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Estimation of Groundwater Recharge in Limestone Aquifer using an Improved Soil Moisture Balance Method: A Case Study in Jaffna District

T. Mikunthan and C. S. De Silva[1]

Department of Agricultural Engineering
Faculty of Agriculture
University of Jaffna
Sri Lanka

ABSTRCT. *Estimation of recharge is extremely important for proper management of groundwater systems. The main purpose of this paper is to study the possibility of estimation of potential recharge in limestone aquifer as a case study in Thirunelvely and Kondavil area of Jaffna district, Sri Lanka using an improved soil moisture balance model (SAMBA). This model was used to estimate the groundwater recharge for a permanent grass and a commonly cultivated vegetable crop chilli for the years 2007 and 2008 for which soil properties, crop characters and climatic conditions were considered. The new concept of near surface soil moisture storage was included in the model and it is used to represent continuing evaporation on the days following heavy rainfall even though the soil moisture deficit is high. Uncertainties and variation in parameter values were explored using sensitivity analysis. The potential recharge resulted from the model was compared with the real field conditions of actual recharge which was derived from the water table fluctuation method.*

INTRODUCTION

Water shortage is a major problem in Jaffna peninsula, Sri Lanka and groundwater often serves as an important and safe source of water. Groundwater is replenished when rainfall percolates below the vadose zone and it is highly variable due to erratic rainfall patterns. The low rainfall in Jaffna district coupled with an increasing demand for irrigation and domestic water use, means that the total abstraction in groundwater resources approaches the limits of sustainable yield. The high stress due to abstraction of large quantities of groundwater through pumping has threatened the sustainability of limestone aquifer. Quantitative evaluation of groundwater resources of an area is an essential pre-requisite for its management because the total abstraction from any groundwater resource should not exceed the long term annual average rate of replenishment (Finch, 1998). Thus, there is an urgent need to improve the accuracy and reliability of groundwater recharge calculations.

Groundwater recharge is the amount of surface water which reaches the permanent water table either by direct contact in the riparian zone or by downward percolation through the overlying zone of aeration (Rushton and Ward, 1979). It really expresses the total quantity of groundwater resource available and their supply potential. Continuous and at least monthly

[1]Faculty of Engineering Technology, The Open University of Sri Lanka, Sri Lanka

recording of groundwater hydrographs is essential to obtain recharge rates from groundwater level fluctuation method (De Silva and Amarasinghe, 2008).

Rushton *et al*., (2006) stated that any methodology selected for the estimation of potential recharge must be applicable in a wide variety of climate and hydrological situations. They also stated that a soil moisture balance technique can be used for routine recharge estimation in many situations provided that the important physical processes are represented adequately.

A water balance technique which is similar to soil moisture balance method was used to estimate recharge in sand aquifer of Mannar Island in Sri Lanka by Senarath (1987). An improved daily soil moisture balance based on a single soil water store is successfully used to estimate groundwater recharge for an area classified as tropical with distinct dry seasons in northwest Sri Lanka and for Vavuniya district where both areas are in hard rock aquifer (De Silva and Rushton, 2007; De Silva and Amarasinghe, 2008). This paper explores the suitability of this model to estimate recharge in limestone aquifer.

MATERIALS AND METHODS

Collection of meteorological and agronomical data

Environmental parameters required for the estimation of potential evapotranspiration such as monthly average mean temperature, humidity, wind speed and sunshine hours were taken from the meteorological station, Jaffna. Crop data including date of planting, full emergence of crop, duration of initial, development, mid and late stages, date of harvesting, root zone depth and percentage of cultivable extent were recorded from the field. Field capacity was measured and permanent wilting point was taken from the literature for Red Yellow latosol soil (Joshuwa, 1973). Frequency of irrigation, rate of pumping and duration of pumping were monitored to estimate the irrigation amount. The CROPWAT programme (crop water requirement) by FAO, land and water division, Version 5.6 was used to calculate the potential evapotranspiration for the study period. The representation of crops and soils is based on FAO guidelines (Allen *et al*., 1998).

Soil moisture balance technique for recharge estimation

The simplified soil moisture balance model (SAMBA) is a simple method for estimating recharge in a variety of climatic conditions (De Silva and Rushton, 2007). The basis of the SAMBA for estimating recharge is that the soil becomes free draining condition when the moisture content of the soil reaches field capacity. Excess water, when moisture content is higher than the field capacity, then drains through the soil profile to become recharge. It is necessary to simulate soil moisture conditions on daily basis throughout the year to determine when the soil moisture reaches field capacity or exceeds field capacity to facilitate the recharge estimation. The soil moisture stored in the soil varies between the permanent wilting point and field capacity. The soil moisture deficit (SMD) is defined as the depth of water required to bring the soil up to field capacity.

A daily estimate of the soil moisture balance is made with an input of precipitation plus irrigation, minus run off and losses due to actual evapotranspiration and deep drainage which may include aquifer recharge. The magnitude of runoff is estimated as a fraction of rainfall and related to rainfall intensity and SMD. Coefficients for the fraction of rainfall which becomes runoff are shown in Table 1. The coefficient values were assigned with the reference of Navaratnarajah, (1994) and field observations. The transpiration and evaporation will occur at the potential rate if there is sufficient water in the soil. However, when soil moisture is limited, transpiration and evaporation may occur at a lesser rate than the potential rate. Reduced rate of evaporation and transpiration depend on properties of the soil and the crop. As soil wetness decreases, the actual transpiration begins to fall below the potential rate because the soil cannot supply water fast enough and/or because the roots can no longer extract water fast enough to meet the requirement of plants.

Table 1. Multiplying coefficients applied to rainfall for runoff estimation

Rainfall intensity (mm/day)	Soil moisture deficit (mm)		
	0 - 20	**20 - 50**	**>50**
0 – 20	0.25	0.20	0.10
20 – 50	0.30	0.25	0.15
> 50	0.35	0.30	0.20

The distribution of moisture in the soil profile is unimportant since the actual evapotranspiration equals the potential value when the SMD is less than the readily available water (RAW). Furthermore, when the SMD is greater than RAW, allowance is made for the reduced soil moisture by introducing stress and evaporation coefficients. Evapotranspiration occurs at the potential rate even when the SMD is greater than RAW and when there is significant rainfall. When a significant SMD exists and there is substantial rainfall, moisture is retained near soil surface. This field response is represented by the introduction of near surface soil storage (NSSS). A proportion of the increase in soil moisture is retained near to the soil surface for transpiration or evaporation on the following day. An empirical factor FRACSTOR is used to define the proportion of the increase in moisture content which becomes NSSS, SURFSTOR.

According to Rushton (2003), a practical approach is used in estimating the value of FRACSTOR from field observations. If the soil surface remains wet after heavy rainfall, it is not possible to work for some days, so that the FRACSTOR is in the range of 0.6 – 0.8. If the soil dries quickly it will be less than 0.3. Recharge will occur on days when the SMD is negative. As the SMD becomes zero, the soil reaches field capacity and becomes free draining. Consequently recharge equals the quantity of water in excess after soil reaches field capacity.

The soil moisture deficit at the start of the day; 1st January 2007 was taken as zero and cross checked 1st January 2009. The SMD for the start of the day for chilli crop was taken from the grass moisture balance for day of planting. Crop coefficients for chilli and perennial grass were taken from Allen *et al*., (1998). The FRASTOR for chilli crop was taken as 0.7 to reflect land preparation and a cultural practice by the farmer to retain moisture near the soil surface whereas for grass it was taken as 0.45. The potential recharge was estimated for permanent grass and chilli for the years 2007 and 2008 using the SAMBA model.

Water table fluctuation method

The water-table fluctuation method (WTF) is based on the premise that the rise in groundwater levels in unconfined aquifers is due to recharge arriving at the water table. The method is based on relating changes in measured water table elevation with changes in the amount of water stored in the aquifer (Delin *et al*., 2007), as shown in equation 1.

$R(t_j) = Sy\ \Delta H(t_j)$ ……………………….[1]

In which

- t_o - Initial time,
- t_j -Time taken to reach the peak water table,
- $R(t_j)$ - Recharge occurring between times t_o and t_j (cm),
- Sy - Specific yield,
- $\Delta H(t_j)$ - the peak water table rise attributed to the recharge period (cm).

Inherent assumptions include (1) the observed hydrograph depicts only natural water table fluctuations caused by groundwater recharge and discharge (2) Sy is known and constant over the interval of the water table fluctuations, and (3) The pre-recharge water level recession can be extrapolated to determine $\Delta H(t_j)$. Limitations of WTF method include the fact that water level fluctuations in a well may only be representative of a small area within a watershed. Water level rises may not always be the result of direct recharge due to rainfall and/or irrigation in the area. Determining a proper value for specific yield is difficult. Favorable aspects of the WTF method include its simplicity and ease of use. The WTF method is best applied to systems with shallow water tables that display sharp raises and declines (Healy and Cook, 2002).

Daily water levels were measured by using dip meters at forty wells (twenty each from Thirunelvely and Kondavil) from April 2007 to December 2008 from a variety of sites across the study area. The selected forty wells were randomly selected and evenly spaced in both area. The specific yield of 0.27 was taken from pumping test analysis of past study from the study areas (NWSDB, 2006). Ultimately, both potential recharge from SAMBA method and the actual recharge from WTF method were compared to see the suitability of the model for limestone aquifer.

RESULTS AND DISCUSSION

The soil moisture balance components rainfall (RF), runoff (RO), potential (PE) and actual evapotranspiration (AE), total available water (TAW), RAW, SMD and potential recharge for the water in the year 2008 for permanent grass and chilli are shown in Figs 1 and 2 respectively.

Water balance for permanent grass

Daily soil moisture balance for the period from 1st January 2007 to 31st December 2008 for permanent grass land is indicated in Fig. 1 in detail. The annual rainfall for 2007 and 2008 were 1291.4 mm and 1966.8 mm, respectively. Out of which 305 mm (24%) and 495.25 mm (25%) were run off. Navaratnarajah, 1994 reported that 20 - 30% of rainfall was lost as runoff from the Peninsula. Hence the selected runoff co-efficients (Table 1) are suitable for the model. Higher percentage runoff occurs when the SMD was zero in October to December, but still there was a considerable amount of runoff even with a significantly small rainfall even though SMD was not zero and greater than RAW. The total PE was estimated as 2355 mm, but the AE was 738 mm (Fig. 1b) for the year 2007. The estimated total AE was 31% of the PE during the study period.

As shown in Fig. 1b, when there was sufficient rainfall, AE equals PE during the period from 301 to 365 days where SMD<RAW. Similarly, when the SMD<RAW even on days with no rainfall which was during 1st to 10th day AE occurs at potential rate. Because the residual soil moisture satisfied the requirement of evapotranspiration. AE was less than the PE during the period of zero rainfall and only if SMD>RAW during the period from 130 to 150 days (Fig. 1b).

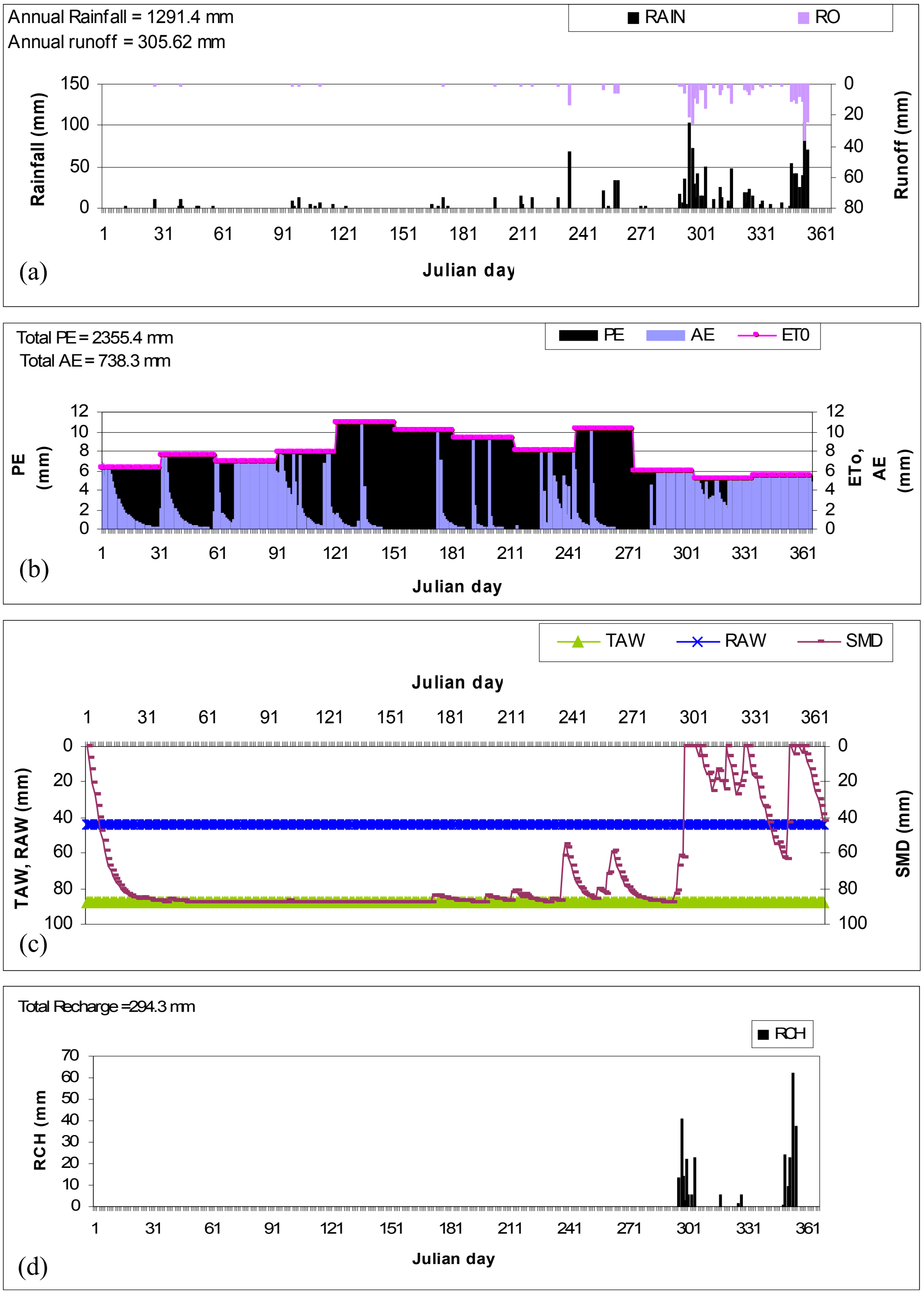

Fig. 1. Soil moisture balance components for permanent grass
When SMD>TAW, actual transpiration should only occur on days when sufficient rainfall occurs. This was the reason for low total AE compared to PE, because during most of the days in a calendar year SMD>RAW with limited number of rainy days.

The moisture content of the soil was tracked through time and shown in Fig. 1c. SMD was less than RAW during the times of rain only. Recharge (RCH) occurred when SMD reachedzero during October, November, and December and shown in Fig. 1d. The total potential recharge was 294 mm and annual recharge was 23% of the total rainfall received during 2007. The highest potential recharge occurred during the month of December but the number of recharge days was greater in October where SMD was zero for 10 days. Groundwater recharge in dry areas is usually the result of an irregular and sporadic rainfall distribution which is mainly concentrated in *Maha* season.

Vegetable crop irrigated chilli

The water input (irrigation + rainfall) during the growing period from 27th March 2007 to 25th September 2007 was 964.7 mm while the estimated PE was 1193.9 mm. Hence the total input of water was 80.8% of the required water for PE. The estimated runoff from the cultivated area was 142 mm and it occurred mainly during rainfall time and not during irrigation time. The field observation also supported this result. Considerable amount of runoff occurred with small amount of rainfall while SMD is not zero (SMD>RAW). This particular runoff loss could be overcome by cultural practices such as mulching and loosening of soil to increase the infiltration and to improve the moisture condition of the soil

AE which is shown as filled bar in Fig. 2b, occurs at PE rate when there was required input of moisture. However, AE was less than the PE because SMD was greater than RAW which indicated that the crop was under water stress. Hence cultural activities such as shortening of irrigation interval and loosening of the soil were recommended to increase NSSS factor. The TAW (83 mm) and RAW (37 mm) was considered as constant throughout the growing season (Fig. 2 c) but obviously the depth of the root zone was very low during the initial stage and gradually reaching the maximum root depth during the mid stage of the crop. This RAW led to an increase in the AE when SMD>RAW and the rainfall was low. The extension to include a NSSS in semi arid climate zones as suggested by Rushton (2003) become more important with lower rainfall intensities and more dry environments and also important for early stages of growth of a crop. There was no recharge during the cultivation period which indicates that there was no excess irrigation.

Sensitivity analysis

Sensitivity analysis helps to understand the significant role played by an individual parameter in the computation of groundwater balance. It is important in investigating the effect of uncertainties of parameter values and variability of crops and soil factors. The principle variable components of groundwater balance to which the groundwater storage changes are NSSS, RO, TAW, depth of root zone (Zr) and crop co-efficient (Kc). Increasing and decreasing conditions of these parameters were used to predict the model out put of recharge. Selections of upper and lower levels of parameters were based on the field observation except for Kc value which was based on Allen *et al*., (1998). Fig. 3 shows the variation of recharge due to changing of tested parameters.

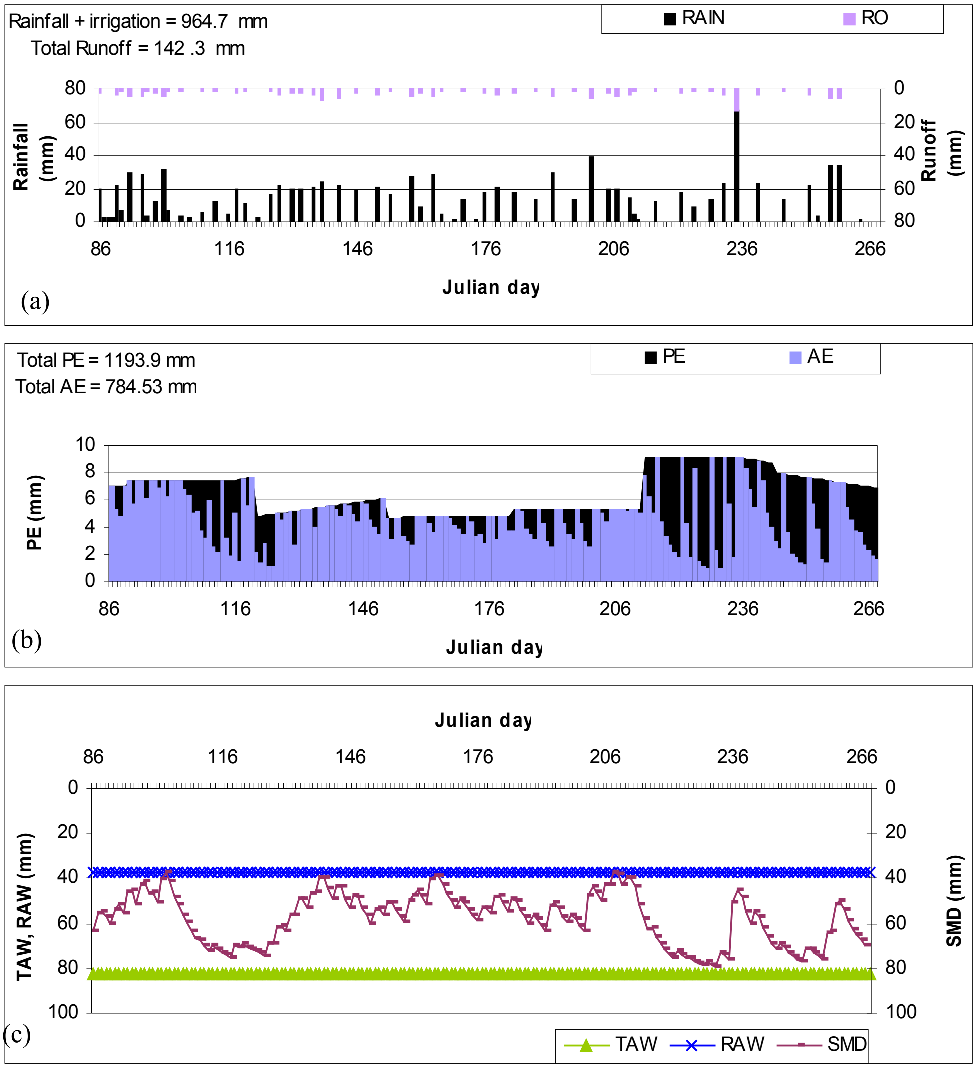

Fig. 2. Soil moisture balance components for chilli

Among the tested parameters, RO co-efficient is the most influential parameter followed by TAW which affects the recharge. RO co-efficient was checked from 10% to 30% and the results are shown for 20% in Fig. 3. These high variations highlight the need to obtain realistic field situations. Since the slope of the study area is less than 2% or almost flat, the considered RO co-efficients are realistic. The matrix of runoff co-efficient can be deduced from field observations of runoff at different times of the year. Changes in the parameter NSSS have only a small effect on recharge estimates, because this factor representsg the conditions of retaining water close to the soil surface and mostly influencing short duration of the early stage of the crop. The NSSS can be inferred from field observations of the wetness of the soil surface on the day following rainfall or irrigation. For the other parameters, the changes in the recharge estimates reflect uncertainties in the parameter values and the variability of crop and soil conditions in the field.

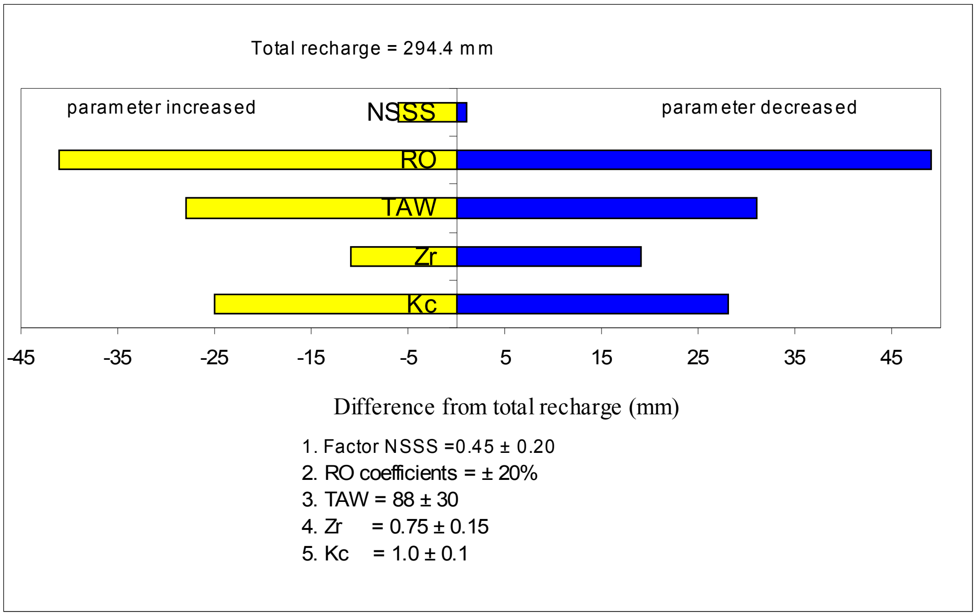

Fig. 3. Sensitivity analysis for changes in soil moisture, crop Kc and root zone and run off

Water table fluctuation method

The Fig. 4 shows the water table fluctuation with rainfall for selected wells from April to December 2007 from both areas. There were substantial differences in the responses of water level in monitored wells due to spatial variability of recharge. Observation of well water level showed that difference response of groundwater fluctuations in time and the rate as well as space. Since the rise and recession of the well hydrograph is sharp or quick, the rise of the groundwater level was estimated as the difference between the peak of the water level rise and the value of the extrapolated antecedent recession curve at the time of the peak (Delin *et al*., 2007). This recession curve is a trace that the well hydrograph would have followed if there had not been any precipitation. The existing wells in the study area were selected for the study purposes and not located specifically to represent the catchments area of the study. This may be due to the fact that differences in elevation, geological situation (presence of cracks and fractures in the limestone aquifer), land slop, land use and other cultural activities. Major limitation of WTF method is water level rises may not be always the result of direct recharge. However, in this study it may have been influenced by direct recharge because there was no river or tank. The recharge to the water table could be considered as steady flow, since the depth to water table or depth of the unsaturated zone is generally less than 10 m.

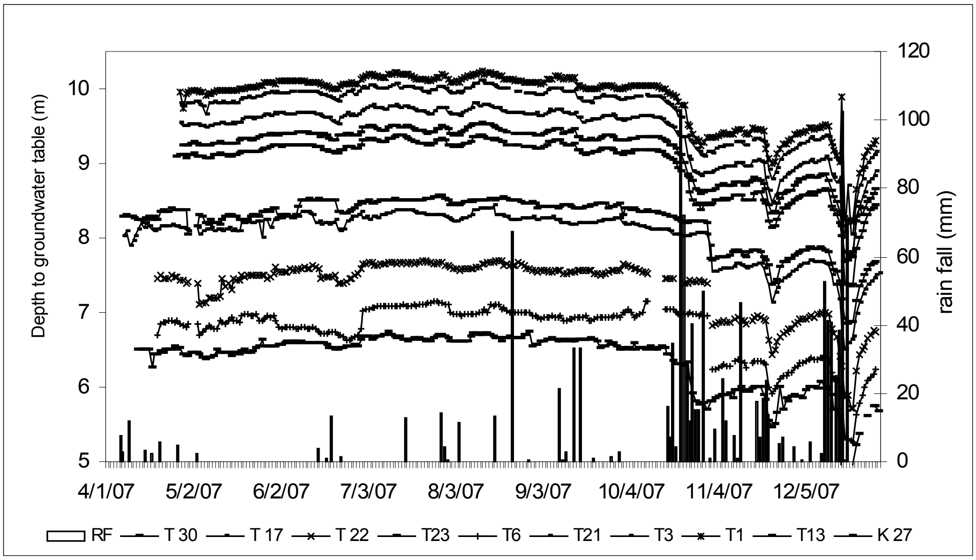

Fig. 4. Water table fluctuation with rainfall

Comparing the model results with field results

Comparison of real field situation of actual recharge with potential recharge estimated by the soil moisture model is important to validate the model results. It is introduced to examine the creditability of the soil moisture balance method. Table 2 shows the recharge estimates from SAMBA model for permanent grass, and WTF method with deviation.

Table 2. Recharge (mm) estimates from SAMBA and WTF method for grass

Recharge period	SAMBA	WTF method
October 2007	126	98 ± 15
November 2007	12	27 ± 8
December 2007	156	112 ± 12
March 2008	15	12 ± 5
October 2008	60	48 ± 10
November 2008	418	460 ± 66
December 2008	6	11± 5

There is an acceptable agreement in identified main period (months of a year) of recharge throughout the study period between recharge estimated from SAMBA model and WTF method. Each method provides information about the temporal variation of recharge. The results indicated that assessment of the annual recharge obtained by SAMBA and WTF method coinciding fairly well. When comparing the results of both methods calculated recharge values were varying from 23% to 25% of the total rainfall received during 2007 and 2008 respectively for SAMBA model whereas it was 19% to 27% for WTF method. The variability of WTF during 2008 was high due to the "Nisha" cyclone. Fig. 5 shows the relationship between estimated recharge by SAMBA model and actual recharge that occurred in the well through WTF method.

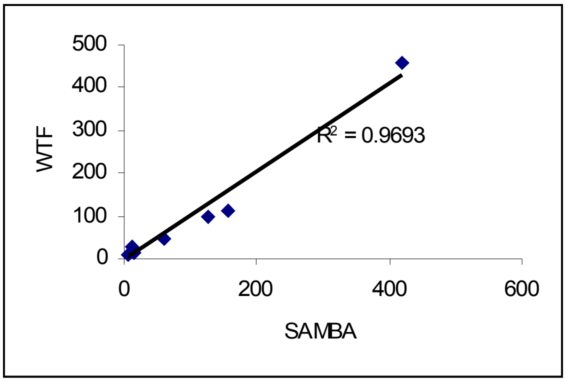

Fig. 5. Relationship between estimated recharge to actual recharge

There were no recharge during March 2007 but it occurred in March 2008 due to shortfall. The recharge during November 2008 was an exception due to "Nisha" cyclone. The amounts of rainfall on 24th, 25th, and 26th of November 2008 were 197.50, 389.80 and 60.00 mm, respectively. The total rainfall received for the month of November 2008 was 830.80 mm. Around 210 to 360 cm groundwater table rises were observed in the selected wells. SAMBA model could be estimating the recharge due to the values of several input parameters which may not represent the real field conditions. On the other hand the WTF method has inaccuracies in manual measurement of the water levels, manually extrapolated antecedent recession curve and the unreliability of the specific yield. However, WTF method is very valuable to check whether the soil moisture balance method represent the field conditions.

CONCLUSIONS

Groundwater recharge rates of the limestone aquifer range from 23% to 25% of annual rainfall as determined by SAMBA model for 2007 and 2008 whereas it was 19% and 27% of annual rainfall by WTF. Uncertainties about the parameter values used in a soil moisture balance and spatial variations of the soil and crop parameters could be explored using sensitivity analysis and runoff which was identified as major factor which influences the recharge. There is an acceptable agreement in identified main period of recharge by both methods. The order of magnitude of the recharge and the main period of recharge could be suitably well simulated by SAMBA model. Hence the model can serve as a useful tool to estimate the recharge in limestone aquifer.

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