Recharge processes: piston flow vs preferential flow in semi-arid aquifers of India

B. S. Sukhija · D. V. Reddy · P. Nagabhushanam · Syed Hussain

Abstract Study of groundwater recharge processes is vital for quantification of total natural recharge to the aquifers. One of the recharge processes demonstrated earlier by tracer experiments in the unsaturated zone is that of piston flow movement of soil moisture. Based on this recharge process, environmental tritium, chloride and injected tritium studies have been carried out extensively in various geological environs of India. The purpose of this paper is to evaluate the validity of the piston flow concept in different geological environs viz. consolidated fractured and weathered granites, semi-consolidated sandstones and unconsolidated alluvial tracts, and quantify the contribution from this process as well as that from the preferential flow mechanism using different tracers. Analysis of tracer data demonstrates that the preferential flow recharge process contributes very significantly (an average of 75% of total recharge) in the case of fractured granites and is important (an average of 33% of total recharge) for semi-consolidated sandstones, whereas the preferential flow recharge component is minimal in unconsolidated alluvial tracts (piston flow model is applicable). These findings necessitate re-evaluation of the total natural recharge potential of the above mentioned geological environs in view of the significant preferential flow recharge that is evidenced and estimated.

Résumé L'étude des processus de recharge de nappes est indispensable pour quantifier la recharge naturelle totale des aquifères. Un des processus de recharge montré dans le passé par des expériences de traçage dans la zone non saturée est celui de l'écoulement en piston de l'humidité du sol. Basées sur ce processus de recharge, des études sur le tritium environnemental, les chlorures et le tritium injecté ont été réalisées dans des environnements géologiques variés de l'Inde. Ce papier propose une évaluation de la validité du concept d'écoulement en piston dans des environnements géologiques différents, à savoir des granites consolidés fracturés et altérés, des grès partiellement consolidés et des épandages alluviaux non consolidés ; il propose également de quantifier la contribution de ce processus ainsi que du mécanisme d'écoulement préférentiel en recourant à différents traceurs. L'analyse des données fournies par les traceurs montre que le processus de recharge par écoulement préférentiel contribue de manière très significative (en moyenne 75% de la recharge totale) dans le cas des granites fracturés, et importante (en moyenne 33% de la recharge totale) pour les grès partiellement consolidés, tandis que la composante de la recharge par écoulement préférentiel est minimale dans l'épandage alluvial non consolidé (le modèle d'écoulement en piston est applicable). Ces résultats imposent une réévaluation du potentiel de recharge naturelle totale des environnements géologiques mentionnés plus haut du fait de la recharge significative par écoulement préférentiel mise en évidence et estimée.

Resumen El estudio de los procesos de recarga de acuíferos es vital para cuantificar la recarga natural total. Uno de los procesos que tienen lugar en la zona no saturada, de acuerdo con experimentos previos de trazadores, es el del movimiento mediante flujo tipo pistón del frente de humedad. Con base en este proceso, se ha llevado a cabo estudios completos de tritio natural, cloruros y tritio inyectado en varios emplazamientos geológicos de la India. El objetivo de este artículo es evaluar la validez del concepto de flujo tipo pistón en ambientes geológicos diferentes, entre los cuales se incluye granitos fracturados y meteorizados, areniscas semi-consolidadas y depósitos aluviales no consolidados. Además, se cuantifica la contribución de este proceso y del mecanismo de flujo preferente por medio de diversos trazadores. Los datos analíticos demuestran que el proceso de recarga vía flujo preferente contribuye muy significativamente (con un promedio del 75% de la recarga total) en el caso de los granitos fracturados, y desempeña un papel importante en areniscas semi-consolidadas (con un 33% del total), mientras que tiene una mínima influencia en materiales aluviales, donde el modelo de flujo tipo pistón es aplicable. Estos hallazgos

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indican que el valor de la recarga natural total debe ser reevaluado en los entornos geológicos antes citados, debido a la notable contribución del flujo preferente.

Keywords Alluvial deposits · Groundwater · Piston flow · Recharge processes · Tracers

Introduction

A priori knowledge of natural recharge processes is a prerequisite in the assessment of groundwater potential. Lloyd (1986) defined direct recharge as the quantity of water added to the groundwater reservoir in excess of soil moisture deficit and evapotranspiration, and by direct vertical percolation of precipitation through the unsaturated zone, whereas indirect recharge results from percolation to the water table following run off and localisation in joints, as ponding in low lying areas and lakes, or through the beds of surface water courses.

Groundwater recharge evaluation (Lerner et al. 1990) assumes great significance in countries that have an arid character and monsoon climate and in areas covered with hard rocks. Several conventional methods used for the above purpose require data such as specific yield, surface runoff and evapotranspiration. Generally such data are neither available nor reliable. Gee and Hillel (1988) observed that errors in recharge estimates for arid and semi-arid sites using water balance methods, soil water flow models and simple estimates of recharge based on fixed factors of annual precipitation are generally high and misleading due to inherent limitations and uncertainties.

During the last two to three decades, isotopic and geochemical tracer methods have been developed to understand the processes of groundwater recharge and its evaluation, which are considered to be more reliable than the conventional methods. Munnich and his co-workers (Zimmermann et al. 1967) made pioneering contributions to the development of tracer methods. From their experiments using environmental and injected tritium as tracers, they postulated that, in the case of homogenous soil, without many cracks and fissures, the bulk of water movement from the unsaturated zone to the saturated zone takes place in layered form and, hence, they developed the concept of 'piston flow' movement of soil moisture. Thus, the piston flow recharge waters in different years of precipitation are stacked one above the other, as younger water does not overtake the older water. This concept provided a convenient method of evaluation of recharge processes and recharge estimates using the thermonuclear tritium peak of 1963–1964 in precipitation, which could be easily identified in the unsaturated zone.

Following this concept, many workers (Datta et al. 1973; Sukhija and Rama 1973; Sukhija and Shah 1976; Verhagan et al. 1979; Athavale and Rangarajan 1988; Sukhija et al. 1996a, 1996b) have utilised environmental and injected tritium to estimate groundwater recharge and evaluate recharge processes in areas situated in semi-arid and arid environments.

Allison and Hughes (1978) developed the environmental chloride profile method for recharge estimates, by studying the conjunctive use of environmental tritium and chloride based on the piston flow model. They studied the Gambier Plain unconfined aquifer in southern Australia using tritium and chloride concentrations of soil moisture within the soil profile, and estimated total mean annual recharge (mean annual recharge × area) to the aquifer. They observed good agreement between the estimates made using the two techniques, and uniform recharge over quite large areas.

Edmunds and Walton (1980) demonstrated that the environmental chloride profile method can be effectively utilised where the assumptions of no additional source or sink of chloride in the profile are valid. They evaluated groundwater recharge based on piston flow recharge processes in semi-arid Cyprus using environmental chloride and tritium profiles of the unsaturated zone.

Through chloride mass balance ($R_d \times C_s = P \times C_p$: where R_d = direct recharge through unsaturated zone; C_s = average chloride concentration of the soil profile; P = average annual rainfall; C_p = average chloride concentration of rainfall) in the profile, it was found that recharge determined from the chloride profiles compared well with recharge estimates using tritium. For recharge evaluation, the deep coastal sands (Swan Coastal Plain) of western Australia was studied by Sharma and Hughes (1985) making use of chloride, deuterium and oxygen-18 profiles. While the chloride profiles of the unsaturated zone could yield recharge rates, the stable isotope profiles could not provide reliable estimates of recharge. Moreover, it was observed that the average chloride concentration of a soil profile is more than double that of the chloride concentration of groundwater. The difference in chloride concentration was attributed to the presence of preferred pathways for water movement through the soil matrix. Sukhija et al. (1988) demonstrated the validity of the chloride method in evaluating groundwater recharge measurements in coastal aquifers.

Nativ et al. (1995), using tritium and bromide profiles, found slow rates of water infiltration in the vadose zone of a fractured chalk aquifer in the northern Negev desert, and attributed the slow rates to the combined effects of low permeability of the matrix and low precipitation associated with the arid conditions. The presence of several smaller tritium peaks at greater depths (4–20 m) accompanied by the gradual depletion of deuterium and oxygen-18, and reduction of bromide and chloride concentrations to a third of their peak concentration near the top of the vadose zone, was attributed to un-evaporated water making its way through the vadose zone via conduits of increased flow.

For the Southern High Plains of Texas and New Mexico, Wood et al. (1997) showed that a significant amount of total recharge in playa lakes is through macropores. Using the profiles of tritium, deuterium, oxygen-18 and chloride, the local as well as regional scale

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recharge rates were evaluated. The total regional annual average recharge was estimated to be 11 mm/year, macropore recharge was about 60 to 80% (7–9 mm/year), interstitial recharge flux beneath the playa floors ranged between 15–35% (1.6–3.85 mm/year), and regional interstitial recharge was about 5% (0.5 mm/year).

Another study by Davidson et al. (1998) in unsaturated tuff of Arizona, using detailed hydrochemical and isotopic analyses on pore water extracted from the core samples collected to a depth of 157 m, shows a substantial quantity of recent recharge through fractures. Scanlon and Cook (2002) emphasised the necessity of groundwater recharge estimation at a variety of spatial and temporal scales, and its importance to aquifer management. Further, they observed that ever increasing demand for recharge estimates is resulting in the development of approaches for thorough understanding of recharge processes, delineating recharge areas and quantifying recharge rates with more certainty.

However, in India, the groundwater recharge measurements using environmental and injected tracer methods, based on the piston flow model of soil moisture movement in several basins and watersheds situated in four main hydrogeological provinces (viz. granites, basalts, sediments and alluvium) indicated a recharge range of 4.1–19.7% of the local average seasonal rainfall (Sukhija et al. 1996a; Rangarajan and Athavale 2000). Therefore, the purpose of this paper is to establish the importance of preferential flow for the realistic assessment of total natural recharge (sum of piston flow recharge and preferential flow recharge) especially through the weathered/fractured granites and semi-consolidated sandstones because the preferential flow component of recharge is generally unaccounted for in the estimation of total natural recharge in these formations. Some of the data in abridged form were reported earlier (Sukhija et al. 2000). The present paper discusses, in detail, the role of preferential flow and the processes of recharge using different tracer methods.

Recharge Processes and Evaluation of Recharge: Different Tracer Methods

Total Tritium Method: Concept

The method aims to determine the total amount of bomb tritium present in a profile as a fraction of the total tritium fallout. The total amount of bomb tritium fallout for a site is calculated by summing up the products of annual precipitation and its weighted mean (proportional to monthly rainfall) tritium concentration. The summation is carried out for the period 1952 (onset of thermonuclear era) to the time at which the investigation is carried out, i.e.

$$T = \sum \mathrm{Ai.Pi} \qquad (1)$$

where T = total tritium fallout (TU-cm); A_i = weighted mean annual tritium concentration (TU) of precipitation in the year i.; P_i = precipitation (cm) in the year i.

The total amount of bomb tritium present in a profile is calculated by adding the differential amounts of tritium present in several segments of a profile up to a depth d, at which tritium content of water is negligible. The total amount is obtained by the following relation:

$$t = \sum_{g}^{d} a_j \theta_j \qquad (2)$$

where t = total amount of tritium (TU-cm) present in a profile summed from ground level g to depth d, a_j = tritium concentration (TU) in soil water of segment j, θ_j = moisture column (cm) of soil segment j.

In the case of a site where the tritium profile is such that a sizeable amount of tritium has penetrated into the saturated zone and if the sampling extends down to the water table only, the total amount of tritium percolation cannot be ascertained accurately.

Since T represents the total fallout of tritium at a site and t is the amount that escaped evapotranspiration and run off losses irrespective of the mode of transport (piston flow or preferential flow) of water in the unsaturated zone, t/T represents the total fraction of the rainfall that goes to recharge the groundwater, i.e. percentage recharge (r) is given by

$$r = \left[\left(\sum_{g}^{d} a_j \theta_j \right) / \left(\sum \mathrm{Ai.Pi} \right) \right] \times 100 \qquad (3)$$

The study of presence or absence of bomb tritium in the saturated zone compared with that in the unsaturated zone further provides evidence for the presence or absence of the bypass mechanism.

Peak Tritium Method: Concept

This method aims to locate the position of 1963–1964 precipitation (having peak tritium concentration) in a soil profile in which it can be established that the movement of soil water has been layered. Recharge computations are made by finding the total amount of water present up to the tritium peak position and comparing this amount with the total rainfall since 1963 to the time of investigation. Thus

$$r = (100/P) \int_{0}^{z} \theta . dz_p \qquad (4)$$

where r = recharge as a percentage fraction of rainfall, θ = soil moisture (cm) column in different segments from surface to the depth where the tritium peak occurs, P = total precipitation (cm) since 1963 to the time of investigation and Z_P = depth of the tritium peak.

Application of environmental tritium for recharge evaluation involves (i) errors in the tritium input function of ~10% in measurements of tritium, and an error of ~5%

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in the usage of rainfall tritium data of nearby stations and an error of 15% due to variation in tritium deposition at different sites observed through repeated experiments. Therefore, the total error in the estimation of recharge would be $\sqrt{(10^2+5^2+15^2)}=18.7\%$.

The environmental tritium studies by Atakan et al. (1974) also showed an error of 25% in the recharge estimates for the Sandhausen shallow unconfined aquifer composed of fine to coarse sand, in the alluvial plain of the Upper Rhine River, Germany.

Injected Tritium Technique: Concept

The injected tritium technique is based on the piston flow model of soil moisture movement in the soil matrix. In the tritium injection technique, the moisture at a certain depth in the soil profile is tagged with tritiated water. The tracer moves downward along with the infiltrating moisture due to subsequent precipitation or irrigation. A soil core is collected from the injection site after a certain interval of time and the moisture content and tracer concentration are measured from various depth intervals. The displaced position of the tracer is indicated by a peak in concentration. The peak may be broadened because of factors such as diffusion, irregularities in water input and streamline dispersion. The centre of gravity of the profile is assumed to correspond to the displaced position of the tagged layer. Moisture content of the soil column, between injection depth and displaced depth, is the measure of recharge to groundwater over the time interval between injection of the tritium and collection of the soil profile. Due to very high tritium activity used in the injection studies, and the calculation of the centre of gravity of the tritium profile for the recharge calculation, the total error in the recharge estimation would be ~10% (Rangarajan and Athavale 2000).

Environmental Chloride Technique: Concept

The environmental chloride technique provides information about the processes of groundwater recharge in a given area. Piston flow recharge rates by the environmental chloride profile method is based on the mass balance of chloride, wherein total input chloride through precipitation for quite a number of years is compared with the total soil chloride in the profile. Such a relation provides the long-term piston flow recharge rate. On the other hand, the relation between input chloride and that in groundwater (chloride ratio method) provides total recharge (piston flow + preferential flow) to the aquifer because the preferential flow component that bypasses the unsaturated zone is accounted for in the groundwater. Assumptions in the chloride technique are that the rainfall is the only source of input chloride (no other source or sink for chloride), steady state conditions exist in the profile/matrix and the area is flat with no lateral flow of groundwater to the sampling point. Study of comparison of chloride concentration of groundwater and that in the soil profile elucidates piston flow or preferential flow.

Approximately the same chloride values in the soil profile and in groundwater indicate that the piston flow process is applicable, whereas the reduction in chloride concentration in groundwater in relation to soil profile indicates that preferential flow occurred through fractures/fissures that escaped the process of evapotranspiration in the unsaturated zone. Recharge estimates using the chloride profile method involve errors in the input chloride estimation because the input chloride concentration is determined by the wet fallout as the data on dry fallout component are generally not available. Assuming a 10% error in the chloride input estimate, a 10–15% error due to extrapolation of chloride input concentration from the measured meteorological station to the study site and about 20% error in the variation in abundance of chloride in the soil profiles at the same site, then, the total error works out to be about 25%.

Results

To evaluate the recharge processes for water in the unsaturated zone and identify the dominant mode of flow process, three areas were selected, one each situated in consolidated hard rocks (fractured granite), semi-consolidated sandstones and alluvial formations (Fig. 1). In general, the fractured granitic–gneissic complex and the semi-consolidated sandstone formation are characterised by low hydraulic conductivity (weathered granite: 1.4 m/day; sandstone fine to medium grained: 0.2–3.1 m/day; Todd 1980), whereas the alluvial formation has a hydraulic conductivity of 5–25 m/day. Despite low hydraulic conductivity, the fractured granitic rocks form fairly good aquifers due to dominant secondary porosity in the form of fractures, fissures, joints, etc. In view of the variations in geologic characteristics, three different geologic areas were studied using tracer techniques, and results are presented pertaining to various recharge processes.

Fractured Granites

The Maheshwaram watershed (Fig. 1, no. 17) located about 30 km from Hyderabad, Andhra Pradesh, India, typically represents the granitic–gneissic area, where groundwater occurs in weathered and fractured zone typically at about 11–20 m below ground level. For recharge process evaluation, the soil chloride profile studies were initiated during 1999. Unsaturated soil samples derived from weathered granite were collected at 10 cm intervals, and up to a maximum possible depth using a hand auger. Soil moisture of individual depth segments are measured gravimetrically, and the chloride content was measured using an ion selective electrode (Hach Co., USA).

The typical soil chloride profile at Maheshwaram site (MRM-1) is shown in Fig. 2a. The profile shows a range

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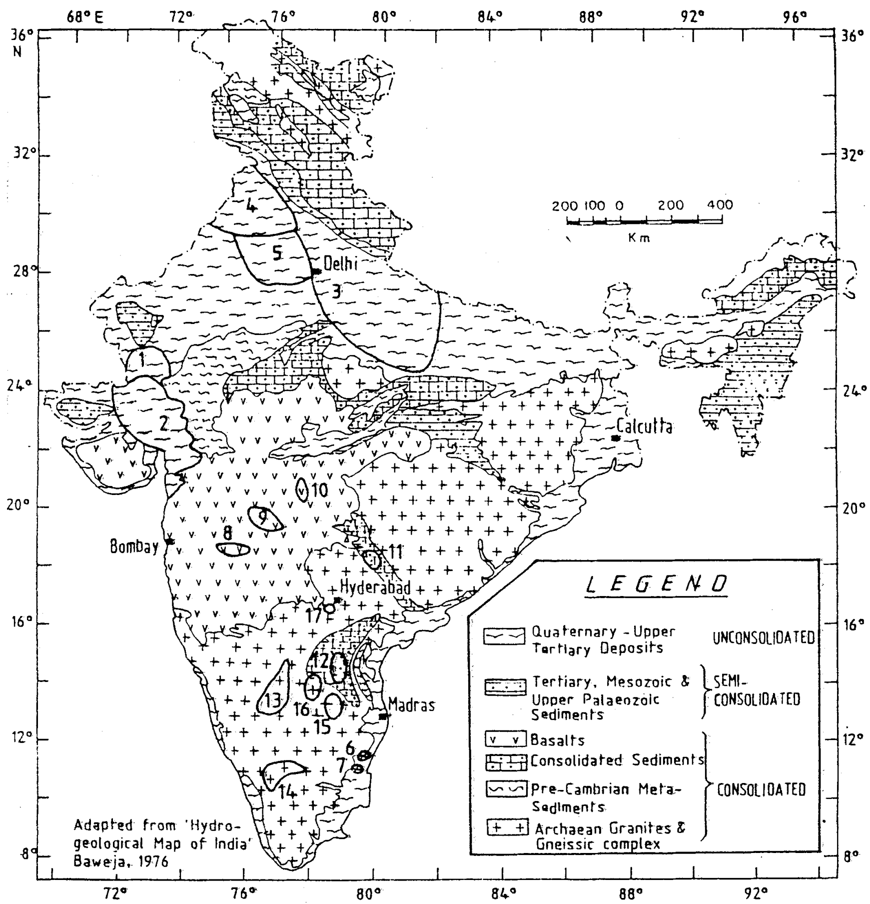

Fig. 1 Hydrogeology map of India (Baweja 1976), showing areas selected for natural recharge studies: (*1*) aeolian deposits of western Rajasthan; (*2–5*) alluvial tracts of Gujarat, western Uttar Pradesh, Panjab, and Haryana; (*6–7*) semi-consolidated sediments of Pondicherry and Neyveli; (*8–10*) Kukadi, Godavari-Purna and Jam basins in basalts; (*11–12*) lower Maner and Kunderu basins in consolidated sediments; and (*13–17*) Vedavati, Noyil-Vattamalai Karai-Ponani, Chitravati, Marvanka and Maheshwaram basins in Archaean gneissic complexes (Sukhija et al. 1996a)

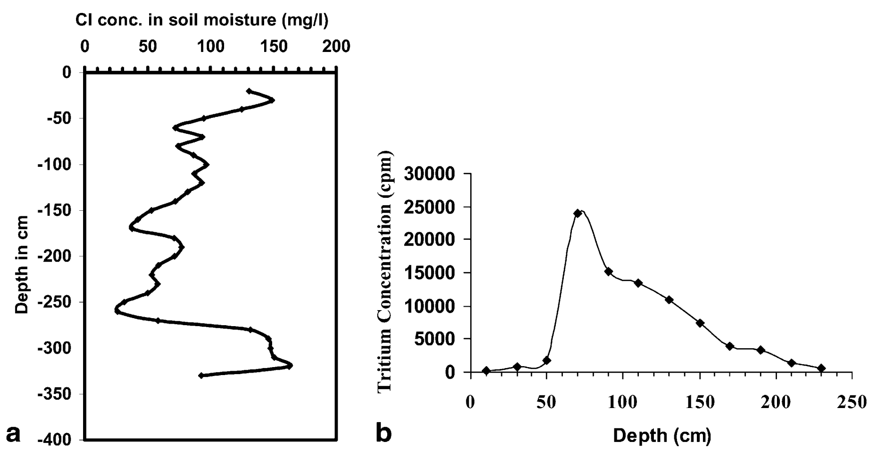

Fig. 2 **a** Typical environmental chloride profile at Maheshwaram (MRM-1) site in the fractured granitic area. **b** Injected tritium profile at Maheshwaram watershed in the granitic area (adapted from Rangarajan and Prasada Rao, 2001). Displacement of the tritium down to 240 cm depth, despite low rainfall (350 mm) during the short span of experimental period (~9 months), is indicative of the existence of preferential flow path(s) in the vadose zone

of 26–160 mg/l chloride concentration with an average value of 86.7 mg/l. The chloride profile depicts soil moisture evaporation effect in the top 40 cm whereby high chloride concentration (>100 mg/l) is observed from ground level to that depth. The chloride concentration between 50–270 cm depth profile depicts a lowering trend, the subsequent high chloride concentration from 280–320 cm depth indicate that a variation of chloride concentration in depth profile can result from many factors such as variation of recharge rate due to annual rainfall, rainfall intensity, duration and spacing between rainfall events, annual evaporation rate, etc. Because the

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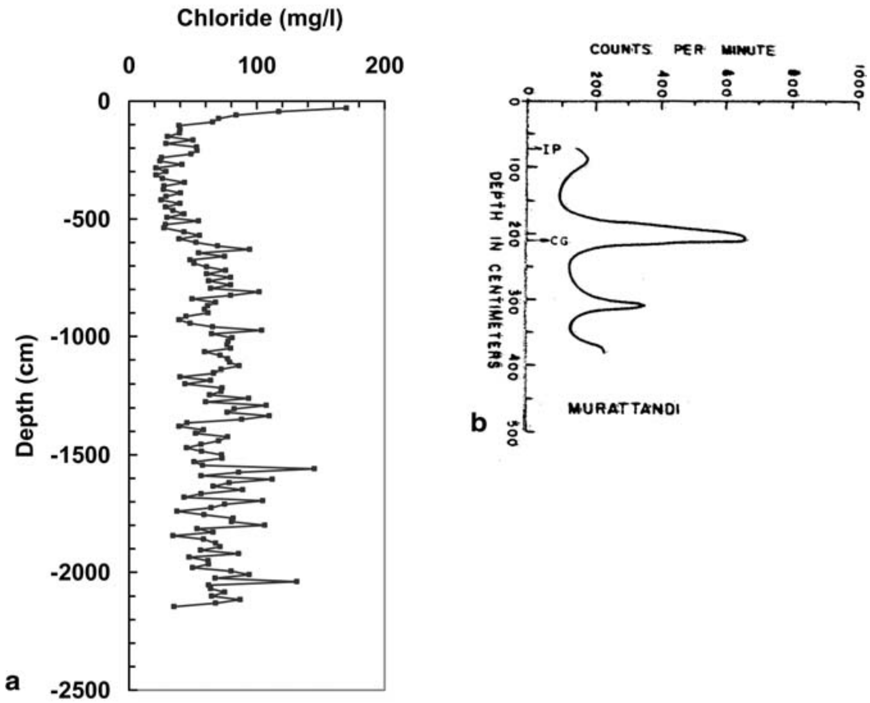

Fig. 3 **a** Environmental chloride profile at the Murattandi site in a semi-consolidated sandstone formation at Pondicherry. **b** Injected tritium profile at the Murattandi site in the semi-consolidated sandstone formation at Pondicherry. The multiple tritium peaks indicate the existence of highly permeable paths in the unsaturated zone

soil chloride profiles provide an integrated picture over several years recharge history, a large variation in the chloride profiles can occur, even when the recharge takes place through piston flow. Generally, it is assumed that the soil chloride profile is from the piston flow component of recharge.

A typical injected tritium profile (Rangarajan and Prasada Rao 2001) from the Maheshwaram study site in consolidated formations is shown in Fig. 2b. Tritium injection was done at a depth of 60 cm at 14 sites during the second week of July 1999 (i.e. before the monsoon intensified). The injected tritium profile (Fig. 2b) shows a dispersion of tritium right from the injected depth (60 cm) to the 240 cm depth of the profile, despite the short span of the experiment (~9 months) and low effective rainfall (350 mm) during the experimental period. Such a wide spread of tritium tracer could be a result of the combination of different flow velocities of the percolating waters through the soil matrix and high velocity conduits (coarser inter-granular path, fractures/fissures, etc.) in the vadose zone.

For recharge evaluation using the chloride profile method, the input rainfall chloride concentration of 2.5 mg/l is used in association with the average chloride concentrations of the studied four profiles viz., Mohabatnagar-1 (MNR-1), Mohabatnagar (MNR), Maheshwaram-1 (MRM-1) and Maheshwaram (MRM), and for the chloride ratio method the respective groundwater chloride concentrations used are 25, 11, 20 and 11 mg/l.

Semi-Consolidated Sandstones

Studies of recharge processes were carried out in the Cuddalore sandstones of Tertiary age located in Pondicherry (160 km south of Chennai; Fig. 1, no. 6; Sukhija et al. 1988), using both soil chloride profiling and the injected tritium technique.

The soil chloride profile at the Murattandi site sampled in 1985 is shown in Fig. 3a. The total profile is 21 m in depth. The top 30 cm of the profile shows a high chloride concentration (>150 mg/l), which is caused by enrichment of chloride by evaporation of soil moisture. Below the top 30 cm, the chloride variation reflects the combined temporal effects of variation in input chloride concentration, rainfall amounts, intensity of rainfall, local temperature, etc. As such, the profile does not indicate any abnormal variation in chloride concentration. Thus, the chloride profile exhibits almost a steady state condition. The range of chloride concentration in the profile (excluding the top 30 cm) is 20–145 mg/l. The average chloride concentration in the profile is 61.3 mg/l. The profile is used to evaluate the recharge process as well as quantify the percolation rate from input rainfall.

The injected tritium profile at the Murattandi site is shown in Fig. 3b. The tritium was injected at a depth of 70 cm in June 1984, and soil sampling was done in March 1985 using a hand auger. The profile depth is 4 m, the centre of gravity (CG) of the profile is at 208 cm, and the soil column length between injection point and CG is 140 cm. The multiple peaks of injected tritium profile are indicative of the existence of highly permeable path(s) in the strata. Otherwise in homogeneous soils, where preferential flow paths are minimal, the tracer movement

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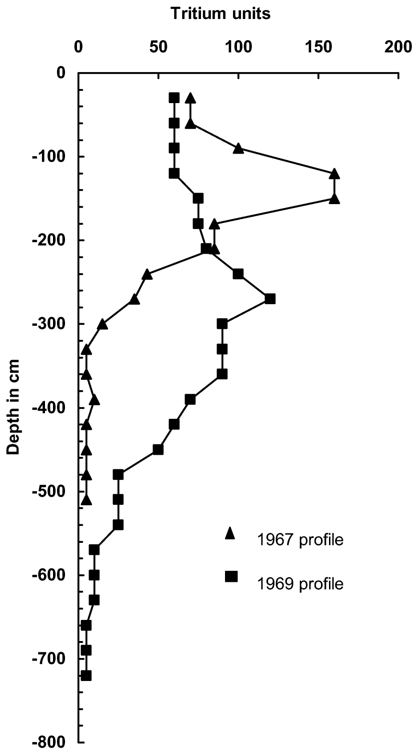

Fig. 4 Environmental tritium depth profile during 1967 and 1969 at the Balol study site in unconsolidated alluvial tracts of Gujarat, western India, utilised to evaluate piston flow and preferential flow recharge processes based on peak and integral tritium methods

will be primarily through molecular diffusion through which the tracer spreads and its profile will show a sharp peak. The observed tritium profile, therefore, does indicate preferential flow at depth.

For computation of recharge using the chloride profile method, the input rainfall chloride concentration of 8 mg/l is used for the studied three profiles in Pondicherry (Fig. 1, no. 6) viz. Lingareddypalayam (L), Murattandi (M) and Idaiyanchavadi (I) and the average chloride concentration of the studied profiles is 30.8, 50 and 54 mg/l, respectively. For the chloride ratio method of recharge evaluation, the groundwater chloride concentrations used are 35, 21 and 21 mg/l, respectively.

Unconsolidated Alluvial Formation

In order to evaluate the recharge processes in the unconsolidated alluvial tracts of Gujarat (Fig. 1, no. 2), environmental tritium studies comprising total tritium and peak tritium methods were carried out over a 2 year period (1967–1969). The environmental tritium profiles of 1967 and 1969 for the Balol study site, in Gujarat, are presented in Fig. 4. The tritium peak corresponding to 1963 is distinctly discernible in the two profiles.

The tritium peak in the 1967 profile is located at 85–145 cm depth. The tritium peak value is 160±10 TU. The lowest measured tritium in the profile is 5±3TU. The top strata of the profile did show relatively high tritium content (70 TU) as expected. After the tritium peak (160 TU) position at 85–145 cm, the tritium content gradually decreased to 5 TU, and the profile ended at 505 cm depth. The 1969 profile also showed relatively high tritium (60 TU) in the top strata, which gradually increased to a peak value (120 TU) at 235–265 cm depth. Further down the profile, the tritium gradually decreased to 5 TU, and the profile ended at 715 cm depth. Both 1967 and 1969 tritium profiles are used to examine temporal variations in the recharge processes and evaluate percolation rates (Table 1).

Table 1 Piston flow recharge values of Balol site, Gujarat, in unconsolidated alluvial formation, using environmental tritium methods

	1967	1969
Total tritium method		
^{3}H in profile ’*t*’ (*TU*)	3,227	3,205
^{3}H rain out (1962–1967) *T* (*TU*)	79,738	75,393 (1952–1969)
Recharge % (*t*/*T*)	4.05	4.2
Peak tritium method		
Depth of the tritium peak (cm)	85–145	235–265
Total moisture up to tritium peak θ (cm)	9.2	19.1
Total rain (1963–1967) *P* (cm)	261.7	322.7 (1963–1969)
Recharge % (θ/*P*)	3.5	5.9

Discussion

With a view to assess whether there is substantial contribution from preferential flow or not in different geologic formations, the three sets of recharge measurements carried out in the consolidated fractured granites, semi-consolidated sandstones and unconsolidated alluvial formation are plotted in Fig. 5a–c, respectively.

In the case of granites and gneisses, the four studied profiles (viz., Mohabatnagar-1 (MNR-1), Mohabatnagar (MNR), Maheshwaram-1 (MRM-1) and Maheshwaram (MRM) are indicative of divergent recharge values obtained by the chloride ratio method (*x*-axis) and the chloride profile method (*y*-axis; Fig. 5a). Whereas the recharge values on the *y*-axis, representing piston flow processes, are in the range of 20–40 mm (average 30 mm), the recharge values obtained with chloride ratio method, presented on the *x*-axis, are in the range of 70–170 mm (average 120 mm). Comparison of both the recharge measurements indicate that a substantial quantity of recharge (50–130 mm; average 90 mm) takes place through preferential paths that exist in the weathered hard rock zone. Such divergent recharge values can result from the highly inhomogeneous character of the weathered medium. From the above recharge results it is obvious that the preferential flow recharge process outweighs the piston flow process by two-and-a-half times (Table 2). Moreover, the variation in recharge values further indi-

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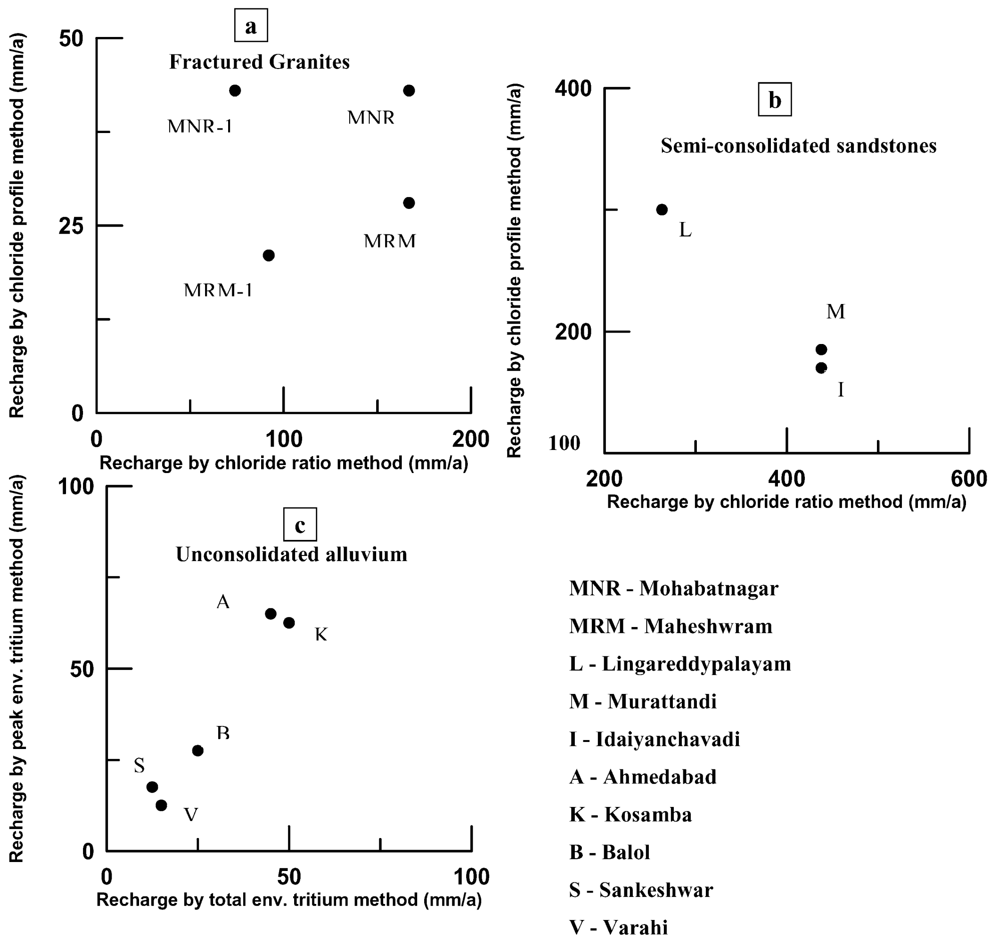

Fig. 5 A comparison of recharge rates estimated (mm/a) using the chloride ratio method/total environmental tritium method (*x* axis) with the chloride profile method/peak environmental tritium method (*y* axis) for **a** fractured granites, **b** semi-consolidated sandstones and **c** unconsolidated alluvium

Table 2 Recharge ranges for piston flow and preferential flow processes in three studied geological provinces

Formation	Piston flow recharge range	Total recharge range	Preferential flow recharge range	Preferential flow recharge % of total recharge
	Average			
Consolidated (Granites)	20–40 (30)	70–170 (120)	50–130 (90)	75
Semi-consolidated (Sandstone)	170–300 (235)	260–440 (350)	90–140 (115)	32
Unconsolidated (Alluvium)	13–66 (39.5)	13–50 (31.5)	–	–

cates divergent inhomogeneity of the weathered rock at the study sites. Thus, it is evident from this study that the aquifers in consolidated fractured granites get substantial recharge from the preferred flow process.

When considering the recharge measurements on semi-consolidated sandstones in Pondicherry, there is wide scatter (Fig. 5b). The studied three profiles (viz., Lingareddypalayam (L), Murattandi (M) and Idaiyanchavadi (I) indicate quite different recharge values. The L profile indicated a recharge rate of 300 mm by chloride profile method (piston flow value), and about 170–185 mm at I and M sites. Thus, the chloride profile method shows a recharge range of 170–300 mm (average 235 mm). The recharge to the aquifer computed by the chloride ratio method is in the range of 260–440 mm (average 350 mm). From the above recharge values, obtained with the chloride profile and ratio methods, it is evident that a significant contribution of preferential flow (90–140 mm; with an average of 33% of total recharge; Table 2) takes place in the semi-consolidated sandstone formation. Interestingly, the high recharge values in the semi-consolidated sandstones appear to be commensurate with the better geologic properties in comparison to those of consolidated fractured granites.

Recharge measurements in alluvial deposits are shown in Fig. 5c. From this figure it can be seen that

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groundwater recharge on both axes, obtained with peak tritium and total tritium methods, shows a fairly good linear relationship for five profiles (viz. Ahmedabad [A], Kosamba [K], Balol [B], Sankeshwar [S], and Varahi [V]) located in alluvial formations of Gujarat, western India (Fig. 1, no. 2). The peak tritium method shows a recharge range of 13–66 mm (average 39.5 mm) and the total tritium method, representative of combined effect of both piston flow and bypass flow, also measured almost the same recharge range (13–50 mm; average 31.5 mm; Table 2). Both the tritium methods show that the alluvial aquifer of Gujarat is primarily recharged by the piston flow process of soil moisture movement in the vadose zone. Both the recharge values also indicate that the regolith conducive to the recharge process is homogeneous. Thus, from the measured recharge values it can be said that the bulk of water movement in the alluvial tracts is due to piston flow.

Conclusions

The study of natural recharge processes carried out in consolidated fractured granites, semi-consolidated sandstones and unconsolidated alluvial formations, using isotopic and geochemical tracers, demonstrated a significant contribution from the preferential flow recharge process, especially in the former two geologic environs. Consequently, these findings necessitate re-evaluation of earlier natural recharge measurements, based entirely on the piston flow recharge process, so as to take in to consideration the preferential flow process in the assessment of total natural recharge potential of semi-arid aquifers.

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