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Environmental and injected tracers methodology to estimate direct precipitation recharge to a confined aquifer

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Abstract

Direct precipitation recharge to a confined aquifer is a vital parameter for groundwater budgeting, management, and modelling. We describe the conjunctive use of environmental isotopes and geochemical tracer technique, and injected tracer method to estimate direct precipitation recharge to an important coastal aquifer undergoing large withdrawal stress. The methodology evolved delineates the intake area of the confined aquifer based on environmental isotope and geochemical data and then utilises the recharge rates of the intake area only, as determined using injected tracer and geochemical data, to estimate the amount of recharge by direct precipitation to the confined aquifer.

1. Introduction

Evaluation of groundwater recharge is vital for proper groundwater management. The significance of estimating recharge further increases in the case of aquifers where the withdrawal rates are very high and are located close to the coast. In such cases properly estimated groundwater recharge will aid in taking measures to protect the groundwater from becoming salinised due to possible seawater intrusion, and help in groundwater management.

Several conventional, isotopic and geochemical tracer methods are available to estimate recharge to the aquifers (Zimmermann et al., 1967; Munnich et al., 1967; Smith et al., 1970; Datta et al., 1973; Sukhija and Rama, 1973; Allison and Hughes, 1974, 1978; Dincer et al., 1974; Sukhija and Shah, 1976; Athavale et al., 1980, 1983; Edmunds and Walton, 1980; Foster et al., 1982; Gupta and Sharma, 1984; Sharma

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and Hughes, 1985; Lerner et al., 1990). In the case of confined aquifers, the input to the aquifer may be direct precipitation in the intake (recharge) area and inter-aquifer flow, and the relative dominance of one over the other will depend on hydrogeological, and spatio-temporal geohydrologic characteristics of the studied basin.

In this paper we demonstrate how conjunctive use of environmental (isotopic and geochemical) and artificial tracers could lead to estimation of the direct precipitation input to the confined aquifers. The novel methodology evolved comprises elucidating the intake area of the confined aquifer based on environmental carbon-14 (supported by tritium, carbon-13 and chloride data), and then utilising the recharge rates determined for the intake area using the artificial and geochemical tracer methodologies to estimate the amount of direct precipitation recharge. This method will provide only the lower limit of recharge to the confined aquifer as inter-aquifer flows are not considered.

2. The study area

The present study area, Neyveli, lies in the South Arcot district of Tamilnadu, India, is bounded by 11°15′ and 11°50′ N latitudes, and 79°15′ and 79°50′ E longitudes (Fig. 1), and is known for the large lignite deposits occurring between 50 and 150 m depths. These deposits overlie a very important and highly pressured artesian aquifer of the Cuddalore Sandstone which is known as the Neyveli Aquifer. The hydrostatic pressure head exerted by the underlying aquifers stood at about 50 to 100 m above the lignite bed prior to the start of mining operations in 1961. Therefore the opencast mining of lignite in the area necessitated depressurisation of the underlying aquifer, which has been going on for more than three decades now, with a present withdrawal rate of 8000 to 9000 $m^3 h^{-1}$.

In the context of the present groundwater withdrawal rate for mining, power projects and irrigation etc., and because of close proximity of the aquifer to the sea, the adverse effect on water quality, if any, needs to be evaluated. The Neyveli Aquifer, therefore, has been investigated in depth through hydrogeological, hydrogeochemical, isotopic and modelling studies (Subramanyam, 1969; Sukhija, 1981; Gupta et al., 1986, 1992; Sukhija et al., 1987, 1990, 1993; Rangarajan et al., 1987, 1989).

Fig. 1 shows the location and geology of the Neyveli area. The Archaeans are exposed to the west, followed by the Cretaceous (Ariyalur stage), Tertiary (Miocene) and Recent (alluvial) deposits towards the east. The Tertiary sedimentary deposits, known as the Cuddalore formation, consist of argillaceous and ferruginous semi-consolidated sandstone, clay beds, water-bearing sands and lignite. These sediments occupy a major portion of the basin and have a vast groundwater potential. Groundwater in the Cuddalore sandstones exists under phreatic, semi-confined and confined conditions. Because of the extensive clay lenses, the confined aquifer is further divided into the upper and lower confined aquifers but as such these confined aquifers (as will be shown later) are connected to a common intake area. Fig. 2 shows the geological cross-section along A-A′ (Pudukkoraipettai to Annamalainagar) as in

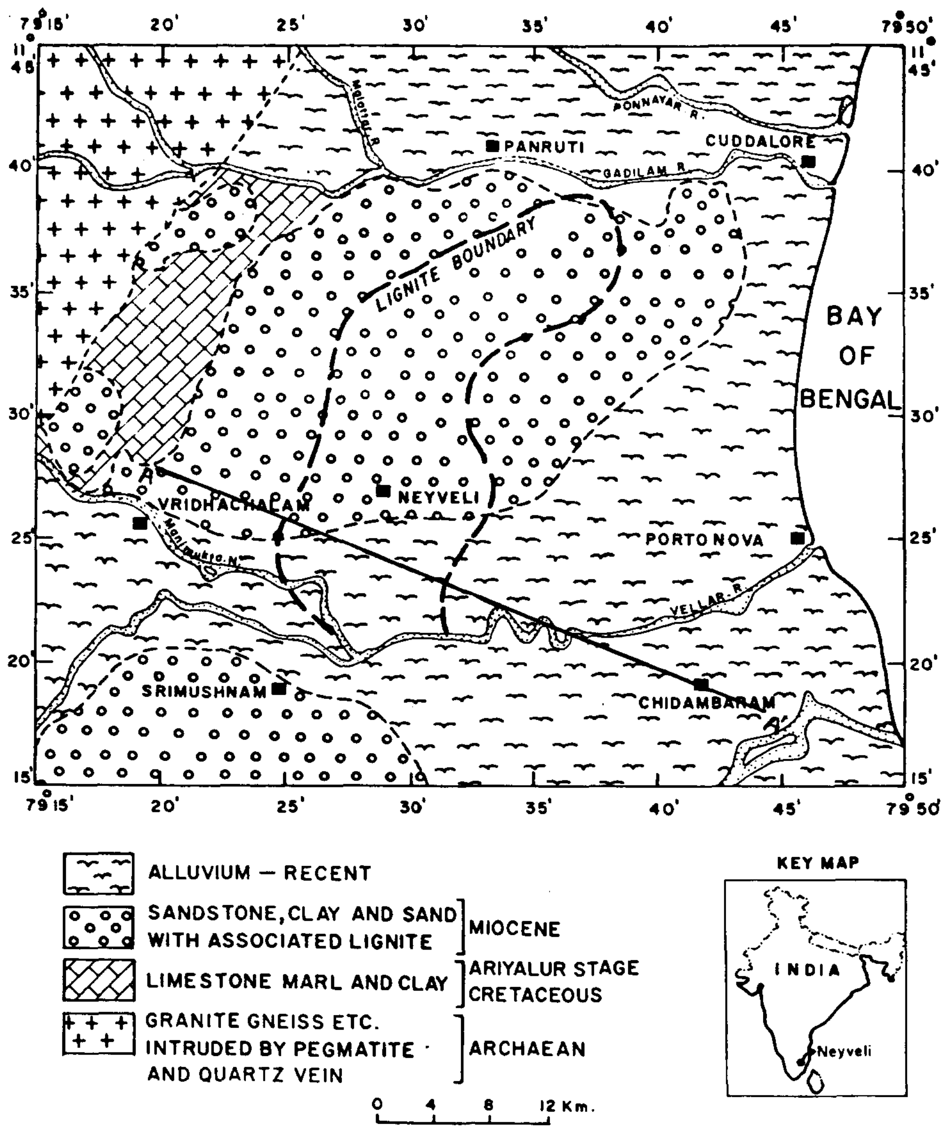

Fig. 1. Geological map of Neyveli area.

Fig. 1, and Fig. 3 presents a schematic section showing water levels of different aquifers near the second mine area.

The average annual rainfall of the study area is about 1200 mm, and the average annual maximum and minimum temperatures are 37° and 20°C, respectively. The area experiences both southwest (June–September) and northeast (October–December)

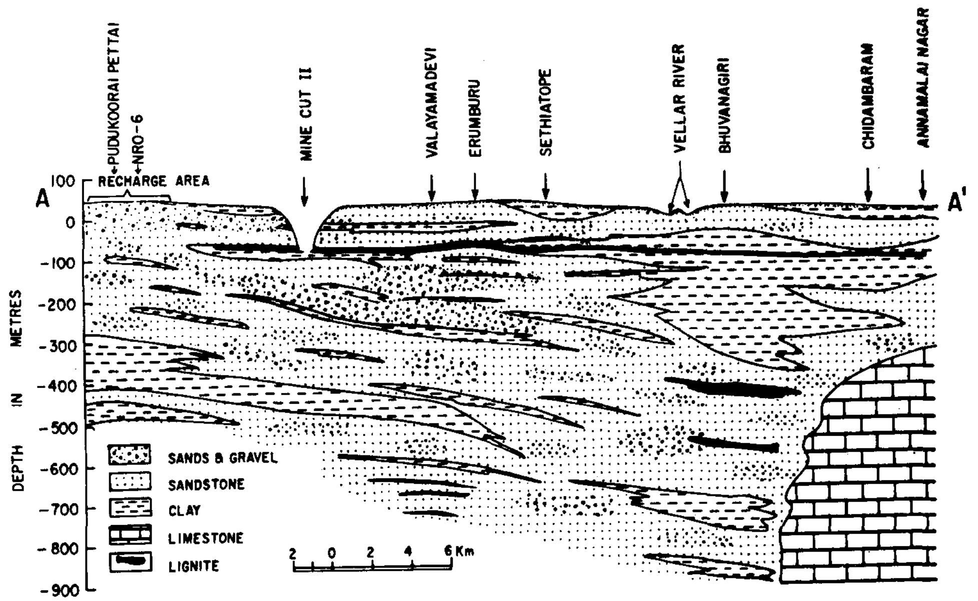

Fig. 2. Geological cross-section along A–A[1] as in Fig. 1.

monsoons. Maximum rainfall contribution takes place from September to October, and the maximum recharge occurs from September to January.

3. Field procedure and laboratory techniques

Water samples from 124 deep wells (Fig. 4, Table 1), from all over the study area, were collected and measured for environmental tritium, radiocarbon, carbon-13, and chloride concentration. For environmental tritium measurements only 0.5 l of water sample was collected; and for radiocarbon 60 to 100 l of water sample was necessary to precipitate the dissolved inorganic carbon species in the field by adding barium hydroxide and barium chloride, taking care to avoid atmospheric contamination. Environmental tritium and radiocarbon concentrations were measured using gas proportional counters with methane as a counting gas (Sukhija, 1982; Sukhija et al., 1990). The detection limit of the environmental tritium measuring system is 5 TU, and for the ^{14}C the limit is 2 pMC (percent modern carbon). Chloride was measured by the standard titration method in groundwater samples, and the spectrometric method was used in soil chloride analysis. The laboratory measurements are reproducible within ± 10% precision.

The artificial tritium tracer tagging technique, developed by Zimmermann et al. (1967), based on the 'Piston Flow Model' concept of groundwater movement, has become a handy tool of hydrologists for estimating the infiltration rate of water through the unsaturated zone to a phreatic aquifer. The tritium injection technique,

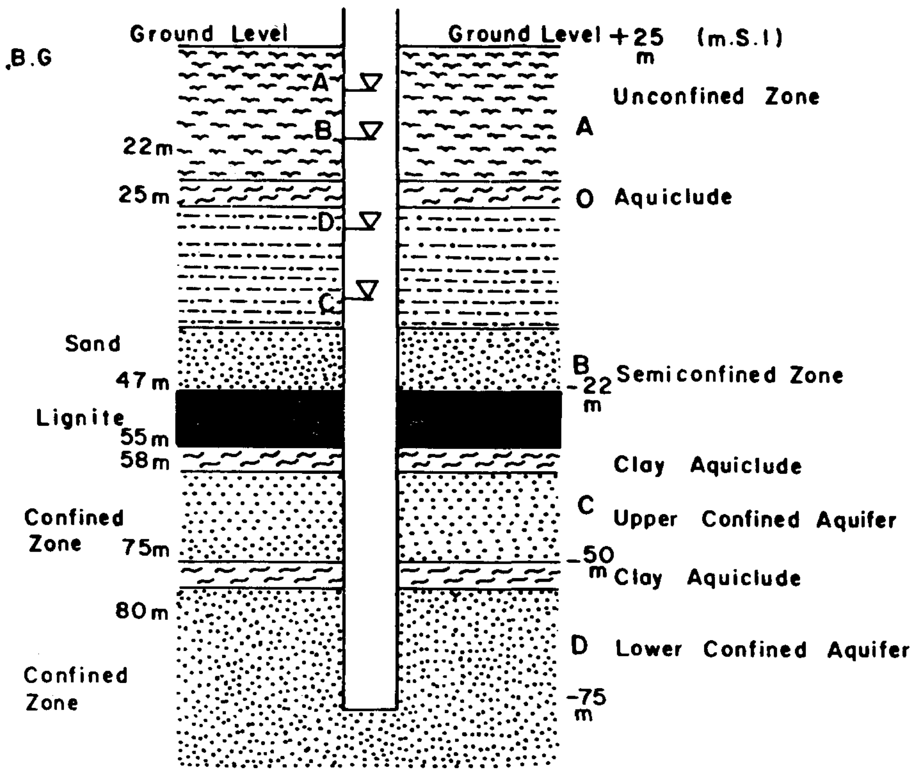

Fig. 3. Schematic cross-section representing important aquifers and their relative water levels.

sample collection and tritium activity measurement procedures are discussed in Athavale et al. (1980).

4. Results and discussions

4.1. Demarcation of recharge area for confined aquifers

In the Neyveli groundwater basin, above the lignite bed are a phreatic and a semiconfined aquifer, and two confined aquifers underlie it (Fig. 3). Before the present study was undertaken the recharge area was conceptualised on hydrogeological considerations. A detailed study carried out by the Geological Survey of India led to the observation of the existence of a deep water table zone which formed the basis for the recharge area. On lithological considerations the recharge area was later restricted to 350 km^2 (Fig. 5). In fact the importance of the extent of the recharge area was realised by the Neyveli Lignite Corporation, and accordingly environmental tritium measurements were initiated in 1966–1968. The tritium measurements on

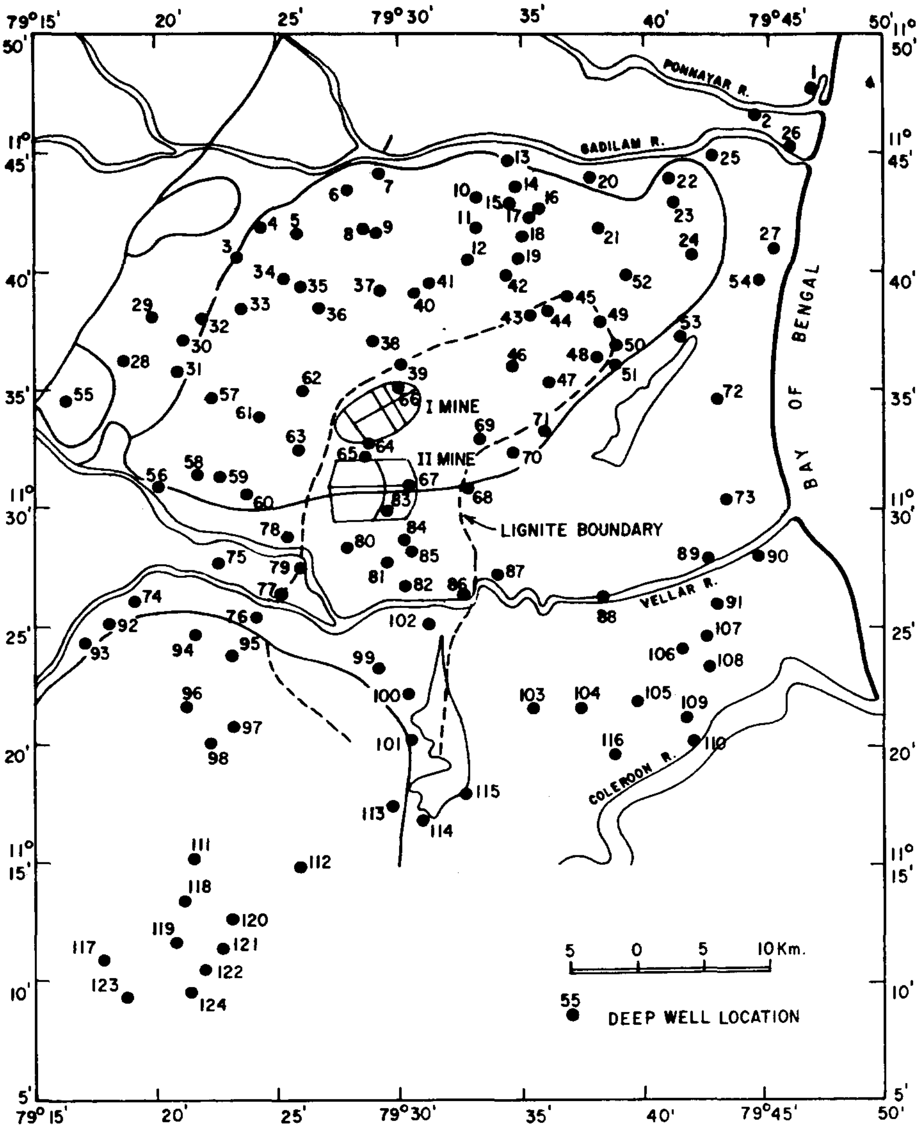

Fig. 4. Sampled well locations in the Neyveli study area.

the first set of samples collected from the hypothetical recharge area, discharge area and the mine area did not show any difference in the concentration of tritium as all the samples were below detection limit (5 TU). At that time it was considered that bomb tritium (of 1963–1964 precipitation) might be seen in some of the wells in the recharge area. However, later it became clear from the works of Munnich et al., (1967), Zimmermann et al., (1967), and Sukhija and Rama (1973) that because of the

Table 1
List of sampled wells shown in Fig. 4

1	Manapattu	43	Vegakollai	85	58M/11/1A-9
2	Chavadi	44	Chattram	86	Kilangadu
3	Palakollai	45	Mylamteruvu	87	Miralur Seedfarm
4	Vanambattu	46	Kilur	88	Bhuvanagiri
5	Toppiyankulam	47	Kanni Tamilnadu	89	B. Muttlur
6	Visur	48	T. Palayam	90	Parangipettai
7	Karukkai	49	Kattiyankuppam	91	Kilanuvambattu
8	Kudiyiruppu	50	Toppukollai	92	Kilimangalam
9	Attirikuppam	51	Ponnankuppam	93	Pelanduri
10	Aurobindo distil.	52	Kattusagaipuliyur	94	Attukuruchi
11	Kadampuliur	53	Ramanathakuppam	95	Redipalayam
12	Konjikkuppam	54	Sangolikuppam	96	Chinna Tadavanallur
13	Sattipattu	55	Periyavadavadi	97	Kavarapalayam
14	Muttirisankuppam	56	Virudhachalam	98	Andimadam
15	Melmambattu	57	Raghavankuppam	99	Valasakadu
16	Kilmambattu	58	Pudugopurapettai	100	Sozhatharam
17	Puduppalayam	59	Sattamangalam	101	Vanamadevi
18	Alagappasamudram	60	Kulappakkam	102	Malavaraya Nallur
19	Arasadikuppam	61	Mudanai	103	Perungalur
20	Naduvirapattu	62	Kolliruppu	104	Kodiyalam
21	Badrakkottai	63	Mangalam	105	Madapuram Vakkaramari
22	Tirumanikkuli	64	J.E. Quarters		
23	Kattayachavadi	65	II Mine (PTF)	106	Chidambaram
24	Ramapuram	66	NS-31	107	Kandamangalam
25	Thiruvandipuram	67	Uyyakkondaravi	108	Annamalai Uni.
26	Cuddalore hospital	68	Karunguli	109	Melkondalapadi
27	Kudikkadu (SIPCOT)	69	Vadalur	110	Vadakkumangudi
28	Puvanur	70	Rajakuppam	111	Kallathur
29	Pavalangudi	71	Kurunjippadi	112	Vettiyar Vettu
30	Guruvankuppam	72	Mettupalaiyam	113	Irrlatheruvu
31	Virareddikuppam	73	Athiyanallur	114	Karunakara Nallur
32	Aladi	74	T.V. Puttur	115	Lalpettai
33	Mohamburikuppam	75	C. Kiranur	116	Kilakarai Koppadi
34	Odappankuppam	76	Kallippadi	117	Udayarpalayam
35	Mudappuli	77	Kavanur	118	Suryamanal
36	Kattugudalur	78	Kammapuram	119	Sussaiapparpattinam
37	Perperiyankuppam	79	Devankudi	120	Chinnavalayam
38	Block-13	80	U. Adanur	121	Kazhuvanthondi
39	Block-24	81	Dharmanallur	122	Angarayanallur
40	Sorattur	82	Perianerkunam	123	T. Cholankurichi
41	Kilkuppam	83	58M/7/10-9	124	Vanathirayanpattinam
42	Siruttondamadevi	84	Valayamadevi		

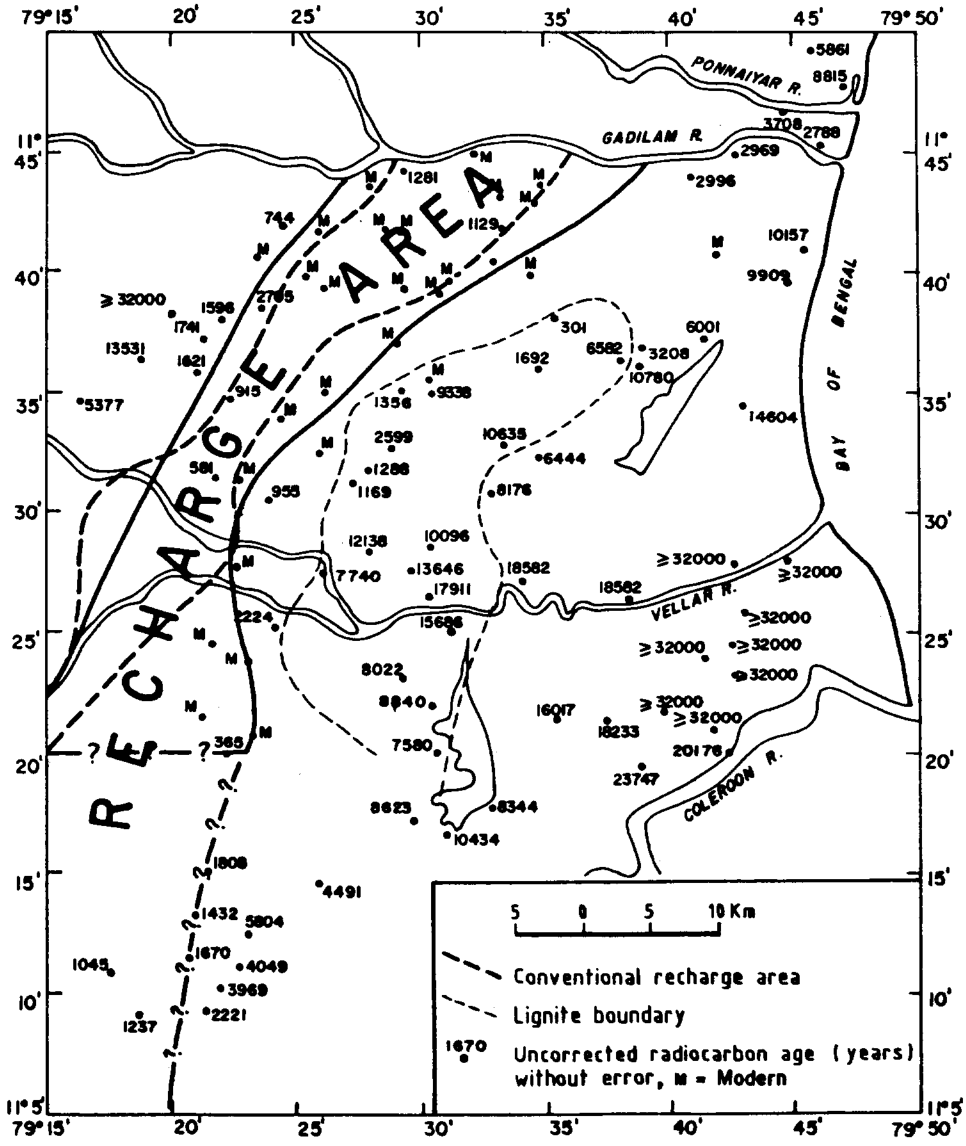

Fig. 5. Delineation of principal recharge area for Neyveli groundwater aquifer based on isotopic (^{14}C ages) data.

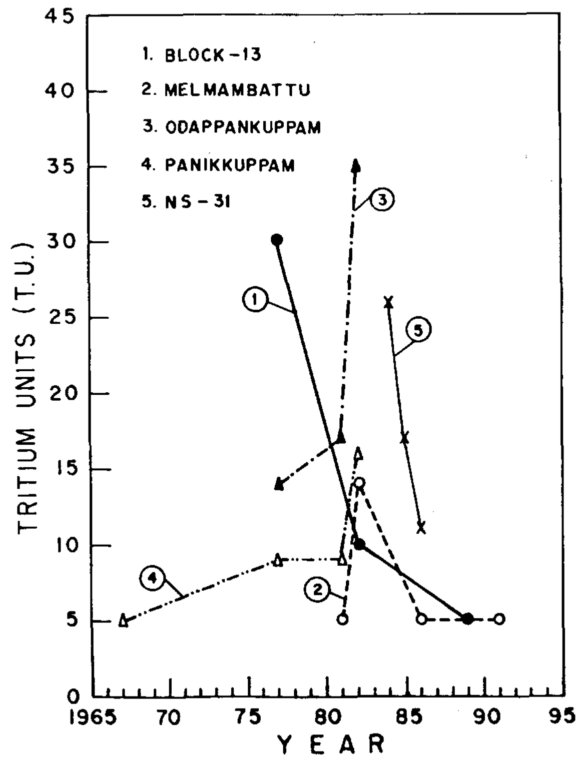

Fig. 6. Variation of environmental tritium with time in some of the wells located in the Neyveli recharge area.

predominant piston flow nature of movement of water in the unsaturated zone the mean travel time in the unsaturated zone before recharging the groundwater is of the order of two decades, especially when the water table is quite deep and the preferential flow of recharge water is minimal. This explains the absence of bomb tritium in the 1966–1968 samples. The ineffective role of preferential flow in the present study area can be evidenced by the following observations. The Cuddalore Sandstone, being generally semi-consolidated in nature, does not appear to have effective fractures and fissures, especially in the recharge area of Neyveli, to facilitate preferential flow. This aspect is clearly evidenced by the data of environmental tritium for some of the locations, as depicted in Fig. 6, where it is observed that only a few wells up to 100 m depth in the recharge area have shown the presence of thermonuclear tritium after one and half decades. The environmental chloride and injected tritium study carried out in Pondicherry, in the same geological formation (Cuddalore Sandstone), has also shown long-term transit time (~ 15 years) for the tracer in the unsaturated zone (Sukhija et al., 1988). A number of injected tritium profiles in the study area (Neyveli) indicate clear single peaks rather than multiple ones (Fig. 7). This pattern is

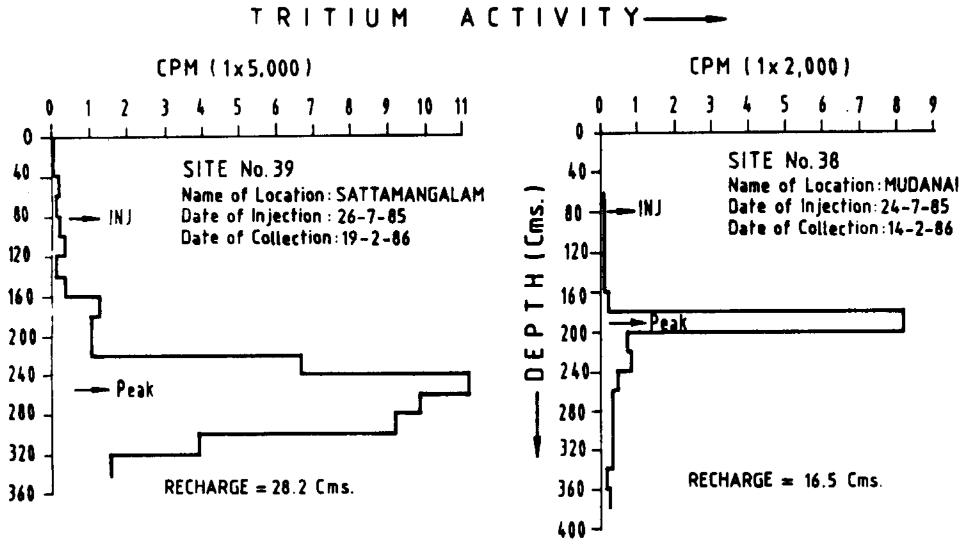

Fig. 7. Tritium profiles (1985–1986) (Rangarajan et al., 1989).

also indicative of the absence of preferential flow of recharge water in the unsaturated zone. Further, a criteria for evaluating the effective role of preferential flow, as suggested by Sharma and Hughes (1985), is utilised to compare the recharge rates obtained by the chloride profile method and by chloride concentration in groundwater in relation to that of precipitation. Our results using this criteria show that the recharge rate, as obtained by the ratio of chloride concentration in groundwater to that of precipitation is not higher than that determined by the soil chloride profiles in the Cuddalore Sandstones of Pondicherry. Thus the preferential flow process of recharge does not appear to be significant in the study area. This aspect is further discussed under Section 4.2.3.

The first isotopic evidence for the recharge area was obtained in 1977 when we observed that some of the samples viz., Block-13 and Odappankuppam showed measurable tritium (Fig. 6) in contrast to the samples from the Vadalur free flow (artesian well) area and mine area where no tritium signal was seen (Fig. 8). During 1981–1985 some more wells showed the presence of bomb tritium, and later because of continued lowering of tritium concentration in groundwater due to decay and mixing the emphasis shifted to radiocarbon measurements. The radiocarbon measurements in conjunction with other measurements clearly supported the concept of Principal Recharge (Input) Area.

From the definition of Principal Recharge (Input) Area it is expected that this area serves not only as the main vehicle to intercept the rainwater but also as an efficient transmission medium connected to confined aquifers. Therefore groundwaters of such an area are expected to be very young (having thermonuclear tritium/radiocarbon) and would indicate increasing groundwater ages in the flow direction

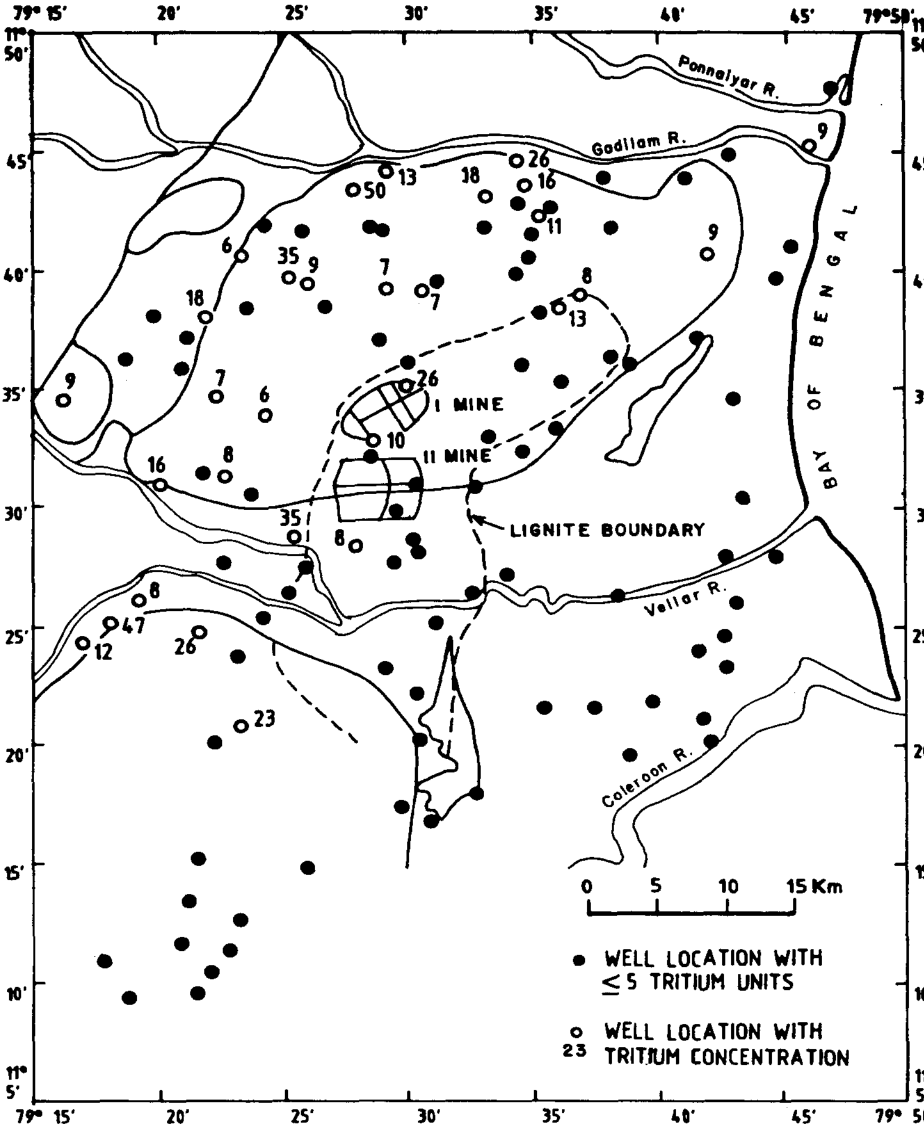

Fig. 8. Spatial distribution of environmental tritium in Neyveli deep groundwaters.

(Figs 5 and 8). On the same basis it is expected that groundwaters in the recharge area would have low chloride (20–30 ppm) (Fig. 9) and carbon-13 (-23 to -17‰ PDB) values (Fig. 10). We have tried to utilise all such indicators, but have based our recharge boundaries principally on radiocarbon measurements and hydrogeological considerations. The western boundary of the recharge area is broadly governed by the Cretaceous-Tertiary contact and the eastern boundary by the combined

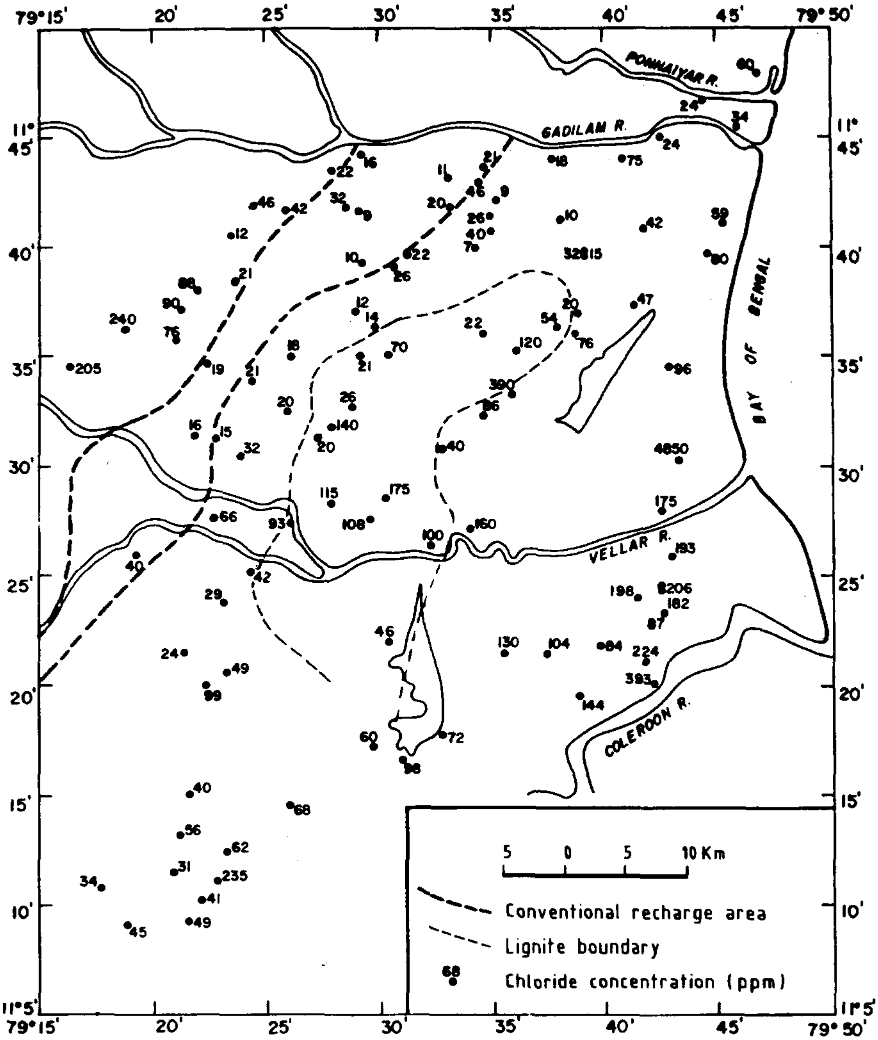

Fig. 9. Spatial variation of chloride concentration (ppm) in groundwater.

confinement due to the associated clay beds sandwiching the lignite bed. In the case of certain wells where we have come across dilution of ^{14}C by CaCO3 (owing to the well tapping the Cretaceous formation), we have utilised other indicators like tritium and chloride. From the carbon-14 measurements, we observe that in the extreme west we have ^{14}C ages varying between $\geqslant$32 000 and 2000 years and 'Modern' age samples towards the east (Fig. 5). On the western side of the recharge area the 50 year contour (Fig. 11) shows a wavy nature because of sudden changes in carbon-14 ages due to possible dilution of ^{14}C by Cretaceous limestone in the tapped aquifers. For example, we have included Mohamburikuppam (2705 years)

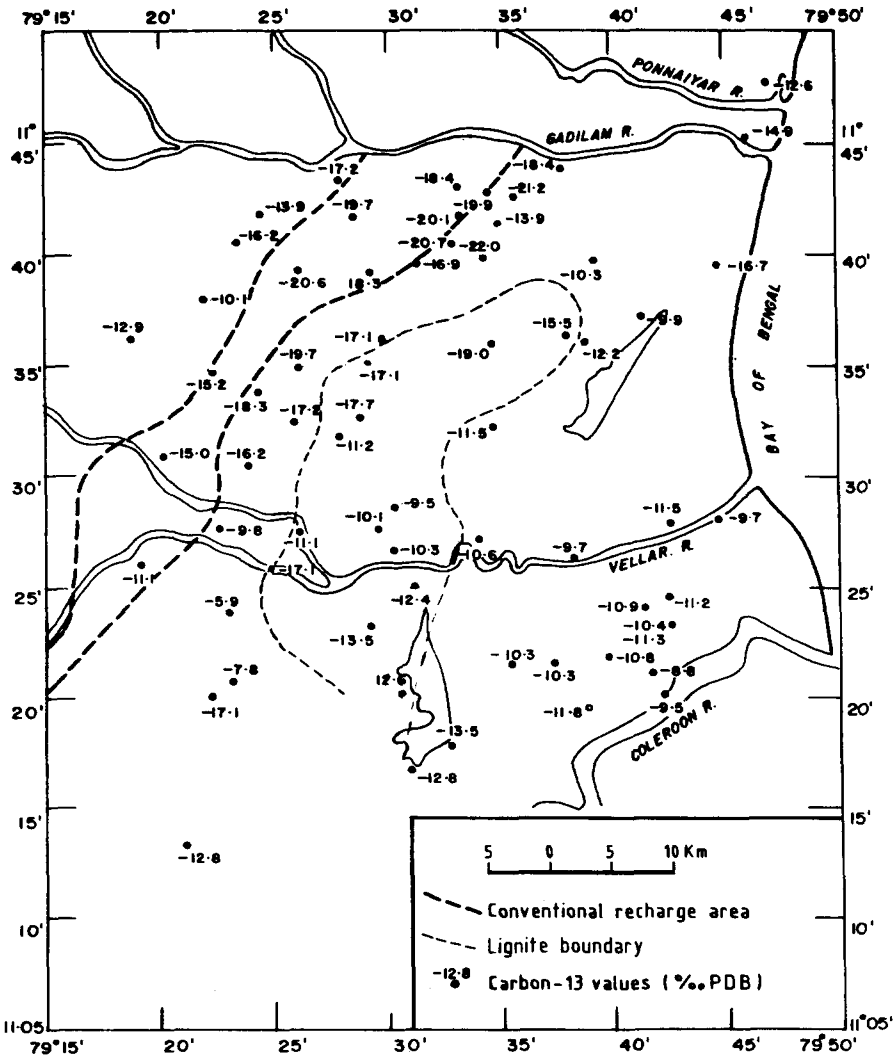

Fig. 10. Spatial variation of carbon-13 (‰PDB) in groundwater.

and Raghavankuppam (915 years) in the recharge area because these samples contained low chloride, although situated on Tertiary outcrops, but showed increased apparent ^{14}C ages because of dilution from Cretaceous rocks in which the wells are completed. On the contact zone, except for a few exceptions with ages of 1500–2000 years, we observe a large number of samples with modern ages. Table 2 shows the data for the wells located between the Cretaceous and Tertiary boundary and the western lignite boundary (Fig. 5); about 75% of the samples show modern ages and such samples are located in a belt striking southwest–northeast from the Vellar River

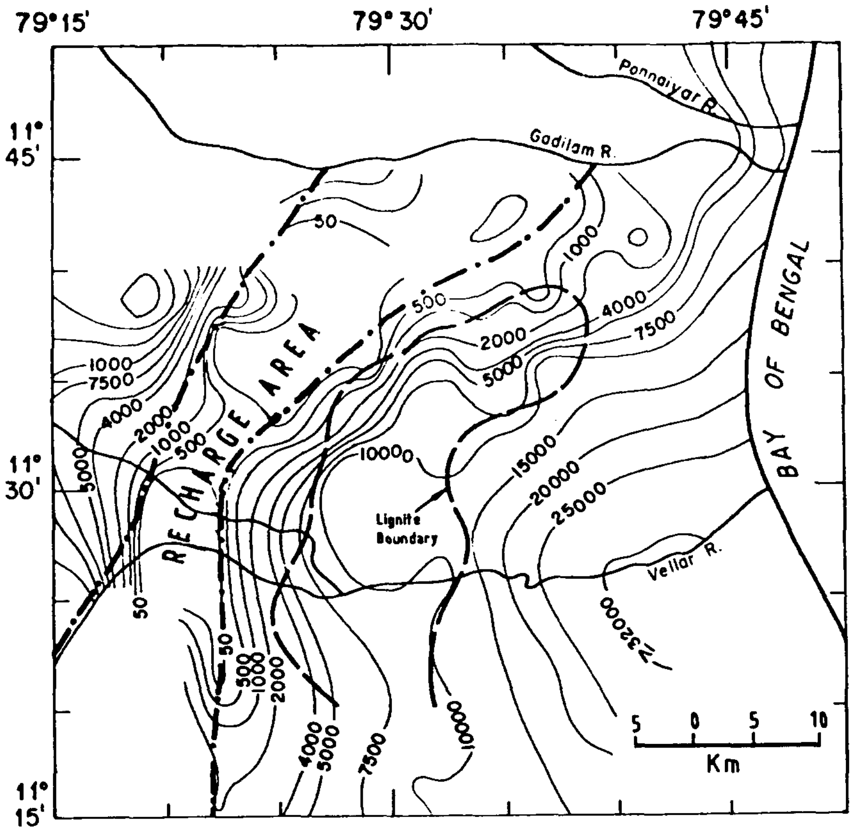

Fig. 11. Isochrones based on uncorrected radiocarbon ages of deep groundwater.

in the south to Gadilam River in the north, delineated as the recharge area. The eastern boundary of the recharge area is based on the 50 year contour (Fig. 11) which essentially runs parallel to the lignite boundary. As the water leaves the recharge area the age increases in the direction of movement and higher ^{14}C ages are noted. Tritium, chloride and carbon-13 data (Figs. 8, 9, 10) serve usefully to support the delineation of the recharge area though not used exclusively for the purpose. Recent measurements of the 1991 sample collection have helped in observing the extension of the recharge area in the southern Jayakondam area. Radiocarbon measurements also show the concentration to be about 80 to 95 pMC and increasing in the northeast. The recharge area thus demarcated is more than 600 sq km^2 (Fig. 11).

We have recent evidence that the extent of the recharge area appears to be expanding towards the mine area because of continued depressurisation of the aquifer, thereby bringing in very young water from the recharge area and old water (from the previously artesian flow area) close by, resulting in the cramping of radiocarbon contours (these results will be published elsewhere).

Table 2
Isotopic and chloride data for the recharge area

Location	Well type	Well depth (m)	Year of collection	^{14}C age (years)[a]	^3H TU[b]	$\delta^{13}C$ ‰PDB	Cl ppm
Alagappasamudram	WSW[d]	247–270	5/86	Modern[c]	$\leqslant 5$	−13.9	26
Andimadam	DEEP	194–286	5/86	494 ± 300	8 ± 2	–	75
Attirikuppam	WSW	122	5/86	Modern	$\leqslant 5$	–	9
Attukuruchi	HP[e]	50	7/85	Modern	22 ± 5	−17.7	41
Aurobindo distl.	DEEP	175	5/86	Modern	17 ± 3	−18.4	11
Block-13	WSW	103–139	12/77	Modern	35 ± 5	–	–
Chinna Tadavanallur	WSW	98	5/86	Modern	–	–	24
C. Kiranur	WSW	91	7/85	Modern	$\leqslant 5$	−9.8	66
Kadampuliur	WSW	116–128	7/84	Modern	$\leqslant 5$	−20.1	20
Karukkai	NRO-5	47–77	10/88	1281 ± 325	13 ± 2	–	16
Kattugudalur	WSW	73–111	12/77	Modern	14 ± 5	–	–
Kavarapalayam	NRO-12	100	10/88	Modern	$23 + 3$	−7.8	49
Kilkuppam	WSW	136–154	5/86	Modern	$\leqslant 5$	−16.9	22
Kilmambattu	WSW	54	10/88	Modern	$\leqslant 5$	−21.2	–
Kolliruppu	WSW	137	7/85	Modern	$\leqslant 5$	−19.7	18
Konjikkuppam	–	–	6/81	Modern	–	−20.6	–
Kudiyiruppu	WSW	76–124	6/81	Modern	$\leqslant 5$	−19.7	32
Melmambattu	WSW	135	6/81	Modern	$\leqslant 5$	−19.7	24
Mohamburikuppam	HP	146	5/86	2705 ± 387	$\leqslant 5$	–	21
Mudanai	WSW	110	7/85	Modern	6 ± 5	−18.3	21
Mudappuli	WSW	98–143	6/81	Modern	$\leqslant 5$	−20.6	–
Muttirisankuppam	WSW	46	5/86	Modern	16 ± 3	–	21
Naduvirappattu 1	WSW	49	5/86	Modern	$\leqslant 5$	−18.4	18
Odappankuppam	WSW	70–95	6/81	Modern	17 ± 3	–	–
Panikkuppam	WSW	41–61	6/81	Modern	6 ± 3	–	16
Perperiyankuppam	WSW	–	7/85	Modern	7 ± 3	−18.3	10
Pudugopurapettai	WSW	56–77	5/86	581 ± 304	$\leqslant 5$	–	16
Puduppalaiyam	WSW	160	5/91	1257 ± 176	11 ± 5	–	9
Raghavankuppam	–	–	7/85	915 ± 315	7 ± 5	−15.2	19
Reddipalayam	WSW	145	10/88	Modern	$\leqslant 5$	−5.85	29
Sattamangalam	WSW	86–130	7/85	Modern	8 ± 3	–	15
Siruttondamadevi	WSW	140	10/88	Modern	$\leqslant 5$	−21.9	7
Sorattur	WSW	150	7/85	Modern	7 ± 5	–	26
Toppiyankulam	WSW	91	5/86	Modern	$\leqslant 5$	–	42
T. Cholankurichi	JK-203[f]	–	5/91	1237 ± 176	$\leqslant 5$	–	45
T. V. Puttur	NRO-9	87–135	10/88	4795 ± 491	8 ± 3	−11.1	40
Udayarpalayam	JK-217	–	5/91	2186 ± 146	$\leqslant 5$	–	34
Uttangal Mangalam	WSW	–	7/85	Modern	–	−17.2	20
Virudhachalam 2	WSW	198	6/81	1351 ± 404	$\leqslant 5$	−15.2	–
Visur	WSW	28–52	6/81	Modern	6 ± 3	−17.1	22

[a] Years, uncorrected ^{14}C years. [b] TU, tritium units. [c] Modern, ^{14}C age ~ 30 years (but rounded off to 50 years in Fig. 11). [d] Water supply well. [e] Hand pump. [f] Observation well.

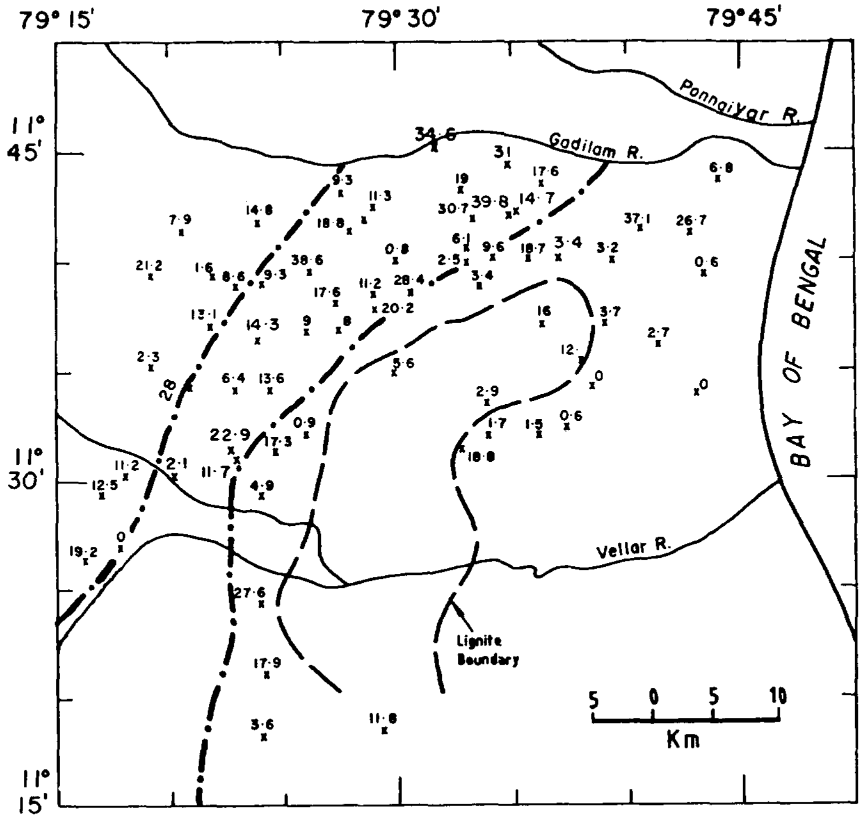

Fig. 12. Percentage of rainfall recharge based on injected tritium method (Rangarajan et al., 1989).

4.2. Direct precipitation input to the confined aquifer

Input to the confined aquifer system was estimated using two approaches: (1) injected tracer technique, (2) environmental chloride method.

4.2.1. Injected tracer technique

Rangarajan et al. (1987, 1989) carried out the investigation with the objective of determining the recharge for the phreatic aquifer using the injected tritium technique. The recharge estimates within the demarcated recharge area varied between 0.5% and 40% of the local rainfall. For estimation of recharge to the confined aquifer we took the mean of recharge values of only those 34 sites which were located in the recharge area delineated as discussed above. The fractional recharge values from the local rainfall are indicated in Fig. 12, and the average was calculated to be 15.5%.

4.2.2. Environmental chloride method

For a conservative geochemical tracer like chloride to be applicable to estimate

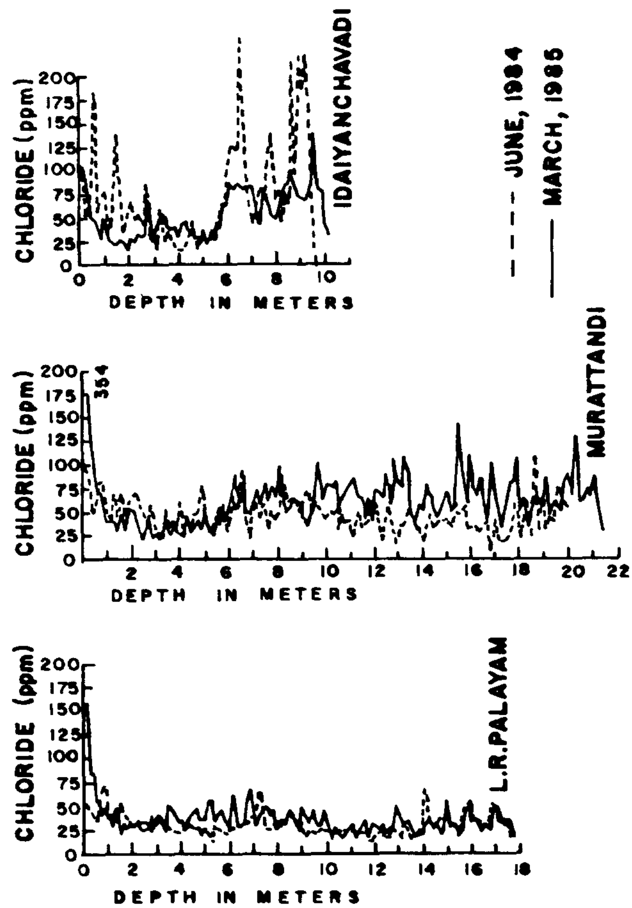

Fig. 13. Soil chloride profiles in Cuddalore Sandstone formation of Pondicherry.

recharge, the important assumptions are that the water and solute percolation down a profile follow the piston flow pattern; rainfall as the only principal source of input; well drained lithology; a monotonously flat ground (for lesser run-off component); no other sources (like fertilisers) or sinks for it; no change in land use pattern; and no change in the natural chloride concentration due to vegetative recycling below the root zone (Walker and Hendrickx, 1995). In such situations, the mass balance of chloride solute seems applicable as in the case of environmental tritium for recharge estimates and steady state concentration of chloride in soil profiles can be used (Allison and Hughes, 1978; Edmunds and Walton, 1980).

Such an approach was utilised in estimating long term recharge in Pondicherry (Sukhija et al., 1988), which is about 50 km away from the present study area. As the geological formation and the environmental conditions are very similar for both regions, it is justifiable to extend the recharge values, obtained for the selected sites

Table 3
Recharge estimation by soil chloride profiles in Cuddalore Sandstones of Pondicherry

Site	Steady state chloride conc. in the profile (ppm)		Recharge (%)		Mean recharge (%)
	6/1984	3/1985	6/1984	3/1985	
L.R. Palayam	31.2	34.7	27.5	23.7	25.6
Murattandi	46.3	61.3	17.7	13.4	15.5
Idayanchavadi	72.1	53.3	11.4	15.3	13.4

in Pondicherry, to the present study area (Neyveli). Fig. 13 shows the solute profiles in the Cuddalore Sandstones of Pondicherry. The solute profile at Idayanchavadi shows increased chloride values at greater than 6 m depth which can be ascribed to the existence of clay lenses there. In the root zone, or top 1 m of soil, high solute concentrations indicate non-steady and responsive state to environmental conditions. Consequently the top 90 cm solute values were not considered for recharge calculations. The recharge values obtained for the Cuddalore Sandstones of Pondicherry are shown in Table 3. The overall average recharge value for the Cuddalore Sandstones is thus calculated to be 18% of the local average annual precipitation.

The second approach (Eriksson and Khunakasem, 1969) which we have adopted is to compare the average chloride concentration of groundwater in the recharge area with that in the precipitation. The basis for such a simplistic approach is obtained from the above mentioned solute profiles (Fig. 13), wherein the solute distribution down the profile suggests a homogeneous rather than a combination of rainfall input and lithologic leached input (Edmunds and Walton, 1980). Notwithstanding, the aforesaid assumptions can be thought of applicable here also. Further we are considering the groundwater samples in the recharge area; it implies there is no lateral inflow of groundwater chloride, and as there are no secondary sources of chloride, its concentration in groundwater is governed by only the recharge process (inverse of evapotranspiration of precipitation). As the average concentration of 40 groundwater samples in the recharge area is 30 ppm, and the average estimated rainfall chloride is 5 ppm (Sukhija et al., 1988), the ratio provides one-sixth (or 16.6%) of rainfall recharge, assuming no contribution either through overland flow, irrigation sources and no change in land use pattern in the delineated recharge area. The delineated recharge area is not irrigated and is devoid of extensive vegetation (except that of scattered cashew plantations) and hence assumptions for the method appear to be valid. As the recharge rate using the soil chloride profile method and the groundwater chloride method are found to be in conformity, we may further infer that bypass flow mechanisms in the unsaturated zone of the recharge area are minimal. Conversely, had this mechanism been dominant the solute concentration in groundwater would have been reduced, and alternatively if there had been a secondary source of chloride due to leaching of low permeability deposits it would have given rise to higher mean chloride values. However, only a few samples in Table 2 suggest such secondary sources from some clay layers.

Since the two approaches provide similar results, it may be worthwhile to assume that both the approaches are applicable in the investigated area. Further to illustrate these points, we had compared the recharge rates obtained by the soil chloride method and the injected tritium technique in Pondicherry, and found that the results from the two methods are in agreement within 30% (Sukhija et al., 1988). Considering all these points and the results from injected tritium data in Neyveli (Rangarajan et al., 1987, 1989), we feel that an average of 16–18% fractional rainfall contributes to the confined aquifer. Thus the recharge to confined aquifers estimated on the basis of injected tritium and chloride data should be a realistic value. As the mean annual rainfall of the study area is 1200 mm, the direct precipitation input to the confined aquifer system throughout the 600 km^2 intake area, is calculated to be 111 mcm $year^{-1}$. However, as mentioned earlier this quantity is only a lower limit for two reasons: as the intake area may extend farther in the south, and inter-aquifer flows are not considered. The inter-aquifer recharge was estimated by Gupta et al., (1992) using a mathematical model. Though the Neyveli Aquifer is a multilayer system, they assumed single layer model due to paucity of available hydrogeological data. They have estimated time varying inter-aquifer recharge (from phreatic to upper confined aquifer) to be from 60 to 109 mcm $year^{-1}$, and the upward feed from the lower confined aquifer varying from 12 to 50 mcm $year^{-1}$ during the model calibration period 1979 to 1990. However, we have neither isotopic nor geochemical evidence for such a large vertical feed, because one could expect the presence of thermonuclear tritium or high carbon-14 concentrations with time over the area where downward flow has been taking place since the commencement of mining operations. On the other hand we have observed the presence of thermonuclear tritium and high ^{14}C concentrations in wells located either in the recharge area and/or mine well samples close to the recharge area (Figs 5 and 8). Further predominance of lateral movement of water into the mine area is evidenced from the temporal changes in carbon-14 and chloride measurements done on samples collected in 1985 and 1991; and also we have observed the crowding of isochrons and isochlors for the 1991 sampling located between the recharge and the mining area (these results will be published elsewhere). Thus more measurements on hydrogeological parameters are required to evaluate accurately the vertical flow across the aquifer boundary.

Thus, we have estimated minimum direct precipitation recharge to the Neyveli confined aquifers to be 111 mcm $year^{-1}$ and this evaluation will help in the preparation of the groundwater budget and groundwater model especially in the wake of continued depressurisation of the coastal Neyveli aquifer due to mining operations, agricultural, industrial and domestic needs.

5. Conclusions

Isotopic and geochemical studies carried out in the Neyveli Groundwater Basin comprised measurements of environmental tritium, radiocarbon, carbon-13, and chloride contents. From the series of samples collected in different years it has been shown that the northwest belt is essentially the principal recharge area wherein very large number of groundwater samples have 'Modern' ages, bomb tritium is seen in a number of samples, chloride content is very low, and carbon-13 contents are also low. From this area the movement of groundwater is evidenced towards the confined aquifer. The area so demarcated is about 600 km^2, but sparse data in the south indicates that this area could be still larger, which needs to be investigated by further detailed studies. The precipitation recharge within this area is calculated to be 16 to 18% of mean annual rainfall, and thus a lower limit of 111 mcm $year^{-1}$ input is estimated for the confined aquifer, as increased recharge area and inter-aquifer flow will add to the total input to the confined aquifer.

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References

Allison G.B. and Hughes, M.W., 1974. Environmental tritium in the unsaturated zone; estimation of recharge to an unconfined aquifer. Proc. Symp. Techniques in Isotope Hydrology, I, IAEA, Vienna, pp. 52–72.

Allison, G.B. and Hughes, M.W., 1978. The use of environmental chloride and tritium to estimate total recharge to an unconfined aquifer. Aust. J. Soil Res., 16: 181–195.

Athavale, R.N., Murthi, C.S. and Chand, R., 1980. Estimation of recharge to the phreatic aquifers of the Lower Maner Basin, India, by using the tritium injection method. J. Hydrol., 45: 185–202.

Ahavale, R.N., Chand, R. and Rangarajan, R., 1983. Groundwater recharge estimates for two basins in the Deccan trap basalt formation. Hydrol. Sci. J., 28(4): 525–538.

Datta, P.S., Goel, P.S., Rama, and Sanghal, S.P., 1973. Groundwater recharge in Western Uttar Pradesh. Proc. Ind. Acad. Sci., LXXVII (A1): 1–12.

Dincer, T., Al-Murgin, A. and Zimmermann, U., 1974. Study of infiltration and recharge through the sand dunes in arid zones with special reference to the stable isotopes and thermonuclear tritium. J. Hydrol., 23: 79–109.

Edmunds, W.M. and Walton, N.R.G., 1980. A geochemical and isotopic approach to recharge evaluation in semi-arid zones; past and present. Proc. Symp. on Arid Zone hydrology investigations with isotope techniques, IAEA, Vienna, pp. 47–68.

Eriksson, E. and Khunakasem, V., 1969. Chloride concentration in groundwater, recharge rate and rate of deposition of chloride in the Israel coastal plain. J. Hydrol. 7: 178–197.

Foster, S.S.D., Bath, A.H., Farr, J.L. and Lewis, W.J., 1982. The likelihood of active groundwater recharge in the Botswana Kalahari. J. Hydrol., 55: 113–136.

Gupta, S.K. and Sharma, P., 1984. Soil moisture transport through the unsaturated zone: tritium tagging studies in Sabarmati basin, Western India. Hydrol. Sci. J., 29(2): 177–189.

Gupta, C.P., Thangarajan, M., Gurunadha Rao, V.V.S., Sharma, M.R.K., Ramachandra, Y.M., Singh, V.S. and Sankaran, S., 1986. Regional groundwater modeling studies in Neyveli Basin. Technical Report, NGRI, Hyderabad, pp. 1–138.

Gupta, C.P., Thangarajan, M., Sarma, M.R.K., Singh, V.S., Ahmed, S. and Rao, V.V.S.G., 1992. Modeling of Neyveli Aquifer System. Technical Report, NGRI, Hyderabad, 3 volumes: vol. 1, pp 1–62; vol. 2, pp F1–F125; vol. 3, pp T1–T80.

Lerner, D.N., Issar, A.S. and Simmers, I. (Editors), 1990. Groundwater Recharge: A Guide to Understanding and Estimating Natural Recharge. Vol. 8. IAH, Heinz Heise, Hannover, pp. 1–345.

Munnich, K.O., Roether, W. and Thilo, L., 1967. Dating of groundwater with tritium and ^{14}C. Isotopes in Hydrology. IAEA, Vienna, pp. 305–320.

Rangarajan, R., Muralidharan, D., Deshmukh, S.D., Hodlur, G.K., Murthy, N.N. and Gangadhara Rao, T., 1987. Estimation of recharge in Neyveli Groundwater Basin by injected tritium method for 1985 monsoon. Tech. Report No. NGRI-87-ENVIRON-20, pp. 1–52.

Rangarajan, R., Deshmukh, S.D., Muralidharan, D. and Gangadhara Rao, T., 1989. Recharge estimation in Neyveli Groundwater Basin by tritium tagging method. Tech. Rep. No. NGRI-89-ENVIRON-65, pp. 1–63.

Sharma, M.L. and Hughes, M.W., 1985. Groundwater recharge estimation using chloride, dueterium and oxygen-18 profiles in the deep coastal sands of Western Australia. J. Hydrol. 81: 93–109.

Smith, D.B., Wearn, P.L., Richards, H.J. and Rowe, P.C., 1970. Water movement in the unsaturated zone of high and low permeability strata by measuring natural tritium. Isotope Hydrology, IAEA, Vienna, pp. 73–87.

Subramanyam, V., 1969. Geology and groundwater aspects of the Neyveli Lignite Field, South Arcot District, Madras State. Mem. G.S.I., Vol. 94: 1–298.

Sukhija, B.S., 1981. Environmental radioisotopes in the study of groundwater in the Neyveli Lignite Mine area, Tamil Nadu, India. Indian Geohydrol. XV: 221–231.

Sukhija, B.S., 1982. Environmental radioisotope studies in groundwater hydrology. Geophys. Res. Bull., 20(3): 225–242.

Sukhija, B.S. and Rama, 1973. Evaluation of groundwater recharge in the semi-arid region of India using environmental tritium. Proc. Indian Acad. Sci., 77(6): 279–292.

Sukhija, B.S. and Shah, C.R., 1976. Conformity of groundwater recharge rate by tritium method and mathematical modelling. J. Hydrol., 30:167–178.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P. and Chand, R., 1987. Conformity of recharge rates by environmental chloride method and injected tritium technique in coastal aquifers. In: S. Awadulla and Ismail Md. Noor (Editors), Proc. Int. Symp. on 'Groundwater and Environment', Kuala Lumpur, Malaysia. 22–26 June, pp. I 1–13.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P. and Chand, R., 1988. Validity of the environmental chloride method for recharge evaluation of coastal aquifers. Indian J. Hydrol. 99: 349–366.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Giri, V.Y. and Syed Hussain, 1990. Environmental tritium in mine hydrology studies. Bul. Radiation Protect. 13(1) TR/18: 71–74.

Sukhija, B.S., Reddy, D.V., Nagabhushanam, P., Syed Hussain, Giri, V.Y. and Patil, D.J., 1993: Isotope studies of Neyveli Groundwater Basin. NGRI Tech. Report No. NGRI-93-GW-149, Hyderabad, pp. 1–141.

Walker and Hendrickx, 1995. Precipitation recharge. In: Groundwater Recharge and Monitoring. IAH, in press.

Zimmermann, U., Munnich, K.O. and Roether, W., 1967. Downward movement of soil moisture traced by means of hydrogen isotopes. Geophys. Mono. Am. Geophys. Union. 11: 28–36.