Estimation of natural recharge and its relation with aquifer parameters in and around Tuticorin town, Tamil Nadu, India

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This article describes the estimation of natural recharge and determination of aquifer parameters of a watershed located in coastal belt around Tuticorin town, Tamil Nadu, India, using radioactive tracer and pumping test methods. Recharge measurements were made at several spots to weathered gneiss, shale limestone, quartzite and coastal alluvium formations using tritium injection technique. Static water level was also monitored spatially and temporally. This study indicates that the natural recharge caused by rainfall varies from 15.5 to 107.2 mm with the average value of 61.7 mm, which is equivalent to 10.6% of seasonal rainfall that occurred during the experimental period. The recharge rates were also found to be linearly correlated with the water-table fluctuations at nearby existing wells in the different geological formations. From the recharge data and the change of water level in the exiting wells, the specific yields of shallow phreatic aquifers were estimated for different formations, i.e. 7.25, 9.57 and 10.57% for weathered charnokite, shale limestone and coastal alluvium respectively, which show good consistency with the results obtained from the pumping tests.

Keywords: Costal belt, natural recharge, pumping test, tracers.

FOR the proper management of groundwater resources in semi-arid regions (mostly coastal belts), it is essential to measure the groundwater recharge and aquifer parameters. Groundwater recharge may be estimated by several conventional methods (i.e. groundwater balance, lysimeter, etc.)[1–6]. However, the tracer technique is only a direct method for estimation of groundwater recharge[7,8]. This tracer technique has been deployed for estimating the recharge on the basis of piston flow model. Several workers[9–13] have shown the usefulness of the injected tracer technique for the evaluation of natural recharge. Pumping test is a well-known method to evaluate the aquifer parameters[14]. During the past few decades several researchers have proposed their own methods of approach for analysing pumping test data[14–17]. Analytical/conventional methods involve either curve matching or finding inflection points or for special cases, fitting straight lines to the pumping test data. Comparatively, in the numerical method a single numerical model is used to obtain a best fit between the field and modelled results for both the pumping and the recovery phases using different parameters. A trial and error technique is adopted to obtain a best fit[18]. The entire computation procedure will be usually written in the form of computer programs to solve the hydrological equations. Each of these methods is based on some basic assumptions and holds good in particular field conditions. In this article we have estimated natural recharge by the injected tritium technique and correlated the recharge values with hydrological parameters to understand the impact of recharge in the different geological formations.

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Study area

The study area (lat. 8.77–8.85°N and long. 78.04–78.17°E) falls in the east coastal belt, west of Tuticorin town, Tamil Nadu, India. It forms a watershed called as a SIIL watershed, covering an area of about 112 km^2 (Figure 1). The watershed is drained by a stream network oriented in the NW–SE direction and is of ephemeral in nature. The topographic elevation varies from 26.22 m amsl to a few metres amsl near Tuticorin town and slopes from west to east. The slope is gentle in the western and the central part and nearly flat in the eastern part of the watershed. The topography of the study area shows that the groundwater trough is developed towards the north-eastern part of the SIIL premises. The area receives rainfall during the northeast monsoon season, which is active during the months of October–December. The long-term average annual rainfall of Tuticorin town is 568 mm (IMD data). But the daily rainfall for the year 2006 recorded at SIIL rain gauge station indicates that it was above normal with significant high-intensity daily rainfall events compared to previous years since 2000. The area experiences semi-arid tropical climatic condition and falls

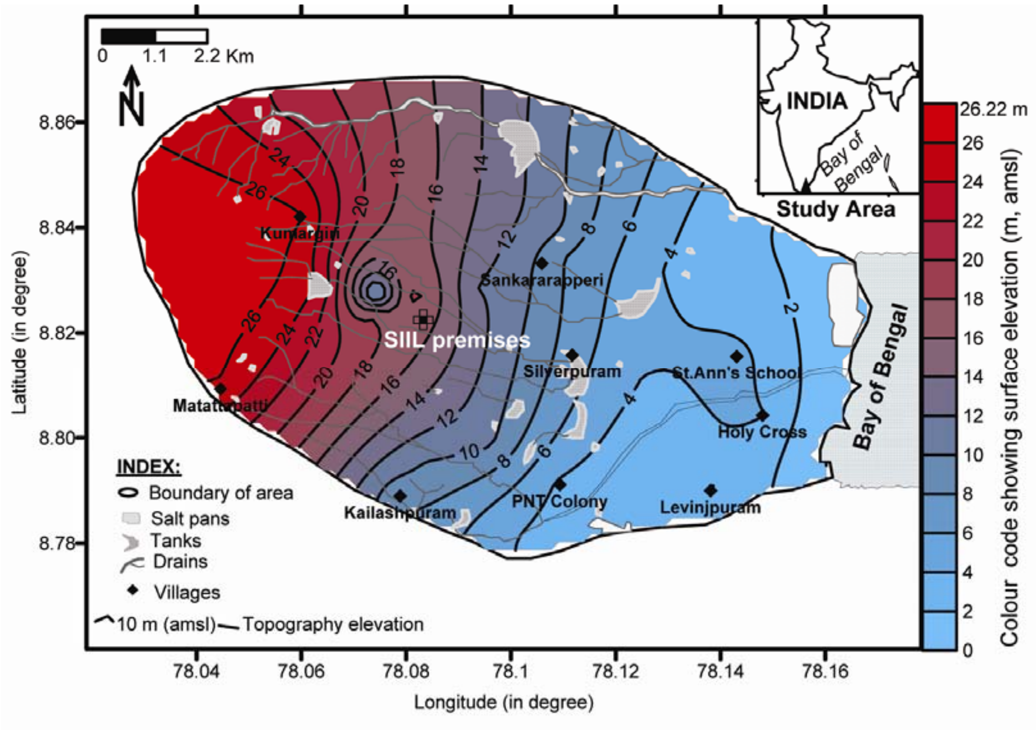

Figure 1. Location map of SIIL watershed.

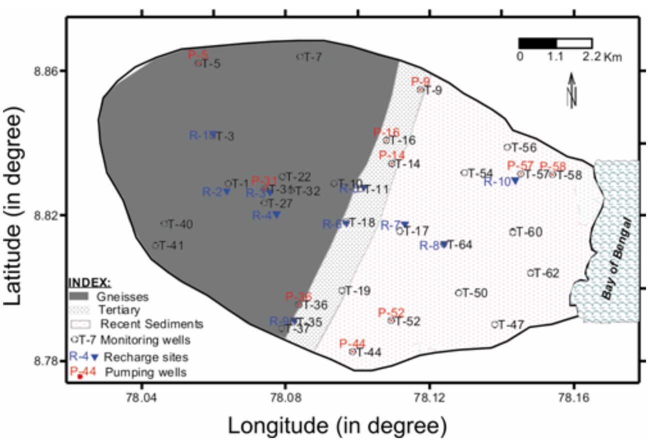

Figure 2. Geology map and experimental sites.

in the east coast plains and hill regions agro-climatic zone, as classified by the Indian Council of Agricultural Research (ICAR). The land is utilized for cultivation of cotton, maize and some medicinal plants. Some of the land is fallow and some barren with a vegetation such as thorny shrubs with a thin cover of dry grass and palms.

Geological and hydrogeological set-up

Gneiss, charnockite and quartzite of Archaean age, calcareous sandstone and shale limestone of tertiary age, and alluvium of recent age underlie the watershed area (Figure 2). The Archaean groups of formation are crystalline and metamorphic, and finely foliated with the general NW–SE trend described by Balasubramanian *et al.*[19]. The formations that include quartzite as ridges in the western part are weathered, jointed and fractured. Recent to sub-recent sand occupies the coastal areas. It consists of coarse and calcareous grit, sandstone and shale limestone.

The watershed area is covered with black soil in the western part (in and around the SIIL plant), red soil (sandy loam to sandy soil) in the central part and alluvial sandy soil in the eastern part. The maximum soil thickness is about 3 m. The sandy soils have originated from sandstone and have low soil-moisture retentivity. The alluvium soils are wind-blown sands and shells constitute beach sand and coastal dunes, which have low soil moisture retentivity.

The watershed area has a large number of open and bore wells tapping shallow phreatic aquifers and fractured aquifer systems. The wells are being used for domestic and irrigation purposes. The depth[20] of open wells ranges from 7 to 12 m and bore wells from a few metres to a maximum depth of 70 m. Most of the wells are less than 20 m in depth. In tertiary and alluvial areas, the sandy zone is the main aquifer system. The static water level during the pre-monsoon period varies from 1.8 to 14.45 m bgl and in post-monsoon period it varies from 0.9 to 12.86 m bgl. Shallow groundwater has been recorded in the SIIL premises and in the coastal area. The water-level contour maps have been prepared with help

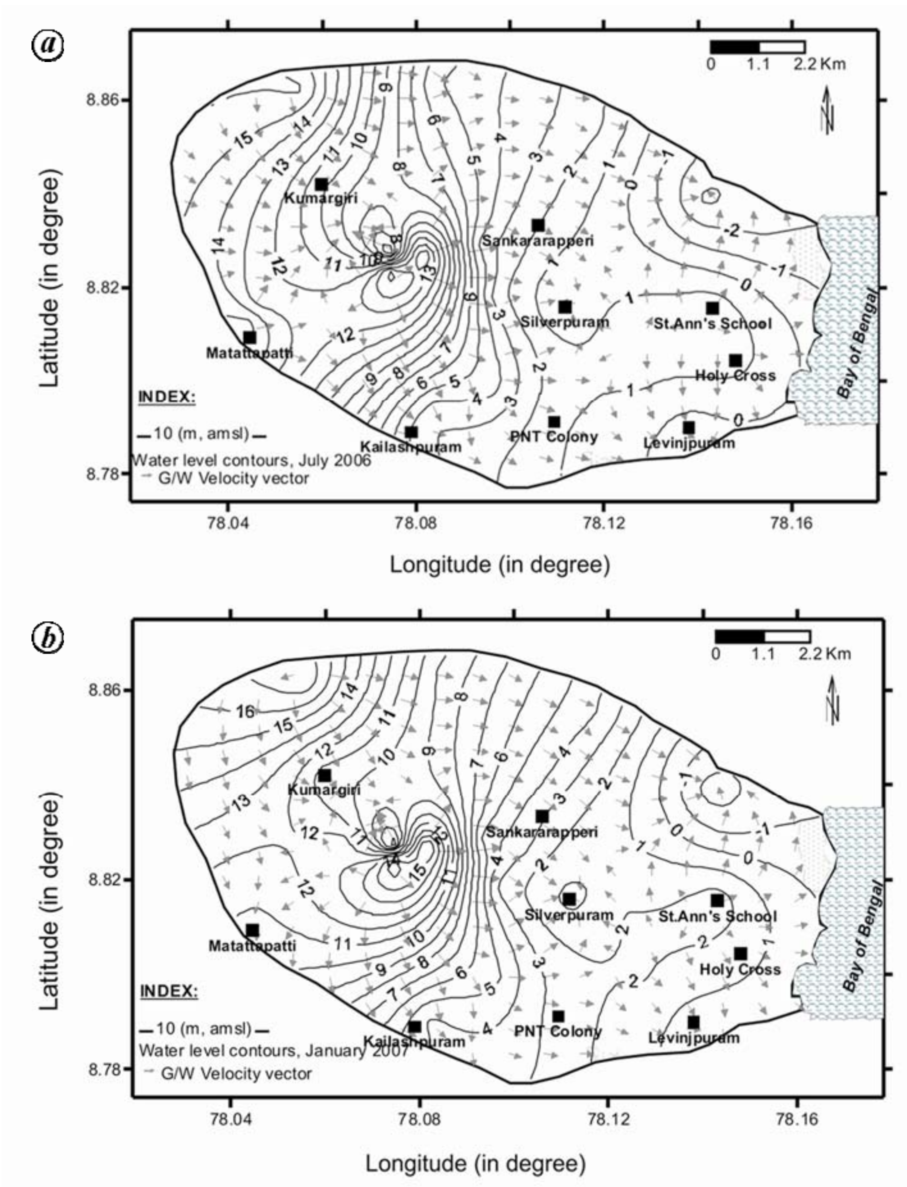

Figure 3. Water-level contours and their flow direction for (***a***) July 2006 and (***b***) January 2007.

of SURFER v.8.0 (2002), Golden Software, Inc. using kriging method. These are shown in Figure 3 *a* and *b* for July 2006 and January 2007 respectively. Figure 3 shows that the groundwater flow direction in the extreme northern, western and southwestern parts of the area is towards NW–SE direction. The groundwater crest has developed in and around the SIIL plant. Groundwater flow is in all directions from the SIIL premises. In the coastal side, it is towards the sea, except the northern and southern sides of the coast; sometimes it is below mean sea level (bmsl). Groundwater mounds and troughs are also visible in a few locations due to local disturbance. However, the water level improves after the monsoon period. In coastal areas, the groundwater is highly saline having electrical conductivity as high as 18,605 μS/cm at 25°C.

Methods

Tritium injection technique

The tritium injection technique[7,8,21] deals with the piston flow model and works on the principle that the soil moisture moves downward in discrete layers through the unsaturated zone under the force of gravity, i.e. any fresh layer of water added to the surface pushes an equal amount of water beneath it further down, and so on. Tritium is tagged below the shallow root zone before the onset of monsoon rains and collected after the monsoon. The displaced position of the tracer is indicated by the peak in its concentration distribution, which corresponds to spot natural recharge to groundwater over the time interval between the injection of tritium and collection of the soil core profile. Moisture content (%) and tritium activity of samples of each site were plotted against depth. The displacement of the tracer was determined and used to estimate the recharge.

In the study area tritium injections were made during July 2006 at ten locations (as shown in Figure 2). An approximate selection and distribution of the injection site in different geological formations was made from geological maps, taking many factors into consideration such as local terrain, drainage pattern, access and representative coverage. A small amount (2.5 ml) of tritiated water (HTO) having an activity 10 μC/ml was injected at 60 cm depth in a 1.00 cm diameter hole made using a drive rod. The hole was filled back by local soil. Tritiated water was injected at four sites in weathered gneiss, three sites in shale limestone and quartzite, and three sites in coastal sands. Care has been taken that every injection site is a relatively flat patch of fallow, non-agricultural land or rainfed agricultural field sufficiently distant from big trees, near important landmarks such as milestones, electrical poles, small trees, etc. Ploughed or unploughed farm plots which have no facility of well/canal irrigation were selected. Care was taken to select the site nearby one of the observation wells being monitored. Each injection site location was precisely determined through triangulation, so that it could be located again easily for collection of vertical soil-core profiles after the cessation of monsoon rainfall. Soil samples in 20 cm sections were collected using recovery pipes having diameter 45 cm up to a maximum depth of 3.0 m during January 2007. Details of tritium injection are given in Table 1. The samples were weighed immediately after collection in the field and double-sealed in a plastic bag. Hoffer-type augers of varying lengths were used. Soil moisture was extracted in the laboratory using a vacuum distillation setup. The moisture content in about 25 g of soil taken from each sample was determined on a torsion balance, heated using an infrared oven at 105°C. Next, 4 ml distillate was mixed with 10 ml of insta-gel (a universal liquid scintillation cocktail for aqueous and non-aqueous samples, manufactured by Packard instrument company, USA) in low-potash glass vials, and tritium activity was counted using liquid scintillation counter having background of about 50 counts per minute. The tritium activity of every 20 cm section was plotted against the sample depth for all the profiles. Typical examples of such plots along with moisture variation are shown in Figure 4 *a* and *b*.

Aquifer characterization studies

Aquifer parameters, chiefly transmissivity (*T*) and storativity (*S*), are vital for the management of groundwater

Table 1. Natural recharge sites

Serial no.	Village	Location (longitude and latitude)	Nearby observation well	Surface cover condition
R-1	Kumargiri	78°03′40″, 8°50′29″	T-3	Black soil, fallow land
R-2	Terku-Veerapandiyapuram	78°03′56″, 8°49′37″	T-1	Black soil, fallow land
R-3	SLF (SIIL)	78°04′34″, 8°49′30″	T-31	Black soil, bushy area, surface cracks
R-4	LPG (SIIL)	78°04′50″, 8°49′06″	T -27	Black soil, fallow land
R-5	Pandarampatti	78°06′10″, 8°49′35″	T-11	Red soil, sandy, fallow land
R-6	Meelavittan	78°05′51″, 8°48′59″	T-18	Red soil, hard surface, fallow rainfed land
R-7	Silverpuram	78°06′57″, 8°49′07″	T-17	Red soil, sandy, rainfed
R-8	Chinnakanapuram	78°07′38″, 8°48′37″	T-64	Sandy soil, fallow, saline area
R-9	Ayynaduppu	78°05′03″, 8°47′21″	T-35	Sandy loam, fallow land
R-10	Arokayipuram	78°08′38″, 8°49′46″	T- 57	Sandy soil, fallow, saline area

Date of tritium injection: 27 and 28 July 2006. Depth of tracer injection: 60 cm bgl.

Table 2. Aquifer parameters in the watershed

Serial no.	Dimension/ diameter (m)	Depth (m)	WL (m bgl)	Constant discharge (m^3/d)	Pumping time (min)	Maximum drawdown (m)	Recovery time (min)	Maximum recovery (m)	*T* (m^2/d)	*S*
T-5	6 × 5.3	11.04	3.74	686	116	1.49	1360	0.33	35.0	9×10^{-3}
T-9	5.07 × 4.74	8.82	4.74	426	146	0.71	295	0.51	7.0	5×10^{-4}
T-14	5.78 × 4.7	8.83	6.40	469	100	0.93	3804	0.10	38.0	1×10^{-5}
T-16	3.12 × 2.92	11.17	7.65	327	78	1.18	5610	0.59	0.8	3×10^{-3}
T-31	0.102	19.2	3.89	269	75	1.40	90	0.12	34.0	1×10^{-5}
T-36	4.15 × 4.2	8.43	5.65	451	105	1.63	1812	0.08	60.0	1×10^{-3}
T-44	6.82 × 5.85	7.78	1.12	459	120	0.68	1406	0.90	80.0	1×10^{-2}
T-52	0.910	2.74	1.62	36	32	1.09	149	0.03	16.0	3×10^{-5}
T-57	1.250	5.90	4.82	51	45	0.96	485	0.04	19.5	6×10^{-3}
T-58	1.460	5.71	3.77	226	23	1.74	305	0.02	60.0	1×10^{-5}

WL, Water level; *T*, Transmissivity; *S*, Storativity.

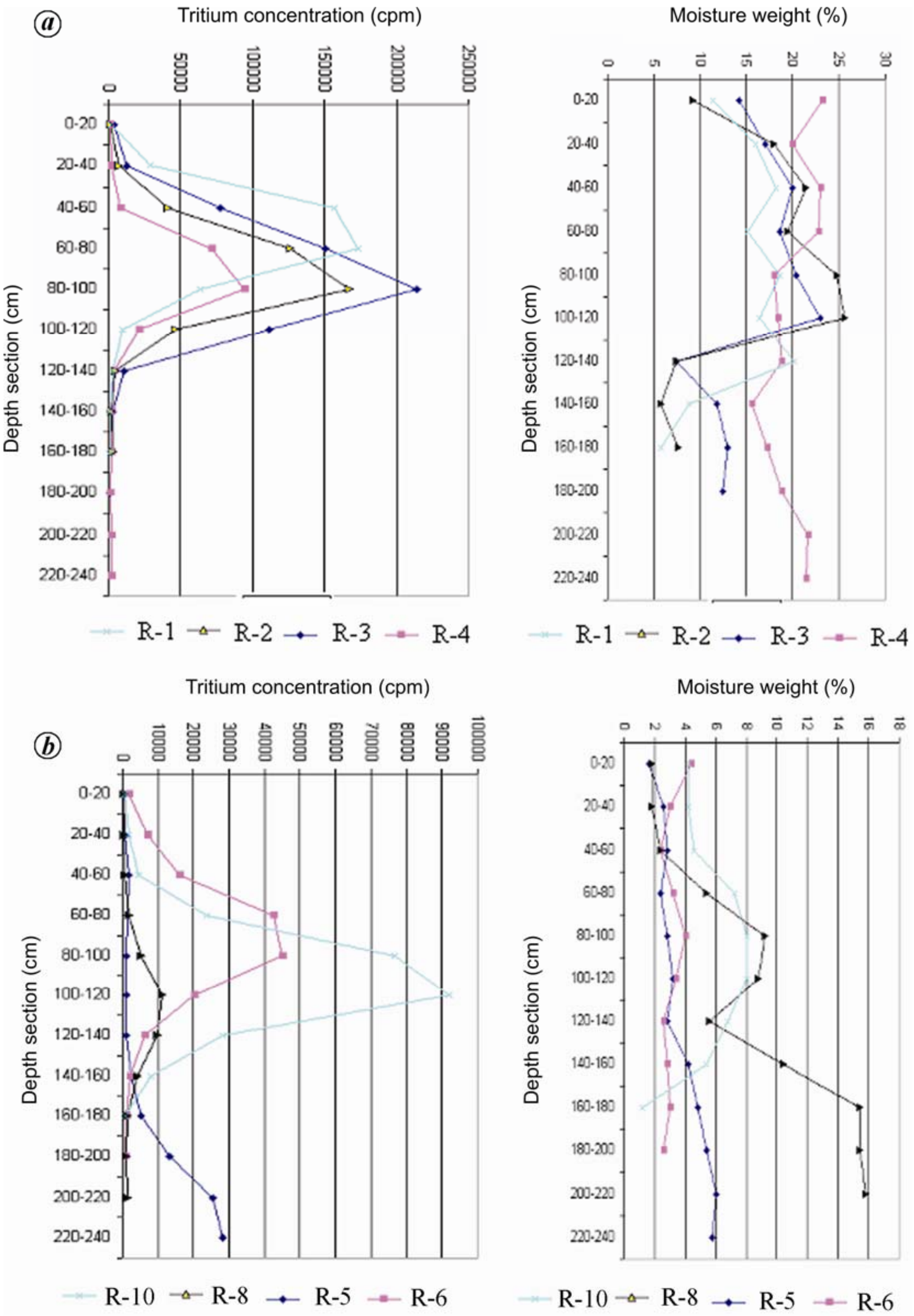

Figure 4. Tritium and moisture profiles at sites located in (***a***) black soils (site nos R-1 to R-4) and (***b***) red soils (site nos R-5, R-6, R-8, R-10).

resources. There are several analytical methods developed to estimate aquifer parameters. However, the numerical approach has advantages in incorporating the actual field conditions with ease and hence the parameters estimated become realistic[22]. The method is described in detail by Singh[23]. During field investigation, ten existing wells were selected to carry out the pumping test. There are four wells located in coastal sands and three wells each in weathered gneiss and shale limestone separately. The location of these wells is shown in Figure 2.

Most of these wells were kept without pumping prior to the test for monitoring the water levels continuously. All the wells were of large diameter (six of these are rectangular), except one, i.e. T-31, which has diameter of 0.102 m. The existing pumps were fitted on the wells to carry out the pumping test.

The summary of test is presented in Table 2. The time–drawdown/recovery data for all the tests have been plotted on a linear scale and a typical time–drawdown plot. Interpretation of the test data has been carried out using forward modelling technique, as suggested by Singh[23]. Nearby features such as water body or lateral inhomogeneities have been incorporated during interpretation. Initial guess of parameters has been considered to generate the time–drawdown curve for individual tests and compared with the observed time–drawdown/recovery data. The aquifer parameters were varied till a close match was obtained. The best-fit match was considered as the representative aquifer parameters. One of the typical best-fit matches is shown in Figure 5.

Results and discussion

Recharge estimation

Natural recharge at each spot was calculated using the displacement of tritium tagged layer from the injection depth. The displacement of injected tritium layer occurs due to rainfall percolation in the vadoze zone during the monsoon season. The displaced position of the tracer is indicated by the peak in its concentration in a plot of depth vs tritium activity (Figure 4). The peak may be broadened because of other factors such as diffusion, irregularities in water input and streamline dispersion. The centre of gravity (CG) of the profile was therefore taken as representing the depth of the tagged layer or displaced depth. The CG represents the depth at which half of the total activity in the collected soil profile lies. The peak of the profile represents the depth at which the maximum tritium activity lies. The numbers given in column 5, Table 3, one below the other, represent the displaced depth evaluated by CG and peak method. The moisture content of the soil column between the injection depth and displaced depth of the tracer in the soil core is

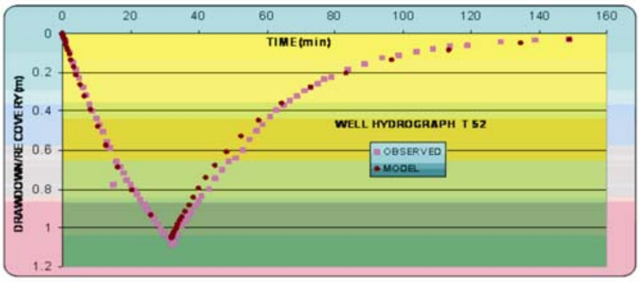

Figure 5. Pumping test hydrograph at well no. T-52 (PNT Colony).

Table 3. Results of recharge measurements (during NE monsoon, 2006)

Site no.	Site name	Depth of collection (cm)	Average volume moisture (%)	Displacement of tracer peak CG/ peak (in cm)	Natural recharge estimated (mm)	Average (mm)
R-1	Kumaragiri	180	22.7	3.66 10.0	8.3 22.7	15.5
R-2	Terkuveerapandiyapuram	180	35.5	22.8 30.0	81.0 106.5	93.7
R-3	SLF (SIIL)	200	30.2	24.57 30.0	74.3 90.6	82.4
R-4	LPG (SIIL)	240	32.6	24.7 30.0	80.7 97.8	89.2
R-5	Pandarampatti	240	6.7	149.9 170.0	100.5 113.9	107.2
R-6	Meelavittan	200	6.3	21.88 30.0	13.7 18.9	16.3
R-7	Silverpuram	240	18.1	33.54 30.0	60.6 54.3	57.4
R-8	Chinnakanapuram	220	9.2	59.49 50.0	54.5 46.0	50.2
R-9	Ayynaduppu	180	13.0	42.35 50.0	55.1 65.0	60.0
R-10	Arokayipuram	240	15.0	32.0 28.0	48.0 42.0	45.0

Date of tritium injection: 27 and 28 July 2006; Date of sample collection: 20 and 22 January 2007; Rainfall occurred: 582 mm at SIIL campus; Mean recharge taking CG (ten sites): 57.7 mm; Mean recharge taking peak as CG (ten sites) = 64.4 mm; Average: 61.7 mm and Percentage recharge = 10.6.

Table 4. Water-level changes in observation wells near recharge sites

Site no.	Site name	Observation well no.	Pre-monsoon SWL	Post-monsoon SWL	WL changes (in m)	Natural recharge (mm)
R-1	Kumargiri	T-3	16.4	16.2	0.20	15.5
R-2	Terku Veerapandiyapuram	T-1	14.2	12.9	1.34	93.7
R-3	SLF (SIIL)	T-31	5.02	3.86	1.16	82.4
R-4	LPG (SIIL)	T-27	2.55	1.30	1.25	89.2
R-5	Pandarampatti	T-11	8.99	7.75	1.24	107.2
R-6	Meelavittan	T-18	9.72	9.58	0.14	16.3
R-7	Silverpuram	T-17	7.87	7.20	0.67	57.4
R-8	Chinnakanapuram	T-64	3.34	2.85	0.49	50.2
R-9	Ayynaduppu	T-35	6.47	5.76	0.71	60.0
R-10	Arokayipuram	T-57	5.26	4.91	0.35	45.0

Average water level change: 0.755 m; Average natural recharge = 61.7 mm.

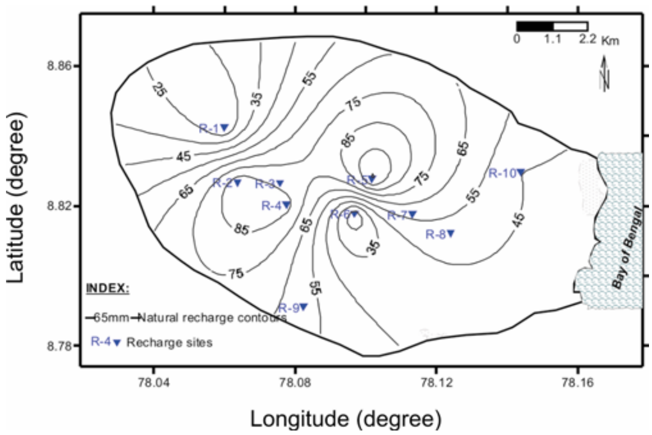

Figure 6. Contours map for natural recharge of seasonal rainfall (2006).

the measure of the recharge to groundwater over the time interval between injection of tritium and collection of soil core. The numbers given in column 6, Table 3, one below the other, represent the moisture flux calculated using CG and peak method. The computed results are presented in Table 3. The mean natural recharge computed from ten sites is 61.7 mm for the average rainfall of 582 mm, which is considered good for the region. The recharge is equivalent to 10.6% of the rainfall, which is small. This is due to the compensation of the soil moisture deficit caused by evapotranspiration during the 2006 dry period. Natural recharge values obtained at tracer-injected sites and their geographical location were used for preparation of recharge contour map with the help of Surfer v. 8.0 software (Figure 6). Figure 6 shows the areal distribution of low and high recharge zones. The tritium and moisture profiles (Figures 4 *a* and *b*) observed at the tracer-injected sites show a distinct single peak within a depth of 2 m bgl.

Comparison of recharge with water-level change

The recharge rate estimates obtained by the tritium method accurately quantify the net downward moisture flux in the unsaturated zone, while the hydrogeological data on the difference between the pre- and post-monsoon water-level changes in the shallow phreatic aquifer system represent the response of the saturated regime to inputs due to monsoon precipitation. The natural recharge was compared with the water-level change observed in observation wells located near the tritium sites. The water-level changes near the recharge site and the recharge values obtained by the tritium method are given in Table 4. A linear correlation between recharge values and maximum water-level changes in wells was established, with the correlation coefficient of 0.97. The correlation coefficient values for individual geologic formations, such as weathered gneiss, shale limestone and quartzite and coastal sand were found to be 0.9998, 0.9991 and 0.9998 respectively (as shown in Figure 7). This indicates that when the recharge value increases in the same geological set-up, the water level of the unconfined aquifer also increases.

Estimation of specific yield of phreatic aquifer system

The specific yield is defined as the volume of water expressed as a percentage of the total volume of the saturated aquifer that can be drained by gravity. It is an important parameter for hydrogeological modelling. The values of recharge and the corresponding water-level changes were used for estimating the specific yield of shallow phreatic aquifer system of weathered gneiss, shale limestone and coastal sand formations in the area. The results are presented in Table 5. The calculated average recharge was 61.7 mm and the average maximum water-level change observed in wells located near the recharge sites was 755 mm (Table 4). The average specific yield (8.17%) of the watershed having different formations was calculated from the two parameters. Maximum specific yield was observed in the coastal sands, followed by shale limestone; it was comparatively less in weathered gneiss.

Comparison of specific yield obtained from recharge with estimated storativity

When water is drained from a saturated material under gravity, only a part of the total volume stored in its pores

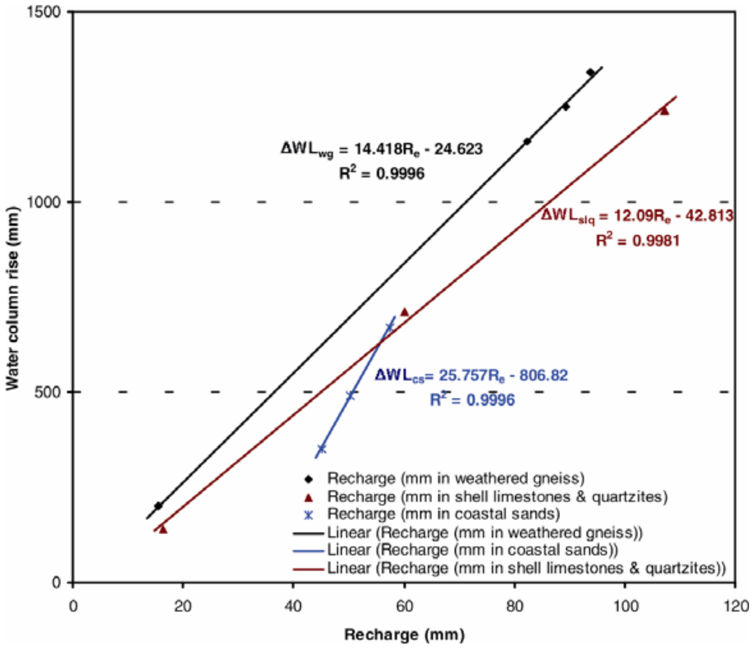

Figure 7. Water-level changes with natural recharge in different geological formations.

Table 5. Estimation of specific yield of phreatic aquifer from natural recharge

Site no.	Site name	Observation well no.	Maximum WL change (m)	Natural recharge (mm)	Specific yield (%)
R-1	Kumargiri	T-3	0.20	15.5	7.75
R-2	Terku Veerapandiyapuram	T-1	1.34	93.7	6.99
R-3	SLF (SIIL)	T-31	1.16	82.4	7.10
R-4	LPG (SIIL)	T-27	1.25	89.2	7.14
Average specific yield (weathered gneiss) = 7.25%					
R-5	Pandarampatti	T-11	1.240	107.2	8.64
R-6	Meelavittan	T-18	0.140	16.3	11.64
R-9	Ayynaduppu	T-35	0.710	60.0	8.45
Average specific yield (shale limestone and quartzite) = 9.57%					
R-7	Silverpuram	T-17	0.67	57.4	8.6
R-8	Chinnakanapuram	T-64	0.49	50.2	10.2
R-10	Arokayipuram	T-57	0.35	45.0	12.9
Average specific yield (coastal sand) = 10.57%					

Table 6. Calculated transmissivity (*T*) and storativity (*S*) from pumping test

Site no.	Site name	Natural recharge (mm)	Specific yield (%)	Calculated storativity (*S*)	Calculated transmissivity (*T*)
R-1	Kumargiri	15.5	7.75	0.0065	38.00
R-2	Terku Veerapandiyapuram	93.7	6.99	0.0045	41.75
R-3	SLF (SIIL)	82.4	7.10	0.0035	39.00
R-4	LPG (SIIL)	89.2	7.14	0.00275	42.25
Average storativity (weathered gneiss) = 0.00431					
R-5	Pandarampatti	107.2	8.64	0.00015	32.00
R-6	Meelavittan	16.3	11.64	0.0005	36.00
R-9	Ayynaduppu	60.0	8.45	0.00001	29.75
Average storativity (shale limestone and quartzite) = 0.00022					
R-7	Silverpuram	57.4	8.6	0.00001	26.00
R-8	Chinnakanapuram	50.2	10.2	0.003	67.00
R-10	Arokayipuram	45.0	12.9	0.006	19.50
Average storativity (coastal sand) = 0.003					

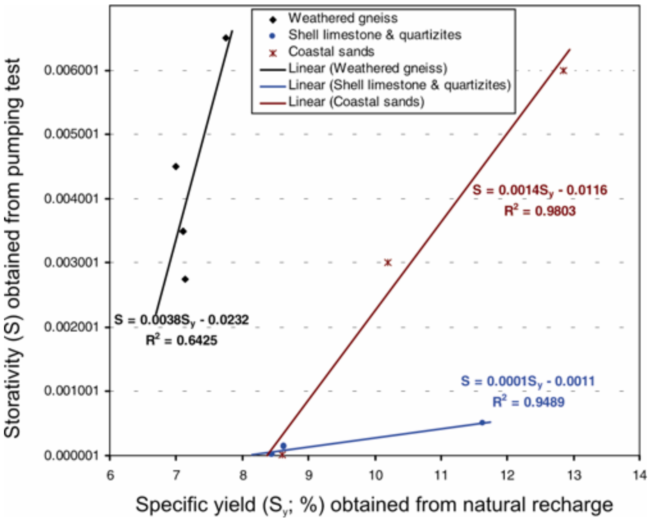

Figure 8. Relationship between specific yield and storativity.

is released. The quantity of water that a unit volume of the material will give up when drained by gravity is called as its specific yield, and is expressed as a ratio or percentage. Todd[24] defined the storage coefficient (S) as the volume of water that an aquifer releases or takes into storage per unit surface area of aquifer per unit component of head normal to that surface. In an unconfined aquifer, the storage coefficient corresponds to its specific yield. The storage coefficient (S) was estimated from ten pumping tests using forward modelling technique, as suggested by Singh[23]. The aquifer parameters are presented in Table 2.

Transmissivity and storativity vary from 0.8 to 80.0 m^2/d, and 0.00001 to 0.01 respectively. The specific yield was calculated at the recharge sites using SURFER v.8.0 (2002), Golden Software, Inc. using kriging method from the field values. Table 6 gives the value of specific yield (S) obtained from the pumping test. A cross-correlation between the specific yield, obtained from natural recharge and the water-level changes in wells, and the storativity calculated from the pumping test was established. The cross-plot is shown in Figure 8, which indicates that the maximum correlation coefficient was obtained for coastal sand (0.99), followed by shale limestone and quartzite (0.97) and weathered gneiss (0.80).

Conclusion

Natural recharge caused by seasonal (northeast monsoon) rainfall in the SIIL watershed area varies from 15.5 to 107.2 mm, with an average value of 61.7 mm. This is equivalent to 10.6% of the rainfall which occurred during the period of tracer injection and soil sample collection. The average and percentage recharge to phreatic aquifer estimated in three different geological formations of the study area is as follows: weathered gneiss/charnockite (four sites): 70.2 mm (12.1%); shale limestone and quartzite (three sites): 61.6 mm (10.6%), and coastal alluvium (three sites): 50.87 mm (8.7%).

The natural recharge obtained using tritium method was found to be linearly correlated with groundwater-level changes observed, with a correlation coefficient of 0.97. The natural recharge response was more prominent in weathered gneiss and shale limestone and costal sand in the study area, it depends on different hydrogeological factors (i.e. topography, drainage pattern, aquifer properties, etc.).

Average specific yield of the shallow phreatic aquifer of the area based on recharge and water-level change was calculated as 8.17%. The average specific yield of the phreatic aquifer for different geological formations was as follows: weathered gneisses and charnockite: 7.25%; shale limestone and quartzite: 9.57% and coastal alluvium: 10.57%.

Transmissivity and storativity values varied from 0.8 to 80.0 m^2/d and 0.00001 to 0.01 respectively, in the study area. There was a good correlation between specific yield obtained from natural recharge and storativity of the phreatic aquifer in the different geological formations. Maximum correlation coefficient (0.99) was obtained in coastal sands, followed by shale limestone and quartzite (0.97), and weathered gneiss (0.80).

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