ORIGINAL PAPER

Coupling geomorphology parameters with lithology for micro-level groundwater resource assessment: a case study from semi-arid hard rock terrain in Tamil Nadu, India

Jeenu Mathai · I. C. Das · S. K. Subramanian · K. S. Lenin · V. K. Dadhwal

Abstract The standard procedure of groundwater resource estimation in India till date is based on the specific yield parameters of each rock type (lithology) derived through pumping test analysis. Using the change in groundwater level, specific yield, and area of influence, groundwater storage change could be estimated. However, terrain conditions in the form of geomorphological variations have an important bearing on the net groundwater recharge. In this study, an attempt was made to use both lithology and geomorphology as input variables to estimate the recharge from different sources in each lithology unit influenced by the geomorphic conditions (lith-geom), season wise separately. The study provided a methodological approach for an evaluation of groundwater in a semi-arid hard rock terrain in Tirunelveli, Tamil Nadu, India. While characterizing the gneissic rock, it was found that the geomorphologic variations in the gneissic rock due to weathering and deposition behaved differently with respect to aquifer recharge. The three different geomorphic units identified in gneissic rock (pediplain shallow weathered (PPS), pediplain moderate weathered (PPM), and buried pediplain moderate (BPM)) showed a significant variation in recharge conditions among themselves. It was found from the study that Peninsular gneiss gives a net recharge value of 0.13 m/year/unit area when considered as a single unit w.r.t. lithology, whereas the same area considered with lith-geom classes gives recharge values between 0.1 and 0.41 m/year presenting a different assessment. It is also found from this study that the stage of development (SOD) for each lith-geom unit in Peninsular gneiss varies from 168 to 230 %, whereas the SOD is 223 % for the lithology as a single unit.

Keywords Lith-geom · Lithology · Recharge · Groundwater draft · Rainfall infiltration factor method · Water table fluctuation method · Groundwater assessment · ASTER-DEM

Introduction

The water resources of India, in general, are unevenly distributed both spatially and temporally. Idiosyncrasies of monsoon and diverse physiographic conditions give rise to unequal distribution of water. Over the years, increasing population, urbanization, and expansion in agriculture have accentuated the situation. The aftermath of unscientific exploitation of groundwater is that the country is moving towards water stress condition. Historical data of Indian water levels for the past two decades indicate that they have typically declined by 6 to 8 m in the discharge zones and by 12 to 15 m on average and up to 25 m in the withdrawal areas (Subramanyam et al. 2000). National Water Policy, 2002 has defined that the groundwater exploitation should be limited to groundwater recharge. Hence, attempts at regular interval are being made to assess the replenishable groundwater resources of the country. Groundwater resources were assessed periodically in India since 1976. The 2004 assessment indicated that dependency on groundwater for meeting the water requirement by various sectors is accelerating at a fast pace. A World Bank report (World Bank 2010) indicated that there are about 20 million

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wells in the country extracting groundwater. Based on groundwater utilization pattern in India as of 2004 (CGWB 2004), the total annual groundwater draft is 231 bcm, out of which 213 bcm is used for irrigation and 18 bcm is for domestic and industrial use. In general, the irrigation sector remains the main consumer of groundwater with 92 % of total annual groundwater draft for all uses (NABARD 2006).

With increasing sophistication in geographic information systems (GIS), allowing integration of data collected from various sources and methods, complex analysis of data is possible, and hence, attempts have been made for robust groundwater assessment. Many researchers have attempted to assess the groundwater recharge quantitatively (Shashidhar and Kaarmegam 2006). Moon et al. (2004) used statistical analysis of hydrographs and water-table fluctuation to estimate groundwater recharge in South Korea. Ramesh Chand et al. (2005) assessed groundwater recharge through neutron moisture probe in Hayathnagar micro-watershed, India. Subash Chandra et al. (2011) developed lithologically constrained rainfall (LCR) method for estimating spatio-temporal recharge distribution in crystalline rocks of Bairasagara watershed and Maheshwaram watershed of India. The government of India has framed a set of guidelines through a Ground Water Resource Estimation Committee (GEC 2009) for recharge estimation based on a water balance approach. The approach followed in the method is essentially a lumped parameter approach. Specific yield values are to be taken from pumping test analysis. Using the change in groundwater level, specific yield, and area of influence, groundwater storage increase could be estimated. Groundwater draft is to be estimated through an established approach. Then, recharge is calculated by adding groundwater draft with groundwater storage increase. This is a simplified method developed for Indian conditions taking into account various field parameters and is widely used. Ravikumar et al. (2005) developed a GIS-based groundwater assessment model with a limited data in a lumped approach, giving better understanding of groundwater potential condition. Pradeep Kumar and Srinivas (2011) assessed the stage of groundwater development in Kurmapalli Vagu Basin in Deccan Plateau utilizing remote sensing and geographical information system techniques in conjunction with conventional methods. Groundwater recharge from rainfall, canals, return flow of irrigation, minor irrigation tanks, and water conservation structures was estimated. The total groundwater recharge and annual utilizable groundwater resources from various sources were computed. Varalakshmi et al. (2012) developed a three-dimensional groundwater flow model for the Osmansagar and Himayathsagar catchments—a semi-arid hard rock area in India with two conceptual layers developed under transient conditions using Visual MODFLOW software.

In this study, an attempt has been made to estimate the recharge from different sources in each lithology unit as well as lith-geom, season wise separately to understand the influence of geomorphology on overall groundwater resource estimation. Comparative analysis was done using water-table fluctuation and rainfall infiltration factor methods to avoid over/under estimation of groundwater quantity. Long-term groundwater trends were generated to help in understanding the uncertainties in estimation of groundwater draft based on indirect assessment using the area irrigated from groundwater.

Study area and site characteristics

The study area Uppodai is a dry watershed covering 702 km^2 which is located in the southern part of Tamil Nadu with a latitude between 8° 30′ N and 9° 18′ N and a longitude between 77° 15′ E and 78° 15′ E (Fig. 1). Sankarankoil, Kayathar, and Kalugumalai are the major townships in the area. The area experiences a hot tropical climate, summer season is from March to May, and average temperature is around 40 °C. The weather is pleasant during the period from December to January. The relative humidity is on an average between 79 and 84 %. The average annual rainfall of the area is around 700 mm. The major soil types found are black, red, and alluvial soil. The plain region is mostly covered by the black soil which is locally known as "Karisal." Cultivation is the major land use while forest is negligible. Various types of cropping pattern practiced in the area are pulses, coconut, paddy, sugarcane, cotton, and groundnut.

Site characteristics

Geologically, the area consist of crystalline rocks of Archaean age, namely gneiss, charnockite, and granite. The gneiss covers a major part of the study area followed by granite, whereas charnockite and recent alluvium occur in small patches. The prominent geomorphic units identified through the interpretation of satellite imagery in the area are buried pediplain moderate (BPM), inselberg (I), linear/curvilinear ridge (LR), pediment (P), residual hills (RH), pediplain moderate weathered (PPM), and pediplain shallow weathered (PPS). The area is underlain by both porous and fissured formations. The important aquifer systems in the area are constituted by weathered and fractured hard rock formations of Archaean age and porous alluvium of recent age. The aquifer at the shallow depth is under unconfined condition, and aquifer at a depth is under semi-confined to confined condition. The shallow aquifer is developed through dug wells and deeper aquifer through tube wells. The dug well can sustain a pumping of 4 to 6 h while the tube wells can sustain a pumping of 6 to 8 h. The long-term water level fluctuation for the period 1998–2007 indicates both rise and fall in the area. The rise in water level is in the range of 0.021 to 1.13 m/year, while the fall in the water level varies between 0.02 and
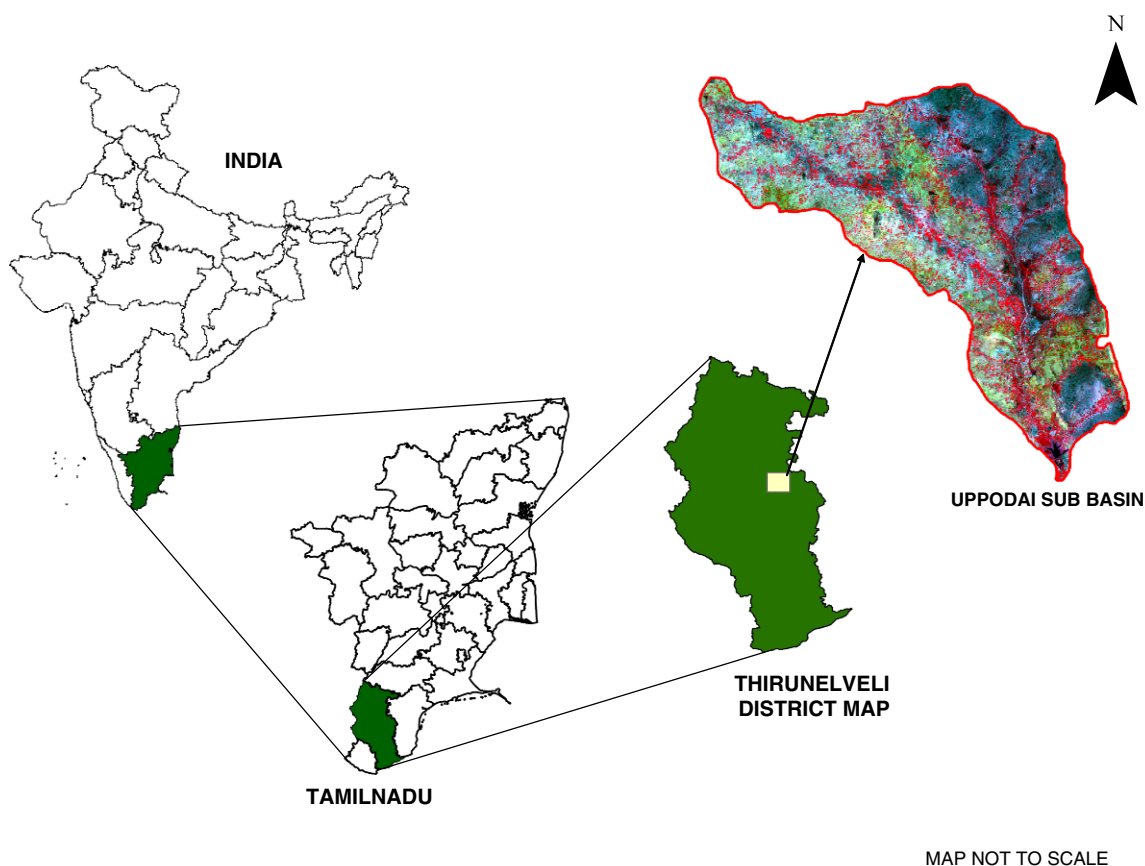
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Fig. 1 Study area, Uppodai sub-basin in Tamaraparni river basin, Tirunelveli and Thoothukudi Districts, Tamil Nadu, India

0.69 m/year (CGWB 2004). The eightfold land use classification for the area are built-up land, kharif, rabi crop land, double/triple crop land, current fallow, scrubland, water body, and wasteland (Table 1). Irrigation through wells and tanks are common whereas canal irrigation is absent in the area. Large numbers of tanks are built in the area in the past for irrigational purposes. However, their capacities have decreased significantly now because of the siltation. The majority of the study area is flat with a slope less than 10 % (Table 1). There are few isolated hillocks such as inselbergs and a small pediment area where slope is more than 10 % (Table 1). The factor maps considered for groundwater resource estimation are shown in Fig. 2.

Conditioning of parameters

Conditioning of parameters is essential for deriving recharge and draft in a particular area depending on the geo-environmental conditions prevailing in the area. A number of factor maps are generally used for deriving such parameters. For the present study, few conditioning were done to derive the desired value of recharge and draft. Table 2 summarizes those factors which were used for conditioning the parameters to derive desired outputs.

Table 1 Various factors, variables, and their area considered for groundwater assessment

Factors	Variables	Area (km^2)
Land use	Built-up land	48.43
	Kharif crop land	56.02
	Rabi crop land	214.86
	Double/triple crop land	34.67
	Current fallow	93.00
	Scrubland	129.10
	Water body	46.62
	Other wasteland	79.91
Lithology	Charnockite	59.42
	Granite and lamprophyre	121.85
	Hornblende biotite gneiss	459.50
	Sandy clay and sand with clay	61.84
Lith-geom	Charnockite PPS	59.42
	Fluvial PPM	61.84
	Granite PPS	121.85
	Gneiss PPS	324.96
	Gneiss BPM	16.97
	Gneiss PPM	46.95
Slope in %	0–10	650.13
	10–46.6	52.48

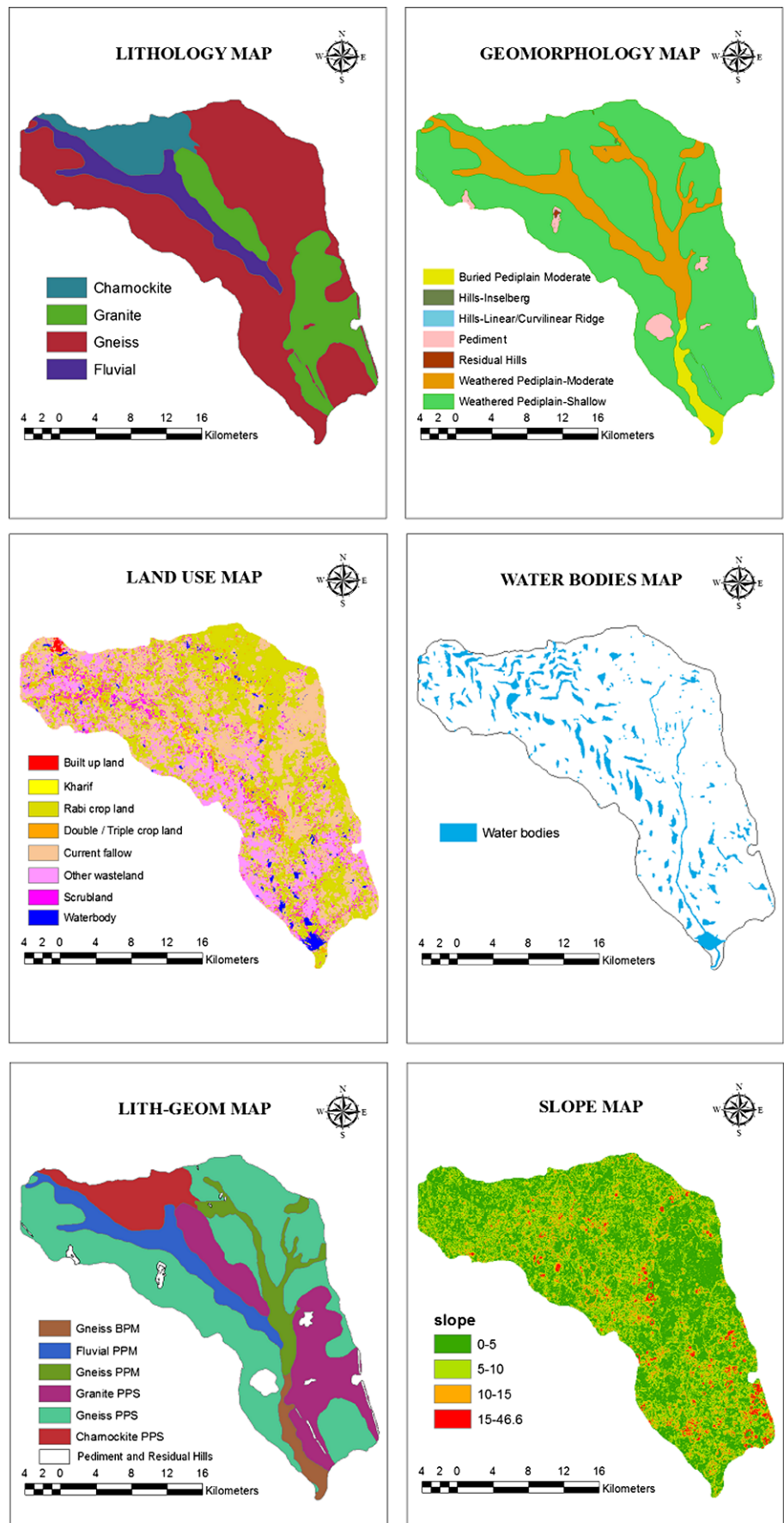**Fig. 2** The factor maps used for groundwater resource estimation

Table 2 Parameters derived for calculation of groundwater assessment in the study area

Type of analysis done	Groundwater assessment factors	Overlay of thematic maps in GIS	Derived parameters
Rainfall infiltration factor method	Lithology	Rain gauge influence map, slope map, lithology map	Area suitable for recharge in each lithology unit in individual rain gauge influencing area
Water table fluctuation method	Lithology	Well polygon map, slope map, lithology map	Area suitable for recharge in each lithology unit in each well polygon
Recharge from other sources	Lithology	Land use map, lithology map	Water spread area
Groundwater draft	Lithology	Land use map, lithology map	Crop area covering in each lithology unit
Rainfall infiltration factor method	Lith-geom	Rain gauge influence map, slope map, lith-geom map	Area suitable for recharge in each lith-geom unit in individual rain gauge influencing area
Water table fluctuation method	Lith-geom	Well polygon map, slope map, lith-geom map	Area suitable for recharge in each lith-geom unit in each well polygon
Recharge from other sources	Lith-geom	Land use map, lith-geom map	Water spread area
Groundwater draft	Lith-geom	Land use map, lith-geom map	Crop area covering in each lith-geom unit

Methodology

Groundwater assessment is generally carried out with the objective of estimating recharge from rainfall and other sources, current groundwater draft, and net groundwater availability. The approach involves estimation and quantification of annual groundwater recharge and groundwater extraction. Recharge due to rainfall is estimated separately for monsoon, R_{rf}(mon), and non-monsoon, R_{rf}(non-mon), seasons. Moreover, the area represented by recharge rates (fluxes) arrived through water-table fluctuation method ranges from tens of square meters to several hundred or thousand square meters. These recharge fluxes can be spatially integrated over large areas, which is important for large-scale water resources assessment. Thus, this method is suitable for regional estimates. The time period represented by the recharge estimates using water-table
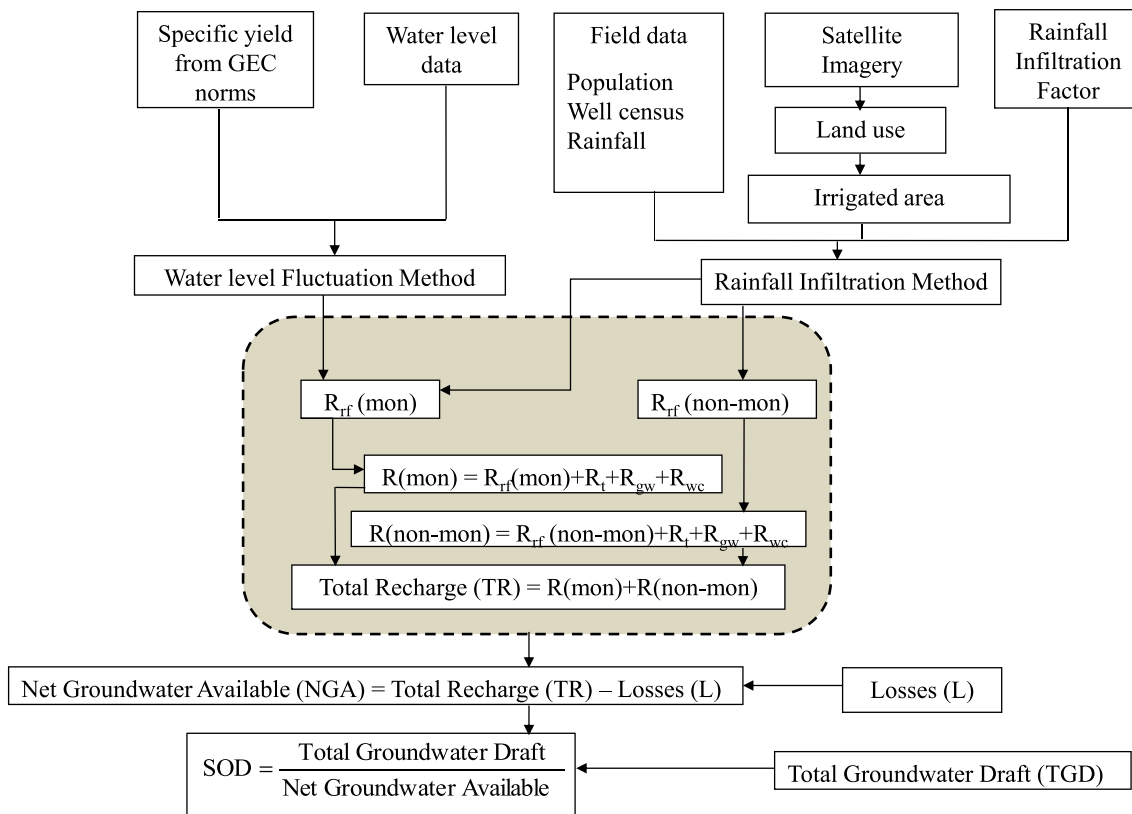

Fig. 3 Methodology for groundwater assessment

Table 3 Area of each lith-geom unit in each rain gauge station and infiltration factor used in rainfall infiltration factor method

Lith-geom	Area of each formation covered by rain gauge station (km^2)						Infiltration factor
	Sankarankoil	Kalampatti	Kalugumalai	Kayathar	Kadambur	Alagiapandi	
Charnockite PPS	27.22	0.00	32.19	0.00	0.00	0.00	0.08
Fluvial PPM	22.55	6.87	26.56	5.86	0.00	0.00	0.20
Granite PPS	0.00	11.97	26.29	49.21	34.38	0.00	0.12
Gneiss PPS	59.89	72.58	98.99	79.87	11.99	1.63	0.08
Gneiss BPM	0.00	0.00	0.00	16.97	0.00	0.00	0.08
Gneiss PPM	0.00	25.80	10.64	10.50	0.00	0.00	0.08

fluctuation method ranges from event (short time) scale to the length of the hydrographic record. Thus, there is scope for assessment both at short-time intervals as well as for longer periodical intervals using water-table fluctuation method (Scanlon et al. 2002). For comparison of figures obtained from the abovementioned two methods, percent deviation has been computed, and the recharge has been calculated according to the recommended methodology of GEC norms (GEC 2009). Percent deviation is calculated using the following relation:

$$\text{P.D.} = 100 \times \left(R_{\text{rf}}^{\text{wtf}} - R_{\text{rf}}^{\text{rif}}\right) / R_{\text{rf}}^{\text{rif}}$$

where

P.D.=percent deviation
$R_{\text{rf}}^{\text{wtf}}$=recharge from rainfall as computed by water-table fluctuation method
$R_{\text{rf}}^{\text{rif}}$=recharge from rainfall as computed by rainfall infiltration factor method

Since monsoon rainfall is the most significant contributor to groundwater recharge in the study area, rainfall recharge during the monsoon season is estimated using two methods: (i) water-table fluctuation method and (ii) rainfall infiltration factor method. Recharge from other sources like return flow from irrigation R_{gw}, recharge from water channels R_{wc}, and

tanks R_{t} are estimated using norms recommended by GEC (2009). Natural discharges like base flow and subsurface inflow/outflow are considered as losses (L), and they have been deducted from total recharge (TR) to ground to find out the net groundwater available (NGA) in the area. Based on net groundwater availability and total groundwater draft (TGD), stage of groundwater development (SOD) was determined using the following relation:

$$\text{Stage development (SOD)} = \frac{\text{Total groundwater draft}}{\text{Net groundwater available}}$$

This result of the stage of groundwater development was used, to categorize the area as safe, semi-critical, critical, or over-exploited for the purpose of future groundwater development (GEC 2009). The schematic representation of groundwater estimation methodology is shown in Fig. 3.

In this study, an attempt was made to estimate the recharge from different sources season wise of lithology and lith-geom unit wise. Similarly for each of the lithology and lith-geom units, groundwater draft has been estimated considering domestic, industrial, and irrigation purposes. Finally, the recharge and draft of each unit of lithology and lith-geom were compared to understand the SOD of groundwater.

Table 4 Normal monsoon rainfall recharge estimated using rainfall infiltration factor method

Lith-geom	Normal recharge in monsoon (ham)						Total monsoon recharge (ham)
	Sankarankoil	Kalampatti	Kalugumalai	Kayathar	Kadambur	Alagiapandi	
Charnockite PPS	108.84	0.00	125.16	0.00	0.00	0.00	234.0
Fluvial PPM	225.38	55.60	258.18	55.44	0.00	0.00	594.6
Granite PPS	0.00	58.14	153.28	278.93	182.95	0.00	673.3
Gneiss PPS	239.48	235.06	384.83	301.81	42.54	5.78	1209.5
Gneiss BPM	0.00	0.00	0.00	64.14	0.00	0.00	64.14
Gneiss PPM	0.00	83.57	41.36	39.67	0.00	0.00	164.60

Table 5 Normal non-monsoon rainfall recharge estimated using rainfall infiltration factor method

Lith-geom	Normal recharge in non-monsoon (ham)						Adopted non-monsoon recharge (ham)
	Sankarankoil	Kalampatti	Kalugumalai	Kayathar	Kadambur	Alagiapandi	
Charnockite PPS	62.07	0.00	57.43	0.00	0.00	0.00	119.5
Fluvial PPM	128.53	39.60	118.47	29.70	0.00	0.00	316.3
Granite PPS	0.00	41.41	70.34	149.57	112.18	0.00	373.5
Gneiss PPS	136.59	167.41	176.59	161.83	26.09	3.04	671.55
Gneiss BPM	0.00	0.00	0.00	34.39	0.00	0.00	34.39
Gneiss PPM	0.00	59.52	18.98	21.28	0.00	0.00	99.78

Results and discussion

Recharge from rainfall using water level fluctuation has been estimated through the following relation:

$$R_{rf} = S + D + R_{other},$$

where R_{rf} is the recharge from rainfall during the assessment year (Mcum), S is the change in storage (Mcum), D is the gross draft (Mcum), and R_{other} is the recharge from other sources during the assessment year (Mcum).

Twenty-one well-distributed wells in the study area were chosen. Water table fluctuation of 20 years from 1993 to 2012 has been found out from water level data collected from State ground & surface water resources data centre (SG & SWRD C), Chennai. The specific yield value in the computation is determined using normative estimates in GEC (2009). The areas suitable for recharge in each of the lith-geom formations are calculated by an overlaying well-influencing map and lith-geom map by excluding a slope greater than 10 %, and the recharge computed has been normalized with normal monsoon rainfall.

In rainfall infiltration factor method,

$$R_{rf} = N \sum f_i A_i P_i,$$

where R_{rf} is rainfall recharge in hectare meters, N is the number of regions, P is the rainfall in meters, f is the infiltration factor (% in decimals), and A is the area of recharge in hectares (Ravikumar et al. 2005).

Slope map derived from ASTER-DEM was used to identify the hilly areas and are considered as areas not suitable for recharge. The lith-geom map which contains the areal extents of different rock formations along with the geomorphology in the study area was overlaid with rain gauge influence map prepared by drawing Theissen polygons. Table 3 shows the area of each lith-geom units in each of the rain gauge stations along with the rainfall infiltration factor used in rainfall infiltration factor method. Infiltration factor values are recommended for major lithological units of the country under the GEC (2009).

Using rainfall infiltration factor method, estimated normal monsoon and non-monsoon rainfall recharges of lith-geom units are tabulated in Tables 4 and 5, respectively. Adopted monsoon recharge from rainfall for each of the lith-geom units is tabulated in Table 6. Similarly for groundwater assessment with lithology as a major factor without considering its geomorphic variations, the only difference is with the considered areas for the calculation. The areas suitable for recharge in each of the lithological formations are calculated by overlaying lithology with well-influencing map and rain gauge influence map for water-table fluctuation method and rainfall infiltration factor method, respectively.

As per GEC norms, 1.44 mm/day for the period in which the tank water may be taken as seepage from tanks. The water spread may be taken as 60 % of the maximum water spread area. Seepage from tanks=60 % of maximum water spread area×number of days water available×seepage factor. The recharge due to irrigation return flow (R_i) may also be estimated, based on the source of irrigation (groundwater or surface

Table 6 Adopted monsoon recharge from rainfall for each of the lith-geom units

Lith-geom	Rainfall infiltration factor (Mcum)	Water-table fluctuation (Mcum)	Percent deviation	Adopted monsoon recharge (Mcum)
Charnockite PPS	2.34	4.00	70.94	2.81
Fluvial PPM	5.95	4.34	−27.05	4.76
Granite PPS	6.73	11.07	64.48	8.08
Gneiss PPS	12.09	28.66	137.05	14.51
Gneiss BPM	0.64	6.05	845.31	0.77
Gneiss PPM	1.65	5.76	249.09	1.98

water), the type of crop (paddy, non-paddy), and the depth of water table below ground surface, using the norms provided by GEC (2009).

Groundwater draft for irrigation has been computed from crop water requirement method. Crop water requirement (season wise) of the crop grown in the assessment unit has been multiplied with the season-wise area irrigated by groundwater. The gross annual groundwater draft will be the sum total of annual groundwater consumption for all the crops grown through groundwater irrigation in the assessment area. Since no reliable data is available to demarcate the annual draft, well inventory data has been considered with respect to hours of pumping in the monsoon and non-monsoon seasons. Based on this, 65 % of the annual draft is from the monsoon season and the remaining 35 % is for the non-monsoon season. The estimation of groundwater draft for domestic and industrial purposes has been carried out based on the population data projected to year 2012 and per capita requirement of water for domestic use and relative load on groundwater for urban and rural water supply using the following empirical relation as recommended by the GEC norms (assuming that the requirement of water for domestic and industrial use as 70 lpd per head), $22 \times N \times L_g \times A/1000$ Mcum per year, where N is the population density in the unit in thousands per km^2, L_g is the fractional load on the groundwater for domestic and industrial water supply (<1.0), and A is the area of the unit in km^2. Gross groundwater draft is the sum of the groundwater draft for irrigation and groundwater draft for domestic and industrial purposes.

Comparison of lithology and lith-geom results

Table 7 shows the comparison of lithology and lith-geom wise recharge and draft calculations. In the study area, significant geomorphological variations were observed in Peninsular gneisses, whereas other rock types were covered under single geomorphic unit. While analyzing the influence of geomorphology on lithology for overall recharge and draft estimation, it was observed that lithology unit gneiss gives a value of 0.13 m/year (net recharge per unit area), whereas the same area in combination with geomorphology (lith-geom) drastically gives values between 0.1 and 0.41 m/year, and the SOD also varies significantly as shown in Table 7. It signifies the importance of incorporating geomorphology with lithology for getting a finer level of details in resource estimation of groundwater.

Spatial variation in resource estimates

Volumetric estimates are dependent on the areal extent of the assessment unit. Moreover, the relative comparison of recharge and draft of different assessment units based on volumetric estimates is not possible. Hence, volumetric estimates of groundwater recharge and draft have been divided by the

Table 7 Comparison of recharge and draft for lithology vs lith-geom units in the study area

Lithology:

Rock types	Area (km^2)	Net recharge from rainfall, tank, and GW return flow in both monsoon + non-monsoon (Mcum)	Net Recharge per unit area (m)	Total GW draft from irrigation and drinking (Mcum)	GW draft per unit area (m)	SOD (%)
Gneiss	388.88	49.41	0.13	119.60	0.29	223.07
Charnockite	59.42	6.86	0.11	12.01	0.20	181.81
Fluvial	61.84	14.41	0.23	20.90	0.34	147.82
Granite	121.85	16.88	0.14	28.49	0.23	164.28

Lith-geom:

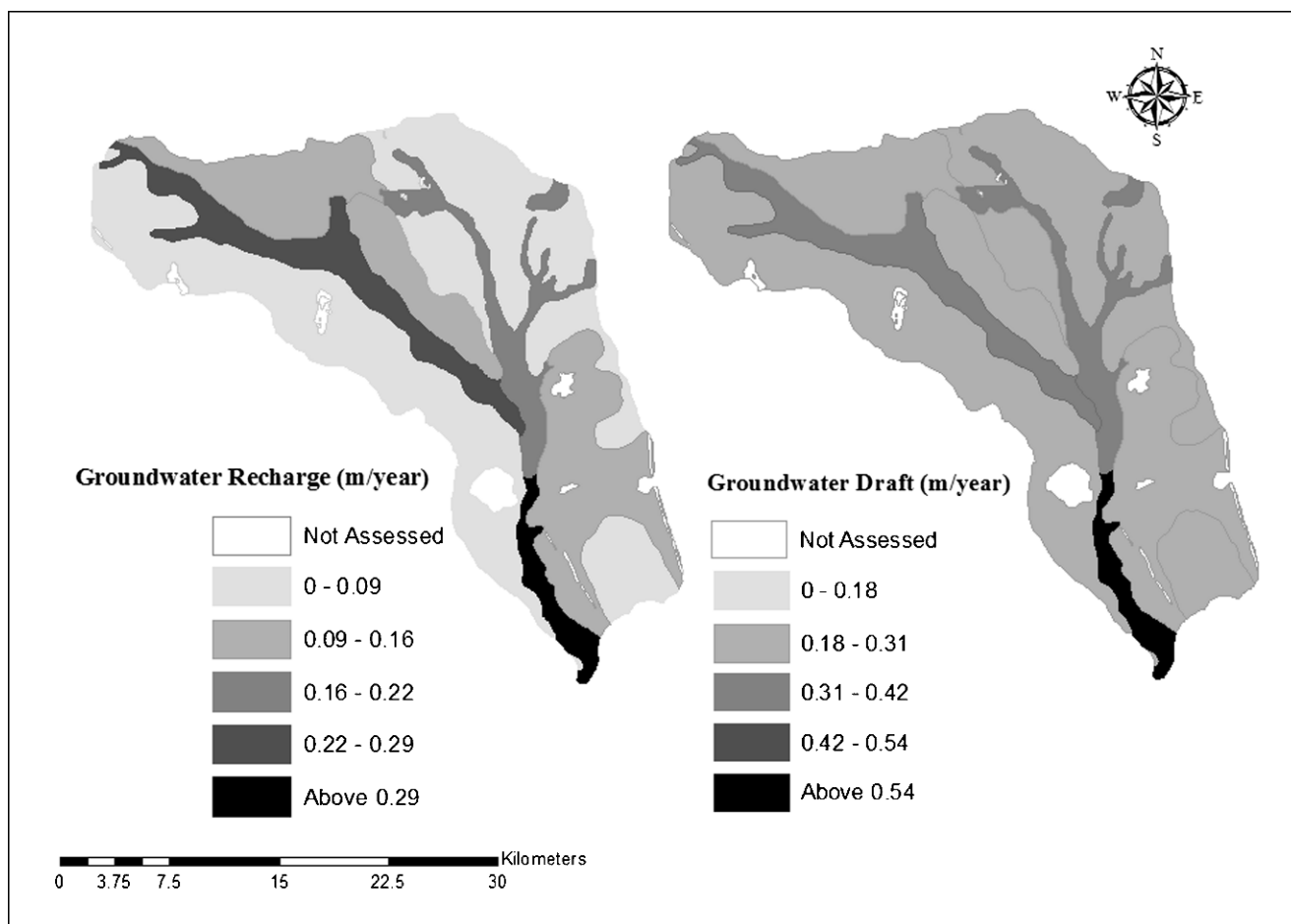| Litho-geomorphic units	Area (km^2)	Net recharge from rainfall, tank, and GW return flow in both monsoon+ non-monsoon (Mcum)	Net recharge per unit area (m)	Total GW draft (Mcum)	Total GW draft per unit area (m)	SOD (%)
Gneiss PPS	324.96	32.02	0.1	76.39	0.23	230.0
Gneiss BPM	16.97	6.98	0.41	14.21	0.84	204.87
Gneiss PPM	46.95	8.90	0.19	14.96	0.32	168.42
Charnockite PPS	59.42	6.86	0.11	12.01	0.20	181.81
Fluvial PPM	61.84	14.41	0.23	20.90	0.34	147.82
Granite PPS	121.85	16.88	0.14	28.49	0.23	164.28

**Fig. 4** Annual groundwater recharge and draft scenario in the study area during the year 2012

area of the assessment unit to arrive at estimates per unit area. Maps on estimates per unit area (km^2) have been generated to present the relative situation of recharge and draft across the sub-basin. Figure 4 presents the spatial variation of recharge and draft scenario in the lith-geom units. It reveals that in gneiss PPS, the recharge is very low due to shallow weathering condition. The gneiss BPM unit and fluvial PPM show high recharge respectively due to its highly weathered conditions. Charnockite PPS and granite PPS show less recharge due to its shallow weathering condition. In gneiss BPM, draft is very high, and in fluvial PPM, it is moderate. After comparing the recharge and draft conditions in the entire sub-basin, zone 1 is found relatively better, because the relative draft is less when comparing recharge conditions (fluvial PPM). Since the relative draft and recharge are comparable in zone 2, it is considered as semi-critical (gneiss BPM, gneiss PPM, charnockite PPS, and granite PPS). Zone 3 is the most critical area, since the relative recharge is very less compared to the draft, and hence, it requires immediate formulation of necessary groundwater management practices (gneiss PPS). Figure 5 shows the classification of lith-geom units for groundwater management.

Though the entire area is an over exploited zone with SOD >100 % (Table 7), the finer analysis of the lith-geom units resulted in three different scenarios of the area and helped in further categorization of the over exploited zones for better management practices of groundwater. Therefore, this study was able to strongly bring out the subtle variations in the groundwater assessment scenario that can be a step forward for groundwater management in general and in the study area in particular.

Conclusion

Groundwater resource estimation is a dynamic and continuing process, since the natural recharge and discharge pattern of the aquifers change with changing groundwater scenario. Therefore, there is an urgent need for the formulation of a long-term action plan for periodical re-assessment of groundwater resources. The comparative analysis of recharge estimation considering the basic unit of assessment as lithology and lith-geom emphasizes the importance of incorporating geomorphology along with lithology in characterizing aquifer at

Fig. 5 Groundwater
management scenario generated
in the study area using combined
lithology and geomorphology
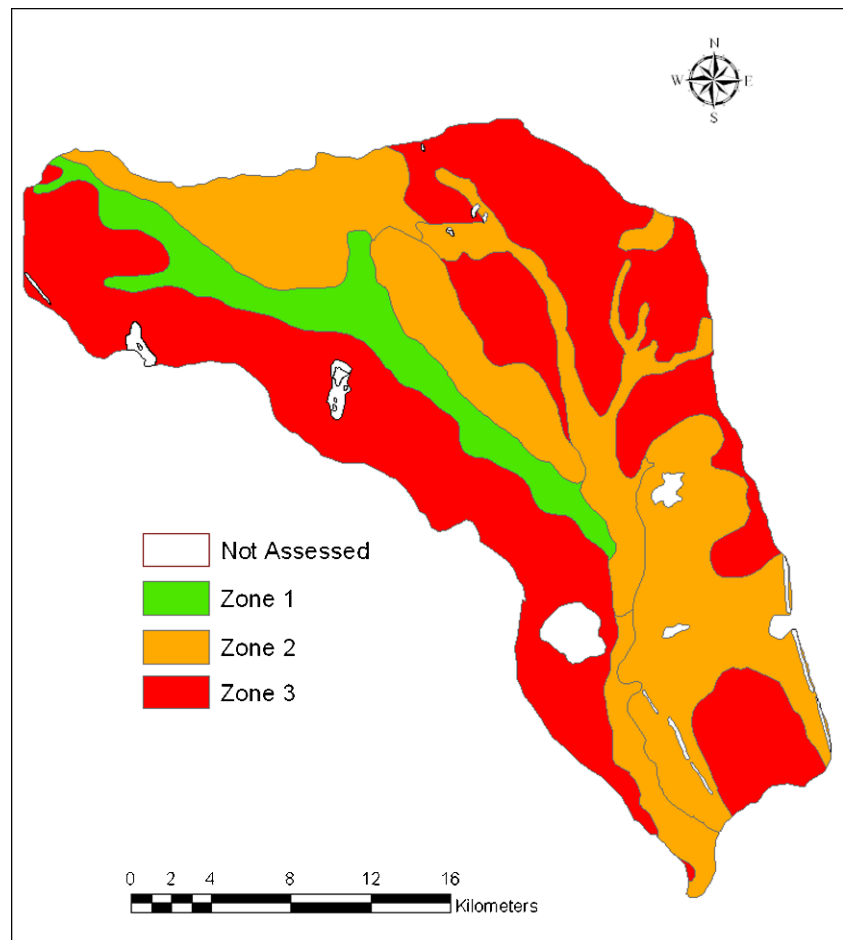
a microscale. Finally, recharge and draft have been compared lith-geom unit wise to give different classification zones for the management of groundwater in the area. In this study, it was found that accurate results could be obtained by using lith-geom as the basic unit for groundwater quantitative assessment than the conventional idea of using only lithology. Considering the changing groundwater scenario, reassessment of groundwater resources needs to be carried out at regular intervals. The GEC (2009) has considerable scope for refinement and improvement. Lith-geom serves as a second level of micro characterization of aquifer whereas lithology serves as a broad level of characterization. The groundwater management practices will also differ in the geomorphologically different units rather than lithology units. While characterizing gneissic rock, it was found that the geomorphologic variations in the gneiss (three units such as PPS, PPM, and BPM) have behaved differently with respect to aquifer recharge. The gneiss BPM unit shows very high recharge and fluvial PPM high respectively due to its highly weathered nature. Charnockite PPS and granite PPS show less recharge due to its shallow weathering condition. Zone 3 is the most critical area where recharge is less when compared to

draft, requiring immediate groundwater management practices (gneiss PPS). It was found from this study that the SOD for each lith-geom unit varies 164 to 230 % with overall SOD 194 %, requiring immediate attention and necessary management practices towards over-exploitation of groundwater. We conclude that the study strongly brought out the subtle variations in the groundwater assessment scenario using combined lithology and geomorphology that can be a step forward towards the micro-level groundwater management. It is strongly suggested that the GEC methodology in India, in the future, may adopt this method while prioritizing the critical areas for groundwater resource assessment, sustainability, and development.

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