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A simple soil water balance model to estimate groundwater recharge in the dry zone of Sri Lanka

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ABSTRACT

Estimating the rate of recharge is essential in developing the ground water resource. The soil water balance of the root zone is a simple method of estimating recharge. This paper analyses the important components of a soil water balance and determines the essential components of the water balance equation for the dry zone of Sri Lanka to estimate recharge. From the data presented in this paper it is shown that the processes of rainfall interception, surface runoff and preferential flow are all important processes in the hydrological cycle for the dry zone. A simple model thus formed is verified with data from studies in the dry zone of Sri Lanka as well as from other parts of the world.

Key words: Dry zone, groundwater recharge, soil water balance method, Sri Lanka.

INTRODUCTION

Unlike the wet and intermediate zones (Fig. 1), the dry zone of Sri Lanka is faced with a severe shortage of water for domestic, agricultural, industrial and other uses, during the dry months of the year. The construction of tube wells (150-200 mm diameter) and agrowells (3-5 m diameter) have resulted in meeting this shortage to some extent. As an example it is reported that the income of a particular farmer increased ten fold on irrigating from agrowells because it enabled successful cultivation of crops both in the *Maha* (October - January) and *Yala* (April - August) seasons.

The development of both types of wells however, has been done in a haphazard manner without a proper assessment of the hydro-geological potential, particularly the yield and siting of wells. As a result a permanent drop in the water table is noted in several areas of the dry zone of Sri Lanka (Premanath and Liyanapatabendi 1994).

Lowering of the water table has disastrous consequences like, (a) uneconomical pumping depths often resulting in failure of crops, (b) deterioration of the quality of groundwater (especially if near the coast as intrusion of salt water will occur) making the groundwater unfit (often toxic) to drink and also not suitable for irrigation, (c) ground subsidence as lowering the groundwater table by one meter adds one more metric ton of load per square meter to the sub soil and (d) changes in local ecology resulting in changes in fauna and flora.

Therefore, it is important to assess the safe yield that can be extracted from an aquifer (to prevent a significant drop of the groundwater level and thereby to prevent the development of any of the above situations), prior to developing the groundwater resource of the aquifer.

In the assessment of the safe yield of an aquifer, the most important parameter is the rate of replenishment of the water table or recharge. This parameter actually determines the amount of groundwater that can be extracted without causing a permanent drop in the groundwater level.

Methods of estimating recharge can be broadly grouped into physical and chemical methods. Physical methods include the use of lysimeters, soil water balance models, water table fluctuation method, catchment water balance method, numerical modelling of the unsaturated zone, zero flux plane method and Darcy's method. Chemical methods are tritium method and chloride method (de Silva 1996; de Silva 1998). Of these methods, the soil water balance method is a useful method of estimating recharge and is quite often the only method that can be used under many climatic conditions (de Silva 1996; de Silva 1998).

This paper reviews the use of soil water balance method to estimate recharge in different parts of the world and after carefully considering the essential components of the water balance equation, develops a simple soil water balance model to estimate recharge in the dry zone of Sri Lanka.

MATERIALS AND METHODS

Soil water balance method

In a soil water balance, recharge is estimated using a volume balance for the water entering and leaving the root zone after considering the change in soil moisture storage. If the balance is carried out annually (especially from the end of rainy season to the same time the following year), the change in soil moisture storage is negligible. Therefore, the water balance of the root zone can be written as;

$$R_e = P - I - RO - ETa \ldots\ldots\ldots\ldots\ldots(1)$$

where R_e is deep percolation below the root zone (recharge), P is precipitation, I is interception of rainfall by vegetation, RO is run off (or overland flow) and ETa is actual evapotranspiration.

The basis for almost all soil water balance models is equation 1, however, the differences result from the way variables I, RO and ETa are estimated.

In equation 1, the importance of preferential flow is not immediately clear as there is no such term in it. However, the same equation can be written as in equation 2, where the first term within brackets is the matrix flow (MF) and the second term within brackets is the preferential flow (PF) meaning the flow through cracks and fissures in the soil profile by-passing the soil matrix.

$$R_e = (P - I - RO - PF - ETa) + (PF) \ldots(2)$$

Now, the estimation of actual evapotranspiration is affected by matrix flow, which in turn is affected by the amount of preferential flow. Therefore, estimates of recharge (which are affected by estimates of actual evapotranspiration), are affected as a result of preferential flow (i.e., for estimates of recharge to be affected by preferential flow, it is not necessary for preferential flow paths to be effective for deeper depths, but depths just around root zone are sufficient).

Instances of using a soil water balance to estimate recharge in literature are summarised in Table 1. It appears (Table 1) that in most of the cases, recharge had been estimated by ignoring some components of the water balance (e.g., interception) without reasonable justification. Furthermore, model parameter values (e.g., root constant) and sub-models for actual evapotranspiration used in UK have been used in entirely different climates (Uganda and Sri Lanka) without an appropriate justification.

Study locations

Fig.1 shows the study locations in the Sri Lanka dry zone where rainfall, potential evapotranspiration data are used in conjunction with soil and vegetation properties of each area to determine important information on interception of rainfall, runoff and preferential flow. Details of climate, soils and vegetation of each site are given in Table 2.

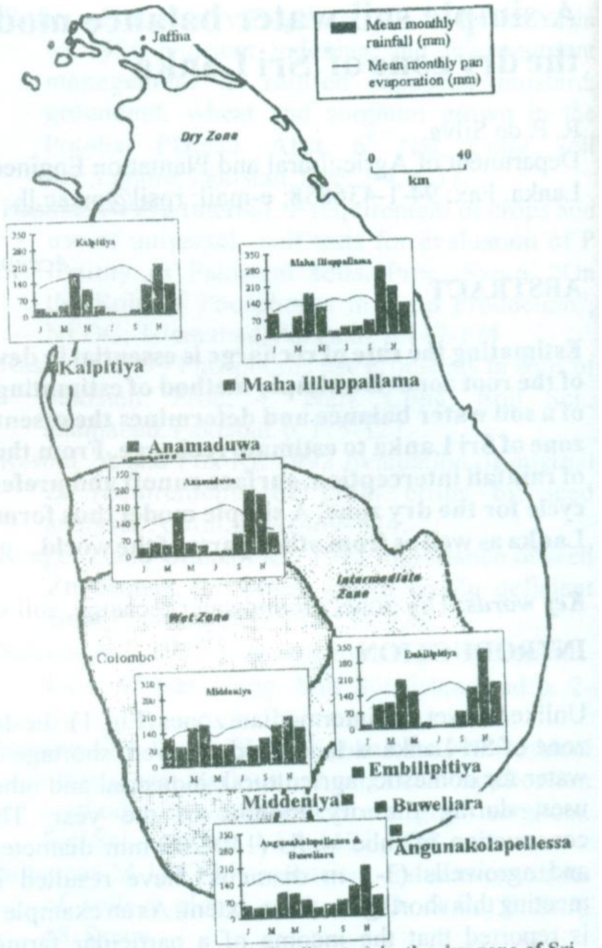

Fig. 1. Study locations (and their climates) in the dry zone of Sri Lanka (wet intermediate and dry zone of Sri Lanka are also shown)

RESULTS

Essential components of a soil water balance

Rainfall and actual evapotranspiration are important variables in a soil water balance in any part of the world. However, the importance of interception, runoff and preferential flow can vary depending on the location. Therefore, it is necessary to consider the importance of these components of soil water before formulating a balance to estimate recharge.

Interception

Interception of rainfall is likely to be high in the dry zone for the following reasons.

(a) The vegetation of the dry zone of Sri Lanka is described as a "2 storey" vegetation (Fernando

Table 1. Some published instances of the use of soil water balance model to estimate recharge at different locations of the world.

Case no.	Country & Location	Mean annual rain (mm y^{-1})	Mean annual Pan Evep. (mm y^{-1})	Vegetation	Soils	inter-ception	Runoff	Pref. flow	actual	root evapotran-spiration	ΔS constant	Recharge	Source
1	Jordan, North east	100-550	1700	Grass Crop and Trees	Clayey,	-	4.8 % of rain	-	root constant approach	65%-92% of AWC	ignored	0-2-% of rain	Loyd *et al.* (1996)
2	Uganda, South east	750-1000	1450	Scrub and Wooded Savanna	Loamy	-	1 % of rain	-	root constant approach	55%-80% ofo AWC	ignored	30 mm y^{-1}	Howard and' Karundu (1992)
3	Sri Lanka, Mannar	975	1800	Palm trees and shrubs	Sandy	-	-	-	root constant approach	50 to 150 mm	ignored	121 mm y^{-1}	Senarath (1990)
4	UK	762	533	Shallow Rooted and Deep rooted	-	-	-	-	root constant approach	76 and 200 mm	ignored	337 mm y^{-1}	Headworth' (1970)
5	UK Bedford and Cambridge	550-640	526	Woods, Cereals, Crops, Grass, Fallow, Urban and riparian	Areas of clay and squifer outcrop	-	None in squifer outcrop areas, Coefficient in clay areas	-	root constant approach	50%-100% of AWC	ignored	94-183 mm y^{-1} in outcrop areas, 35 mm y^{-1} in clay areas	Monkhouse (1974)
6	UK, North Lincolnshire	663	523	-	-	-	1.5% of rain	Thresh old and Coefficient	root constant approach	66%-76% of AWC	ignored	243 mm y^{-1}	Rushion and Ward (1979)

Note ; A hyphen is shown where the comphonents appear not to have been considered or where the relevent information is not reported.

Table 2 Details of study location of Sri Lanka.

Location	No. of holes augured	Mean annual rain [1] (mm y^{-1})	Mean annual pan evaporation (mm y^{-1})	Vegetation	Major plant type	Top soil
Embilipitiya	8	1397	1729[2]	Shrub jungle	Maana (Grass about 30 cm tall)	Loamy sand
Middeniya	16	1484	1729[2]	Mango and Teak Plantation	Eluk (Grass about 30 cm tall)	Sandy loam
Buweliara[3]	12	1041	1868	Shrub jungle	-	Sandy Clay Loam
Angunukola-pellassa	12	1041	1868	Shrub jungle	Eraminiya (Bush about 1.5 m tall)	Sandy Clay Loam
Maha illuppallama	8	1305	1579	Jungle	-	Loamy Sand
Anamaduwa	1	1117	1958	Jungle	-	Sandy Loam
Kalpitiya	5	955	1958	Sparse	Bolpana (Tree about 3 m tall)	

[1] 6 year mean value except for Angunukolapellassa and Buweliara where the mean values are 17 year ones.

[2] Pan eveporation values are from the climate station at Sevanagala (i.e., the nearest agro-climate station)

[3] Since no rainfall or pan eveporation data are available for Buweliara, data from the nearest climate station (Angunukolapellassa) is used for Buweliara.

[4] Pan eveporation values are from climate station at Vanathavillu(i.e., the nearesst station where eveporation daata is available).

1967) consisting of taller trees and shorter bushes and a layer of leaf litter on the ground, effectively forming 3 different stages for rain interception.

(b) As Herwitz (1985) points out there are usually more than 100 species per ha in a tropical forest. Therefore, the vegetation is "well graded" (like a well graded soil having low porosity) and would tend to intercept more rain.

(c) Trees in tropical forests have large trunks and branches and therefore large surface areas. The bark of trees can intercept significant amounts of rain water (Herwitz 1985).

(d) Rainfall tends to be of high intensity and short duration, allowing sufficient time for leaves and bark to dry thus intercepting a significant amount of rain from each rainfall event.

Therefore, it is evident that interception of rainfall must be included in a soil water balance in the dry zone of Sri Lanka.

Runoff

The following factors need consideration in deciding the importance of runoff.

(a) The soil surface in the dry zone is generally hard which could be the result of drying out of the sealed layer formed during heavy rains where

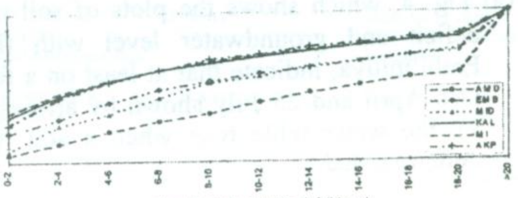

Fig.. 2. Cumulative frequency distribution of rainfall at 7 locations in the dry zone of Sri Lanka (Source: de Silva 1996).

finer soil particles are washed into the cavities between coarse particles (Brady and Weil, 1996)

(b) High rainfall intensities, as seen from Fig. 2, where more than 60% of the rain at all locations range between 2 mm d^{-1} and 20 mm d^{-1}. It is likely that a 2 mm and a 20 mm rain would have durations of about 2 and 30 minutes respectively in the dry zone and therefore, it is possible that more than 60% of the rains have intensities between 2 mm/ 2 minutes = 60 mm h^{-1} and 20 mm/30 minutes = 40 mm h^{-1}.

(c) Low infiltration capacities of soil compared to rain intensities (Fig. 3), where more than 85% of infiltration capacity values are less than 4 cm h^{-1}.

(d) Flow in streams in the dry zone is significantly higher during rainy days than in other days, suggesting higher surface runoff than base flow. In fact most of these streams dry up soon after rains.

(e) A high portion [37.5%, Arumugum (1969)] of mean annual rain flows in rivers to the sea in the dry zone. This figure comprises both base flow and runoff, but, from item (d) above, it is seen that runoff is the major component. Therefore, it is concluded that runoff is likely to form an important component of the water balance in the dry zone of Sri Lanka.

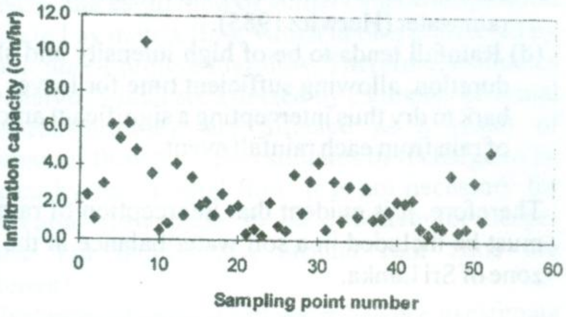

Fig. 3. Infiltration capacity of surface soils at all the locations (Source; de Silva 1996)

Preferential flow

The following factors suggest that preferential flow at least in the shallower depths is likely.

(a) Fig. 4, which shows the plots of soil moisture deficit and groundwater level with time for Embilipitiya, indicate that at least on a few days (2-6 April and 25 July shown by arrows in Fig. 4), the water table rose when a soil moisture deficit existed.

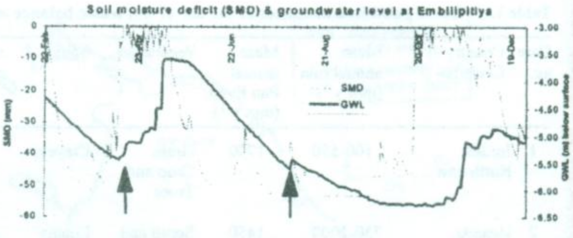

Fig. 4. Groundwater level at Embiilipitiya with soil moisture deficit in 1995 (after de Silva 1996).

The possibility of rainwater infiltrating along the casing of the piezometer to cause an apparent water table rise soon after a rainfall event was avoided by carefully refilling it and a depth of about 0.5 m from the surface was filled with impermeable clay (and also the surface covered with cement mortar). It is unlikely that any preferential flow paths were present along the outside of the casing causing a water table rise during periods where a soil moisture deficit existed. It is also possible to have a rise in water table due to other reasons like water well recovery after pumping and regional groundwater flow. However, for the period concerned, there was no pumping and the water levels from other piezometers suggest that the water table was flat and therefore, it is likely that the water level rise when a soil moisture deficit existed was caused by preferential flow (de Silva 1996).

(b) The soils found in the dry zone are more clayey than sandy and structured clayey soils are more likely to have preferential flow, through cracks which often remain open even when wetted.

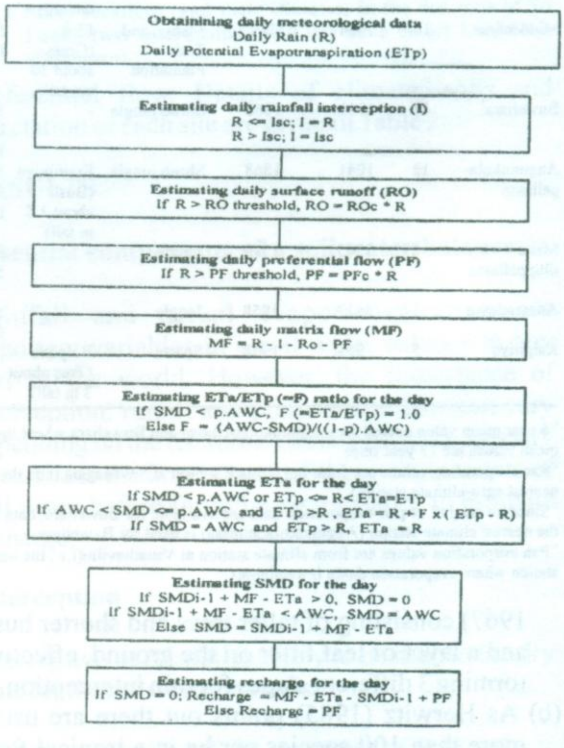

Fig. 5. Flow chart of the soil water balance model suitable for the dry zone of Sri Lanka.

(c) Some of the values of infiltration rates (Fig. 3) are rather high for the textures encountered, which may be due to the presence of preferential flow paths.

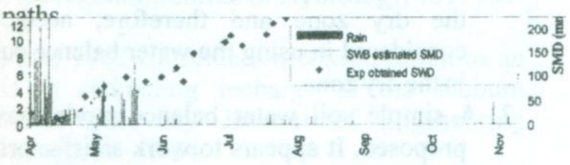

Fig. 6. Experimental soil moisture deficit and soil water balance model estimated soil moisture deficit

It must be noted here that, for preferential flow to be important (from the point of view of a soil water balance), it is not necessary for these paths to be deep, as the amount of water by passing the soil matrix, even though small, may affect actual evapotranspiration, and hence recharge.

Therefore, it is concluded that all the three processes of interception, runoff and preferential flow need to be considered in a soil water balance in estimating recharge in the dry zone of Sri Lanka.

A soil water balance model suitable for estimating groundwater recharge in the dry zone of Sri Lanka

Having identified the essential components, a simple soil water balance model is formulated in this section.

A review of models for estimating interception is given in de Silva (1996). However, in the absence of necessary parameters for the complicated models the simple model in equation 3 is used to estimate interception (I).

$$R \leq I_{sc}; I = R \qquad \text{.....................(3)}$$
$$R > I_{sc}; I = I_{sc}$$

Here I_{sc} is the interception storage capacity value, usually ranging from about 0.5 to 11.0 mm (de Silva, 1996) and R is daily rainfall. A review of models for estimating runoff and preferential flow is also given in de Silva (1996). Here again, in the absence of

$$RO = RO_c (R - RO_t)\text{.................}(4)$$

$$PF = PF_c (R - PF_t)\text{...................}(5)$$

in equations 4 and 5 are chosen to estimate these variables respectively.

RO_c and PF_c are dimensionless coefficients and RO_t and PF_t are threshold values of daily rainfall above which runoff and preferential flow are assumed to occur.

Therefore, considering the above sub models for interception, runoff and preferential flow, the flow chart for a soil water balance model suitable to estimate recharge in the dry zone is shown in Fig. 5. To estimate actual evapotranspiration, the approach used by Doorenbos and Kassam (1979) is used. A detailed discussion on estimating actual evapotranspiration for the Sri Lankan dry zone is found in de Silva (1996).

Constructing and validating the soil water balance model

The soil water balance model shown as a flow chart in Fig. 5, was programmed on a computer spreadsheet to estimate daily recharge for any number of years (depending on computer memory available).

To check the performance of the model, results of studies reported for Silsoe in UK, Ngwazi Tea Research Unit in Tanzania and for Nguru in Nigeria, data and estimates/experimentally obtained values of recharge and/or soil moisture contents are shown in Table 3.

Table 3. Data and estimates/measurements of recharge/soil moisture contents available.

Location	Mean annual precipitation mm y^{-1}	Mean annual pan evap. mm y^{-1}	Available estimate and method this estimate was obtained	Source	Soil water balance model estimate	Time steps and Duration of SWB
Ngwazi	630	1397	Soil moisture deficit (see fig.6) from field measurement (on 15 Nov. the SMD measured was 338 mm)	de Silva (1991)	See fig.6 (on 15 Nov. the SMD predicated was 335 mm)	Daily for 365 days (1 Apr 89 - 1 Dec. 89, both days inclusive)
Ngura	463	2090	Recharge, 30-60 mm y^{-1} from groundwater flow modelling and chloride method	Carter (1994) and Carter (1996) Personal communication	29 mm y^{-1}	Daily for 11 years (1965-1975, both years inclusive)
Silsoe	560	721	Recharge 94-184 mm y^{-1} from a SWB and recharge 168 mm y^{-1} from chloride method	Monkhouse (1974) Irving (1982)	121 mm y^{-1}	Daily for 30 years (1962-1991, both years inclusive

[In the SWB model, 5%, 0% and 5% (of annual precipitation) for annual interception, runoff and preferential flow for Ngwazi were used. for Silsoe and Nguru these value were 5%, 0% and 5% and 0% respectively. The critical deficit was considered as 0.5AWC]

Table 4. **Comparison of estimates of recharge for different locations in Sri Lanka by different workers and by the SWB model developed**

Location	Mean annual precipitation mm y-1	Mean annual pan evap. mm y-1	Estimate of recharge in mm y-1 (and the method used)	Source	Estimate of recharge with the model developed in this paper mmy^{-1}
Mannr	975	1830	121 (soil water balance model)	Senerath (1990)	104-147
Nikaweratiya	875	1958	173 (Tritium profiling)	Dharmasiri & Dharmawardena (1980)	150-221
Maha Illuppallama	1200	1579	170 (Tritium profiling)	Dharmasiri & Dharmawardena (1980)	146-188
Middeniya	1225	1484	220 (Tritium profiling)	Dharmasiri & Dharmawardena (1980)	201-236
Uda Walawe	1084	1484	90 (Tritium profiling)	Dharmasiri & Dharmawardena (1980)	93-131

Note: A range for the recharge estimates by the model developed in this paper is obtained because precise information on the process of interception, runoff and preferential flow are not available for the dry zone.

As can be seen from Table 3, recharge estimates for Silsoe and Nguru obtained by soil water balance are comparable with those obtained by different workers (with different methods). Fig. 6 shows the experimentally obtained soil moisture deficit [obtained by measuring the volumetric soil moisture content with a neutron probe at every 200 mm in the whole 5 m of the root zone and by knowing the field capacity values for each soil type in the profile (de Silva, 1991)] and the soil water balance model calculated soil moisture deficit and it is seen that agreement between the two are excellent.

Table 4 summarises the validation of the model for the dry zone of Sri Lanka. As seen from Table 4, the model estimated recharge compare well with those obtained by different workers at different locations in the dry zone of Sri Lanka.

CONCLUSIONS

This paper presents a simple, easy to use soil water balance model which can be used in estimating groundwater recharge in the dry zone of Sri Lanka. The model has been validated with results from a few locations in the dry zone of Sri Lanka and also with the available information from different parts of the world.

The conclusions can be summarised as follows.

1. In applying the soil water balance to estimate recharge, interception of rainfall by vegetation, preferential flow and changes in soil moisture storage (i.e., components in the soil water balance equation) appear not to have been considered adequately. Unless this can be proved beyond reasonable doubt, all these processes need to be considered in using the soil water balance equation.
2. Runoff, interception and preferential flow are essential components of a soil water balance in the dry zone and therefore, need to be considered in using the water balance equation in the dry zone.
3. A simple soil water balance model has been proposed. It appears to work satisfactorily and therefore, can be used in estimating recharge in the dry zone. Further, to obtain realistic estimates of recharge, more precise information on the processes of runoff, interception and preferential flow may be needed.

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