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Full Length Research Paper

Demarcation of prospective groundwater recharge zones in hard rock area from Southern India

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In semi-arid regions, particularly in hard rock areas (Southern India), shallow aquifers are a major source of potable groundwater. These aquifers are indiscriminately exploited to meet the growing demand of water for domestic, irrigation as well as industrial uses. In order to achieve sustainable development, it is essential not only to delineate the groundwater potential zones but also suitable augmentation schemes which, in turn, require delineation of feasible recharge zones. Such zones are conventionally delineated through the application of various indirect methods, such as geological, hydro-geomorphological, geophysical, ^{14}C-age dating, tracer, entropy method, and groundwater modeling. These methods are, in general, time consuming and may not be economical in the developing countries. A simple, efficient and cost-effective based on cross-correlation method, which takes into consideration the shallow aquifer response to rainfall, is presented to delineate groundwater recharge zones in hard rock areas. The zones so delineated were compared with the results obtained from remote sensing (RS) and GIS techniques and were further validated with the aid of estimated recharge values calculated using the modified water-table fluctuation (WTF) method.

Key words: Shallow aquifers, rainfall, cross-correlation coefficient, recharge zone, water-table fluctuation, hard rock, Southern India.

INTRODUCTION

In many countries, particularly in Asia, there has been a rapid development in various fields particularly in agriculture, industry and energy during the last couple of decades. This has led to ever increasing demand for groundwater to meet domestic, agricultural and industrial requirements (Abdulrazzak et al., 2002; Espino et al., 2004; Batayneh and Qassas, 2006; Narayanamoorthy, 2007; Naik et al., 2008; Davies et al., 2009). Such demands are often met with indiscriminate exploitation of groundwater. The only source of replenishment of this exploited resource is rainfall, which is limited to a few monsoon months in a year, particularly in semi-arid regions such as in India (Rangarajan and Athavale, 2000; Raj, 2004; Zaidi et al., 2007). For example, according to some estimates, there is merely a 4.1 to 19.7% of the local average seasonal rainfall that replenishes groundwater in semi-arid regions. Based on tritium injection studies, the annual replenishable groundwater potential in India for a normal monsoon year has been calculated as 476 × 10^9 m^3/year (Rangarajan and Athavale, 2000). Annual rainfall in semi-arid regions is often scanty and recurring drought often prevails. The over-exploitation of groundwater in such regions, especially during droughts, leads to a progressive depletion of recharge potential and consequent decline in groundwater level year after year (Singh and Singh, 2002; Senthilkumar and Elango, 2004; Ambast et al., 2006; Panda et al., 2007; Vittala et al., 2008; Tiwari et al., 2009; Narayanamoorthy, 2010). In order to arrest the depletion in groundwater potential and to achieve sustainable development, several measures including

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artificial groundwater recharge have been suggested by Muralidharan and Shanker (2000), Bouwer (2002), Lerner (2002) and Anbazhagan and Ramasamy (2006). In order to implement artificial groundwater recharge, it is essential to delineate potential groundwater recharge zones. Conventionally piston-flow model (Zimmermann et al., 1967; Munnich, 1968; Gupta and Sharma, 1984; Athavale et al., 1992; Rangarajan and Athavale, 2000; Chaulya, 2004; Chand et al., 2005; Mondal et al., 2009; Rangarajan et al., 2009; Samadder et al., 2011), remote sensing (Saraf et al., 2004; Chowdary et al., 2009; Elewa and Qaddah, 2011), photogeological (Salama et al., 1994; Jackson, 2002), hydrogeological (Fetter, 2001; Scanlon et al., 2002; Nonner, 2006; Kumar et al., 2011) and geophysical methods (Shankar and Mohan, 2005; Maliva et al., 2009), ^{14}C-age dating (Bredenkamp and Vogel, 1970), entropy method (Mondal and Singh, 2010) and regional groundwater models (Sibanda et al., 2009) have been deployed to select favorable sites for implementation of artificial recharge schemes.

These methods are time consuming and sometimes even uneconomical in the developing countries, particularly when one has to deal with a large basin area. Instead, one can adopt simple and rapid methods to scan the entire area and arrive at suitable zones where further investigations can be undertaken later. In semi-arid regions where groundwater occurs in shallow weathered zones, the rise in groundwater level is a direct consequence of precipitation, particularly in the monsoon season, when the groundwater withdrawal is minimum (Raj, 2001; Public Works Department, 2008). The rise of water level at a particular place is a characteristic feature of unsaturated zone (Todd, 1980; Athavale et al., 1992; Raj, 2001; Moon et al., 2004; Lee et al., 2005). Therefore, there exists a definite relationship between the amount of rise in water level and precipitation for a particular region. In other words, each zone is characterized by a parameter that correlates the rise in groundwater level with precipitation. A higher correlation coefficient implies a significant groundwater recharge characteristic or most favorable recharge zone. Considering this feature data on the rise in groundwater level and rainfall from an area in a semi-arid region in southern India have been analyzed to delineate suitable artificial recharge zones. Monthly water level data, recorded for 37 years (from January 1971 to December 2007) by Public works department (PWD), Tamil Nadu, India, in 6 monitoring wells in the study area (Figure 1) were considered. The cross-correlation between rainfall and depth to water level were then determined. The correlation coefficient of these two variables varied from place to place and from time to time. Thus, the objective of this study is threefold: 1) delineate groundwater recharge zones using cross-correlation, 2) compare the cross-correlation method with the results obtained from remote sensing (RS) and geographical information systems (GIS) techniques, and 3) validate the demarcated groundwater recharge zones using the modified water-table fluctuation (WTF) method.

MATERIALS AND METHODS

About study area

The study area is a drought prone hard rock terrain and is located about 400 km southwest of Chennai, the capital city of Tamil Nadu state, India. It lies between 10° 13’44” to 10° 26’ 47” N latitude and 77° 53’ 08” to 78° 01’ 24” E longitude (Figure 1), and encompasses an area of about 209 km^2, covering parts of Dindigul, Attur, Reddiarchattram and Sanarpatti blocks. The area is characterized by undulating topography with hills located in southern parts, sloping towards north and northeast. The highest elevation (altitude) in the hilly area (Sirumalai Hill) is of the order of 1350 m (amsl), whereas in plains it ranges from 360 m (amsl) in the southern part to 240 m in the northern part. No perennial streams exist in the area, except for short distance streams encompassing 2nd and 3rd order drainage (Singh et al., 2003; Mondal et al., 2005). Runoff from precipitation within the area ends in small streams flowing towards the main Kodaganar River. From a period of 1971 to 2007 (Public works department, 2008) the average annual rainfall is of the order of 905.3 mm.

Geological and hydrogeological settings

The study area is covered with Achaean granites and gneisses, intruded by dykes (Balasubramanian, 1980; Chakrapani and Manickyan, 1988). These, including granite, grandiosities, gneissic granite and gneisses (Krishnan, 1982) are the most widespread groups of rocks, and have heterogeneous mixtures of different types of granites intruding into schistose rocks after the latter folded and metamorphosed. The rocks are mainly composed of gray and pink feldspar with quartz grains, biotite and hornblende (Barker et al., 2001). These formations are crossed by sets of joints and fractures, which have also caused weathering of coarser rocks. Weathering occurs due to mechanical and mostly chemical processes that take place, while water in the fractures interacts with the formation. The shallow hard and massive rocks are exposed mostly in the southern part. Red sandy soil is obtained in northern and southern parts of the area where black cotton soil occurs in the middle part. The weathered thickness varies from 3.1 to 26.6 m (Mondal et al., 2011a). Such shallow weathered zones may not be stable sources of groundwater for meeting large demands of groundwater (Singh et al., 2003; Mondal, 2005; Mondal et al., 2011a). There are many lineaments which are oriented mainly in the NNE to SSW, NEE to SWW, and NW to SE directions, but the major lineament is running in the NNE to SSW direction for several kilometers situated northwest of Dindigul town along Kodaganar River (Figure 1). The weathered zone facilitates the movement and storage of groundwater through a network of joints, faults and lineaments, which form conspicuous structural features. Apart from the structural controls on the groundwater movement, the area is covered with pediment and buried pediment on southern and western sides of the area. The other most dominant formation is the charnokite, which is found in southern and southeastern parts of the Sirumalai hills. This formation is less weathered, jointed or fractured compared to the previous one (Public works department, 2008) and can therefore be considered as impermeable. Groundwater occurs mostly in weathered and fractured zones, which are unconfined,

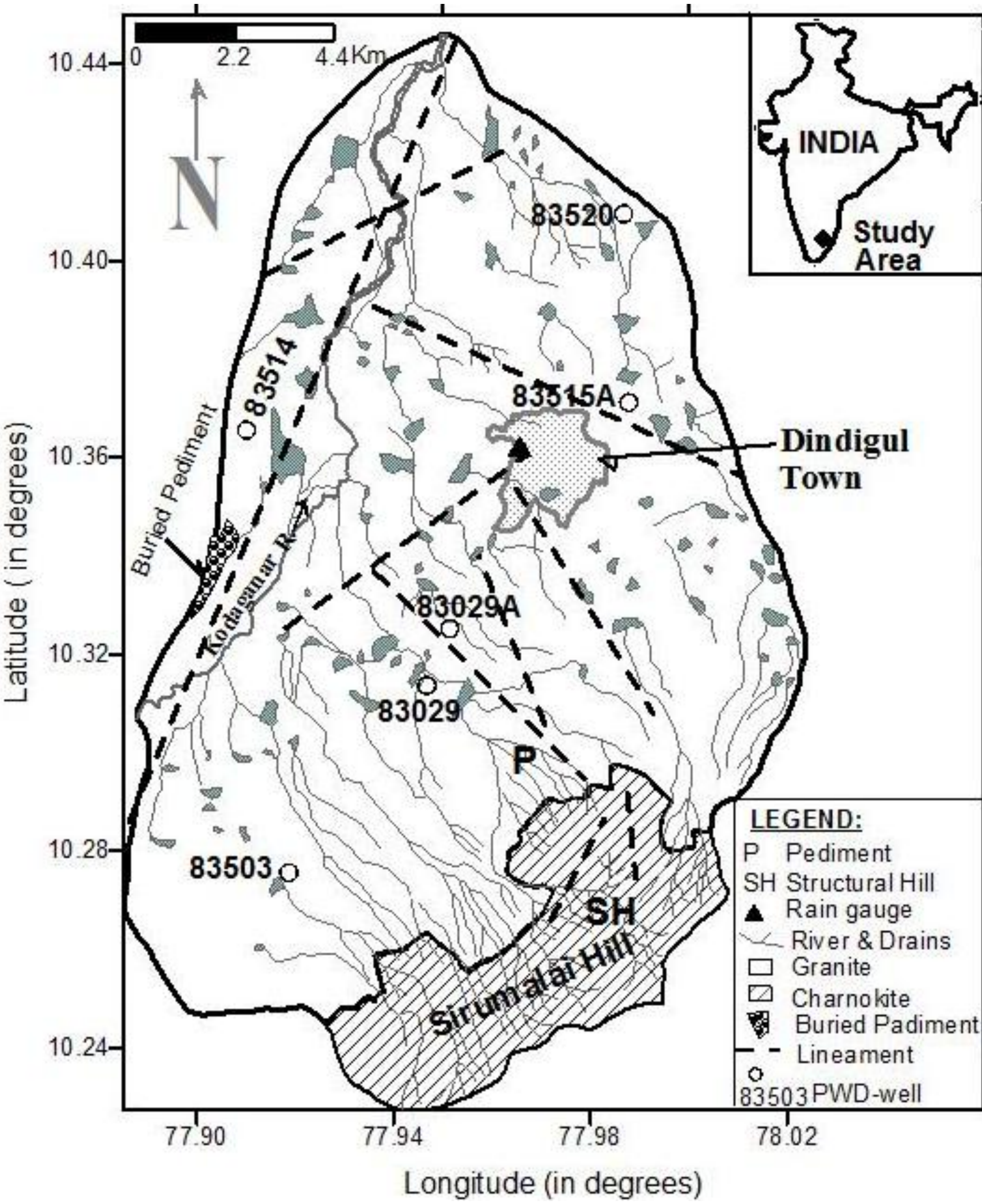

Figure 1. Location map of the study area.

semi-confined or confined (Mondal et al., 2011b). These aquifer confining conditions may change rapidly and vary over a wide range from place to place.

The thickness of weathered/fractured zone varies over even a small region. Shallow aquifers are usually phreatic, which may not be a stable source for meeting large demands on groundwater, but deeper aquifers are partly confined, that is, they are recharged from shallow unconfined aquifers through dug-cum-bore wells/bore wells as water accumulates in dug wells, percolates into confined aquifers through bore wells which are provided in dug wells.

Data collection

Monthly rainfall data from the Dindigul rain gauge station (Figure 1) was collected for the period of January 1971 to December 2007 (Public works department, 2008). During the same period the monthly water level data was also collected from 6 PWD open wells, which are not used for domestic and gardening uses. The missed water level data at the PWD wells varied from 0.48 to 3.81% with an average 2.24% of total 2100 events, which were calculated using a moving average method (Medhi, 2005). Although rainfall distribution in the study area is non-uniform due to the presence of surrounding hills, undulating topography and other meteorological conditions, it was presumed that rainfall was uniformly distributed throughout the area, because there was only one rain gauge station. Using remote sensing (RS) and geographical information system (GIS) techniques, the Institute of Remote Sensing, Anna University, Chennai, India has divided the study area into four recharge zones. These zones are: i) high, ii) moderate, iii) less, and

iv) poor zones for groundwater recharge. The categorization of zones are based on the integration of the different themes namely: geomorphology, geology, hydrological soil group, slope, depth to weathered zone, depth to basement, run-off, water level, land use, drainage density, lineament density, water quality and rainfall. The well areas of PWD 83520 and 83514 (Figure 1) are fallen in high and less groundwater recharge zones, respectively.

The wells 83029A and 83503 are in moderate whereas poor groundwater recharge zones are found at the wells 83029 and 83515A, which were compared with the cross-correlation coefficients obtained between water level fluctuations corresponding to rainfall.

Cross-correlation technique

Changes in the depth to the water table were correlated with changes in rainfall (Todd, 1980). First, mean values of monthly rainfall (p) and monthly depth to water level (d) values were computed, and then deviations from the mean values were computed as:

$$P = p - p^{/} \quad (1)$$

$$D = d - d^{/} \quad (2)$$

Where, P = deviation from the mean, = p – p’; D = deviation from the mean, = d – d’; p’ and d’ are the means of monthly rainfall and monthly depth to water level, respectively. Deviations of rainfall and depth to water level were plotted on a linear graph (Davis, 1986). Points (P, D) are so distributed over the fourth quadrant of the PD-plane that the product PD is negative. Cross-coefficient (r) between p and d was computed using the following relation:

$$\mathrm{r} = \frac{\sum PD}{n\sigma_p \sigma_d} \quad (3)$$

Where σ_p = standard deviation of p-series; σ_d = standard deviation of d-series and n = number of data sets of depth to water level corresponding to rainfall.

Cumulative WTF for recharge estimation

Recharge based on the water-table fluctuation (WTF) method for an unconfined aquifer was calculated as (Healy and Cook, 2002):

$$R = S_y \frac{dh}{dt} = S_y \frac{\Delta h}{\Delta t} \quad (4)$$

Where S_y is specific yield, h is water-table height, and t is time. The method is best applied over short time periods (hours or a few days) in regions having shallow water tables that show sharp rises and declines (Scanlon et al., 2002). When delayed drainage occurs, the method would underestimate the recharge rate (Healy and Cook, 2002). Moon et al. (2004) suggested a modified water-table fluctuation (WTF) method to estimate groundwater recharge as the product of specific yield and ratio of water level rise over the cumulative precipitation during the rainy period that caused water level rise:

$$\alpha = \frac{h_1 + h_2 + - - - h_n}{P_1 + P_2 + - - - P_n} \times S_y = \frac{\Sigma h}{\Sigma P} \times S_y \quad (5)$$

where α is recharge ratio, h_1, h_2, ….., h_n is the water level rise for each precipitation event, and P_1, P_2, P_3, ….., P_n is the precipitation at each time, Σh is the total water level rise due to the cumulative precipitation, and ΣP is the cumulative precipitation in the period corresponding to water level rise (∆h). This modified WTF method was employed for recharge estimation in hard rock area.

RESULTS

Climate and rainfall patterns

Normally, sub-tropical climate prevails over the study area without sharp variations. The temperature increases slowly to a maximum in summer months up to May and after which it drops slowly. The mean of maximum temperature ranges from 36.5 to 41.8°C and in the hills, it ranges from 7.9 to 21.8°C. The mean of minimum temperature varies from 17.4 to 24°C and in the hills it varies from 6 to 8.5°C (PWD, 2008). The season wise normal rainfall values for the period of January 1971 to December 2007 shown that about 4.11% of the annual rainfall precipitated in winter (January and February), where 15.77% in summer (March to May), 31.39% in Southwest monsoon period (June to September) and 48.73% in Northeast monsoon period (October to December). As there was only one rain gauge station, the whole study area was considered to be affected by the same rainfall (Athavale et al., 1980, 1983; Rangarajan, 1997; Rangarajan and Athavale, 2000, Chand et al., 2005), which was monitored at the Dindigul rain gauge station (Figure 1). The total annual and average monthly rainfall values are illustrated in Figure 2. It indicates that the average monthly rainfall was in four different stretches. More rainfall, however, occurred in the last stretch each year (Figure 2A). The average annual rainfall was also estimated to be about 905.3 mm from January 1971 to December 2007 (Figure 2B) and a linear trend showed that average annual rainfall was uniform. Based on the natural recharge values (Rangarajan and Athavale, 2000), the entire country (India) has been grouped into four main hydrogeological provinces. They are granitic, basaltic, sedimentary and alluvial. The best fit lines, obtained by the least square method, show a linear correlation between seasonal rainfall and natural recharge in each case. This linear relation between rainfall and natural recharge exists for all four major

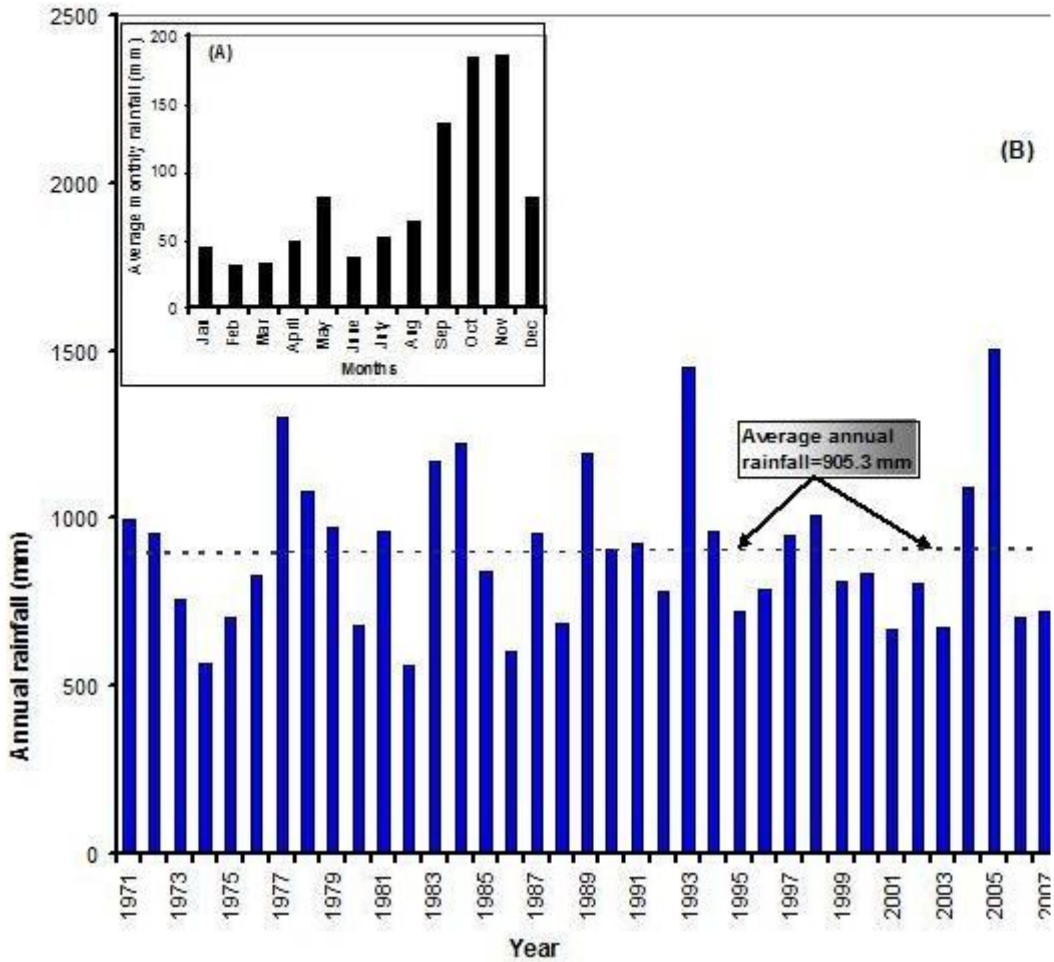

Figure 2. Average (A) monthly rainfall (mm), and (B) annual rainfall (mm).

hydrogeological units.

The regression equation derived for each of the hydrogeological provinces indicates a certain minimum rainfall requirement to initiate groundwater recharge. The minimum values were 255 mm/year for granite, 355 mm/yr for basalt, 220 mm/year for sediments and 40 mm/year for alluvial areas. The seasonal normal rainfall was 441.1 mm during months of October and December in the study area. Therefore this season was considered for cross-correlation analysis between water level fluctuations to rainfall.

Water level fluctuation

The details of well inventory are given in Table 1. All the open wells were rectangular shaped, except for two circular structures with depth ranging from 14.05 to 28.50 m below ground level (bgl). The depth to water bearing zone varied from 2.5 to 3.8 m (bgl) and the thickness ranged from 4.0 to 14.6 m under phreatic conditions. The transmissivity varied from 10 to 140 m^2/day, whereas the specific yield ranged from 0.002 to 0.004 (Mondal, 2005). The well reduced levels varied from 259.499 to 301.045 m above mean sea level (amsl), but the groundwater was measured from the measuring points, which varied from 0.45 to 1.05 m. When water level hydrographs with rainfall data were plotted, there was approximately one month time lag in the response of water table to rainfall events. One typical well hydrograph (at PWD well 83520) and monthly rainfall variation is shown in Figure 3. It was confirmed by cross-correlation analysis between depth to water level and rainfall events in the next section. The aquifer system is spread over the area, responding within one month lag of rainfall. It can be also observed that the aquifer responded maximally particularly to the rainfall that occurred from October to January when most of the rainfall occurs and withdrawal could be minimized (Figures 4A, B). Measured groundwater levels at the 6 PWD wells of the study area in the months of September, October, November, December and January for the years 1974, 1994, 2000 and 2004 corresponding to monthly

Table 1. Detailed well inventory of PWD wells located in hard rock area of Southern India.

Well Ids.	Village name	Global location (Latitude, Longitude)	Dimension (m)	Depth of well (m)	Lining depth (m)	Water bearing zone (m, bgl)	T^a (m^2/d)	S_y^a	MP (m)	Reduced level (m, amsl)
83029	A. Vellodu	10° 18' 50'', 77° 56' 50''	3.02	21.65	3.0	2.6- 8.1	65	0.002	1.00	279.760
83029A	A. Vellodu	10° 19' 26'', 77° 57' 50''	3.93	28.50	3.0	3.0 - 7.0	80	0.002	0.45	282.800
83503	Ambathurai	10° 16' 25'', 77° 55' 14''	3.85 × 3.00	16.65	4.0	3.4 - 9.0	10	0.003	0.66	301.045
83514	Sinthalakundu	10° 21' 55'', 77° 54' 20''	2.41 × 2.47	14.05	5.0	2.9 - 8.0	40	0.004	0.90	259.499
83515A	Dindigul	10° 22' 10'', 77° 59' 45''	7.36 × 6.08	14.40	3.0	2.5 - 11.1	140	0.002	1.05	267.435
83520	Seelapadi	10° 24' 22'', 78° 00' 23''	2.82 × 2.93	18.40	4.0	3.8 - 18.4	85	0.002	0.78	260.695

Well type: dug well; type of aquifer: phreatic; geology: granite and gneisses; stratigraphy: archaean; T: transmissivity (m^2/day); S_y: specific yield; MP: measuring point; [a]after Mondal (2005).

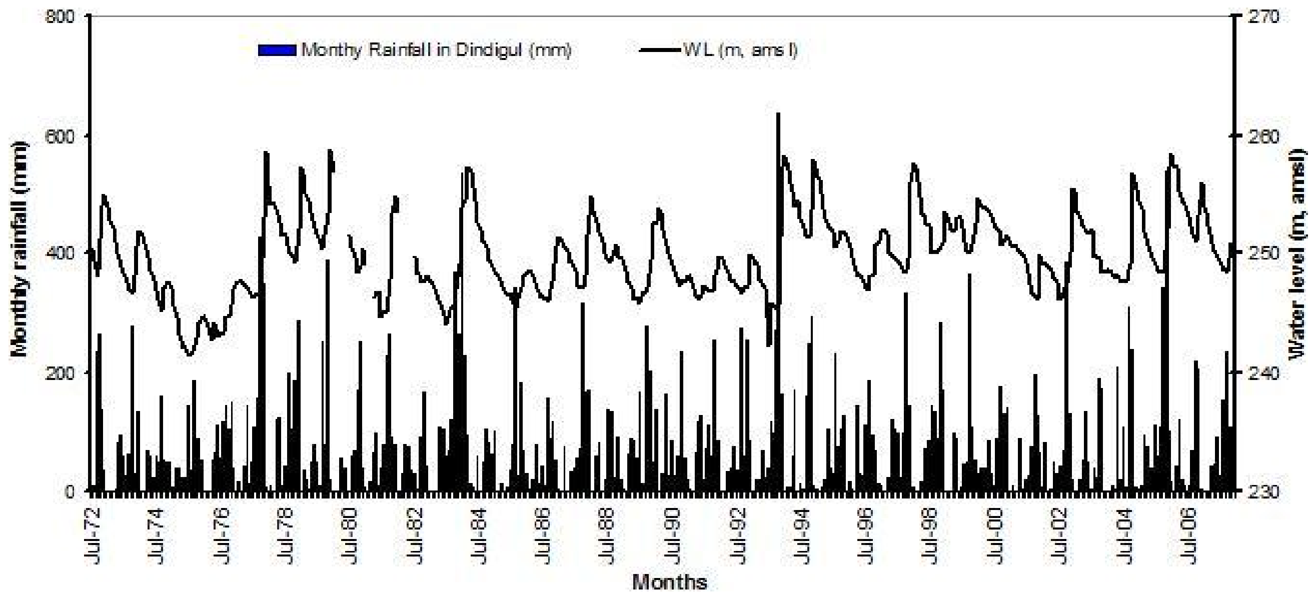

Figure 3. Comparison of water level fluctuation with rainfall at PWD well 83520 (Seelapadi village) from July 1972 to December 2007.

rainfall are shown in Figures 5A, B, C, D. Depths to groundwater ranged from 6.50 to 18.10 m below the ground surface for the period of September 1974 to January 1975 (Figure 5A). Median values decreased, which meant water level rise by 0.83 from 12.23 m in September to 11.46 m in January. For the period of September 1994 to January 1995 depths to groundwater ranged between 1.55 and 13.05 m below the ground surface (Figure 5B). Medians of the values decreased, which meant the water level rise by 4.25 from 9.53 m in September to 5.28 m in

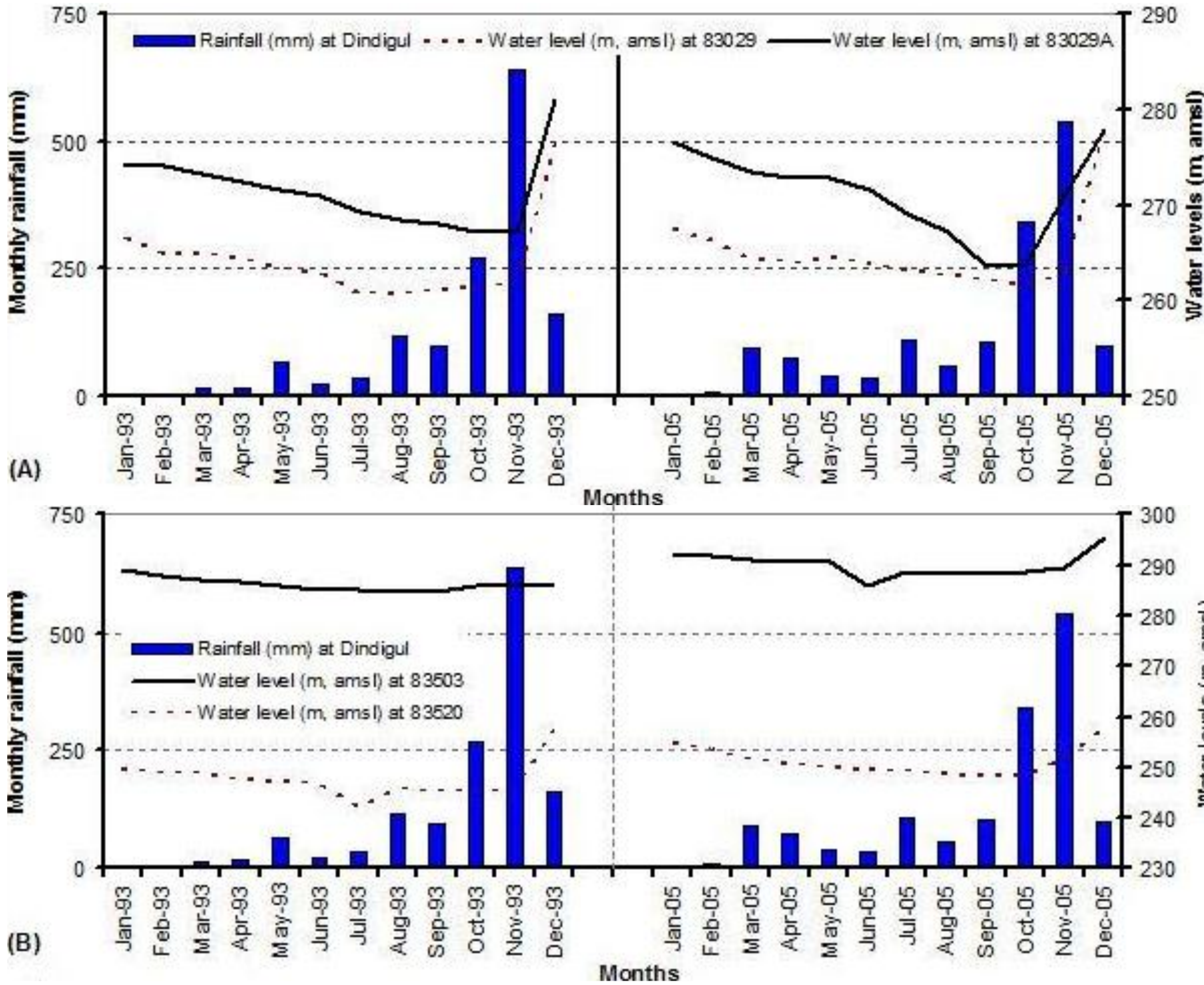

Figure 4. Well hydrographs (A) at PWD well 83029 (A. Vellodu) and (B) at PWD well 83503 (Seelapadi).

January. Below the ground surface, depths to groundwater ranged between 5.35 and 18.55 m for the period of September 2000 to January 2001 (Figure 5C). Medians of the values also decreased, which meant the water level rise by 4.31 from 13.98 m in September to 9.67 m in January. Further, the depth to groundwater ranged between 2.65 and 22.05 m (bgl) for the period of September 2004 to January 2005 (Figure 5D). The median values decreased, which meant the water level rise by 8.00 m in the study area from 15.12 m in September to 7.12 m in January. This rise in the water level coincided with amount of monthly precipitation with 1-month lag in all the above cases (Figure 5).

Cross-correlation analysis

For confirming the response of water level in open well, cross-correlation coefficients were determined between the depth to water table and corresponding rainfall for 37 years of data. The coefficient values with one-month lag between depth to water level and rainfall at PWD well 83029, 83029A, 83503, 83514, 83515A and 83520 were comparatively higher, which were 0.171, 0.251, 0.169, 0.215, 0.161 and 0.255, respectively. The correlation coefficient values were plotted against the corresponding lags in the water table rise, as shown in Figure 6. It was seen that all PWD wells responded with one-month lag after the rainfall in this hard rock area.

Applying cross-correlation analysis to the water table variation in response to rainfall, the following observations were made: 1) The time lag of one-month for the maximum response of unconfined aquifer after rainfall is observed; 2) the amplitude of correlation decreases when lag increases/decreases in a systematic manner; and 3) the depth to the aquifer also plays an important role in the delay because of subsurface losses as well as travel time for vertical percolation (Todd, 1980). The travel time may vary from a few minutes for shallow water tables in permeable formations to several

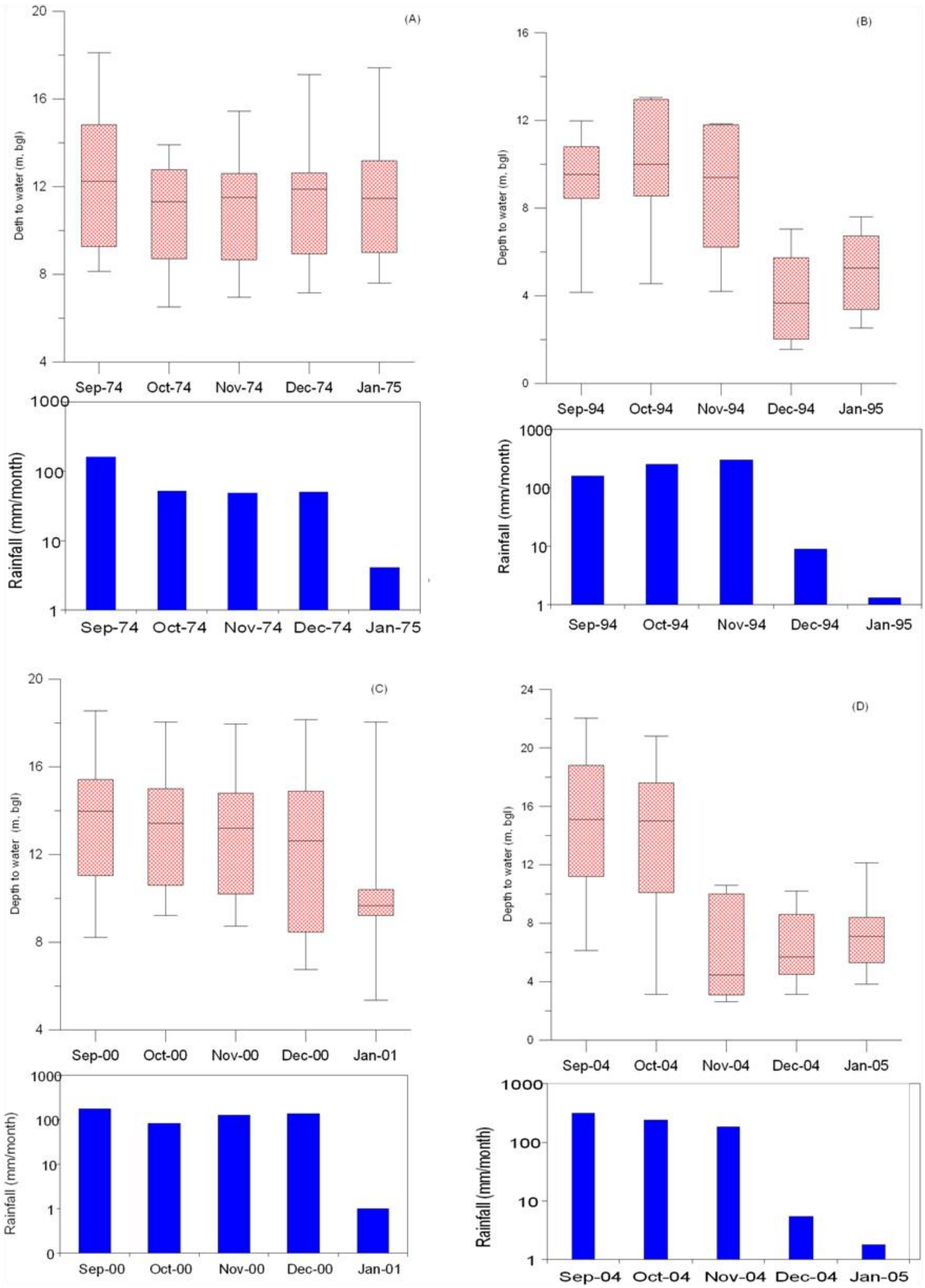

Figure 5. Ranges of depth to water (DTW) from September to January with monthly rainfall for year (A) 1974, (B) 1994, (C) 2000 and (D) 2004.

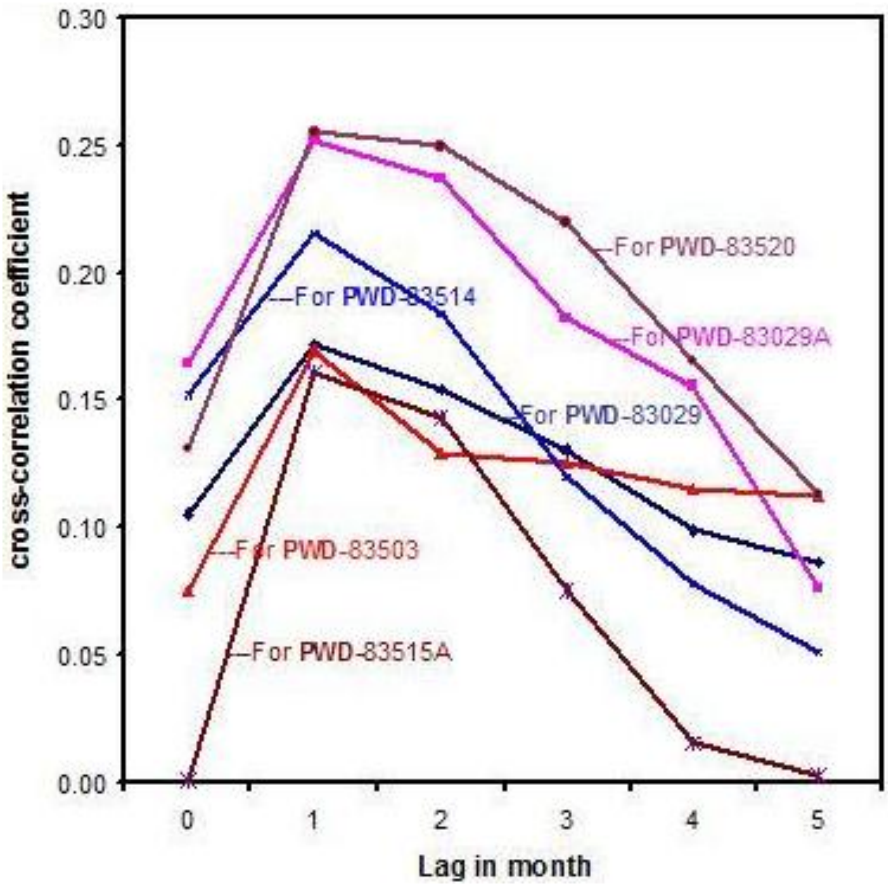

Figure 6. Plots of cross-correlation between depth to water level and precipitation with different lags.

months or years for deep water tables underlying sediments or weathered zones with low vertical permeabilities.

Qualitative recharge estimates

On the basis of correlation coefficient values from August to March (including wet period) with corresponding response lag for the period of January 1971 to December 2007, a qualitative estimation of groundwater recharge zones of this hard rock area was made. The seasonal normal rainfall was 441.1 mm in the months of October to December. In this period unconfined aquifers are in more suitable condition for natural recharge (Rangarajan and Athavale, 2000). High coefficient values indicated good recharge and low value indicated poor recharge (Figure 7). Due to rainfall in the month of November, PWD wells 83520, 83503, 83029A, 83514 and 83029 responded in December where the value of correlation coefficients were 0.676, 0.551, 0.544, 0.471 and 0.388, respectively. Well 83515A gave a good response to rainfall in January; the value being 0.368. The correlation values indicated the behavior of the recharge response of unconfined aquifers in this hard rock area.

Categorization of recharge zones

Using remote sensing (RS) and geographical information system (GIS) techniques, the study area has been divided into four recharge zones. These zones are: i) high, ii) moderate, (iii) less, and (iv) poor for groundwater recharge. On the basis of estimated cross-correlation coefficients, the well areas were also divided into four recharge zones, which yielded a good agreement with the results obtained from RS and GIS techniques. They are: (i) zones of high recharge for value ($r>0.60$), (ii) moderate zone for recharge ($0.50 \leq r \geq 0.60$), (iii) zones of less recharge ($0.40 \leq r \geq 0.50$), and (iv) zones of poor recharge ($r < 0.40$). It was difficult to identify the response behavior of unconfined aquifers with coefficient values, because it depended on the combined effect of hydrogeological variables, such as precipitation-related variables (amount, duration, and intensity), stream levels, the thickness and materials of the vadose zone,

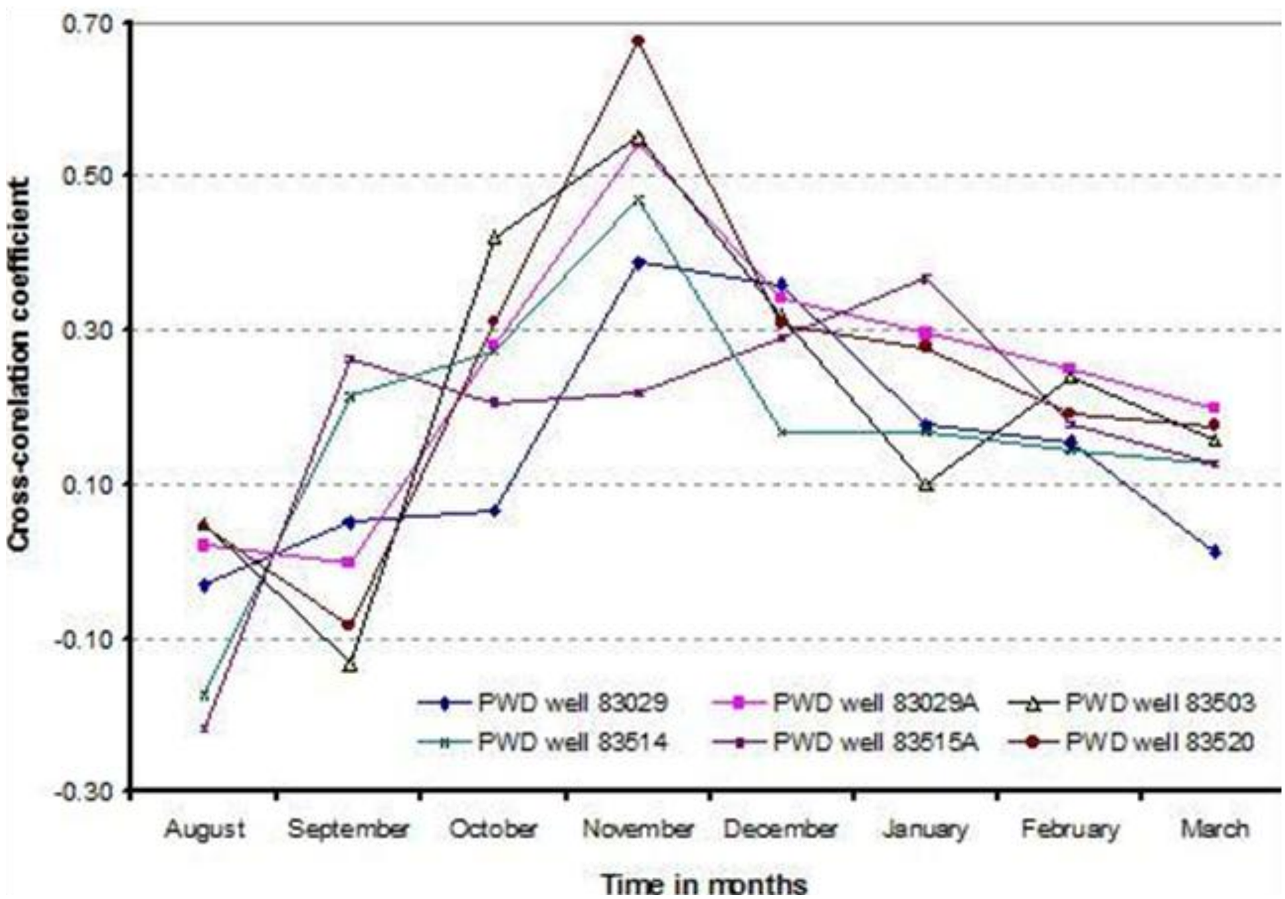

Figure 7. Qualitative recharge response at PWD wells due to rainfall.

geometry and properties of aquifer, crops and topography patterns, and bed-rock geology (Moon et al., 2004). The recharge rates of any unconfined aquifer are very “site specific” (Viswanathan, 1983). This means that results obtained at one location may not be applicable to another. The highly favorable recharge zone was found around well 83520 at Seelapadi village. This area is characterized by bajada, shallow pediment with high weathered (thickness>10 m), hydrological soil group ‘A’ with moderate infiltration characteristics as well as runoff (50-130 mm) with a slope of 3 to 10%. Moderate recharge zones were around the ‘A’ Vellodu (at well 83029A) and Ambathurai (at well 83503) villages. These zones are characterized by pediment, moderated weathered zone (thickness 12 to 20 m), hydrological soil group ‘B’ with moderate infiltration rate and runoff (65 to 80 mm) with a slope of 5 to 10%.

The area around the Sinthalakundu village (at well 83514) is less favorable for groundwater recharge. This is characterized by hydrological soil group ‘C’ with less runoff (75 to 95 mm) and a slope of < 3%. The poor condition for recharge zone existed only for hills and PI complex having less thickness (< 20 m) of weathered chances zones within hydrological soil group ‘D’ having poor infiltration rate and runoff (> 130 mm) with a slope of > 15% in ‘A’ Vellodu and Dindigul town.

Recharge estimation and its validity

Recharge ratios at the monitoring PWD wells were estimated using the modified WTF method (Moon et al., 2004) in consideration of 1-month time delay. First, the water-level rise due to rainfall event was calculated for the period of January 1971 to December 2007 (Figures 8 A to F). Any noticeable water-level rise in the case of no rainfall indicated the existence of delayed drainage by preceding rainfall or horizontal component of groundwater recharge. In this case, meaningful water-level rises were observed at minimum rainfall values of 5.50 to 20.92 mm. The water-level rises versus event rainfall values were fitted with linear equations, but they yielded a wide range of coefficients of determination (R^2 = 0.125 to 0.433). As expected, the same amount of precipitation did not produce the same amplitude of water level rise. Water level rises due to specific amounts of rainfall were largest at PWD well 83520, while those were smallest at PWD well 83514. At PWD well 83029 and

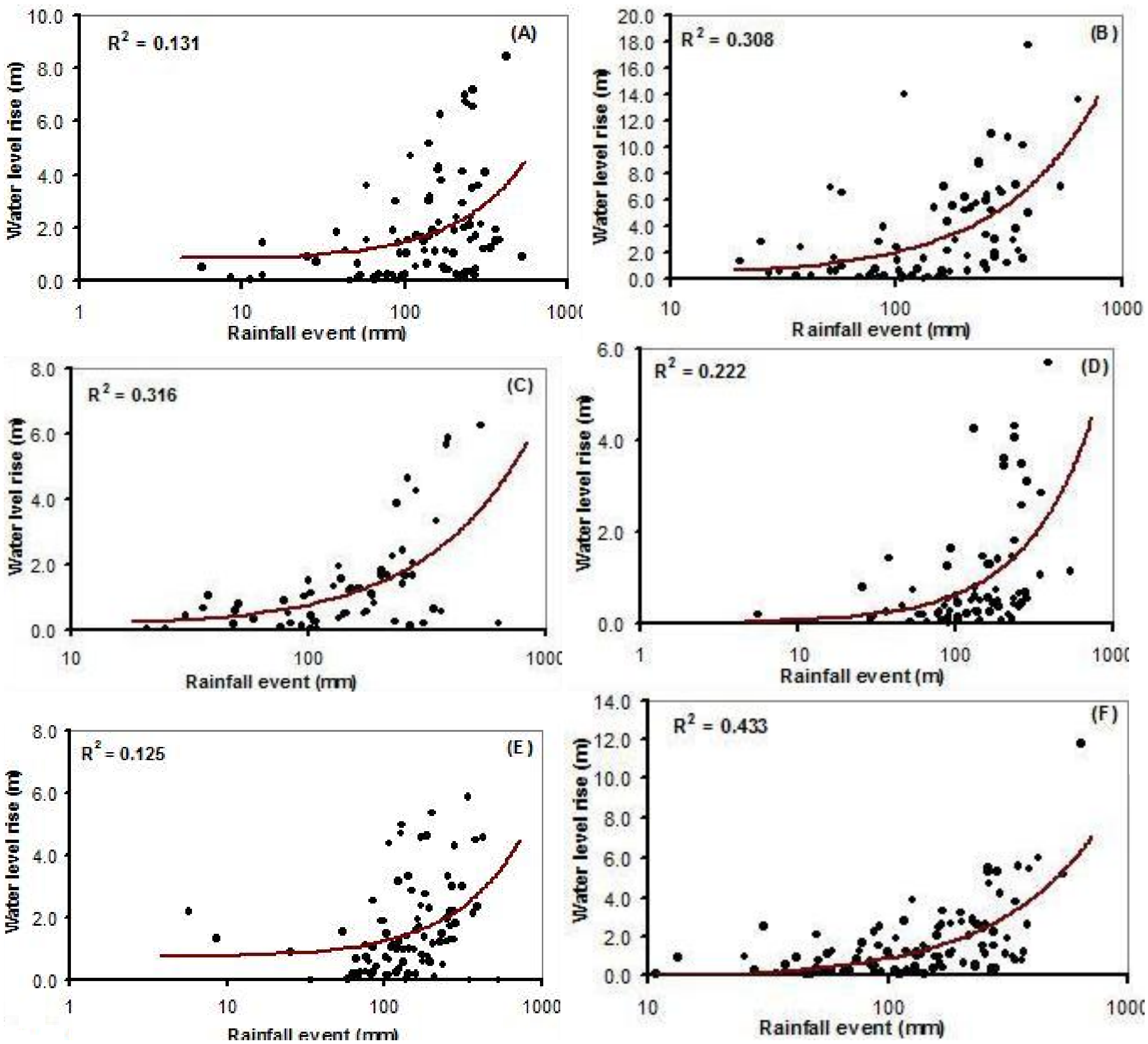

Figure 8. Water level rises due to rainfall events at PWD well (A) 83029, (B) 83029A, (C) 83503, (D) 83514, (E) 83515A and (F) 83520.

83515A, the water level rises were relatively moderate and linearity between the water level rise and the rainfall was poorest. The fact is highly correlated with larger attenuation of the input stress through the thinnest black cotton soil, which amplified the non-linearity (Mondal, 2005). This was also supported by the lowest correlation between rainfall and water level. Relatively, a significant linearity between water level rise and site rainfall was observed at PWD well 83520 (R^2 = 0.433) which is located at highly weathered zone (>10 m).

The values of the ratio of the rise in groundwater level and the cumulative rainfall during the rainy period for the entire data set were calculated (Table 2).

Subsequently, recharge ratios were computed using these ratios and specific yields (Table 1). As expected, the same amount of the cumulative precipitation produced a wide range of water level rises for different monitoring locations due to different hydrogeological conditions, such as the thickness of the unsaturated zone, topography pattern, weathered thickness, etc. The estimated recharge ratios based on the modified WTF method ranged from 1.92 to 4.06% (Table 2). The largest value of the recharge ratio was obtained at PWD well 83520, while the lowest value was estimated at PWD well 83515A. Although the spatial extent of the monitoring area is only 209 km^2 (Mondal et al., 2011b), the estimated recharge ratios were very different within an average of 2.89%. Rangarajan and Athavale (2000) and Rangarajan et al. (2009) meanwhile estimated an average recharge ratio of 10.11% for 15 granitic and gneiss areas in varying climatic and hydrogeological provinces of India. Out of them, the average recharge

Table 2. Cumulative precipitation, water level rise and recharge ratios at six PWD wells in hard rock area (Southern India)

Wells	83029	83029A	83503	83514	83515A	83520
R^2	0.131	0.308	0.316	0.222	0.125	0.433
ΣP(mm)	14407.5	13954.5	10721.4	11030.2	14794.6	15140.3
Σh(m)	166.02	262.64	98.92	69.50	141.71	307.15
Σh/ΣP	11.52	18.82	9.23	6.30	9.58	20.29
α	2.30	3.76	2.77	2.52	1.92	4.06
*Recharge potential zone	P	M	M	L	P	H

R^2: Coefficient of determination; ΣP: Sum of precipitation; Σh: Sum of water level rise due to corresponding rainfall event; α = Recharge ratio (%); average recharge = 2.89% during wet seasons; and *H: high, M: moderate, L: less, and P: poor recharge zone based on RS & GIS methods

ratio was about 9.90% for 4-granitic and gneiss areas in Tamil Nadu. But the simple mean of these six recharge values estimated in the study area was 2.89%, which was underestimated (Table 2). However, considering the great variation in recharge ratios according to the monitoring locations in hard rock area, it is important to compare the estimated correlation coefficients obtained between water level fluctuation and the corresponding rainfall events for choosing appropriate locations of groundwater potential recharge zones.

DISCUSSION

Groundwater recharge potential zones in hard rock area (Southern India) are important in planning sustainable groundwater development. These potential zones are demarcated into: (i) high recharge zone for value ($r>0.60$), (ii) moderate zone for recharge ($0.50 \leq r \geq 0.60$), (iii) less recharge zone ($0.40 \leq r \geq 0.50$), and (iv) zones of poor recharge ($r < 0.40$) with the aid of cross-correlation coefficients (r) between water level corresponding to rainfall for the period of January 1971 to December 2007. This yields a good agreement with the results obtained from RS and GIS methods. A modified water-table fluctuation (WTF) technique is also used to estimate the groundwater recharge ratio from the water level monitoring data and corresponding rainfall records. The recharge ratio during the rainy season is calculated as the ratio of water level rise to the cumulative rainfall amount. Using this technique, groundwater recharge ratios are calculated for all the PWD wells. The estimated recharge ratio values vary from 1.92 to 4.06%, which are in sequential order corresponding to the demarcated groundwater potential recharge zones classified from the cross-correlation coefficients between water level and precipitation in this hard rock area. Thus, identification of groundwater potential recharge zones in large areas, specifically hard rocks, by the existing geological, hydro-geomorphological, geophysical, ^{14}C-age dating, entropy, groundwater modeling, and tracer techniques is sometimes difficult and time consuming. Hence, the cross-correlation technique is a potential exploratory tool for demarcating possible quantative groundwater recharge zones using simply water level fluctuation due to rainfall in hard rock areas at a glance.

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REFERENCES

Abdulrazzak MJ, Jurdi M, Basma S (2002). The role of desalination in meeting water supply demands in Western Asia. Water Int., 27(3): 395-406.
Ambast SK, Tyagi NK, Raul SK (2006). Management of declining groundwater in the Trans Indo-Gangetic Plain (India): Some options. Agri. Water Manage., 82(3):279-296.
Anbazhagan S, Ramasamy SM (2006). Evaluation of areas for artificial groundwater recharge in Ayyar basin, Tamil Nadu, India through statistical terrain analysis. Jour. Geol. Soc. India, 67(1):59-68.
Athavale RN, Chand R, Rangarajan R (1983). Ground water recharge estimates for two basins in the Decccan Trap Basalt formation. Hydrol. Sci. J., 28(4-12): 525-538.
Athavale RN, Murti CS, Chand R (1980). Estimation of recharge to phreatic aquifers of Lower Maner Basin by suing the Tritium injection method. J. Hydrol., 45: 185-202.
Athavale RN, Rangarajan R, Murlidharan D (1992). Measurement of natural recharge in India. Jour. Geol. Soc. India, 39: 235-244.
Balasubrahmanian K (1980). Geology of parts of Vedasandur Taluk, Madurai District, Tamil Nadu. Progress Report, GSI Tech. Rept. Madras p. 14.
Barker RD, Rao TV, Thangarajan M (2001). Delineation of contaminant zone through electrical imaging technique. Curr. Sci., 81(3): 101-107.
Batayneh AT, Qassas HA (2006). Changes in quality of groundwater with seasonal fluctuations: an example from Ghor Safi area, southern Dead Sea coastal aquifers, Jordan. J. Environ. Sci. China, 18(2):

263-269.

Bouwer H (2002) Artificial recharge of groundwater: hydrogeology and engineering. Hydrogeol. J., 10(1): 121-142.

Bredenkamp DB, Vogel JC (1970). Study of a dolomite aquifer with carbon-14 and tritium. In: Isotope Hydrology 1970, Proceedings of an IAEA symposium, Vienna, pp. 9-13.

Chakrapani R, Manickyan PM (1988). Groundwater resources and developmental potential of Anna District, Tamil Nadu State. CGWB Rept.,Southern Region, Hyderabad, p.49.

Chand R, Hodlur GK, Ravi Prakash M, Mondal NC, Singh VS (2005). Reliable natural recharge estimates in granite terrain. Curr. Sci., 88 (5): 821-824.

Chaulya SK (2004). Water resource accounting for a mining area in India. Environ. Monit. Assess., 93(1-3): 69-89.

Chowdary VM, Ramakrishnan D, Srivastava YK, Chandran V, Jeyaram A (2009). Integrated water resource development plan for sustainable management of Mayurakshi watershed, India using Remote Sensing and GIS. Water Resour. Manage., 23 (8): 1581–1602.

Davies PA, Hossain AK, Vasudevanm P (2009). Stand-alone groundwater desalination system using reverse osmosis combined with a cooled greenhouse for use in arid and semi-arid zones of India. Desalination and Water Treatment-Science and Engineering, 5(13): 223-234.

Davis JC (1986). Statistics and data analysis in geology. Second ed.[n], Wiley, New York pp. 527–579.

Elewa HH, Qaddah AA (2011). Groundwater potentiality mapping in the Sinai Peninsula, Egypt, using remote sensing and GIS-watershed-based modeling. Hydrogeol. J., 19(3): 613-628.

Espino MS, Navarro CJ, Perez JM (2004). Chihuahua: a water reuse case in the desert. Water Sci. Tech., 50(2): 323-328.

Fetter CW (2001). Applied Hydrogeology. 4[th] edn. Prentice Hall, Englewood Cliffs, NJ.

Gupta SK, Sharma SC (1984). Soil moisture transport through the unsaturated zone-tritium tagging studies in Sabarmati basin, West India. Hydrol. Sci. J., 29(2): 177-189.

Healy RW, Cook PG (2002). Using groundwater levels to estimate recharge. Hydrogeol. J., 10: 91-109.

Jackson TJ (2002). Remote sensing of soil moisture: implications for groundwater recharge. Hydrogeol. J., 10 (1): 40-51.

Krishnan MS (1982). Geology of India and Burma. CBS Publishers and Distributions, India.

Kumar M, Rao MS, Kumar B, Ramanathan A (2011). Identification of aquifer-recharge zones and sources in an urban development area (Delhi, India), by correlating isotopic tracers with hydrological features. Hydrogeol. J., 19(2): 463-474.

Lee JY, Yi MJ, Hwang D (2005). Dependence of hydrological responses and recharge estimates on water-level monitoring locations within a small catchment. Geosci. J., 9(3): 277-286.

Lerner DN (2002). Identification and quantifying urban recharge: a review. Hydrogeol. J., 10 (1): 143-152.

Maliva RG, Clayton EA, Missimer TM (2009). Application of advanced borehole geophysical logging to managed aquifer recharge investigations. Hydrogeol. J., 17: 1547–1556.

Medhi J (2005). Statistical methods-an introductory text. New Age International Publishers, New Delhi, India, pp. 438.

Mondal NC (2005). Integrated approach to delineate the contaminated groundwater and its migration in the tannery belt, Dindigul, Tamilnadu, India. Unpublished Ph.D. Thesis, Osmania University, Hyderabad, p.249.

Mondal NC, Saxena VK, Singh VS (2005). Assessment of groundwater pollution due to tanneries in and around Dindigul, TamiInadu, India. Environ. Geol., 48(2):149-157.

Mondal NC, Singh VP (2010). Entropy-based approach for estimation of natural recharge in Kodaganar River basin, Tamil Nadu, India. Curr. Sci., 99 (11):1560-1569.

Mondal NC, Singh VP (2011a). Chloride migration in groundwater for a tannery belt in Southern India. Environ. Monit. Assess. DOI 10.1007/s10661-011-2156-x (Online published).

Mondal NC, Singh VP (2011b). Hydrochemical analysis of salinization for a tannery belt in Southern India. J. Hydrol., 405(2-3): 235-247, DOI:10.1016/j.jhydrol.2011.05.058.

Mondal NC, Singh VS, Rangarajan R (2009). Aquifer characteristics and its modeling around an industrial complex, Tuticorin, Tamil Nadu, India: A case study. J. Earth Syst. Sci., 188(3): 231-244.

Moon SK, Woo NC, Lee KS (2004). Statistical analysis of hydrograph and water-table fluctuation to estimate groundwater recharge. J. Hydrol., 292: 198-209.

Munnich OK (1968). Moisture movement measured by isotope tagging. In: Guide Book on Nuclear Techniques in Hydrology, IAEA, Vienna, pp. 112-117.

Muralidharan D, Shanker GBK (2000). Various methodologies of artificial recharge for sustainable groundwater in quantity and quality for developing water supply schemes. In: Proc. All Indian Seminar on Water Vision for 21[st] Century, IAH, Jadavpur University, Kolkata, pp. 208-229.

Naik PK, Tambe JA, Dehury BN, Tiwari AN (2008). Impact of urbanization on the groundwater regime in a fast growing city in central India. Environ. Monit. Assess., 146: 339–373.

Narayanamoorthy A (2007). Does groundwater irrigation reduce rural poverty? Evidence from Indian states. Irrig. and Drain, 56(2): 349–362.

Narayanamoorthy A (2010). India's groundwater irrigation boom: can it be sustained? Water Policy, 12(4): 543-563.

Nonner JC (2006). Introduction to hydrogeology. IHE Delft Lecture notes series. Taylor and Francis, London.

Panda DK, Mishra A, Jena SK, James BK, Kumar A (2007). The influence of drought and anthropogenic effects on groundwater levels in Orissa, India. J. Hydrol., 343(3-4):140-153.

Public Works Department (2008). Public Works Department Irrigation Policy Note for the year 2008-2009. Govt. of India, Chennai, p.51.

Raj P (2001). Trend analysis of groundwater fluctuations in a typical groundwater year in weathered and fractured rock aquifers in parts of Andhra Pradesh. Jour. Geol. Soc. India, 58: 5-13.

Raj P (2004). Classification and interpretation of piezometer well hydrographs in parts of southeastern peninsular India. Environ. Geol., 46(6-7): 808-819.

Rangarajan R (1997). Natural recharge evaluation in selected basins of semiarid India using injected tritium method. Unpublished Ph.D. Thesis, Osmania University, Hyderabad, p. 180.

Rangarajan R, Athavale RN (2000). Annual replenishable ground water potential of India-an estimate based on injected tritium studies. J. Hydrol., 234: 38-53.

Rangarajan R, Mondal NC, Singh VS, Singh SV (2009). Estimation of natural recharge and its relation with aquifer parameters in and around Tuticorin town, Tamil Nadu, India. Curr. Sci., 97(2): 217-226.

Salama RB, Tapley I, Ishii T, Hawkes G (1994). Identification of areas of recharge and discharge using Landsat-TM satellite imagery and aerial-photography mapping techniques. J. Hydrol., 162(12): 119-141.

Samadder RK, Kumar S, Gupta RP (2011). Paleochannels and their potential for artificial groundwater recharge in the western Ganga plains. J. Hydrol., 400(1-2): 154-164.

Saraf AK, Choudhury PR, Roy B, Sarma B, Vijay S, Choudhury S (2004). GIS based surface hydrological modeling in identification of groundwater recharge zones. Int. J., Remote Sensing, 25(24): 5759-5770.

Scanlon BR, Healy RW, Cook PG (2002). Choosing appropriate techniques for quantifying groundwater recharge. Hydrogeol. J., 10(1): 18-39.

Senthilkumar M, Elango L (2004). Three-dimensional mathematical model to simulate groundwater flow in the lower Palar river basin, Southern India. Hydrogeol. J., 12(2): 197–208.

Shankar MNR, Mohan G (2005). A GIS based hydrogeomorphic approach for identification of site-specific artificial-recharge techniques in the Deccan Volcanic Province. J. Earth Syst. Sci., 144(5): 505-514.

Sibanda T, Nonner JC, Uhlenbrook S (2009). Comparison of groundwater recharges estimation methods for the semi-arid

Nyamandhlovu area, Zimbabwe. Hydrogeol. J., 17: 1427-1441.
Singh DK, Singh AK (2002). Groundwater situation in India: problems and perspective. Int. J. Water Resour. Dev., 18(4): 563-580.
Singh VS, Mondal NC, Ron Barker, Thangarajan M, Rao TV, Subramaniyam K (2003). Assessment of groundwater regime in Kodaganar river basin (Dindigul district), Tamil Nadu. Tech. Rept. No.-NGRI-2003-GW-269, p. 104.
Tiwari VM, Wahr J, Swenson S (2009). Dwindling groundwater resources in northern India, from satellite gravity observations. Geophys. Res. Lett., 36, L18401, doi:10.1029/2009GL039401.
Todd DK (1980). Groundwater Hydrology. 2nd edition, John Wiley and Sons, p. 535.
Viswanathan MN (1983). The rainfall/water table level relationship of an unconfined aquifer. Ground Water, 21(1): 49-56.
Vittala SS, Govindaiah S, Gowda HH (2008). Prioritization of sub-watersheds for sustainable development and management of natural resources: An integrated approach using remote sensing, GIS and socio-economic data. Curr. Sci., 95(3): 345-354.
Zaidi FK, Ahmed S, Dewandel B, Maréchal JC (2007). Optimizing a piezometric network in the estimation of the groundwater budget: a case study from a crystalline-rock watershed in southern India. Hydrogeol. J., 15 (6): 1131-1145.
Zimmermann U, Munnich OK, Roether W (1967). Downward movement of soil moisture traced by means of hydrogen isotopes. American Geophysical Monograph, 11: 28-36.