

Recharge rate in a carbonate rock covered watershed in Kurnool district, Andhra Pradesh, India using Tritium injection and Soil Water Balance methods

Farooq Ahmad Dar*, R. Rangarajan, D. Muralidharan and Shakeel Ahmed

CSIR-National Geophysical Research Institute, Uppal Road Hyderabad, 500007

*Corresponding Author: farooq.dar1@gmail.com

ABSTRACT

Groundwater in the carbonate aquifers of the southern Andhra Pradesh, India has approached to stress level as water table has declined due to increasing groundwater draft, low to moderate rainfall, less availability or absence of surface water sources and semi-arid climate. In Kallugotla watershed of Kurnool district, groundwater is overexploited for irrigation and static water level exhibit declining trend. In order to manage the aquifers for sustainable water supply, understanding and accurate assessment of groundwater recharge is necessary. Two approaches, namely soil water balance and injected tritium tracer methods were used to estimate the recharge. Tritium injection method yields 14.5 %, while soil water balance indicates 13.5% of annual rainfall as recharge. Daily and monthly recharge variability is highly dependent on soil properties and climatic parameters. The research study demonstrated that the recharge could be estimated over a watershed/sub-basin area by integrating spatial tritium injected estimates and soil water balance method.

INTRODUCTION

Groundwater resource is under constant stress in semi arid regions of India, where groundwater development and usage is continuously increasing. In southern Andhra Pradesh, groundwater is extensively pumped for agriculture and presently meets ~85% of the domestic needs in rural areas (Jain et al. 2009). The problems emerge as serious in carbonate aquifers, which are the main source of water supply to the major population of Kurnool district of this region. In Kallugotla watershed of this district, about 74% of the population use groundwater extensively for agriculture and domestic needs. The area experiences declining trend in groundwater levels, reduction in well yield, increase in agricultural area irrigated by groundwater, increase in bore well density and increased population (CGWB 2007; GEC 2009; Jain et al. 2009) as well as decline or change of monsoon pattern. Aquifers are recharged predominantly by rainfall and are vulnerable to frequent droughts, depletion and contamination. This demands integrated groundwater management as the hydrodynamics of these aquifers are little understood (Dar et al. 2014). In order to understand the hydrogeological processes, groundwater recharge must be estimated with minimum possible errors so that proper management practices can be taken to sustain groundwater resources. Accurate groundwater recharge evaluation (Lerner et al. 1990) assumes great significance in semi-arid and arid hard rock terrains where rainfall is highly variable and unpredictable. Identification and quantification of recharge in semi-arid aquifers is difficult, where recharge depends on the intensity and time variability of rainfall (Eilers et al. 2007). Recharge volume is generally low

compared to annual rainfall or evapotranspiration.

Recharge is measured through various physical and chemical methods in semi-arid areas but the resolution of methods is questioned in carbonate regions due to heterogeneous aquifer properties (Gee and Hillel 1988; De Vries and Simmers 2002; Scanlon et al. 2006). Isotopic and geochemical tracer methods have lead to understand and evaluate the recharge processes and are considered to be more reliable than the conventional methods. Munnich and his co-workers (Zimmermann et al. 1967) made pioneering contributions to the development of tracer methods. Using the piston flow model, many workers have worked on injected tritium to estimate recharge (Rangarajan et al. 2000). Sukhija et al. (1996) have utilized environmental and injected tritium to estimate and evaluate recharge processes in semi-arid and arid environments. Allison and Hughes (1978) developed the environmental chloride profile method for recharge estimates by studying the conjunctive use of environmental tritium and chloride, based on the piston flow model. Sukhija et al. (2003) have demonstrated and estimated through tracer data that the preferential flow recharge process contributes an average of about 75% of total recharge in the case of fractured granites and 33% of total recharge for semi-consolidated sandstones.

Various techniques are used for estimation of recharge in carbonate aquifers in semi-arid areas (De Vries and Simmers 2002) with very limited or negligible studies in India's little-known carbonate aquifer systems. The aim of the present study is to estimate recharge to a soil-covered carbonate aquifer using two approaches (soil water balance and injected tritium tracer) and validating their applicability by comparing with other studies from semi-arid regions.

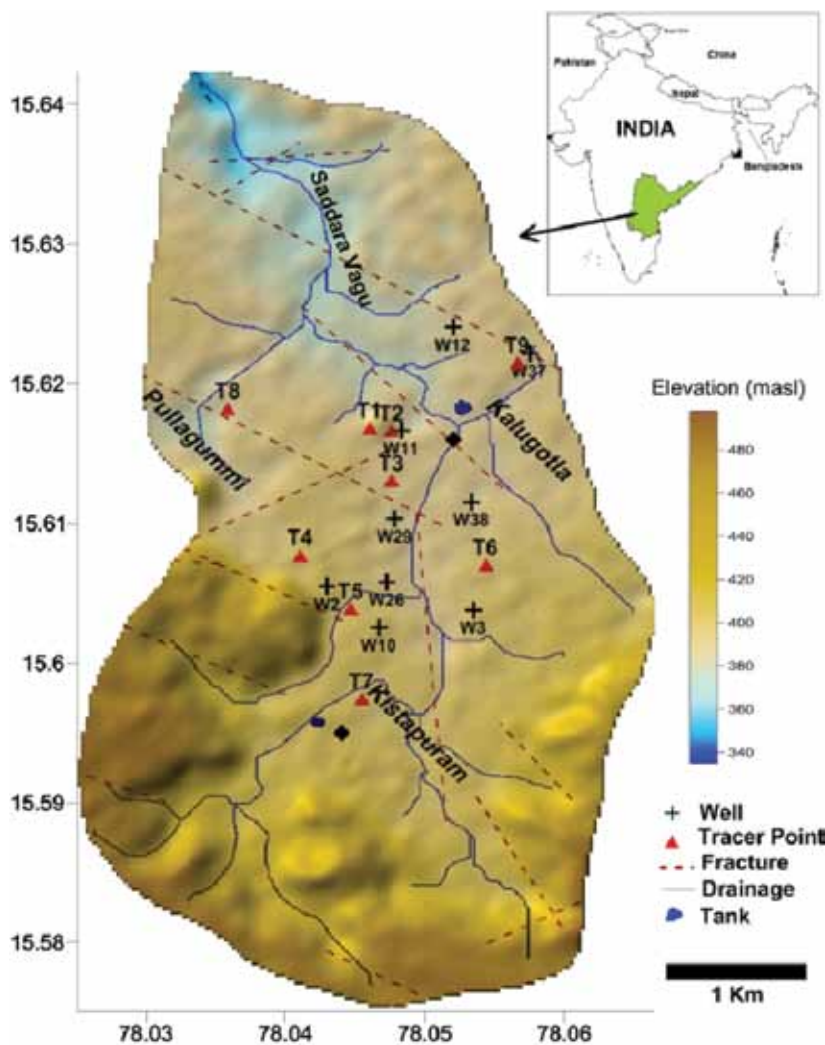


Figure 1. Topographic map of Kallugotla watershed showing surface elevation in m amsl using ASTER 30m DEM data (<http://gdem.ersdac.jspacesystems.or.jp/>). Location of wells and tritium injection sites are also shown.

STUDY AREA

Kallugotla watershed (32 km²) is located 30 km south of Kurnool town in the state of Andhra Pradesh, India (Fig. 1). Elevation of the watershed varies from 335-492m amsl (Fig. 1). Structural hills, buried pediments (moderate and shallow) are the main geomorphic units. Slope varies from ~0-18° with a mean of 3°. The effective recharge area with slope less than 5° is ~25km². Most of the lineaments trend in NW-SE direction. Saddara Vagu stream, tributary of the River Hundri is dendritic, controlled by fractures/lineaments and has a drainage density of 0.9 km/km². The climate is semi-arid with hot and dry summers and temperature varies from 17-45°C. Mean annual rainfall is ~758 mm with large variability. Monthly rainfall varies from 0 to >200 mm and 95% of rainfall occurs in monsoon season (June-October) as high intensity, but sparse number of events.

Soils include Vertic Inceptisol (black clay loam) to Alfisol (loam) types (Fig. 2). Black soils possess swelling montmorillonite clay and develop cracks during swelling and shrinking in alternate wet and dry days. Soils comprise 40-63% gravel+sand and 37-60% silt+clay. Soil depth is generally 1-3 m with an average depth of 1.6 m. The structure and hydrological properties of soils are almost uniform.

Soils favor rain-fed and irrigated crops and groundwater from a bore well irrigates about 0.04 km² of land, which is pumped for about 6 hours/day. Major crops include groundnut, jowar, cotton, castor, pigeon pea, sunflower, rice, vegetables and some fruits. Geology (Dar et al. 2011) comprises Banganapalle Quartzite, Narji limestone, Owk Shale, Paniam Quartzite and Vempalle Dolomite of the Proterozoic Cuddapah Basin (Fig 3 a & b). About 71% of the watershed area includes carbonate aquifers. The rocks gently dip in S-SE direction.

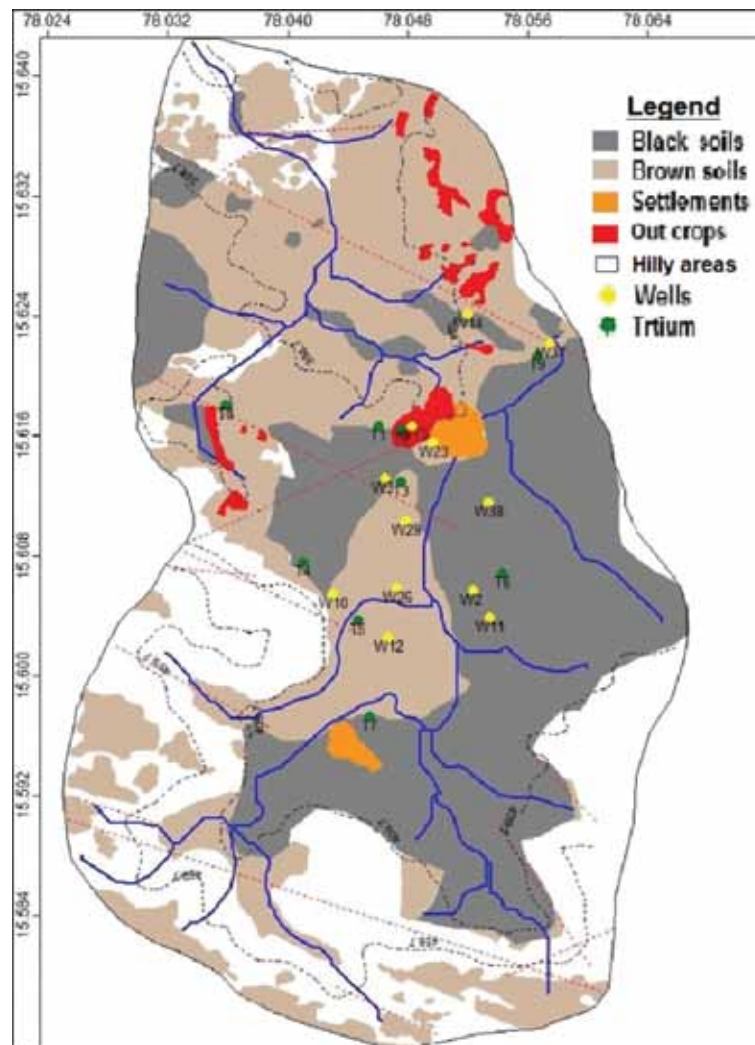


Figure 2. Land-use/land-cover map of watershed showing different land use classes along with drainage, wells and tritium sites.

Carbonate aquifers are fractured and karstified to a certain degree in the watershed, which yield groundwater for domestic and irrigation purposes. The depth to water level varies from 17-30.3 mbgl in pre-monsoon to 9.9-24.7 mbgl in post-monsoon. Dug wells tap aquifers up to 6-8m depth and borewells that yield 1.7-5.2 l/s are 60-90 m deep.

METHODOLOGY

Injected Tritium Method

Natural recharge to the aquifer was first estimated by tritium injection method at selected locations (Fig. 1). Tritium, a radioisotope of Hydrogen is commonly used as a tracer for hydrological studies. It is a soft beta emitter of low energy (max. 18 killo electron volt) and belongs to lowest radio toxicity class. It has a half-life of 12.43 years and can be measured with high detection sensitivity. It is the most suitable tracer for soil moisture movement and

recharge studies.

The tritium injection method (Zimmermann et al. 1967, Munnich, 1968), assumes a piston flow model for movement of water infiltrating the vadoze zone. It means that the soil moisture moves downwards in discrete layers. Fresh water added at the surface (through precipitation or irrigation) percolates by pushing an equal amount of water beneath it further down and so on, such that the moisture of the last layer in the unsaturated zone is added to the saturated zone, i.e. groundwater. This method works over any formation (granites, sediments, alluvium), which has sufficient soil cover of about 1.5-2 m. In the method, the moisture influx is measured in the soil zone only and not in deeper weathered zone, where preferential flow can be expected. Based on piston flow analogy, it is inferred that the amount of moisture influx in the soil zone is added to the groundwater regime.

At the selected spots five holes of diameter 12.5 mm down to a depth of 0.6–0.8 m were made with a drive

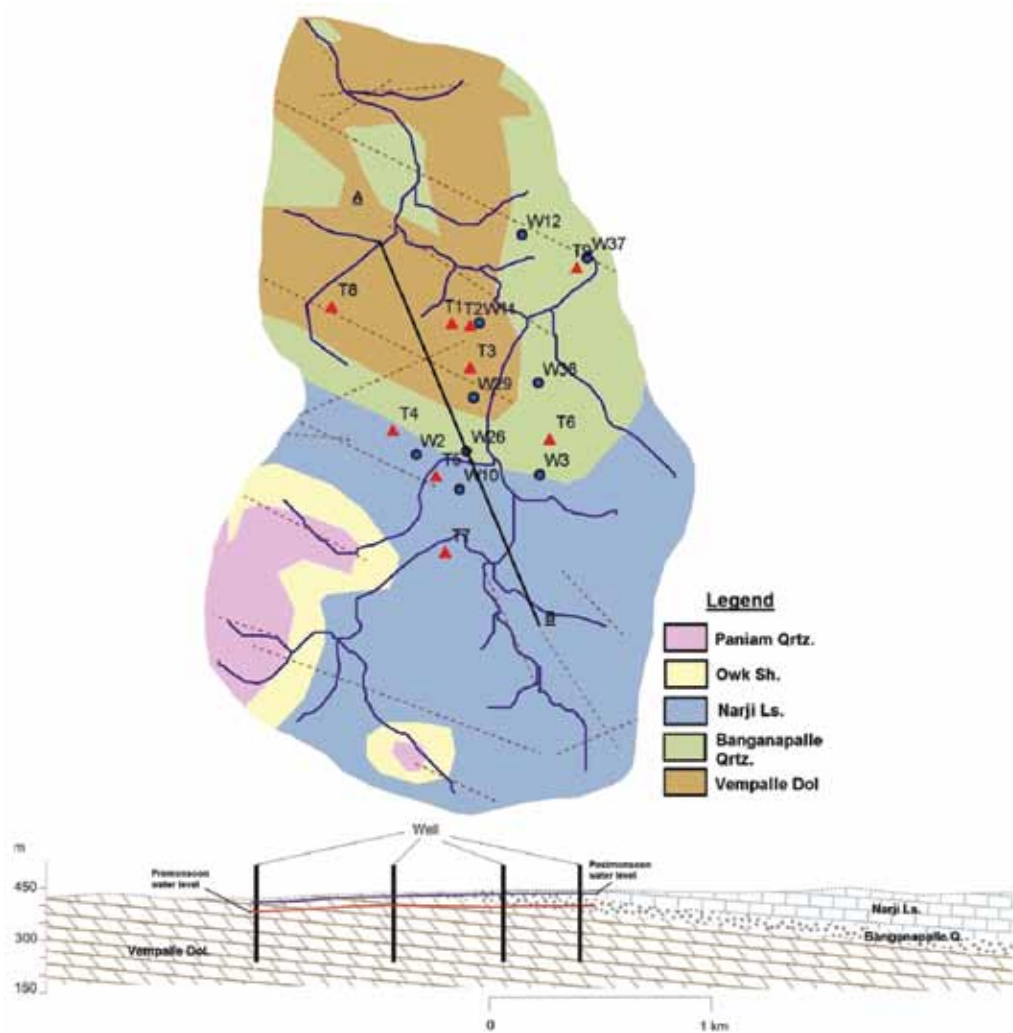


Figure 3. Geological map of Kallugotla watershed (a) The geological section (b) along line AB with water level variation in wells from pre-monsoon (red line) to post monsoon (blue line)

rod, with one hole at the centre and the other four placed symmetrically on the circumference of a circle of radius of 50 mm. A seamless copper pipe of 4 mm diameter is pushed to the bottom of each hole and 3 ml of tritiated water having a specific activity of 3.7×10^5 Bq corresponding to 3.2×10^9 TU is injected with a surgical syringe. The injection holes are back filled with local soil and gently tamped. Each site is precisely marked for accurate relocation and collection of soil profiles after monsoon.

The artificially tagged tritiated water was injected into the soil in Kallugotla watershed at 9 sites, where the slope was $< 1^\circ$ before the onset of monsoon and the tracer moves downwards with the infiltrating fraction of precipitation. A soil core is collected from the injection site after the monsoon from which depth-wise samples at 10 cm interval are collected. Steel pipes having an inner diameter of 40 mm and a wall thickness of 5 mm were used for obtaining cores. Sample is weighted in the field immediately and the in situ wet bulk density for each depth is calculated from

the known volume and the weight of the soil core sample. The samples of each depth profile are packed and labeled in polythene bags and checked for moisture loss in laboratory. Twenty to twenty five grams of sample from each depth interval are used to measure the moisture content, using an infrared torsion moisture balance method or the oven drying method. The moisture content determination through the torsion moisture balance agreed with that from the oven drying (gravimetric method) within $\pm 1\%$. The rest of the soil core sample is used for extracting soil moisture and for measuring tritium activity. The soil moisture is extracted through a partial vacuum distillation method with a recovery efficiency of 92–95%. Four milliliter of the distillate is mixed with 10 ml of Hisafe scintillator cocktail and the tritium activity is measured on a liquid scintillation counter having a background of 30 cpm and counting efficiency of 58% for unquenched standards. A plot of the variation of tritium activity with depth is used to determine the displaced position of the tritium tagged

layer from the injection depth. The moisture content of the soil zone between the injection and displaced peak depth is used to estimate the natural recharge rate. The experimental standard deviation of this technique was determined as $\pm 10\%$.

The displaced position of the tracer is indicated by the peak in its concentration in depth/tritium activity plots. The peak may be broadened because of other factors, such as diffusion, irregularities in water input and streamline dispersion. The center of gravity of the profile is, therefore taken as representing the depth of the tagged layer. The moisture content of the soil column between the injection depth and displaced depth of the tracer in the soil core is the measure of recharge to groundwater over the time interval between injection of tritium and collection of soil core. The piston flow model is verified in the laboratory and field conditions for various soil types of India (Athavale et al. 1980; Rangarajan and Athavale 2000; Sukhija et al. 1996).

The moisture content in volume percent and tracer concentration in counts per minute (CPM) was measured at regular depth intervals from each sample. The peak tracer concentration and moisture content was used to estimate groundwater recharge at only 6 sites as the data at other sites was not sufficient to find the peak concentration depth. The moisture data also gives information about the soil water properties, which is otherwise lacking and this was later used to calibrate the results from soil moisture balance. Infiltration tests were also carried out in the soils using double ring infiltrometer at two locations.

The recharge or the amount of water added per square centimeter of the soil, was calculated by determining the peak of tritium profile and the moisture content of the zone between the injection depth and depth of the displaced tritium spiked layer

$$R = \left[\frac{m_d}{(100 + m_d)} \right] \gamma_w h \dots \dots 1$$

R = Recharge, m_d = dry weight percent of soil moisture, γ_w = wet-bulk density of the soil in situ, h = displacement

of tracer, i.e. the distance between injection depth and the centre of gravity of the profile.

Soil cores obtained in 10 cm sections were deemed to be small. As a result the average values of m_d and γ_w were obtained from all the samples over the depth interval of tracer displacement for each site (Athavale et al. 1980; Rangarajan and Athavale, 2000).

Soil Water Balance Method (SMB)

Soil Water Balance method (Allen et al. 1998; Gee and Hillel 1988; Eilers et al. 2007) is based on estimating recharge through soil zone by taking various hydrological parameters in to account, assuming a single soil layer and negligible interception of rainfall by vegetation. SMB is used in semi-arid areas at small scales (Rushton et al. 2006; Scanlon et al. 2006; Eilers et al. 2007) as well in semi-arid karst aquifers (Canton et al. 2010; Touhami et al. 2014). When rainfall starts, the initial infiltrating water reduces the soil moisture deficit (SMD) to zero and soil attains field capacity after some time and becomes free draining. When soil moisture deficit at any time (θ_t) becomes negative (i.e., soil moisture > field capacity), the extra water percolates and reaches the groundwater as diffuse recharge (R_D). R_D was estimated on daily basis by computing the soil water content at the end of each day from daily rainfall by taking into account the previous day moisture conditions as discussed in Canton et al. (2010) using equation;

$$R_D = \theta_t \text{ (for } \theta_t < 0 \text{) and } R_D = 0 \text{ (for } \theta_t \geq 0 \text{) } \dots \dots 2$$

where, θ_t is the volumetric percentage of water or depth of water greater than field capacity at any given day t. The method also estimates evapotranspiration and runoff and assumes no bypass recharge as no well-developed karst features are present except little infiltration through bedding planes that too after water crosses the soil layer. The soils of the watershed are generally homogeneous in composition, depth, moisture distribution, rooting depth and structure. The computation was done in excel

Table 1. Different parameters and values used in the soil water balance method for estimating diffuse recharge in the watershed.

Parameter	Value	Source
Daily rainfall	Variable, daily	Indian Meteorological Data
Reference crop evapotranspiration	Variable, daily	PAN evaporation; Allen et al. 1998
Crop coefficient	1.1	Allen et al. 1998
Soil evaporation coefficient	1.05	Allen et al. 1998
Field capacity	0.23 m ³ /m ³	Computation results, soil moisture vs. depth information
Wilting point	0.13 m ³ /m ³	
Soil thickness	1.6 m	Field information
Depth of roots	1.2 m max	Allen et al. 1998; FAO, 2008; Field information
Surface storage factor	0.54	Eilers et al. 2007; Field evidence

worksheet and various parameters were used suiting the area as per literature and field data (Tab. 1). Because data on soil water properties are not available, combinations of field capacity (FC) and wilting point (WP) corresponding to major soil types were used to estimate recharge.

RESULTS AND DISCUSSION

Recharge Estimation From Tritium Method

The tritium was injected at 9 sites in the watershed area. The soil cover in the area is almost uniform in composition, structure and depth. Hence, a single layer of model was used in the computation. The area of the watershed is also small, which favors taking average soil properties.

The soil core collections at 6 sites (T1, T2, T3, T4, T5, and T7) were in the depth range of 160-300 cm. In 4 out of 6 sites, the collections were made in the depth range of 240-300 cm. In the remaining 2 sites, the collections were up to 160 cm and 200 cm, respectively. The recharge data could be interpreted at these 6 sites, where the sample collections were in the range of 160 cm to 300 cm as the tritium profiles were complete. This in turn means the depth of soil profile at which the maximum activity lies could be determined (Fig. 4a). However, at 3 sites (T6, T8, T9), the collection was made in the depth range of 90-110 cm only due to shallow basement. At these sites, the tritium profiles are not complete i.e., the tritium concentrations showed an increasing trend at the bottom depths of the respective tritium profiles (Fig. 4b) and it was not possible to determine the depth at which the tritium peak activity lies. Hence, recharge was not computed at these sites. The moisture and tritium depth profiles observed at 6 injection sites are shown in Fig 4a and given in Table 2. Rainfall-recharge values estimated at 6 sites vary from 69.1-129.7mm, with a standard deviation of 22 mm. The tritium depth profiles observed at 3 injection sites, where recharge could not be interpreted are shown in Fig 4b.

The moisture variation with depth is highly variable in the area and does not follow simple distribution curves as discussed in Rusthon et al., (2006). This variability may be due to thin soils, which become wet and dry very rapidly. In addition, the variability could be due to sporadic rainfall, which on an average occurs in this semi-arid area in 37 annual rainy days (rainfall ≥ 2.5 mm a day). However, a rough conclusion can be drawn regarding the FC and WP values as shown by vertical dashed lines in Fig 4a. Tritium concentration with depth showed almost uniform pattern and the peak concentrations reached between 1.3-1.7 mbgl, with an average depth of ~ 1.5 m. The tritium concentration above and below the peak has lower tritium concentration in the order of few hundreds of Tritium counts only.

Recharge was estimated using equation 1, which indicates that an average recharge of 110.3 mm occurred during year 2000 in the watershed area. This is equivalent to 14.5 % of the total annual rainfall of 758.5 mm in the watershed.

In the watershed a major stream (Sadara Vagu) flows from south to north along a lineament. Pre monsoon and post monsoon water level monitoring was done for 6 wells in the watershed. The wells drilled by government agency (APSIDC) provide water for irrigation to the marginal and medium farmers. Out of 6 wells, 4 were located near to the stream course. The water level fluctuations in these 4 wells were in the range of 18.0 m to 24.7 m with an average fluctuation of 20.05 m. Other 2 wells were slightly away from the stream, where the fluctuations were in the range of 9.9 to 11.7 m with an average value of 10.8 m. The rainfall events in the month of September (total rainfall of 220 mm for consecutive 6 days) have substantially increased the water level in wells near the stream with the maximum value of 24.7 m. The water level rises immediately after the first high intensity rainfall event, which indicates that the stream contribution to recharge is significant. This also agrees with the established concept that recharge rates through secondary sources such as stream flow is several times higher than that through deep percolation of rain water. It is inferred that the wells nearer

Table 2. Soil moisture and tritium data calculated with depth at the injection sites in the area. The site numbers correspond to Fig. 1.

Site	Depth of collection m	Depth of peak conc. M	Peak dispersion m	Volume Moisture %	Recharge computed mm
T1	2.4	1.6-1.7	1.05	12.3	128.9
T2	2.8	1.4-1.5	0.84	14.1	119
T3	1.6	1.3-1.4	0.75	17.3	129.7
T4	2.5	1.4-1.5	0.87	8.0	69.1
T5	2.0	1.5-1.6	0.95	10.6	101.0
T7	3.0	1.5-1.6	0.95	12.0	114.4

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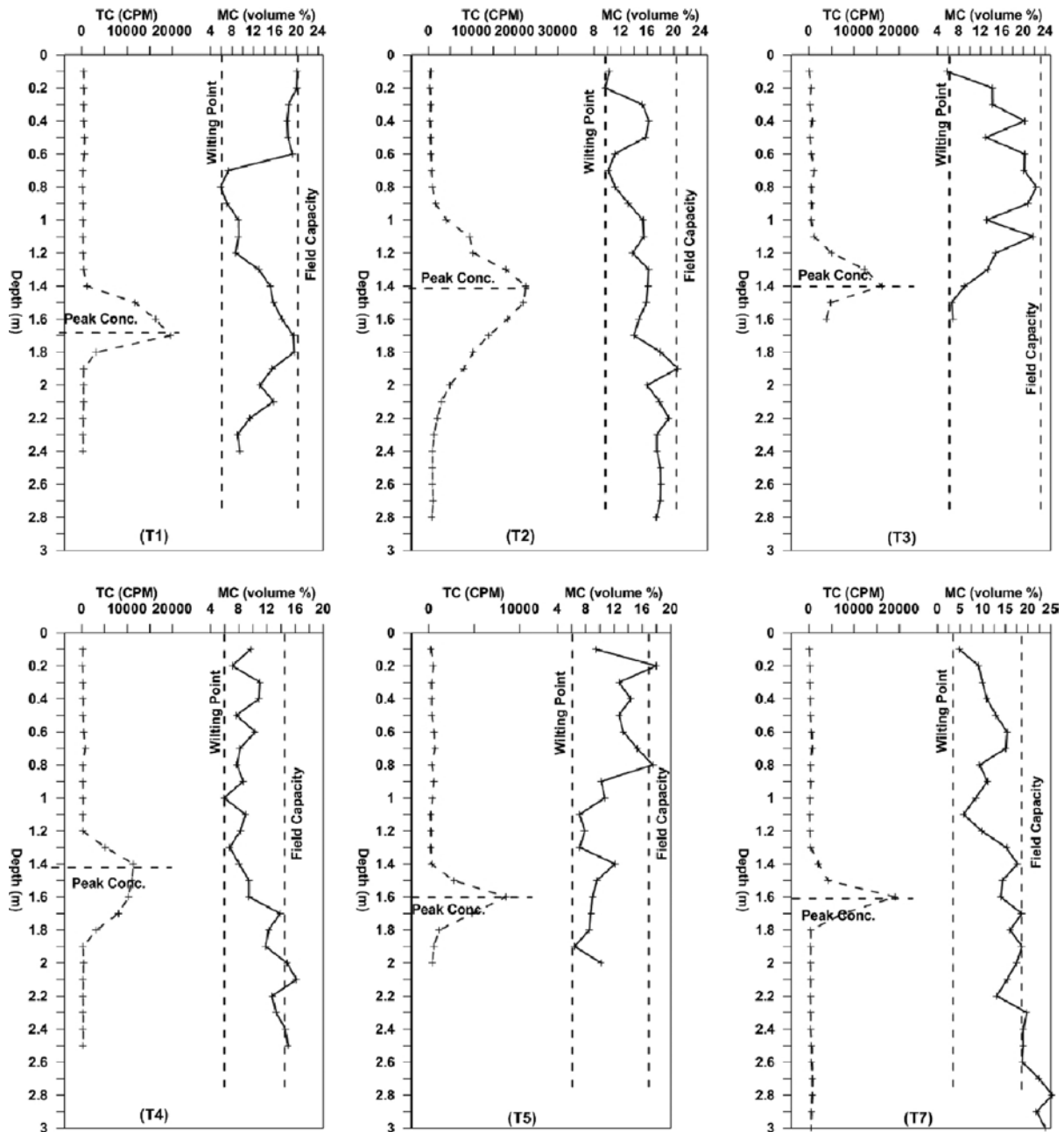


Figure 4a. Tritium concentration in counts per minute (CPM) and soil moisture content in volume (MC) percent measured with depth from the soils cores for tritium sites shown in Fig 1

to the stream section will be more influenced by the water flow as compared to the wells away from the stream course. Natural recharge studies through tritium technique have indicated that recharge due to rainfall in the watershed is 110.3 mm. These sites are located away from the stream course. The average specific yield value for limestone aquifers is 2 % (GEC report, 1997) and for limestone aquifer in the study area range from 1-2 % (Dar et al. 2014b). Taking into account the average water level change of 10.8 m (for the wells away from the stream course) and the estimated average recharge rate of 110.3 mm, the

specific yield computed is 1.02 %. This value lies within the specific yield range considered for the watershed by previous studies.

Thus, the higher water level change observed may be probably from a smaller area closer to the stream. The high intensity rainfall events make significant runoff in the stream and causes water level rise in bore wells near to the stream immediately after a high intensity event. This made us to infer that the significant water level rise in bore wells is due to quick inflow through stream sections and not bypass/preferential flow through soil zone.

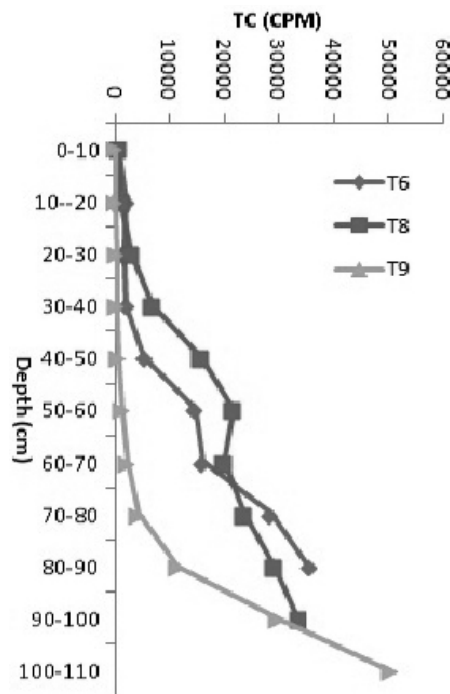


Figure 4b. Tritium profiles of non interpreted 3 recharge sites

Preferential flow may probably take few hours to few days to reach the groundwater system. The hydrographs of the wells nearer to the stream section showed immediate rise in water level. This suggests that fissures and bedding planes do contribute, as conduits, to increase water levels in borewells.

Recharge Estimation Using SMB

From the moisture profiles shown in Fig. 4a, average FC and WP values were computed as shown by vertical dashed lines. Daily recharge was estimated using a pair of FC and WP values corresponding to various soil compositions from loamy sand to sandy loam in the computation, as the exact values of these properties were not available. Recharge results estimated using Eq. 2 were then summed over the total time period and plotted against the used FC and WP values, as shown in Fig 5. The average recharge rate of 102.1 mm corresponds to the field capacity of 0.16-0.18 m^3/m^3 and permanent wilting point of 0.06-0.08 m^3/m^3 in these plots and represents loamy sand to sandy loam soils (Allen et al. 1998; Reed 1990; Rushton et al., 2006). These FC and WP ranges are in the same range as observed in depth-moisture profiles in injection soils (Fig. 4a). Since the soils contain a significant amount of clay in limestone areas, the composition generally shifts to the loams with varying clay content. Reasonably, FC and WP are higher than sandy loams or loamy sands, and as such values of these components have been taken as 0.23 and 0.13 m^3/m^3 , respectively. Usage of these values has resulted in

more representative value of recharge, which is equal to 106 mm (Fig. 5).

Soil infiltration at two locations showed a steady rate of 2.58-3.12 mm/d. Field saturated hydraulic conductivity calculated from infiltration values vary from 0.20-1.33 mm/d. The value in wet soils was lower, which indicates a limited near surface storage water in the soils. Such a situation results in delayed recharge. Therefore, a factor 0.54 (Tab. 1) was used in the SMB computation (Eilers et al. 2007), which is less than 1 due to high evapotranspiration, thin soil cover coupled with little vegetation (nearly bare). However, it does not reach zero level due to the presence of clay minerals in the soils. From this it is evident that the soils maintain saturation for much shorter periods. The daily estimated cumulative rainfall, AE and recharge from May-December 2000 using SMB are compared in Fig 6. The cumulative recharge is constant up to 23 August followed by sharp increase in slope due to 13 recharge steps generated by 11 rainfall events.

The results of monthly water balance parameters estimated from SMB are given in Fig. 7. Annual actual evapotranspiration (Tab. 3) represents 76.1% of annual rainfall, which is valid in semi-arid conditions. Daily recharge varies from 0-12.9mm/day. Annual recharge is ~106.1mm, which represents about 13.5% of annual rainfall. Generally, clayey soil produces less recharge due to higher water holding capacity and allows more loss of water through evapotranspiration than sandy soil (Athavale et al. 1980). The results are averaged over the watershed with little spatial variability according to the assumptions

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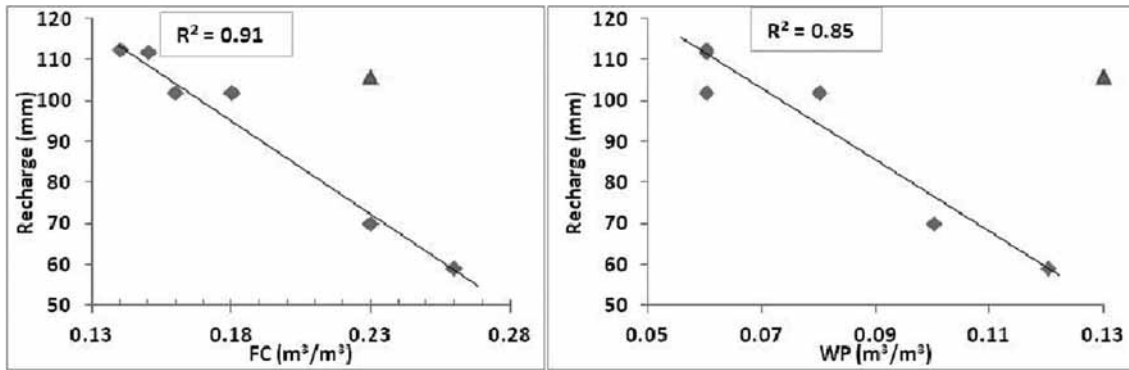


Figure 5. Estimated recharge plotted against FC (left) and WP (right) shows the dependency of recharge on soil properties.

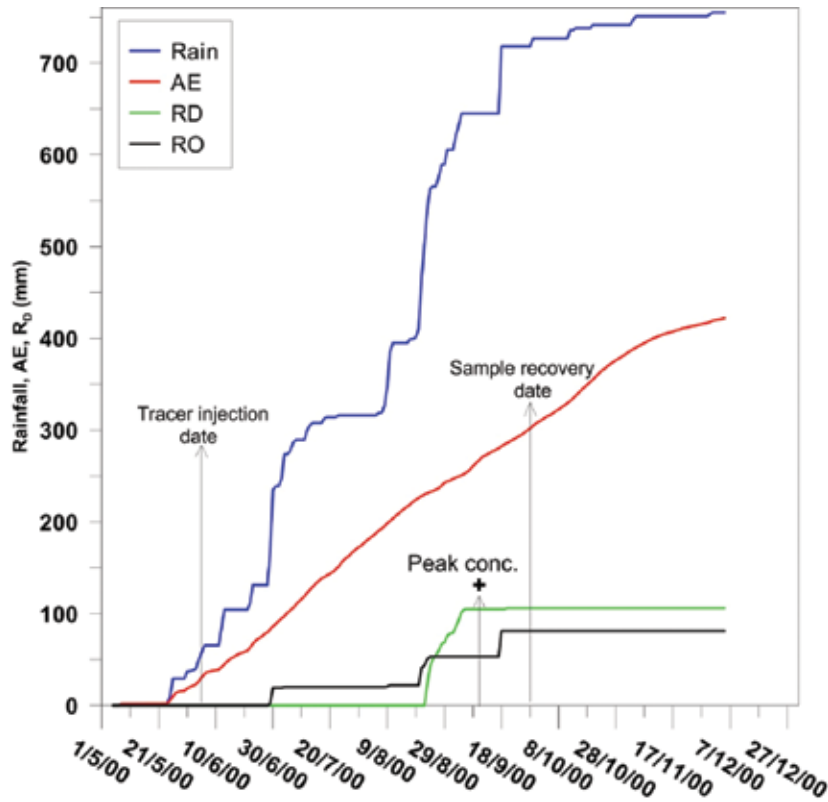


Figure 6. Daily cumulative rainfall, actual evapotranspiration and diffuse recharge estimated from soil water balance method.

Table 3. Estimated value of annual rainfall, AE, runoff and recharge in mm for the watershed and their percentage values of total annual rainfall.

	Rainfall (mm)	Runoff (mm)	AE (mm)	Recharge (mm)
Annual	758.5	81.3	572.2	106.1
% of rainfall		10.4	76.1	13.5

of uniform conditions.

The method also estimates daily runoff by using soil parameters, such as SMD at the start and end of the day. For this, FAO run-off coefficients are used (Allen et al. 1998). The annual runoff of 81.3mm (10.4% of the annual

rainfall) is comparable with the previous studies in similar conditions in this region (Kesava Rao et al. 2006). Major part of the runoff flows through the drainage channels as observed in the field and part gets collected in small tanks at Krishnapuram and Kallugotla (Fig. 1).

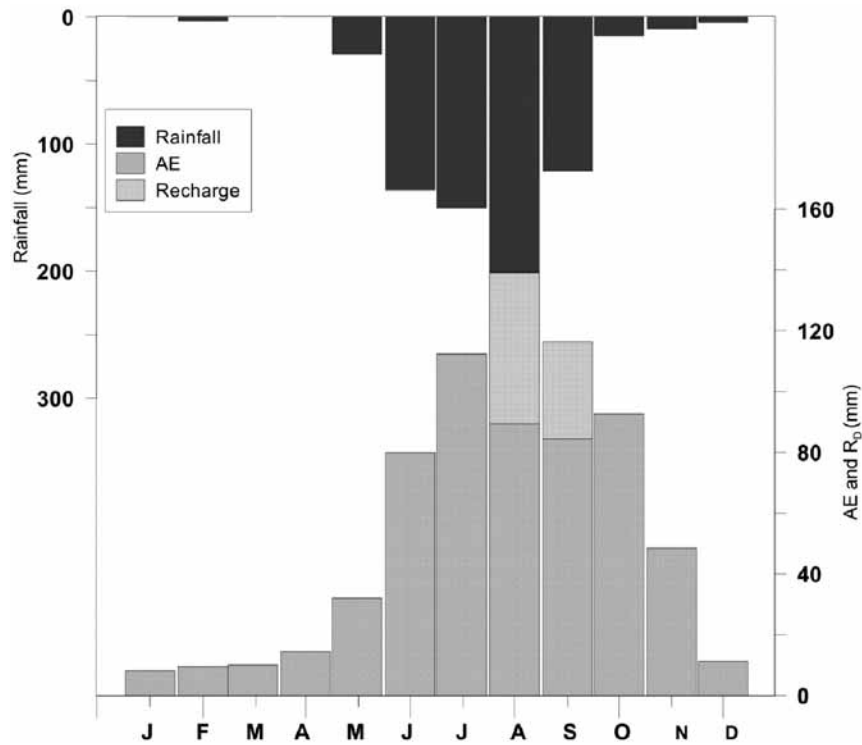


Figure 7. Monthly Rainfall, AE and recharge values for year 2000 in the watershed

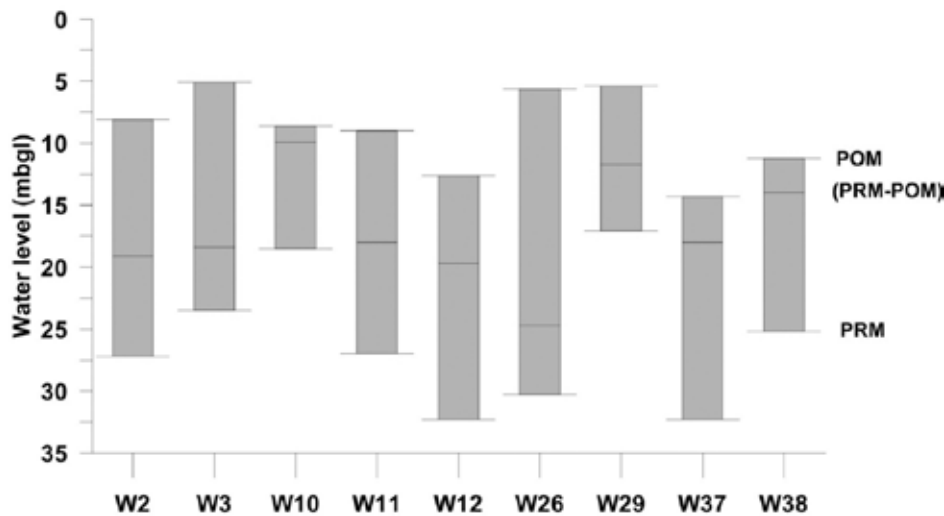


Figure 8. Box-whisker plot showing water level in bore wells during PRM (pre-monsoon) and POM (post-monsoon). The change from PRM to POM is indicated by middle point. Location of wells is given in Fig 1.

The effective recharge is observed by the change in static water level from 17.0-30.3 mbgl in pre-monsoon to 9.9-24.7 mbgl in post-monsoon (Fig. 8). The average water level change is 15.4m in carbonate rocks and 24m in other rocks (Fig. 3b & 9), with an average of ~17m due to monsoon recharge in the watershed. This large change is common in limestone aquifers, which have high hydraulic conductivity (Dar, et al., 2011).

The large sporadic rainfall events during which no

recharge is generated (Fig. 9) produce considerable runoff. This usually gets collected in the shallow tanks present in the area (Fig. 1) with silt and clay at the bottom. These ponds act as percolation tanks and have a low resistivity depth zone up to 25m below them, corresponding to a water storing zone in the aquifer. More than 30% of the runoff collected in such percolation tanks infiltrates to groundwater, as reported from various studies in southern India (Mehta and Jain 1997; Massuel et. al., 2014). This

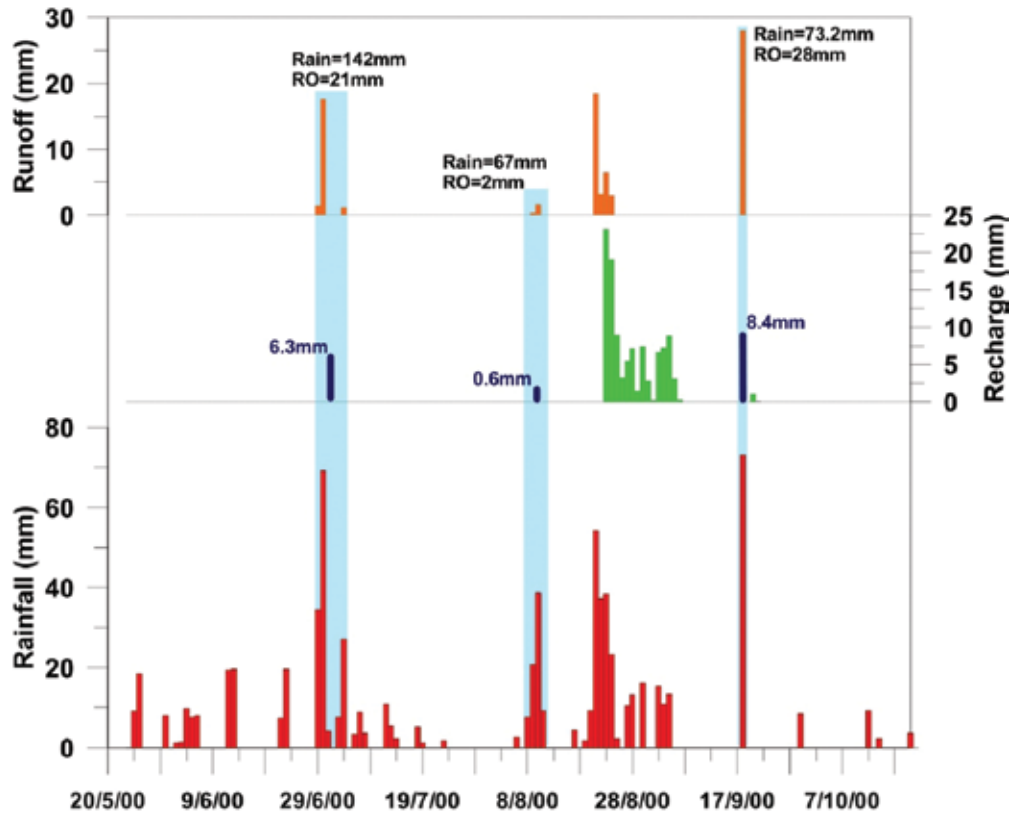


Figure 9. Daily rainfall, recharge and runoff in mm for the period of 20/5/2000 to 20/10/2000. The dark blue bars and values indicate the expected recharge from the generated runoff when properly harvested

is also evident from greater water level rise in wells closer to stream course than far off wells. These large rain events have significant importance in terms of groundwater management. If appropriately harvested, the assumed 30% of runoff is likely to get recharged and will lead to extra water level rise (Muralidharan et. al., 1995). These expected recharge values are shown as dark blue bars in Fig 9. Now assuming that ~17m water level rise in the wells is due to diffuse recharge of 106mm through the soils, the additional recharge generated from tank infiltration will lead to extra 2.5 m rise in water level at least in the surrounding wells. Thus, runoff and percolation tank water management in such semi-arid areas will be of significant contribution to the groundwater management.

The time of generation of diffuse recharge considerably depends on the frequency and intensity of rainfall and the antecedent soil moisture conditions. This can be clearly observed in major rainfall events (May to October) as shown in Fig 9. About 739.7mm of rainfall during this period generated a recharge amount of 106mm, which is 100% of the total annual recharge. The graph shows that most sporadic rainfall events become evaporation and part of it only decreases the soil moisture deficit (SMD) and

could not lead soils to the field capacity condition. The first rainfall events satisfy the soil moisture deficit (SMD) up to the field capacity. Subsequent rainfall events can only contribute to build up of recharge volume. In other words, recharge only occurs when the soils remain continuously in FC condition and the continuing rains during the succeeding days generate recharge. In addition, it was observed that recharge occurs even on immediate rainless days, as the soils were still fully saturated ($\theta_t > FC$). This extra moisture infiltration continued till θ_t reaches zero.

COMPARISON OF RECHARGE RESULTS

An average recharge rate of 110.3 mm from the tracer method is comparable to that of 106.1 mm calculated by the soil water balance method. From the two methods used in the Kallugotla watershed, an average recharge value of 108.2 mm (equivalent to 14% of annual rainfall) can be considered optimal. The results are comparable with various studies from semi-arid and soil covered carbonate aquifers (e. g., United Nations 1976 cited in Sukhija et al. 1996; Canton et al. 2010; Alcalá et al. 2010; Touhami et al. 2014; Rangarajan and Chand 1987).

CONCLUSIONS

The soil water balance and injected tritium tracer methods used for estimating groundwater recharge to a soil-covered carbonate aquifer of semi-arid Kallugotla watershed, southern Andhra Pradesh, India are comparable. The SWB approach indicates that annually ~106.1 mm recharge occurs, which is highly dependent on the soil properties, antecedent moisture and rainfall variability. The average annual recharge by injected tracer method is 110.3 mm. The two methods agree within the experimental error limit of $\pm 10\%$. A mean recharge rate of 14% of annual rainfall is optimal.

The tritium injection method is costly, involves sampling and rigorous laboratory analysis. However, it provides reliable point recharge estimates but does not take into account the secondary source of recharge that takes place along the stream sections and surface water bodies. The soil water balance method provides information on catchment scale. The method though, cheaper demands high accuracy of parameters used in computation of recharge.

The obtained results are useful for groundwater resource assessment and management in other carbonate areas of the country. There is lot of scope to manage these overexploited aquifers using appropriate methodologies like harvesting runoff through proper tank management, recharge pits, check dams with infiltration bore wells and filter bed assemblies, etc. This is important keeping in view the changing climate, more frequent monsoon aberrations, continuing groundwater draft, in addition to enhanced demand due to ever increasing population. As groundwater regime is dynamic in nature it is advisable to repeat the exercise to better understand the impact of various natural and anthropogenic factors, in space and time.

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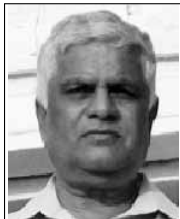
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Farooq A Dar is working as Project scientist at CSIR-National Geophysical research Institute, Hyderabad. His research interests include geology, geomorphology, chemistry, isotopes and tracers, karst geomorphology, hydrogeology of carbonate aquifers, integration of hydrogeological and hydrochemical data for groundwater exploration and management, and hydrogeophysics.



Dr. R. Rangarajan is working as Chief Scientist at CSIR-NGRI, Hyderabad. His fields of interest are tracer hydrology, hydrogeology, recharge, groundwater exploration, estimation and management of groundwater resources. He has carried out groundwater recharge studies in several watersheds and basins in different geological terrains of India, using various approaches. He has published research papers in high impact factor journals.



Dr. D. Muralidharan is an earth scientist, with more than 35 years experience in the field of groundwater. He published more than 70 research papers and 80 technical reports. He developed a semi-empirical method for interpreting electrical sounding data for identifying thin layers forming potential groundwater zone. He filed Patents for three innovations in the field of hydrology and geophysics. Currently working on Aquifer Mapping Program and serving as an Advisor in Ministry of Drinking Water & Sanitation, Govt. of India. He is also helping many state governments in effective management of Rural Drinking Water Supply.



Dr. Shakeel Ahmed is chief scientist and team leader IFCGR at CSIR-NGRI. He is a geophysicist and has applied geostatistics for exploration, management and sustainability of groundwater resources. He has published more than 200 papers, supervised many PhD students. He has also completed significant number of groundwater projects in India with international collaborations.