Isotope hydrology studies on water resources in western Rajasthan

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Environmental isotope studies in the Jalore and Barmer areas show that deep groundwaters have depleted ^{2}H and ^{18}O compared to the present day precipitation and have negligible tritium. Radiocarbon levels indicate groundwater ages ranging from 2400 to 7400 BP. Shallow groundwaters, on the other hand, show bomb tritium indicating some component of modern recharge. Studies on the effect of the Indira Gandhi canal on groundwater environment helped in differentiating the areas waterlogged by canal seepage and those affected by return flow of irrigation. A study on the buried channel of the legendary 'Saraswati' river in Jaisalmer district indicates shallow waters are old with ^{14}C content of 54.9 pMC to 58.8 pMC (uncorrected ages: 4950 to 4400 BP) with a velocity of about 20 m/a.

ARID zones pose special problems to hydrologists anywhere in the world. Conventional techniques have methodological constraints[1]. Some are: a) paucity of rainfall data due to irregular distribution in time and space and frequently disastrous and ungaugable storm events, b) untested extrapolation of the estimates of potential evapotranspiration to arid regions, and c) limitations on the use of geoelectric profiles due to dry shallow horizons and deep saline formations.

On the other hand, experience in the applications of isotope techniques in India and elsewhere indicated that the techniques are better suited to arid zones than to any other geographical situation. The reasons are: 1) The isotopic composition (^{2}H and ^{18}O) of rainwaters depends on the temperature of condensation, altitude and intensity of rainfall. This results in different isotope signatures for different rain events, particularly in the arid and semi-arid regions. 2) Evaporation, unlike condensation, causes kinetic fractionation of ^{2}H and ^{18}O and provides an identifiable isotopic characteristic. 3) Paleowaters from earlier pluvial episodes have depleted ^{2}H and ^{18}O, insignificant tritium and low levels of ^{14}C in dissolved bicarbonates. Radiocarbon helps in the age-dating of paleowaters.

In addition to the above, it is possible to tag a layer of soil moisture in the unsaturated zone with a suitable radioactive tracer like tritiated water or ^{60}Co labelled $K_3Co(CN)_6$ (ref. 2) and follow its movement to evaluate rainfall recharge.

Recharge to shallow aquifers is the subject of great interest to groundwater management in arid areas since modern recharge to deep groundwater is relatively rare.

Isotopes help in answering such questions as

- Is there modern recharge?
- If so, what is the recharge process; direct infiltration of rainwater, contribution during flash floods, return flow of irrigation, etc.?
- If not, when was the aquifer last recharged?

Some typical isotope studies carried out in western Rajasthan are discussed briefly in the following sections.

Jalore district

An environmental isotope study was undertaken to investigate groundwater recharge in the Jalore area of Rajasthan. The study area located in Jalore district of southwestern Rajasthan (Figure 1) is arid and receives mean annual rainfall of 380 mm. The area is covered extensively by alluvium. Presence of sand dunes is a common feature in the area, especially in the western part of the study area. The surface drainage consists of Sukri river, a tributary of the Luni river system, which is ephemeral in nature and flows towards southwest, i.e. towards the Rann of Kachchh in Gujarat.

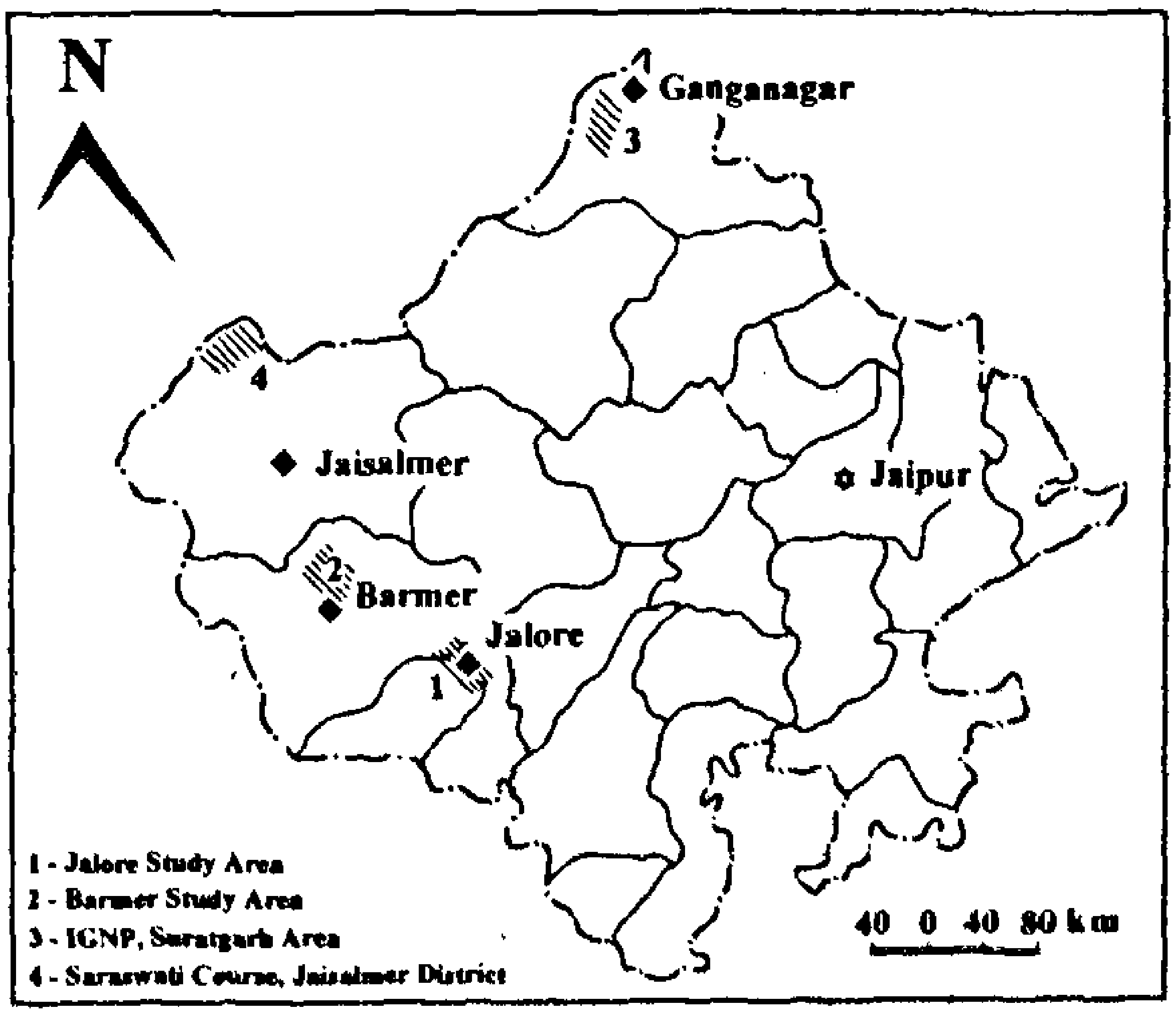

Figure 1. Locations of isotope studies in western Rajasthan.

The younger alluvium is mostly present along the course of Sukri river and comprises unconsolidated to semi-consolidated coarse to fine sand and gravel. The older alluvium of sub-recent to the Pleistocene age consists of semi-consolidated to consolidated coarse to medium sand with clay lenses, caliche and rock fragments. Tertiary sediments, consolidated clays with sand and shale fragments, are encountered at depth in the western as well as southwestern portion of the study area.

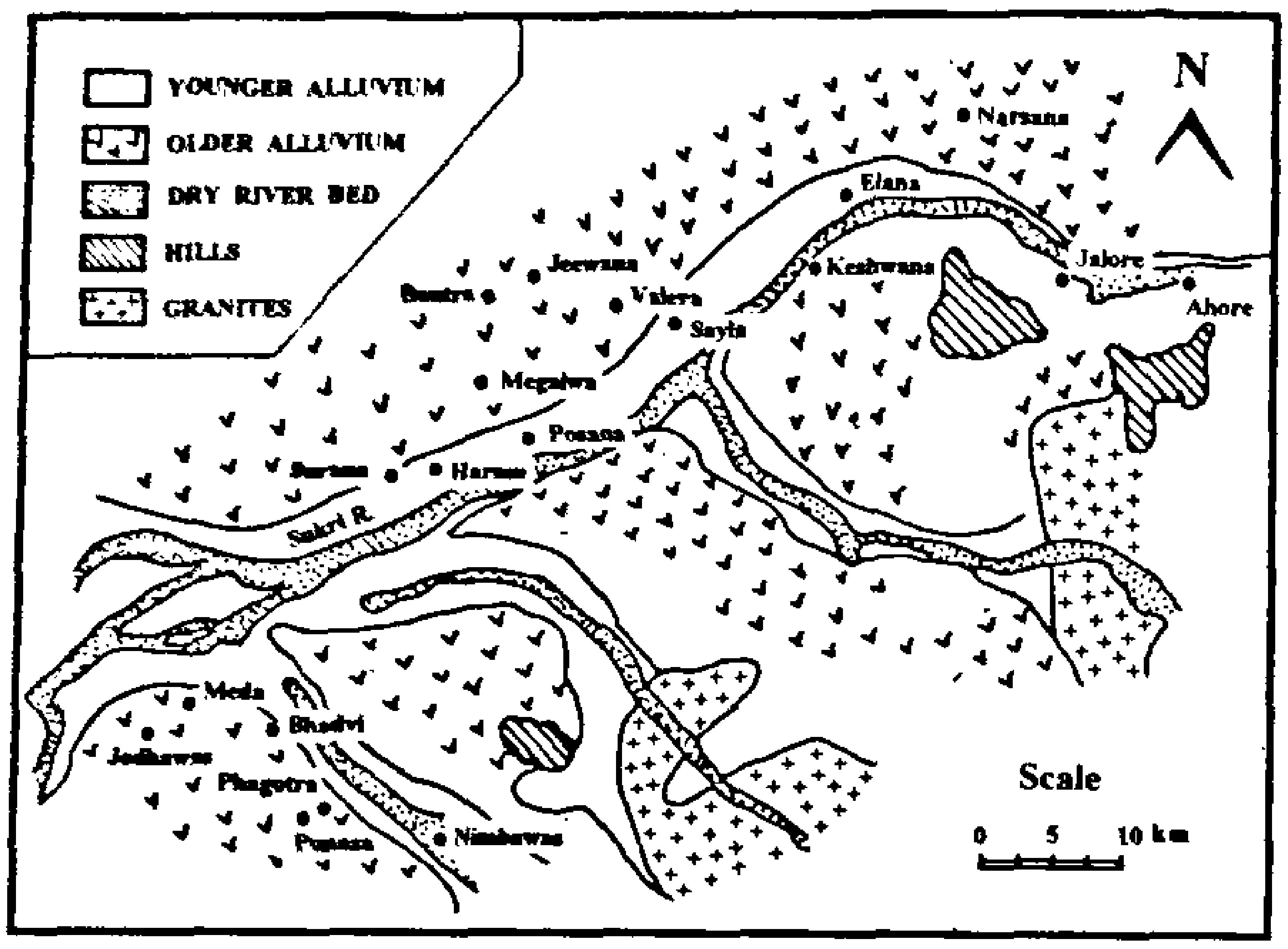

Figure 2. Jalore study area – sample locations (note: Bhadrajun (D14 in Table 1), NNE of Narsana not shown in Figure).

Study of subsurface geology based on borehole data shows that depth to basement increases abruptly west of Sayla probably due to presence of a fault. Sukri river also flows along a NE–SW trending fault. A number of smaller faults are also suspected in the area.

Shallow groundwater mostly occurs under phreatic conditions. Conditions changing from confined to artesian flowing type are observed in the southwestern part. An artesian flowing well is located at Jodhawas which mainly taps the Tertiary aquifer. Groundwater flows towards west-southwest.

A number of samples from shallow (depth < 50 m) and deep (depth > 150 m) wells were drawn from various places (Figure 2) for environmental isotopes as well as major ion chemical analyses[3]. The relevant results are given in Table 1.

In general, fresh, shallow groundwater in the northern part of the study area is of Ca–HCO_3 type. Shallow groundwater along the river course and fresh, deep groundwaters at Punasa and Sayla are of Na–HCO_3 type indicating base exchange. Majority of brackish groundwaters, shallow as well as deep, are of Na–Cl type. Electrical conductivity (EC) of shallow groundwaters ranges from 960 µS/cm to 5300 µS/cm and that of deep groundwaters varies from 1200 µS/cm to 5400 µS/cm.

Table 1. Isotope and other relevant data of samples from Jalore district, Rajasthan

Sample identity	Place	Depth of well (m)	Electrical conductivity (µS/cm)	Chloride (mg/L)	δ^2H (‰)	$\delta^{18}O$ (‰)	^3H (TU)	^{14}C (pMC)
Deep wells								
T1	Bautra	290	1215	168	−41.8	−5.80	0.8	–
T2	Megalwa	205	3800	801	−51.6	−6.80	0.6	–
T3	Punasa	300	1500	256	−42.2	−6.10	2.4	–
T4	Jodhawas	305	5350	1360	−35.3	−5.10	1.2	12
T5	Meda	280	5400	1333	−35.1	−5.50	1.6	–
T6	Posana	182	3800	781	−50.9	−7.00	0.9	–
T7	Phagotra	150	–	–	−50.2	−6.70	–	–
T8	Sayla	174	1320	229	−42.2	−6.40	3.0	71
Shallow wells								
D1	Bautra	50	1230	162	−39.8	−6.50	1.9	–
D2	Megalwa	12	3950	946	−42.0	−6.60	3.0	–
D3	Punasa	46	1350	162	−44.4	−5.85	4.0	–
D4	Phagotra	40	3550	728	−42.3	−5.65	1.4	–
D5	Narsana	–	3400	751	−35.9	−4.75	5.2	–
D6	Jalore	21	1080	121	−12.5	–	12.0	–
D7	Elana	15	5300	1475	−35.7	−5.25	6.4	–
D8	Jeevana	–	4400	1028	−34.0	−4.25	2.4	–
D9	Harmu	12	2910	362	−46.1	−6.95	1.4	–
D10	Surana	–	1230	149	−39.9	−5.98	17.5	–
D11	Bhadri	–	4000	879	−41.4	−6.70	4.8	–
D12	Nimbawas	41	960	106	−32.5	−4.50	12.1	–
D13	Keshwana	14	3000	624	−30.1	−4.95	11.2	–
D14	Bhadrajun	12	1230	149	−27.5	−3.70	19.5	–
D15	Valera	43	–	–	−53.2	−7.10	–	–
D16	Sayla	15	–	–	−55.4	−7.30	–	–
D17	Posana	–	–	–	−50.4	−7.00	–	–
D18	Ahore	27	1380	199	−42.5	−5.95	2.0	–

Figure 3 shows the plot of δ^2H versus depth of samples from the study area. It could be seen from the plot that the three different aquifers have different isotope signatures. The groundwater in the aquifer situated at about 300 m depth is enriched in stable isotope content compared to that of groundwater occurring at the intermediate depth of about 150–200 m below ground level. In the intermediate aquifer, the groundwater is isotopically most depleted. Most of the samples are brackish. Shallow aquifer shows samples of variable isotope composition with measurable tritium.

Figure 4 shows δ^2H versus δ^{18}O plot of samples from the study area. It could be observed that most of the groundwater samples are depleted in δ^2H and δ^{18}O compared to the 1983 rain events in this area. The samples fall into three distinct categories.

Shallow groundwaters along the river course are isotopically enriched and fall in group C in Figure 4. These samples have higher tritium concentration ranging from 5 TU to 20 TU. These samples fall on a lower slope exhibiting a typical evaporation effect. Shallow groundwater away from the river course and located in the western and southwestern portions of the study area have comparatively depleted stable isotope composition. They fall in group B. Tritium content of these samples ranges from 1.4 TU to 4.8 TU. Some of the shallow wells show depleted stable isotope composition similar to the one exhibited by groundwater in the intermediate aquifer. These samples fall in group A.

In general shallow groundwaters along the river course have enriched stable isotope composition and high tritium. Shallow groundwaters located on the western and southwestern side of the river course and probably along the fault zone have comparatively depleted stable isotope composition and low tritium.

The depleted brackish groundwater (T2, T6, T7) having negligible tritium and occurring at an intermediate depth falls in group A in Figure 4. This aquifer does not appear to be replenished by any recent recharge.

The wells T1, T3 in the deep aquifer and T8 fall in group B in Figure 4. The well T8 taps intermediate aquifer as well as shallow aquifer. This sample shows tritium content of 3 TU and ^{14}C content of 71 pMC (uncorrected age ~ 2800 BP). Samples T1, T3 and T8 are fresh in quality. The stable isotope contents of shallow as well as deep wells (D1, D3 and T1, T3) are similar indicating interconnection between them. Also the deeper aquifer has piezometric surface at an elevation of the shallow water table.

The samples T4 and T5 fall in group C in Figure 4 and are located in the southwestern corner of the area. The well T4 at Jodhawas is of artesian flowing type and the sample has ^{14}C content of 12 pMC (uncorrected age ~ 17500 BP).

It is concluded from the isotope geochemical studies that the shallow aquifer receives recharge by infiltration through river channels during episodic floods caused by sporadic rain events. Some portions of this shallow aquifer also receive recharge from deeper confined aquifers due to upward leakage of groundwater through subsurface fault zones in the area. The deeper (~ 300 m) aquifer was replenished during the cool, pluvial period in early Holocene. The intermediate aquifer (150–200 m) was recharged during the cooler, humid period in the

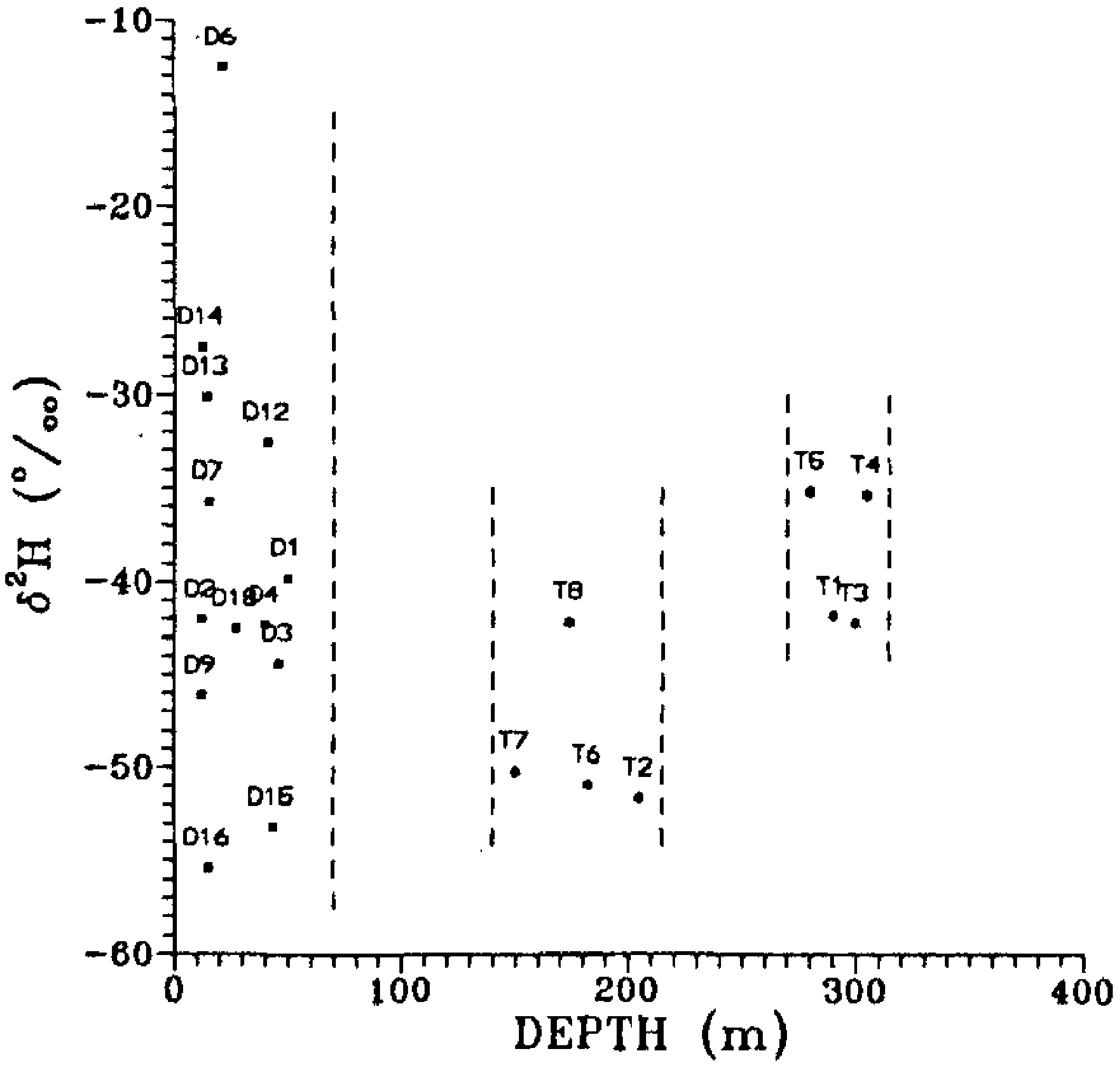

Figure 3. δ^2H vs depth (Jalore samples).

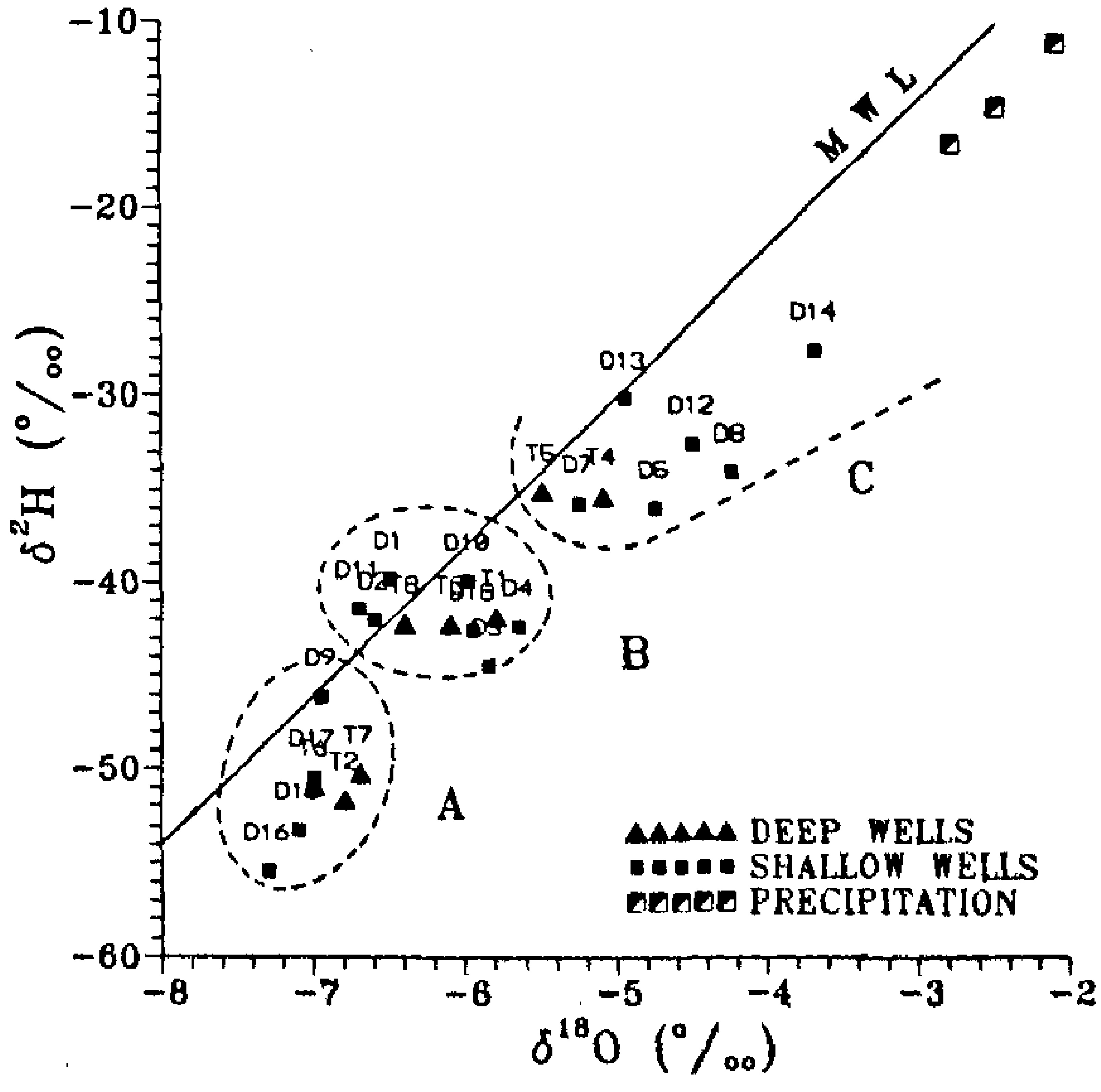

Figure 4. δ^2H vs δ^{18}O (Jalore samples).

mid Holocene. These deeper aquifers do not appear to receive any modern recharge.

Barmer district

An environmental isotope study was undertaken to study groundwater recharge processes in Bhadka–Bheemda area in Barmer district[4]. The study area is arid and receives a mean annual rainfall of 280 mm. A thin veneer of wind blown sand is present over the area. The Tertiary (Eocene) aquifer comprising loosely consolidated to consolidated arenaceous sediment with intercalations of gravel, argillaceous sediment, lignite, etc. and having generally freshwater was of particular interest. Figure 5 shows the sample locations and the geology of the study area. Lathi sandstone of Jurassic age is present on the northern side and Precambrian–Lower Palaeozoic Malani suite of igneous rocks are present on the eastern, southern and western sides. The latter are mainly rhyolites and granites. Two lenticular outcrops of the Tertiary sandstone in the central zone are found to be dry.

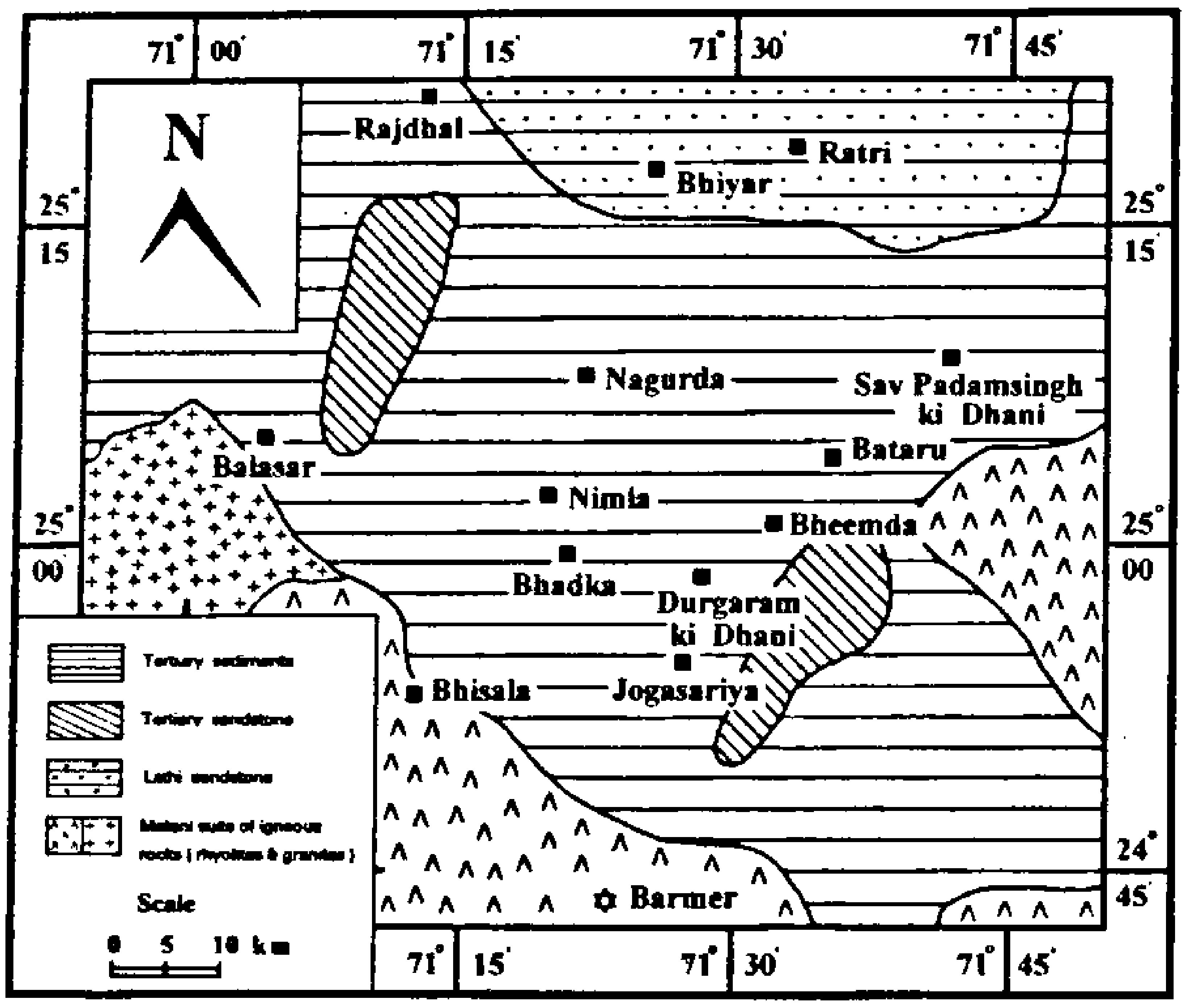

Figure 5. Barmer study area – sample locations.

In the central portion of the area, Nagurda–Nimla–Bheemda, fresh groundwater forms a basin leaving a narrow valley on the eastern and western sides. Shallow aquifers are under phreatic conditions whereas deeper ones change from semi-confined to confined conditions.

Shallow well sample from Balasar is fresh (EC = 630 μS/cm) and is of Ca–HCO_3 type. Other shallow groundwater samples are brackish and of Na–Cl type. The deep fresh groundwater is of Na–HCO_3 type and the deep brackish groundwater is of Na–Cl type. Table 2 lists the isotope and other relevant data of the Bhadka–Bheemda area.

Figure 6 shows δ^2H versus $\delta^{18}O$ plot of samples from the study area. The samples falling in the group A in the plot represent fresh deep groundwater (except the one at Bhadka which is brackish) and most of these are in the groundwater basin in the central portion of the area (except Rajdhal which is situated on the northern side in the dunal area).

The deep and shallow groundwaters from Durgaram ki Dhani and Bataru as well as other shallow samples fall in group B in Figure 6. This group has also the samples from the aquifer in the Lathi sandstone. All these samples show evaporation effect on the stable isotope content. EC also increases along the flow direction in the shallow aquifers. The samples in the group have measurable tritium indicating some component of recent recharge. Higher EC in the shallow aquifer

Table 2. Isotope and other relevant data of groundwater samples from Barmer district, Rajasthan

Sample identity	Place	Depth of well (m)	Electrical conductivity (μS/cm)	δ^2H (‰)	$\delta^{18}O$ (‰)	^3H (TU)	^{14}C (pMC)	^{14}C Model age (BP)
Deep wells								
2	Bheemda	280	1830	−50.1	−7.30	0.0	22	7400
3	Jogasariya	285	2450	−51.7	−7.70	1.4	25	5500
4	Bhadka	200	4500	−51.5	−7.47	0.7	–	–
5	Nimla	220	1560	−56.1	−7.98	1.0	50	2400
6	Durgaram ki Dhani	100	3850	−43.2	−6.00	0.9	–	–
7	Rajdhal	125	1380	−53.4	−8.10	1.7	–	–
9	Bhiyar	100	3000	−36.3	−5.20	4.5	–	–
10	Ratri	100	1820	−35.9	−5.19	–	–	–
11	Nagurda	95	1710	−53.4	−8.00	–	–	–
Shallow wells								
D1	Bheemda	–	6700	−40.8	−5.60	6.0	–	–
D2	Bataru	–	5600	−34.1	−4.45	3.0	–	–
D3	Durgaram ki Dhani	–	4450	−45.1	−6.48	3.0	–	–
D4	Balasar	–	630	−20.3	−4.19	21.0	–	–
D5	Sav Padamsingh ki Dhani	70	3200	−38.9	−5.03	2.9	–	–
D6	Bhisala	40	4400	−26.9	−3.95	–	–	–

is probably the manifestation of the leaching of salts from soils and aeolian sand by water during return flow of irrigation as well as concentration due to evaporation. The samples, shallow as well as deep, from Durgaram ki Dhani and Bataru are a mixture of deep and shallow groundwaters. A shallow sample from Balasar is fresh and contains high (21 TU) tritium. This well probably taps groundwater from weathered igneous rocks. This sample represents water which is about three decades old.

The deeper fresh groundwater is depleted in stable isotopes and has negligible tritium. The model ^{14}C ages[5] for these samples range from 2400 to 7400 BP. This deeper aquifer appears recharged during the cooler, pluvial phase in the Holocene. No modern recharge is discernible. However, if the outcrop of Malani suite of igneous rocks is a probable recharge zone, the groundwater velocity is 6 to 10 m/a.

Indira Gandhi Nahar Pariyojana (IGNP)

The IGNP is a large irrigation and drinking water project to cater to five districts in the western Rajasthan. The Stage I of the canal is in existence for the last 15 years. The canal project is facing twin problems of waterlogging and development of secondary salinity in soils and groundwater in some areas.

The possible causes of waterlogging are: (i) Poor irrigation practices and irrigation return flow, (ii) Non-exploitation of groundwater due to poor quality, (iii) Presence of hydrological barriers at various depths which affect the process of infiltration, (iv) Seepage losses from the canal and its branches.

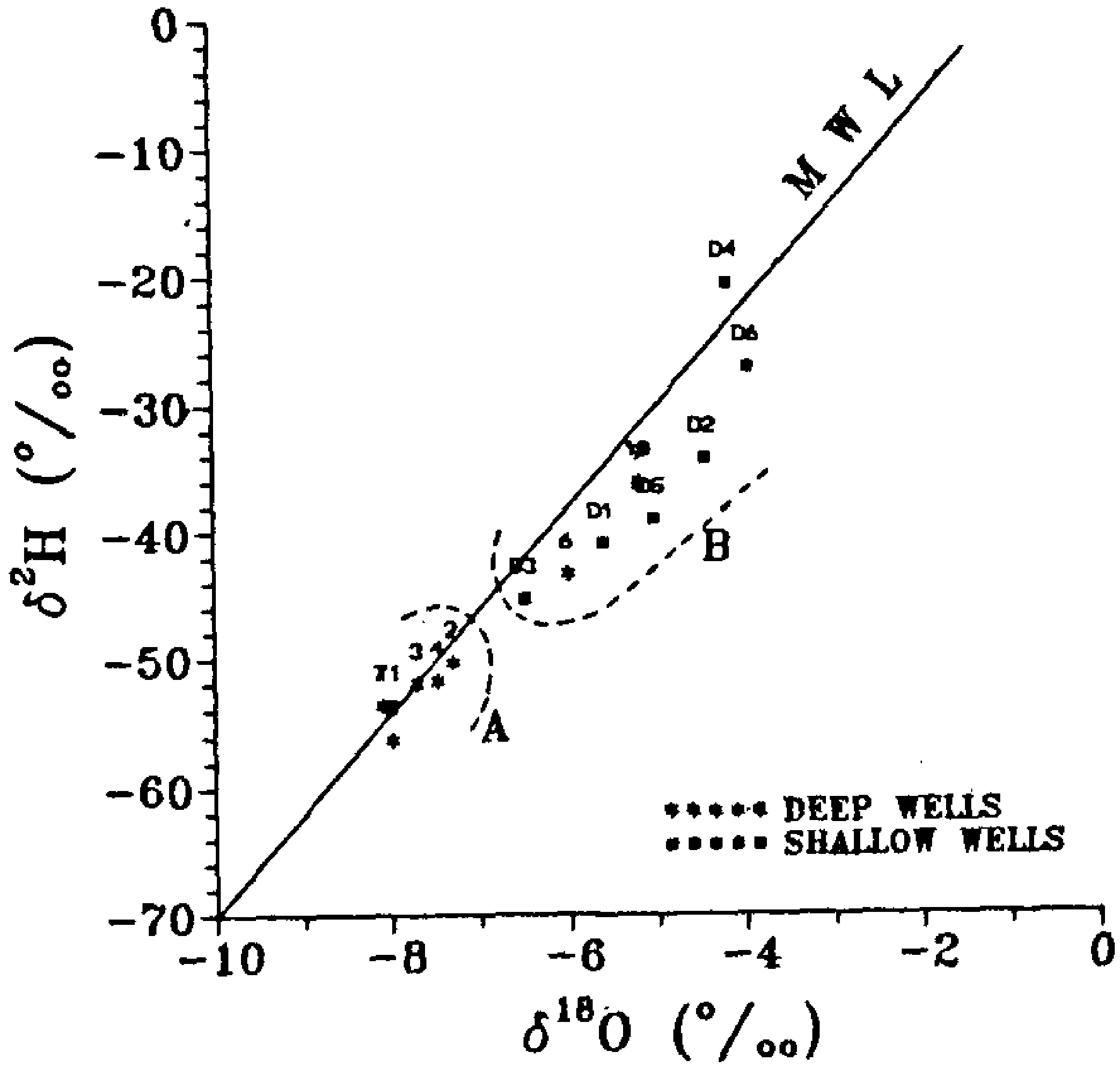

Figure 6. δ^2H vs δ^{18}O (Barmer samples).

Isotope investigation has been initiated in Suratgarh area (Figure 1) in collaboration with the Groundwater Department, Rajasthan to study the contribution to groundwater from canal seepage and irrigation return flow as well as interconnections between shallow and deep aquifers.

Figure 7 shows δ^2H versus δ^{18}O plot of samples collected in the ongoing study. The preliminary observations indicate that the canal water originating from the higher altitudes in the north is depleted in stable isotope composition compared to local precipitation and groundwater. These samples fall in group A. Groundwater samples influenced by seepages from the canal fall in group B. These samples fall on a regression line with equation, $\delta^2\mathrm{H} = 8.2\delta^{18}\mathrm{O} + 17.3$ ($r = 0.975$; $n = 12$). Piezometer samples affected by irrigation return flow, waterlogging and saline groundwaters fall in the group C showing evaporation effect.

Tritium level of canal water (~ 12 TU) is slightly higher than that of the precipitation (~ 9 TU). Native saline groundwaters show negligible tritium.

The canal seepage to groundwater consists of two end points; canal water and pure groundwater and the admixture. If the stable isotope compositions of the end points and those of the admixtures are known, it is possible to calculate the percentage contribution of canal water to the admixture. It is estimated that the contribution is about from 3 to 5% for a period of 15 years or so.

Lost courses of Saraswati River

The legendary 'Saraswati' river has been described as a mighty Himalayan river in the ancient Indian literature,

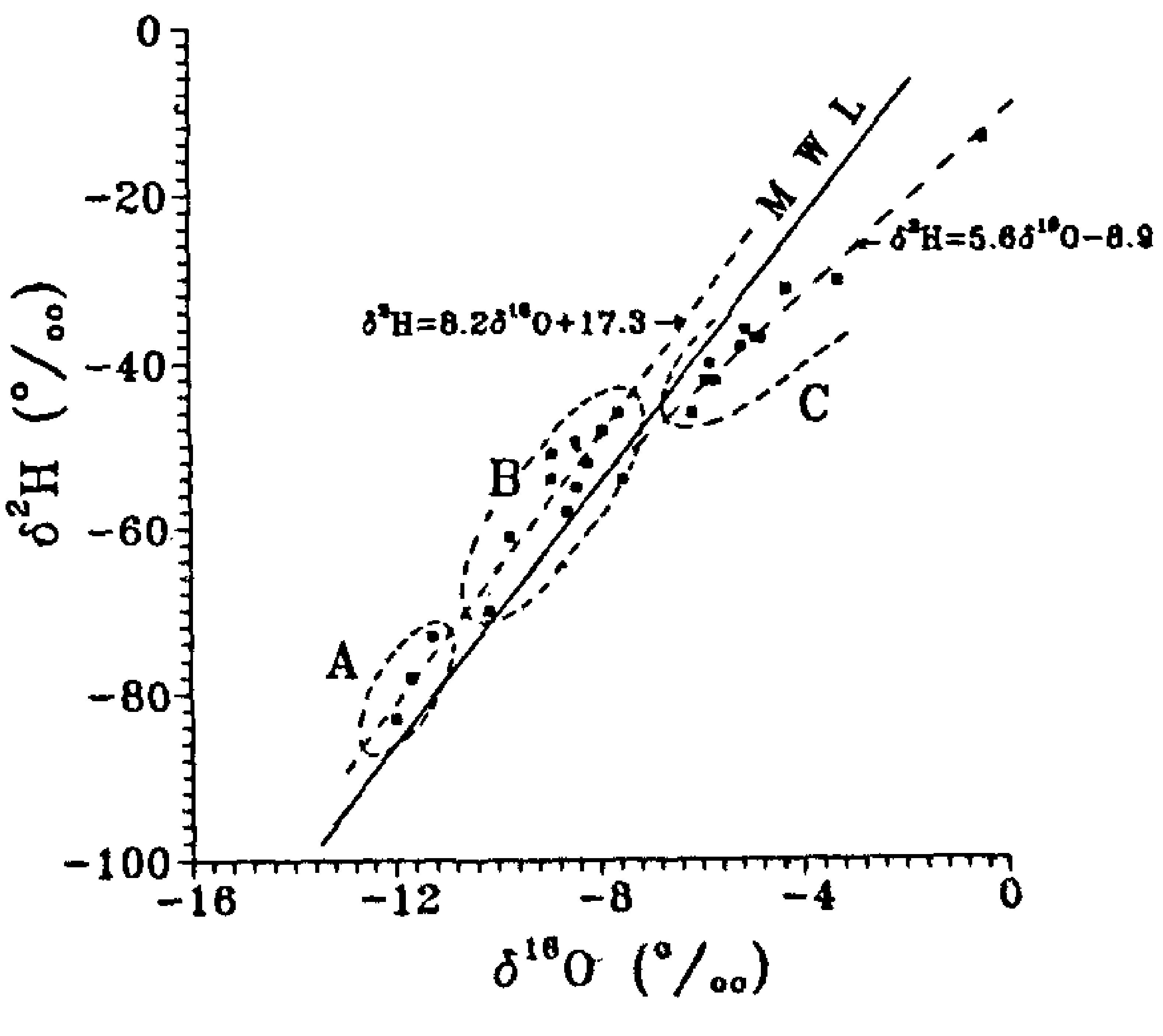

Figure 7. δ^2H vs δ^{18}O (IGNP samples).

e.g. *Rigveda*[6]. Thereafter, there have been many references to the Saraswati river and its disappearance. Early literature indicates the existence of the river before 3000 BP. Most of this literature was, however, aimed at studying the relics of the once great Indus Valley Culture in the region. Many attempts have been made to explore the former courses of the Saraswati river in the last and this century. Allchin *et al.*[7] have summarized these findings in the following way:

> 'Evidence from many sources, including that of archaeological remains associated with older river courses, indicates that a major river, stemming mainly from the same sources as the present Sutlej, flowed through Northern Rajasthan, Bahawalpur and Sind – to the southeast of the present course of the Sutlej and the Indus – in the third to second millennium BC. This river known as Saraswati in its upper course, at different times either joined the lower course of the Indus in Sind, or found its way independently into the Arabian sea via Rann of Kutch' (p. 198).

The river is supposed to have changed its course several times in the westward direction. Recently, interpretation of LANDSAT imagery of the western part of Jaisalmer district revealed buried courses of the river running from NE to SW[8,9]. This course is found to have links with the dry bed of Ghaggar river in the northeast (Ganganagar district) while in the southwest it met with or even cut across the surviving courses of the Hakra and Nara rivers in Pakistan.

In northwestern part of Jaisalmer district, in spite of very low rainfall (less than 150 mm) and extreme conditions of the desert, groundwater is available at depth of about 50–60 m along the course of the defunct river and a few dug wells do not dry up throughout the year. It is found that the area through which the river bed is traced supports vegetation even during summer. It is thought that these courses of river in the area still maintain their head water connection and could form potential groundwater sanctuaries for exploitation.

To confirm the scenario, an environmental isotope study was undertaken in collaboration with the Groundwater Department, Rajasthan in the Jaisalmer district. A set of samples collected in 1995 was analysed for isotopes δ^2H, δ^{18}O, δ^{13}C ^{3}H and ^{14}C. The preliminary observations are mentioned below.

The groundwater in the area is enriched in stable isotope content (δ^{18}O: -6 to -2‰) compared to that of Himalayan rivers (δ^{18}O: -11 to -10‰). The groundwater samples exhibit negligible tritium content indicating absence of modern recharge. Radiocarbon data suggest the groundwater is a few thousand years old. The ^{14}C levels decrease along the suspected river course downstream (58.8 pMC to 54.9 pMC) indicating hydraulic continuity of the Saraswati buried channel from Kuria Beri to Ghantiyalji. A groundwater velocity of about 20 m/a is estimated from ^{14}C data. Further work is in progress.

Concluding discussion

Deserts occupy waste regions mainly in the latitude belts between 15° and 30°. The Sahara desert in the Northern Africa, the largest in the world has a surface area of about 9 million km^2. Other large deserts are those of Arabian Peninsula and Iran (which might be considered a continuation of the Sahara), the Turkesthan desert, the Thar desert in India, the Gobi desert in Mongolia, the Great American desert and in southern hemisphere the Kalahari desert in South Africa, the Great Australian desert and Atacama desert in Northern Chile. The last, though relatively small in size, is the driest – no precipitation has been recorded over most of it for more than one century.

Western Rajasthan, which forms part of the Thar desert, has all the attributes of an arid zone – aeolian topography concealing geological features and formations, scarce and erratic rainfall and large evapotranspiration. Evidence from archaeological sites, radiocarbon and thermoluminescence dating of quartz sediment and pot shreds show that the dunes were accumulating from at least 20000 BP and were stable by the middle to late Holocene. The continuation of dune construction into the Holocene distinguishes the Thar from other mid-latitude dunefields[10].

The stabilization of dunes in Africa and Australia, and probably Arabia, broadly coincides with the global warming that post-dated the Last Glacial Maximum (LGM)[11,12]. The monsoon circulation ceased to exist during LGM[13]. It is most likely that the monsoon circulation re-established during the global warming that began around 14000 BP (ref. 11). This warming peaked in the period 8000–6000 BP, along with a general water surplus which, in many places, has been interpreted as the result of increased rainfall[14].

The history of lacustrine sedimentation in the Thar shows that hypersaline conditions prevailed at about the LGM and violent fluctuations of water level occurred between this maximum of aridity and the onset of freshwater conditions about 6000 BP. Freshwater, high lake level conditions prevailed until about 4000 BP when sediments rather like those of today began to be deposited[10].

Singh *et al.*[15] carried out a pollen analytical study of lakes, providing a Holocene record of vegetation changes in the northern Thar. They were able to propose a series of climatic changes:

Phase 6	1100–0 BP	Conditions same as today (ephemeral playas with very thin halite crust)
Phase 5	3000–1100 BP	Drying of lakes and lack of pollen
Phase 4	5000–3000 BP	Wettest period – lacustrine conditions and swamp vegetation, increased rainfall
Phases 2 and 3	10000–6000 BP	Wet period – lacustrine conditions with rainfall greater than at present
Phase 1	Beyond 10000 BP	Active dune development

Isotope hydrological studies carried out in western Rajasthan essentially echo the climatic changes mentioned above, especially phases 2, 3 and 4. The replenishment of groundwater resources took place in the early to mid Holocene in the Thar desert. The depleted stable isotopic composition and low radiocarbon content of groundwaters in deeper aquifers suggest cool, pluvial phase(s) in the Holocene responsible for the replenishment. Moreover, comparison of isotopic composition (δ^2H and δ^{18}O) and radiocarbon content of groundwaters from Jalore and Barmer areas indicates that the climatic conditions in the Thar desert changed from cool, pluvial in early Holocene to cooler, pluvial in the mid-Holocene. However, more comprehensive isotope hydrological data will shed more light on the climatic aspects of the Thar desert.

It is true that groundwater is relatively abundant under most of the deserts, but is seldom easily accessible. Also practical implementation of rational exploitation of groundwater and agricultural development of desert is rather problematic. In most of the deserts, including the Thar desert, the need for an accurate assessment of whether a small quantity of rainfall recharge is occurring appears rather academic when the withdrawal from an aquifer clearly surpasses the present day maximum possibilities of infiltration through catchment area. The heavy withdrawal of groundwater will not only pose the problems of accessibility but also of the stability of the ground due to pressure decrease as well. The conjunctive use of precious groundwater resources with improved irrigation practices will help arrest the secondary soil and groundwater salinization.

Isotope techniques are an important tool in arid-zone hydrology. When applied effectively with multi-disciplinary approach, one can evaluate groundwater recharge, investigate recharge processes, understand the dynamics of groundwater, study mechanism of salinization and related problems among others. The information will also help in planning the development of groundwater resources through artificial recharge of aquifers. From the foregoing, it is clear that isotope techniques should form an integral part of any hydrogeological investigation undertaken for the development of groundwater resources, particularly in the arid zones.

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