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The effect of using different time steps in a soil water balance model to estimate groundwater recharge in the dry zone of Sri Lanka

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Abstract

Importance of groundwater as a natural, renewable resource is well documented. The rate of replenishment of water table (or rate of groundwater recharge) is a key issue central to sustainable development of this valuable resource. Although many workers have used a soil water balance to estimate groundwater recharge, not many workers have investigated the effect of using different time steps (i.e. a day, 7 days etc) in the water balance on the estimates of recharge. This study looks at the effect of using weekly, 10 daily and monthly time steps in a soil water balance to estimate recharge in the dry zone of Sri Lanka. The findings suggest that the larger the time step, the lower the recharge estimate as found in a different study in Grimsby in UK (Howard and Lloyd, 1979). Combining the results of documented studies and the current study, it is shown that wherever possible, a daily time step needs to be used in a soil water balance and if daily evapotranspiration data is not available, the available data may be evenly distributed (e.g. say weekly data divided by 7) and used as daily data in order to arrive at reasonable estimates of recharge together with actual daily rainfall data, which are likely to be available in most parts of the world.

Key words: groundwater recharge, soil water balance, Sri Lanka

Introduction

Groundwater recharge, defined as the rate at which the water table below the ground level is replenished (usually measured as mm/year), is one of the most important parameters required in the development of the groundwater resource. As Scanlon et al (2002) point out, this parameter is important not only in global water budgets and proper management of the groundwater resource, but also in locating contamination of groundwater and identifying sites for wastes; especially nuclear waste where temporal scales running into thousands of years are possible. However, in practice, most people including the decision makers have the notion that groundwater is available as an infinite resource and hence unfortunately, overlook the importance of knowing the rate of groundwater recharge, before commissioning expensive groundwater resource development projects. Abandoned tube wells in many parts of the Island, which cost large sums of money to install, bear ample testimony for this fact.

A number of methods are available for the estimation of recharge to an aquifer (Xu & Beekman, 2003; Simmers et al 1997; Rushton 2005). These methods of estimating recharge can be broadly grouped into physical and chemical methods (de Silva, 1996). Physical methods include (a) Lysimeters, (b) Soil Water Balance models, (c) Water table fluctuation method, (d) Catchment water balance method, (e) Numerical modelling of the unsaturated zone (f) Zero flux plane method and (g) Darcy method. Chemical methods are (h) Tritium method and (i) Chloride method. Xu and Beekman (2003) and Simmers et al (1997) give detailed descriptions of each method and need to be consulted for more information.

Out of the above methods, the soil water balance method is a simple method of estimating recharge in most conditions and quite often, is the only suitable method (de Silva, 1996; Lerner et al, 1990). In this method, a volume balance for the water entering and leaving the root zone and change in soil moisture storage of the upper soil profile is carried out and recharge (Re) is estimated as;

$$R_e = P - I - RO - ET_a \pm \Delta S \qquad \text{……………….(1)}$$

Where P is precipitation, I is interception of rainfall by vegetation, RO is run off, ETa is actual evapotranspiration and ΔS is 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 as during these times, the moisture contents of the soil in the root zone is likely to be at field capacity), the change in soil moisture storage is negligible. Therefore equation 1 reduces to;

$$R_e = P - I - RO - ET_a \text{ ………………(2)}$$

Thus knowing the parameters P, ETa, I and RO, the only unknown, Re may be estimated, which is the basis for any root zone, soil water balance. The differences result in the way parameters I, RO and ETa are determined as P is often available as raw data.

Thornhtwaite and Mather are credited as the first to use a soil water balance. However, they used it to estimate actual evapotranspiration rather than recharge. Many workers have since used this method to estimate recharge in many parts of the world like Taiwan (Lee and Yeh, 2008), Sri Lanka (Senerath, 1990; de Silva and Rushton, 2007), Nigeria (Eilers and Carter, 2007), USA (Dripps and Bradbury, 2007) Australia (Bari and Smettem, 2006) and Canada (Mccoy and Parkin, 2006).

Despite the wide usage of SWB method, questions such as the minimum length of time period (i.e. the difference between the starting and ending dates of the SWB) a SWB needs to be carried out or the optimum time step (i.e. daily, weekly, 10 daily etc) for a SWB required for acceptable results have not received much attention from many workers. From a study at

Silsoe, UK and at Angunakolapellessa in Sri Lanka, de Silva (2002) has demonstrated that it is difficult to come up with a minimum length of a time period suitable for a SWB. However, if the SWB is carried out for a wet, dry and average year, the results obtained were very close to that of an estimate from a very long term (30 years in the case of Silsoe) SWB.

Only Howard & Lloyd (1979) and de Silva (1999b) have carried out any work related to the optimum time step for a SWB though many have used the time step as one day (Beverly et al. 1999; Bari and Smettem, 2006; Carrera-Hernandez and Gaskin, 2008). From a study in Grimsby in northern Lincolnshire in UK, Howard & Lloyd (1979) found that if weekly data (i.e. a time step of 7 days) is used for both rainfall and evaporation, the recharge estimates on average are likely to be about 10% less than that would be obtained by daily data and if monthly data is used, resulting recharge values are about 25% less compared to recharge with daily data. In a study for the dry zone of Sri Lanka, de Silva (1999) demonstrated that weekly, 10 daily or even monthly evaporation data can be evenly distributed to form daily values and used together with actual daily rainfall data in a SWB to estimate recharge without significant difference with those obtained with actual daily values of input data.

Since the only study of using large time steps for both rainfall and ET data in a SWB is reported by Howard & Lloyd (1979) and also since this study has been carried out only for 3 years of data for one location in UK, a similar study for a different location with a larger data set was appropriate and therefore, this study was carried out to investigate the effect of using weekly, 10 daily or monthly rainfall and evaporation data (ie a time step of 7, 10 and 30 days respectively) in a soil water balance model to estimate recharge in the dry zone of Sri Lanka. It was also hoped that together with the results from the two studies mentioned above, it would be possible to enhance the knowledge on the question of optimum time step for a SWB in estimating groundwater recharge.

Methods and Materials

The study locations chosen in the dry zone, Angunakolapellessa (AKP), Embilipitiya (EMB), Maha Illuppallama (MI) and Kalpitiya (KAL) are shown in Fig. 1 along with the mean monthly rainfall distribution and mean monthly pan evaporation distribution for each location. The reasons for choosing these study locations were the availability of required climatic data and presence of different soil types and vegetation. Climatic, soil and vegetation details at the study locations and information on data collected are shown in Table 1.

Geologically, Angunakolapellessa, Embilipitiya and Maha Illuppallama are on crystalline hard rocks with a thick overburden of soils which range from loams to clays as shown in Table 1. In these areas groundwater accumulations are found in a deep (>30m) fracture zone where joints, cracks and fissures of the crystalline rocks are found and also occasionally in heavily metamorphosed marble and quartzite formations. In general the water holding capacity and transmissivity in these crystalline rocks are low and hence the groundwater potential is limited. Some groundwater accumulations are also found in the weathered rock zone and is termed the shallow regolith aquifer. At Kalpitiya the sandy soils overlie a Miocene limestone aquifer bearing significant amounts of groundwater (Panabokke and Perera, 2005: Cooray, 1984).

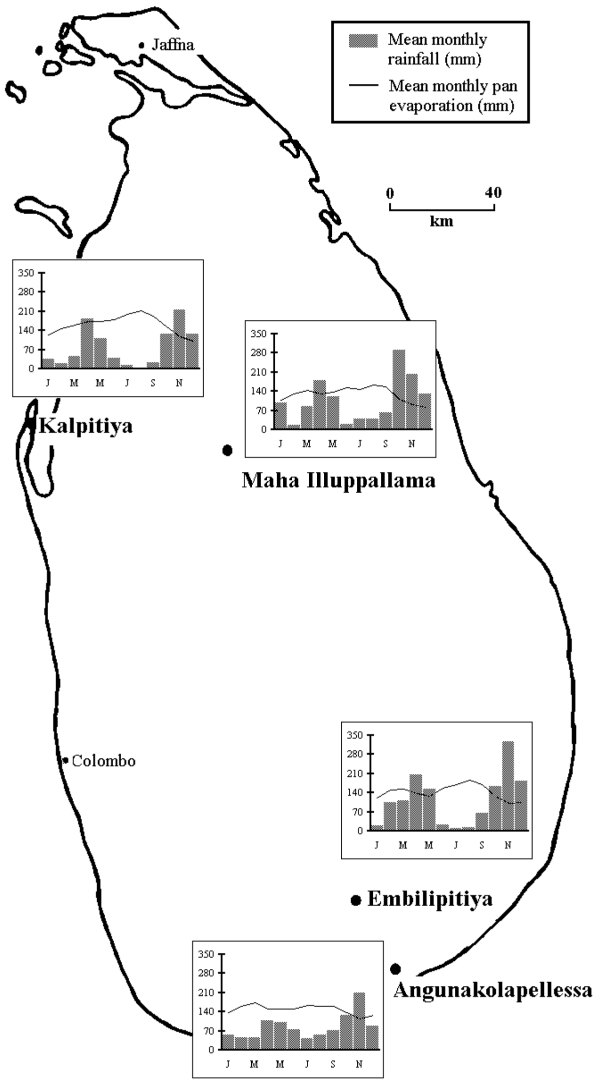

Fig. 1 - Study locations in the dry zone of Sri Lanka (Mean monthly rainfall and pan evaporation for each location is also shown).

Table 1 Details of study locations in the dry zone

Study Location	Embilipitiya	Angunakolapellessa	Maha Illuppallama	Kalpitiya
Mean Annual Rain[#] (mm/y)	1397	1041	1305	955
Mean Annual Pan Evaporation[1] (mm/y)	1729[$]	1868	1579	1958[*]
Vegetation	Shrub jungle	Shrub jungle	Jungle	Sparse Jungle
Major Plant type	*Maana* (Grass about 0.3 m tall)	*Eraminiya* (Bush about 1.5 m tall)	-	*Bolpana* (Tree about 3m tall)
No of sampling points in the site	8	12	12	5
Top soil	Loamy Sand	Sandy Clay Loam	Loamy Sand	Sand
Root zone depth (m)	0.69	0.95	1.17	1.5
Field Capacity (%)	21.4	20.2	20.9	14
Permanent Wilting Point (%)	15.7	12	11	4
Depth to water table (m)	>2.9	>4.1	>3.2	2.3
No of years daily rainfall data collected	6 (1989-1994)	17 (1976-1992)	6 (1986-1991)	6 (1970-1975)
No of years daily pan evaporation data collected	6 (1989-1994)	17 (1976-1992)	6 (1986-1991)	6 (1970-1975)

[#] 6 year mean value except for Angunakolapellessa where the mean value is the 17 year one.
[$] Pan evaporation values are from the climate station at Sevanagala (i.e., the nearest agro-climatic station).
[*] Pan evaporation values are from climate station at Vanathavillu (i.e., the nearest station where evaporation data is available).
[1] Pan evaporation values were converted to potential evapotranspiration values by multiplying with the relevant pan coefficient.

A suitable soil water balance (SWB) model was developed (Fig. 2) considering the important processes of the hydrological cycle in dry zone of Sri Lanka. In developing this model processes such as rainfall interception by vegetation, runoff and also preferential flow was taken into consideration as there is evidence (de Silva, 1999a) to suggest the importance of these processes in the dry zone hydrology. Most SWB models do not appear to consider the preferential flow (Ranatunga et al, 2008), but, as Rushton & Ward (1979) report, summer recharge takes place despite the presence of an obvious soil moisture deficit, which suggests flow by passing the soil matrix through preferential flow paths like cracks and worm and root channels in the soil. A detailed description of the model is given in de Silva (1996).

As can be seen from the flow chart in Fig. 2, parameters of rainfall interception storage capacity (Isc), Runoff threshold (ROt), runoff coefficient (ROc), Preferential flow threshold (PFt), Preferential flow coefficient (PFc) and root constant (RC) for a particular location are required for the SWB model. Table 2 shows the range of values of these parameters obtained by considering the vegetation, rainfall distribution and soil types at each location. A detailed explanation of obtaining these parameters for each location are given in de Silva (1996). Table

3 shows the values of these parameters used in this study (which are the mid points of the said ranges in Table 2).

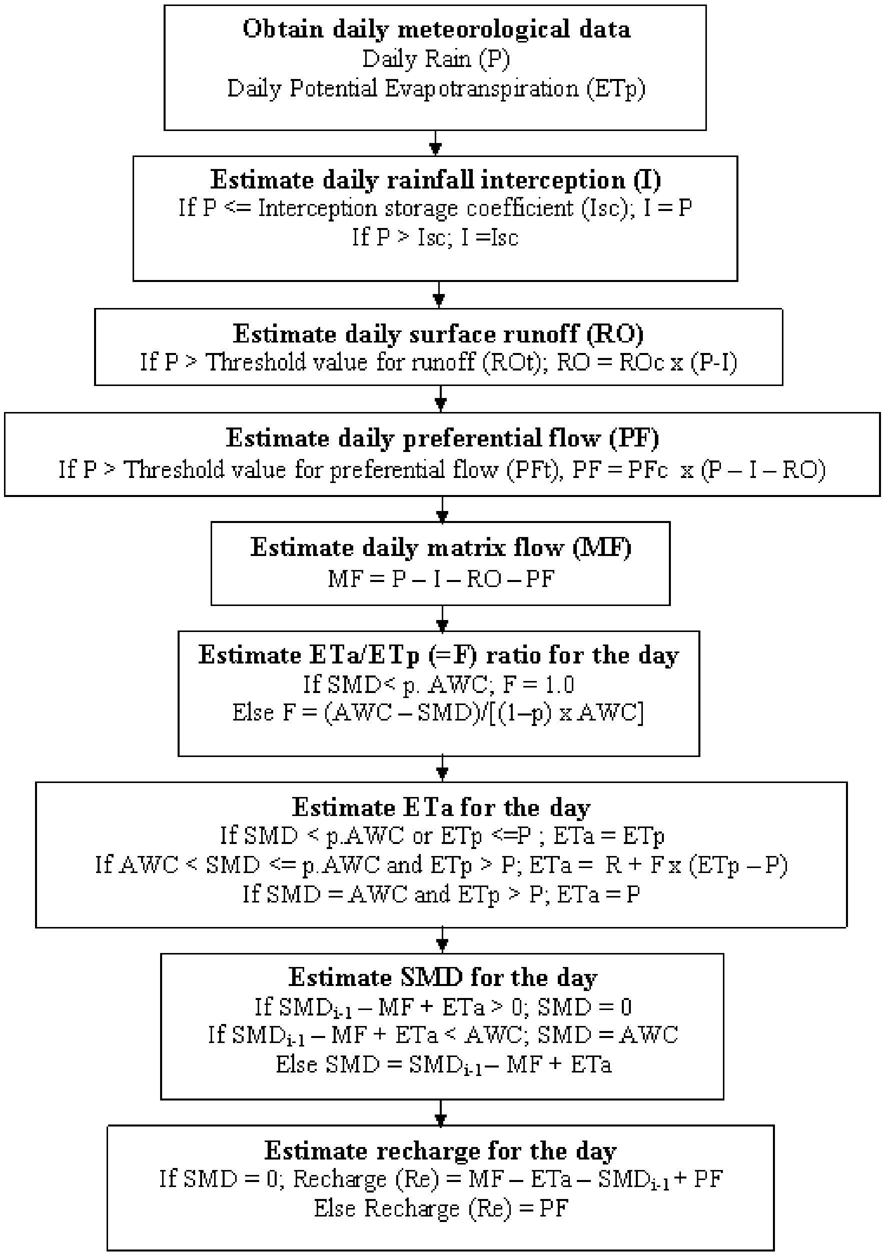

Fig. 2 Flow chart of the soil water balance model to estimate soil moisture deficit

To compare estimates of recharge with time steps of 1, 7, 10 and 30, the SWB was carried out for each study location 4 times, with time steps as 1, 7, 10 and 30 days. The parameters of Isc, ROt and PFt were multiplied respectively by 7, 10 and 30 when the SWB was carried out with a time step of 7, 10 and 30 days.

Table 2 Likely model parameters for different sites in Sri Lanka (de Silva, 1996)

Location	% daily Rain with amount > 8 mm/d	Soil	Vegetation	Topography	Likely Interception (% of rain)	Likely Runoff (% of rain)	Likely Pref. Flow (% of rain)	Isc (mm/d)	ROt (mm/d)	ROc	PFt (mm/d)	PFc
Embilipitiya	45%	Sandy Loam	Shrub jungle	Flat	10% - 15%	15% - 25%	1% - 10%	1.2 - 2.5	5 - 20	0.15 - 0.35	5 - 15	1% - 15%
Angunakolapellessa	30%	Sandy Clay Loam	Dense Shrub jungle	Flat-undulating	15%-20%	15%-30%	1% - 10%	1.2 - 2.0	5 - 20	0.15 - 0.5	5 - 15	1% - 15%
Maha Illuppallama	30%	Loamy Sand	jungle	Flat	15%-20%	15% - 25%	1% - 10%	1.5 - 2.5	5 - 20	0.15 - 0.4	5 - 15	1% - 15%
Kalpitiya	30%	Sand	Sparse Jungle	Flat	10%-15%	0%	1% - 10%	0.8 - 1.8	5 - 20	0.0	5 - 15	1% - 15%

Table 3 Rainfall interception storage capacity (Isc), Runoff threshold (ROc), runoff coefficient (ROc), Preferential flow threshold (PFt), and Preferential flow coefficient (PFc) for the study locations.

Location	Isc	ROt	ROc	PFt	PFc
Embilipitiya	1.8	12.5	0.25	10	0.075
Angunakolapellessa	1.6	12.5	0.32	10	0.075
Maha Illuppallama	2.0	12.5	0.27	10	0.075
Kalpitiya	1.2	15.0	0.00	10	0.075

Results

Estimates of recharge obtained for 4 locations with different time steps are shown in Table 4 below. The percentages in parentheses indicate the percentage difference of the particular estimate if compared with the recharge estimate using a daily time step (which is given in the top row of the table).

Table 4 – Estimates of recharge for different time steps at the 4 study locations

Time Step	**Estimate of recharge (mm/year) for location**			
	AKP	**EMB**	**MI**	**KAL**
Daily	70	331	192	179
Weekly	42 (40%)	236 (29%)	161 (16%)	115 (36%)
10 daily	45 (35%)	231 (30%)	140 (27%)	94 (47%)
Monthly	46 (33%)	203 (39%)	130 (32%)	60 (66%)

Fig. 3 shows the distribution of rain and recharge depending on the time step used for location Angunakolapellessa (AKP). Though not shown here, similar results were obtained for other 3 locations as well.

Concluding discussion

The SWB model developed was tested using experimental soil moisture data obtained for a tea plantation in Ngwazi in Tanzania (in the absence of any suitable data from the dry zone in Sri Lanka). Fig. 4 below shows the experimental soil moisture deficit (SMD) and the SWB model predicted SMD and as seen from Fig. 4 the two agree well, thus demonstrating that SWB model developed would yield reasonable results.

Also the estimates of recharge obtained using the SWB developed for Silsoe in Bedfordshire in UK (mean annual rainfall = 560 mm, mean annual evaporation = 721mm) of 121 mm/year compare well with those reported by Monkhouse (1974) of 94-183 mm/year for the same area. This again demonstrates that the model is likely to forecast reasonable estimates of recharge.

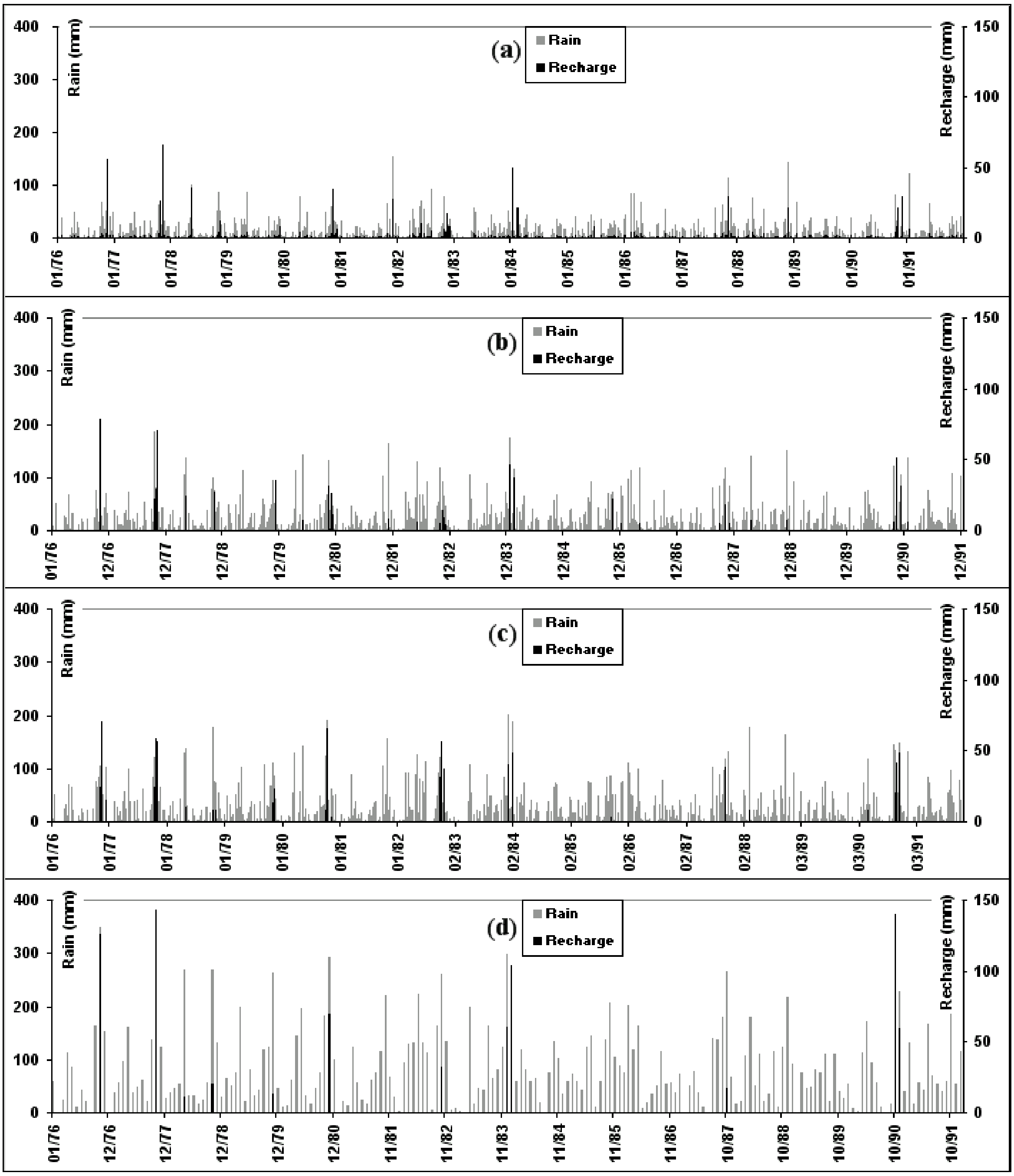

Fig. 3 (a), (b), (c) and (d) Rain and recharge estimated with daily, weekly, 10 daily and monthly time steps for Angunakolapellessa from 1976-1991

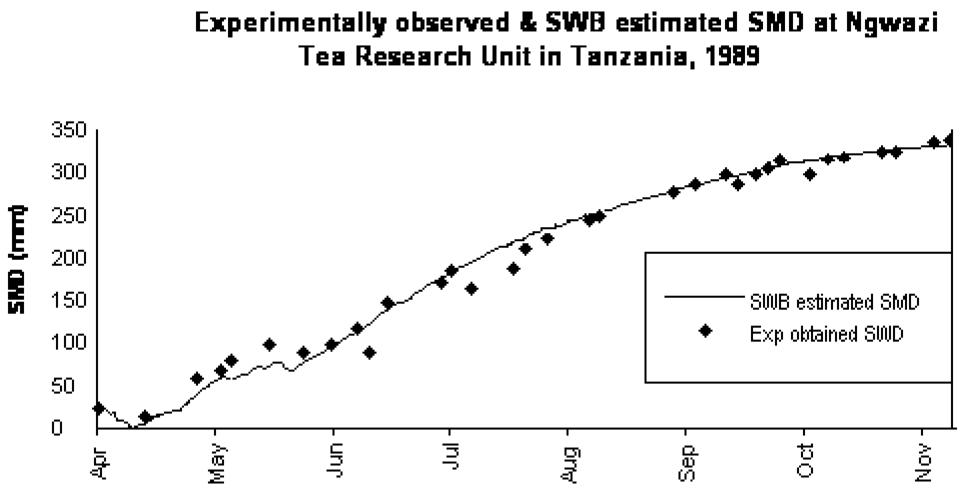

Fig. 4 Experimental and model predicted soil moisture deficit (SMD)

For the study locations in the dry zone, the differences of recharge values when different time steps are used are much higher than in the case reported by Howard & Lloyd (1979). The highest difference for their study location (i.e. Grimsby) is about 32% if a time step of ten days is used and 42% if a monthly time step is used. As seen from Table 4, the corresponding difference are higher for all the locations in dry zone with values of about 40%, 47% and 66% for weekly, ten daily and monthly time step respectively. This is possibly due to the fact that variation of rainfall is higher in the dry zone than it is for Grimsby in UK.

This underestimation of recharge when large time steps are used is caused by the masking effect of individual rainfall events by aggregating of rain and ET values. This can be demonstrated by considering a week's duration (as an example) where there is only one rainfall event of 35 mm in a day. Assuming daily ET to be about 8 mm (typical for the dry zone), this rainfall event is likely to cause a recharge event if a daily time step is used, where as if the time step is 7 days, the corresponding rainfall event of (35 mm) will not cause a recharge event as the ET of 8 mm/day x 7 = 56 mm is much greater than the 35 mm rain event. This masking effect becomes even larger if a large time step of 10 days or 30 days is used, thus reducing the recharge estimate even further.

This masking effect is further seen from Fig. 5(a), where the number of rainfall events greater than the number of ET events are significant as the time step for the SWB is one day. However, as seen from Fig. 5(d), the corresponding events are only a handful as the

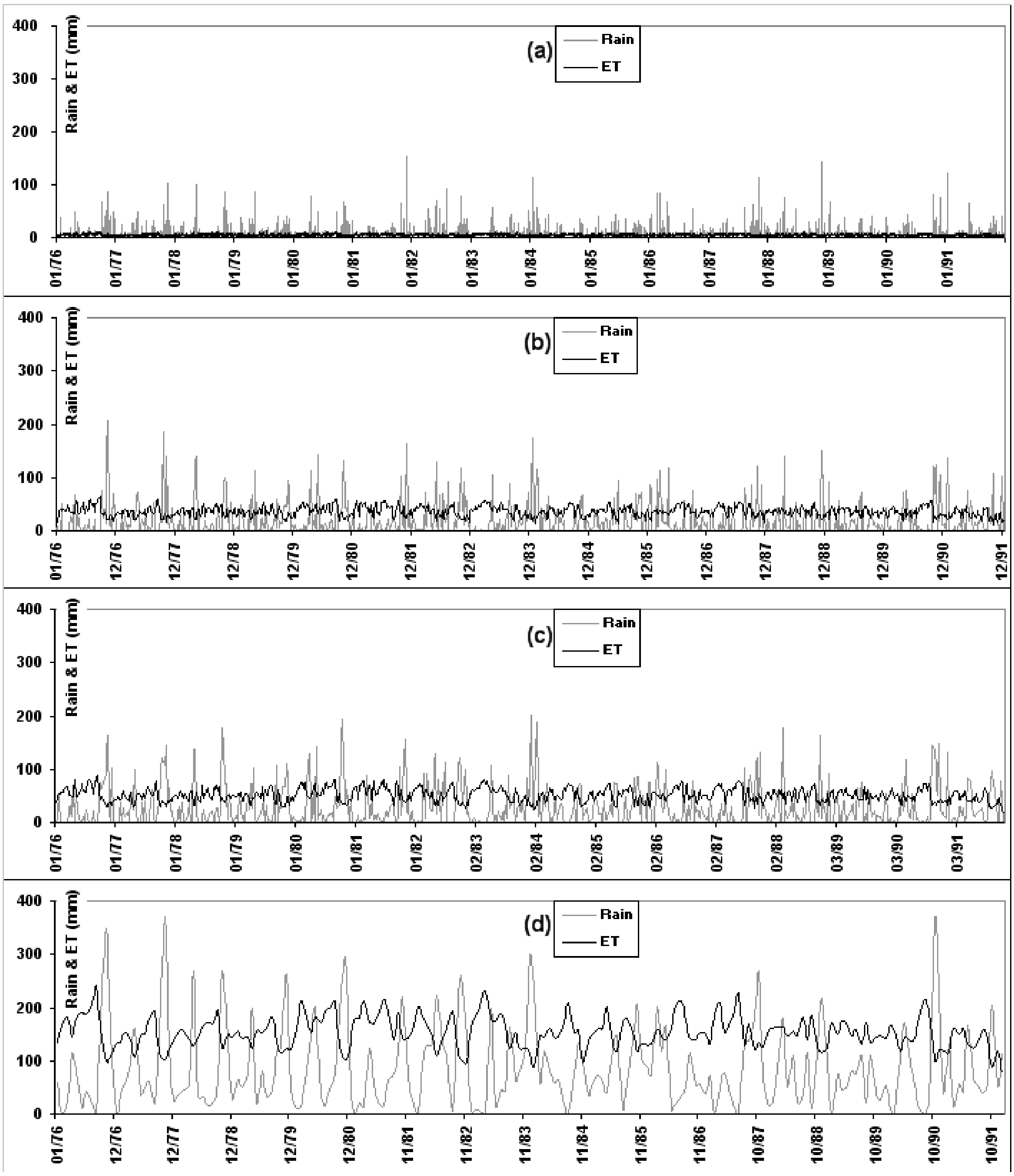

Fig. 5 (a), (b), (c) and (d) Rain and ET data used in SWB model with daily, weekly, 10 daily and monthly time steps for Angunakolapellessa from 1976-1991

time step is one month in the SWB. Table 5 shows the number of recharge events in the period 1976 – 1991 at Angunakolapellessa if different time steps are used in the SWB. As seen, the number of recharge events tend to become significantly less if larger time steps are used demonstrating the masking effect of aggregating occurring with large time steps.

These results are likely to similar even if different type of SWB models are used, as the physical process for any such model remains essentially the same.

Table 5 – Number of recharge events at Angunakolapellessa depending on the time step used

Time step	Number of recharge events
Daily	1562
Weekly	585
10 daily	457
Monthly	187

Therefore, the present study adds to the results reported by Howard & Lloyd (1979) for Grimsby in UK, and it is evident that for the dry zone too, if a weekly, 10 daily or monthly time step is used, the resulting estimates of recharge are likely to be less by a significant amount. Therefore, it is clear that daily time steps and daily climate data must be used if proper estimates of recharge are to be obtained using this method. Hence it is concluded that in general, the larger the time step, the smaller will be the estimate of recharge if, a SWB method is used to estimate it. However, as demonstrated by de Silva (1999b), if daily ET data is not available they may be evenly distributed (e.g. say weekly data divided by 7 and monthly data divided by 30) to form approximate daily values and used in a SWB with a daily time step to estimate recharge. However, since that study considered only distributing ET and not rainfall, it would be interesting to investigate into the effect of evenly distributing rainfall data and used in a SWB to estimate recharge. Since rainfall in the dry zone is highly varying even on a daily basis (unlike ET), it is unlikely that distributing rainfall values will yield same results as distributing ET values. In any case, that exercise will be academic as in most areas of the world, daily rainfall data is available and the question of distributing weekly, 10 daily or monthly rainfall data do not arise.

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Appendix- Abbreviations & Notations

The abbreviations and notations used in general in this paper are as follows.

AKP	= Angunakolapellessa (Study location)
AWC	= Available water capacity of soil in the root zone (mm/m)
EMB	= Embilipitiya (Study location)
ETa	= Actual evapotranspiration (mm/day or mm/y)
ETp	= Potential evapotranspiration (mm/day or mm/y)
F	= The ratio of ETa/ETp when soil moisture deficit is greater than root constant
FC	= Field capacity of soil (%)
Isc	= Interception (rainfall) storage capacity (mm/day)
KAL	= Kalpitiya (Study location)
MI	= Maha Illuppallama (Study location)
P	= Rainfall (mm/day or mm/y)
PFc	= Preferential flow co-efficient
PFt	= Threshold of daily rainfall above which preferential flow occurs (mm/day)
PWP	= Permanent wilting point of soil (%)
RC	= Root constant (% of AWC) – soil moisture deficit above which Eta differs from ETp indicating water stress
ROc	= Runoff coefficient
ROt	= Threshold of daily rainfall above which runoff occurs (mm/day)
SMD = smd	= Soil moisture deficit (mm)
SWB	= Soil water balance