
Characterisation of recharge processes and groundwater flow mechanisms in weathered-fractured granites of Hyderabad (India) using isotopes

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Abstract In order to address the problem of realistic assessment of groundwater potential and its sustainability, it is vital to study the recharge processes and mechanism of groundwater flow in fractured hard rocks, where inhomogeneities and discontinuities have a dominant role to play. Wide variations in chloride, $\delta^{18}\text{O}$ and ^{14}C concentrations of the studied groundwaters observed in space and time could only reflect the heterogeneous hydrogeological setting in the fractured granites of Hyderabad (India). This paper, based on the observed isotopic and environmental chloride variations of the groundwater system, puts forth two broad types of groundwaters involving various recharge processes and flow mechanisms in the studied granitic hard rock aquifers. Relatively high ^{14}C ages (1300 to \sim 6000 yr B.P.), $\delta^{18}\text{O}$ content (-3.2 to -1.5‰) and chloride concentration (<100 mg/l) are the signatures that identified one broad set of groundwaters resulting from recharge through weathered zone and subsequent movement through extensive sheet joints. The second set of groundwaters possessed an age range Modern to \sim 1000 yr B.P., chloride in the range 100 to \sim 350 mg/l and $\delta^{18}\text{O}$ from -3.2 to $+1.7\text{‰}$. The $\delta^{18}\text{O}$ enrichment and chloride concentration, further helped in the segregation of the second set of groundwaters into three sub-sets characterized by different recharge processes and sources. Based on these processes and mechanisms, a conceptual hydrogeologic model has evolved suggesting that the fracture network is connected either to a distant recharge source or to a surface reservoir (evaporating water bodies) apart from overlying weathered zone, explaining various resultant groundwaters having varying ^{14}C ages, chloride and $\delta^{18}\text{O}$ concentrations. The surface reservoir contribu-

tion to groundwater is evaluated to be significant (40 to 70%) in one subset of groundwaters. The conceptual hydrogeologic model, thus evolved, can aid in understanding the mechanism of groundwater flow as well as migration of contaminants to deep groundwater in other fractured granitic areas.

Résumé Afin d'évaluer d'une manière réaliste le potentiel et l'exploitation durable des eaux souterraines il est vital d'étudier la recharge et le mécanisme d'écoulement dans des massifs rocheux où les hétérogénéités et les discontinuités sont essentielles. Les grandes variations dans l'espace et le temps de la concentration en chlorures ainsi que de la teneur en les isotopes de ^{18}O et ^{14}C observées dans les granites fracturés de la région de Hyderabad de l'Inde peuvent être expliquées seulement par la grande hétérogénéité des conditions géologiques. À partir de la distribution des isotopes et des chlorures cet article présente les deux types d'eaux souterraines qui impliquent des processus de recharge et des mécanismes d'écoulement différentes dans le massif granitique étudiés. Un premier système des eaux souterraines a été différencié par les ages assez élevés d'après le ^{14}C (de 1300 à 6000 ans), la teneur en $\delta^{18}\text{O}$ (-3.2 à -1.5‰) et la concentration en chlorures (<100 mg/l). Ce système est caractérisé par la recharge dans la zone désagrégation et par l'écoulement dans un système bien développé des fractures planes. Le deuxième système est caractérisé par des ages d'approximativement de 1000 ans d'après le ^{14}C , une concentration en chlorures de 100 à 350 mg/l et par une teneur en $\delta^{18}\text{O}$ de -3.2 à $+1.7\text{‰}$. L'enrichissement en ^{18}O et en chlorures a permis en plus de différencier trois sous-systèmes dans le second système, caractérisés par de processus de recharge et des sources différentes. Basé sur ces processus et mécanismes on a mis à point un modèle conceptuel hydrogéologique qui suggère que le système de fractures soit en contact, outre la zone altérée de la couverture, soit à une source éloignée de recharge, soit à source de surface (un corps d'eau évaporable). Ces sources différentes peuvent bien expliquer la présence des eaux souterraines différenciées par leurs ages en ^{14}C ainsi que par leurs concentrations en chlorures et en ^{18}O . Pour la recharge d'un des sous-systèmes des eaux souterraines on a estimé une contribution importante, de 40 à 70% du réservoir de surface. Le modèle conceptuel hydrogéologique permet de mieux comprendre

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le mécanisme d'écoulement ainsi que le transfert de polluants dans les eaux souterraines profondes, cantonnées dans les massifs granitiques fracturés.

Resumen Con el fin de abordar el problema de hacer una evaluación representativa del potencial de aguas subterráneas y de su sostenibilidad, en el caso de rocas duras fracturadas, donde las inhomogeneidades y discontinuidades juegan un papel dominante, es vital estudiar los procesos de recarga y los mecanismos del flujo de agua subterránea. Las variaciones amplias que se observaron, tanto en el espacio como en el tiempo, para las aguas estudiadas, en las concentraciones de cloruros, $\delta^{18}\text{O}$ y ^{14}C podrían reflejar únicamente la heterogeneidad en el marco hidrogeológico de los granitos fracturados de Hyderabad (India). Con base en las variaciones observadas, tanto para los cloruros ambientales como para los isótopos en el sistema de aguas subterráneas, el presente artículo propone dos tipos generales de agua subterránea, incluyendo varios procesos de recarga y mecanismos de flujo en los acuíferos graníticos estudiados. Las edades relativamente altas de ^{14}C (1300–6000 años A.P.), el contenido de $\delta^{18}\text{O}$ (-3.2 a -1.5%) y la concentración de cloruros (<100 mg/l), son los distintivos que identifican a una amplia gama de aguas subterráneas, provenientes de la recarga a través de la zona meteorizada y de su posterior movimiento a través de las extensas diaclasas laminadas. Un segundo grupo de aguas subterráneas, tiene un rango de edad entre moderno hasta 1000 años A.P., un contenido de cloruros entre 100 y 350 mg/l y un $\delta^{18}\text{O}$ entre -3.2 hasta $+1.7\%$. El enriquecimiento en $\delta^{18}\text{O}$ y en el contenido de cloruros sirvió además para subdividir a este segundo grupo de aguas subterráneas, en tres subgrupos caracterizados por diferentes fuentes y procesos de recarga. Con base en estos procesos y mecanismos, fue desarrollado un modelo hidrogeológico conceptual, el cual sugiere que la red de fracturas está conectada bien a una fuente de recarga distante o bien a un embalse superficial (cuerpos de agua sometidos a evaporación), diferente a la zona meteorizada sobrepuesta, explicando así varias aguas subterráneas que resultaron poseer unas edades variables por ^{14}C , lo mismo que las concentraciones de cloruros y $\delta^{18}\text{O}$. La contribución del embalse superficial al agua subterránea, fue determinada como significativa para un subgrupo de aguas subterráneas (entre 40 al 70%). El modelo hidrogeológico conceptual así desarrollado, puede ayudar a entender el mecanismo del flujo del agua subterránea, así como la migración de contaminantes hacia las aguas subterráneas profundas en otras áreas graníticas fracturadas.

Keywords Fractured rocks · Groundwater recharge processes · Groundwater flow mechanism · Radiocarbon · Stable isotopes · Conceptual model

Introduction

Fractured rocks pose a great challenge to the earth scientists (hydrogeologists, geophysicists, geochemists) as well as to engineers and environmentalists. They play an important

role in the groundwater flow, sustainability of groundwater, transport of pollutants, siting of successful bore holes and wells, geothermal resources, etc. This challenge emerges from the heterogeneities and discontinuities in fractured rocks, as the flow and transport processes within discontinuities are complex in comparison to those in porous media. There exists a great contrast between the hydraulic conductivity of the fractures and that of the matrix, and the permeability of some fracture zones may be higher by orders of magnitude than that of matrix. Flow through fractures and transport of contaminants could be very significant, especially when the fractures serve as preferential flow paths.

During the last three decades, a great effort employing multi-disciplinary scientific tools has helped in addressing the problems associated with the fractured rock aquifers (Faybishenko et al. 2000). One of the important approaches has been to use isotopic and geochemical methods (Scanlon et al. 2002; de Vries and Simmers 2002). Isotopic methods have proved valuable in elucidating the recharge processes and flow mechanisms in fractured hard rocks. Within the framework of the unsaturated zone, quantification of recharge through the matrix and that through the fractures is vital for making a realistic assessment of groundwater recharge through precipitation and secondary sources (Allison and Hughes 1978; Verhagen et al. 1979; Sukhija et al. 1996; Wood et al. 1997; Rangarajan and Athavale 2000). Of late, it has been observed that groundwater flow through macro pores in the unsaturated zone is significant (Nativ et al. 1995; Davidson et al. 1998; Sukhija et al. 2000, 2003). The preferential flow through the macro-pores is even observed in alluvial tracts (Dahan et al. 2000), notwithstanding the bulk of transport taking place through the micro-pores, thus showing the piston flow model to be valid (Jury and Wang 2000).

The purpose of this paper is to study the recharge processes and flow dynamics involving weathered and fractured zones using environmental isotopes and geochemical tracer (chloride) in the hard rock region of Hyderabad (India). The research work was carried out mainly around Hyderabad (India) urban conglomerate and its suburbs (Ranga Reddy District). The role of recharge processes and also the combined effect on the quality of groundwater and the flow mechanism involved is inferred. The isotopic and chloride data demonstrate that the groundwater flow can be very complex in the hard rock type systems. Using radiocarbon ages, $\delta^{18}\text{O}$ and chloride concentration of groundwater samples, a conceptual hydrogeologic model has evolved to address complex flow dynamics and recharge processes of groundwater in the studied fractured rock aquifers in granites. Such a model is compared with other known models (Cook et al. 1996).

The study area

The study area mainly comprises Hyderabad and its suburbs, the Ranga Reddy district, Andhra Pradesh state, India (Fig. 1). The region is underlain by a Precambrian granite-gneissic complex with dolerite intrusives and many

outcrops; undulating topography characterizes the area. The granite gneissic complex occurs in two colors, gray and pink. Pink granites are coarse grained and younger than gray granites. The contact zone between these two rock types is favorable for weathering, creating potential zones for groundwater development.

As there is no primary porosity in these rocks, water-holding capacity and water-yielding capacity of the rocks depend on secondary porosity developed due to weathering, fracturing, joints, etc. The thickness of the weathered zone is minimum (0.5–2.0 m) near the outcrops and hill slopes, and maximum (10–15 m) in topographical lows and valleys. The area has a large number of shallow lakes (surface reservoirs), though urbanization has encroached upon many of them, replacing them with huge masonry structures. Apart from a few reservoirs being used for domestic water supply, like Himayat Sagar and Osman Sagar (not shown in Fig. 1) in the west of Hyderabad, many other big and small reservoirs such as Hussain Sagar, Miralam Cheruvu, etc. (Fig. 1) are evaporating water bodies. The average annual rainfall in the studied area is 750 mm and the climate is semi-arid with recorded maximum and minimum temperatures of 44 and 10°C respectively.

In the study area, groundwater occurs under phreatic conditions in shallow weathered zones and under semi-confined and confined conditions in the fractured and sheared zones at deeper levels. However, it is very difficult to separate the different aquifers on a regional scale because the system is very heterogeneous. Natural recharge measurements carried out in the hard rock areas of India using

tracers estimated the groundwater recharge to be 7–8% of precipitation considering only the piston flow component of recharge (Sukhija et al. 1996). However, it is estimated that a substantial quantity of recharge takes place through preferred pathways (Sukhija et al. 2000, 2003) in the unsaturated zone. At present, except for some low-lying areas, groundwater occurs at a depth of 20–30 m below ground level, while the top weathered zone is practically dry. Therefore, the present groundwater exploitation is from fracture zones occurring between 50–150 m depths. This scenario has emerged because of over-exploitation of groundwater necessitated by extensive and intensive domestic and industrial usage.

Methods

The environmental tracers methods were utilized to characterize the movement of deep groundwater in fractured rock aquifer through determination of radiocarbon ages, $\delta^{18}\text{O}$ and chloride concentration in groundwater. Isotopes and geochemical tracers have been extensively utilized to identify the source and movement of groundwater (Vogel 1970; Geyh and Backhaus 1979; Sukhija et al. 1996; Dahan et al. 2000).

^{14}C Isotope

Radioactive isotope of carbon ($^{14}\text{C}_6$), produced in the upper atmosphere due to cosmic ray interaction with

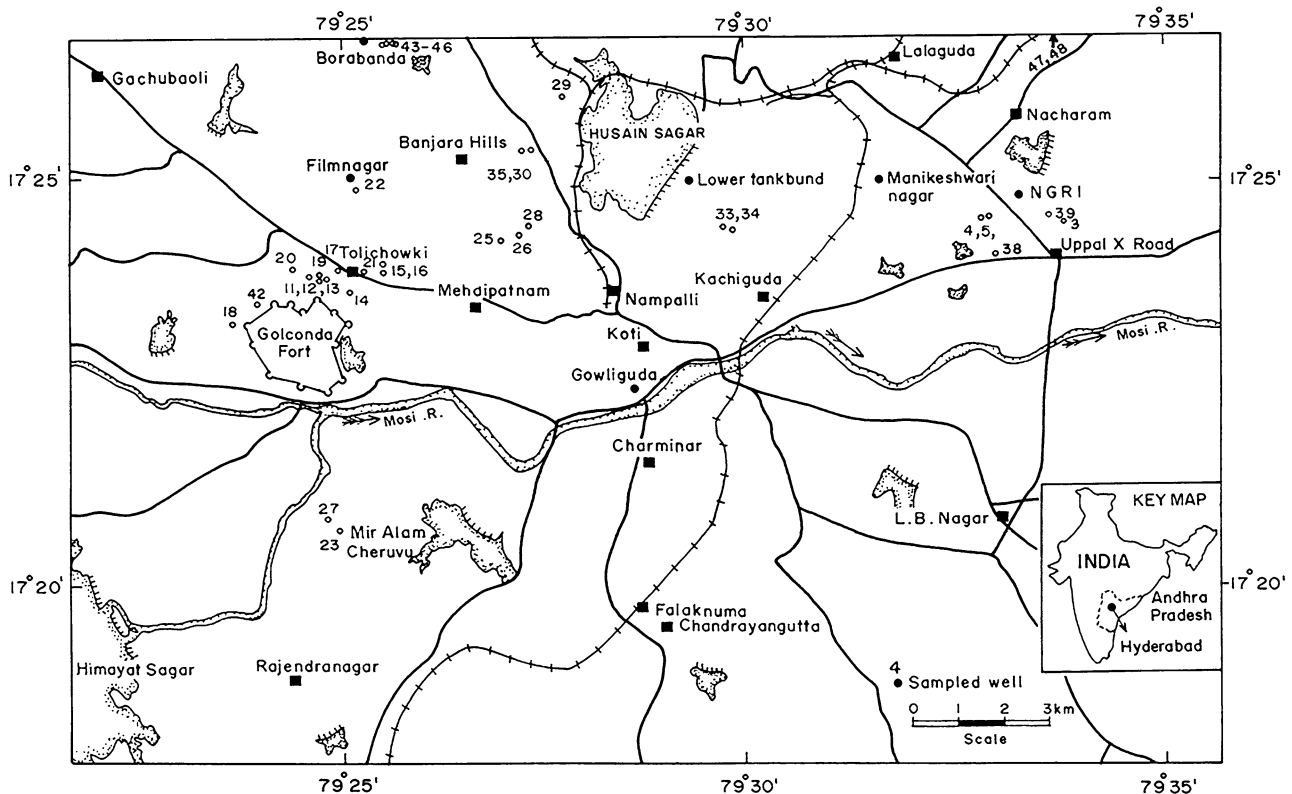


Fig. 1 Location map of deep groundwater sampled wells in and around Hyderabad City, Andhra Pradesh (India)

atmospheric nitrogen, gets oxidized to CO_2 and mixes with the atmospheric CO_2 reservoir, then assimilated by plants for photosynthesis, released in the subsoil through root respiration, and reacts with soil moisture and soil calcium forming CaCO_3 and $\text{Ca}(\text{HCO}_3)_2$. For groundwater age determinations ^{14}C is selected due to availability of its measuring facility with us. The ^{14}C dating of groundwater can extend up to 45,000 years before present with respect to 1950 (45 Ky B.P.). Dissolved inorganic carbon species from the collected groundwater samples were obtained in the form of precipitates, using $\text{Ba}(\text{OH})_2$ and BaCl_2 . Carbon dioxide evolved through acidification of the precipitates was converted to methane, which was used for radiocarbon measurements.

The groundwater ages were determined using the radiocarbon activity of groundwater samples. The age calculations are based on radiocarbon half-life 5,730 yr and using 100 PMC (percent modern carbon) as initial ^{14}C activity. No attempt was made to correct ^{14}C age using $\delta^{13}\text{C}$, because there is no dead carbon source in the form of CO_3 or HCO_3 in the weathered or solid granite. This argument is further supported from the radiocarbon measurements of the samples from a number of shallow wells where the ^{14}C ages were found to be modern. Since absolute dates of chronological events of paleo-waters were not used, relative ages can be used for elucidating recharge processes. In addition, the $\delta^{13}\text{C}$ content of most of the measured groundwaters did not vary much (range: -11 to -12‰). The precision for ^{14}C measurements is ± 1.8 PMC (percent modern carbon). The other isotopes viz. ^{36}Cl and ^{41}Ca require accelerator mass spectrometry (AMS) for dating but the age limit starts from 10 Ky onwards. Groundwater ages in association with other isotopic and tracer data enables the investigators to infer its source and flow dynamics.

^{18}O Isotope

The stable isotope (deuterium and oxygen-18) composition of precipitation undergoes variations due to altitude, latitude, amount of rainfall, temperature, etc. The heavy isotope composition of groundwater can be helpful as an indication of the genesis and mixing of groundwater in hydrogeological studies (Gat and Gofiantini 1981). The water molecules with different masses exhibit differing vapour pressure so that during a change of phase viz. evaporation, condensation and sublimation, enrichment of heavier isotopes in the more volatile phase takes place. This process is known as isotope fractionation. The higher temperature and low precipitation during the early rainfalls of the summer monsoon result in the enriched heavy isotope content, and depleted heavy isotope content of heavy rainfall during subsequent months of the summer monsoon.

Soil and subsurface waters inherit the isotopic characteristics of the meteoric and surface water inputs, and change in isotopic composition occurs as a result of recharge process and mixing with waters of different compositions. In semi-arid zones, the water loss by evaporation assumes importance in the sense that heavy isotope content of groundwater gets enriched relative to that of precipitation.

Oxygen-18 (^{18}O) stable isotope is utilized to identify the recharge process and mixing of groundwater from different sources. Surface waters contain a distinct composition of stable isotopes due to enrichment caused by evaporation. Therefore, ^{18}O isotope makes it possible to distinguish between evaporated waters and waters directly recharged from precipitation. Artificial recharge, large-scale irrigation and over exploitation of aquifers alter the isotopic composition of groundwater through admixture of different flow regimes.

$\delta^{18}\text{O}$ was measured on water samples using a mass spectrometer at the Physical Research Laboratory, in Ahmedabad, India, and $\delta^{18}\text{O}$ concentrations (‰) were obtained in comparison to SMOW (Standard Mean Ocean Water). The precision for $\delta^{18}\text{O}$ was $\pm 0.1\text{‰}$. During the study period, rainfall data and $\delta^{18}\text{O}$ content was available only for the year 1998. Nevertheless, the weighted mean values of $\delta^{18}\text{O}$ would represent the typical value for Hyderabad (India) rainfall.

Environmental chloride

Environmental chloride has potential utility in hydrology. It is deposited on land by atmospheric deposition processes (rainfall and dry fallout) and chloride fallout is concentrated near coastlines. The other important sources of chloride in addition to precipitation could be from applied fertilizers, human waste, etc. If the chloride present in the unsaturated zone and groundwaters has surface environment (i.e. sea) as its source, and there exists no other source or sink underground, it is possible to obtain chloride balance. The ratio of chloride concentration in rainwater to that in percolated water is utilized to estimate recharge. In semi-arid regions, combined geochemical and isotopic studies of both unsaturated zones and shallow groundwaters can be effectively undertaken to determine not only the present day direct recharge component, but also a recharge chronology of immediate historic times, which may be important in the estimation of long-term water resources (Edmunds and Walton 1980).

Many researchers have effectively utilized the environmental chloride present in the unsaturated zone and groundwater regimes for natural and artificial recharge estimates, salinity problems, soil water movement studies, etc. Continuous monitoring of the chloride concentration and hydraulic head in space and time can reveal important information about change in groundwater recharge characteristics as a result of deforestation (Williamson et al. 1987).

The chloride concentration of sampled groundwaters and surface waters were measured using an ion-selective electrode. The precision for chloride measurements was $\pm 5\%$.

In all, 34 deep groundwater samples were collected from Hyderabad and its suburbs. Sampling was done covering the maximum possible geomorphic units including elevated grounds, low-lying areas and close to surface reservoirs to observe their influence. Depth of the sampled wells ranged between 20–200 m. However, water-yielding zones are restricted to only limited thickness i.e., sheet joints or fracture

zones. Most of the sampled wells draw water from sheet joints/deep fractures, as there is no water in the phreatic zone. The information about fractures was obtained from the driller's records. Water samples were collected during pumping, and in case of more than one fracture zone it is likely that the water from different fractures was mixed, as no attempt was made to collect water from individual fracture zones.

Results

In order to elucidate recharge processes and groundwater flow mechanism in fractured granitic aquifers, wells were sampled from Hyderabad and the adjoining District of Ranga Reddy.

The highly heterogeneous character of the fractured hard rock aquifers in the study area is evident from the exploratory drilling carried out by the Central Ground Water Board (CGWB) in Hyderabad. The drilling indicated the existence of fracture zones at various depths between 20 and 173 m, and the discharge rate (measured using 90° V-notch) during drilling varied from 0.02 to 6.91 l/s (l/s) (Fig. 2) (Reddy et al. 2002). The fracture depths from the ground level are recorded by the driller using the length of drilling pipe.

As can be seen from Fig. 2, wells from different parts of Hyderabad indicate that the thickness of the weathered zone is meager (0.5–2.0 m) in elevated areas (Borabanda and Film Nagar, Fig. 1), and quite substantial (about 15 m thick) in the low-lying areas along the river/stream (Gowliguda and Lower Tank Bund).

Though Borabanda well passed deeply into basement rock, it encountered two fractures at a depth of 93–95 m and 135–137 m with a discharge of only 0.02 and 0.08 l/s, respectively, during drilling. However, another sheet joint at a depth of 172–173 m provided a discharge of about 7.0 l/s. The Film Nagar well, also in basement rock, encountered a sheet joint at a depth of 127–128 m (Fig. 2) with a discharge rate of 5.5 l/s. Though a thick weathered zone was encountered in the Lower Tank Bund and Gowliguda areas (Fig. 2), the discharge during drilling of wells in these areas was nil. This shows that the weathered zone in most of the study area is presently non-yielding. The above drilling data demonstrate the control of fractures on well yields in the hard rock aquifers of the studied area.

Another very important field observation was the existence of laterally extensive sheet joints. These were encountered in drilling at different depths in granites as revealed in a quarry shown in the photograph (Fig. 3). This figure represents the geologic section obtained from an open rock quarry of about 10 m deep and about 200–300 m long. However, the sheet joints extend laterally much beyond the exposed quarry. The geologic section shows three sets of sheet joints dipping southwards with a gradient of about 5–10°. The thickness of these sheet joints varies from 30–50 cm with 2–3 m thick solid granite below and above. It is expected that once the recharge water enters the sheet joint, it moves horizontally for a considerable distance. In fact, such sheet joints are explored in fractured hard rock areas, which serve commonly as a source for groundwater that occurs under sub-artesian conditions due to the presence of a confining medium. A general hydrogeological perception is that such sheet joints may

Fig. 2 Litho-logs of some typical exploratory wells drilled by Central Ground Water Board in Hyderabad City, indicating different sheet joints and its discharge during drilling

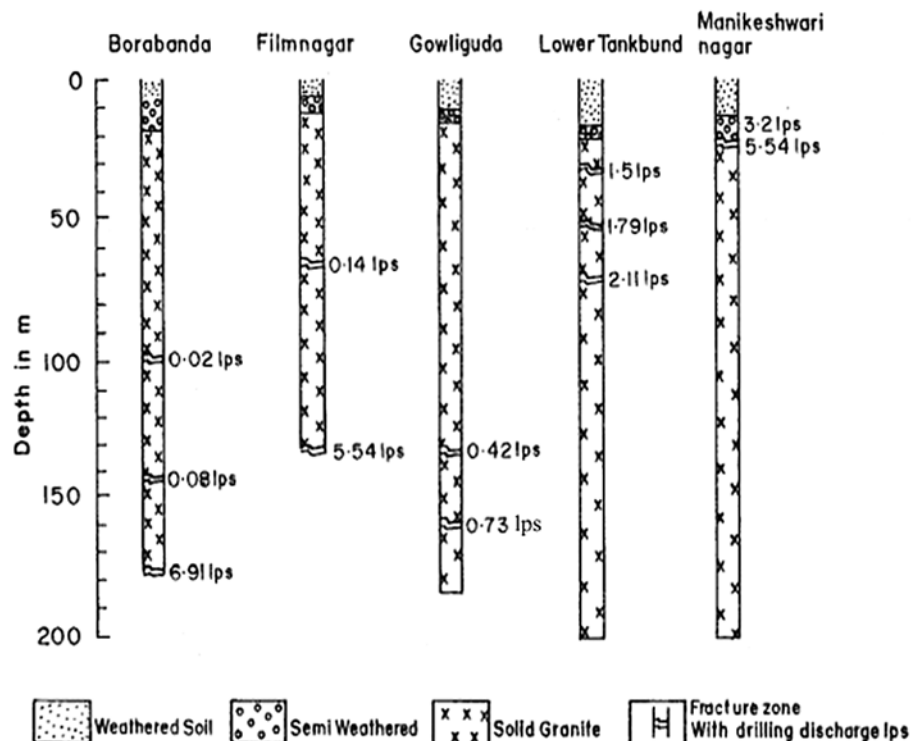




Fig. 3 Photograph shows the sheet joints in the granite basement rock in the exposed quarry near Hyderabad, which act as potential groundwater zones

extend laterally from a few hundred meters (as shown in Fig. 3) to perhaps up to kilometers, though no detailed investigations are available to support this. Some of the drilled wells shown in Fig. 2 may be tapping sheet joints similar to those shown in Fig. 3, yet because of lack of sufficient borehole data, it is difficult to prove their lateral extent. Lateral extent of fractures shown in Fig. 2 cannot be determined from the available bore well data.

Table 1 presents the results of measurements of chloride concentration and $\delta^{18}\text{O}$ of Hyderabad precipitation. The radiocarbon ages, chloride concentration and $\delta^{18}\text{O}$ of groundwater samples with their location and fracture depths are shown in Table 2.

Monthly average chloride concentration of precipitation at Hyderabad and its environs varies from 1–10 mg/l. Generally, a low chloride concentration is associated with heavy precipitation and vice-versa (amount effect). Chloride concentration of collected groundwater samples varies between 20 and 350 mg/l. However, the majority of samples have chloride concentration between 50 and 200 mg/l, several samples have concentrations <50 mg/l, and very few samples have concentration >200 mg/l. The measured average chloride concentrations in four major surface water bodies are 243 mg/l (Mir Alam Tank), 210 mg/l (Hussain Sagar), 11 mg/l (Himayat Sagar) and 11 mg/l (Osman Sagar). Out of these, Himayat Sagar and Osman Sagar, are located away from the urban area and are being used for drinking water supply to Hyderabad, while the Hussain Sagar and Mir Alam Tank are surrounded by thickly populated areas and are not protected, hence, enormously polluted water finds its way into them.

The measured $\delta^{18}\text{O}$ concentration in the Hyderabad rainwater varied from -10.2 to $+4.2\text{‰}$ SMOW. The $\delta^{18}\text{O}$ concentration was positive for initial showers of the summer monsoon, and in subsequent rainfall it was relatively depleted (Table 1). Kumar and Kingi (1981) measured $\delta^{18}\text{O}$ concentration in a surface reservoir which is being used for domestic water supply as $\sim 4.0\text{‰}$ (SMOW). The groundwater samples collected for this study show the $\delta^{18}\text{O}$ content between -3.2‰ and $+1.7\text{‰}$ (SMOW). However, about

Table 1 $\delta^{18}\text{O}$ and chloride data of Hyderabad rainfall for the period 1997–2001

Year	Month	Precipitation (mm)	$\delta^{18}\text{O}$ (‰)	Chloride (mg/l)
1997	6	30	–	4.0
1997	7	100	–	3.0
1997	8	71	–	2.0
1997	9	74	–	3.0
1997	10	95	–	–
1997	11	34	–	–
1997	12	41	–	–
1998	4	6	2.9	–
1998	5	18	4.2	–
1998	6	44	–1.5	–
1998	7	222	–4.5	–
1998	8	266	–4.7	–
1998	9	142	–7.9	–
1998	10	240	–10.2	–
1998	11	6	–6.0	–
1999	4	9	–	–
1999	5	88	–	4.0
1999	6	38	–	–
1999	7	150	–	2.0
1999	8	122	–	1.0
1999	9	124	–	–
1999	10	32	–	–
2000	4	13	–	–
2000	5	65	–	–
2000	6	216	–	10.0
2000	7	126	–	–
2000	8	469	–	2.5
2000	9	51	–	2.5
2000	10	22	–	1.5
2001	1	11	–	–
2001	3	61	–	–
2001	4	14	–	–
2001	6	225	–	8.0
2001	7	43	–	5.5
2001	8	238	–	2.5
2001	9	92	–	2.5
2001	10	140	–	1.5
2002	1	11	–	1.0
Weighted average			–6.5‰	4.0 mg/l

50% of the samples show around -2‰ and about 25% of the samples show enrichment of $\delta^{18}\text{O}$ (positive values).

As can be seen from Table 2, there is a wide range of uncorrected radiocarbon ages from “Modern (≤ 50 yr)” to 5570 yr B.P. More than half of the samples show “Modern” age and quite a few samples show higher ages (> 1000 yrs) particularly from the northwestern part of the study area.

Discussion

For fractured hard rock aquifers, some conceptual models have been developed to address groundwater flow and

Table 2 Radiocarbon dates (uncorrected), chloride and $\delta^{18}\text{O}$ concentrations of groundwaters collected from fractured hard rock aquifers

Sl. no.	Sample no.	Location	Fracture depth (m)	^{14}C age (yr B.P.)	Cl Conc. (mg/l)	$\delta^{18}\text{O}$ ‰ (SMOW)
1	DAS-3	Beerappagadda, Uppal,R.R Dt	100	Modern	230	-1.8
2	DAS-4	Habsiguda, R.R Dist	122	1720±125	110	-2.1
3	DAS-5	Habsiguda,	47	Modern	210	-0.96
4	DAS-11	Tolichowki, HYD Distt	135	Modern	169	-1.2
5	DAS-12	Tolichowki, HYD Distt	96 & 111	1590±230	48	-1.7
6	DAS-13	Tolichowki, HYD Distt	51-54	Modern	126	-0.78
7	DAS-14	Tolichowki, HYD Distt	87	Modern	158	-2.2
8	DAS-15	Tolichowki, HYD Distt	141	3550±120	46	-2.4
9	DAS-16	Tolichowki, HYD Distt	21 & 75	240±120	69	-3
10	DAS-17	Tolichowki, HYD Distt	137	1920±170	77	-2.2
11	DAS-18	Dollar Hills HYD Distt	60-135	5570±230	59	-3.2
12	DAS-19	Tolichowki HYD Distt	141	Modern	122	-1.29
13	DAS-20	Tolichowki HYD Distt	39	Modern	350	-3.2
14	DAS-21	Tolichowki HYD Distt	48 & 142	770±150	85	-1.9
15	DAS-22	Filmnagar HYD Distt	151	620±150	117	-2.7
16	DAS-23	Akbar Hills, R.R. Distt	90	430±150	18	-0.3
17	DAS-25	Banjara Hills, "	114	395±150	38	1.2
18	DAS-26	Banjara Hills, "	75-82	Modern	100	1.7
19	DAS-27	Parmar Reddy Hills, "	26-27	2520±170	88	-1.7
20	DAS-28	BanjaraHills, "	88	Modern	83	1.35
21	DAS-29	Somajiguda, "	180	225±140	204	0.6
22	DAS-30	Panjagutta "	109	820±150	106	0.2
23	DAS-33	Domalguda "	106	Modern	130	1.41
24	DAS-34	Domalguda "	85	Modern	96	0.3
25	DAS-35	Panjagutta, "	136	430±100	87	-2.4
26	DAS-38	Bhadra Reddy, St.no.8, Hub.guda	52	Modern	240	0.03
27	DAS-39	Amina Com.opp.Survey of India	122 & 123	1340+95	325	-2.49
28	DAS-42	Pasha Bahi, behind Qub.shahi tombs	58 & 107	535+70	25	-1.66
29	DAS-43	Saibaba nagar, Borabanda	175	Modern	175	-1.96
30	DAS-44	NRR Puram, Borabanda	69 & 93	Modern	53	-1.84
31	DAS-45	NRR Puram, Borabanda	76	Modern	240	-2.6
32	DAS-46	NRR Puram, Borabanda	177	Modern	175	-2.12
33	DAS-47	Laxmipuram, AS Rao Nagar	104 & 229	1450+95	110	-2.52
34	DAS-48	Laxmipuram, AS Rao Nagar	167	Modern	127	-2.78

solute transport, using short-term tracer methods as well as environmental isotopes (especially chlorofluorocarbon, tritium, tritium-helium-3 ratio) methods (McKay et al. 1993; Cook et al. 1996; Cook and Simmons 2000; Flint et al. 2000; Shapiro 2001). The advantage of environmental tracers is quite understandable, as experiments using dye tracers require field injections to be pursued for a considerable time in order to study equilibrium between matrix and fracture flows. Further, the transport models evolved from small-scale measurements of aquifer properties may not truly represent the actual large-scale solute migration rates as the aquifer parameters in fractured hard rocks are prone to large spatial variability (Aeschbach-Hertig et al. 1998). A conceptual hydrogeologic model, evolved from the present study, is compared with some of the conceptual models developed by others in various geologic settings. The environmental tracer data discussed in this paper include the

development of a conceptual model of the recharge processes in a granitic terrain.

Depth variation of environmental tracer data

In order to elucidate the recharge process and flow mechanism in fractured aquifers of granite- gneisses, measurements of radiocarbon, $\delta^{18}\text{O}$ and chloride were made. These parameters were plotted as a function of depth (Fig. 4). Fig. 4a shows the depth variation of drilling discharge for individual fractures at that depth; few of the sampled wells depicted in Fig. 4a are shown in Fig. 2. There is no systematic trend of either increase or decrease of drilling discharge with depth. They show much higher discharge than average. For example, high drilling discharge is encountered at different depths viz. 16-25, 34-72, 127-128, 172-173 m in different wells (Fig. 2).

Fig. 4 Depth variation of (a) exploratory well discharge during drilling, (b) chloride concentration, (c) $\delta^{18}\text{O}$ content and (d) uncorrected ^{14}C ages of sampled groundwaters (exploratory and sampled wells for groundwaters are different)

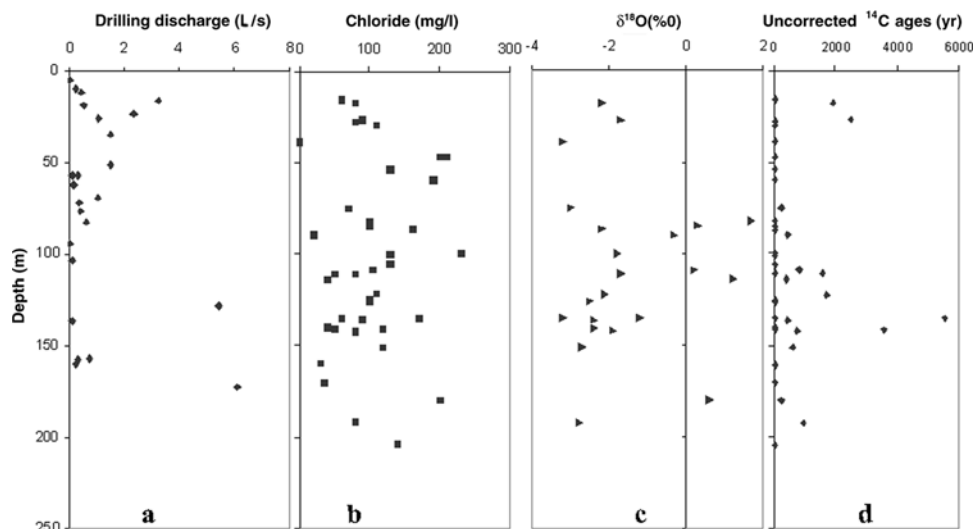


Figure 4b and c show chloride and $\delta^{18}\text{O}$ plots, with respect to depth of fracture respectively, which indicate a random variation. Such variation can be attributed to multiple sources of recharge as well as multiple flow paths at various stages of the recharge process. Figure 4d is the plot of depth variation of ^{14}C ages. Unlike the chloride and $\delta^{18}\text{O}$ variations, which are primarily controlled by environmental conditions during the recharge process, the variation in ^{14}C ages is because of residence time of groundwater in the aquifer. The measured ^{14}C ages do not show any increase with depth, which is in contrast to the observation of Cook et al. (1996) and Aeschbach-Hertig et al. (1998), wherein they found increasing groundwater ages with depth. Our observations indicate that because of highly undulating topography, deeper fractures also may have recharge sources close by.

In the present study area (granite basement), the hydrogeologic setting varies on a regional scale because of different sets of fractures/joints as well as thickness of the weathered zone. There are thick weathered zones at places, and at other places, outcrops with a thin weathered zone accompanied by vertical fracture zones and a combination of thick weathered and fracture zones is observed elsewhere. In such a hydrogeologic frame work, since there is substantial flow through vertical fractures and inter-granular pores in thick weathered zones, and there exists a little lateral flow, particularly in low-lying valley areas, the residence time of water in the aquifer is small as water does not travel to any great depth/distances before it is withdrawn from the wells. Thus, quite young ages (Modern) in this scenario are expected. On the other hand, if the recharging water from the vertical fractures in weathered zones enters the sheet joints, which are confined by the compact hard rock on top and bottom, it subsequently maintains its stable isotope and chemical composition (chloride, assuming non-reactive system), but radiocarbon concentration is expected to decrease with time. Thus it can be inferred that high radiocarbon ages in groundwater could result from the movement of groundwater in extensive sheet joints (spanning tens of meters to few kilometers) connected either to

vertical joints in the vadose zone or thin weathered zone which are found to be prevalent in the fractured granites (as evidenced in Fig. 3). Thus considering the overall hydrogeological situation, no systematic depth variation of different tracers would occur.

Relationship between ^{14}C ages, chloride and $\delta^{18}\text{O}$

The studied groundwater ages, chloride concentration and $\delta^{18}\text{O}$ data are plotted in Fig. 5. This figure shows broadly two types of groundwaters, one possessing age range from 1300–5600 yr B.P. and the other group having Modern to 800 yr B.P. The high ages could result from movement of the groundwater to large distances through the sheet joints (Fig. 3), which are confined. Once the recharging waters from the weathered zone enters these sheet joints, the hydrochemical signatures would not alter except for a decrease in the ^{14}C content due to radioactive decay. If the transit time of the recharging water were large, before its entry into the abstraction point, the groundwater age would be proportionately high and vice-versa. The wells, which possessed the high ages, are: 4, 12, 15, 17, 18, 27, 39 and 47. The chloride content of these wells is ≤ 100 mg/l except well no. 39, which has 325 mg/l of chloride content. The $\delta^{18}\text{O}$ content of these wells ranged from -3.2 to -1.7‰ . The enrichment of chloride and $\delta^{18}\text{O}$ content, in relation to the rainwater values, suggests normal evaporation process during recharge through unsaturated zone. After passage of these waters through the vadose zone, the waters enter the extensive sheet joints, thereby, the chloride and $\delta^{18}\text{O}$ contents remain intact. The exceptionally high chloride content of well no. 39 suggests a contamination from a local subsurface chloride rich water source (e.g. septic tank, leaking drainage etc.).

The second broad group having ^{14}C ages Modern to 800 yr B.P., contained chloride in the range 20 to 350 mg/l and $\delta^{18}\text{O}$ in the range -3.2 to $+1.7\text{‰}$. Such a wide range in chloride and $\delta^{18}\text{O}$ contents of groundwater demonstrates multiple processes and sources of recharge. This group is further sub divided into three subgroups. The

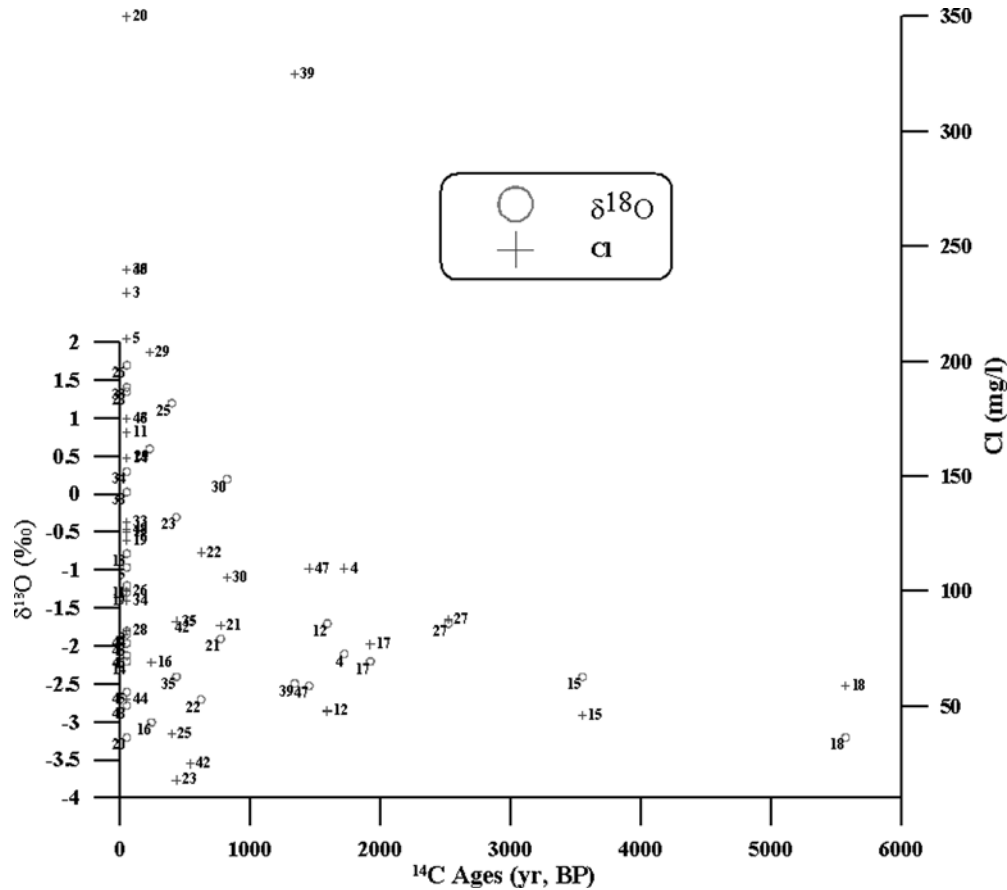


Fig. 5 Relationship between ^{14}C ages, $\delta^{18}\text{O}$ and chloride concentration of studied groundwaters in the fractured hard rocks, reveal broadly two types of groundwaters. One type groundwaters is characterized by high ^{14}C ages (1300 to 5600 yr B.P.), $\delta^{18}\text{O}$ -3.2 to -1.5‰ and chloride concentration of <100 mg/l, which imply recharge processes involving weathered zone followed by large transit time through extensive sheet joints. The second type is comprised of ^{14}C age (Modern to ~ 800 yr B.P.), a wide range of $\delta^{18}\text{O}$ (-3.2 to

$+1.7\text{‰}$) and chloride concentrations (up to 350 mg/l). The three subsets are resultant of recharge involving weathered zone and vertical fractures ($\delta^{18}\text{O}$: -3.2 to -1.5‰ , Cl: ≤ 100 mg/l, ^{14}C ages: Modern to 800 yr B.P.), local contamination from chloride rich sub-surface sources ($\delta^{18}\text{O} \sim -1.5\text{‰}$, Cl: 100–150 mg/l, ^{14}C ages: Modern), and contribution from polluted and evaporative surface water bodies ($\delta^{18}\text{O} \sim +0.03$ to $+1.7\text{‰}$, Cl: >150 mg/l, ^{14}C ages: Modern)

groundwaters that contained chloride <100 mg/l and $\delta^{18}\text{O} < -1.5\text{‰}$, indicate normal recharge through weathered zone and fractures. Some of these waters have residence time to the extent of 800 years, implying moderate transit time through fractures. The above subgroup with <100 mg/l of chloride, shows enrichment of $\delta^{18}\text{O}$ during percolation of recharging waters through the unsaturated zone, before entering the fracture network. The well nos. 16, 21, 22, 35, and 42 exemplify this type of groundwaters.

The other subgroup of groundwaters with Modern ages, chloride content >150 mg/l and having positive $\delta^{18}\text{O}$ values (0.3 to $+1.7\text{‰}$) clearly show the recharge from polluting and evaporative surface water bodies. The $\delta^{18}\text{O}$ content of surface water bodies undergo enrichment due to continued evaporation. The typical $\delta^{18}\text{O}$ content of one of the surface water bodies in the present study area was 4.0‰ (Kumar and Kingi 1981). Thus, the observed positive $\delta^{18}\text{O}$ values seem to have resulted from mixing of normal groundwater and feed from surface water bodies. The wells 29 and 38 represent this category of groundwaters.

The contribution of evaporative surface reservoirs to the groundwaters, having $\delta^{18}\text{O}$ in the range of -0.9 to

$+1.7\text{‰}$, is computed taking the $\delta^{18}\text{O}$ content of recharging waters in the unsaturated zone and fractures as one end member while the second end member is the $\delta^{18}\text{O}$ value of tank water, which was determined to be $+4.0\text{‰}$ (Kumar and Kingi 1981) for one of the surface water bodies in the present study area. The first $\delta^{18}\text{O}$ end member is computed using the rainfall $\delta^{18}\text{O}$ value (-6.5‰) and assuming 5% annual average recharge (Sukhija et al. 2003) through matrix flow and about 50% of bypass flow to the total recharge (Sukhija et al. 2003). The resultant $\delta^{18}\text{O}$ input from 5% matrix flow would be -0.32‰ , and from bypass flow, it will be -3.25‰ . Thus the total input $\delta^{18}\text{O}$ content would be -3.57‰ (as one end member). Then the contribution from surface reservoir, computed taking -3.57‰ (recharging waters) and $+4.0\text{‰}$ (tank waters) as two end members, ranged from 43 to 70% corresponding to the resultant $\delta^{18}\text{O}$ content -0.3 to $+1.7\text{‰}$ of groundwaters.

Quantification of the mixing of recharging groundwaters and waters from chloride-rich subsurface sources is not attempted owing to various non-point diffusive sources like septic tanks and leaking drainage pipes in the subsurface.

Alternatively, enriched $\delta^{18}\text{O}$ groundwaters are considered to address the mixing phenomenon from sample reservoirs.

The groundwaters with intermediate $\delta^{18}\text{O}$ values around -1.0‰ and chloride contents in the range of 100 to 150 mg/l and having Modern ^{14}C ages, demonstrate contribution from subsurface contaminant sources such as septic tanks and leaking drainage pipes. The groundwaters from well nos. 19, 26, 33, 34 etc. belong to this category. The various recharge processes and their representative wells are listed in Table 3.

Conceptual hydrogeologic model

The source and recharge processes of different types of groundwaters with their isotope and chloride data can be interpreted using Fig. 6, which represents a conceptual hydrogeologic model of granite-gneissic area. The model takes into account the following observations: (i) lithology as revealed through a number of boreholes in and around Hyderabad and quarries, (ii) geomorphic variations, (iii) qualitative yields of fracture zones, (iv) variation of $\delta^{18}\text{O}$ and chloride concentration in groundwater, (v) high and low radiocarbon ages etc.

The model shows varying thickness of weathered zone overlying hard and fractured basement. Field observations indicate that a thick weathered zone is generally associated with an intense fracture network as well as with the courses of past and present streams. From the observation of a number of quarries (Fig. 3) and boreholes (Fig. 2) the general perception is that sheet joints which are a few cm to tens of cm thick, are quite extensive and are connected to high yielding wells. Such sheet joints can be found at

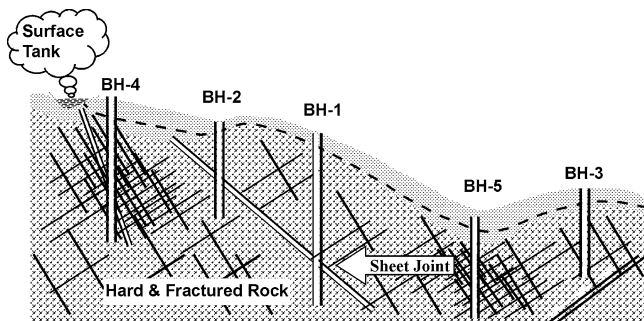


Fig. 6 A conceptual hydrogeologic model evolved to elucidate various recharge processes and flow mechanisms in the studied fractured hard rock aquifers, based on varying ^{14}C ages, chloride and $\delta^{18}\text{O}$ contents of groundwater. Hypothetical wells like BH-1 and BH-2 are recharged from distant sources and water moves through the weathered zone and sheet joints resulting in quite large residence times of groundwaters. Wells like BH-3 are characterized by young ^{14}C ages due to low turnover time, and relatively high chloride concentrations in comparison to BH-1 and BH-2 result from natural recharge through a thick weathered zone. Groundwaters being recharged from surface water bodies connected through an intense fracture network are characterized by young ^{14}C ages and positive $\delta^{18}\text{O}$ values and are represented by wells like BH-4. The groundwaters in the valley (low lying) areas are characterized by a thick weathered zone, intensive fracturing in the subsurface, and minimal lateral flow of groundwaters are represented by wells like BH-5 which possess young ^{14}C ages and high levels of chloride due to mixing of waters from subsurface contaminant sources (soak pits, drainage lines etc.)

various depths in the study area, and are connected to an upper horizon, which may have a thin weathered zone for recharging the aquifer or vertical joints in the unsaturated zone. Another important aspect of the hydrogeologic system is the presence of surface water bodies, which could serve as one of the recharge sources.

Thus the type of groundwater samples with ^{14}C ages >1300 yr B.P., chloride concentration ≤ 100 mg/l, and $\delta^{18}\text{O} < -1.7\text{‰}$ (Table 3) are indicative of having relatively large transit time and recharged through upper weathered zones and sheet joints. This situation can be described from the conceptual hydrogeologic model (Fig. 6) in which hypothetical wells like BH-1 and BH-2 are located where the source of recharge is some distance away. In an actual field situation, the sampled groundwater wells numbered 4, 12, 15, 17, 18, 27, 39 and 47, mainly from the Tolichowki area (Fig. 1), represent the above hydrogeological situation. From the radiocarbon age data and considering extensive fracture zones (Fig. 2) with good yield (5–7 l/s) prevalent in the area, it is envisaged that groundwater moves laterally through such fracture zones for sufficiently long periods and over distant areas rather than consider that groundwater is locked in a deeper horizon in low permeability fractures as we have not observed any depth variation. Flint et al. (2000) in their attempt to estimate regional recharge and travel time through the unsaturated zone of arid fractured rocks in Yucca Mountains, Nevada, conceptualised a model of groundwater recharge. According to them, recharge is nearly vertical and the travel time to the saturated zone is dependent on the thickness of the unsaturated zone and effective travel path porosity. The flow path may be in a rock matrix or in fractures. Further, a significant flux of recharge occurs through fractures under saturated or nearly saturated conditions. Infiltrated water is expected to travel laterally through sheet joints until intercepted by deep wells. A higher infiltration rate is assumed to take place through fractures while a lower value of infiltration moves through the matrix. However, Cook and Simmons (2000), in their study using environmental tracers of ^{14}C , CFC-12, and ^3H , and in combination with hydraulic properties in Clare valley, Australia, have identified two separate groundwater systems with contrasting vertical recharge to be 100 mm/yr for the upper fractured system and less than 0.1 mm/yr for the deeper flow system. Since the present study area is in the part of the Peninsular granitic shield, extensive sheet joints are common, through which groundwater moves laterally for a long distance, whereas groundwater movement in Yucca Mountains and Clare valley is almost vertical.

The type of groundwater samples having Modern to 800 yr B.P. radiocarbon ages with 20 to 350 mg/l chloride concentration and $\delta^{18}\text{O}$ values from -3.2 to $+1.7\text{‰}$ (Table 3) involve various recharge processes and sources as detailed below:

Wells like BH-3 (Fig. 6) form subgroup-1 (^{14}C age range: Modern to 800 yr B.P., Chloride: ≤ 100 mg/l, $\delta^{18}\text{O}$: $\leq -1.5\text{‰}$, Table 3) where the source of recharge is at a moderate distance, essentially receives recharge from a thick weathered zone and there may be vertical recharge

Table 3 The characteristics of studied deep groundwaters

Groups	Recharge source and processes	^{14}C ages (yr B.P.)	Chloride (mg/l)	$\delta^{18}\text{O}$ ‰ (SMOW)	Representative Wells no
Broad Group-1	(i) Distant source and sheet joints	>1300	≤ 100	< -1.7	4, 12, 15, 17, 18, 27, 39, 47
Broad Group-2	Multiple Recharge processes and sources	Modern to 800	20 to 350	-3.2 to $+1.7$	
Subgroup	(i) Direct recharge and weathered zone and vertical fractures	Modern to 800	≤ 100	≤ -1.5	16, 21, 22, 35, 42
Subgroup	(ii) Surface reservoirs/ evaporation effect	Modern	> 150	$+0.3$ to $+1.7$	29, 38
Subgroup	(iii) Contamination from subsurface pollution sources	Modern	100 to 150	Around -1.0	19, 26, 33, 34

to a considerable extent. In comparison to the groundwater whose residence time in the sheet joints is >1300 yr B.P., this type of well may have less travel time as well as residence time in the aquifer. This group consists of the samples like 16, 21, 22, 35 and 42, where the weathered zone is thick and water is recharged through this zone.

Wells like BH-4 form subgroup-2 (^{14}C ages: Modern, chloride: >150 mg/l, $\delta^{18}\text{O}$: $+0.3$ to $+1.7$ ‰, Table 3), which are connected to the nearby polluting and evaporative surface water bodies through weathered and fractured zone. In the study area, there are prominent polluting surface water bodies like Hussain Sagar, Mir Alam Cheruvu, Nacharam Cheruvu (Fig. 1), which are likely to contribute to groundwater recharge. Groundwater samples like 29 and 38 may have their recharge from such sources, as evidenced by enriched $\delta^{18}\text{O}$ and higher chloride concentrations.

Wells like BH-5 form subgroup-3 (^{14}C ages: Modern, chloride: 100 to 150 mg/l, $\delta^{18}\text{O}$: around -1.0 ‰, Table 3), situated in low-lying areas where a thick weathered zone with an intense fracture system, are prone to accumulation of groundwater along with feed from subsurface pollution sources. Groundwater samples like 19, 26, 33, 34 may have their recharge from such sources, as evidenced by higher chloride concentrations.

The hydrogeologic model presented above has also some similarities with a conceptual model of groundwater flow developed by Cook et al. (1996) for Saprolite and fractured rock using environmental tracers. In this model, most of the recharge is through discrete fractures in the vadose zone that becomes saturated during rainy season, though the micropores may remain unsaturated and most recharge to groundwater is transmitted laterally. In the hydrogeologic model developed in this study, it is believed that sheet fractures, which are connected to the vadose zone, carry recharge water laterally a few hundreds of meters to a few kilometers, which result in ageing of the recharged water. However, in contrast to the above situation, younger radiocarbon ages with similar chemical and isotopic characterization are also obtained. This situation may occur due to infiltration and movement of water through the matrix as well as the fractures within the weathered zone, and mix together resulting in apparent young age of groundwater.

Such systems are generally unconfined in nature. In the former case involving sheet joints, higher groundwater ages are associated with semi artesian conditions.

However, despite the fact that the studied fractured hard rock aquifer system is a complex geologic environment comprising unsaturated rock matrix and multiple fracture network, the study has identified dominant recharge processes and flow mechanisms operative in the area. The possible sources of errors that would offset the data from its real value could be recharge contributions from unidentifiable subsurface regimes as well as contribution from multiple fractures during pumping of wells.

Conclusion

The isotopic and geochemical analysis of various groundwaters of the studied area with undulating topography, fractured hard rock outcrops and basement, varying thickness of weathered zone with low primary porosity and dominant secondary porosity, identified various recharge processes operative in the study area. In such a complex geological setting, the recharge processes involved unsaturated rock matrix, high permeable paths in the regolith, sheet joints etc., thus demonstrating the groundwater flow pattern to be quite complicated involving various sources. Apart from rainfall, the recharge sources include surface water bodies and the subsurface polluting sources like leaking drainage pipes and septic tanks. The contribution from surface reservoir to groundwater is evaluated and found to be significant (40 to 70%) for certain type of groundwaters. To understand such a heterogeneous hydrogeological scenario, a model has been developed based on the isotopic and geochemical data. The developed model could be applicable to areas having similar hydrogeological environments. The importance of such models further increases from the practical utility of studying the transport of contaminants to the aquifers in the industrial and urban areas.

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