OUSL Journal (2014)
Vol 7, (pp43-65)

Simulation of Potential Groundwater Recharge from the Jaffna Peninsula of Sri Lanka using HYDRUS-1D Model

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Abstract

In drier regions, accurate knowledge of groundwater recharge is important for the sustainable management of scare water resources. Thirunelvely in Jaffna Peninsula is an area where groundwater is being utilized for domestic, agricultural and municipal water supply. Further the groundwater in this area also contaminated with nitrogenous fertilizer application due to intensive agriculture, as post war conditions in the Peninsula encourage farmers to engage in intensive agricultural activities. Very few or no studies have been conducted in the recent past on groundwater recharge or solute transport such a fertilizer leaching in this area. HYDRUS-1D is a Windows-based modelling environment for analysis of water flow and solute transport in variably saturated porous media. HYDRUS-1D is just as quick and cheap as other soil moisture balance models but more physically based and flexible as it allows for building up complexity as data are available whether for solute transport or non-equilibrium flow etc. Therefore the main objective of this paper is to simulate potential groundwater recharge using HYDRUS-1D and compare it with the results obtained in Thirunelvely using soil moisture balance and water table fluctuation methods. Results have shown that the HYDRUS-1D simulated potential groundwater recharge (41.8 cm) has close agreement with that estimated by other methods with high coefficient of determination (R^2 = 0.95). Further runoff, soil moisture storage and bottom pressure head simulated by HYDRUS-1D too have good agreement with field observation. Therefore HYDRUS-1D is capable of simulating potential groundwater recharge close to the previously estimated values in Thirunelvely as it has good agreement with the water table fluctuation measured in the study site and the bottom head pressure at the 1 m soil profile simulated in the HYDRUS-1D model. Now that it has been demonstrated that HYDRUS-1D adequately reproduces the water fluxes predicted by other

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methods, it could be used for groundwater recharge with more confidence and to investigate pollution in soil zone and groundwater.

Introduction

Estimating groundwater recharge is important for management of water resources and aquifer vulnerability to pollutants (Scanlon and Cook, 2002). Recharge estimation can be difficult in areas where groundwater tables are typically deep. The recharge rate is limited by the availability of the water in the soil surface which is depend on the temporal and spatial variation of climatic factors such as precipitation, temperature and evapotranspiration (Scanlon and Cook, 2002).

Knowledge of groundwater recharge is essential in virtually in all groundwater hydrology investigation and it is depending on the application, which needs to be estimated at a variety of spatial and temporal scale as stated by Delin *et al.* (2007) and Scanlon and Cook (2002). While groundwater recharge is one of the most important parameters required to support sustainable management of groundwater resources, it is one of the most difficult to evaluate accurately, due to the numerous factors involved in recharge processes. The amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the groundwater recharge. Thus, a quantitative evaluation of spatial and temporal distribution of groundwater recharge is a pre-requisite for operating groundwater resources system in an optimal manner.

Groundwater recharge is that 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). Also De Vries and Simmers (2002) defined groundwater recharge in a general sense as the downward flow of water reaching the water table, forming an addition to the groundwater reservoir. It really expresses the total quantity of groundwater resource available and their supply potential. Recharge is the quantity which may be available in the long term for abstraction and is therefore of prime importance in the assessment of any groundwater resources management.

Methods such as soil moisture balance, chloride profile, water table fluctuation and several other methods of estimation of groundwater recharge are been reviewed with varying degrees of success (Scanlon and Cook, 2002; de Vries and Simeers, 2002). These methods can be grouped in to three based on whether the focus of the method is surface water, the vadose zone, or saturated zone. Further most of the recharge estimation models are basically simulating only water flow and a very few for both water and solute flow. Therefore, the objective of this study is to simulate potential groundwater recharge using HYDRUS-1D which can be used to estimate the potential groundwater recharge with the intention of using the model to simulate solute transport in the future. The modelling approach used HYDRUS-1D (Šimůnek *et al.*, 2005); a well known numerical computer model that simulates water, heat and solute movement in variably saturated porous media. This study also provides an opportunity for comparing recharge rates estimated with modified soil moisture balance (MSMB) method and water table fluctuation method (WTF) by Mikunthan and De Silva (2009) at similar sites.

Further HYDRUS-1D is a full physical process model available, and therefore should be the best if parameter values can be estimated well enough. Overall no method is perfect, and inter-comparisons are useful. HYDRUS-1D is also just as quick and cheap as MSMB but more physically based and flexible as it allows for building up complexity, as data are available whether for solute transport or non- equilibrium flow. In this study HYDRUS -1D is used only for water flow.

Study Site Description

Thirunelvely was selected in this study because it has received much attention due to its significant groundwater dependence, groundwater being utilized for domestic, agricultural and municipal water supply: the assessment of groundwater recharge plays major role in the management of water supply schemes such as this one. Thirunelvely, an intensive farming village of Jaffna district and located in Nallur divisional secretariat was considered for the simulation of potential recharge using HYDRUS-1D. The Jaffna Peninsula is situated at the Northern extreme of Sri Lanka. Geographically confined to North and East by the Indian Ocean, to the West by the Palk Strait and to the South extending to the mainland of the country (Figure 1), the Jaffna district occupies an extent of 1023 km^2, which includes inland waters. Farmers in Thirunelvely are cultivating agricultural crops such as red onion, chillies, potatoes, tobacco, cabbage, leafy vegetables, banana and grapes for commercial purposes. Nagarajah *et al.* (1988) reported that high levels of organic manure such as cattle, goat and green manures and inorganic fertilizers and agrochemicals are applied to these high value crops. Other crops such as paddy, pulses and coconut are also cultivated in the study area. The population density of Nallur divisional secretariat is 1920 person/km^2 the second highest population density area in the Jaffna district. The Jaffna municipal area receives drinking water from three major water supply schemes including the old and new Thirunelvely schemes. The extent of the study site at Thirunelvely is 342 ha. The elevation of the study area is 8 m above the mean sea level. The site is flat and slightly undulating with only 2 % slope and consists of red yellow latosols (red earth) occurs as a thin layer (0-2 m) on the surface of the Jaffna limestone (Arumugam, 1970). The description of the study area is shown in Figure 1.

Thirunelvely experiences typical dry zone climate of Sri Lanka, characterized by a wet and a dry season. The major rainy season occurs during October to February due to the 2nd inter-monsoon and North-East monsoon and the minor rainy season occurs during April and May due to the 1st intermonsoon. Thirunelvely is located in DL_3 agro climatological region of the dry zone, which receives an average rainfall of 1300 mm annually (Arumugam, 1970). Months of September/October to January/February and February/March to August/September are called *Maha* (wet season) and *Yala* (dry season), respectively. The bulk of the rainfall is received during the months from October to January and with little or no rainfall afterwards. The estimated 75% probability rainfall in this district is 510 mm in *Maha* and 102 mm in *Yala* (Cooray, 1984).

The Jaffna Peninsula is unique in geology and aquifer conditions. The northern and northwestern coastal belt of Sri Lanka (stretching from Puttlam to the Jaffna Peninsula) represents the major sedimentary formation of the island. This formation mainly consists with Miocene Limestone (Cooray, 1984). In general, this Miocene formation unconformably overlies high-grade pre-Cambrian metamorphic rocks (the Wanni complex, formerly the West Vijayan complex) but in places is underlain by sedimentary layers of Upper Jurassic (Gondwana) age (Arumugam, 1970). Lithologically this limestone is off white or cream coloured varying from white grey to light brown, compact, highly karstic, indistinctly bedded and partly crystalline (Arumugam, 1970). It also contains sandy (siliceous) friable layers with cavities

(Arumugam, 1970). The vertical thickness of the Miocene limestone exceeds 35 m (Arumugam, 1970). In the north-east the limestone scarcely crops out, but there are a number of karstic features including surface depressions (*e.g* at Manipay Idikandu), tidal wells (Puthur Nialvarai), cliffs and springs (Keerimalai). The limestone is generally overlain by highly porous thin (maximum 2 m) soil cover of red earth (Rajasooriyar *et al.*, 2002).

The water table in this unconfined aquifer responds to the onset of monsoon rains and shows a more peaked response than the underlying limestone aquifer (Arumugam, 1968). The annual WTF is 1-2 m (Arumugam, 1968). Data from several pumping tests were analysed using Hantush (1956) and Walton (1962), the vertical permeability is in the range of 0.003 to 0.07 m/day. Results from slug injection tests carried out on the unconfined sand aquifer indicate a low permeability typically in the range of 0.05 to 0.30 m/day (Lawrence and Dharmagunawardena, 1983).

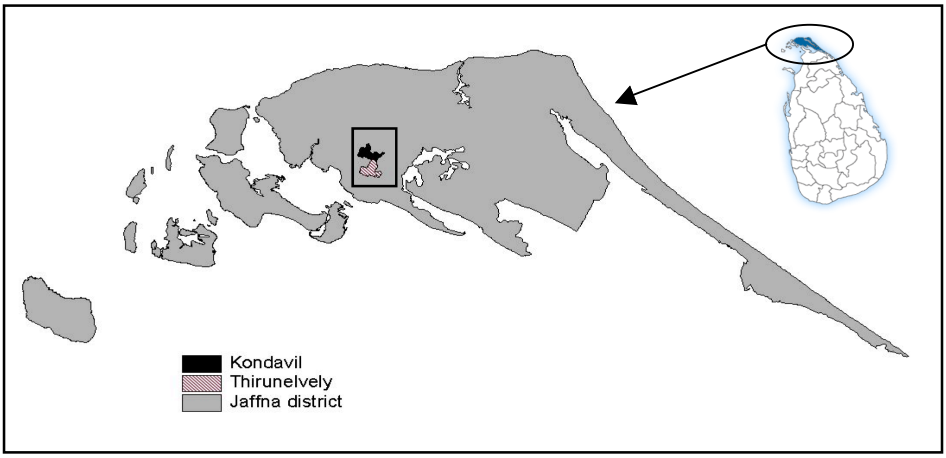

Figure 1. Location of the study in the Jaffna Peninsula

Methodology

Data for simulation

Data of year 2007 at Thirunelvely was considered for HYDRUS-1D simulation as this year has complete set of data including weather, crop, soil, and WTF needed for the numerical model simulation required by HYDRUS 1D for this paper. However the analysis was done for the complete cycle of two years.

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 (Cabbage) data such as date of planting, full emergence of crop, duration of initial, development, mid and late stage, date of harvesting, root zone depth and soil data such as field capacity, permanent wilting point and bulk density recorded from the field in Thirunelvely were also used in this simulation (Mikunthan and De Silva 2009). Crop coefficients for required crops were taken from Allen *et al.* (1998). The selected cropping situation for simulation by HYDRUS-1D was unirrigated grassland with small trees and cabbage cultivated from mid March to late June. Grass was used in the model to represent the area when cabbage is not in the field.

Daily WTF data measured by using dip meters at twenty wells in Thirunelvely from January 2007 to December 2008 from a variety of sites across Thirunelvely were also used to compare the HYDRUS-1D simulated results.

Simulation of Potential Recharge using HYDRUS-1D

Numerical modelling of water flow

In this study, water flow and root zone moisture dynamics were simulated using HYDRUS-1D (Šimůnek *et al.*, 2005). HYDRUS-1D 3.0 is a Windows based modelling environment for water flow and solute transport analysis in variably saturated porous media. The base of this model is the variable saturated vertical soil domain where water flow is simulated. In HYDRUS, the root zone moisture dynamics are simulated with the Richard's equation assuming (i) that the soil is homogenous and isotropic, (ii) that the air phase does not affect the liquid flow processes, and (iii) the water flow due to thermal gradients is negligible. The governing equation for water flow is the 1D Richard's equation for unsaturated flow as follows:

$$\frac{d\theta(h)}{dt} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S(h) \qquad (1)$$

subject to the initial and boundary conditions chosen to implement

$$h(z,0) = ho(z) \quad (2)$$

$$-K(h)\left(\frac{\partial h}{\partial z}+1\right)\Big|_{z=0} = qo(t) \quad (3)$$

$$\frac{dh}{dz}(L,t) = 0 \quad (4)$$

or

$$h(L,t) = h_L(t) \quad (5)$$

where:

h = soil water pressure head; θ= volumetric water content; t = time; z = vertical space coordinate assumed to be 0 at the soil surface and directed upward; K = unsaturated hydraulic conductivity; S = sink term to account for root water uptake; $h_0(z)$ is the initial condition; and $q_0(t)$ is the fluid flux across the soil surface boundary (Šimůnek *et al.*, 2005). This sink term is specified in terms of a potential uptake rate and stress factor (Feddes *et al.*, 1978) as follows:

$$S(h) = \propto (h) S_p \quad (6)$$

where S_p is the potential water uptake rate and α(h) is the dimensionless water stress response function (0 ≤ α ≤ 1) that prescribes the reduction in uptake that occurs due to drought stress. The functional form introduced by Feddes *et al.* (1978) was used for α(h). This function assumes h_1, h_2, h_3 and h_4 are threshold parameters such that uptake is at the potential rate when the pressure head is between h_2 and h_3. It drops off linearly when $h > h_2$ or $h < h_3$, and it becomes zero when $h < h_4$ or $h > h_1$. The crop specific default parameter values were taken from the database contained in HYDRUS-1D (Šimůnek *et al.*, 2005). The default parameters for grass used in this simulation were: h_1 = −10 cm, h_2 = -25 cm, h_{3l} = −200 cm, h_{3h} = −800 cm, h_4 = −8000 cm. The default parameters of Cabbage were: $h_1 = -10$ cm, $h_2 = -25$ cm, $h_{3l} = -600$ cm, $h_{3h} = -700$cm, $h_4 = -8000$ cm (Wesseling, 1991).

The surface boundary (Equation 3) was implemented as an atmospheric condition without surface ponding in which $q_0(t)$ equals rainfall minus potential evaporation as long as the pressure head determined at the soil surface exceeds some minimum negative value (-10000 cm in this study). It is assumed that surface runoff occurs when the surface becomes saturated, in which case $q_0(t)$ in Equation 3 decreases in value. The lower boundary condition is simulated as a free drainage condition (unit hydraulic gradient or constant head boundary at the bottom being appropriate due to the fact that the water table was far below the root zone (7-9 m below the root zone in the study area). Drainage from the bottom of the soil profile or bottom flux was assumed to be equal to the potential groundwater recharge.

Soil hydraulic properties

van Genuchten-Mualem's constitutive relationships were used to model the soil hydraulic properties (Mualem,1976; van Genuchten,1980).

$$\theta(h) = \begin{cases} \theta_r + \frac{\theta_s - \theta_r}{[1+|\alpha h| \quad n] \quad 1-1/n} & h < 0 \\ \theta_s & h \geq 0 \end{cases} \qquad (7)$$

$$K(h) = K_s S_e^1 \left\{ \ 1 - \left[1 - S_e^{n/(n-1)}\right] \quad 1-1/n \right\} \quad 2 \qquad (8)$$

where: θ_r and θ_s are the residual and saturated water contents, respectively; α and n are empirical shape factors that depend on soil type; K_s is the saturated hydraulic conductivity; and S_e is the effective saturation. The latter is given by:

$$S_e = \frac{\theta(h) - \theta_r}{\theta_s - \theta_r} \qquad (9)$$

Where: θ_s= saturated water content; θ_r= residual water content; α = air entry parameter; n= pore size distribution parameter; and l=pore connectivity parameter. The parameters α, n and l are empirical coefficients that determine the shape of the hydraulic functions. Running the model required specifying the hydraulic parameters θ_r, θ_s, α, n, K_s and l. HYDRUS-1D default parameter values for each of these parameters for sandy clay loam were used in this modelling initially. The default values for sandy clay loam were θ_r=0.1, θ_s=0.39, α=0.059, n=1.48, K_s=31.4 and l=0.5. All the units used in HYDRUS-1D were in cm and cm/day.

Evaporation and transpiration

In this study the Penman-Monteith equation (Allen *et al.*, 1998) was used to estimate the reference crop evapotranspiration rate, ET_o (mm/day). Potential evapotranspiration (ET_p) was calculated using the formula given by Allen *et al.* (1998):

$$ET_p(t) = K_c(t) \times ET_o(t) \tag{10}$$

where $ET_o(t)$ was discretized using daily time steps and $K_c(t)$ is a dimensionless crop coefficient that characterizes the plant water uptake and evaporation relative to the reference crop. The time variation of $K_c(t)$ in terms of annual crop growth is divided into the stages such as initial, crop development, mid season and late season. Allen *et al.* (1998) provide data on the length of growth stage and values of K_c for various crops. In this study the Allen *et al.* (1998) method and data to specify the crop and the values of K_c during each growth stage are used (Table 2). Then the potential evaporation rate of a soil under a standing crop was derived from the Pan Evaporation method (Meteorological Data, Colombo) and potential transpiration rates were calculated by subtracting evaporation from total ET.

The potential groundwater recharge simulated by HYDRUS-1D is compared with potential groundwater recharge estimated by modified soil moisture balance (MSMB) method (Mikunthan and De Silva, 2009) and water table fluctuation (WTF) method based on groundwater levels monitored in the study area. For the completeness of this paper these two methods (MSMB and WTF) are summarized below.

Estimation of Potential Recharge using Modified Soil Moisture Balance (MSMB) Method

The MSMB, a spreadsheet model was developed by Rushton (2003) and used in dry zone of Sri Lanka successfully (De Silva and Rushton, 2007). A daily estimate of the soil moisture balance is made with an input of rainfall minus run off and losses due to actual evapotranspiration and drainage, which may include aquifer recharge. Inputs and outputs for the soil moisture balance are shown schematically in Figure 3.

Features of modified soil moisture balance (MSMB) model are as follows:

- ***Runoff***

The main source of water is rainfall or irrigation. The actual infiltration of soil zone may be reduced due to interception or runoff. Runoff coefficient based on rainfall intensity and SMD were used in this model (Mikunthan and De Silva, 2009).

- ***Evapotranspiration***

The reference crop potential evapotranspiration ET_o can be estimated using the Penman-Monteith equation (Allen *et al.*, 1998). The FAO CROPWAT program (Smith, 1992), Version 5.6, was used to calculate the potential evapotranspiration for the study period. The crop water requirement differs according to type of crop, the date of planting, the stages of the crop and the date of harvesting which is determined by Kc the crop co-efficient. Crop stress is included using the concepts of total and readily available water. The reduced evapotranspiration depends on total and readily available evaporable water. As soil wetness decreases, the actual evapotranspiration 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 meteorological demand. Figure 4 shows how actual evapotranspiration is assumed to vary with SMD.

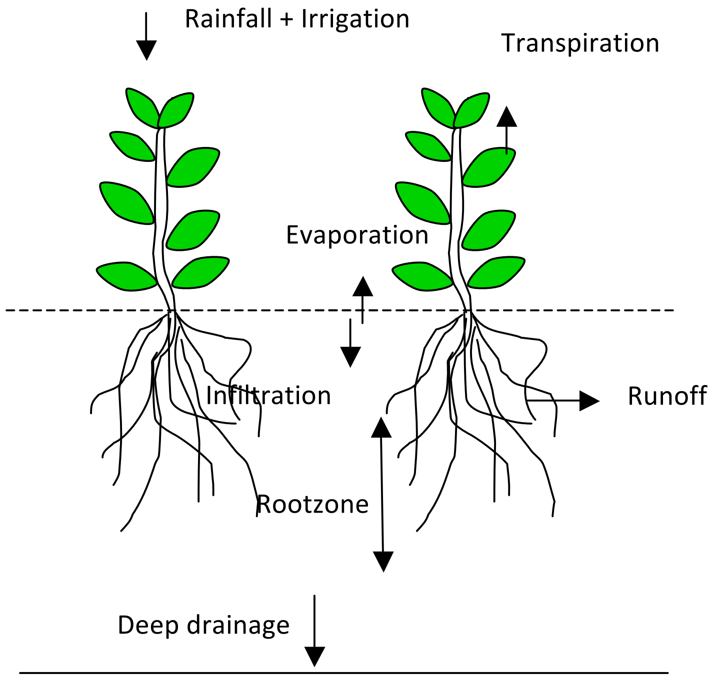

Figure 3. Diagram of soil water balance

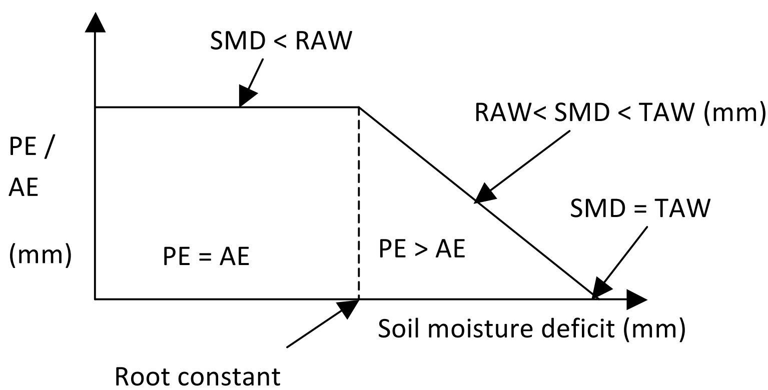

Figure 4. Situation of evaporation under different soil moisture deficits

The SMD on the start of the day, 1st January 2007, was taken as zero as it is more appropriate to consider after wet season rains.

The near surface soil storage (NSSS) reflects the idea that a certain percentage of soil moisture from rainfall or irrigation is retained for a short time near to the soil surface and might be used the next day. When a significant SMD exists and there is substantial rainfall, moisture is retained near the soil. The soil remains moist near the ground surface and crops continue to revive for several days after significant rainfall.

- ***Recharge***

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 of that required bringing the soil to FC.

Estimating Recharge using Water Table Fluctuation Method (WTF)

Healy and Cook (2002) stated that the water table fluctuation method may be the most widely used technique for recharge estimation in unconfined aquifers. The WTF approach is applicable to unconfined aquifers where WTF are caused solely by variations in net recharge or groundwater drainage. It is assumed that recharge over a period of interest is equal to the increase in water table elevation, after accounting for the groundwater recession that would have occurred during this period, multiplied by the specific yield. This is illustrated as follows:

$$R(t_j) = S_y \times \Delta H(t_j) \qquad (11)$$

in which

t_j -Time taken to reach the peak water table

$R(t_j)$ - Recharge occurring between times t_o (initial time) and t_j .

Sy - Specific yield and

$\Delta H(t_j)$ - The water table rise attributed to recharge .

$\Delta H(t_j)$ is estimated as the difference between the peak of a water level rise and the value of the extrapolated antecedent recession curve at the time of the peak. This recession curve is the trace that the well hydrograph would have followed if there had not been any precipitation. Predicting the recession curve is not always straightforward.

The data from the recovery phase of the single well pumping test was used to calculate specific yield of the aquifer by Slicnter recuperation method (Sirimanne and Vaidya, 1955). Specific yield of the limestone aquifer varied from 0.15 to 0.29 with the average value of 0.27 at Thirunelvely (Mikunthan and De Silva, 2009).

Results and Discussion

Soil Water Dynamics

Several parameter value combinations were considered while running HYDRUS-1D that varied from the soil hydraulic parameters, soil depth and root zone depth until the results of the HYDRUS-1D model simulations were similar to those of the MSMB and WTF methods. The following model out puts of HYDRUS-1D which had reasonable agreement were compared with the results obtained by MSMB and WTF methods and are explained in detail.

(i) Surface runoff
(ii) Soil Water Storage (SWS)/SMD
(iii) Bottom pressure head/ groundwater levels
(iv) Recharge

(i) Surface runoff

Surface runoff simulated by HYDRUS-1D was 35.7 cm for the year 2007 where the MSMB model gave 30.5 cm for the same period. When monthly values of runoff predicted by HYDRUS-1D were compared with those predicted by the MSMB model, there was a good agreement with R^2 = 0.91 (Figure 5) in 1:1 plot. Even the daily values of runoff showed good agreement, with R^2 = 0.8.

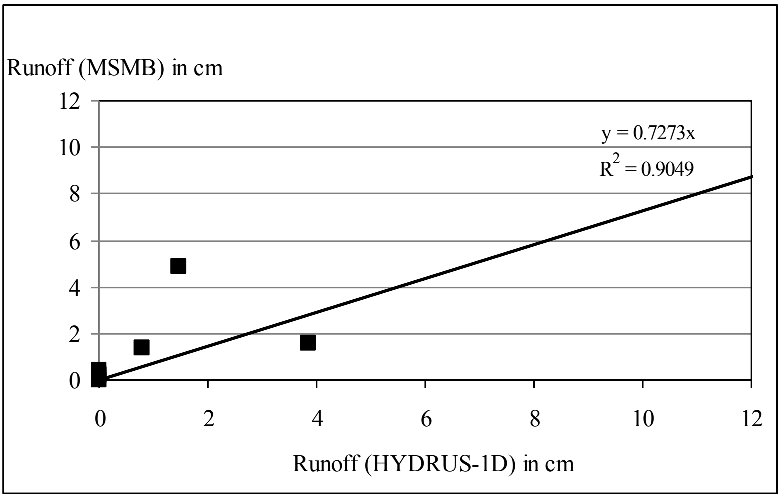

Figure 5. Relationship between the runoff simulated by HYDRUS 1D and MSMB models

(ii) SWS/SMD

SWS simulated by HYDRUS-1D and the SMD simulated by MSMB models are shown in Figure 6. Even though the approach used in the two models is fundamentally different, the model predictions follow a very similar pattern. The effect of differences in the initial conditions can be seen at the start of the year, but has decays rapidly so that by around mid-year the effect is no longer detectable. The linear correlation is good, with R^2= 0.88.

(iii) Bottom pressure head predicted by HYDRUS and groundwater levels observed in the field

Figure 7 shows the measured groundwater level fluctuation in the study area for a period of 2 years and 4 months from January 2007. Groundwater levels showed a cyclic seasonal variation during the years. Groundwater levels are deep in the study area varying from 7 to 10 m. Generally the groundwater recharge takes place from October to December/ January with wet season rains from early October. During this period the groundwater levels rise by up to 1.5 m to 2.0 m depending on the location. During the dry period from January to October the groundwater levels fall by about 0.5 m to 0.75 m due to the fact that there are surface storage tanks and other surface water sources around the study area to maintain this drop. Year 2007 was a normal year with an annual rainfall of 1291 mm compared with other years, for example 2008, where the rainfall was higher than the average. The mean annual rainfall in the Jaffna Peninsula is approximately 1255 mm (Rajasooriyar *et al.*, 2002). In the years 2008 and 2009 the annual rainfall was higher than in 2007. During 2008 and 2009 there was a considerable amount of rainfall during April/May due to first inter-monsoon rainfall and it was possible that a small percentage of recharge to take place during that period (Figure 7).

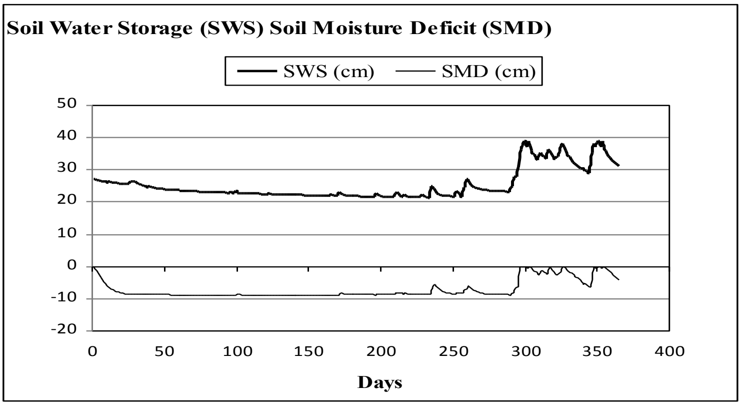

Figure 6. HYDRUS-1D simulated SWS and MSMB model Simulated SMD

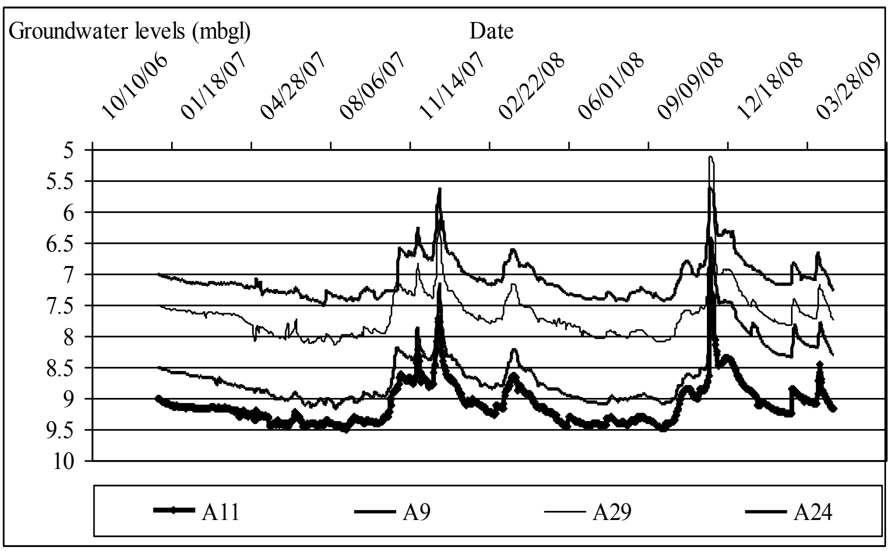

Figure 7. Observed WTF measured in meter below ground level in selected 4 wells in the study area

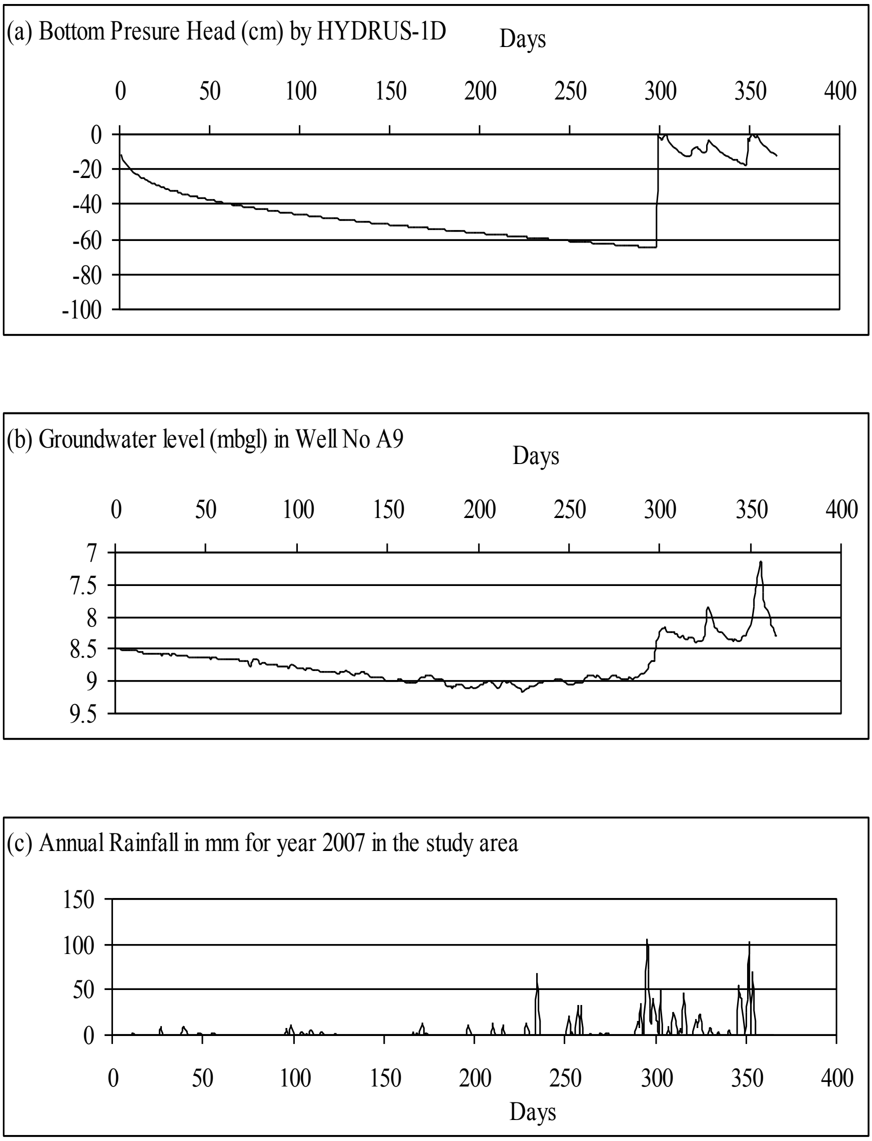

Figure 8. (a) HYDRUS-1D predicted bottom pressure head (cm) (b) WTF in Well no 9 (mbgl) (c) Rainfall in the study area

Figure 8(a) and (b) shows that the simulated bottom pressure head variation at 1 m depth soil using HYDRUS-1D closely agrees with the observed groundwater levels variation in the field at 8-9 m below ground level with a good coefficient of determination (R^2=0.83). The groundwater level drop of 0.50 - 0.75 m from January to October closely agreed with the simulated pressure head drop. Further, the groundwater levels started to rise with wet season rains from mid October 2007 (Figure 8 c) and HYDRUS-1D too predicted the rise on during the same period.

(iv) Recharge

In HYDRUS-1D, when the SWS is the maximum and no more water can be stored in the root zone, drainage will occur to the groundwater (bottom flux). The HYDRUS-1D simulated potential groundwater recharge was 41.8 cm per year. This is 30-35 percent of the annual rainfall, in agreement with the estimates of Rajasooriyar *et al.* (2002) for the study area. The recharge calculated by the WTF method based on measured groundwater levels was 29.8 cm. But the MSMB model estimated recharge was 35.0 mm (Mikunthan and De Silva, 2009). However, as shown in Figure 9, the HYDRUS-1D results have a higher coefficient of determination (R^2 = 0.95) with the WTF method results than they do with the MSMB model results in (R^2 = 0.91) in 1:1 plots.

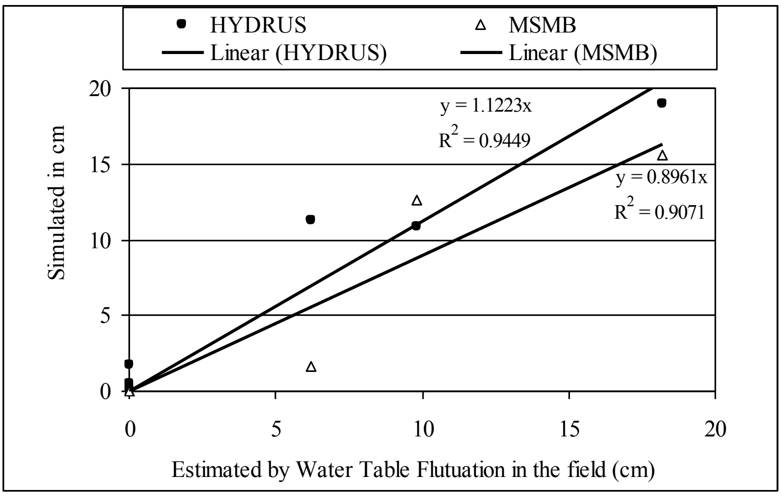

Figure 9. Relationship between the recharge estimated by the water table fluctuation method and that simulated with the HYDRUS-1D and MSMB models

In the HYDRUS-1D simulation root zone of 1 m is only considered. Similarly in the MSMB also the soil moisture balance is carried out only for the 1 m root zone. Recharge estimated with MSMB and that simulated using HYDRUS-1D for the same study conditions are more or less same with certain percentage of error. But when compared with measured groundwater fluctuation at the depth of 7-8 m in the study areas HYDRUS-1D seems to overestimated the recharge which could be justified as HYDRUS-1D deals with only 1 m root zone.

Overall, good agreement was achieved between recharge calculated using field measurements on groundwater fluctuations, estimated by MSMB and HYDRUS-1D predictions. Compared with the methods available for recharge calculation, HYDRUS-1D the numerical simulation is a far more convenient and cost effective approach.

Sensitivity Assessment

The root zone modelling methodology adopted in HYDRUS-1D is crucial for calculating recharge in arid and semi-arid regions where evapotranspiration may drop below potential rates. Several potential sources of uncertainty exist, however, in the vadose zone modelling approach used in this study. Possible sources of uncertainty include the values of several model parameters needed to run HYDRUS-1D, including soil hydraulic parameters, crop coefficient and drought stress parameters in the uptake model of Feddes *et al.* (1978). However, to minimise the error, sensitivity analysis was done with several model parameters. The simulations showed that the most important parameters for groundwater recharge were the soil hydraulic parameters. Amongst the soil hydraulic parameters (n, θ_s, K_s, α and θ_r) residual water content was found to be the least sensitive, which agrees with Jimenez-Martinez *et al.* (2009). Compared with the other parameters, K_s was the most sensitive: for example, an increase or decrease by 50% causes ±15-20% in recharge rates. Lower values of K_s, such as might be the case for finer textured soils, leads to a lower recharge rate due to more runoff. However, the accurate characterization of the prediction uncertainty is problematic because of a lack of knowledge about parameter variability and parameter correlation structure.

Limitations of Recharge Estimation Methods

The MSMB used in this study is a simple spreadsheet model which has less flexibility. For the MSMB, the main limitation is that it relies on the subtraction of large quantities (ET and P) to estimate a small quantity (recharge). The uncertainty associated to estimate thus greatly depends on the relative magnitude of these inputs. The availability of a data set covering a longer period would also have helped to reduce uncertainty in recharge estimates. The other source of error identified relates to the estimation of MSMB inputs in this study for which measured data were unavailable due to the situation prevailed in the study area. Therefore extra time and funds were used to check the validity of the data to make it reliable and relevant before using for this study. Evapotranspiration was estimated with a recognized method for which measured inputs (e.g. wind, relative humidity) were available. However, run-off, which was approximated with a constant coefficient, could represent a significant source of error. Reliable and complete run-off data sets for a few gauging stations would ideally be required in order to obtain more accurate run-off estimates. Therefore using MSMB for recharge estimation is a tedious and an expensive process.

Data collection and monitoring groundwater levels are expensive and difficult to manage in developing countries especially in the areas such as the study area in this paper where research or any sort of continuous monitoring of groundwater levels has not been taken place except isolated studies for the last 30 years due to the ethnic conflict. The WTF method needs continuous monitoring of groundwater levels which was not available in the study area and the continuous monitoring of groundwater levels is expensive. Therefore in this study groundwater levels were monitored in the wells in the study area carefully using a trained person as installing piezo meters will cause additional financial burden for the research study.

Further, there were no estimated specific yield values for the area study area as the recharge was calculated by multiplying the rise and fall of groundwater levels by specific yield. Therefore pumping tests were conducted and the specific yield value was estimated. Therefore depending on WTF method for recharge estimation is also fairly expensive and a tedious procedure.

This study has shown that HYDRUS-1D which is a numerical model is having good agreement with MSMB and WTF method even though these methods are different in its principles. Therefore HYDRUS-1D is fairly reliable method to use for recharge estimation instead of MSMB and WTF methods with an additional advantage of having solute transport facility.

Conclusions

In the dry zone of Sri Lanka, accurate knowledge of groundwater recharge is important for sustainable water resources management. In this study groundwater recharge was simulated with HYDRUS-1D using root zone modelling approach with rainfall, evapotranspiration and soil moisture dynamics for grass with cabbage from mid March till late May for the year 2007 in the Jaffna Peninsula, northern Sri Lanka. HYDRUS-1D was found to be a very useful tool for simulating potential groundwater recharge when actual field data are limited. Good agreement on potential groundwater recharge was achieved between HYDRUS-1D simulations, MSMB results and estimates using WTF method based on the field observed groundwater levels. HYDRUS-1D produced 41.8 cm of recharge whereas as the previously used MSMB estimated 35.0 cm. Recharge calculated using WTF method in this study is 29.8 cm. Even though HYDRUS-1D seems to overestimate it may not be the case as the HYDRUS-1D simulate 1 m root zone and the coefficient of determination (R^2) between measured and predicted groundwater recharge for individual events was 0.95 for the water level fluctuation method and 0.91 for that with MSMB.

Further, HYDRUS-1D is used for solute transport, for example in predicting groundwater pollution due to nitrogen fertilizer application which cannot be achieved by MSMB model (De Silva and Tellam, 2011). Now that it has been demonstrated that HYDRUS-1D adequately reproduces the water fluxes predicted by other methods, it can be used with more confidence to investigate groundwater recharge and pollution issues.

Acknowledgements

Author acknowledges the Commonwealth Scholarship Commission, UK for offering academic commonwealth fellowship to carry out this research from 15th January 2011 at the Department of Earth Sciences, School of Geography, Earth and Environmental Sciences, University of Birmingham, UK. Author also acknowledges the assistance given by Prof. John Tellam and Dr Mark Cuthbert of University of Birmingham, UK on analysing the data using HYDRUS-1D and by Dr Thushyanthi Mikunthan of University of Jaffna, Sri Lanka for providing necessary data for this study.

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