the central zone and from the major springs of the Yarmouk Basin are mixtures of freshwater, which is isotopically depleted and salty groundwater of Laja plateau area. The interpretations of tritium and radiocarbon (^{14}C) data indicate that the recharge zones of the groundwater in the Yarmouk Basin occur on the high-land of more than 1000 m of altitude. The residence time of the mountainous springs is short (of about 40 years or less). However, water ages corrected by Vogel's concept and Gonfiantini's Model show, in general, a range from 1000 to 11000 years for the central zone groundwater. The groundwater moves from the Mt. Hermon and Mt. Arab towards the central zone and from the north-east (i.e. the Laja plateau) towards south-west (i.e. the major springs). The radiometric flow velocities range from 20 to 60 m/year within the central zone, while the flow velocities from both sides of Mt. Hermon and Mt. Arab are lower (1-7 m/year).

1. INTRODUCTION

The fissured basaltic aquifer systems of Yarmouk Basin are among the most important aquifer systems for the drinking water supply of Syria. In fact, the continuous increasing demand of water of rapidly growing population and expanding agriculture was the primal cause to conduct this study.

The development and management of the water resources in the Yarmouk Basin play an outermost role in the development of the national economy: for the water supply of three big citys (Suwieda, Daraa and Kounietra) and many villages belonging to this basin and for realizing the irrigation plan in this area, which is considered as an important sector for agricultural production in the country.

The main objective of this study was to make a supplementary assessment of the availability of water resources on the basis of a better understanding of the hydrological and hydrogeological features. This includes the localization of recharge zones, estimation of the groundwater flow dynamics as velocity and direction, residence time and groundwater ages as well as the identification of hydraulic interconnection between the aquifer systems.

The hydrological investigation of the fissured basaltic aquifer systems of the Yarmouk Basin, using chemical and environmental isotope techniques was initiated within the framework of the on-going IAEA Regional Technical Co-operation Project entitled " Isotope Hydrology in the Middle-East (RER/8/002)".

2. GENERAL CHARACTERISTICS OF THE STUDY AREA

The Yarmouk Basin is situated in the south-western part of Syria and located between 32°15' and 33°20' N. and between 35°45' and 36°45' E. (Fig. 1). This basin is located in both Syria and Jordan, It covers in Syria an area of about 5700 km^2. The remaining 25 % of the basin land belongs to Jordan.

2.1. RELIEF

The relief of the study area has formed as a result of intensive volcanic and erosion activities during the Pliocene and Quaternary [1]. The elevation ranges from 0 in the deep erosion river valley up to 2200 m at the slopes of Mt. Hermon (Ash-Sheikh). In general, the relief is dominated by the presence of the piedmont and slopes of Mt. Hermon in the north-west (1100-2200 m.a.s.l), the Golan Heights with numerous volcanic cones in the west (up to 1200 m.a.s.l), the Mt. Arab in the east (up to 1790 m.a.s.l) and the volcanic plateau (Hauran plateau) in the central part (Fig. 2). The volcanic plateau rises from 250 to 800 m.a.s.l. Several valleys cut the flat plain of the Yarmouk River and its tributaries down to 200 m.

2.2. CLIMATE

The climate of the Yarmouk Basin is of Mediterranean type characterized by a rainy cool winter and a dry hot summer. The mean annual air temperature varies from 11.3 °C in the mountainous regions to 17.4 °C in the plain. The relative air humidity ranges between 73 and 81 % in winter and between 39 and 55 % in summer. The mean annual relative humidity amounts to 60 %.

The mean annual soil evaporation rate varies from 230 to 290 mm/year in the plain and from 300 to 350 mm/year in the mountainous regions. The long-term annual average of the potential evaporation rate oscillates between 1240 and 1490 mm/year.

2.3. PRECIPITATION

The amount of precipitation in the studied area is characterized by its irregularity and a considerable change from year to year. The precipitation, usually, occurs as rain. Snow fall is common in the mountainous highlands. The maximum precipitation amounts to 800 mm/year. In the western part of the basin at the Golan Heights and the piedmont of Mt. Hermon it is even higher. The amount of precipitation decreases eastward and ranges between 230 and 270 mm/year in the central flat plain. Farther to the east, the amount of precipitation increases again on the slopes of the Mt. Arab reaching 530 mm/year near its top (Fig. 3). The weighted long-term average of precipitation amounts to 340 mm/ year in the whole study area.

2.4. GEOLOGY

The geological characteristics of the Yarmouk Basin have been a subject of several studies, but the most detailed works were carried out by Selkhozpromexport, 1982 [1] and Ponikarov, 1967 [2].

According to these works, the rock exposures in the Yarmouk Basin are represented by the Upper Jurassic, Cretaceous, Paleogene, Neogene and Quaternary (Fig. 4).

- The Upper Jurassic deposits outcrop on the slopes of Mt. Hermon as thick layers (1150 m) of carbonate rocks, mainly, composed of limestone and marl interbeded with clayey limestone and dolomite.

- The Cretaceous deposits are found in limited localizations in the north-western part on the slopes of Mt. Hermon. They are divided into Lower Cretaceous (Aptian and Albian formations) and Upper Cretaceous (Cenomanian-Turonian formations). The Aptian deposits are represented by gray limestone interbeded with clay, argillite, quartz, sandstone and basalt. The Albian formation is composed of limestone, clay, marl and clayey dolomite. The total thickness of both formations is 370 m.

- The Upper Cretaceous deposits outcrop also at the foothills and slopes of Mt. Hermon are represented by limestone and dolomite (Cenomanian) and limestone and marl (Turonian). The estimated thickness of Cenomanian-Turonian formations is about 800-1000 m in the Mt Anti-Lebanon [3].

- The Paleogene deposits outcrop in the piedmont of Mt. Hermon and along the slopes of Jordan uplift. These deposits are composed of marl and clayey limestone and usually covered by sedimentary and volcanic Neogene and volcanic Quaternary.

- The Neogene formation is subdivided into sedimentary and volcanic deposits. The outcrops of the sedimentary Neogene are recognized in the Yarmouk River Valley and represented by conglomerate up to 20 m of thickness. The volcanic Neogene (βN) deposits are widespread in the eastern and the western parts of the basin. These deposits reach a thickness of 800 m in Mt. Arab.

- The Quaternary formation is represented by lacustrine, alluvial and proluvial deposits, developed in the valley of Yarmouk River and its tributaries and the volcanic series, widely developed and predominant on a considerable portion of the investigated land. The effusive formations are mostly composed of basalt. They are distinguished into the Lower Quaternary (βQ1)- widely extended in the western and the eastern zones of the basin, the Middle Quaternary (βQ2)- developed in western slopes of Mt. Arab and the western part of the basin, and the Recent Quaternary (βQ4)- covering the major part of Laja plateau and small lava sheets in the eastern and western part of the basin.

2.5. HYDROGEOLOGY

Many studies were devoted to the hydrogeological features of Yarmouk Basin [1, 4, 5, 6, 7 & 8].

As a result of intensive cyclic volcanic activities during Neogene and Quaternary, the effusive formations are widespread in the study area. Therefore, about 95 % of the area is covered by the pillow lava with a thickness varying from dozen to several hundred of meters. Hyrogeologically, the effusive formations of Pliocene-Lower Quaternary age (βN-βQ1), contain the most important groundwater resources in the area. The Paleogene, Cretaceous and Jurassic deposits have secondary importance as water resource [7].

From the hydrogeological point of view, several groundwater bearing systems (aquifers) are distinguished:

- **Upper Quaternary Basalt (βQ4):** the groundwater occurs in the north-western part of the area where several shallow lava layers exist with high but an isotropic permeability. The basalt is fissured with a polygonal system of joints. The Nourieh, Fawar and Halasse springs are the largest and representative for this aquifer system. The recent basalt covering a large part of Laja plateau belongs also to this system but is practically waterless [1].

- **Middle Quaternary (βQ2):** the basalt of Middle Quaternary is developed in the north-western part of Harah Village and characterized by the presence of polygonal joints filled with clay. The total thickness of these deposits is up to 60 m. Numerous springs such as N.Sakher and A.Dakar represent this aquifer.

- **Pliocene-Lower Quaternary (βN-βQ1):** the basalt of Pliocene and Lower Quaternary ages constitutes a formation which is widely developed in the east and the west of the basin. The total thickness varies between 530 m in Mt. Arab piedmont and 20-80 m in the area between Yarmouk and Hreer Rivers. The permeability of the basalt is rather non-uniform, the transmissivity of water bearing zone ranges from 12 to 2600 m^2/day. Many springs with high discharge emerge from this aquifer: the springs of Badeer and Irah in Mt. Arab, the springs of Mzeireeb, Hreer, Ashaary and Ziezoun, so-called the major springs of the Yarmouk Basin and the springs of Cheikh Saade, Der-Labo and Soraya in the central part. The discharge of many of these springs follows a pronounced seasonal pattern and is correlated with the precipitation, while the minors springs dry up during summer period.

- **Paleogene:** the outcrop of Paleogene deposits is rather limited and is represented by clayey limestone, limestone and marl. This aquifer has no potential for extensive utilization [1].

- **Cenomanian-Turonian:** the deposits of this complex outcrop in a limited area of Mt. Hermon piedmont and are represented by dolomite and limestone. This complex is found at a depth ranging from 600 to 1500 m.a.s.l and form a good potential aquifer [1].

- **Aptian:** the Aptian deposits are found at the foot of Mt. Hermon and represented by gray compact limestone and interbeded with clay, basalt and argillite. This aquifer has minor importance as water resource.

- **Upper Jurassic:** the Upper Jurassic deposits located at the highest elevation on the slopes of Mt. Hermon may form a good aquifer which still has only secondary importance in Yarmouk Basin due to its limited exposure.

2.6. HYDROLOGY

The hydrological network of Yarmouk Basin is controlled, mainly, by the Yarmouk River and its tributaries: Raqqad, Allane, Hreer, Dahab and Zeidi (Fig. 1).

The flow patterns of Raqqad, Dahab and Zeidi follow the seasonal pattern of rainfall with floods during winter and spring. These rivers become dry in summer.

The Yarmouk and Hreer Rivers are characterized by a mixed regime of recharge, mainly, influenced by the presence of several springs. The average discharge of Yarmouk tributaries is estimated to be about 171.8 million m^3/year [7].

3. CHEMICAL AND ISOTOPIC CHARACTERISTICS

3.1. SAMPLING AND ANALYSES

The chemical and isotopic investigations were carried out within the framework of the ongoing IAEA Regional T/C Project (RER/8/002). These investigations were started on July 1989. Two campaigns of sampling were undertaken in the study area. The first one was started on 2 July 1989 for a period of one month, during which samples from 56 selected springs and shallow wells were collected representing the dry period. Figure 5 shows the location map of the sampling sites in the Yarmouk Basin.

The second campaign of sampling was started on 15 January 1990, during which samples were collected from the same sites but representing the rainy season. Moreover, the major springs (Mzeireeb, Hreer and Ashaary) of the Yarmouk Basin, were sampled monthly from January to April 1990. In addition, ^{14}C and $\delta^{13}C$ samples were taken from 27 shallow wells and springs with tritium values below the detection limit of 2 TU. The total dissolved inorganic carbon was precipitated from 120 litters of water according to the IAEA procedures (reaction with barium chloride at high pH),

The temperature, electrical conductivity and pH of water samples were taken during sampling in the field. The water samples were stored in three bottles for the isotopic and chemical analyses. The $\delta^{18}O$, $\delta^{2}H$ and tritium analyses, together with $\delta^{13}C$ and ^{14}C, were performed in the Laboratory of Amman/Jordan. The chemical analyses of these samples were carried out in the Laboratory of Ein-El-Figeh Establishment in Damascus.

3.2. WATER CHEMISTRY OF GROUNDWATER

3.2.1. HYDROCHEMICAL DATA

The hydrochemical properties of the groundwater samples from the Yarmouk Basin are compiled in Table I. The majority of the samples were freshwater since the total dissolved solids (TDS) did not exceed 500 mg/L [9]. Four exceptions are reported for wells no. 32, 33, 34 and 50 located in Laja plateau north-west of the basin. Their TDS contents varies within 670-920 mg/L.

The chemistry of the groundwater emerging along the slopes of Mt. Hermon and Mt. Arab are characterized by a low solute content (TDS <200 mg/L). Two springs (no. 25 and 26) emerging from the basaltic aquifer in the Mt. Arab have even only 90 mg/L TDS.

The average water temperature of most of the water samples ranges from 11.5 °C to 25 °C. The mean water temperatures of the major springs of Yarmouk Basin (springs no. 1,3,4 and 7) scatter around 25 °C. An exceptional high water temperature of 30 °C was observed for two groundwaters of Laja area, covered by recent Quaternary basalt (wells no. 34 and 56) which is attributed to the recent volcanic activities [7]. Figure 6 shows that the temperature over the Yarmouk Basin increases gradually from the mountainous regions of Mt. Hermon and Mt. Arab towards the central zone and the basin outlet.

The pH values measured in the field range from 7.25 (springs no. 42 and 43) to 8.60 (well no. 28). The pH values of groundwater emerging along the slopes of Mt. Hermon and Mt. Arab are less than 8, those for the central zone are usually higher than 8.

The spatial distributions of the major ions, the electrical conductivity and TDS over the Yarmouk Basin are somewhat similar. They show an increase from the mountainous regions (recharge areas) towards the central zone and the basin outlet (Fig. 7 & 8). Five exceptions, however, were observed in Laja plateau (wells no. 32, 33, 34, 50 and 56) for which the ionic contents, electrical conductivity and TDS were significantly higher.

3.2.2. GEOCHEMICAL RATIOS OF GROUNDWATER

Groundwater flowing through different aquifer systems may be identified and differentiated by their salinity levels and ionic ratios [9, 10, 11, 12, 13 & 14]. In fact, the calculation of ionic ratios (expressed in meq/L or "r value") of all groundwater samples allowed to differentiate between the following hydrogeologic units:

- **The Upper Jurassic Aquifer.** The groundwater emerging from the Upper Jurassic Aquifer on the slopes of Mt. Hermon (no. 37, 38, 39, 40 and 54) are of calcium bicarbonate type, with the following ionic sequences: rCa>rMg>rNa>rK and HCO_3>rCl>rSO_4. These groundwaters are characterized by a low rMg/rCa ratio (0.17-0.30), which is below the range of 0.5-0.9 given for limestone and dolomite aquifers by Schoeller, 1956 [10]; Hsu, 1963 [11] and Rosenthal, 1987 [13]. However, our results are comparable to those for rainwater [13]. Thus, the transit time of the infiltrated rainwater is too short to approach the chemical equilibrium with the rocks. The rNa/rCl ratios range from 0.71 to 0.85, indicating a natural mineralization [10]. The rNa/rK ratios range from 10 to 17, which is normal [15].

- **The Pliocene-Lower Quaternary Aquifer.** The chemistry of the groundwater emerging from the Pliocene-Lower Quaternary Aquifer on the slopes of the Mt. Arab (springs no. 25 and 26) is of calcium-magnesium and bicarbonate type: rCa>rMg>rNa>rK and $rHCO_3$>rCl>rSO_4. The rMg/rCa ratio is about 0.55, while the rNa/rCl ratio ranges from 0.94 to 1.08. The chemistry of the groundwater discharged from the same aquifer at the outlet of the basin (springs no. 1, 3, 4 and 8) and from the central zone (springs no. 46, 47 and 53) is on the contrary, of sodium-magnesium and bicarbonate-chloride type: rNa>rMg>rCa>rK and HCO_3>rCl>rSO_4 in the case of major springs and of sodium-calcium and bicarbonate-chloride type: rNa>rCa>rMg>rK and $rHCO_3$>rCl>rSO_4 in the case of the central zone springs. The rMg/rCa ratio varies slightly around 1.8 and the rNa/rCl ratio ranges from 1.5 to 1.8 in the case of major springs. The rMg/rCa ratio varies around 0.8 and the rNa/rCl ratio stays close to 1.5 in the case of the central zone springs.

The rMg/rCa and rNa/rCl ratios of the water from the basaltic aquifers have an additional source of magnesium and sodium. In fact, the basaltic rocks often containing silicate minerals are frequently distinguishable by high (rMg/rCa >0.9) and (rNa/rCl >1) ratios [12 & 16]. The source of magnesium is derived from weathering of olivine, while the additional amount of sodium is derived from feldspar weathering .

The groundwater chemistry of Pliocene-Lower Quaternary basalt in the Laja plateau (wells no. 32, 33, 34, 50 and 56) is, generally, characterized by a sodium-magnesium and chloride-sulfate or bicarbonate-chloride types: rNa>rMg>rCa>rK and rCl>rSO_4>$rHCO_3$ or $rHCO_3$>rCl>rSO_4. The chemical behavior of these groundwaters seems to be different from those groundwaters from the same aquifer of Pliocene-Lower Quaternary and also from all the basaltic aquifers in Yarmouk Basin. In fact, the rMg/rCa (1.4-4.5), rNa/rK (44-177) and $rSO_4/rHCO_3$ (0.64-1.03) ratios are the highest ratios in the basin. Meanwhile, the rNa/rCl ratio (0.84-1.9) fills in the above estimated range for the basaltic aquifers in the basin. The particularity, of the Laja plateau wells may be attributed to the dissolution process of salts accumulated in the soil horizon as will be seen further.

- **The Middle Quaternary Aquifer.** The chemistry of groundwaters discharged from this aquifer (springs no. 42 and 45) is of calcium-magnesium and bicarbonate type: $rCa>rMg>rNa>rK$ and $rHCO_3>rCl>rSO_4$. The rMg/rCa (0.76-0.83) ratio is somewhat lower than the characteristic ratio of basalt (0.9), while the rNa/rCl ratio (1.12-1.88) is similar to the above estimated ratios for the Pliocene-Lower Quaternary Aquifer.

- **The Upper Quaternary Aquifer.** The chemistry of groundwaters of the Upper Quaternary Aquifer (springs no. 19, 20 and 21) located in the north western part of Yarmouk Basin is of calcium-magnesium and bicarbonate type: $rCa>rMg>rNa>rK$ and $rHCO_3>rCl>rSO_4$. The rMg/rCa ratio varies from 0.5 to 0.97, while the rNa/rCl ratio ranges from 1 to 2.2. These characteristic ratios seem to be similar to those of the Middle Quaternary Aquifer.

The Piper diagrams of the investigated groundwater samples from Yarmouk Basin are shown in figures 9 and 10.

The different groundwater bodies of the Yarmouk Basin have deviating ionic ratios. The chemical evolution of groundwater from the mountainous region towards the major springs area and the central zone is marked by a progressive decrease in calcium and bicarbonate with an increase of sodium, magnesium and chloride.

3.2.3. HYDROCHEMICAL EQUILIBRIUM CONDITIONS

The hydrohemical equilibrium conditions controlling the Yarmouk groundwater were studied with the program WATEQF [17]. The saturation index (SI) of a water sample with respect to a mineral precipitation is expressed by

$$\mathbf{SI = \log (IAP/K_{sp(T)})} \qquad [1]$$

where: IAP is the ion activity product of the solution and $K_{sp(T)}$ is the equilibrium constant of the reaction considered at the temperature T (K).

The calculated partial pressure of carbon dioxide ($\log pCO_2$), calcite saturation index ($SI_{cal.}$) and dolomite saturation index ($SI_{dol.}$) are compiled in Table II. The partial pressure of carbon dioxide is within the range of $10^{-2.28}$ atm (16 times higher than that of the atmosphere) to $10^{-3.52}$ atm (identical to that of the atmosphere). The spatial distribution patterns of the calcite and dolomite saturation indices are shown in figures 11 and 12, respectively. The groundwaters from the mountainous regions with low TDS and pH values have high partial pressure of CO_2 comparing to those of the groundwater in the central zone.

The spatial distributions of calcite and dolomite saturation indices show similar trends. The saturation indices increase from the high-land regions towards the central zone of the basin. The groundwaters of the mountainous regions are under saturated with respect to both calcite and dolomite while the groundwaters of the central zone show an equilibrium state or over saturated with respect to calcite and dolomite. The over saturated groundwaters occur in the central zone area, where the partial pressure of carbon dioxide is close to that of the atmosphere. Hence, the groundwaters in the Yarmouk Basin behave as closed system [18].

3.3. ISOTOPIC COMPOSITION OF GROUNDWATER

3.3.1. STABLE ISOTOPES COMPOSITION

The average isotopic composition of the groundwater samples collected at various sites of Yarmouk Basin are summarized together with deuterium excess in Table III. According to these data, it is possible to distinguish between the following units:

- **Upper Jurassic groundwaters.** The stable isotope compositions of the groundwater from the Upper Jurassic aquifer are characterized by low $\delta^{18}O$ values ($-8.18 < \delta^{18}O < -6.98$ ‰), low δ^2H values ($-44 < \delta D < -33.5$ ‰) and with a high deuterium excess close to 22 ‰.

- **Spring waters from Mt. Hermon and Mt. Arab.** The stable isotope compositions of the spring waters from Mt. Hermon and Mt. Arab are characterized by $-7.2 < \delta^{18}O < -6.90$ ‰ and $-36.4 < \delta D < -34.5$ ‰ with a deuterium excess higher than 21 ‰ . Several Mt. Arab springs could have been slightly affected by evaporation never found for Mt. Hermon springs.

- **Spring waters from the central zone.** The spring waters from the central zone springs are characterized by $-6.31 < \delta^{18}O < -5.87$ ‰ and $-30.3 < \delta D < -28.0$ ‰ with also a high deuterium excess ($19 < d < 20$ ‰).

- **Major springs.** The stable isotope compositions of the major springs are similar to those of the central zone springs: $-6.0 < \delta^{18}O < -5.85$ ‰ and $-31.4 < \delta D < -29.6$ ‰. The deuterium excess however differs between the major springs ($16 < d < 18$ ‰) and those of the central zone ($19 < d < 20$ ‰).

- **Wells drilled on the slopes of Mt. Hermon and Mt. Arab.** The samples from the wells drilled on the slopes of Mt. Hermon show similar stable isotope compositions to those of the Hermon springs, while the water from Mt. Arab is isotopically enriched compared to those from the Mt. Arab springs.

- **Central zone wells.** The stable isotope compositions of the samples from the central zone wells deviate even more from the MMWL and may reflect enrichment due to mixing process. They have a low deuterium excess ($14 < d < 18$ ‰). The gradual decrease of the deuterium excess from the eastern Mediterranean region towards the inland valleys, is in agreement with the observations of Gat & Carmi, 1970 [19].

- **Laja plateau wells.** The stable isotope compositions of the samples from the Laja plateau wells have the following ranges: $-6.67 < \delta^{18}O < -5.09$ ‰ and $-37 < \delta D < -28.4$ ‰ with a deuterium excess of $12.5 < d < 16.7$ ‰.

The δ^2H-$\delta^{18}O$ plot of the groundwater samples is shown in figure 13. The isotopic compositions scatter widely between the Mediterranean Meteoric Water Line (MMWL) and the Global Meteoric Water Line (GMWL). It is also possible that few samples were affected by evaporation. One sample (no. 48) was enriched as a consequence of admixed evaporated surface water. It was collected from a shallow well close to a small dam. The least square of the data points is given by

$$\mathbf{\delta D = (5.3 \pm 0.26).\ \delta^{18}O + (1.7 \pm 1.7) \quad (n = 56, R^2 = 0.89)} \qquad [2]$$

The intersection of this line with the MMWL corresponds to $\delta^{18}O = -7.52 \pm 0.1$ ‰ and $\delta D = -36.16 \pm 2.9$ ‰, respectively. These values correspond more or less to the isotopic compositions of the groundwaters emerging from both Mt. Hermon and Mt. Arab springs as well as the groundwaters of the Upper Quaternary basalt springs. Hence, this line corresponds somewhat to a mixing line.

Figures 14 and 15 are plots of the δD values versus the $\delta^{18}O$ values of the samples of springs and wells in the Yarmouk Basin. The Upper Jurassic springs and the springs discharged towards Mt. Hermon and Mt. Arab mach the MMWL. However, the data from the major springs of the Yarmouk Basin deviate significantly from the MMWL. The data from the central zone springs represents an intermediate position between major springs and the mountainous springs. In fact, the deviation of the data from the major springs and those from the central zone springs from MMWL implies rather a mixing process than an evaporative effects before or during recharge occurrences [20, 21 & 22].

The spatial distribution of the stable isotope compositions of samples from the Yarmouk Basin are shown in figures 16 and 17. The groundwater is progressively enriched in both ^{18}O and D during its movement from the mountainous groundwaters towards the major springs. A part of a few exceptions (wells no. 27 and 48) of highly evaporated groundwater samples, the spatial distribution corresponds to the topographical feature of the Yarmouk Basin (Fig. 2). Consequently, it may be said that isotopic enrichment of groundwaters could be considered as an indication of low recharge movement through the considered aquifers [23].

The relationship between the stable isotope compositions and the altitude of selected springs in the Yarmouk Basin (Fig. 18 & 19) yield gradients of about -0.20 and -1.24 ‰ per 100 meter for oxygen-18 and deuterium, respectively. These results agree with those for the atmospheric precipitation (-0.23 and -1.65 ‰ per 100 meter, respectively for ^{18}O and deuterium [24]). This result suggests as pointed out by Fontes, 1983 [25], the possibility of vertical infiltration occurrences through the fissured basaltic rocks of the Yarmouk Basin.

In order to evaluate the sources of groundwater salinity in the Yarmouk Basin, the chloride concentration is plotted against $\delta^{18}O$ values (Fig. 20). Two processes increase the salinity:

- enrichment by evaporation: samples number 48, 27, 24 and 49.

- enrichment due to salt dissolution: stable isotope concentration does not change with increasing chloride concentration. This is the case for groundwater from the Laja plateau (wells no. 32, 33, 34, 50 and 56).

In summary, we can conclude that the groundwater of the major springs, those of the central zone springs and wells, located on the mixing line between fresh water (mountainous springs) and salty groundwaters (Laja plateau wells) are of a mixture origin of the above two groundwater bodies.

3.3.2. TRITIUM CONTENT IN GROUNDWATER

Tritium is the only environmental radioactive isotope which is a constitute of the groundwater as a part of the water molecule. For this reason, the use of tritium (half-life = 12.43 years) has become a very valuable radioactive tracer for the estimation of groundwater residence time of less than 150 years [18 & 26].

The average tritium content of groundwater samples collected from the Yarmouk Basin are compiled in Table III. It ranges from the detected limit (tritium free) up to 16.3 TU (spring no. 40). The highest tritium contents were found for the groundwater emerging on the slopes of both Mt. Hermon and Mt. Arab, while the lowest tritium contents were found for the groundwaters from the central part of the basin. The relatively high tritium content for well number 48 (7.4 TU), located in the central zone close to a small reservoir is attributed to admixture of surface water with high tritium content.

The tritium contents of the samples from the groundwater of mountainous regions are higher than those of the present atmospheric precipitation, which was about 7-8 TU in 1989-1990 [24].

The spatial distribution of tritium values over the Yarmouk Basin (Fig. 21) shows a gradual decrease from the Hermon and Arab mountainous regions towards the central zone of the Basin, where the tritium contents fall below the detection limit of 2 TU. A few exceptions are the springs no. 46, 47, and 53 for which the tritium contents are significantly above 2 TU.

Based on the spatial distribution of tritium values, two main directions of groundwater flow are defined: from the north-west and the west towards the south-east and the east (i.e. from Mt. Hermon and Golan Heights towards the central zone) and from the east towards the west (i.e. from Mt. Arab towards the central zone). These two flow paths are in an agreement with the piezometric map (Fig. 22) of Yarmouk Basin [1 & 7].

In conclusion, the groundwater recharge is identified in limited catchment areas of the high land and the piedmont of both Mt. Hermon and Mt. Arab. The contribution of local vertical infiltration on the high discharge of several springs in the central zone, such as Soraya (d=20 ‰ with presence of tritium), could not be excluded.

3.3.3. CARBON ISOTOPES CONTENT IN GROUNDWATER

The dissolved inorganic carbon compounds are presented as dissolved CO_2, carbonate and bicarbonate depending upon the pH (total alkalinity) and temperature of the solution [27].

The ^{13}C content of the total dissolved inorganic carbon compounds is used to estimate the quantities of different carbon sources within the carbon chemistry. The principal is that the constituted dissolved biogenic carbon (soil carbon dioxide derived from the decomposition of organic matter and root respiration) has a lower ^{13}C content than that of the solid carbonates. In the delta-PDB (Pee Dee Belemnite) scale the soil carbon dioxide is about -22 ± 1 ‰, while the solid carbonate has a value of about 0± 2 ‰. Thus, the determination of $\delta^{13}C$ value of the total dissolved inorganic carbon compounds (TDIC) can be corrected with the dilution of the initial ^{14}C activity of the total dissolved inorganic carbon by admixing of carbon forms.

As can be seen from Table IV the $\delta^{13}C$ values range from -8.54 to -15.94 ‰. Low $\delta^{13}C$ values have occurring in the groundwater of Laja area (wells no. 29 and 33). They may reflect admixture of volcanic carbon dioxide, as reported by Gasparini et al., 1990 [28] for the volcanic basalt in Canary Islands. Since the Laja plateau was also subject to recent volcanic activity [7]. On the other hand, the high $\delta^{13}C$ values of the sample 44 (from the only confined well in the Yarmouk Basin) may reflect an isotopic exchange with atmospheric CO_2.

The measured ^{14}C activity of the groundwater samples from the Yarmouk Basin (Tab. IV) ranges from 22 pMC for sample 17, collected very close to the Jordanian border, up to 95.7 pMC in sample number 27 from the slopes of Mt. Arab.

4. GROUNDWATER DATING

Radiocarbon (^{14}C) is the most often used environmental radioactive isotope for groundwater dating of more than 1000 years. Tritium with its short half-life (τ=12.43 years) can just be used to calculate the mean residence time (exponential model) up to 150 years [25].

According to the fundamental law of radioactive decay it is possible to determine the time t of groundwater elapsed in a closed reservoir by measuring its ^{14}C activity (A_t). Knowing the initial ^{14}C activity (Ao) then the groundwater age is calculated from

$$t = \frac{\tau}{\log 2} \log \frac{A_0}{A_t} \qquad [3]$$

where, τ is the half-life of ^{14}C ($\tau = 5730 \pm 30$ years).

The estimation of the initial ^{14}C activity (Ao) is still difficult [18, 29, 30 & 31]. In fact, the radiometric age of groundwater is referred to that of the total dissolved inorganic carbon compounds (TDIC). For this reason several models are proposed to correct convential ^{14}C ages. They consider either only chemical mixing between the carbon compounds, or isotopic fractionation (18, 29 & 30].

In this study, 27 groundwater ages were determined from samples without detectable tritium. These groundwater is supposed to be recharged before 1952. Based on the geological situation we could assume closed system conditions. We applied two approaches: Vogel's concept and Gonfiantini's Model for the correction of the initial ^{14}C activity.

In Vogel's concept the initial ^{14}C activity was proposed to be 85 ± 5 pMC (percent modern carbon), an empirically determined value for groundwater in Europe and South Africa.

The Gonfiantini's Model, widely used in several IAEA studies [32] is also based on isotopic mixing but considers the isotopic fractionation between the bicarbonate and the dissolved CO_2:

$$A_0 = \frac{\delta_t - \delta_c}{\delta_g - \varepsilon_g - \delta_c} \left(1 + 2\,\varepsilon_g / 1000\right) \qquad [4]$$

δ is the $\delta^{13}C$ value, t, c and g refer to TDIC, solid carbonate and soil CO_2, respectively. ε_g is the ^{13}C fractionation factor between bicarbonate and CO_2. The following values were used: $\delta_c = 0 \pm 1$ ‰, $\delta_g = -25 \pm 1$‰ and $\varepsilon_g = 7.92 \pm 0.5$ ‰ at 25 °C.

The $\delta^{13}C$ and ^{14}C values, the convential ages (i.e. Ao=100 pMC) and the corrected groundwater ages are compiled in Table IV. The missing $\delta^{13}C$ values were adopted from the available ^{13}C data of the groundwater samples, by taking the $\delta^{13}C$ value of the nearest sample being analyzed.

The minimum initial ^{14}C values of 50-56 pMC calculated by the Gonfiantini's Model were obtained for the groundwater from the Laja area. All other Ao values range from 70 to 95 pMC. This difference in Ao is the reason that groundwater ages calculated by the two models differ by up to 3000-4000 years for Laja plateau wells.

Groundwater ages of less than 1000 years old are found along the slopes of the mountainous regions and Golan Heights. Groundwater ages for the central zone rise from 1000 years to 11000 years. Low groundwater ages in the east (i.e. from Mt. Arab), the west (from Golan Heights and Mt. Hermon) and the north-east (from the Laja plateau) rise to the south, where 5000 years are found for the major springs. Farther to the south, groundwater ages approach 10000-11000 years (well no. 17) close to the Jordanian border.

These results show that the recharge of groundwater in the Yarmouk Basin occurred in a steady state condition and still continuous since 11000 years BP. The paleoclimatic humid conditions prevailing during the Holocene period (4500-6000 years BP) as reported by Gat and Magaritz, 1980 [33] may have changed the recharge rate which is not detectable.

5. GROUNDWATER MOVEMENT AND FLOW VELOCITY

The spatial distribution of groundwater ages are shown in figures 23 and 24. Both corrected values yield similar isochrons which reflect groundwater flow from west and east towards the central zone and from Laja area towards the southern part of the central zone. Hence, two main directions from both sides of the mountainous regions towards the central zone and from the north-eastern part of the central zone (Laja area) towards the south-west and the south (i.e. towards the major springs). This result agrees with the piezometric map of Yarmouk Basin (Fig. 22).

The traces velocities calculated with the radiometric ages along flow movement range from 1 to 7 m/year in both mountainous regions. The flow velocity within the central zone along the north-south axis is much higher (20-60 m/year). This result was also expected from the hydrogeological investigations (pumping tests) which resulted in high productivity wells in the Laja plateau and the large discharge of the major springs [1 & 7].

6. CONCLUSIONS

The combination of both hydrochemical and environmental isotope methods for the study of the fissured basaltic aquifer systems of the Yarmouk Basin has provided a useful hydrogeological information.

The groundwater resources in the Yarmouk Basin can be distinguished by their solute contents and ionic ratios. The groundwater from the mountainous regions has low water temperature, low pH value, low solute content and high partial pressure of carbon dioxide and under saturated with respect to calcite and dolomite. In contrary, the groundwater from the central zone, including the major springs are characterized by high water temperature, high pH value, high solute content, low partial pressure of carbon dioxide and are in equilibrium or are over saturated with respect to calcite and dolomite.

The geochemical evolution of groundwater facies from the mountainous regions towards the basin outlet is marked by a gradual increase of sodium and magnesium as a consequence of silicate leaching.

Groundwater recharge occurs in both Mt. Hermon and Mt. Arab regions of about 1000 m of altitude, where the mean residence time of mountainous springs is less than 100 years.

The groundwater found in the central zone and discharged from the major springs is a mixture of groundwater recharged in the mountains and groundwater being recharged by vertical infiltration within the central zone (Laja plateau).

The ^{14}C groundwater ages within the Yarmouk Basin range from 1000 to 11000 years. This result proves that the recharge of groundwater is occurred in a steady state conditions.

The spatial distribution of the tritium values and radiocarbon groundwater ages reflect two main directions of flow: from both sides of mountainous regions towards the central zone and from the north-east (i.e. from Laja plateau) towards the south-west (i.e. the major springs) as already learned from the piezometric map of the Yarmouk Basin.

The tracer velocity within the central zone amount to 20-60 m/year and is higher than that one for both side of Mt. Hermon and Mt. Arab. This is also in good agreement with the highly productive wells and large springs in the central zone.

Table I. Mean chemical compositions of groundwater samples collected in the Yarmouk Basin during 1989-1990

No	Location	Type	Sample size	T (°C)	pH	E.C (µS/cm)	Ca^{++} (mg/l)	Mg^{++} (mg/l)	Na^{+} (mg/l)	K^{+} (mg/l)	HCO_3^{-} (mg/l)	SO_4^{--} (mg/l)	Cl^{-} (mg/l)	NO_3^{-} (mg/l)	TDS (mg/l)
1	Mzeireeb	S	6	25.0	8.38	412	16.7	17.2	52.0	4.3	146	24	44.7	15.0	247
2	Mzeireeb	L	1	26.0	8.25	412									
3	Hreer	S	6	24.5	8.34	598	25.3	25.5	78.2	3.7	175	62	76.0	17.0	375
4	Ashaary	S	6	24.4	8.20	597	23.2	26.2	77.4	3.8	173	60	73.6	17.2	369
5	Daeel	W	2	25.9	8.06	690	28.0	28.0	91.0	3.5	195	70	88.0	19.0	428
6	Tafasse	W	2	25.9	8.21	592	24.0	20.5	75.0	3.5	171	57	74.0	14.0	353
7	Mzeireeb	W	2	25.0	8.21	499	16.0	21.0	62.5	3.5	159	34	62.0	14.5	295
8	Ziezoun	S	2	24.5	8.13	639	22.0	24.0	81.0	3.8	165	57	85.0	17.0	373
9	Ch.Meskin	W	2	23.1	7.95	902	40.0	32.0	96.5	4.3	159	77	149.0	25.5	504
10	Izraa	W	2	22.8	8.12	727	26.0	30.5	86.0	6.0	177	82	86.0	29.5	397
11	Chacra	W	2	22.4	8.29	506	20.0	16.0	70.5	3.5	146	47	55.0	17.0	304
12	Hojedel	W	2	23.5	8.17	509	24.0	17.0	59.5	3.5	140	18	73.0	20.5	286
13	B.Harir	W	2	23.1	8.23	671	24.0	30.5	82.0	3.5	183	59	86.0	21.0	393
14	Hosefzeh	W	2	24.9	8.19	398	16.0	20.0	42.5	4.5	159	5	41.0	14.0	223
15	Sahweh	W	2	25.2	8.32	427	14.0	22.0	42.5	4.5	159	7	44.0	18.0	232
16	Koheel	W	2	25.3	8.29	500	24.0	22.0	50.0	5.0	159	16	68.0	17.5	283
17	Nouimeh	W	2	23.4	8.04	746	30.0	35.5	78.0	4.5	171	48	113.0	27.5	432
18	Nourieh	S	1	19.0	7.65	190	12.0	7.0	14.0	3.0	85	6	10.0	11.0	105
19	Fawar	S	2	17.5	7.20	247	18.0	7.0	23.5	5.0	104	7	18.0	12.5	145
20	Halasse	S	1	19.0	7.43	306	24.0	7.0	17.0	12.0	98	13	26.0	22.0	170
21	Al-Koum	W	2	20.0	8.23	280	26.0	13.5	20.0	3.8	140	5	21.0	10.5	170
22	Rasase	S	1	19.5	7.64	355	32.0	17.0	19.0	8.0	146	13	30.0	30.0	225
23	Irah	S	2	17.2	7.79	268	24.0	12.5	15.5	4.8	85	13	28.0	19.5	160
24	Kraya	S	1	18.0	7.78	284	28.0	12.0	19.0	3.0	122	12	28.0	15.0	180
25	Badeer	S	2	13.0	7.72	148	18.0	6.0	7.0	0.8	67	7	10.0	8.5	90
26	Qineh	S	2	11.5	7.38	138	18.0	6.0	5.5	0.5	61	7	9.0	10.0	85
27	Al-Sijen	W	2	21.0	7.38	555	56.0	30.5	31.0	1.5	262	14	50.0	31.5	347
28	Nijran	W	1	25.0	8.58	270	8.0	10.0	42.0	2.0	134	6	20.0	11.0	170
29	Smned	W	2	20.3	8.36	326	24.0	11.0	50.0	3.3	147	20	41.0	14.5	237
30	Majadel	W	1	18.0	8.46	265	24.0	7.0	26.0	8.0	110	11	26.0	16.0	175
31	Brekeh	W	1	21.0	8.08	640	64.0	27.0	44.0	4.0	244	31	80.0	30.0	405
32	Bouidan	W	2	22.3	7.95	1403	34.0	41.5	240.0	2.3	250	203	255.0	17.5	919
33	Bourak	W	2	24.7	7.81	1257	70.0	68.5	125.0	4.0	207	215	230.0	15.0	831
34	Sawarah K.	W	1	28.0	8.03	1032	40.0	56.0	120.0	2.0	238	160	154.0	19.0	670
35	Darkah	S	2	15.5	8.08	399	44.0	21.0	21.5	3.3	208	13	28.0	16.5	252
36	Lowieseh	W	2	18.8	8.27	263	12.0	9.5	34.0	2.0	110	8	25.0	13.0	158
37	Nidda	S	2	13.8	7.70	209	50.0	7.0	9.5	1.3	171	5	15.0	13.0	187
38	Hadar	W	1	15.0	8.03	513	48.0	5.0	82.0	1.5	305	50	10.0	7.0	355
39	Bet-Jeen	S	2	11.3	8.19	211	40.0	7.0	3.3	0.5	134	8	6.0	8.5	142
40	Erneh	S	2	12.0	7.96	222	44.0	5.0	3.0	0.5	146	3	6.5	6.5	141
41	Jabah	W	2	17.5	8.37	207	12.0	7.0	22.5	3.8	92	7	14.0	12.5	125
42	N.Sakher	S	1	19.0	7.27	233	20.0	10.0	16.0	3.0	85	11	22.0	16.0	140
43	Rafid	S	1	20.0	7.27	248	20.0	10.0	16.0	3.0	85	11	22.0	16.0	140
44	C. Boustan	W	2	20.0	8.20	301	12.0	13.5	39.0	3.5	146	6	29.0	11.5	189
45	A. Dakar	S	2	21.0	7.91	320	24.0	11.0	39.0	3.5	153	8	32.0	12.5	206
46	Ch.Saade	S	1	22.0	8.18	388	28.0	12.0	40.0	4.0	171	11	40.0	11.0	235
47	Der-Labo	S	2	19.0	7.95	419	30.0	14.5	45.5	3.8	171	14	45.5	19.0	258
48	Hawa	W	1	21.0	7.98	505	36.0	15.0	60.0	2.0	195	36	58.0	12.0	320
49	Khabab	W	2	22.3	7.98	424	24.0	12.0	48.0	3.0	147	19	42.0	28.5	251
50	Housmieh	W	2	23.9	7.71	1076	52.0	43.5	125.0	3.0	232	178	145.0	14.0	678
51	Harah	W	2	20.5	8.29	327	18.0	13.5	41.0	4.0	159	8	30.0	12.5	205
52	D.Adasse	W	2	21.8	8.04	499	40.0	14.5	48.0	3.5	146	16	71.0	23.5	290
53	Soraya	S	2	18.3	8.23	391	28.0	16.0	38.5	5.0	165	11	39.0	17.5	239
54	Hadar	S	1	13.0	7.75	326	64.0	7.0	5.0	0.5	207	13	6.0	9.0	207
55	Dama	W	1	21.2	8.12	325	16.0	15.0	35.0	8.0	146	8	26.0	16.0	194
56	Sawarah S.	W	1	29.8	8.3	722	8.0	22.0	130.0	5.0	159	80	106.0	16.0	446

Where: S, spring; W, Well and L, lake

Table II. Mean partial pressure of carbon dioxide (log pCO_2) as well as calcite and dolomite saturation indices ($SI_{cal.}$ and $SI_{dol.}$, respectively) of groundwater collected in the Yarmouk Basin during 1989-1990

No	Location	Type	Sample size	T (°C)	pH	HCO_3^- (mg/l)	log pCO_2 (atm)	$SI_{cal.}$	SI_{dol}
1	Mzeireeb	S	6	25.0	8.38	146	-3.24	0.30	0.92
2	Mzeireeb	L	1	26.0	8.25	146	-3.24	0.30	0.92
3	Hreer	S	6	24.5	8.34	175	-3.15	0.47	1.24
4	Ashaary	S	6	24.4	8.20	173	-2.99	0.29	0.92
5	Daeel	W	2	25.9	8.06	195	-2.73	0.28	0.87
6	Tafasse	W	2	25.9	8.21	171	-2.70	0.37	0.98
7	Mzeireeb	W	2	25.0	8.21	159	-3.03	0.13	0.68
8	Ziezoun	S	2	24.5	8.13	165	-3.03	0.21	0.73
9	Ch.Meskin	W	2	23.1	7.95	159	-2.79	0.20	0.59
10	Izraa	W	2	22.8	8.12	177	-2.90	0.21	0.77
11	Chacra	W	2	22.4	8.29	146	-3.18	0.25	0.67
12	Mojedel	W	2	23.5	8.17	140	-3.04	0.20	0.64
13	B.Harir	W	2	27.1	8.23	183	-3.01	0.38	1.21
14	Mosefreh	W	2	24.9	8.19	159	-3.03	0.16	0.70
15	Sahweh	W	2	25.2	8.32	159	-3.18	0.24	0.98
16	Koheel	W	2	25.3	8.29	159	-3.13	0.42	1.08
17	Houimeh	W	2	23.4	8.04	171	-2.86	0.23	0.81
18	Hourieh	S	1	19.0	7.65	85	-2.80	-0.75	-1.51
19	Fawar	S	2	17.5	7.20	104	-2.28	-0.99	-2.18
20	Halasse	S	1	19.0	7.43	98	-2.44	-0.70	-1.74
21	Al-Koum	W	2	20.0	8.23	140	-3.10	0.26	0.48
22	Raasse	S	1	19.5	7.64	146	-2.48	-0.24	-0.52
23	Irah	S	2	17.2	7.79	85	-2.92	-0.42	-0.92
24	Kraya	S	1	18.0	7.78	122	-2.76	-0.18	-0.52
25	Badeer	S	2	13.0	7.72	67	-2.89	-0.67	-1.78
26	Qineh	S	2	11.5	7.38	61	-2.70	-1.14	-2.64
27	Al-Sijen	W	2	21.0	7.38	262	-2.43	0.42	0.84
28	Nijran	W	1	25.0	8.58	134	-3.50	0.19	0.77
29	Smaed	W	2	20.7	8.36	147	-3.29	0.42	0.75
30	Majadel	W	1	18.0	8.46	110	-3.52	0.39	0.46
31	Brekeh	W	1	21.0	8.08	244	-2.77	0.73	1.34
32	Bouidan	W	2	22.3	7.95	250	-2.63	0.23	0.82
33	Bourak	W	2	24.7	7.81	207	-2.54	0.45	0.98
34	Sawarah K.	W	1	28.0	8.03	238	-2.65	0.43	1.34
35	Barkah	S	2	15.5	8.08	208	-2.86	0.45	0.76
36	Lowisseh	W	2	18.8	8.27	110	-3.27	-0.17	-0.22
37	Bidda	S	2	13.8	7.70	171	-2.54	0.04	-0.61
38	Radar	W	1	15.0	8.03	305	-2.59	0.53	0.26
39	Bet-Jeen	S	2	11.3	8.19	134	-3.11	0.27	-0.11
40	Erneh	S	2	12.0	7.96	146	-2.86	0.16	-0.50
41	Jabah	W	2	17.5	8.37	92	-3.49	-0.07	-0.16
42	N.Sakher	S	1	19.0	7.27	85	-2.41	-0.95	-1.97
43	Rafid	S	1	20.0	7.27	85	-2.40	-0.94	-1.93
44	G. Boustan	W	2	20.0	8.20	146	-3.08	-0.08	0.16
45	A. Dakar	S	2	21.0	7.91	153	-2.75	-0.03	-0.13
46	Ch.Saade	S	1	22.0	8.18	171	-2.80	0.19	0.29
47	Der-Labo	S	2	19.0	7.95	171	-2.77	0.13	0.16
48	Nawa	W	1	21.0	7.98	195	-2.75	0.31	0.50
49	Khabab	W	2	22.3	7.98	147	-2.87	0.07	0.06
50	Mousmieh	W	2	23.9	7.71	232	-2.38	0.19	0.59
51	Harah	W	2	20.5	8.29	159	-3.15	0.25	0.62
52	D.Adasse	W	2	21.8	8.04	146	-2.93	0.31	0.43
53	Soraya	S	2	18.3	8.23	165	-3.09	0.37	0.71
54	Hadar	S	1	13.0	7.75	207	-2.56	0.30	-0.20
55	Dama	W	1	21.2	8.12	146	-2.97	-0.01	0.20
56	Sawarah S.	W	1	29.8	8.3	159	-3.10	-0.05	0.67

Where: S, spring; W, Well and L, lake

Table III. Mean isotopic composition of groundwater collected in the Yarmouk Basin during 1989-1990

No	Location	Type	Sample size	Altitude (m.a.s.l)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	d (‰)
1	Mzeireeb	S	6	435	-6.00	-29.6	0.60	18.40
2	Mzeireeb	L	1	435	-5.76	-29.6		16.48
3	Hreer	S	6	445	-5.93	-31.1	0.60	16.34
4	Ashaary	S	6	440	-5.99	-31.4	0.80	16.52
5	Daeel	W	2	520	-5.85	-32.3	1.10	14.50
6	Tafasse	W	2	490	-5.88	-31.1	0.90	15.94
7	Mzeireeb	W	2	460	-6.00	-29.7	0.50	18.30
8	Ziezoun	S	2	400	-5.85	-30.0	0.70	16.80
9	Ch.Meskin	W	2	540	-5.00	-26.3	0	13.70
10	Izraa	W	2	580	-5.20	-24.9	0	16.7
11	Chacra	W	2	590	-5.97	-30.3	0	17.46
12	Mojadel	W	2	610	-6.15	-31.0	0.20	18.20
13	B.Harir	W	2	650	-5.86	-30.7	1.90	16.18
14	Mosefreh	W	2	690	-5.56	-26.5	0.10	17.98
15	Sahweh	W	2	735	-5.70	-27.6	1.00	18.00
16	Koheel	W	2	615	-5.52	-26.7	0	17.46
17	Nouimeh	W	2	555	-4.76	-26.1	0.20	11.98
18	Nourieh	S	1	943	-7.00	-34.4	15.20	21.60
19	Fawar	S	2	940	-7.21	-36.6	14.80	21.08
20	Halasse	S	1	690	-6.91	-34.3	11.00	20.98
21	Al-Koum	W	2	995	-6.61	-31.5	8.40	21.38
22	Reasse	S	1	1005	-6.89	-33.2	15.90	21.92
23	Irah	S	2	960	-6.80	-34.3	13.90	20.10
24	Kraya	S	1	1220	-4.97	-24.6	21.3	15.16
25	Badeer	S	2	1570	-7.30	-35.8	12.00	22.60
26	Qlneh	S	2	1700	-6.98	-34.5	10.10	21.34
27	Al-Sijen	W	2	800	-4.44	-22.0	1.80	13.52
28	Nijran	W	1	760	-6.44	-32.0	5.90	19.52
29	Smeed	W	2	780	-6.20	-32.0	1.10	17.60
30	Majadel	W	1	840	-6.21	-30.0	10.30	19.68
31	Brekeh	W	1	870	-5.75	-28.1	5.50	17.90
32	Bouldan	W	2	615	-6.61	-37.4	0.70	15.48
33	Dourak	W	2	620	-5.09	-28.4	0.20	12.32
34	Sawarah K.	W	1	665	-5.77	-30.5	0.60	15.66
35	Barkeh	S	2	1350	-6.18	-30.2	9.60	19.24
36	Lowieseh	W	2	940	-6.76	-34.6	5.30	19.48
37	Bidda	S	2	980	-6.98	-33.5	13.30	22.34
38	Hadar	W	1	1300	-7.48	-38.5	8.60	21.34
39	Het-Jeen	S	2	1280	-8.16	-43.4	13.70	21.88
40	Kruch	S	2	1440	-8.18	-44.0	16.30	21.44
41	Jabah	W	2	980	-7.00	-34.0	6.40	22.00
42	H.Sakher	S	1	815	-6.53	-33.2	11.20	19.04
43	Rafid	S	1	690	-6.32	-29.2	13.50	21.36
44	G. Boustan	W	2	575	-6.47	-29.4	1.70	22.36
45	A. Dakar	S	2	500	-6.25	-28.3	1.90	21.70
46	Ch.Saade	S	1	510	-5.87	-28.0	3.20	18.96
47	Der-Labo	S	2	500	-5.99	-28.1	3.80	19.82
48	Nawa	W	1	540	-2.69	-10.6	7.40	10.92
49	Khabab	W	2	610	-6.14	-32.9	0.40	16.22
50	Housmieh	W	2	615	-6.67	-37.5	0	15.86
51	Harah	W	2	780	-6.39	-29.8	1.40	21.32
52	D.Adasse	W	2	730	-5.80	-29.7	1.00	16.70
53	Soraya	S	2	590	-6.31	-30.3	1.60	20.18
54	Hadar	S	1	1300	-7.37	-36.9	11.40	22.06
55	Dama	W	1	720	-6.04	-29.4	3.70	18.92
56	Sawarah S.	W	1	745	-5.92	-30.6	0	16.76

Where: S, spring; W, Well and L, lake

Table IV Mean isotopic values of carbon isotopes, uncorrected radiometric ages (Age 1) and corrected ones using the Vogel's conception (Age 2) and the Gonfiantini's Model (Age 3)

No	Location	Type	^{14}C (pMC)	$\delta^{13}C$ (‰ PDB)	Age (1) (Years)	Age (2) (Years)	Age (3) (Years)
1	Mzeireeb	S	48.40±1.60	-14.52 *	6000±280	4655±280	4775±2410
3	Breer	S	43.75±0.80	-14.52 *	6835±150	5490±150	5610±2285
4	Ashaary	S	43.40±1.30	-14.52 *	6900±250	5555±250	5675±2380
5	Daeel	W	40.70±1.40	-14.52 *	7430±290	6090±290	6220±2420
6	Tafasse	W	40.40±2.20	-14.52 *	7490±465	6150±465	6270±2595
7	Mzeireeb	W	53.10±1.40	-14.52 *	5235±220	3890±220	4010±2350
8	Ziezoun	S	52.40±1.50	-14.52 *	5340±240	4000±240	4120±2370
9	Ch.Meskin	W	50.50±2.40	-14.52 *	5650±400	4305±400	4435±2530
10	Izraa	W	60.40±1.70	-14.52	4170±235	2825±235	2955±2365
11	Chacra	W	38.15±1.56	-11.88	7965±345	6625±345	5095±2645
12	Mojedel	W	44.05±1.98	-13.26	6780±380	5435±380	4815±2585
13	B.Harir	W	32.06±1.23	- 9.76	9405±325	8060±325	4910±2820
14	Mosefreh	W	67.32±1.90	-14.60	3270±240	1930±240	2105±2360
15	Sahweh	W	71.50±2.20	-13.02	2775±260	1430±260	660±2475
16	Koheel	W	65.90±2.60	-12.36	3450±335	2105±335	905±2595
17	Nouimeh	W	22.40±1.10	-12.36 *	12370±415	11025±415	9825±2680
27	Al-Sijen	W	95.72±2.08	-13.84	360±180	R	R
29	Smeed	W	74.72±2.20	- 8.60	2410±245	1065±245	R
33	Bourak	W	42.52±2.66	- 8.54	7070±535	5725±535	1470±3190
44	G. Boustan	W	62.63±1.88	-15.94	3870±250	2525±250	3430±2310
45	A. Dakar	S	66.40±1.80	-14.52 *	3385±225	2040±225	2160±2355
49	Khabab	W	49.10±1.60	-13.26	5880±275	4540±275	3920±2475
50	Mousmieh	W	39.90±1.31	-8.54	7595±265	6250±265	1995±3000
51	Harah	W	75.75±1.98	-14.01	2295±220	950±220	790±2375
52	D.Adasse	W	32.57±2.10	-13.22	9275±550	7930±550	7285±2755
53	Soraya	S	89.10±2.40	-14.52 *	955±225	R	R
55	Dama	W	93.53±2.98	-12.39	555±270	R	R

Where: S, spring; W, Well; R, recent and *, value are assumed.

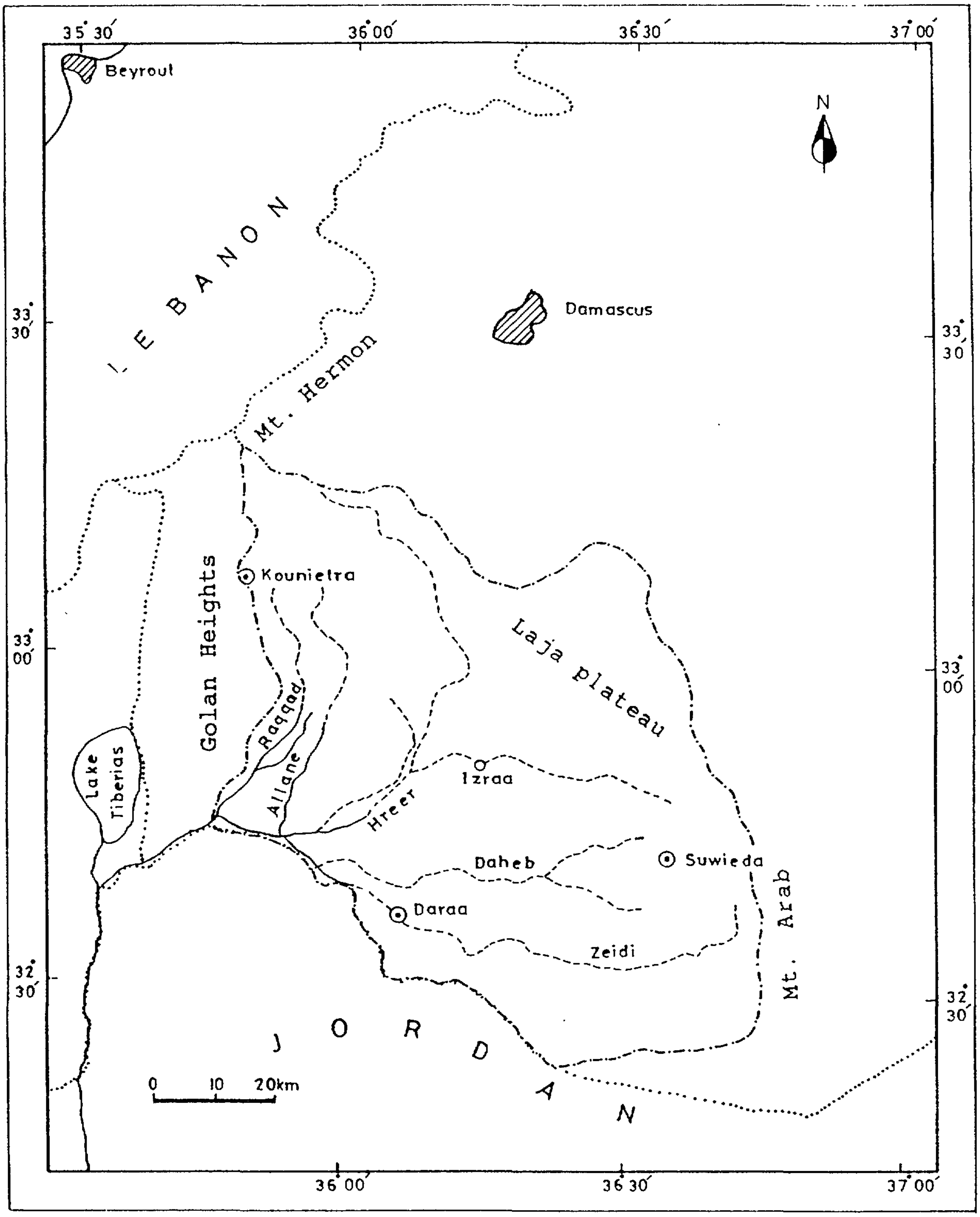

Fig. 1. Location map of Yarmouk Basin showing the hydrographic network

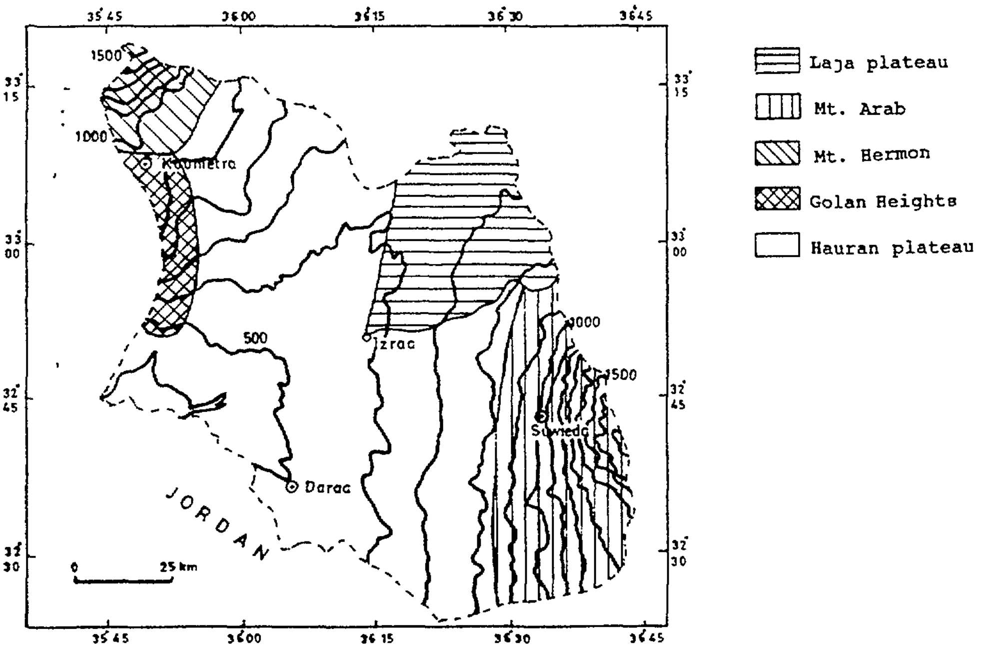

Fig. 2. Geomorphological map of Yarmouk Basin showing the topographic contour lines

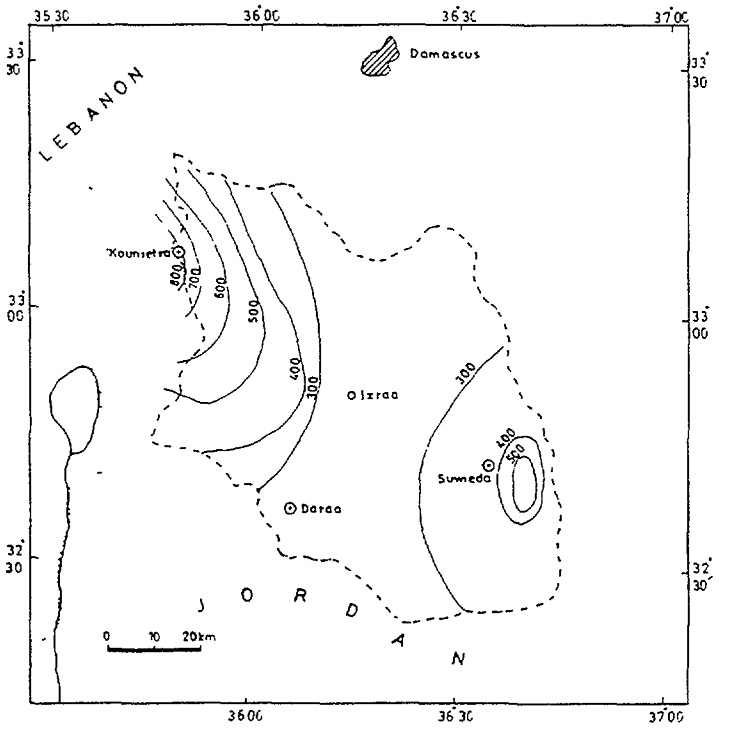

Fig. 3 Spatial distribution of the mean annual precipitation (mm) over Yarmouk Basin

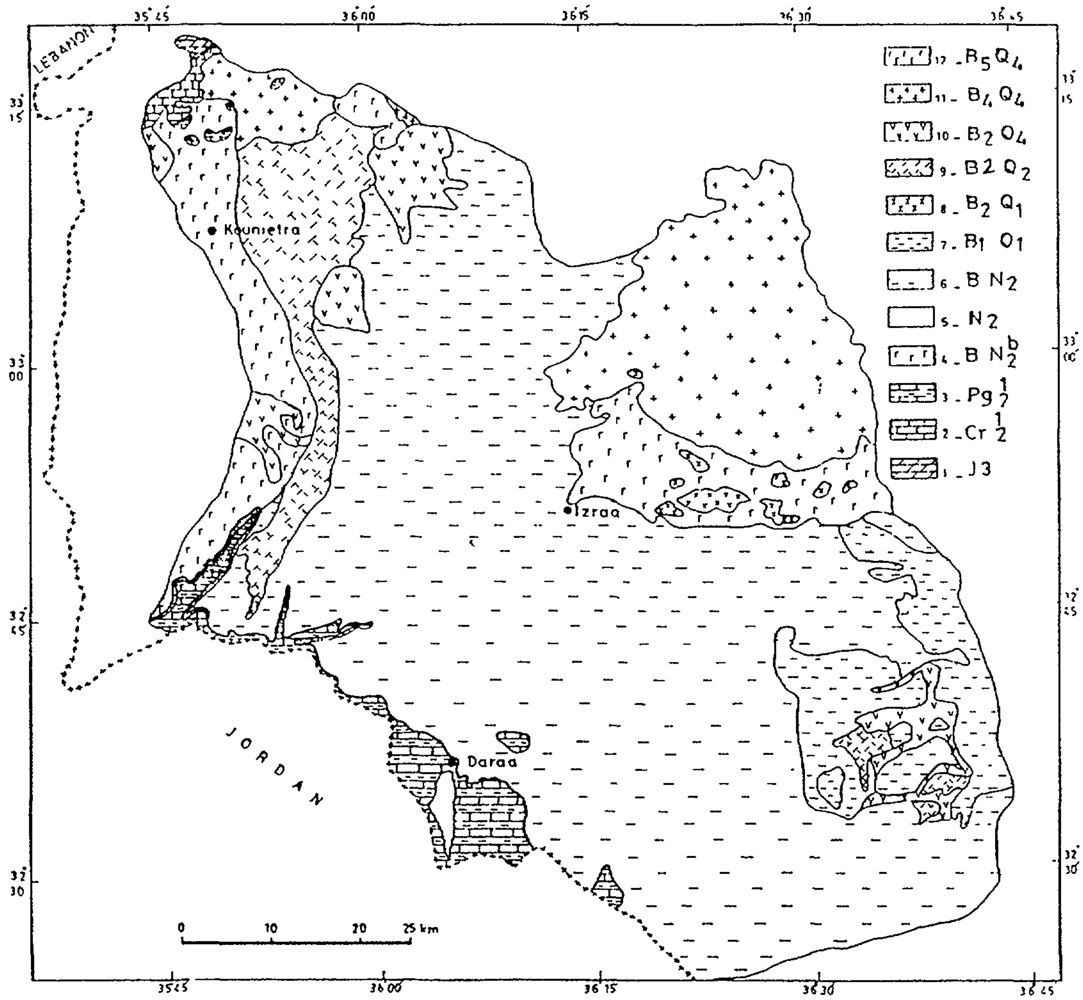

Fig. 4. Geological map of the Yarmouk Basin

Where, 1: Upper Jurassic, 2: Cretaceous, 3: Paleogene, 4: Upper Pliocene Basalt, 5: Sedimentary Neogene, 6: Undivided Pliocene Basalt, 7&8: Lower Quaternary Basalt, 9: Middle Series of Basalt, 10, 11 and 12: Upper Quaternary Basalt

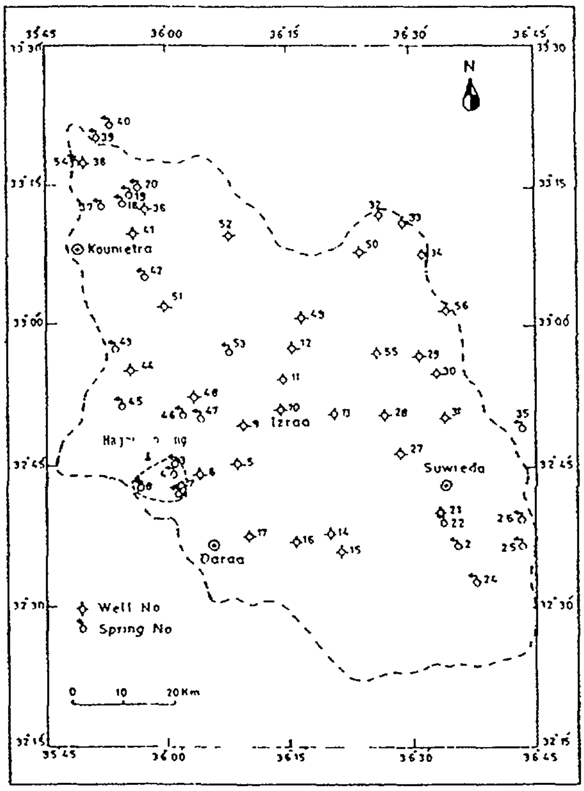

Fig. 5. Location map showing the sampling sites in the Yarmouk Basin

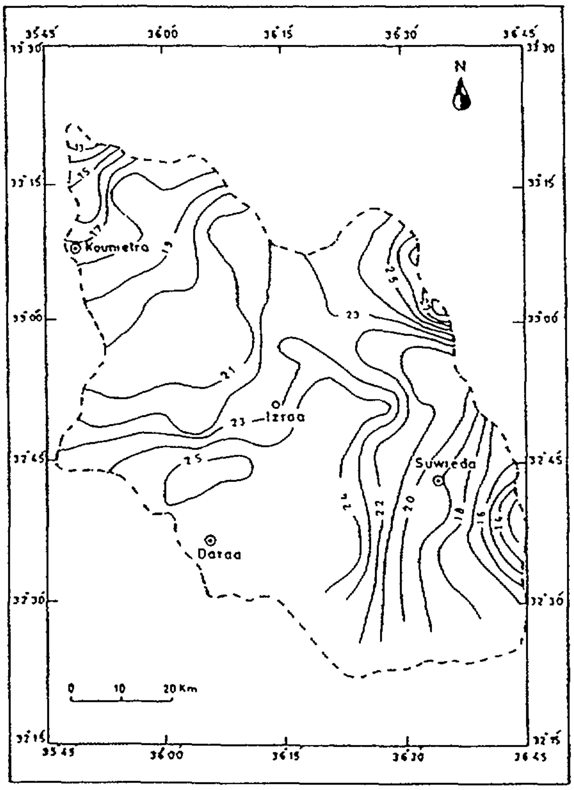

Fig. 6. Spatial distribution of the groundwater temperature (°C) in the Yarmouk Basin

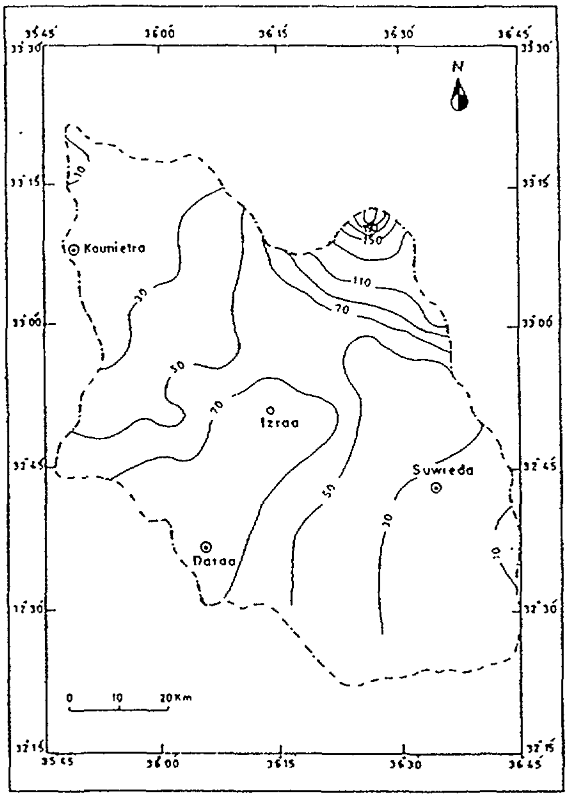

Fig. 7. Spatial distribution of the sodium concentration (mg/L) of the groundwater in the Yarmouk Basin

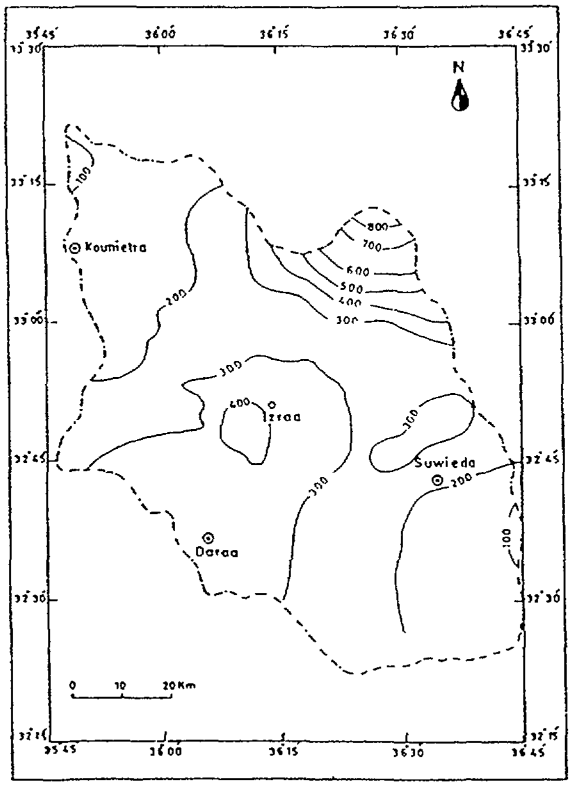

Fig. 8. Spatial distribution of the TDS content (mg/L) of the groundwater in the Yarmouk Basin

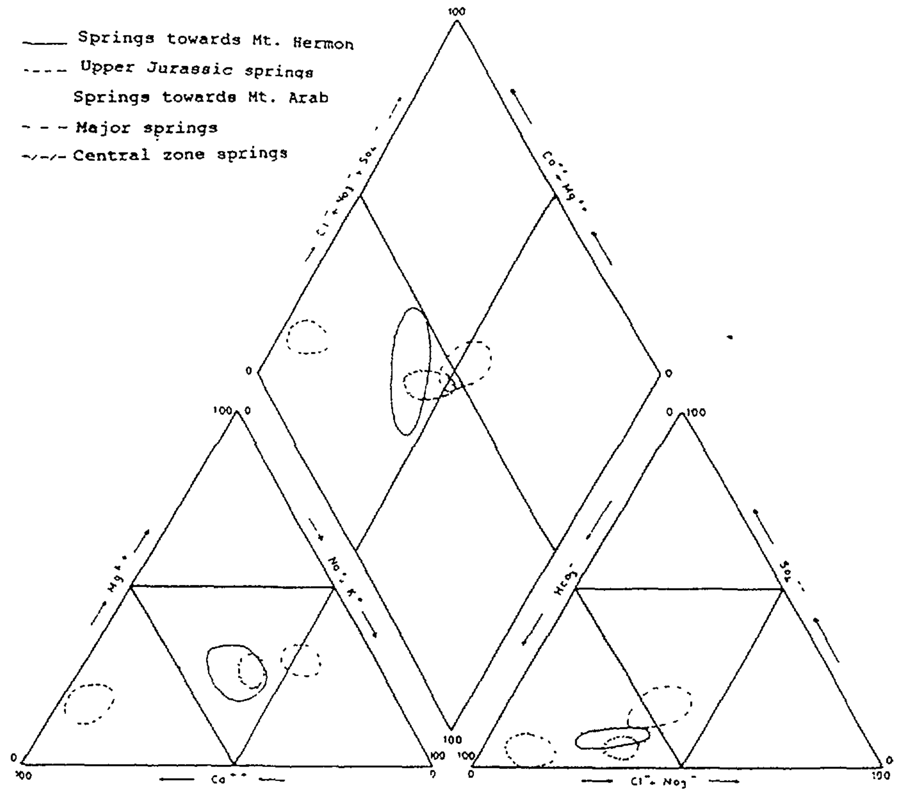

Fig. 9. Piper diagram of the chemical composition of spring water samples collected from the Yarmouk Basin

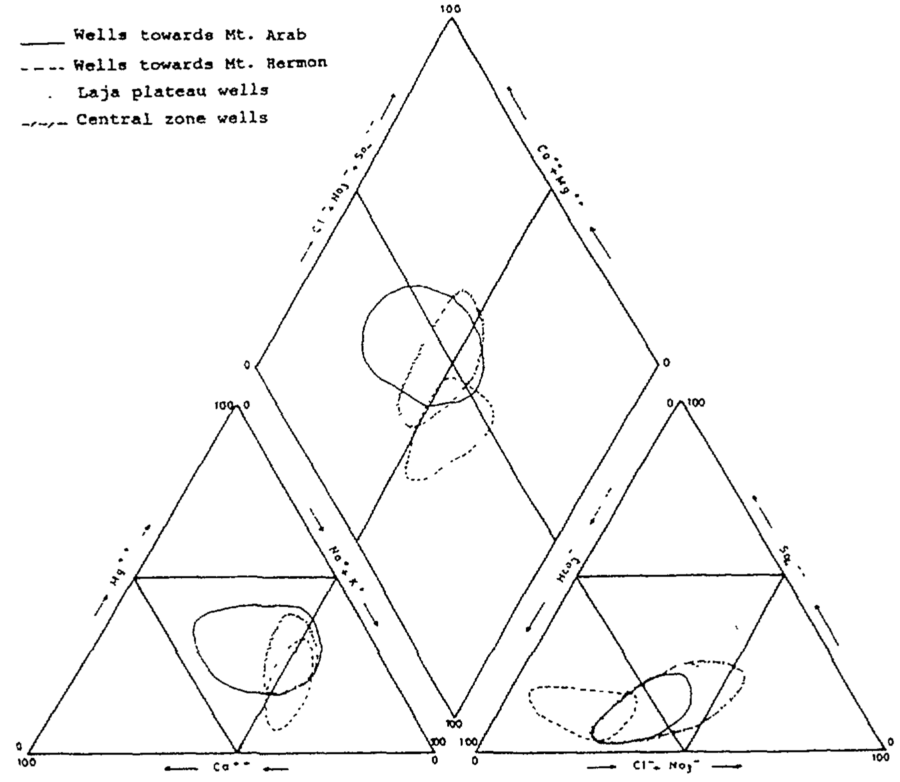

Fig. 10. Piper diagram of the chemical composition of groundwater samples collected from the Yarmouk Basin

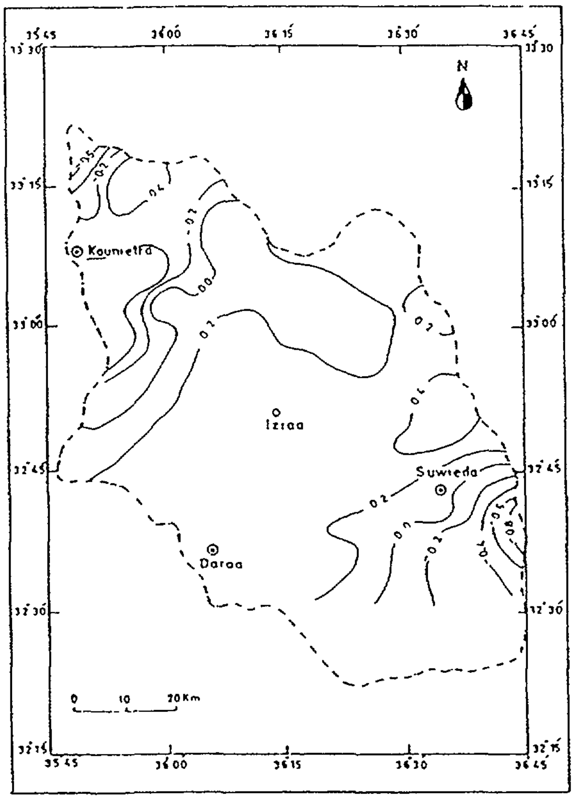

Fig. 11. Spatial distribution of calcite saturation index ($SI_{cal.}$) of the groundwater in the Yarmouk Basin

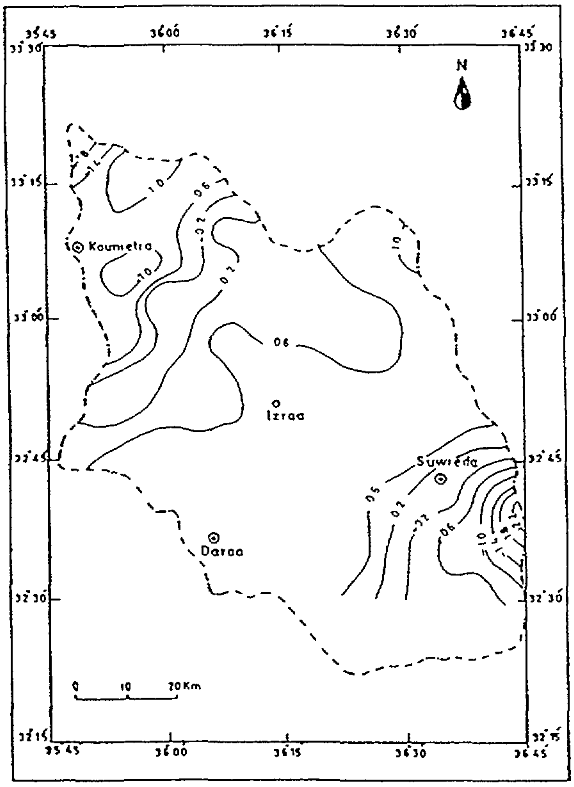

Fig. 12. Spatial distribution of dolomite saturation index ($SI_{dol.}$) of the groundwater in the Yarmouk Basin

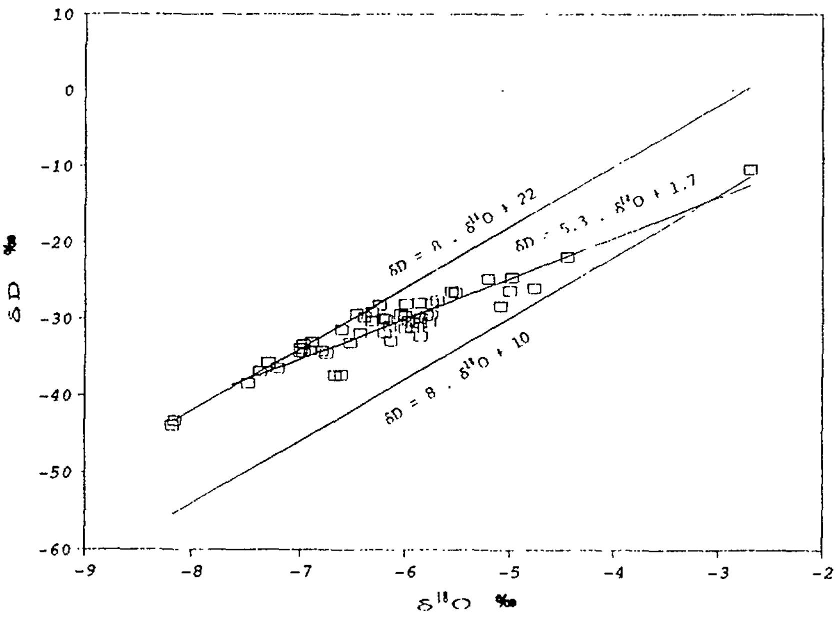

Fig. 13. Relationship between $\delta^{18}O$ and δD values of the groundwater samples collected from the Yarmouk Basin

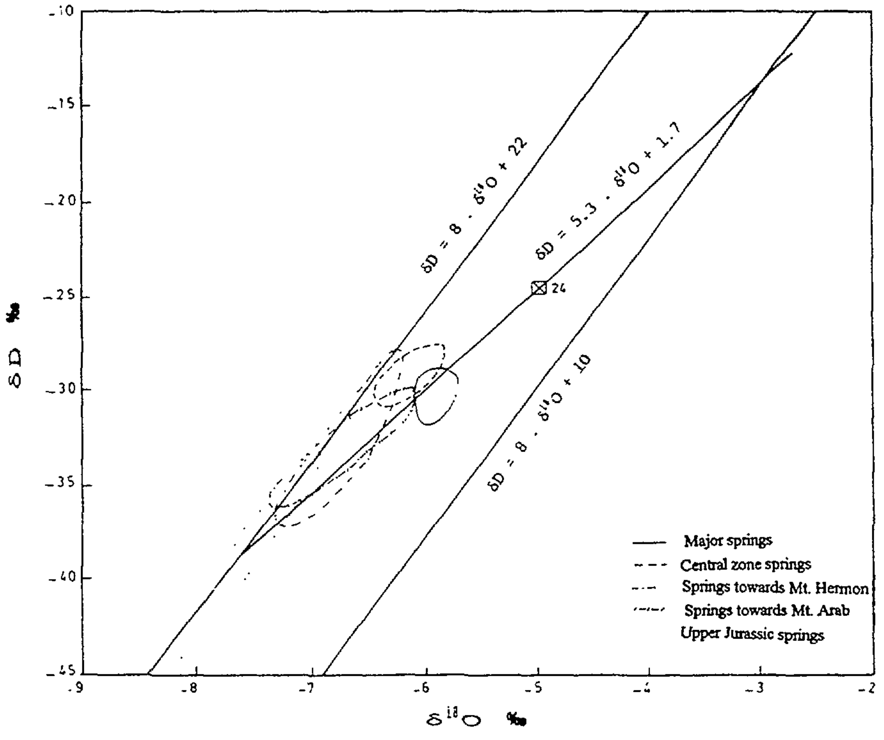

Fig. 14. Relationship between $\delta^{18}O$ and δD values of spring water samples collected from the Yarmouk Basin

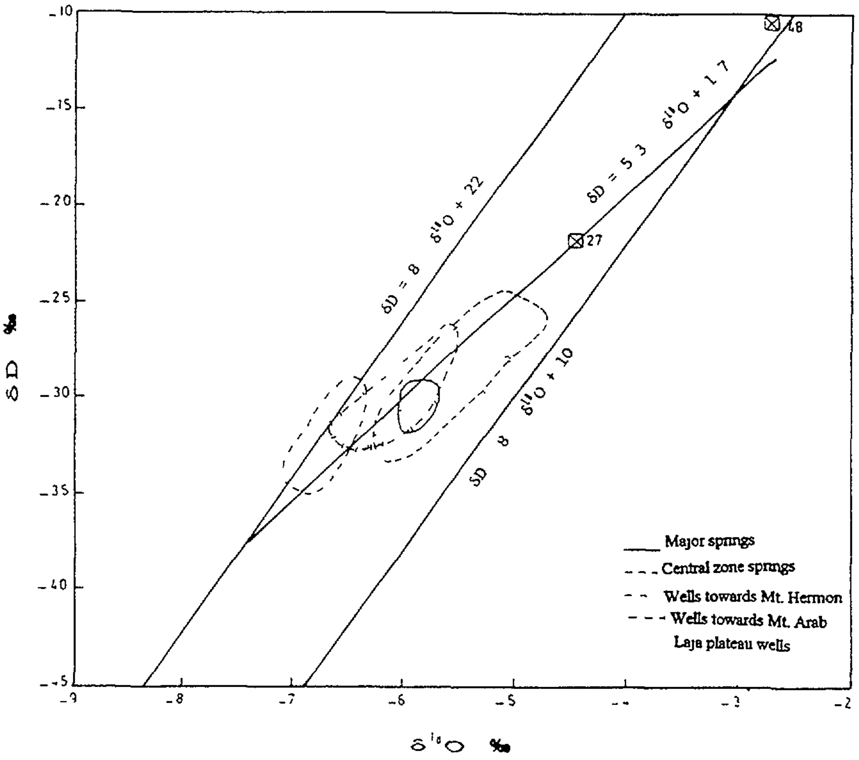

Fig. 15. Relationship between $\delta^{18}O$ and δD values of well water samples collected from the Yarmouk Basin

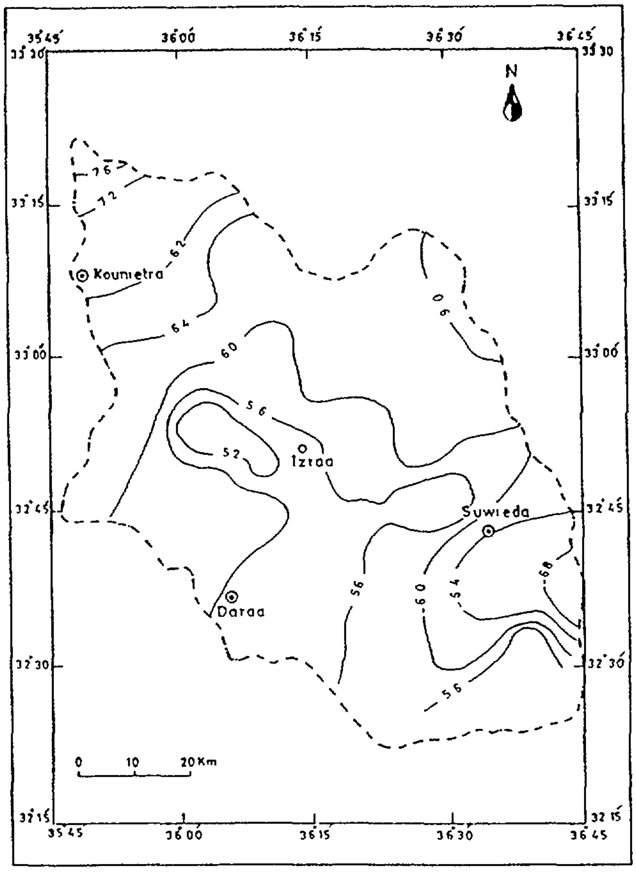

Fig. 16. Spatial distribution of $\delta^{18}O$ (‰) values of the groundwater in the Yarmouk Basin

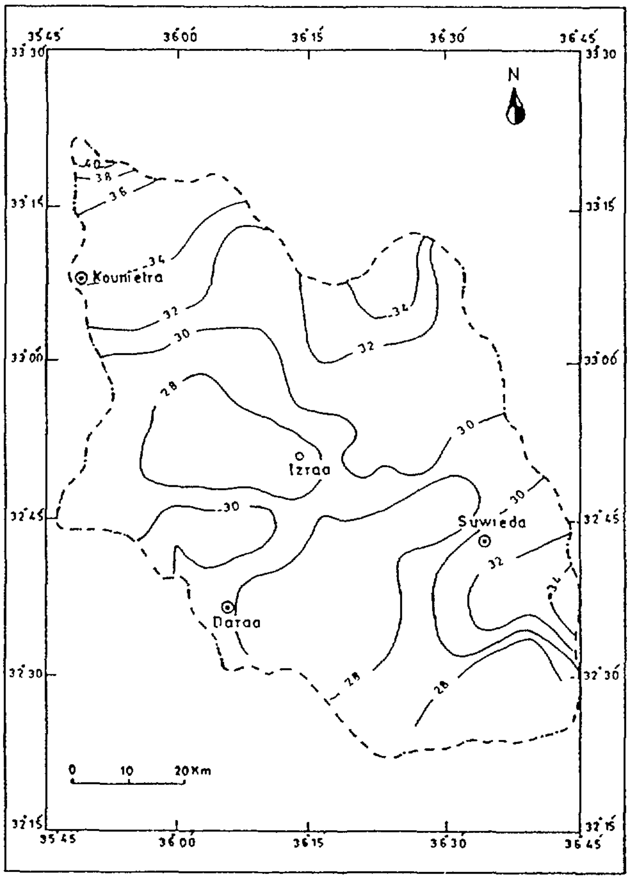

Fig. 17. Spatial distribution of δD (‰) values of the groundwater in the Yarmouk Basin

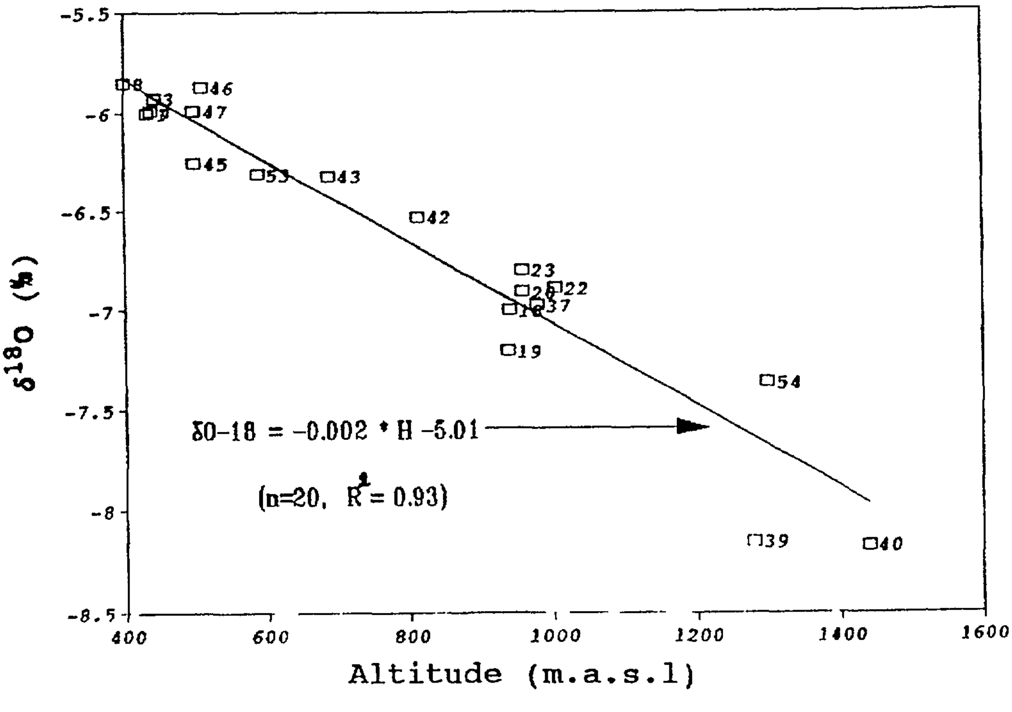

Fig. 18. Relationship between $\delta^{18}O$ and altitude (m.a.s.l) for selected springs in the Yarmouk Basin

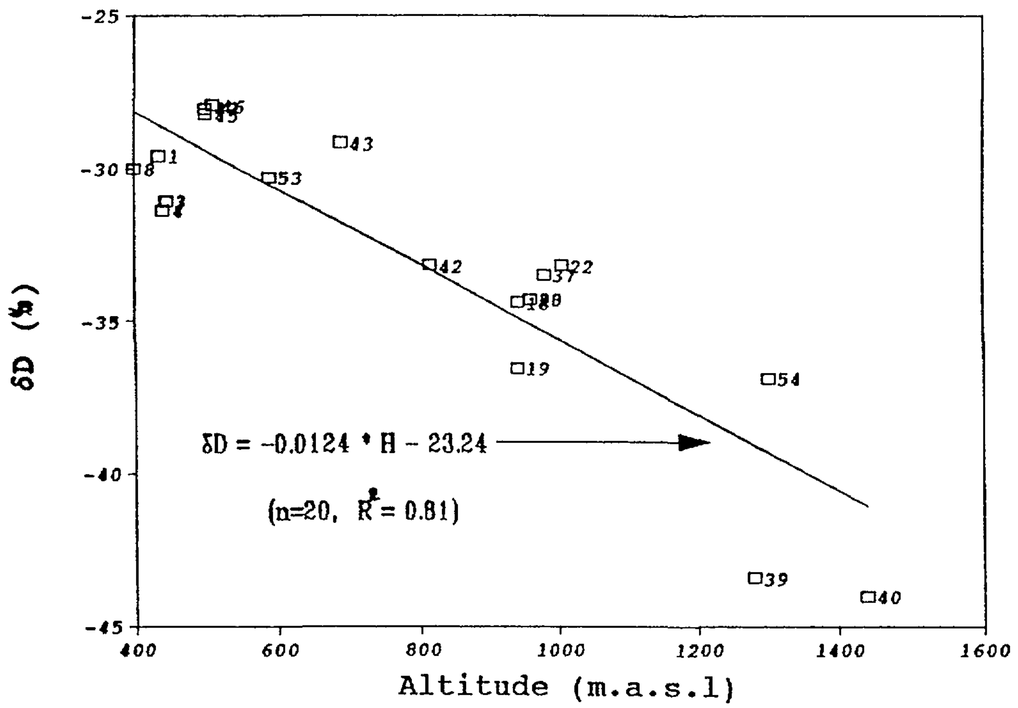

Fig. 19. Relationship between δD and altitude (m.a.s.l) for selected springs in the Yarmouk Basin

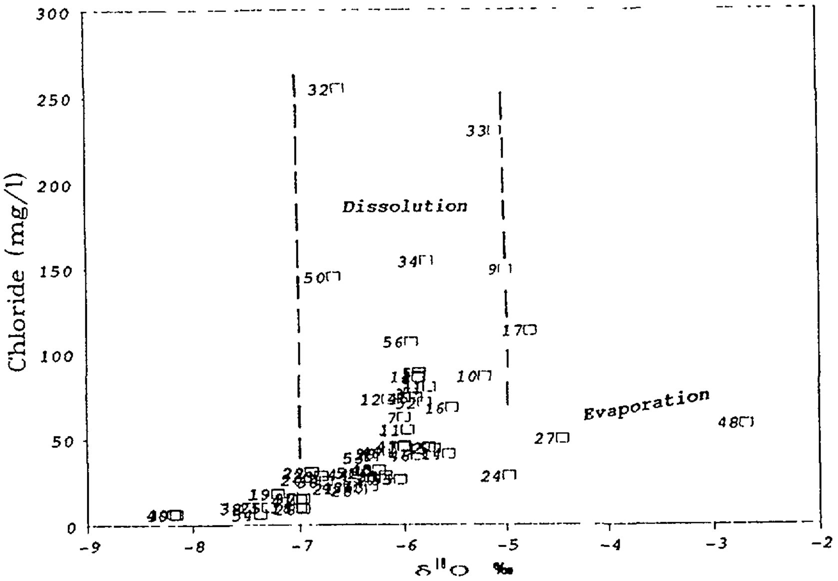

Fig. 20. Relationship between $\delta^{18}O$ and chloride concentration of the groundwater in the Yarmouk Basin

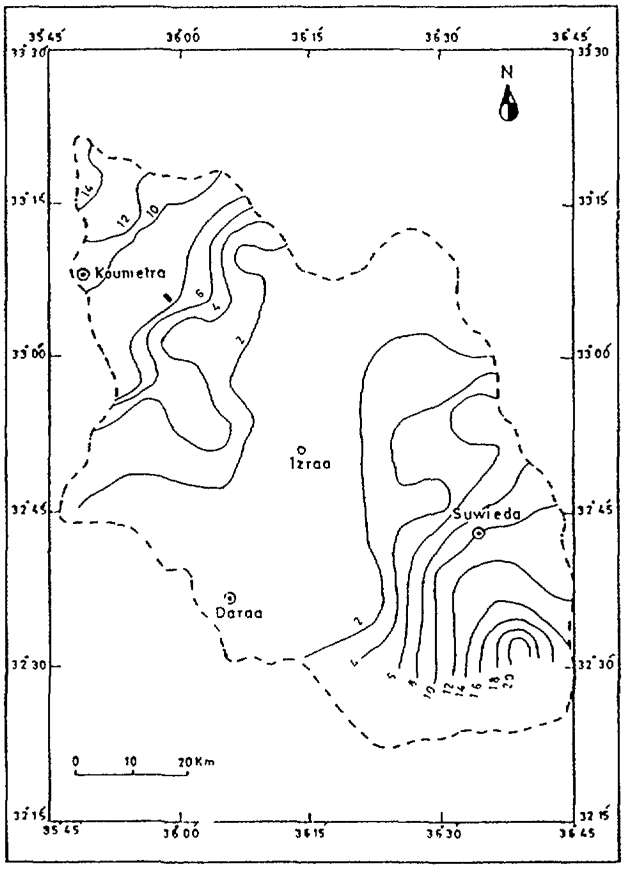

Fig. 21. Spatial distribution of tritium (TU) values of the groundwater in the Yarmouk Basin

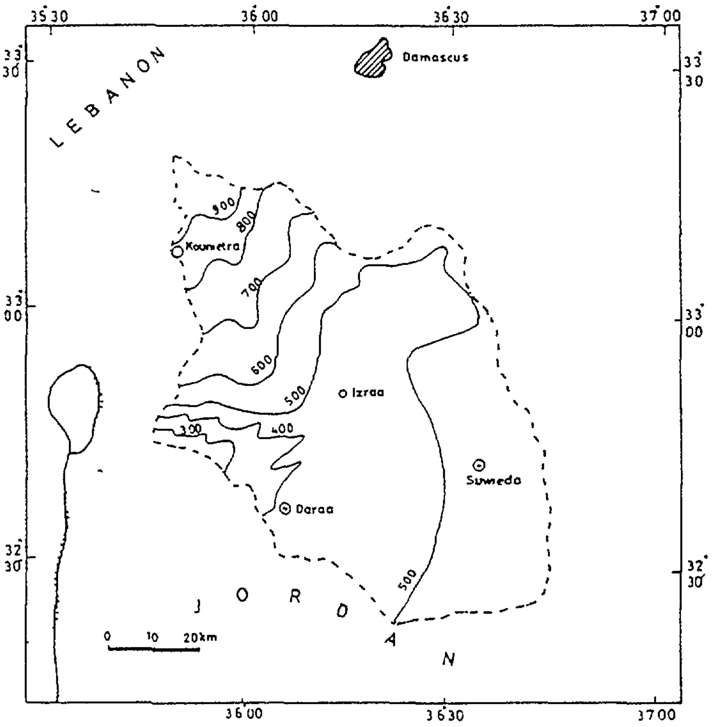

Fig. 22. Piezometric map of the shallow groundwater in the Yarmouk Basin [7]

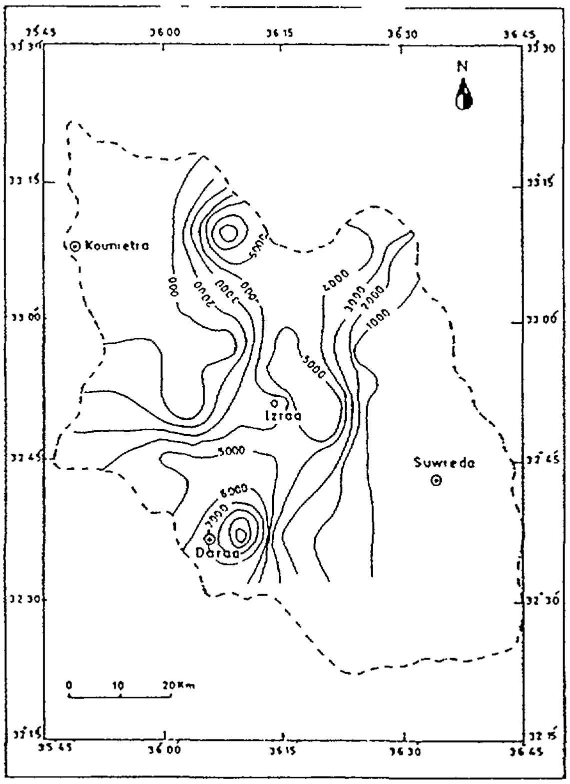

Fig. 23. Spatial distribution of the groundwater ^{14}C ages (years), corrected by the Vogel's Model, in the Yarmouk Basin

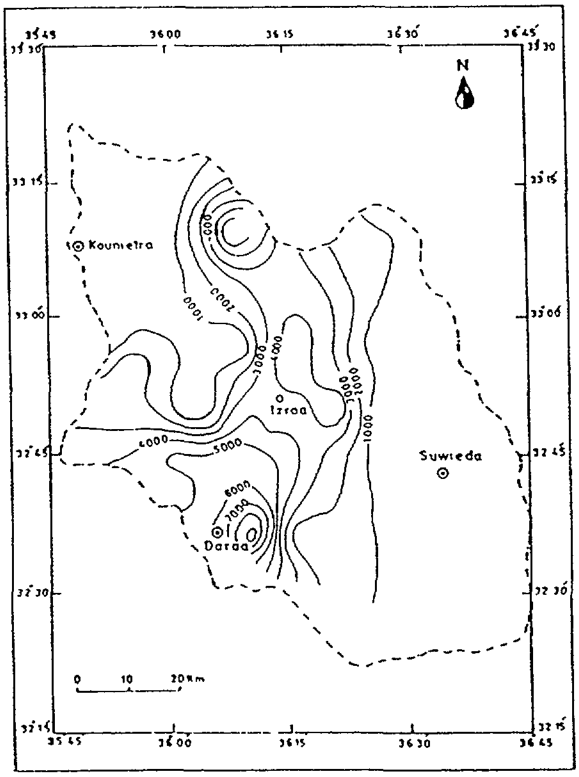

Fig. 24. Spatial distribution of the groundwater ^{14}C ages (years), corrected by the Gonfiantini's Model, in the Yarmouk Basin

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I would like to acknowledge gratefully Prof. I. Haddad, Director General of A.E.C. of Syria and Prof. M. Mouty, Head of the Department of Geology and Nuclear Ores for the facilities provided to me during this study. I am also very grateful to Mr. Y. Yurtsever, IAEA staff member for his useful and continuous help during the implementation of this project. Special thanks are due to Prof. M. Geyh for the corrections of the manuscript and to Drs. Ch. Safadi and A. Droubi for the valuable discussions. Thanks are due to the Isotope Laboratory of Amman/Jordan and the Laboratory of the Establishment of Ain-El-Figeh for the isotopic and chemical analyses. I acknowledge Ms. R. Saadeh for the graphs drawing. Finally, thanks are due to the staff of the Geology and Nuclear Ores Department who contribute to this study.

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CHEMICAL AND ENVIRONMENTAL ISOTOPE STUDY OF PRECIPITATION IN SYRIA

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Abstract

The rain waters from a network covering 9 meteorological stations distributed mainly in the western part of Syria have been investigated using chemical and environmental isotope techniques during a period of 5 months from Dec. 1989 to Apr. 1990. The chemistry of rain waters falling over the mountainous stations shows a low solute concentration (16-55 mg/L) comparing with those falling over the coastal and anterior stations (36-150 mg/L). The study shows also that the rain waters are generally characterized by a high deuterium excess (d = 19 ‰) comparing with that of the global meteoric waters (d = 10 ‰). Mean while, the estimated deuterium excess is found to be lower than that given for the eastern Mediterranean meteoric water (d = 22 ‰). The altitude effect is shown up by a depletion of heavy stable isotopes of about -0.23 ‰ and -1.65 ‰ per 100 meters for δoxygen-18 and δdeuterium, respectively. The spatial distribution pattern of tritium contents shows a gradual build up with the increasing distance from the Syrian coast. The weighted mean tritium content in rain waters falling over the country is estimated to be around 9.5 TU during the period of observation.

1. INTRODUCTION

Atmospheric precipitation is the main input to the majority of hydrological and hydrogeological systems. Thus, the knowledge on the distribution pattern of the environmental isotope compositions in rainfall is an indispensable parameter for the use of these isotopes as natural tracers in hydrological and hydrogeological investigations.

The hydrological investigations using environmental isotope technique for the study of the atmospheric precipitation were initiated within the framework of the ongoing IAEA Regional Technical Co-operation Project entitled "Isotope Hydrology in the Middle-East (RER/8/002)".

This work which discuss the preliminary results of monitoring of the chemical and isotopic compositions of atmospheric precipitation in Syrian during one hydrological year is followed by another detailed study being undertaken within the same project, but devoted to the monitoring of atmospheric precipitation for a period of three years (1991-1993).

The purpose of this study was, therefore, to determine the chemical and isotopic properties of rainfall waters in order to be used in the evaluation and interpretation of hydrochemical and isotopic data related to the area under investigations [1&2].

2. SAMPLING AND ANALYSES

A precipitation network, covering mainly the western part of Syria (Fig. 1), was established for rainfall sampling. This network includes 9 meteorological stations distributed in the following areas: Aleppo, Bloudan, Damascus, Homs, Izraa, Kounietra, Palmyra, Suwieda and Tartous.

The rainfall samples have been collected as a monthly composite, from all these stations, during a period of 5 months from December 1989 to April 1990. The total number of rain water samples collected during the period of investigation is 45.

The water samples were collected in three bottles for the isotopic and chemical analyses. The isotopes being determined in this study include ^{18}O, ^{2}H and tritium of which the analyses were performed in the Laboratory of Amman/Jordan. The chemical analyses of these samples were carried out in the Laboratory of Ain El-Figeh Establishment in Damascus. In the case of tritium and chemical measurements, the analyses were performed only for the samples having enough water to carry out these determinations. The temperature, electrical conductivity and pH of water samples were taken in the field.

3. CHEMICAL COMPOSITION OF ATMOSPHERIC PRECIPITATION

The results of the hydrochemical analyses of rain water falling over the investigated stations are reported in Table 1. According to these data, we can note that the pH of rainfall varies within the range from 5.97 (Suwieda station) to 9.46 (Aleppo station). The low pH values of rain water were observed for Izraa and Suwieda stations, while the highest pH values were reported for Aleppo station. The relative increase of pH in rain water falling over Aleppo station may be due to the dust produced by the cement factory, situated very close to the station. Low pH values were also observed by Native & Mazor, 1986 [3] for the rainfall of eastern Mediterranean region.

The chemistry of the rain water falling over the sampling sites shows, in general, a low solute concentration (16-55 mg/L) over the mountainous and the southern regions such as Bloudan, Izraa, Kounietra and Suwieda. The total dissolved solids (TDS) in rain water becomes higher over the coastal and the anterior areas such as Aleppo, Damascus, Homs, Tartous, and Palmyra, where the total dissolved solids changes from 36 to 150 mg/L. The rain water chemistry for all the stations is of calcium-bicarbonate type, with a clear predominance of calcium over magnesium and sodium, and bicarbonate over chloride and sulfates. The highest concentrations of Cl^- and Na^+ were observed in rain water falling over Tartous, indicating hence the influence of sea on the water chemistry [4 &5]. The relatively high sulfate concentrations observed for Damascus (12-30 mg/L) and Homs (12-18 mg/L), could indicate an industrial pollution. The abundence of calcium and magnesium in rain water may be attributed to the presence of carbonte dust in the atmosphere[5]. The chemical representation of atmospheric precipitation in Piper diagram is shown in figure 2.

4. ISOTOPIC COMPOSITION OF ATMOSPHERIC PRECIPITATION

The results of isotopic composition in rain waters collected from the 9 meteorological stations, are compiled together with precipitation amount, air temperature, relative humidity and deuterium excess in Table 2. In general, the isotopic composition of rain water is highly scattered between the different stations, which should be the result of many factors such as: altitude, temperature, precipitation amount and evaporation, that affect these variations.

The weighted means of isotopic composition for the different stations were calculated by the following equation [6]:

$$\delta_w = \sum_i^n [p_i - \delta_i] / \sum_i^n [p_i] \qquad [1]$$

where δ_W: weighted mean, P_i: amount of monthly precipiation and δ_i: isotopic composition of rainfall for the month i.

4.1. STABLE ISOTOPE COMPOSITION

The stable isotope concentrations in rainfall from Bloudan station (altitude = 1540 m.a.s.l) are the most depleted values in both oxygen-18 and deuterium. The weighted mean isotopic compositions of these two isotopes for this station are -8.55 ‰ and -48.8 ‰ for δoxygen-18 and δD, respectively. In the contrary, the rains collected from Tartous station (altitude = 5 m.a.s.l) appear to be more enriched in these heavy isotopes (weighted means are -4.96 ‰ and -22.9 ‰ for δoxygen-18 and δD, respectively).

The rain waters collected from Palmyra station, situated in the central part of Syrian desert, and far from the coast of about 210 km, show the most enriched concentrations in these two isotopes (weighted means are -3.65 ‰ and -12.6 ‰ for δoxygen-18 and δD, respectively).

The values of deuterium excess d, calculated by the following equation:

$$\mathbf{d = \delta D - 8\,\delta^{18}O} \qquad [2]$$

are significantly higher than 10, value estimated by Craig, 1961 [7] for a large number of stations over the world. This relatively high deuterium excess is an indication of Mediterranean type of precipitation [8].

In fact, the increase of deuterium excess has been attributed to the moisture originating from the Mediterranean Sea, which is characterized by lower relative humidity conditions prevailing in this region [9].

Although deuterium excess values lower than 10 ‰ can be observed in some stations (Aleppo and Damascus) during some months, these values are most probably related to the isotopic enrichment due to evaporation. In general, one can observe that the highest deuterium excess (>20 ‰) is found, especially, for the stations having higher altitude, short distance from the coast and during the months in which the precipitation amount and relative humidity were high and also during the months having lower mean temperature (Fig. 3).

4.1.1. OXYGEN-18-DEUTERIUM RELATIONSHIP FOR PRECIPITATION

Figure 4 shows the deuterium and oxygen-18 relation of precipitation for all the samples collected from the 9 meteorological stations in Syria. It is seen that, approximately, all the sample points are situated between the Mediterranean MeteoricWater Line (MMWL):

$$\mathbf{\delta D = 8.\delta^{18}O + 22} \qquad [3]$$

and the Global Meteoric Water Line (GMWL):

$$\mathbf{\delta D = 8.\delta^{18}O + 10} \qquad [4]$$

The sample points situated out side of this range for some months are observed for Palmyra, Aleppo and Damascus stations. These samples seem to be mostly effected by evaporation. In fact, the spatial evolution of isotopic composition is due to a partial evaporation from droplets during their fall, causing hence the enrichment of heavy isotopes in the residual rain drops [10, 11, 12 & 13].

The plot of weighted mean values of δD and δoxygen-18 for the different stations is illustrated in figure 5. It can be seen that the stable isotope composition of the rain waters from

Bloudan station are the most depleted, while the rain waters from Palmyra are the most enriched.

The equation of the least squares regression line fitting all of the sampled rain water in the country is given by the following equation:

$$\delta D = (8.26 \pm 0.37)\ \delta^{18}O + (19.3 \pm 2.7) \quad \text{with } R^2=0.96 \text{ and } n=43 \qquad [5]$$

This equation defines the Syrian Meteoric Water Line (SMWL). The slope of this line (8.26) is slightly different from the slope (8) of GMWL, estimated by Craig, 1961 [7]. The conservation of the slope around a value of 8 is due to the fact that the condensation of atmospheric moisture occurs under equilibrium conditions and that the fractionation factor, defined by the partial vapor pressures of different isotope species of water has not large variations under the climatic conditions, generally observed in the nature [9].

The value of the estimated intercept of the line (19.3 ‰) representing the deuterium excess in Syrian rainfall is lower than the estimated value (22 ‰) for the eastern Mediterranean region [8].

On the other hand, we tried to estimate the Regional Meteoric Water Line (RMWL), on a basis of data collected from Syria during this study and Jordan during the period from 1987 to 1989 [14]. As can be seen in figure 6, the Regional Meteoric Water Line fitting all the samples has the following equation:

$$\delta D = (7.8 \pm 0.34)\ \delta^{18}O + (19.25 \pm 2.4) \quad \text{with } R^2=0.94 \text{ and } n=75 \qquad [6]$$

This equation is very comparable to that one established for the Syrian Meteoric Water Line (SMWL), and especially deuterium excess value, is conserved between the two equations.

4.1.2. ALTITUDE EFFECT

The determination of the altitude effect of atmospheric precipitation is a useful tool for the identification of groundwater recharge zones, as well as for the identification of groundwater origin and the dynamics of flow in the area under investigation.

The plot of $\delta^{18}O$ and δD weighted mean values for each station versus the corresponding altitudes for all the stations selected in this study are illustrated in figures 7 and 8, respectively. As can be shown in these two figures, the points are largely scattered in these diagrams. However, we can observe that the stations of Bloudan, Suwieda, Izraa, Kounietra, Homs and Tartous fit significantly two negative regression lines having the following equations for $\delta^{18}O$-altitude and δD-altitude, respectively:

$$\delta^{18}O = -0.0023 \,.\, \text{Altitude} - 5.15 \qquad [7]$$

$$\delta D = -0.0165 \,.\, \text{Altitude} - 28.11 \qquad [8]$$

From the above equations, we can conclude that altitude effect can be shown up by a progressive depletion of heavy stable isotopes of about -0.23 ‰ and -1.65 ‰ per 100 meters, for δoxygen-18 and δD, respectively. The magnitude of the estimated altitude effect, which depend on the local climate and topography, fills in the range established by Yurtsever & Gat, 1981 [6], in which gradient in $\delta^{18}O$ is of between -0.15 and -0.5 ‰ per 100 meters and gradient in δD is of between -1.5 and -4 ‰ per 100 meters.

The estimated altitude effect for Damascus region by Russian researchers [15] was of about -0.19 ‰ per 100 meters for $\delta^{18}O$ gradient. For Jordan precipitation gradients of about -0.26 and -1.31 ‰ per 100 meters were found for $\delta^{18}O$ and δD, respectively [16]. Other examples of altitude effect were cited by Payne & Yurtsever, 1974 [17];; Fontes & Olivry, 1976[18]; Gonfiantini et al., 1976 [19]; Fontes, 1983 [20]; Gasparini et al., 1990 [21] for different case studies.

Although the stations of Aleppo and Damascus do not fit the earlier regression line, one can observe that these two stations may fit another regression line, parallel to that one. The scattering points of these two stations, may be due to the fact that the rain waters falling over these stations belong to similar conditions, particularly, as regards to the cause of moisture. On the other hand, it seems to be normal that the station of Palmyra, which has a particular topographic and climatic condition do not fit any of these two lines.

4.2. TRITIUM CONENT IN ATMOSPHERIC PRECIPITATION

The tritium concentration in atmospheric precipitation during 5 months of observation period ranges from 4.3 TU (Bloudan station), during the month of December 1989 up to 13.6 TU (Damascus station), during April 1990. Although the data of tritium content in rain water are insufficient for the evaluation of temporal variations, it can be noted, however, as shown by Carmi & Gat, 1973 [22] a build up of tritium content with increasing distance from the coast (Fig. 9). The mean annual weighted value estimated for tritium content in rain water over the country during the period of observation is 9.5 TU.

5. CONCLUSIONS

In conclusion it may be said that the use of chemical and environmental isotope techniques in the investigation of atmospheric precipitation in the western part of Syria has provided useful information about the chemical and isotopic characteristics of precipitation in Syria.

Although the information gained from this study should be considered as approximate, there is no doubt that continuous monitoring of atmospheric precipitation for long-term will give a better understanding of the distribution pattern of chemical and environmental isotope compositions in rain waters falling over the country.

TABLE I. CHEMICAL COMPOSITION OF RAIN WATERS COLLECTED FROM SYRIAN METEOROLOGICAL STATIONS DURING 1989-1990

Station	Date	T (°C)	pH	E.C (µS/cm)	Ca^{++} (mg/L)	Mg^{++} (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	HCO_3^- (mg/L)	SO_4^{--} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	TDS (mg/L)
Aleppo	Dec.89	14.0	8.52	108	28	2	1.0	0.0	73	8	4	9	90
	Jan.90	14.0	9.46	103	20	2	0.5	0.5	37	11	2	7	61
	Feb.90	16.0	9.07	95	16	2	1.0	0.5	49	7	6	9	65
	Mar.90	22.0	8.64	92	8	7	1.0	1.0	49	8	4	16	69
	Apr.90	21.0	8.31	159									
Bloudan	Dec.89	7.5	7.28	28	8	0	0.5	0.0	12	1	2	9	26
	Jan.90	5.5	7.62	46	0	5	2.5	0.0	24	6	4	9	38
	Feb.90	6.0	7.41	44	4	2	3.0	0.5	12	5	8	8	36
	Mar.90	7.0	7.49	34	8	2	1.0	0.0	24	4	4	9	40
	Apr.90	14.5	7.48	40									
Damascus	Dec.89	19.0	6.91	162									
	Jan.90	15.0	8.31	146	36	2	1.5	0.5	61	30	2	9	115
	Feb.90	18.0	6.65	98	16	2	2.5	0.5	24	18	8	11	70
	Mar.90	24.0	6.32	103	20	2	1.5	0.5	49	13	6	5	72
	Apr.90	22.0	7.18	87	20	2	1.0	0.5	49	18	2	8	75
Homs	Dec.89	13.0	7.58	109	12	2	3.0	1.0	24	18	4	6	60
	Jan.90	15.0	7.95	85	8	2	4.0	1.0	24	13	6	10	56
	Feb.90	17.5	6.24	120	8	7	6.0	1.0	37	14	12	8	74
	Mar.90	17.0	7.27	202									
	Apr.90	18.0	7.30	104	16	2	1.5	1.0	37	12	4	7	60
Izraa	Dec.89	12.0	6.03	16	4	0	0.5	0.0	6	1	2	6	16
	Jan.90	12.5	5.62	30	0	2	1.5	0.0	6	3	2	6	17
	Feb.90	11.0	6.67	51	4	5	4.5	0.5	12	7	10	8	45
	Mar.90	12.0	6.70	37	8	2	2.0	0.5	24	6	6	10	46
	Apr.90	19.2	6.45	18	2	1	1.0	0.5	12	6	0	6	22

TABLE I (cont.)

Station	Date	T (°C)	pH	E.C (µS/cm)	Ca^{++} (mg/L)	Mg^{++} (mg/L)	Na^{+} (mg/L)	K^{+} (mg/L)	HCO_3^- (mg/L)	SO_4^{--} (mg/L)	Cl^- (mg/L)	NO_3^- (mg/L)	TDS (mg/L)
Kounietra	Dec.89	13.0	7.62	49	4	2	2.5	0.0	0	2	4	17	35
	Jan.90	12.5	7.14	36	4	2	1.5	0.0	12	3	2	8	26
	Feb.90	14.0	7.69	72	12	2	4.0	0.5	24	5	10	8	53
	Mar.90	11.0	7.75	89	16	2	3.0	0.5	61	5	8	8	72
	Apr.90	18.5	7.72	67									
Palmyra	Dec.89	15.0	7.32	135	20	5	2.0	0.5	61	9	4	9	80
	Jan.90	8.0	7.44	205									
	Feb.90	12.5	6.98	134	24	2	2.0	1.0	61	9	4	12	84
	Mar.90	12.5	7.42	204	44	5	2.5	1.0	110	25	8	10	150
	Apr.90	21.1	7.77	170									
Suwieda	Dec.89	10.0	6.40	36	4	2	1.5	0.5	6	6	4	10	31
	Jan.90	10.5	6.25	30	4	2	1.5	0.5	10	5	2	9	29
	Feb.90	11.0	6.87	69	8	2	5.0	0.5	12	7	12	11	51
	Mar.90	12.0	6.11	40	8	2	2.5	0.5	49	7	6	6	56
	Apr.90	17.1	5.97	21	2	1	1.0	0.5	12	3	0	7	20
Tartous	Dec.89	14.0	7.70	71	8	2	5.0	0.5	24	3	8	9	50
	Jan.90	17.5	7.98	92	8	2	9.5	0.5	24	6	18	9	65
	Feb.90	20.0	7.17	146	4	7	18.0	1.0	12	7	30	7	80
	Mar.90	17.0	7.08	100	16	2	5.0	3.0	37	7	10	8	69
	Apr.90	23.9	6.90	54	6	1	3.0	0.5	24	3	4	7	36

TABLE II. ISOTOPIC COMPOSITION OF ENVIRONMENTAL ISOTOPES IN RAIN WATERS COLLECTED FROM THE SYRIAN METEOROLOGICAL STATIONS DURING 1989-1990

Station	Altitude (m.a.s.l)	Date	P (mm)	T (°C)	R.H (%)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	d (‰)
Aleppo	410	Dec.89	45.1	6.1	87.4	-7.12	-37.8	6.7	19.2
		Jan.90	24.9	2.7	72.9	-10.74	-65.0	10.8	20.9
		Feb.90	47.1	6.0	75.8	-7.13	-38.9	9.1	18.1
		Mar.90	20.5	10.4	61.9	-2.81	-10.9	9.0	11.6
		Apr.90	3.5	12.7	60.8	-2.00	-14.0		2.0
Weighted mean						-7.00	-38.5	8.6	17.5
Bloudan	1540	Dec.89	48.1	3.2	80.4	-8.02	-44.1	4.3	20.1
		Jan.90	46.1	1.0	76.6	-7.77	-40.2	6.9	22.0
		Feb.90	101.9	1.9	81.2	-8.68	-48.7	7.3	20.7
		Mar.90	51.5	6.4	60.0	-8.21	-47.8	7.0	17.9
		Apr.90	18.0	15.2	39.0	-12.22	-87.4	9.5	10.4
Weighted mean						-8.55	-48.8	6.8	19.6
Damascus	625	Dec.89	4.8	7.2	73.6	-7.32	-47.8	5.5	10.8
		Jan.90	14.9	5.2	64.7	-9.64	-62.6	9.0	14.5
		Feb.90	30.6	7.1	71.3	-7.18	-35.5	8.6	21.9
		Mar.90	28.2	10.5	58.6	-6.46	-37.9	7.0	13.8
		Apr.90	8.4	16.2	52.5	-9.44	-71.7	13.6	3.8
Weighted mean						-7.59	-45.1	8.5	15.6
Homs	490	Dec.89	49.6	8.3	83.9	-6.59	-32.9	5.1	19.8
		Jan.90	40.8	4.8	71.9	-6.44	-29.7	7.0	21.8
		Feb.90	36.6	7.7	71.5	-6.54	-30.1	7.9	22.2
		Mar.90	10.5	11.5	59.3	-5.09	-30.1	9.2	10.6
		Apr.90	19.5	15.7	58.8	-6.41	-41.1	11.3	10.2
Weighted mean						-6.42	-32.2	7.3	19.2
Izraa	580	Dec.89	37.0	8.7	74.3	-7.13	-36.9	5.6	20.1
		Jan.90	65.9	6.2	73.2	-7.05	-41.6	9.7	14.8
		Feb.90	60.9	7.5	76.1	-6.75	-29.6	9.4	24.4
		Mar.90	55.4	11.2	63.8	-5.23	-21.5	8.0	20.3
		Apr.90	10.1	15.2	57.3	-7.84	-48.7	9.4	14.0
Weighted mean						-6.58	-33.1	8.5	19.5

TABLE II (cont.)

Station	Altitude (m.a.s.l)	Date	P (mm)	T (°C)	R.H (%)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	^{3}H (TU)	d (‰)
Kounietra	930	Dec.89	55.6	7.4	75.8	-6.44	-30.6	6.5	20.9
		Jan.90	70.3	4.3	74.5	-8.49	-48.8	7.5	19.1
		Feb.90	115.9	5.5	82.6	-7.04	-34.6	7.6	21.7
		Mar.90	86.6	9.0	63.1	-7.67	-42.3	6.5	19.1
		Apr.90	7.3	13.2	57.7	-7.23	-44.5		13.3
Weighted mean						-7.41	-39.1	7.1	20.2
Palmyra	400	Dec.89	11.5	8.9	68.3	-6.96	-45.2	7.1	10.5
		Jan.90	3.8	5.1	56.2	-6.36	-38.7	12.4	12.2
		Feb.90	29.0	8.2	63.7	-6.27	-22.2	11.4	27.9
		Mar.90	24.2	13.2	45.6	-0.39	16.4	9.8	19.5
		Apr.90	11.4	18.0	42.8	-0.31	-9.6	11.8	-12.1
Weighted mean						-3.65	-12.8	10.4	16.4
Suwieda	1020	Dec.89	44.7	8.4	69.3	-7.79	-40.2	4.6	22.1
		Jan.90	100.0	5.1	73.3	-8.76	-52.5	9.2	17.6
		Feb.90	65.8	5.7	76.0	-6.87	-31.7	8.7	23.3
		Mar.90	76.3	9.7	60.8	-4.99	-17.6	7.5	22.3
		Apr.90	30.6	14.1	52.4	-8.32	-49.0	10.3	17.6
Weighted mean						-7.28	-37.7	8.1	20.54
Tartous	5	Dec.89	96.6	13.8	71.8	-4.61	-18.5	5.1	18.4
		Jan.90	72.4	10.5	57.9	-5.38	-24.9	7.3	18.1
		Feb.90	132.2	12.5	64.0	-3.82	-14.2	5.4	16.4
		Mar.90		14.8	65.0	-4.07	-17.3	5.6	15.3
		Apr.90	54.8	17.7	69.3	-7.79	-49.0	11.8	13.3
Weighted mean						-4.96	-22.9	6.7	16.8

Where: P, precipitation amount; T, air temperature and R.H, relative humidity

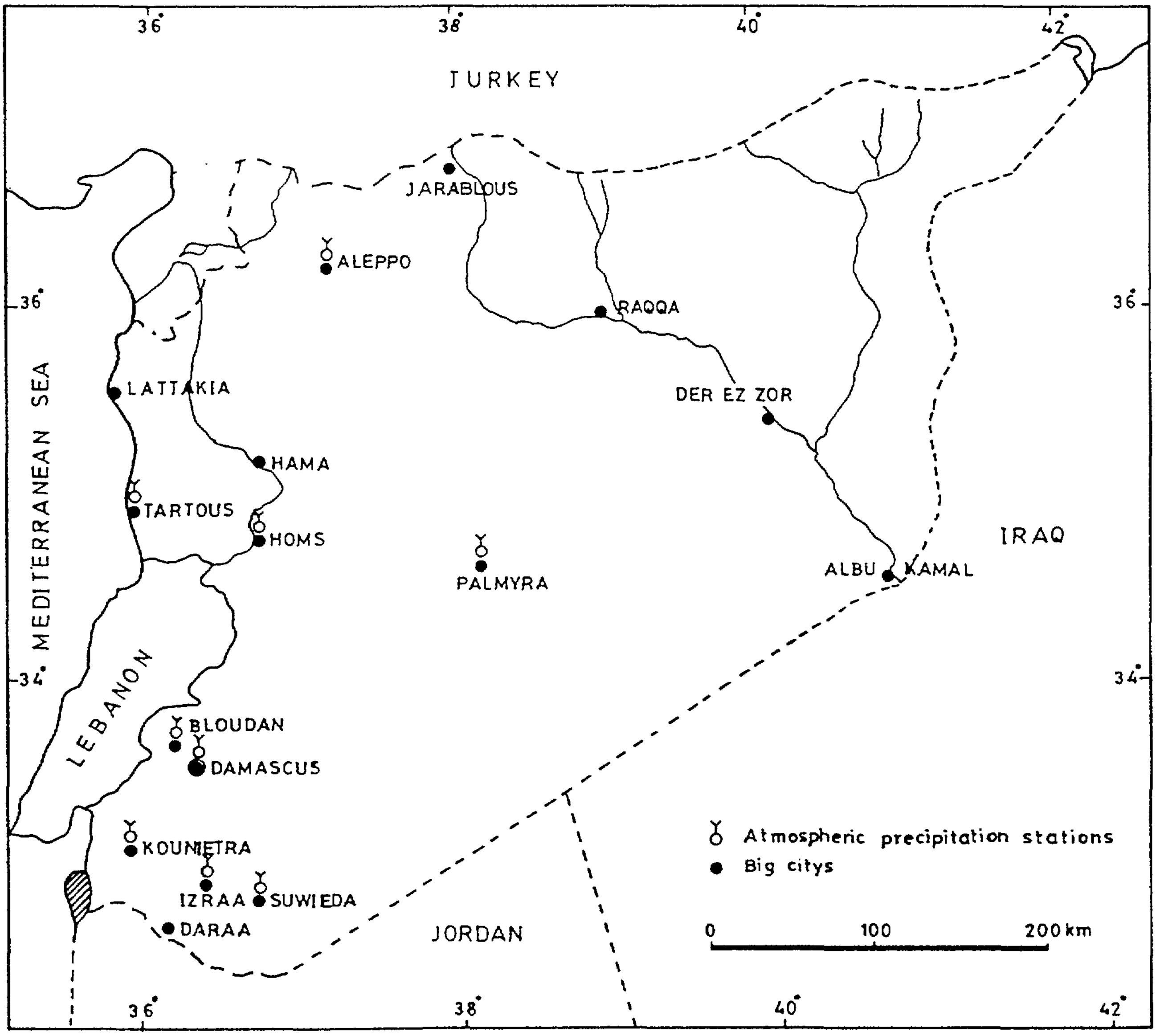


Fig. 1. Location map showing the network of atmospheric precipitation sampling sites in Syria

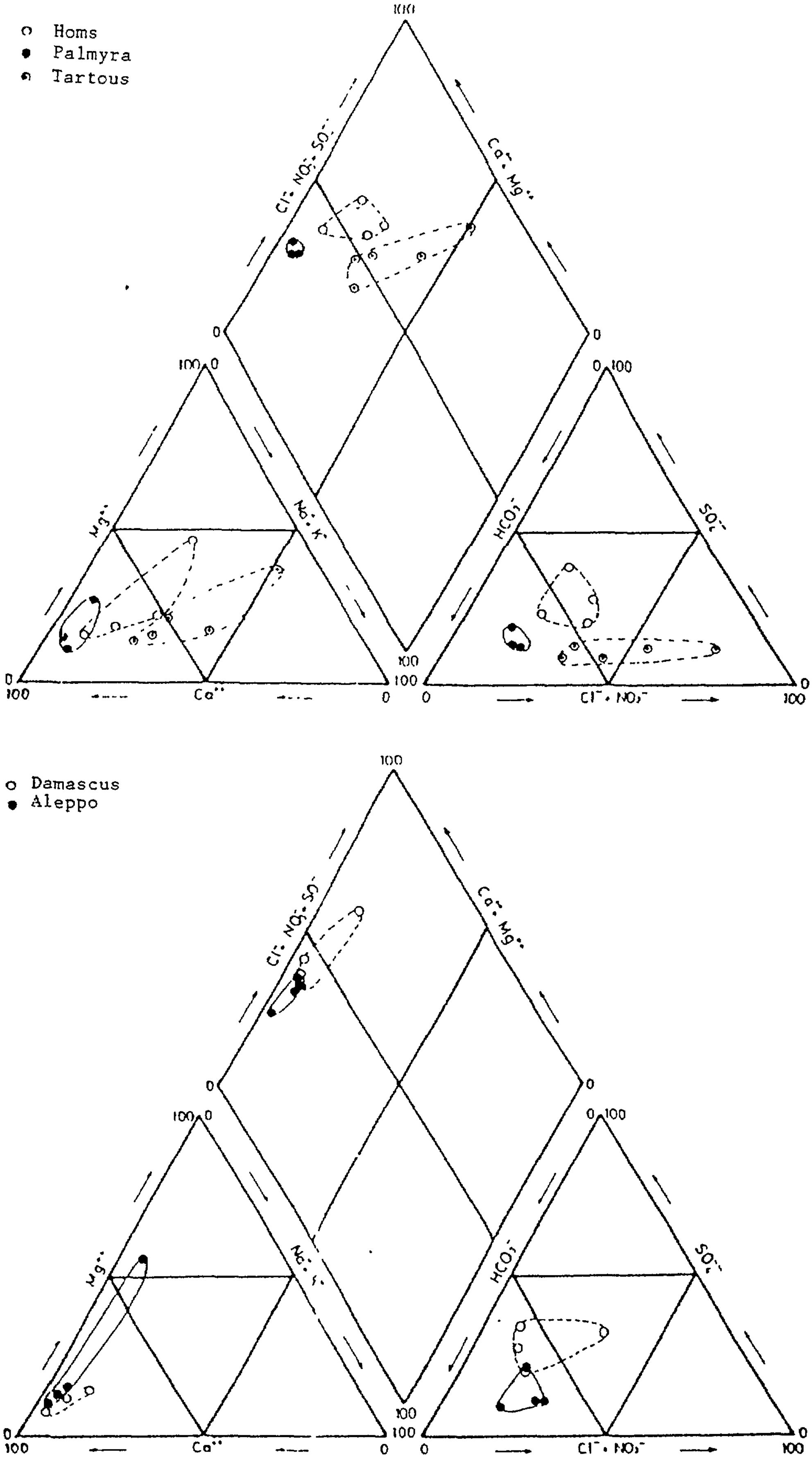
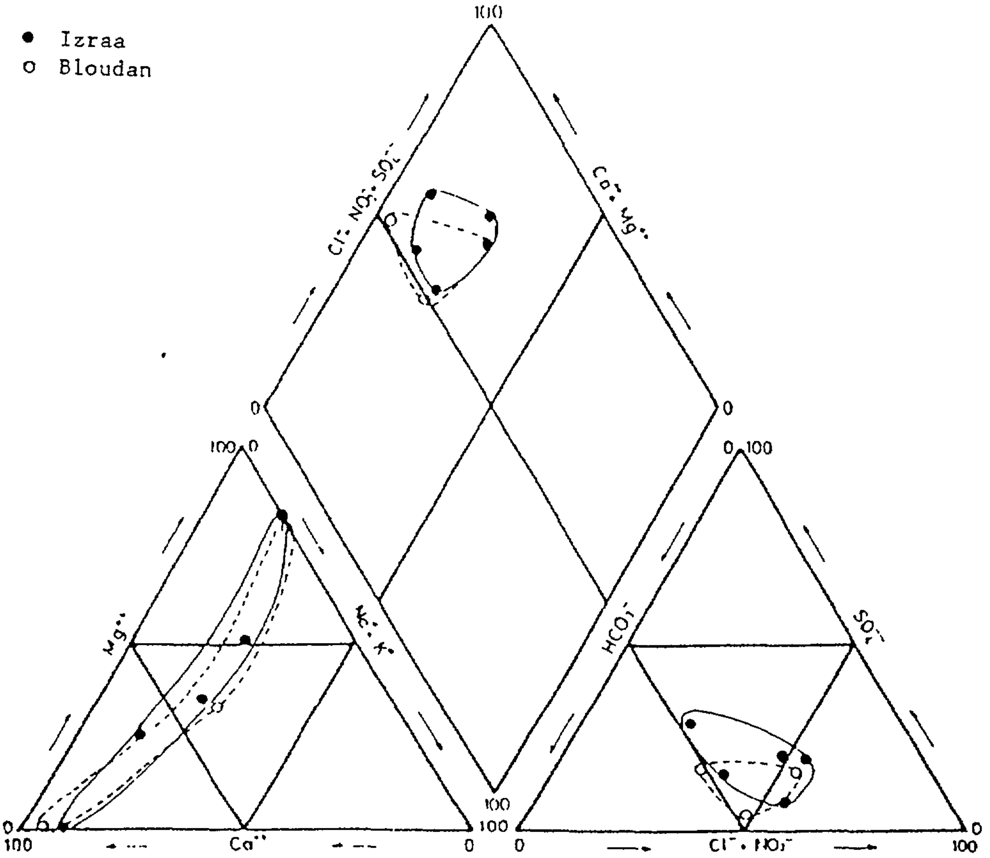


Fig. 2. Piper diagrams of the chemical composition of rain water samples collected from the meteorological stations in Syria



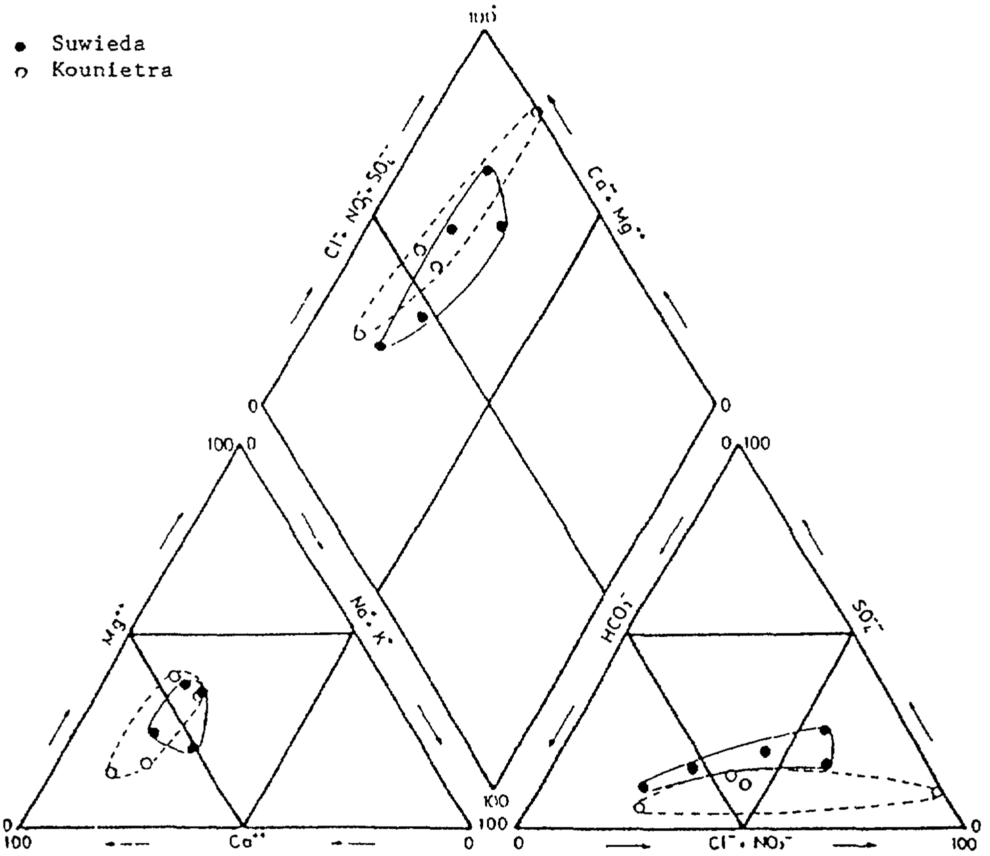


Fig. 2 (continue). Piper diagrams of the chemical composition of rain water samples collected from the meteorological stations in Syria

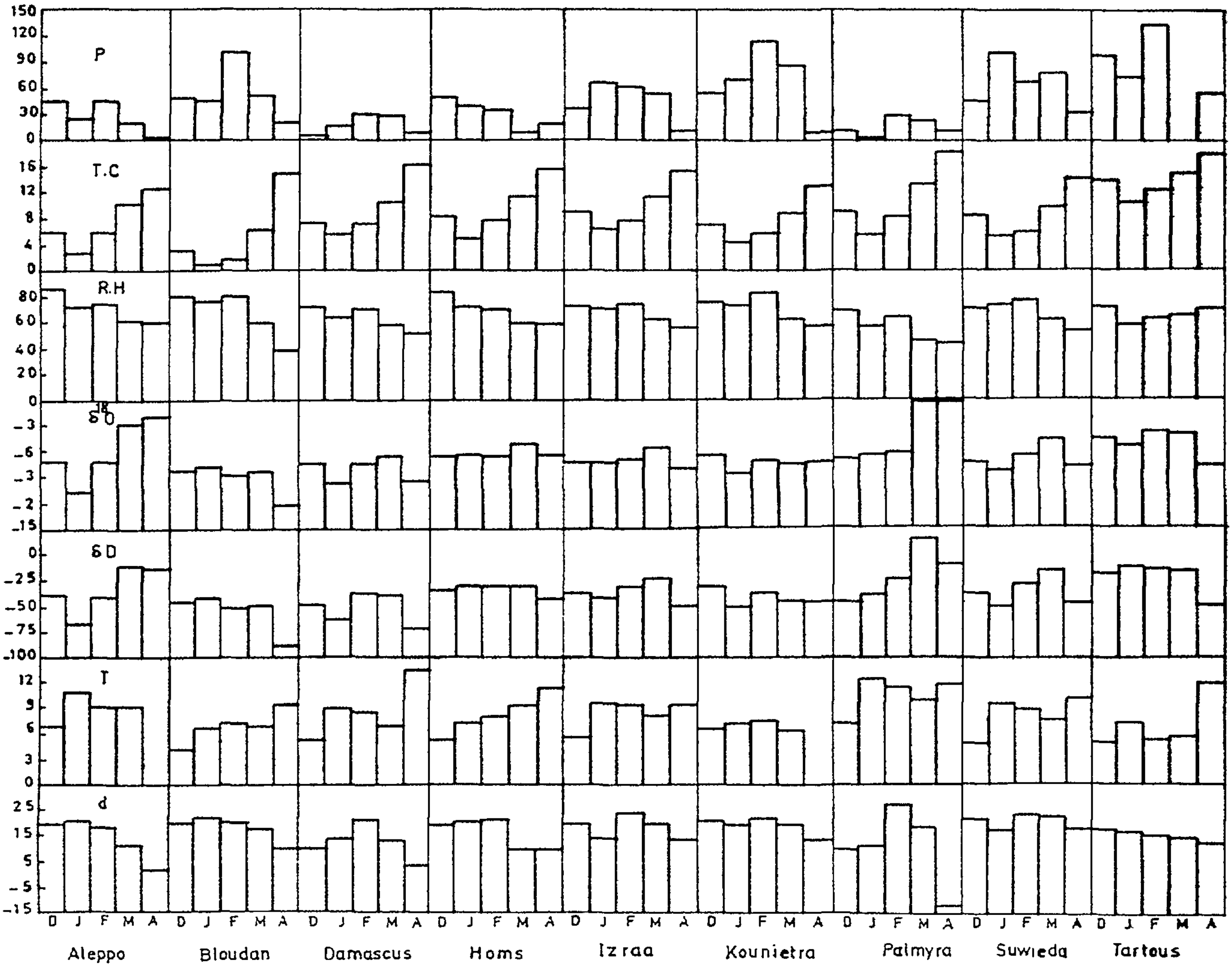


Fig. 3. Representation of the mean monthly precipitation amount, mean monthly air temperature and mean monthly relative humidity together with the weighted means of isotopic concentrations and deuterium excess of rain water during the period of investigation

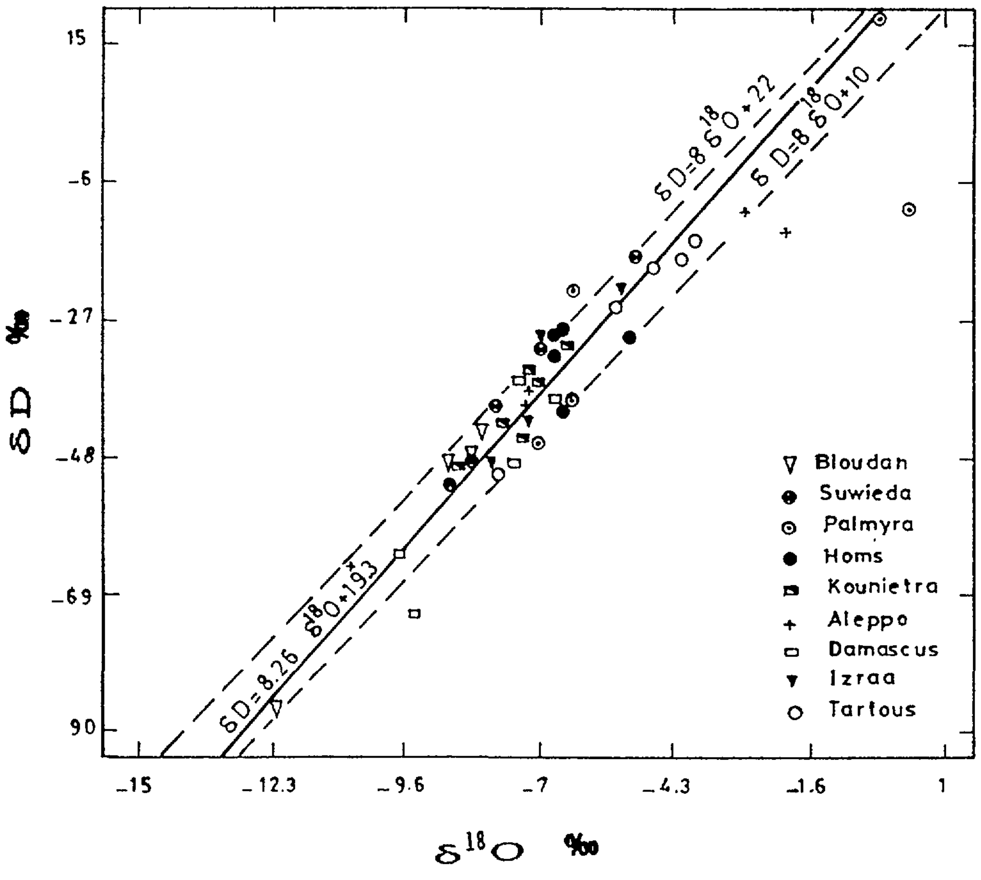


Fig. 4. Relationship between $\delta^{18}O$ and δD values of precipitation in Syria

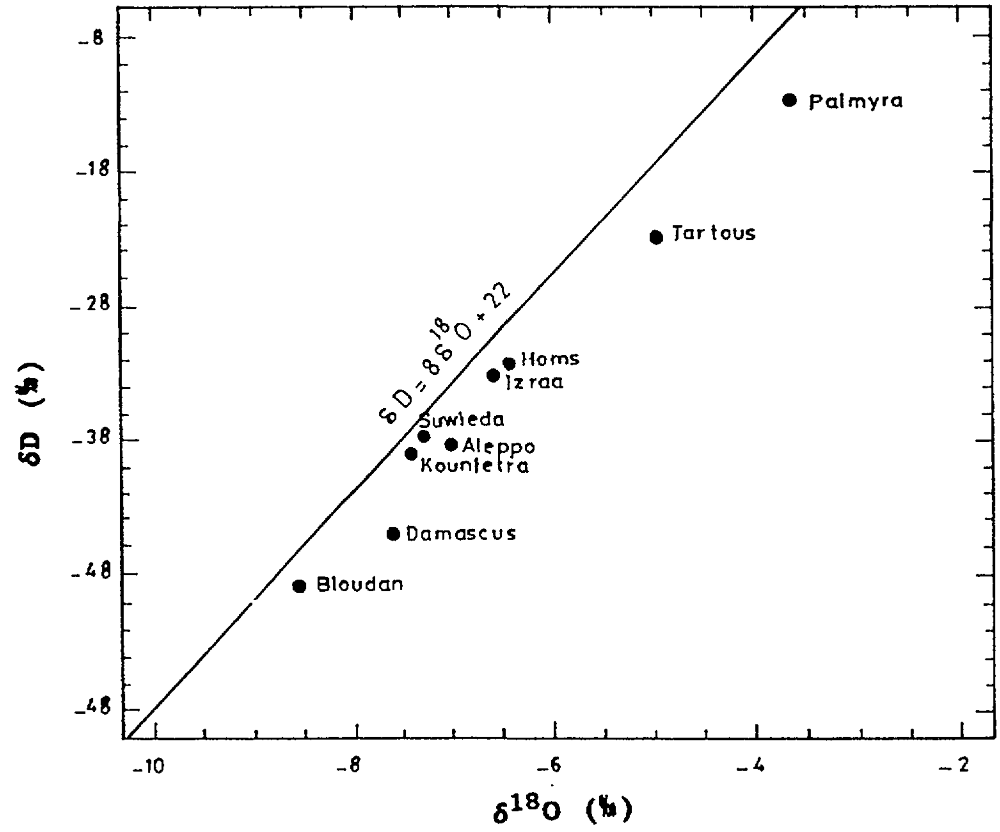


Fig. 5. Relationship between the weighted means of $\delta^{18}O$ and δD values in rain water collected from the different meteorological stations in Syria

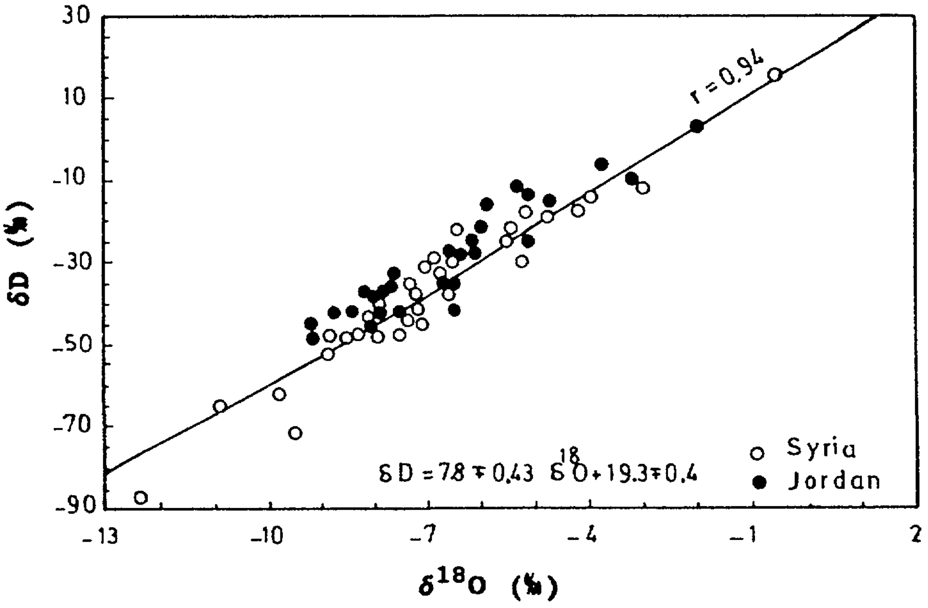


Fig. 6. Relationship between $\delta^{18}O$ and δD values of precipitation in Syria and Jordan

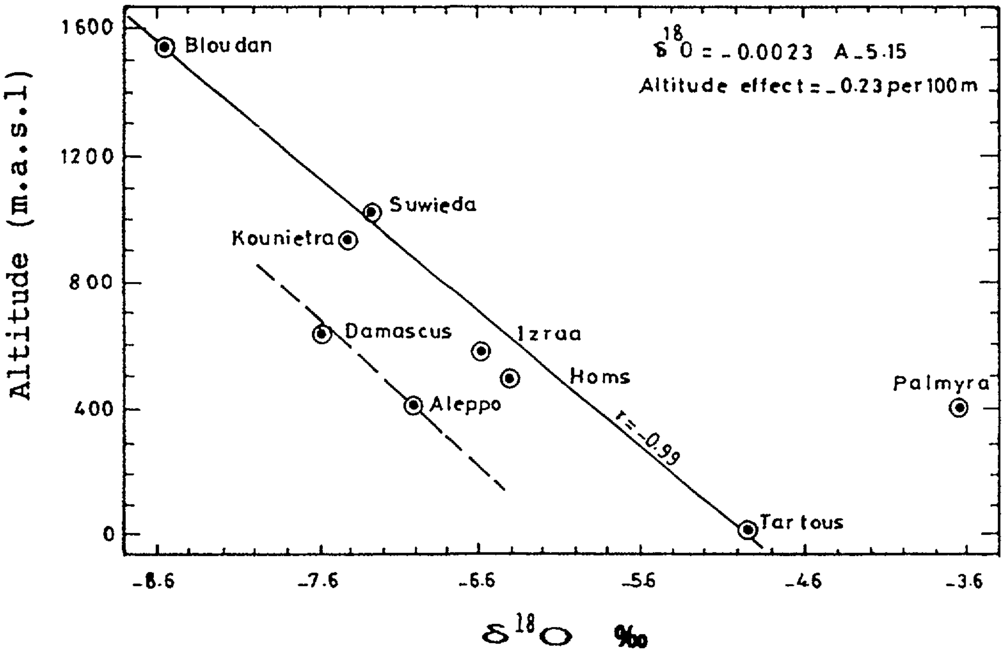


Fig. 7. Relationship between the weighted means of $\delta^{18}O$ values and the altitude for the different meteorological stations in Syria

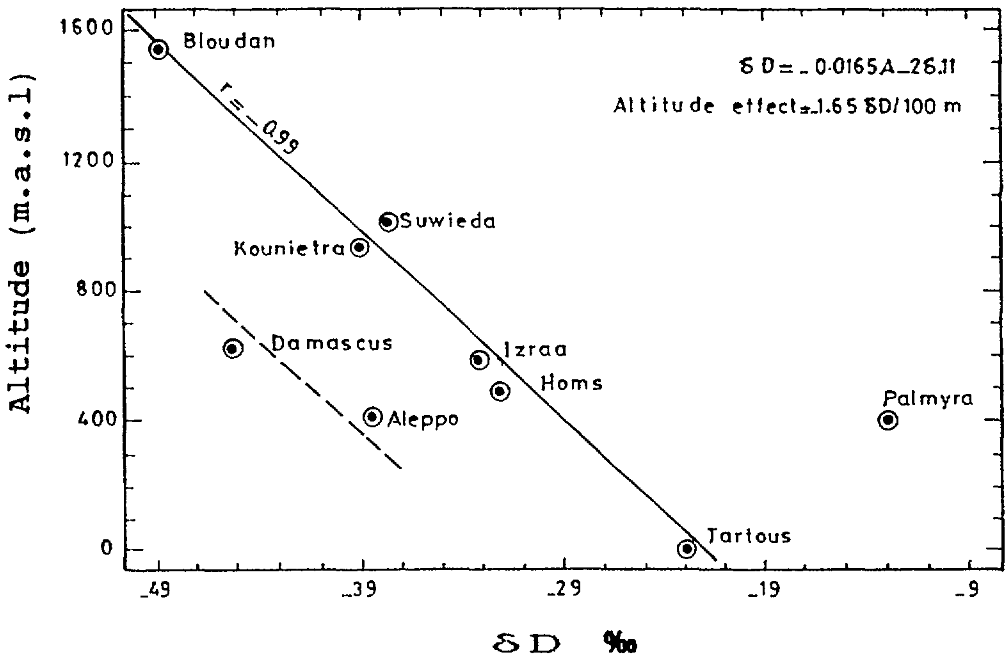


Fig. 8. Relationship between the weighted means of δD values and the altitude for the different meteorological stations in Syria

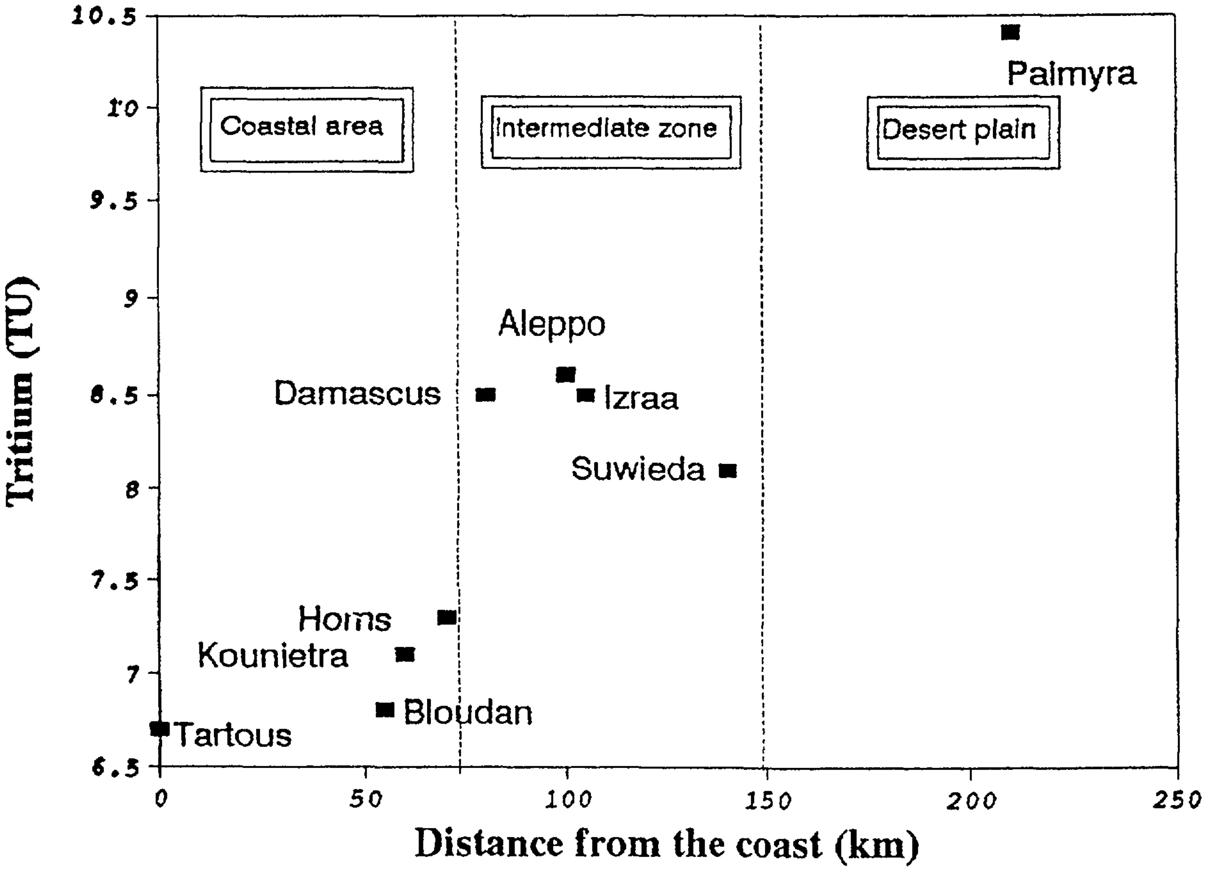


Fig. 9. Relationship between the weighted means of tritium values and the distance from the coast for the different meteorological stations in Syria

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TO DETERMINE WHETHER THERE IS A CONNECTION BETWEEN KARAMIK AND HOYRAN LAKES BY MEANS OF ISOTOPES

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Abstract

Karamık lake is a closed basin. It's drainage has been made by only Büyük and Küçük sinkholes. The lake is contaminated by the waste water of the SEKA paper factory.

Hoyran lake is in the northern part of Eğirdir (Eğridir) lake. Drinking and usage water of Isparta city will be supplied from Eğirdir lake. The lake has also a great fishery potential. Hoyran lake is located at 85 meters lower altitute than Karamık lake.

Therefore a research was made in order to determine if there is a hydraulic connection between Karamık and Hoyran lakes. In the study hydrochemical, hydrogeological and hydrological data were also used in addition to isotopic data.

Using all the data it is concluded that Karamık lake seems to have no contribution to the water coming from the springs which flow into Hoyran lake.

INTRODUCTION :

Karamık lake is a closed basin. It's drainage has been made by only Büyük and Küçük sinkholes. There are a lot of springs around Karamık lake. The most important discharge point of Karamık basin is Geneli springs. The usage water of the SEKA paper factory has been supplied by Geneli spring and drilled wells. The waste water of the paper factory may cause contamination of Karamık lake (Fig.1).

If there is a connection between the sinkholes of Karamık lake and Hoyran springs, the contamination will be carried to Hoyran lake through Taşevi, Gençali and Pınarönü springs which are along the shore of Hoyran lake (Fig.2) (Fig.5)

Hoyran lake is at the northern part of Eğridir lake. Drinking and usage water of Isparta city will be supplied from Eğridir lake. The lake has also a great fishery potential.

Therefore it is very important to determine if there is a connection between Karamık lake and the springs of Hoyran lake. For this reason a research was made in order to solve the problem by means of environmental isotopes. In the study hydrochemical, hydrogeological and hydrological data was also used in addition to isotopic data.

INTERPRETATION OF THE ISOTOPIC, CHEMICAL AND HYDROLOGICAL DATA

Investigation of the stable isotope input value in the precipitation.

The shape of recharge water is snowfall and rainfall. Snowfall is measured at snow course and rainfall

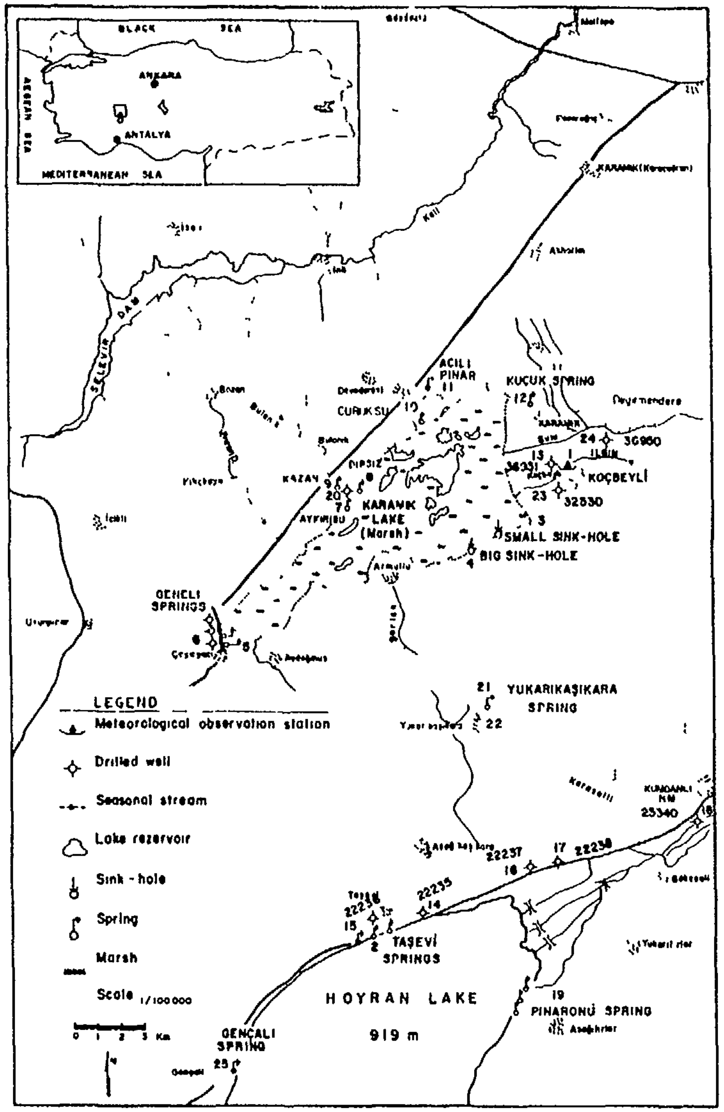


Fig.1. Map of the investigation area and the locations of the samples

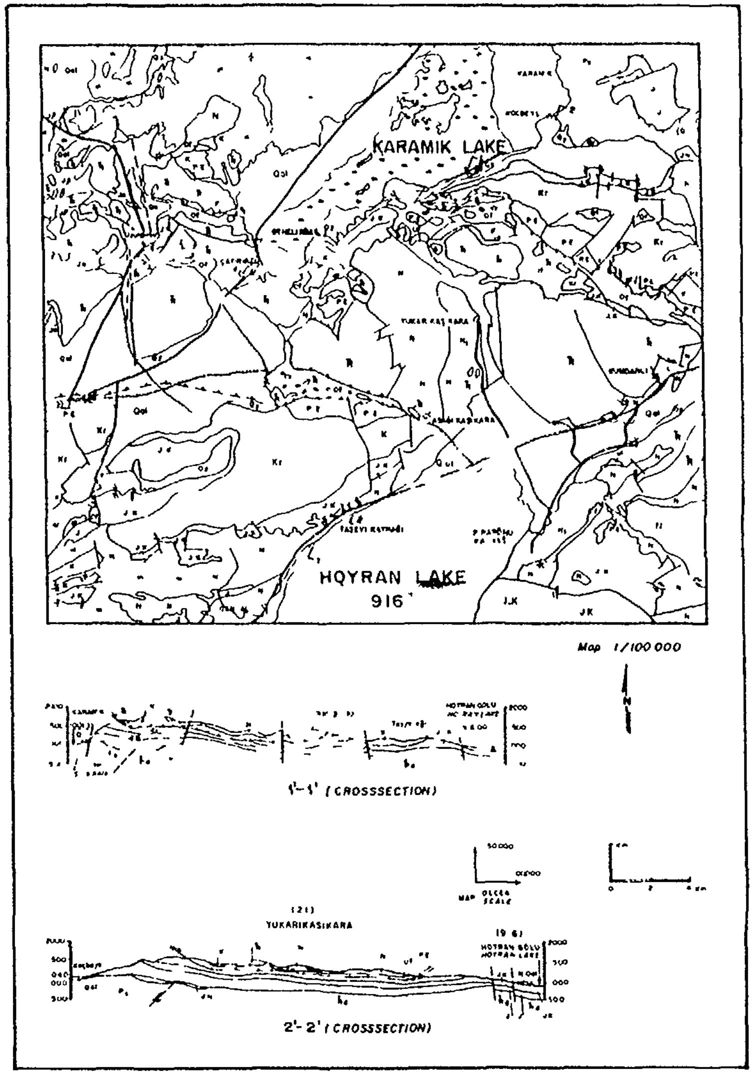


Fig.2. Geological map of the study area Schematic geological cross-section through Karamık and Hoyran lakes

(rain+snow) is observed at the precipitation station. $\delta^{18}O$ values of snowfall is more negative than rainfall values [11-12-13].

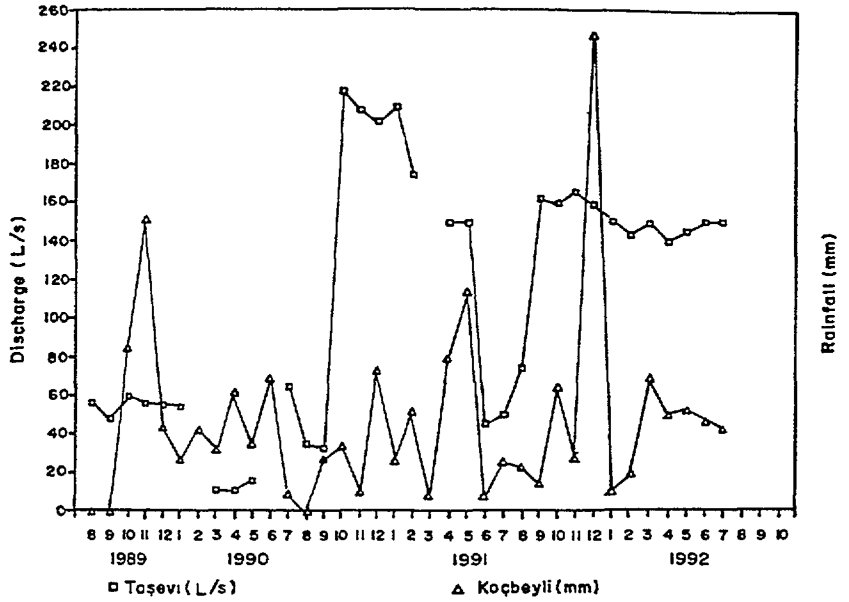


Fig.3. The variations of Taşevi spring discharge and Koçbeyli station rainfall versus time

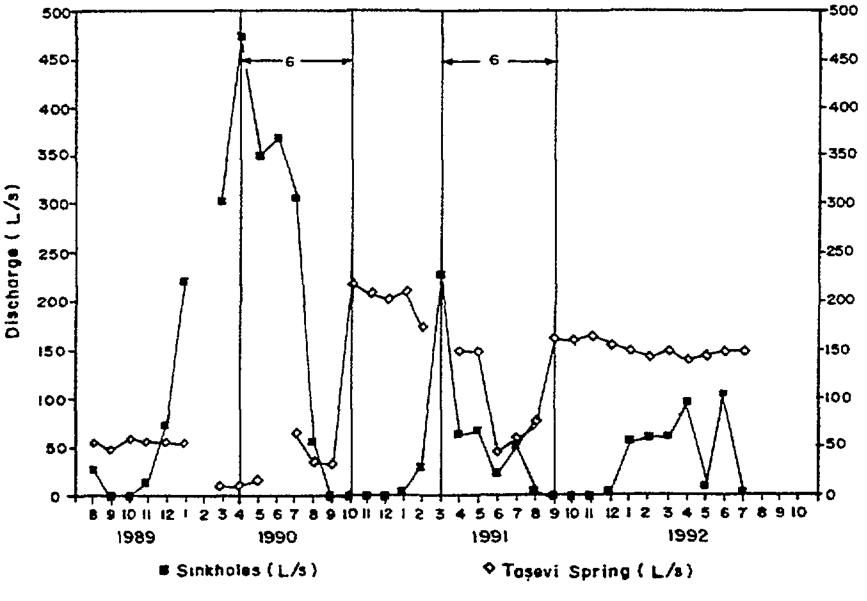
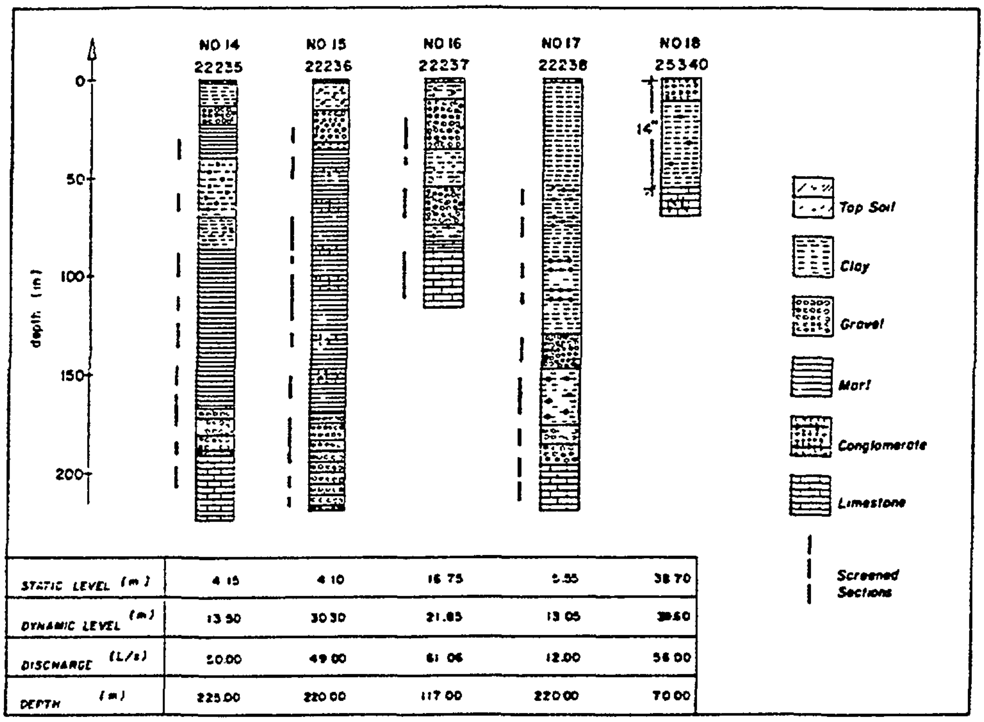


Fig.4. The variation of the discharge of the Sinkholes and Taşevi spring versus time

In the study, rainfall (precipitation) samples have been collected from Koçbeyli station during 1990, 1991 and 1992 water years (Fig.3).

The variations of the amount of the precipitation and the $\delta^{18}O$ values are shown in Fig.7. In this figure,



STATIC LEVEL (m)	4.15	4.10	16.75	5.55	38.70
DYNAMIC LEVEL (m)	13.50	30.30	21.85	13.05	39.50
DISCHARGE (L/s)	20.00	49.00	61.06	12.00	56.00
DEPTH (m)	225.00	220.00	117.00	220.00	70.00

Fig.5. The logs of the drilled wells

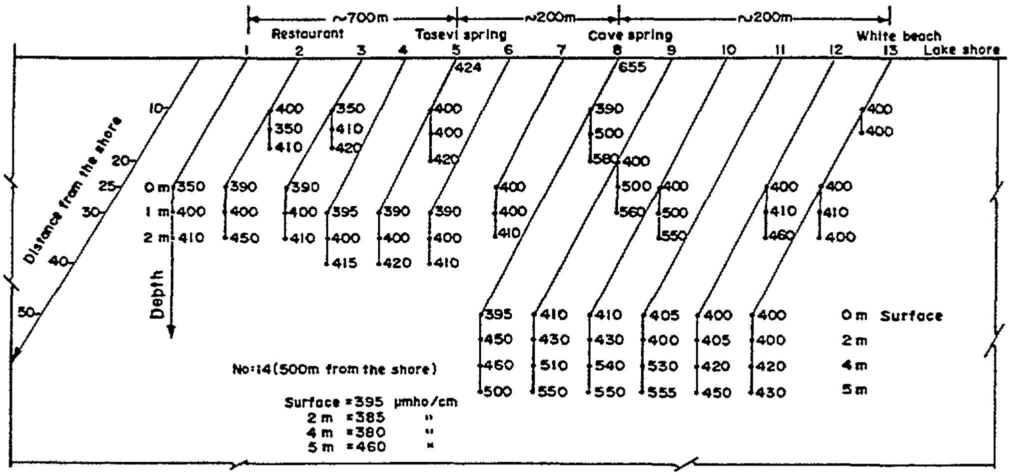


Fig.6. The variation of the electrical conductivity in the northern part of Hoyran lake at various distances from the shore and depths from the surface of the lake

it is seen that the amount of precipitation is low but it's $\delta^{18}O$ values is more negative in winter. In the study area snowfall is observed at high altitude and a large portion of the recharge water comes from snowmelt. As a matter of fact the weighted mean of the precipitation in Koçbeyli station was computed -9,29 o/oo but $\delta^{18}O$ values of the springs and drilled wells were -10 o/oo and/or -11 o/oo respectively. They are more negative than the input value of the precipitation on the plain. Therefore it is necassary to estimate the mean input isotopic composition of the recharge water, in order to determine whether there is a hydraulic connection between Karamık and Hoyran lakes.

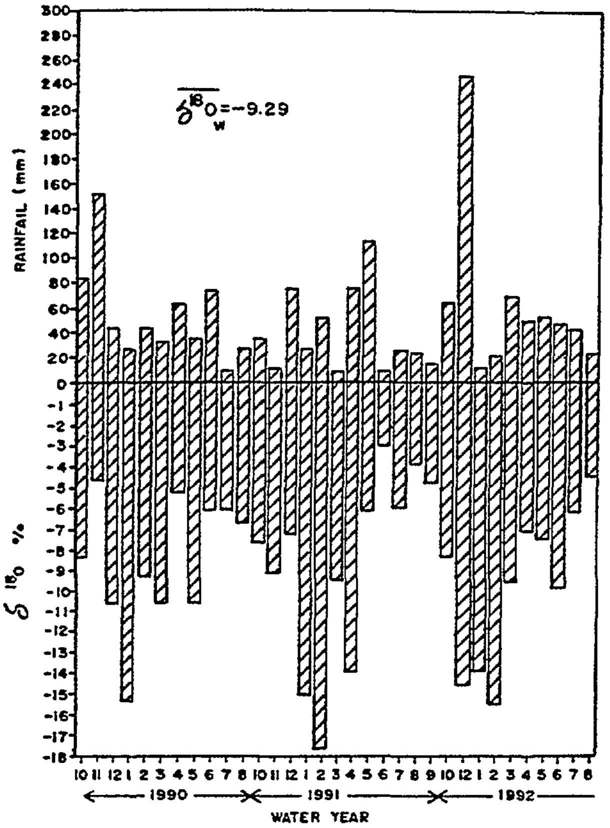


Fig.7. The variations of the rainfall and the $\delta^{18}O$ value at Koçbeyli

Determination of $\delta^{18}O$-δD relations in the precipitation.

International Atomic Energy Agency (IAEA) has been conducting a world-wide survey of hydrogen and oxygen isotopes in precipitation in order to provide basic data for hydrological application of environmental isotopes such as oxygen-18, deuterium and tritium. The global relationship between $\delta^{18}O$ and δD has been found for a large number of samples. Where 10 is the so-called deuterium excess.

$$\delta D = 8\delta^{18}O+10 \text{ o/oo} \quad . \; . \; . \; . \; . \; . \; . \; . \; . \; . \; .(1)$$

However the $\delta^{18}O$-δD relationship for precipitation in a given region often differs from the above global equations. Because of local climatic and topographical features the regional line of the precipitation differs from global line.

For the regional line, isotopic content of precipitation at Koçbeyli station were used during three years. Independent variable $\delta^{18}O$ and dependent variable δD were taken and the equation of the regional precipitation was obtained (Fig.8).

$$\delta D = 7,84\ \delta^{18}O + 9,92\ o/oo \ldots\ldots (2)$$

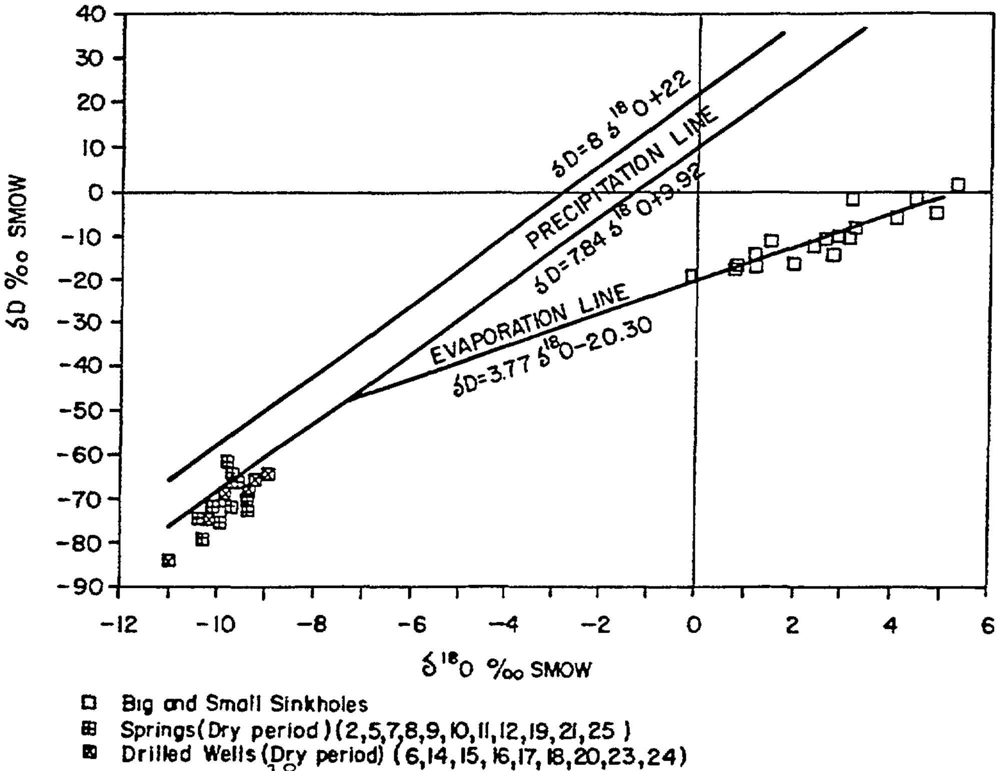


Fig.8. $\delta D-\delta^{18}O$ relationship for the water of the sinkholes and dry period groundwater

Computation of weighted mean values in the precipitation

The weighted mean values ($\bar{\delta}_w$) are more appropriate indexes for tracer-input considerations in hydrological applications since the $\bar{\delta}_w$ eliminated either seasonal variation or the amount effect.

The weighted mean value for Koçbeyli station was computed as follows :

$$\bar{\delta}_w = \frac{{}^{n}\Sigma_{i=1}\ P_i\ \delta_i}{{}^{n}\Sigma_{i=1}\ P_i} \quad . . . . (3)$$

where P_i and δ_i are monthly precipitation and δ value respetively.

The weighted mean values were computed for oxygen-18 and deuterium during 1990, 1991 and 1992 water years. The results are as follows:

water year	$\bar{\delta}_w{}^{18}O$	$\bar{\delta}_w D$
1990	-8,46	-58,90
1991	-9,40	-64,84
1992	-10,92	-71,54
1990+1991+1992	-9,29	-62,76

Weighted $\delta^{18}O$ values obtained are -9,29 for Koçbeyli precipitation, around -10, for Geneli, Taşevi and Gençali springs and -10 or -11 for drilled wells.

It is seen that the weighted value of Koçbeyli precipitation doesn't represent the total recharge water; neither the amount of water nor it's isotope value. For this reason the altitude effect of oxygen-18 and area-elevation relationship must be investigated [13]. Therefore a study was made for the determination of the isotope input value of the recharge water for surface drainage area.

Investigation of the altitude effect in the precipitation

The δ values of precipitation at higher altitudes generally will be more negative. The variation of the stable isotope composion of precipitation is called altitude effect. The magnitude of the effect depends on local climate and topography with gradients in $\delta^{18}O$ of between 0,15 and 0,5 o/oo/100 m. [15].

For the investigation of the altitude effect, Antalya (49 m), Koçbeyli (1085 m) precipitation station and local spring (No 21) Yukarıkaşıkara (1318 m) were used.

The weighted average of Antalya precipitation was calculated -5,59 for $\delta^{18}O$ [14]. The weighted mean of Koçbeyli precipitation was computed -9,29.The mean $\delta^{18}O$ value of the Yukarıkaşıkara spring was found -10,1. The mean $\delta^{18}O$ values versus altitude is shown (Fig.9).The average rate deplation was found -0,36/100 meters.

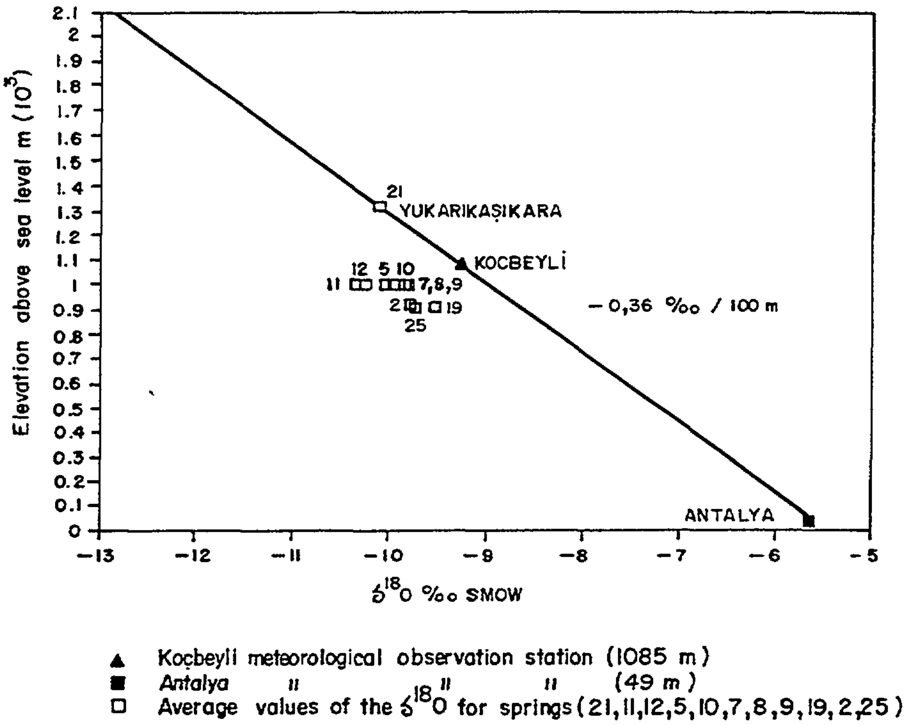


Fig.9. The variation of the $\delta^{18}O$ value in precipitation with altitude

Investigation of the area-elevation relationship and estimation of the mean recharge altitude and the mean stable isotope input value in the surface drainage area

The amount of snow increased with altitude and it's $\delta^{18}O$ content is more negative than rainfall [10-11-12-13]. In the study area snowfall is effective.

As mentioned above the weighted $\delta^{18}O$ content of the Koçbeyli precipitation is found -9,29 o/oo but the average $\delta^{18}O$ content of waters of the springs and drilled wells are around -10 o/oo or -11 o/oo.

For this reason area-elevation relationships have been investigated for Taşevi, Gençali and Pınarönü springs in order to determine the mean altitudes of the recharge areas of the springs and to find the mean isotope input values of the springs which belong to these mean altitudes.

From the knowledge of the hydrogeology the mean altitude of the springs was determined. The recharge area of Taşevi springs is accepted limestones which lies at the north part of the springs. Various altitude spaces of the surface drainage area of Taşevi springs are measured by planimeter. Altitude versus percentage of the drainage area above elevation was drown (Fig.10). The mean altitude of the surface drainage area of Taşevi spring was found as 1270 meters.

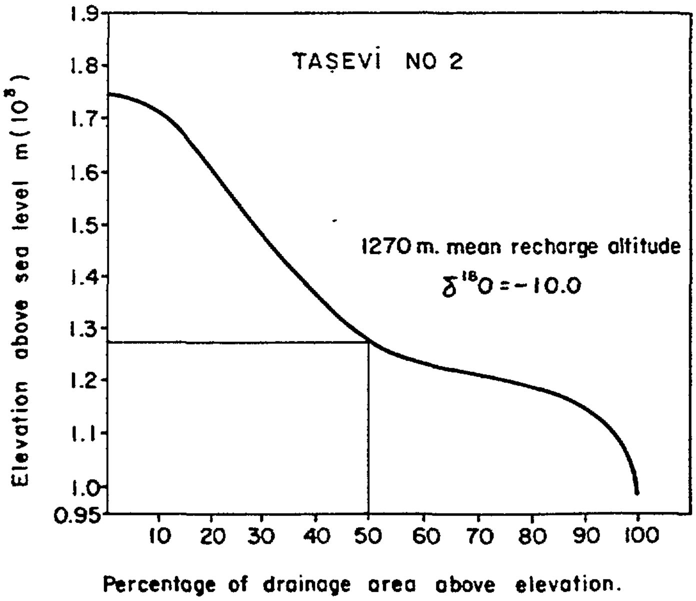


Fig.10. Area-altitude relation for Taşevi springs

In the same way, mean altitudes of the surface drainage areas were determined for Gençali and Pınarönü springs. They were found 1250 and 1350 meters.

Mean $\delta^{18}O$ concentrations of the precipitation for the mean altitude were obtained -10 o/oo,-9,8 o/oo,-10,2o/oo for Taşevi, Gençali and Pınarönü springs respectively (Figures.10,11,12,13).

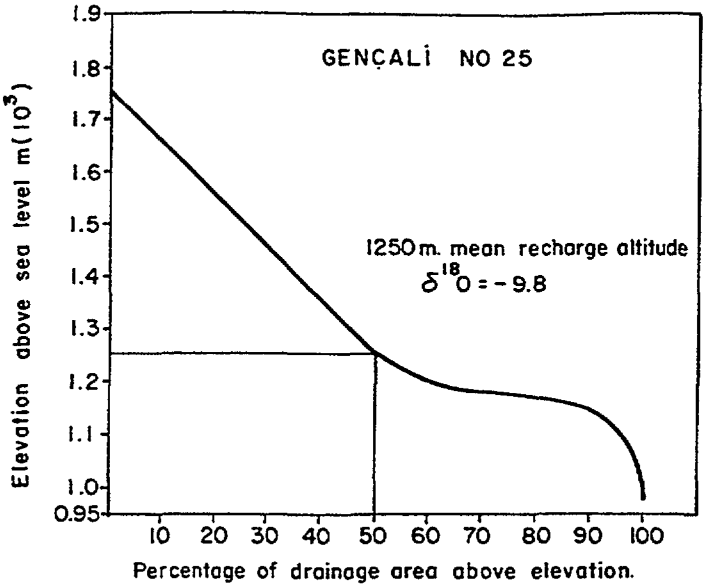


Fig.11. Area-altitude relation for Gençali springs

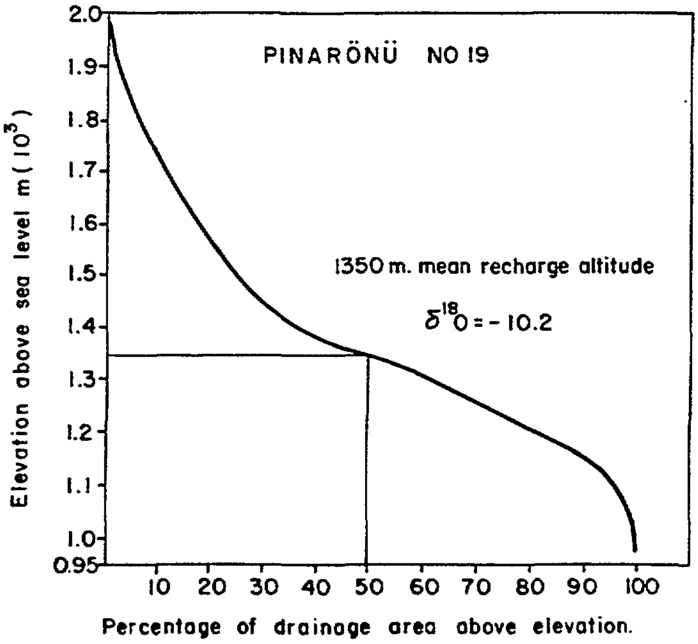


Fig.12. Area-altitude relation for Pınarönü spings

It is accepted that these altitudes (1270,1250 and 1350 m.) are the mean recharge area altitudes and the $\delta^{18}O$ concentrations (-10,0, -9,8, -10,2) are the mean isotope input value for Taşevi, Gençali and Pınarönü springs respectively (Fig. 13).

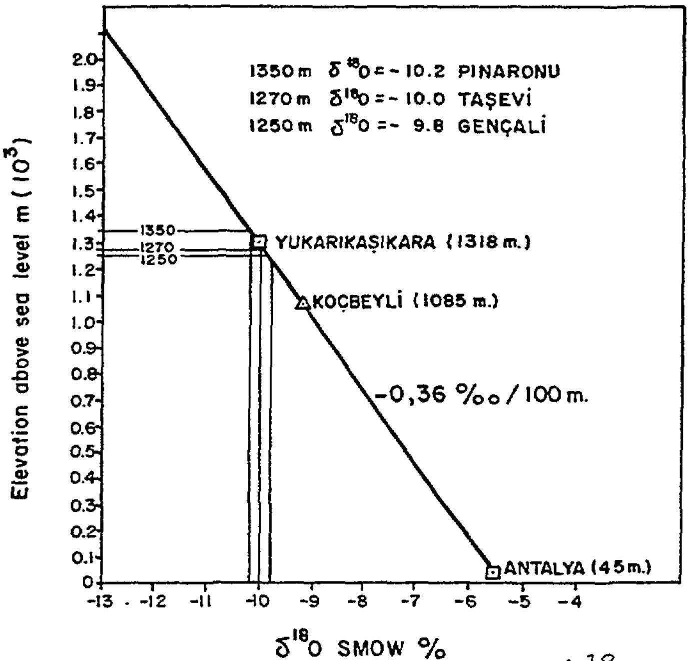


Fig.13. The variation of the $\delta^{18}O$ values in Pınarönü,Taşevi and Gençali springs with mean altitude

Correlation between Koçbeyli and Ankara precipitation

During three years there are oxygen-18, deuterium and tritium values for precipitation of Koçbeyli station. Isotope values of precipitation are stochastic. For some hydrological investigation such as turn-over time, it is necessary to know tritium input values for many years. The long-term data are present for tritium content of precipitation at Vienna-Austria and Ottawa-Canada, which are IAEA network stations. In order to lack some data, tritium analyses of Ankara precipitation have been performed since 1963.

The tritium values of Ottawa precipitation are taken independent variable. By applying the statistical methods regression coefficients a=-0,38379 and b=1,152873, correlation coefficient R=0,98 are calculated for n=20 years (Fig.14). By using following equation the lack of tritium values of Ankara precipitation are calculated.

$$\log(TU)_{ANKARA} = a+b \log(TU)_{OTTAWA} \; . \; . \; . \; . \; . \; (4)$$

Regression coefficients a=0,262925, b=0,73084 and correlation coefficients R=0,72 are calculated for n=24 months (Fig.15).

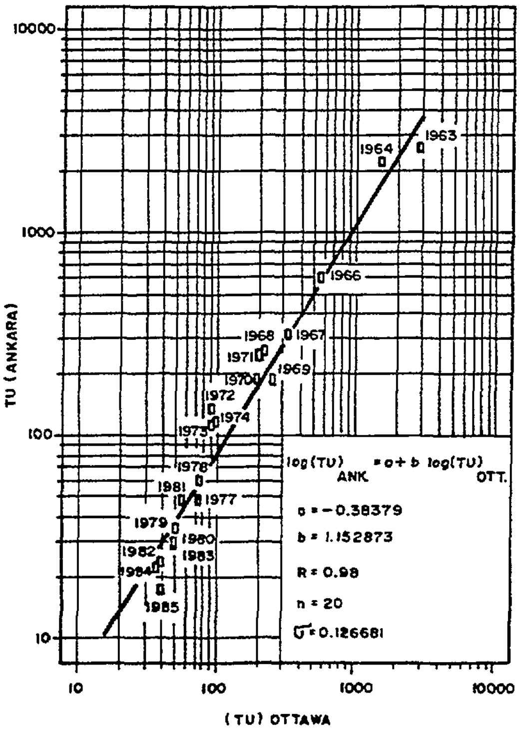


Fig.14. Correlation between Ottawa and Ankara precipitation

There is a correlation between the tritium values of Koçbeyli and Ankara precipitation. It is accepted that the tritium contents of Ankara precipitation can be used instead of the tritium contents of Koçbeyli precipitation.

Interpretation of the isotopic and hydrological data in the surface water

Total discharge of Büyük and Küçük sinkholes and the amount of Koçbeyli precipitation were plotted versus time (Figures 4,16). The discharge of the sinkholes and the amount of precipitation variations with a difference in time of about 4 months. Can be seen in Fig.16, the total discharges of the sinkholes are increased during wet periods.

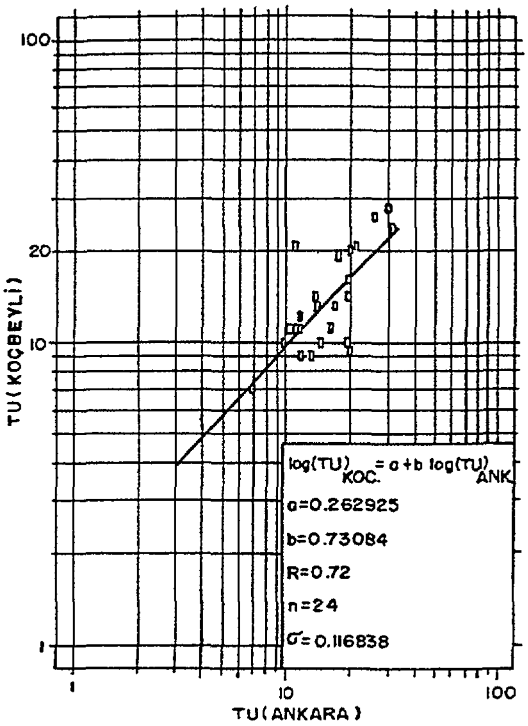


Fig.15. Correlation between Ankara and Koçbeyli precipitation

When the water level of Karamık lake rises 1001 meters, lake water which has heavy isotopes is discharged through the sinkholes.

It is seen that the total water of the sinkholes has the most heavier isotope concentration as expected. So it is a good tracer for this study.

The $\delta^{18}O$ and δD o/oo values of the sinkhole waters were plotted on graph, the values fell to evaporation line (Fig.8). Equation of regresion line was computed for n=19.

$$\delta D = 3,77\ \delta^{18}O - 20,30 \quad . . . . (5)$$

Determination coefficient; 0,813, correlation coefficient; 0,90, gradient; 3,77 and deuterium excess -20,30 were computed.

The heavy isotope values of Büyük and Küçük sinkholes were calculated $\delta^{18}O$ o/oo.=+2,56 and δD o/oo =-9,91. But $\delta^{18}O$ and δD values of Taşevi and Pınarönü springs were computed $\delta^{18}O=9,87$, $\delta D=-68,51$ and $\delta^{18}O=-9,54$, $\delta D=-69,84$ respectively.

The $\delta^{18}O$ and δD values of the sinkholes are different from that of the springs. Forthermore deuterium excess of the sinkholes is very low.

Therefore it is suggested that none of the spring waters receives any contribution of water from Karamık lake.

Estimation of the turnover time in the groundwater by using tritium

In the study area tritium content of the groundwater varies between 0 to 10 TU. Generally it is zero. In the research, it is very important to estimate the turn-over time of the groundwater.

As mention above correlation coefficent of Koçbeyli and Ankara precipitation for tritium values was found R=0,72. It is shown that a good relation exist between TU values of Koçbeyli and Ankara precipitations (Fig.15). For this reason, it is accepted that we can use the tritium values of Ankara precipitation instead of Koçbeyli precipitation.

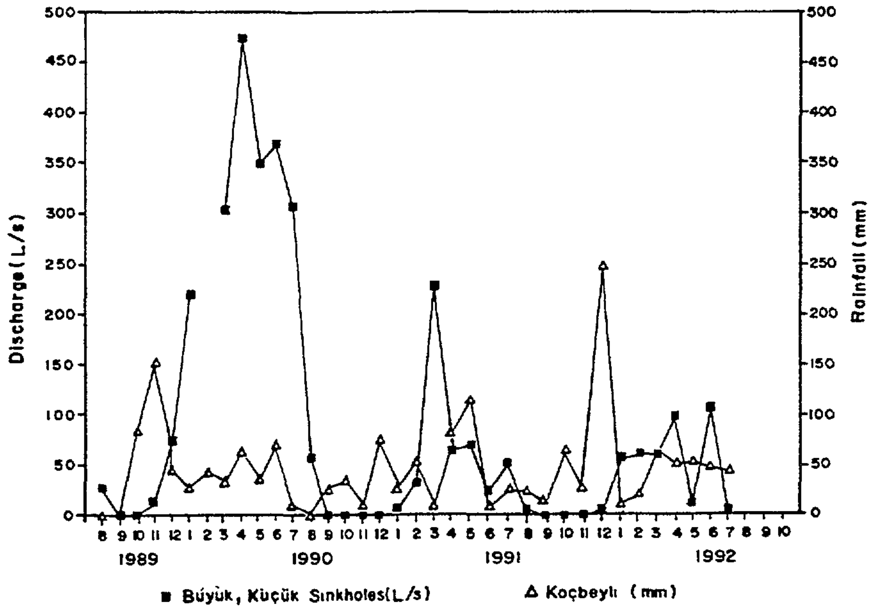


Fig.16. The variations of the total discharge and rainfall versus time

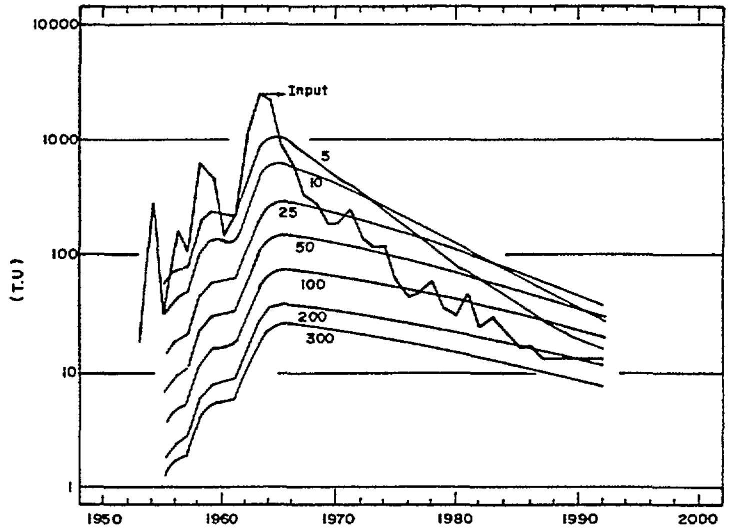


Fig.17. Tritium-input colculated tritium-output curves for exponential model(ANKARA)

For exponential models, tritium-input and calculated tritium-output curves were drown in Ankara (Fig. 17), [20]. Tritium-output value of Taşevi spring and well water, which represented the groundwater between Karamık and Hoyran lakes, is about 0-2 TU. For this reason from Fig.17, it is estimated that turn-over time of the groundwater is 300 years.

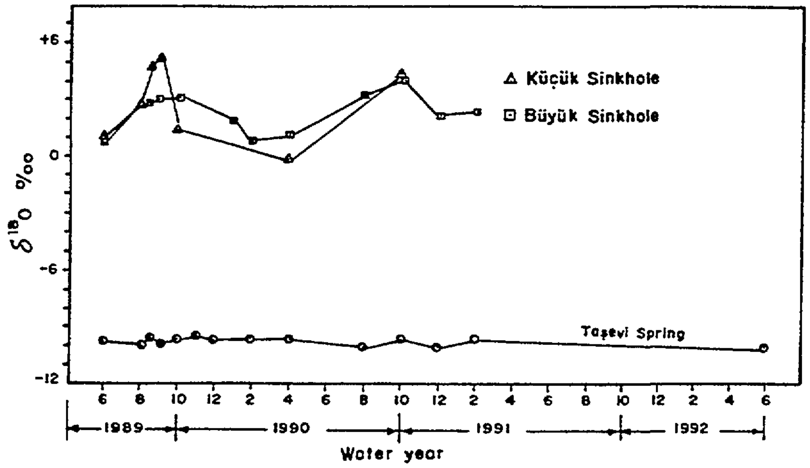


Fig.18. The variations of the $\delta^{18}O$ values at the sinkholes and Taşevi spring versus time

Turn-over time (τ_0): for a given total flux F_0 and a total mass M_0 the ratio

$$\tau_0 = \frac{M_0}{F_0} \quad \ldots\ldots\ldots\ldots\ldots (6)$$

defines the turn-over time of the system. It is equivalent to the mean transit time.

$$\text{Turn-over time} = \frac{\text{Volume (V)}}{\text{Discharge (Q)}} = \frac{\text{Volume (V)}}{\text{Inflow (I)}} \quad \ldots (7)$$

It has a dimension of time.

The amount of discharge from Karamık lake through the sinkholes is very low (1/s) and turn-over time of the groundwater is very long. For this reason it is impossible to observe the evaporated lake water from Taşevi, Gençali and Pınarönü springs.

Previously a dye experiment was made in the study area. Fluorescent dyes were used as tracers [16]. It is estimated that because of the long turn-over time of the groundwater, dye was not observed from the springs by the dye experiment.

To determine whether there is a hydraulic connection between Karamık lake water and the groundwater by using the origin of the groundwater in the region

If the sinkhole waters have been connected with groundwater located between Karamık and Hoyran lakes, mixing can be seen easily during dry periods. Therefore in the dry periods $\delta^{18}O$ and δD values of the groundwater were plotted $\delta^{18}O$ versus δD and the stable isotope values geathered on the precipitation line (Fig.8). But the isotopic composition of the sinkhole waters fall down on the evaporation line. It's isotope composition is markedly different from that of waters falling on the precipitation line, which would be the other component in the case of mixing of lake water and groundwater (Fig.8).

It is concluted that the spring waters don't receive any contribution of water from Karamık lake [4-9], [19], [1], [17-18].

Determination of the mixed ratio of the groundwater and the sinkhole waters

The isotope approach to the interelation between surface water and groundwater is based on the fact that the surface water system has a stable isotope composition significantly different from that of recharge by infiltration of local precipitation. In this research Karamık lake water undergoing partial evaporation is enriched in heavy isotopes. The mean $\delta^{18}O$ values of the sinkholes and Taşevi springs were measured +2,56 and -9,87 respectively.

The steady state mass balance equation is expressed by the following equation: [8]

$$V_S C_S + (100-V_S)\ C_P = 100\ C_{TS} \quad . \ . \ . \ . \ . \ . \ . \ . \quad (8)$$

The contribution of the sinkholes is given by the above equation.

$$V_S = \frac{100\ (C_{TS}-C_P)}{C_S-C_P} \quad . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \ . \quad (9)$$

Where

V_S : Inflow of the sinkholes (1/s)

C_S : The isotope concentration of the sinkholes (+2,56)

C_P : Weighted isotope concentration of the precipitation which is corrected with altitude effect. (-10)

C_{TS} : The isotope concentration of Taşevi spring (-9,87)

Mixture ratio it was calculated that the mean possible contribution of the sinkholes would exceed one per cent. But the isotope composition of Taşevi spring does'nt change with time. Furthermore, the turn-over time of the groundwater is 300 years.

To determine whether there is a hydraulic connection between Karamık lake water and the groundwater by using the origin of the groundwater in the plain

Average $\delta^{18}O$ contents of Taşevi, Gençali and Pınarönü springs are measured -9,87o/oo, -9,75o/oo and -9,52o/oo respectively. Located altitude of the springs were plotted versus the average $\delta^{18}O$ contents of the springs for dry period. Karamık springs (No:5,7,8,9,10, 11,12) and Hoyran springs (No:2,19,25) are gathered in two groups. Their isotopic composition is different from each other.

The average $\delta^{18}O$ values of the springs were more negative than the weighted $\delta^{18}O$ input value of the Koçbeyli precipitation (-9,29 o/oo). It is shown that the groundwater has been recharged not only by infiltration of local precipitation (1085 m.) but also by groundwater originating at the higher altitude.

If a water with different isotope-composition such as evaporated lake water hasn't been mixing with groundwater it is possible to estimate mean elevation of recharge area for groundwater from Fig.9. But the aim of the research is to determine if there is any relation between Karamık lake water and the springs of Hoyran lake. For this reason it is imposible to use Fig.9. Therefore the mean altitude of the drainage area and the isotope contents of the recharge waters were determined for Taşevi, Gençali and Pınarönü springs (Figures 10,11,12,13).

The mean recharge altitude (1270 m) and mean $\delta^{18}O$ input value (-10,00 o/oo) were determined for Taşevi spring (Figures 10,13) mean isotopic composition of Büyük and Küçük sinkholes was calculated to be +2,56 o/oo and -9,91 o/oo for $\delta^{18}O$ and δD respectively. It is seen that the mean isotopic composition of the sinkhole water is markedly different from that of Taşevi spring water. It has been concluded that any contribution of Karamık lake water can't be observed at the Taşevi Spring water.

The mean recharge altitude of Gençali spring was found 1250 meters. The spring occurs from 925 meters. The mean $\delta^{18}O$ input value of the precipitation was found -9,8 o/oo (Figures 11,13). The mean $\delta^{18}O$ value of the spring was measured as -9,75 o/oo. The conclusion is that Gençali spring water doesn't receive any contribution water from Karamık lake.

Pınarönü spring occurs from 917 meters. The mean recharge altitude was found 1350 m. and the mean $\delta^{18}O$ input value of the recharge water was obtained as -10,2 o/oo (Figures 12,13). The $\delta^{18}O$ value of the well waters varies between -9,33 to -11,0 o/oo. The mean $\delta^{18}O$ value of Pınarönü spring water was measured -9,52 o/oo. As an evaluation of the isotope data, the followings have been concluded:

If the discharge of Pınarönü spring has been measured during the sampling of the water, weighted mean will be found around -10,2 o/oo.

The mean recharge altitude of Pınarönü spring is lower than 1350 meters.

The water of Pınarönü spring has been mixing with an evaporated water but the $\delta^{18}O$ value of the mixing water is not significantly different from the value of the mean recharge water.

Determination of a possible hydraulic connection between the waters of the sinkholes and springs by using tracers

Fluorescent dyes, chemical, artificial radioisotopes and environmental isotopes can be employed as tracers. The advantages of using artificial radioisotopes as opposed to conventional tracers are:

The actual amount of the element introduced into the system relatively small.

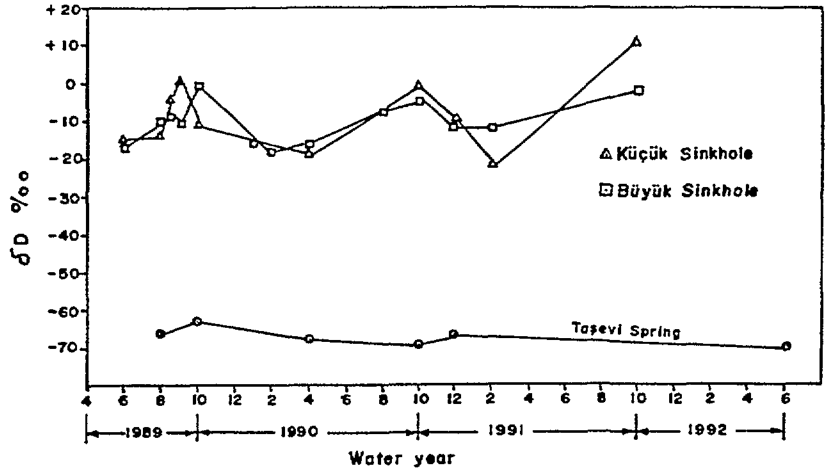


Fig.19. The variations of the δ D values at the sinkholes and Taşevi spring versus time

The radiation emitted can be measured with a high degree of sensivity and precision. However the use of artificial radioisotopes in hydrological studies must take into account considerations of health and safety [5-6-7].

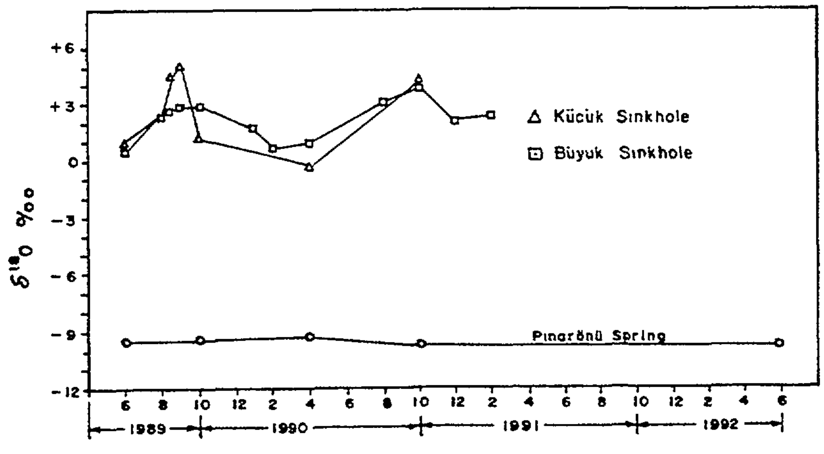


Fig.20. The variations of the δ^{18}O values at the sinkholes and Pınarönü spring versus time

Environmental isotopes as oxygen-18, deuterium and tritium occur in natural waters. All of these are ideal tracers for hydrology.

The variations of the δ^{18}O, δD and chloride (Cl^-) concentrations versus time are given in Figures 18,19,22 for Büyük, Küçük sinkholes and Taşevi spring.

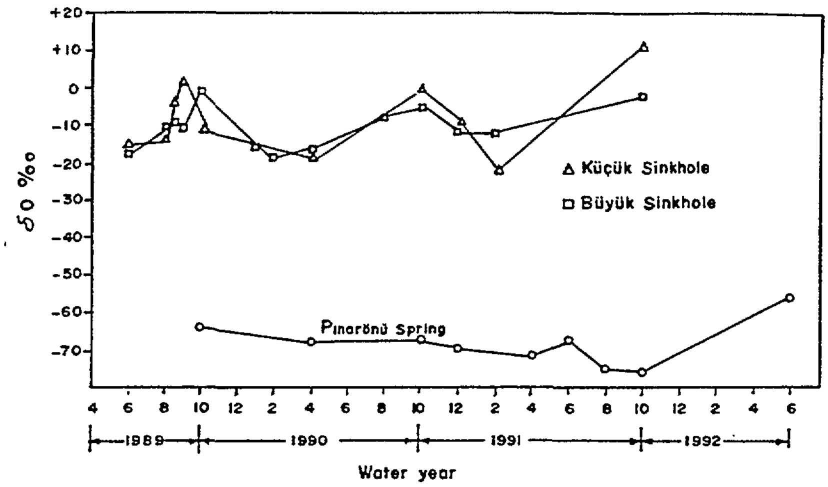


Fig.21. The variations of the δ D values at the sinkholes and Pınarönü spring versus time

It is shown that the $\delta^{18}O$, δD and chloride concentrations of the sinkhole water are significantly different from the concentration of Taşevi spring waters. It is clear that evaporated water of the sinkholes can't be seen from Taşevi spring (Figures 18,19,22).

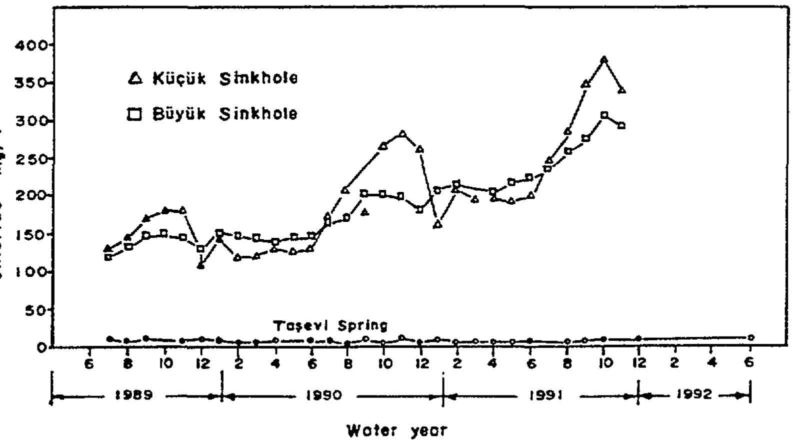


Fig.22. The variations of the chloride at the sinkholes and Taşevi spring versus time

Similar study has also been made for Pınarönü spring and the isotope concentration of the sinkhole waters can't be seen from Pınarönü spring (Figures 20,21).

To determine whether there is a hydraulic connection between the waters of Karamık lake and Taşevi spring by using chemical and isotopic content of waters in 1969

In order to solve the problem a study was made in 1969 [3]. Waters were taken from Geneli and Taşevi springs and from the sinkholes to determine $\delta^{18}O$, δD and to make chemical analyses. At that time $\delta^{18}O$, δD and tritium analyses were not performed in Turkey. The water samples were sent to WEIZMANN-Institute of Israel to make the analyses of the stable isotopes. The results are given in the following table.

location	Weizman Ins. in 1969		DSİ Isotope Lab. in this study	
	$\delta^{18}O$ o/oo	δD o/oo	mean $\delta^{18}O$ o/oo	mean δD o/oo
Geneli spring	-10,48	-68,7	-10,04	-69,87
Taşevi springs	-10,13	-68,3	-9,87	-68,51
Karamık lake (sinkholes)	+2,77	-32,4	+2,56	-9,91

It is seen that the isotope values of Taşevi spring waters are more negative than that of the sinkhole waters both in 1969 and during this study. Furthermore, the stable isotope concentrations of the Taşevi spring do not change in 20 years.

In addition to isotopic data, chemical analyses of the waters were performed. The chloride, sulfate and sodium concentrations of Karamık lake water were markedly higher than that of Taşevi spring water.

Depending on the isotopic and chemical contents of the waters, it was concluded that the character of Taşevi spring water was very different from that of Karamık lake water.

6. CONCLUSIONS

-- In the research area snowfall has a great effect on total recharge water. The weighted $\delta^{18}O$ value of Koçbeyli precipitation was computed as -9,29 o/oo and the mean $\delta^{18}O$ content of the groundwater was found around

-11 o/oo. Therefore Koçbeyli precipitation doesn't represent the total recharge water; neither the amount of the water nor it's isotope content (Fig.7).

-- It is found that the average rate deplation in the precipitation is -0,36 o/oo / 100 meters (Fig.13).

-- The mean altitudes of the surface drainage area of Taşevi, Gençali and Pınarönü springs were found as 1270, 1250, 1350 m. respectively. Mean $\delta^{18}O$ concentration of the precipitations of the mean altitudes were obtained as -10,0 o/oo, -9,8 o/oo, -10,2 o/oo for Taşevi, Gençali and Pınarönü springs respectively (Figures 10,11,12,13).

-- It is estimated that turn-over time of the groundwater is 300 years. In the aquifer between Karamık and Hoyran lakes there is an amount of water three hundred times more than the water of the input or output waters (Fig.17). Because of the long turn-over time the hydrologist has not had successes in previous dye experiment.

-- In 1969, depending on the isotopic and chemical contents of the waters, it was found that the charecter of Taşevi spring water was very different from that of Karamık lake water.

-- Choloride concentrations of Büyük and Küçük sinkhole waters have increased with time but that of Taşevi spring water haven't changed. The chloride concentrations of the sinkholes and the spring are different from each other (Fig.22). It is shown that there is no relation between sinkholes and Taşevi spring.

-- Average electrical conductivity (EC) of Büyük and Küçük sinkholes is 1700 µmhos/cm but that of Taşevi, Gençali and Pınarönü springs are 556, 425, 563 µmhos/cm respectively. The overage electrical conductivity of the sinkholes is significantly different from that of the springs (Fig.6).

-- The $\delta^{18}O$ and δD concentration of the sinkhole waters are significantly different from that of Taşevi spring water. It is shown that evaporated water of the sinkholes can't be seen from Taşevi spring by using tracers as $\delta^{18}O$ and δD (Figures 18,19).

-- It is a fact that the water of Pınarönü spring has been mixing with an evaporated water. The $\delta^{18}O$ value of the mixing water is not being significantly different from the mean recharge water but that of the mixing water is being significantly different from that of Karamık lake water. It is predicted that evaporated lake water can't be seen from the Pınarönü spring by using tracers as $\delta^{18}O$ and δD (Figures 20,21).

-- Mean $\delta^{18}O$ input value was determined as about -10,00 o/oo for Taşevi spring and mean isotopic composition of Büyük and Küçük sinkhole water are measured to be +2,56 o/oo and -9,91 o/oo for $\delta^{18}O$ andδD respectively. It is seen that the origin of the sinkhole water is markedly different from that of Taşevi spring water. It has been concluded that any contribution of Karamık lake water can't be observed at the Taşevi spring water (Figures 10,13).

-- The mean $\delta^{18}O$ input value of the precipitation was found -9,8 o/oo. The average $\delta^{18}O$ value of Gençali spring was measured as -9,75 o/oo. The average $\delta^{18}O$ and δD

values of Büyük and Küçük sinkholes were +2,56 o/oo and -9,91 o/oo respectively. It is seen that the origins of the spring and sinkhole waters are markedly different from each other. By evaluation of the isotope data it has been concluded that Gençali spring water doesn't receive any contribution water from Karamık lake (Figures 11,13).

-- The mean $\delta^{18}O$ input value of the recharge water was found -10,2 o/oo and the mean $\delta^{18}O$ value of Pınarönü spring water was measured -9,52 o/oo. A little evaporation was observed on the isotopes values of the spring water but the origins of Pınarönü spring and Karamık lake waters are significantly different from each other. Therefore it is predicted that there is no relation between sinkholes and Pınarönü spring (Figures 12,13).

-- During the dry periods the stable isotope values of the groundwater geathered on the precipitation line but that of the sinkhole waters fall down on the evaporation line. It's isotope composition is markedly different from that of waters falling on the precipitation line, which would be the other component in the case of mixing of lake water and groundwater. Therefore it is concluded that groundwater and all the spring waters don't receive any contribution of water from Karamık lake (Fig.8).

-- It is assumed that the waters of Büyük and Küçük sinkholes are mixing with Taşevi spring water. Mixture ratio was calculated from the average $\delta^{18}O$ contents of the waters. The mean contribution of the sinkholes to the spring water is about one per cent.

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RESEARCH ON THE GROUNDWATER FLOW DYNAMICS OF LAMAS BASIN BY ISOTOPE METHODS

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Abstract

The main objective of Lamas Project is to define the relation between the recharge to highlands and the discharge realized by the springs along the Mediterranean coast and thus assist to the development of karst water resources by preparing a dependable evaluation of the water budget.

The investigation area covers almost 4400 square kilometers where the elevation rises from 0 to 2900 m. Lamas is the main river crossing the area from northwest to southeast with a yield between 13.48 to 2.77 cu.m/s. The karstification in the area has at least reached 300 m in depth.

The water samples were collected from 16 springs, 3 drilled wells, stream and two meteorological stations, to define the groundwater dynamics and investigate the relation between the sampling points and to assist the establishment of an evaluation in isotope hydrology.

By taking into consideration the unmeasured discharges along the coast line, the infiltration from the precipitation is approximately 50-60 %. The water in the aquifer is isotopically effected by the infiltration of low altitude precipitation. The hydrogeological and isotope hydrology investigations have reached to the conclusions that the karst water resources can be developed by drilling of deep wells near the karst springs.

1. INTRODUCTION

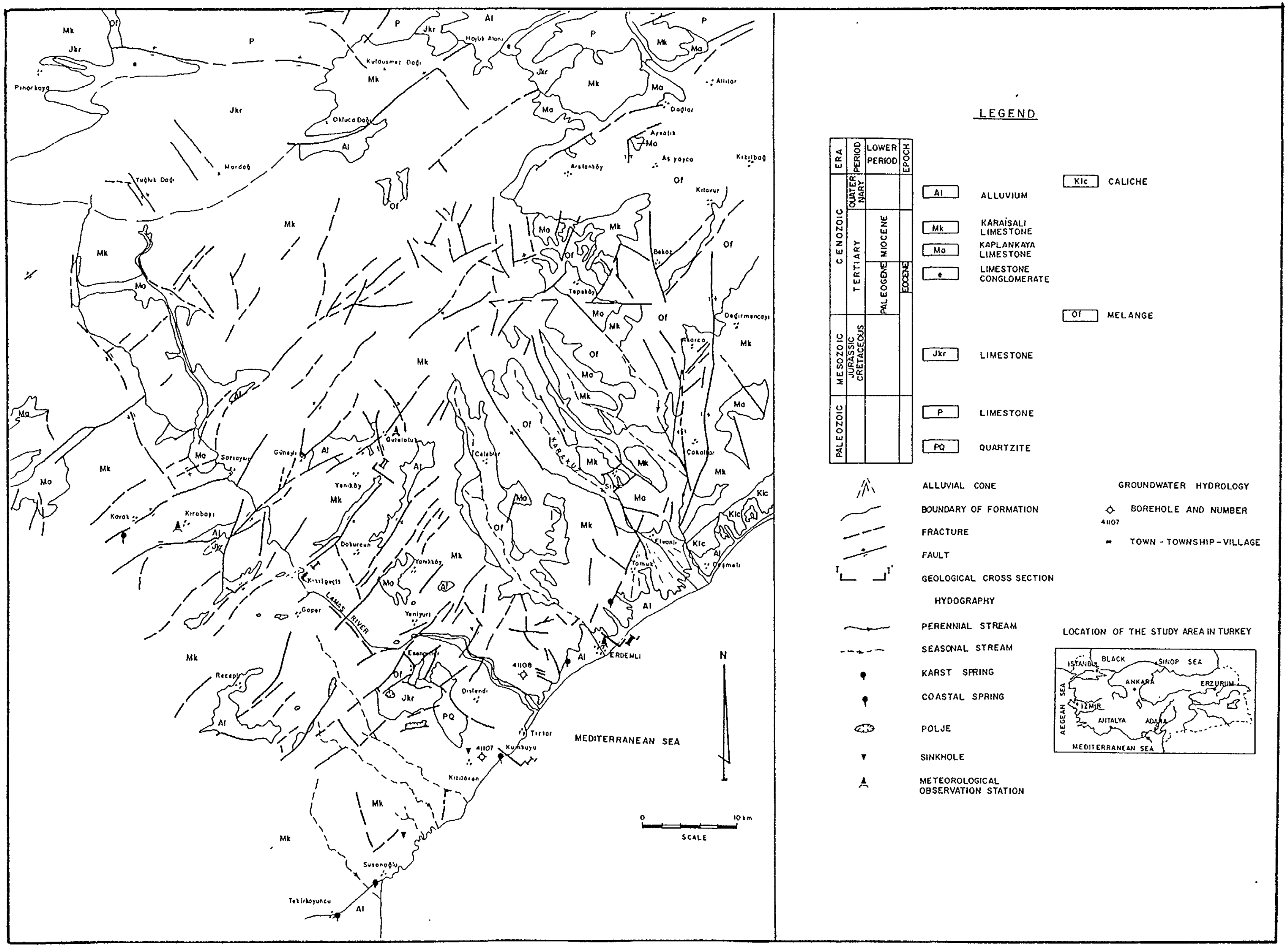
This project which is a part of IAEA contract RER/8/002 (TUR/8/011) has been realized to investigate the relation between the recharge (infiltration) and discharge (by karst springs) and thus emphasize a balance to assist the development of karst water resources. The large scale survey of the environmental isotopes assisted to determine:

a. Mean residance time of the groundwater
b. The estimation of infiltration by precipitation

2. HYDROGEOLOGICAL BACKGROUND

The investigation area is located on the Mediterranean coast between Mersin and Silifke. The area of investigation is mostly mountanous starting from a narrow coastal strip to highlands reaching up to 2900 m elevation.

The oldest formation cropping out in the area is the quartzites of Devonian near Sandaldağ. Schists and crystalline limetsones of Paleozoic crop out at the north of the area. The limestones in this region are effectively karstified (Map: 1).



MAP 1. Hydrological map of the study area.

The dolomitic limestones of Mesozoic lain unconformitably over the quartzites. They are dark in color, generally massive, thin to thick layered , folded and brittle. In a part of the northern drainage area, Eocene limestones lain unconformitably over the Paleozoic and Mesozoic.

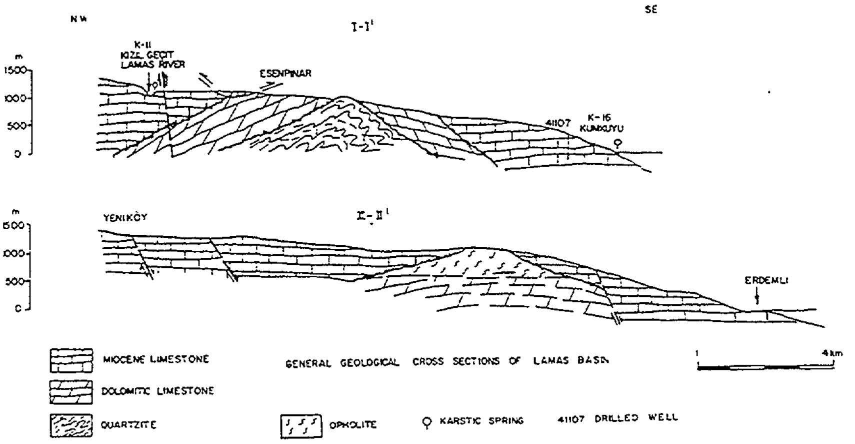
Kaplankaya formation starts with the base conglomerates and clays at the lower parts and rich in carbonates in the upper sections. They are yellow to gray in color and consists of interbedings of marls, clayey sandy limestones, sandstones and siltstones which are the representative of a shallow marine deposition of lower Miocene.

Karaisalı formation of lower-middle Miocene is the most widespread outcrop. The limestones are generally white, light gray to beige in color, thick to medium layered, sometimes massive, hard and sound, karstified.

Alluvium is spread out on the coastline in Limonlu and Erdemli vicinity. The thickness is about 50 m consisting of clay, silt, sand and gravel.

Ophiolitic melange is observed in the east and north of Esenpınar. This is named as Tepeköy formation thrusted over on Paleozoic and Mesozoic.

The main faults in the region trends from northeast to southwest and a secondary system trends in northeast to southwest direction. Fracture and joint systems have been effectively developed in carbonate rock formations. Perpendicular joint systems have been formed by the collapse of the karstic depressions.



GENERAL GEOLOGICAL CROSS SECTIONS OF LAMAS BASIN

The karstification in the region has been investigated by photogeological evaluations. The dolomitic limestones cropping out especially near Esenpınar and near Kırobası have been intensively karstified. The Miocene limestones which covers all the basin is the main point of investigation. The impervious Kaplankaya formation has caused the karstification in Karaisalı formation. The karstification is 250-300 m deep in the southern parts. The precipitation to the outcrops and runoff from precipitation infiltrates to the sinkholes or poljes travels until down to 0-50 m elevation. The heterogenity of the fracture system and consequently of the karst system influences the transit time of the groundwater in the aquifer and also the direction of flow.

The transmissibility values of the carbonate rocks are between 0 to 2500 cu.m/d/m which clearly define the characteristics of the karstic aquifer.

The region is under the influence of the Mediterranean climate. However, depending on the elevation, rain and snowfall is observed in the investigation area which reaches up to 2900 m. The mean annual precipitation in Güzeloluk (1400 m) is 765,5 mm and 673,0 mm in Kırobası (1400 m) which are located 30-35 km away from the coast. In Erdemli, on the coast, the mean annual precipitation is 605,2 mm. The highlands of the Taurus mountain range in the north of Lamas basin receive important snowfall. The snow cover is rather thick and residence time of the snow is quite long where the karstic features are extensively observed.

Lamas river crosses the investigation area in northwest-southeast direction. The mean discharge is 6,86 cu.m/s, maximum 13,48 and mimimum 2,77 cu.m/s. The stream inflows and outflows to Miocene limestones along its route as given in the related table (Table: I) and in (Map: 2).

The discharges of springs vary between 0,2 to 2500 L/s in the investigation area. The important springs are:

K-2 (Dedekavak), K-3 (Erdemli), K-4 (Karasu), K-14 (Tekirkoyuncu) and K-19 (Susanoğlu).

K-3 (Erdemli spring): It discharges from limestone-alluvium contact from five different points. The measured mean discharge is 2.1 cu.m./s where 1 cu.m/s is pumped for irrigation.

K-14 (Tekirkoyuncu spring): A karstic spring discharging from Miocene-Alluvium contact. According to the observations made between 1977 to 1982, the minimum yield is 442 L/s in November 1980 and maximum 2055 L/s in February 1981.

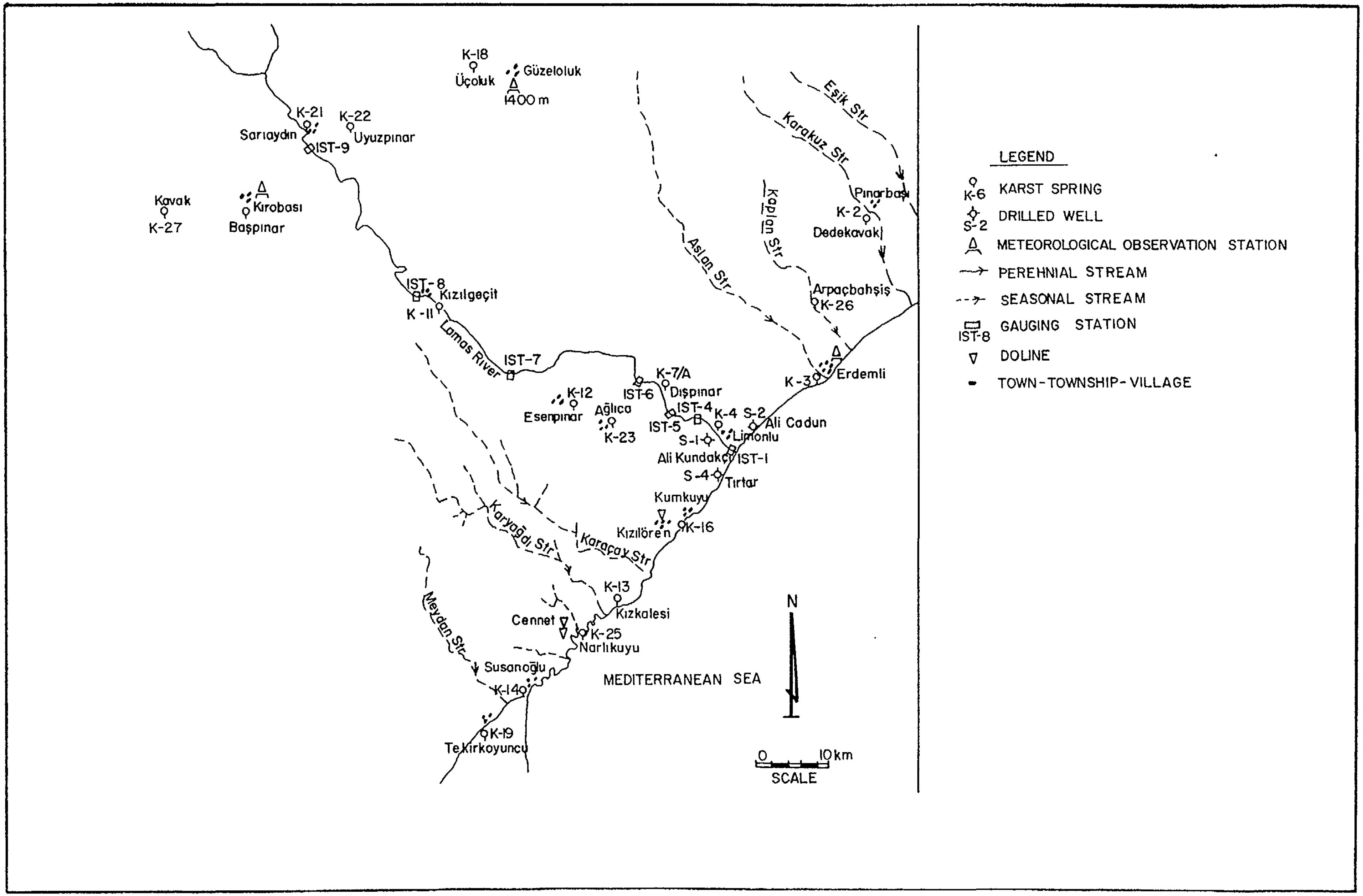
K-19 (Susanoğlu spring): According to the measurements made between 1979 and 1991, the minimum yield is 26 L/s in August 1990 and maximum 2198 L/s in February 1981.

The hydrology of important springs have been evaluated depending on the available runoff measurements made between 1976-1981. The baseflows are as follows (in hm^3):

Spring	1978	1979	1980	1981	Mean
K-13	31,75	30,45	37,60	36,28	34,00
K-14	19,70	18,40	17,10	17,62	18,00
K-19	22,00	19,70	16,84	17,10	19,00

The recession coefficients and active volumes are as follows:

	K-3		K-14		K-19	
Year	α day^{-1}	V hm^3	α day^{-1}	V hm^3	α day^{-1}	V hm^3
1976	$3,2x10^{-3}$	31,55	_	_	-	-
1977	$4,3x10^{-3}$	52,71	-	-	$5,07x10^{-3}$	23,18
1978	$4,8x10^{-3}$	31,63	$3,0x10^{-3}$	21,0	$3,32x10^{-3}$	21,85
1979	$5,4x10^{-3}$	49,56	$3,7x10^{-3}$	38,1	$3,03x10^{-3}$	15,40
1980	$7,8x10^{-3}$	37,86	$2,0x10^{-3}$	32,6	$5,40x10^{-3}$	22,12
1981	-	-	$2,6x10^{-3}$	21,9	-	-
Mean	$5,12x10^{-3}$	40,66	$2,8x10^{-3}$	28,4	$4,20x10^{-3}$	20,63



MAP 2. Sampling locations in Lamas basin.

Table I: RUNOFF MEASUREMENTS ALONG LAMAS RIVER (APRIL-DECEMBER 1989)

Months				STATIONS					
	9	8	7	6	5	4	3	2	1
1989				cu.m/s					
April	8,407	10,400	10.281	11,662	11,993	0,409	0,231	0,046	12,191
May	3,435	5,450	4,223	7,282	7,340	0,375	0,425	0,042	7,240
June	2,710	4,270	3,357	5,369	5,102	0,432	0,470	0,058	4,750
July	2,053	3,460	2,447	3,349	3,655	0,460	0,243	0,039	3,044
August	2,195	3,100	2,391	4,222	4,469	0,516	0,416	0,045	3,504
Septem.	1,760	2,950	1,993	3,600	3,849	0,455	0,499	0,033	2,943
October	-	3,190	-	-	-	-	-	-	-
November	1,710	4,270	2,127	3,671	3,748	0,238	0,235	0,035	3,355
December	1,718	3,460	2,045	4,093	4,110	0,295	0,046	0,045	3,887

9. Sarıaydın 8. Kızılgeçit 7.Kalaycı Valley 6. Eşek Bridge
5. YSE Bridge 4. Belediye Channel 3. DSİ Channel 2. Karasu Spring
1. Lamas River (Discarge to the sea)

TABLE II: CORRECTED $\delta^{18}O$ and δD VALUES %O

Site No	Location	Measured $\delta^{18}O$	D	Corrected $\delta^{18}O$	δD
K-3	Erdemli	-7,53	-44,68	-7,61	-45,08
K-13	Kızkalesi	-7,11	-40,05	-7,27	-40,86
K-14	Susanoğlu	-7,01	-39,00	-7,10	-39,40
K-16	Kumkuyu	-8,17	-49,15	-8,45	-50,67
K-19	Tekirkoyuncu	-8,05	-51,15	-8,14	-51,67
K-25	Narlıkuyu	-7,62	-44,40	-8,62	-49,30
S-4	Tırtar	-7,60	-42,45	-7,70	-43,31

3. DATA COLLECTION AND EVALUATION

3.1. Data Collection

3.1.1. Sampling

The environmental isotopes are one of the main data for the solution of hydrogeological problems to be tackled. The stable isotopes of oxygen and hydrogen and radioactive isotopes of hydrogen (tritium) are widely used in such problems.

In Lamas area, the contribution of the precipitation to the groundwater by direct infiltration and from the runoff is very important. In order to provide the actual data for stable isotopes of precipitation, Güzeloluk Observation Station in the north at an elevation of 1400 m was selected for the collection of precipitation. On the other hand, Erdemli Observation Station at an elevation of 9 m on the coast was also sampled to provide data of the low altitudes.

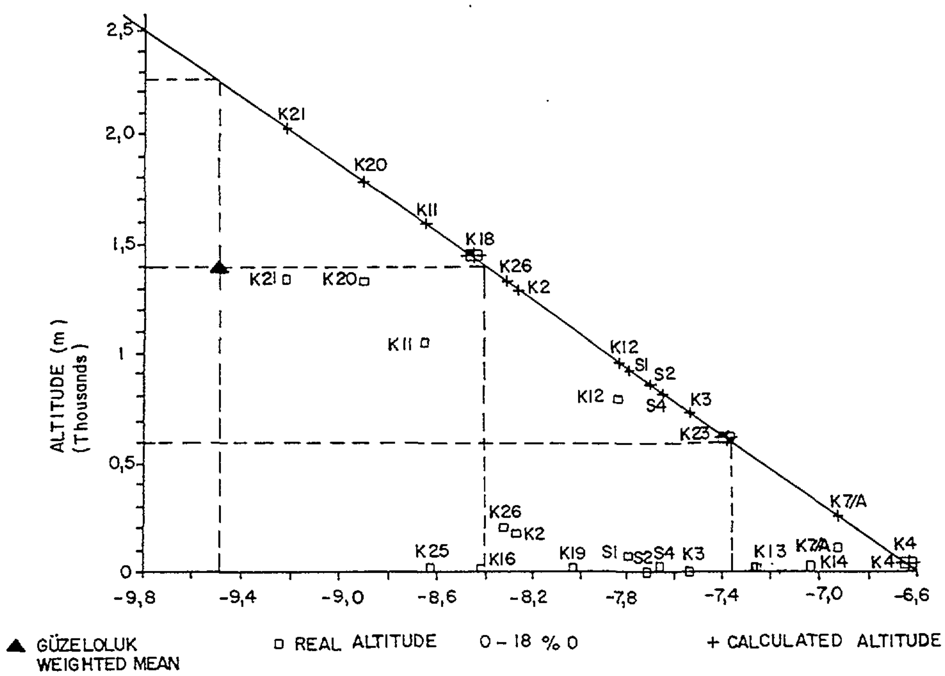


FIG I : ALTITUDE EFFECT FOR $\delta^{18}O$ VALUES

In addition to the precipitation samples, some small springs in different altitudes were selected to establish the altitude effect (Fig: 1) while some springs and drilled wells on the coast line were selected to observe the seawater encroachment.

As a conclusion, the stable isotope data collected from precipitation, springs, Lamas stream and drilled wells were sufficient to provide necessary information on the groundwater dynamics of the region (Map: 2).

The data collected for tritium can provide information on the general flow pattern of the groundwater in the investigated area. The tritium content of the groundwater enables information on the replenishment of the aquifer and with the stable isotope data can also be used as a parameter of mixing and as a tracer. The tritium values were not low enough to require C-14 counting and C-14 samlpling was not considered.

Although the investigation area is situated between important stations like Adana, Antalya and Konya, to get a precise data, two precipitation stations were sampled. Sampling from Güzeloluk started from February 1990 until June 1992 and for Erdemli from February 1991 until June 1992.

Sampling from 16 springs, 3 drilled wells started in August 1989 and ended in September 1991.

Lamas river was sampled at the begining of the project and provided results reached to the conclusion that it will be unnecessary to sample the river due to similar results of high altitude precipitation or its mixture.

During the investigation 197 analyses for $\delta^{18}O$, 125 analyses for δD were realized and 106 samples were determined for tritium.

3.1.2.Other Available Data

The complete chemical analyses of the samples have been realized to assist the preliminary and isotopic evaluations. The samples were analysed as fast as possible to prohibit failures. In October 1991, five samples were collected from the certain points of Lamas river with special procedures as recommended for a revised evaluation. However, similar results prior to analyses were obtained.

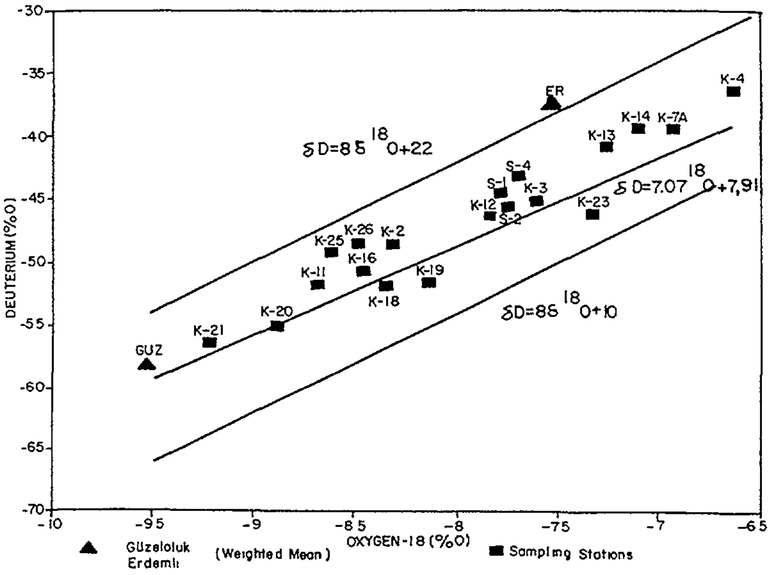


Fig 2 δ^{18}O-δD Plot For Güzeloluk and Erdemli Precipitation

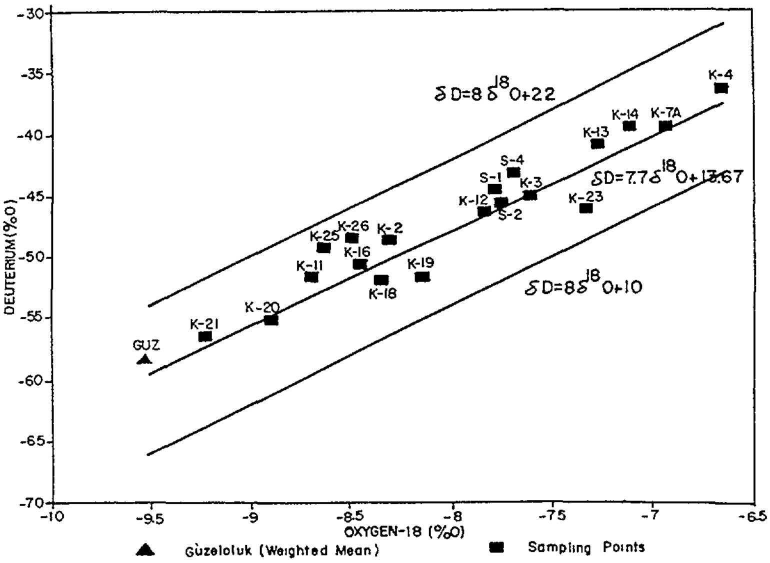


Fig 3 δ^{18}O Versus δD Plot

According to the results, all samples collected from the investigation area are similar and their origin is from the same aquifer. However,the seawater encroachment has effected K-13, K-14, K-16, K-19 and K-25 springs and drilled well S-4. The electrical conductivity values are higher compared to other sampling points reaching 5900 micromhoS/cm.

The samples of K-23, K-26 springs and drilled well S-1 have been influenced by the dolomitic limestones and $Mg^{++} > Ca^{++}$.

The precipitation of April 1990 has effected the cations and anions and elctrical conductivities by decreasing their values. Such a decrease has also been observed in April 1991.

3.2. Interpretation of The Isotopic Results

3.2.1. Precipitation

The samples of the precipitation has been collected from February 1990 to June 1992 from Güzeloluk Observation Station (elev. 1400 m) and from February 1991 to june 1992 from Erdemli Observation Station (elev. 9 m).

Stable Isotopes In Precipitation

The O-18 contents of the precipitation in Güzeloluk varies between -11.74 to -2.58 %o and deuterium values between -78.06 to -23.32 %o showing important flactuations and the most depleted value is -113.98 %o in January 1992, this exceptional result is provided from repeated analyses.

The deuterium contents of Erdemli Observation Station is between -8.08 to -3.67 %o and -56.16 to -21.52 %o for deuterium.

The mean values of O-18 and deuterium of total precipitation weighted for the amount of rain fall during the investigation period are:

	O-18	δD
Güzeloluk	-9.52	-58.19
Erdemli	-7.53	-37.37

The linear regression line for(O-18)- D line relationship is:

Güzeloluk $\delta D = 7.07\,\delta^{18}O + 7.91$ $r^2 = 0.91$

Erdemli $\delta D = 5.32\,\delta^{18}O - 1.42$ $r^2 = 0.59$

In the calculation of the regression lines, precipitetion below 20 mm and samples under the effect of the evaporation have been excluded (Fig: 2).

Tritium In Precipitation

The tritium content of the precipitation for Lamas basin is maximum 47 TU in March 1991 and lower values are observed for the other months. The decrease in tritium content together with the global values is also observed in the region.

3.2.2 Groundwater

Stable Isotopes

The stable isotope contents of the groundwater together with the chemical analyses enables the evaluation of the available data more precisely.The results of the sampling points under the influence of seawater encroachment, like K-16, have been corrected for the stable isotope values by taking into consideration the ratio of Cl^- contents. The corrected values are tabulated in

(Table: II) for $\delta^{18}O$ and plotted accordingly to estimate the altitude effect (Fig: 1). The regression line representing the sampling points is (Fig: 3):

$$\delta D= 7.7\ \delta^{18}O+ 13.67 \qquad r^2 =0.91$$

Depending on the results of analyses, geological and hydrogeological evaluations, the sampling points can be grouped by taking into consideration the $\delta^{18}O$ and T values (Fig: 4):

Group I

This group has been represented by the springs K-18, K-20 and K-21:

$\delta^{18}O= -8.81$ ‰

$\delta D= -54.50$ ‰

Group II

This group is represented by springs K-2,K-11, K-16, K-19 and K- 26:

$\delta^{18}O= -8.41$ ‰

$\delta D= -49.87$ ‰

Group III

This group represents important springs on the coast K-3 and K-12:

$\delta^{18}O= -7.73$ ‰

$\delta D= -45.49$ ‰

Group IV

This group represents S-2 and S-4 located on the coast line:

$\delta^{18}O= -7.73$ ‰

$\delta D= -44.10$ ‰

Group V

This group is formed by springs K-13 and K-23:

$\delta^{18}O= -7.30$ ‰

$\delta D= -43.09$ ‰

Group VI

This group represents springs K-4, K-7/A and K-14 located on the coastline:

$\delta^{18}O= -6.89$ ‰

$\delta D= - 38.26$ ‰

The significance of difference between the $\delta^{18}O$ indices for the different groups have been submitted of variance analyses:

Variance Ratio Table

	Degrees of Freedom	Sum of Squares	Mean of Squares	Variance Ratio
Between Groups	5	7.71	1.92	30
Within Groups	11	0.71	0.064	

From the variance ratio table it has been found that the groups are significant at the 95 % confidence level.

The individual differences between the means of the groups have been tested by Fisher's Least Significant Test:

Between Groups	Difference (Group Mean)	Significant 95 %	Between Groups	Difference (Group Mean)	Significant 95 %
1-2	0.40	No	1-3	1.08	Yes
1-4	1.08	Yes	1-5	1.51	Yes
1-6	1.92	Yes	2-3	0.68	Yes
2-4	0.68	Yes	2-5	1.11	Yes
2-6	1.52	Yes	3-4	0.00	No
3-5	0.43	No	3-6	0.84	Yes
4-5	0.43	No	4-6	0.84	Yes
5-6	0.41	No			

According to the table in above, the groups (1-2, 3-4, 3-5, 4-5, 5-6) are not significant at the 95 % confidence level and the rest are significant at the 95 % confidence level.

Tritium In Groundwater

The global decrease in groundwater contents of the precipitation have also effected the T contents in the groundwater. The values can be grouped accordingly as follows:

Sites with contents between 0 to 5 TU
Sites with contents between 5 to 10 TU
Sites with contents over 10 TU

Tritium contents between 0 to 5 TU

Sites K-4, K-7/A, K-25 and S-1

All sites are located on the coast or near to the coastline away from the recharge area. K-7/A has a special position on higher elevation.

Tritium contents between 5 to 10 TU

Sites K-2, K-13,K-14, K-16, K-19, K-23, K-26 and S-2, S-4

These sites are distributed to various locations in the investigation area. K-13, K-16 and K-19 are on the coastline and the others near to the drainage area or in between.

Tritium contents over 10 TU

Sites K-3, K-11, K-12, K-18, K-20 and K-21

K-12, K-18, K-20 and K-21 are subject to recent precipitation depending on the locations in the drainage area. However, K-3 which is one of the biggest springs have similar content of tritium with the recharge area.

Some sites like K-11, K-23 and S-2 have sharp increase in tritium values probably as an indication of recent recharges.

As shown in (Fig: 4), the $\delta^{18}O$ plot also indicates similar groupings. K-20 and K-21 represents recent and high altitude precipitation while K-3, K-12 and K-18 represent rather a recent recharge and rapid discharge. However, K-3 is located on the coastline away from the recharge area and a deep karst circulation without any contribution of decent recharge may be accepted.

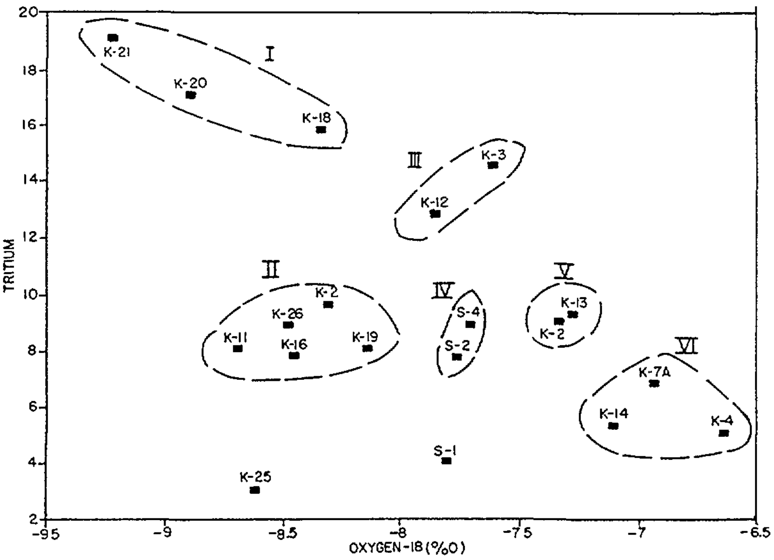
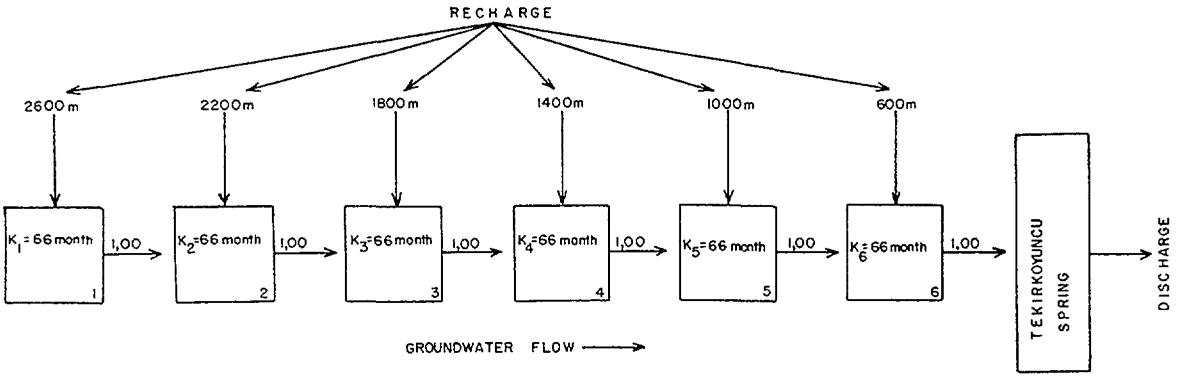


Fig 4: δ^{18}O Versus T Plot



K = 1/α = Mean transit time

Figure 5 . CONFIGURATION OF THE ADOPTED COMPARTMENTAL SIMULATION MODEL

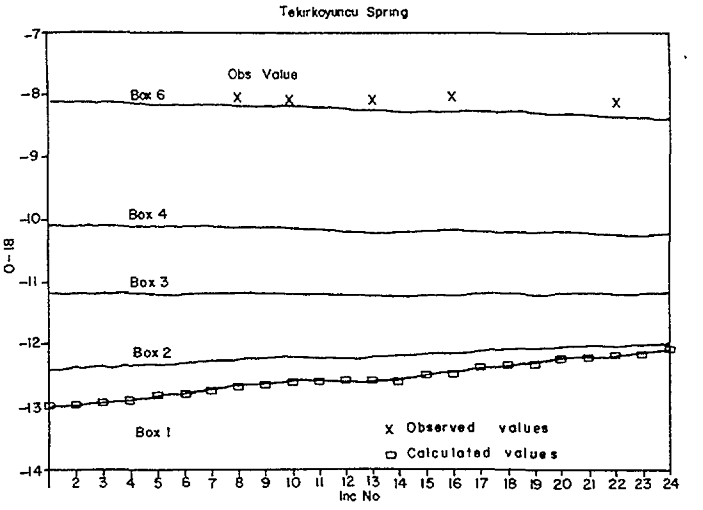


FIG. 6 THE OBSERVED AND CALCULATED δ^{18}O CONTENT OF K-14 SPRING FOR ALL

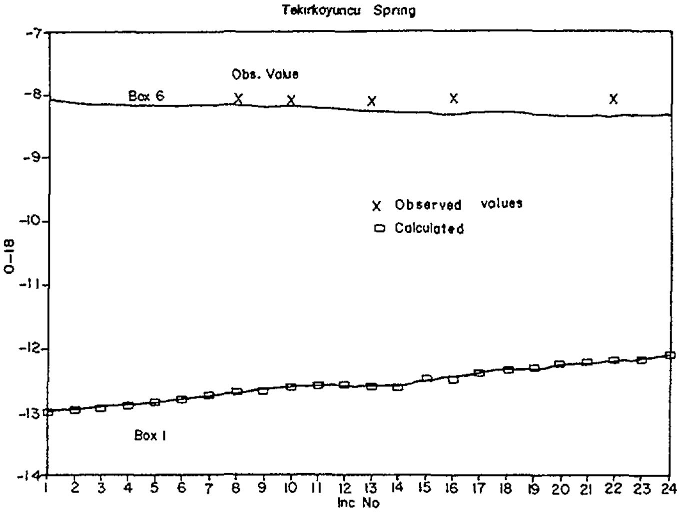


FIG 7 THE OBSERVED AND CALCULATED $\delta^{18}O$ CONTENT FOR INPUT AND OUTPUT

Estimation of The Turnover Time

As described before Lamas is a karstic basin (Map: 1) under the effect of the precipitation occuring in different elevations, generally in winter. The amount of precipitation decreases towards to the north and is in the form of snow in higher elevations. The precipitation as rain directly infiltrates and runoff is seldom observed. The sampling programme was aimed to establish the skeleton for the simulation programme model. The altitude effect has been estimated and is used in the modelling (Fig: 1). The configuration of the adopted compartmental simulation model is based on the $\delta^{18}O$ data which is more sufficient in number than of tritium. A correlation between Güzeloluk-Ankara or Ottawa could not be realized due to the nonavailability of the corresponding data of Ankara or Ottawa for the required years.

The runoff measurements of K-3 (Erdemli), K-14 (Susanoğlu) and K-19 (Tekirkoyuncu) springs were available and as it has previously been indicated the active reservoir volumes were calculated. The recession characteristics of the plotting the time versus discharge indicates single storage element for the discharge process. The mean monthly discharge of springs are K-3= 2.8, K-14= 1.5 and K-19= 1.6 hm^3/month covering 1976-1981.

Mathematical modelling is required to explain groundwater flow dynamics in the karstic basins. The groundwater velocity, residence time, storage volume, dispersivity coefficient and other parameters can be provided by the use of above mentioned models. The modeling of karst groundwater flow could not be deterministically expressed both due to the instability of the recharge system and due to the heterogenity of subsurface geology and hydraulic heads despite a granular aquifer environment. However, attempts are made to express the karst flow dynamics depending on the convolution integral and by parameters of precipitation-runoff model.

After the importance of the isotopes have been accepted in the groundwater flow dynamics, the use of the isotopes forming the molecules of water have been understood and attempts to provide the quantitative data on the origin and transit time of groundwater have been made. Piston flow models, mixed models and exponential models are being used to interpret the hydrological model. The system is completely accepted as a black box and is expressed unically with a single convolution integral. These models which determines the whole system as a reaction function is named as lumped parameter models. In a lumped parameter model, spatial variations are ignored and various properties and state of the system can be considered to be homogenous throughout the entire system.

Complex and heterogenous hydrogeological systems which are divided into homogenous and dynamic subsystems (or cells) are used in hydrogeology. Thus, the equation of groundwater flow can be expressed as distributed parameter model. The shape of the system and the flow distribution can be modelled by arranging the dimensions of the boxes and their interconnections.

The functional relationship between discharge and volume of storage compartment is explained as V= kxQ where k is the discharge coefficient which has a dimension of time and expresses the discharge of the system in relation with the time.

The tracer input-output relation for such a linear storage element can be developed from simple material balance consideration at discrete time interval. If the flow volume with its known tracer concentration is assumed to mix uniformly with the volume of water available in the storage, the tracer concentration in the storage element and the flow at the end of the time interval can be computed from the following equation:

$$C_{Qn} = C_{Vn} \frac{V_{n-1} \times C_{Vn-1} + R_n \times C_{Rn} \times e^{-\lambda T}}{V_n + Q_n}$$

where C_{Qn} = Output concentration during n^{th} interval

C_{Vn-1} = İnput concentration during previous interval

R_n = Volume of recharge during n^{th} interval

$e^{-\lambda T}$ = The decay factors for radioactive tracer (not included into our calculations)

Simulation Model For Lamas Basin By Using Environmental Isotopes

Although the samples for isotopic analyses were collected from 1989 to 1991, the runoff measurements of springs covers from 1976 to 1981. The discharge values of the previous years and the amount effect of the precipitataion were not taken into consideration. The active volumes and the base flow of the karstic springs were used in the computer programme. However the discharge of the basin is by some well known karstic springs and considerable discharge is also towards the Mediterranean Sea by undetected submarine or coastal springs.

All geological, hydrogeological data and data from the hydrochemical and isotopic analyses have reached to the conclusion that the precipitation in the drainage area infiltrates directly to the karst aquifer and under the effect of different aquifer conditions reaches down to the coast line (karstic, coastal and submarine springs). As a complete registration of all the springs cannot be realized with their runoff measurements, only K-19 spring was taken as an example for the calculation of the transit time.

The hydrogeological system of K-19 spring has been laterally divided into six boxes representing the effect of precipitation considering the altitude effect. Güzeloluk precipitation is representative (Map: 2) for the basin and below 600 m elevation, no variation in isotopic contribution is assumed (Fig: 5). The isotopic concentrations provided from (Fig: 1) for 2600, 2200, 1800, 1400 m, 1000 and 600 m elevations is used as an input for the model. The observed $\delta^{18}O$ values and the discharge of the springs and $\delta^{18}O$ value as calculated in the final box are correlated (Fig: 7 and 8). By taking into account the drainage area and by applying alternative parameters like transit time and lateral flow, they were used in order to minimize the difference between the observed and calculated $\delta^{18}O$ values. The best curve-fit of the data gave a result of 33 years transit time for K-19 (Tekirkoyuncu) spring.

5. RESULTS OBTAINED

The investigation performed has once more indicated the relation between the recharge and discharge points clearly for the use of water resources and additionally assisted to reach the following results:

a. The rapid increase in topography clearly indicates the altitude effect on the stable isotopes and enables to make a mathematical model.

b. Like K-16, some springs or deep water levels are not effected or hydrogeologically independent from low altitude precipitation.

c. Coastal and submarine discharge is a big problem to make a realistic balance the groundwater budget. However,the assumptions of 50-60 % infiltration in hydrogeological investigations reflects rather an actual situation.

d. The effect of the seawater encroachment is more clearly observed in the isotopic analyses. It is deem necessary to apply measures to eliminate the seawater encroachment in the settlement areas along the coast line.

e.The development of karst springs can locally be realized by drilling of water wells and establishing a reservoir volume and pumping relation

6. CONCLUSIONS

The goal of this project is to estimate the groundwater recharge and the discharge and assist in the establishment of a dependable groundwater budget.

Depending on the hydrogeological, karstic and photogeological investigations and on the isotopic investigation performed, all lead to conclusion that the infiltration from the precipitation is rather high, up to 50-60 % and the groundwater flow is directly under the control of tectonics and developed karstic systems. The recharge area reaches to the water divide at the Taurus mountain range. The seasonal effects of the precipitation and the contribution of high altitude precipitation are clearly observed.

The isotope hdyrology investigation has once more strengthened the existing results of the previous reports and emphasized the need of the preperation of "Master Plan" on the use of karst water resources. The development of karst springs should seperately be programmed and regular measures to protect seawater encroachment should be taken.

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