JNSF 30-344-109

J. Natn. Sci. Foundation Sri Lanka 2002 **30**(3&4): 109-122

THE EFFECT OF LENGTH OF TIME PERIOD CONSIDERED IN ESTIMATING GROUNDWATER RECHARGE WITH A SOIL WATER BUDGET MODEL

R. P. DE SILVA*
Department of Agricultural and Plantation Engineering,
The Open University, Nawala, Nugegoda

(Received: 21 August 2001 ; accepted: 09 December 2002)

Abstract: The rate of replenishment of water table (or rate of groundwater recharge) is a key issue one needs to know in developing groundwater resources. The soil water budget method is often used to estimate this rate of recharge. The need to use daily climatic data (rather than weekly or monthly data) in the soil water budget has been shown by Howard & Lloyd.[6] However, no recommendations exist on the minimum duration necessary for precise soil water budgeting. This study attempts to find a suitable answer to this question, choosing Angunakolapelessa in the dry zone of Sri Lanka and Silsoe in UK as study locations. The results of the study show that it is good practice to use as many years of daily water balance data as possible. If this is not possible, climatic data for at least 3 years (consisting of a wet year, a dry year and an average year) must be used in order to achieve realistic estimates of recharge.

Key Words: Soil water budget, groundwater recharge, time period

Abbreviations & Notations

The abbreviations and notations (and where appropriate the units of measurement) used in general in this paper are as follows:

AKP	=	Angunakolapelessa (study location)
AWC	=	Available water capacity of soil in the root zone (mm) = [(FC-PWP)/100] x RZD
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)
PFc	=	Preferential flow coefficient
PFt	=	Threshold of daily rainfall above which preferential flow occurs (mm/day)
PF	=	Preferential flow (i.e., flow of infiltrating rainwater through cracks and fissures, bypassing the soil matrix)
PWP	=	Permanent wilting point of soil (%)
R	=	Rainfall (mm/day or mm/y)

* Corresponding author

RC = Root constant (% of AWC) = soil moisture deficit at which water stress begins to effect ETa
ROc = Runoff coefficient
ROt = Threshold of daily rainfall above which runoff occurs (mm/day)
RZD = Root zone depth (mm)
SMD = Soil moisture deficit (mm)

INTRODUCTION

The rate of recharge is defined as the rate of replenishment of the water table. A knowledge of the rate of recharge must be available in developing a groundwater source for domestic, industrial or agricultural purposes, as this parameter determines the rate of safe yield that can be abstracted from the groundwater reservoir.[1]

It is very difficult to determine the rate of recharge to the water table accurately. The best hope is to arrive at a reasonable estimate. There are a few commonly used methods of estimating recharge.[2,3,4] They are (a) the use of 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 (g) Darcy method (h) Tritium method and (i) Chloride method.

Of the above methods, the soil water balance method is a simple and an easy to use one in most climatic conditions and quite often is the only available method for a particular climatic condition.[5] In this method, a volume balance for the water entering and leaving the root zone and change in soil moisture storage is carried out and recharge (Re) is estimated as;

$$R_e = (P- I-RO-ET_a - PF) + (PF) \pm \Delta S \quad .... (1)$$

Here P is precipitation, I is interception of rainfall by vegetation, RO is run off, PF is preferential flow, ETa is actual evapotranspiration and ΔS is change in soil moisture storage. It is important to note that the first term within brackets is the matrix flow (MF) and the second term within brackets is the preferential flow (PF). 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).

If the balance is carried out annually (especially from the end of the rainy season to the same time the following year), the change in soil moisture storage is negligible (as moisture content at both times will be at field capacity). Therefore, equation 1 can be reduced to;

$$R_e = (P- I\text{-}RO\text{-}ET_a - PF) + (PF) \pm \Delta S \quad \text{.................. (2)}$$

Usually, recharge estimated by equation (2) is computed for a few years (normally one or two years) with a daily time step.[6] However, since rainfall varies significantly from year to year (especially in a country like Sri Lanka), the resulting estimates of annual recharge also vary annually. This paper studies the effect of the length of time period considered on the reliability of estimating recharge with a soil water budget model.

METHODS AND MATERIALS

The methodology adopted in general was to estimate recharge for different time periods (for different locations) and compare the estimates. The specific steps of the methodology adopted were as follows:

(a) Select suitable study locations.

(b) Collect relevant data (i.e., daily rainfall and pan evaporation for a number of years, information on rainfall interception and runoff).

(c) Experimentally determine the field capacity and permanent wilting point of soil and also observe the type of vegetation and depth of roots at each location.

(d) Form a soil water balance model to estimate recharge.

(e) Estimate recharge with different time periods as the length of time period considered and arrive at suitable conclusions.

Study locations: The study locations chosen in this research project are Silsoe in Bedfordshire in England, UK and Angunakolapelessa in the southern dry zone of Sri Lanka (Fig.1). These two locations were chosen because of the availability of long term rainfall and evaporation data that were needed for the study and also because of the availability of other required data such as field capacity and permanent wilting point of the root zone soil. Table 1 summarises the climatic, vegetative and top soil details at the study locations.

Determination of field capacity, wilting point and other parameters: A summary of climatic data and soil properties at each location is shown in Table 2. Details of climatic data and details of experiments carried out to determine the soil properties in Table 2 are given by de Silva.[7] The field capacity and permanent wilting point were measured using a pressure plate apparatus as described by de Silva.[7]

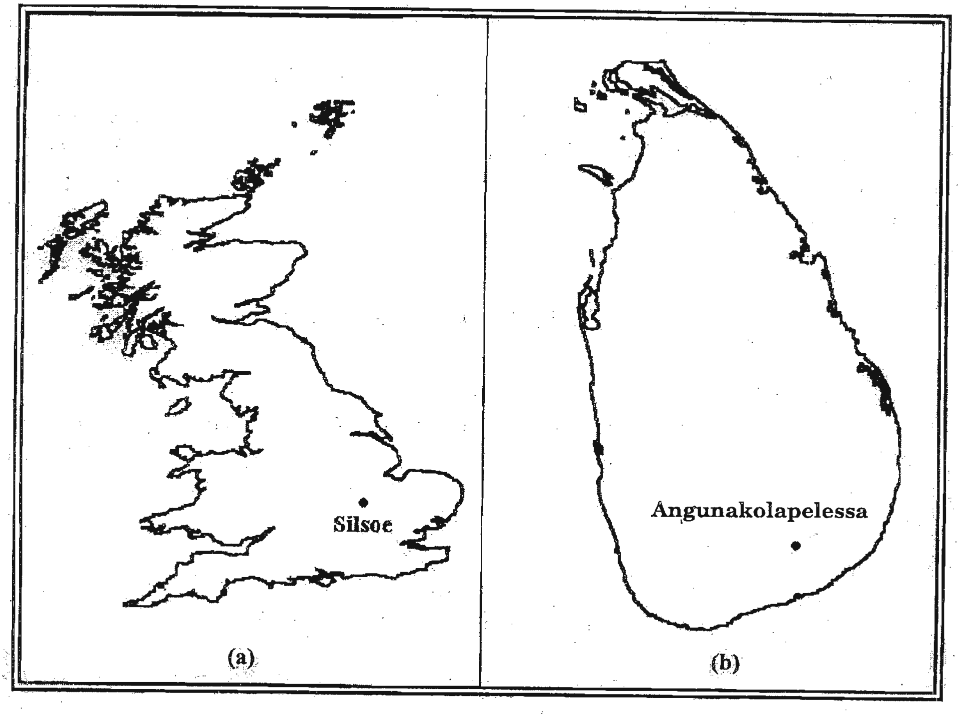

Figure 1: Maps showing the study locations (a) Silsoe in Bedfordshire in the UK and (b) Angunakolapelessa in Sri Lanka

Table 1: Climatic, vegetative and top soil details of the study locations

Location & Country	Mean Annual Rain (mm/y)	Mean Annual Pan Evaporation (mm/y)	Vegetation	Major Plant type	Top soil (Soil order/ Group)*
Angunakola-pelessa, Sri Lanka	1041	1868	Shrub jungle	Eraminya (bush about 1.5 m tall)	Sandy Clay Loam (Solonetz)
Silsoe, UK	559	616	Grass	Thistle	Sandy (Fluvisols)

* Source: Dominant soil groups of the world, based on the FAO-UNESCO Soil Map of the World (could be accessed on the internet at http://www.fao.org or at ftp://ftp.fao.org/agl/agll/wrb/wrbdom.gif)

Obtainining daily meteorological data
Daily Rain (R)
Daily Potential Evapotranspiration (ETp)

↓

Estimating daily rainfall interception (I)
R<=Isc; I = R
R>Isc; I = Isc

↓

Estimating daily surface runoff (RO)
If R> RO threshold (ROt), RO = ROc* (R-I)

↓

Estimating daily preferential flow (PF)
If R> PF threshold (PFt), PF=PFc x (R-I-RO)

↓

Estimating daily matrix flow (MF)
MF=R-I-RO-PF

↓

Estimating ETa/ETp (=F) ratio for the day
If SMD < p.AWC, F (= ETa/ETp) = 1.0 (see below for value of p)
Else F = (AWC-SMD) / (1-p). AWC)

↓

Estimating ETa for the day
If SMD_{i-1}<p.AWC or ETp<=R, ETa=ETp
If p.AWC<$SMD_{i-1} \leq$ p.AWC and ETp>R, ETa = R+ Fx (ETp-R)
If SMD_{i-1} = AWC and ETp > R, ETa = R

↓

Estimating SMD for the day
If SMD_{i-1} - MF + ETa > 0, SMD = 0
If SMD_{i-1} - MF + ETa < AWC, SMD = AWC
Else SMD = SMD_{i-1} - MF + ETa

↓

Estimating recharge for the day
If SMD = 0; Recharge = MF - ETa - SMD_{i-1} + PF
Else Recharge = PF

Figure 2: Flow chart of the soil water model used in this study (please refer the list of abbreviations given at the beginning of this paper)

Table 2: Soil properties and details of data collected at each location of this study.

Location and Country	No. of sampling points in the location	Depth to water table (m)	No. of years daily rainfall and pan evaporation data collected	Root zone depth (m)	Field Capacity (%)	Permanent Wilting Point(%)
Angunukola-pelessa, Sri Lanka	12	>4.1	16 (1976-1991)	0.95	20.2	12.0
Silsoe, UK	21	>12	28 (1962-1989)	1.20	22.9	12.2

Soil water budget model: The flow chart of the soil water budget model used in this study is shown in Fig. 2. The formation of the model with an explanation of the spreadsheet calculations used to estimate recharge with this model is given by de Silva.[7]

Here, the value of p is equal to the root constant. Values of pan evaporation were converted to values of evapotranspiration using pan co-efficients.[2] Table 3, below, gives the values of Isc, ROt, ROc, PFt and PFc used for the two locations. These values were obtained from de Silva.[7]

Table 3 : Values for model parameters used for the two locations

	Isc (mm/d)	ROt (mm/d)	ROc	PFt (mm/d)	PFc
Angunakolapelessa	1.6	12.5	0.32	10	0.075
Silsoe	1.0	2.0	0.01	2.0	0.01

RESULTS AND DISCUSSION

Table 4 and Table 6 give the estimates of recharge for Angunakolapelessa and Silsoe respectively, if the budgeting period is considered as one year. (Some studies have suggested that ETa is normally higher than what is estimated in Column 6 of Table 4 for Angunakolapelessa). However, in this study, ETa was estimated as shown in Fig. 2, from the root constant model.[1] Further, those studies have had water input as irrigation, thus having smaller periods of water shortages for the crops resulting in higher values of ETa. The average recharge values of 80 mm/y for Angunakolapelessa and 116 mm/y for Silsoe agree with studies on the same areas by Dharmasiri & Dharmawardena[9] and by Irving[10] respectively. This suggests that the values of model parameters used in Table 3 are reasonably correct for the two areas of study. Details of how these model parameters were decided are given by de Silva.[7]

As expected, the soil water budget model correctly predicts that at Angunakolapelessa, most components of the hydrological cycle (interception, runoff, evapotranspiration and recharge) are significant (Table 4), but at Silsoe, only evapotranspiration and recharge are significant (Table 6). The reasons for zero runoff at Silsoe is that the soil at the study location is sandy (Table 1) and also the precipitation is low intensity spread over 9 months of the year (except during the summer months). However, at Angunakolapelessa, high intensity rains of shorter duration on hard soils lead to significant amounts of runoff.

Table 4: Yearly estimate of recharge for Angunakolapelessa for the period 1976-1991

Year	P (rain) (mm)	Interception (mm)	Run off (mm)	ETp (mm)	ETa (mm)	Total Recharge (mm)
1976	1020	128	227	2015	528	137
1977	1179	148	252	1691	629	150
1978	993	142	185	1868	579	87
1979	1127	163	231	1746	681	51
1980	1137	135	244	2055	644	114
1981	830	120	151	2136	510	49
1982	1423	173	306	1813	807	137
1983	794	122	141	2058	508	23
1984	1232	171	243	1750	673	145
1985	1041	168	184	1835	650	39
1986	1005	143	197	1931	630	35
1987	1040	133	219	1974	629	60
1988	1011	127	220	1869	611	54
1989	723	119	123	1866	460	20
1990	1144	142	243	1825	609	150
1991	1028	167	177	1597	646	37
Average recharge for the years considered						80

Using the soil water budget model shown in Fig. 2, recharge was estimated for both study locations for different lengths of time periods [ie for Angunakolapelessa the durations were one year, 3 years, 5 years, 7 years and so on and for Silsoe the lengths of time periods were one year, 4 years, 8 years and so on. Fig. 3(a) shows the estimates of recharge for Angunakolapelessa for time periods of one year and Fig. 3(b) shows the estimates of recharge for time periods of 3 years (i.e., for 1976, 1977 & 1978 and 1977, 1978 & 1979 and so on). Fig. 3(c), 3(d) and 3(e) show the estimates of recharge if the time period is considered as 5, 7 and 9 years respectively. From Fig. 3(a) the estimate of recharge could vary from about 20 to 150 mm/y, based on a time period of one year. When the time period is increased, this variation is reduced as shown in Fig. 3 (b), (c), (d) and (e) and as shown in Fig. 5. Similarly, Fig. 4 (a), (b), (c), (d) and (e) show the estimates of recharge for Silsoe with time periods of one year, 4 years, 8 years, 12 years and 16 years respectively. Here again, (as summarised in Fig. 6) the variation of the recharge estimate is high if the time period is one year, and the variation is reduced when longer time periods are used in the soil water budget.

Table 4 shows that the lowest recharge (20 mm/y) was in 1989 and the highest recharge (150 mm/y) was in 1977 at Angunakolapelessa. Table 6 shows a similar result for Silsoe; the lowest recharge of 17 mm/y was in 1964 and the highest recharge of 241 mm/y was in 1979. Fig. 5 and Fig. 6 show the ranges of recharge obtained if different time periods are considered at Angunakolapelessa and Silsoe. It is seen from Fig. 5 and Fig. 6 that it is not possible to decide on a suitable (optimum) time duration (in a soil water budget) for a particular location.

Table 5: Estimates of recharge at Angunakolapelessa for the driest (1989), wettest (1982) and an average year (1987)

Year	P (rain) (mm)	Interception (mm)	Run off (mm)	ETp (mm)	ETa (mm)	Total Recharge (mm)
1989	723	119	123	1866	460	20
1982	1423	173	306	1813	807	137
1987	1040	133	219	1974	629	60
Average recharge for the years considered						72

Table 5 shows the estimates of recharge for the wettest (1982), driest (1989) and an average year of rain (1987) during the time period considered (i.e., from 1976 - 1991) for Angunakolapelessa. At the bottom of Table 5, the average recharge value obtained by considering only these 3 years (ie the wettest, driest and an average year) are shown, which is remarkably close to the average of the estimate of recharge in Table 4. Similarly, Table 6 shows the estimates of recharge for Silsoe with the time duration considered as one year (with an average recharge of 116 mm/y) and Table 7 shows the estimates of recharge for the wettest (1964), driest (1979) and an average year (1980) for Silsoe (with an average recharge of 124 mm/y). As seen from these two tables (ie Tables 6 & 7) the two average estimates of recharge obtained by considering a full 25 years (in Table 6) and by just considering 3 years (in Table 7) are similar.

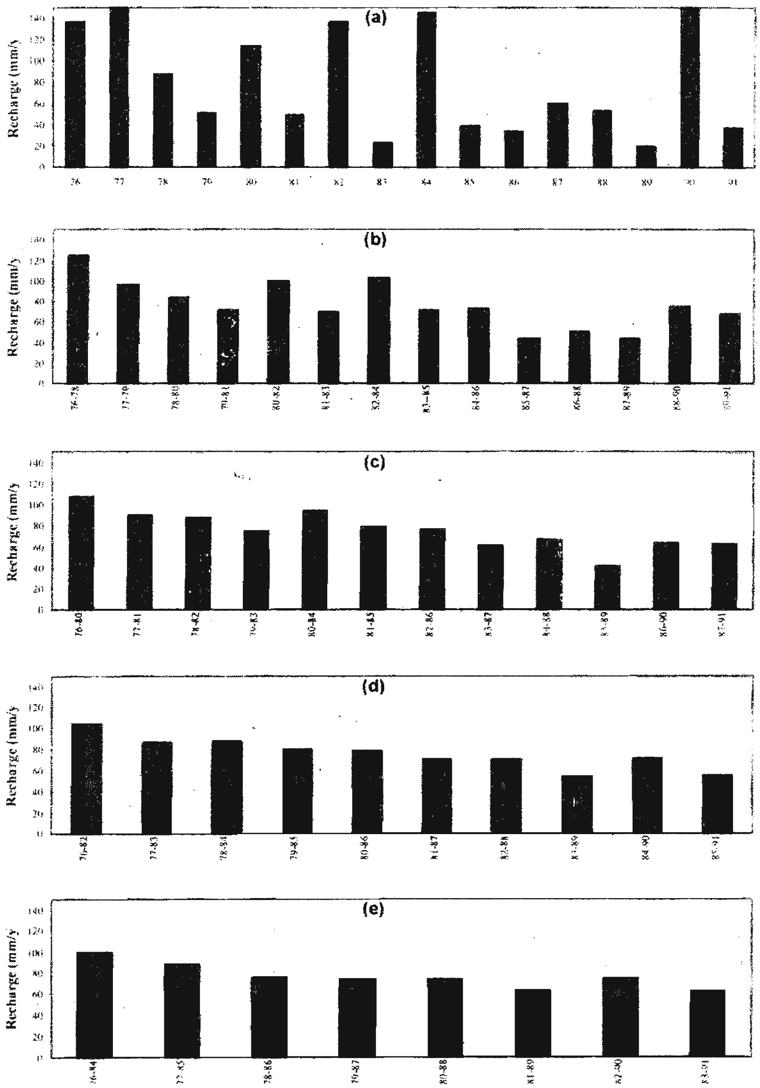

Figure 3: Estimates of recharge for different lengths of time periods in the soil water budget at Angunakolapelessa, Sri Lanka [length of time period considered in the soil water budget is (a) one year, (b) 3 years (c) 5 years (d) 7 years (e) 9 years]

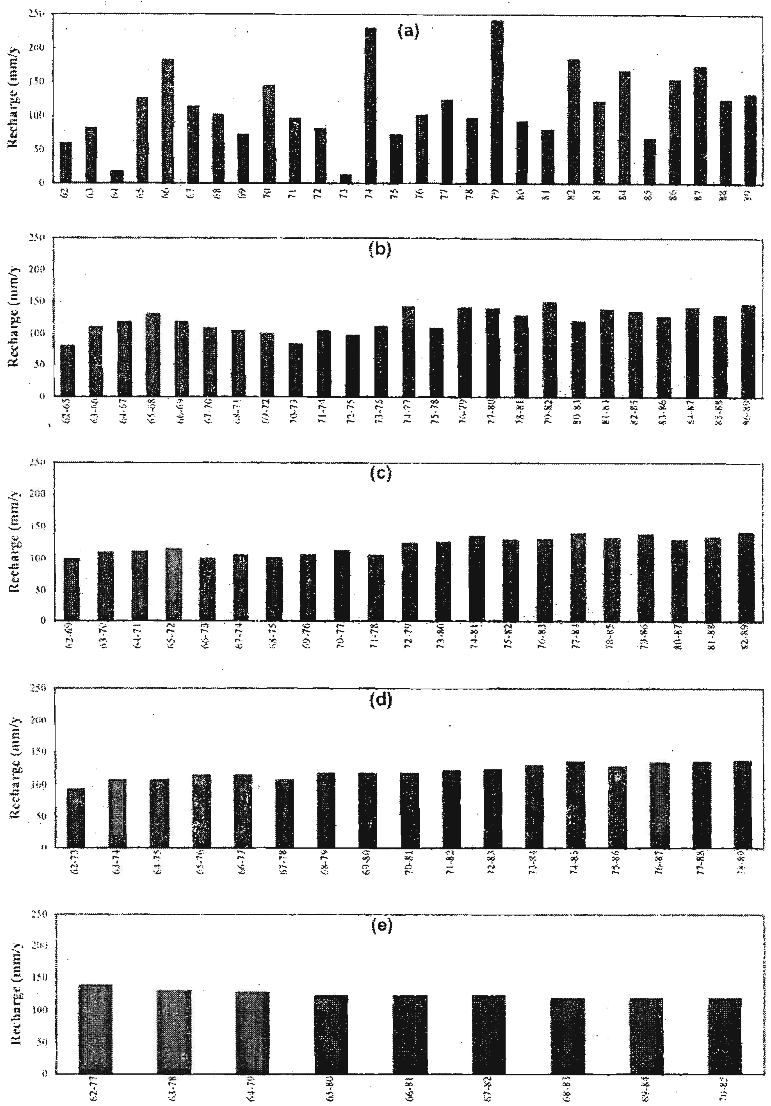

Figure 4 : Estimates of recharge for different lengths of time periods in the soil water budget at Silsoe, Bedfordshire, UK [length of time period considered in the soil water budget is (a) one year, (b) 4 years (c) 8 years, (d) 12 years (e) 16 years]

From the above discussion, it is clear that one is not able to conclude that to estimate recharge at a particular location with a soil water budget, consideration of a certain number of years of climatic data is sufficient. As shown, climatic data of as many years as possible need to be considered if reasonably true values are to be obtained. Considering the results of Tables 5 and 7 (and comparing the results of Table 4 and Table 6 respectively), it is also reasonable to conclude that in situations where a number of years of climatic data cannot be considered, at least a wet, dry and an average year need to be considered in a soil water budget to estimate recharge.

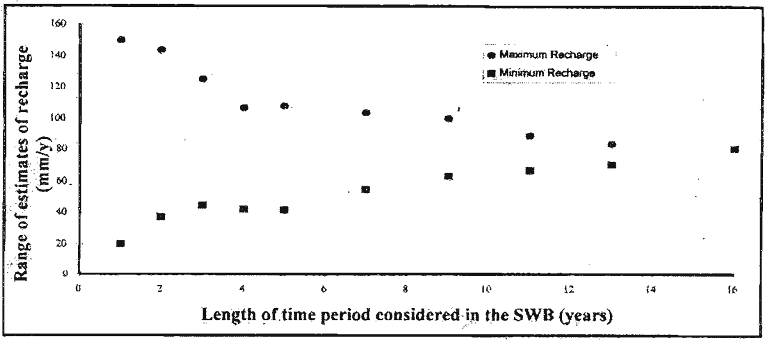

Figure 5: Range of estimates of recharge for different time periods considered in the soil water balance at Angunakolapelessa

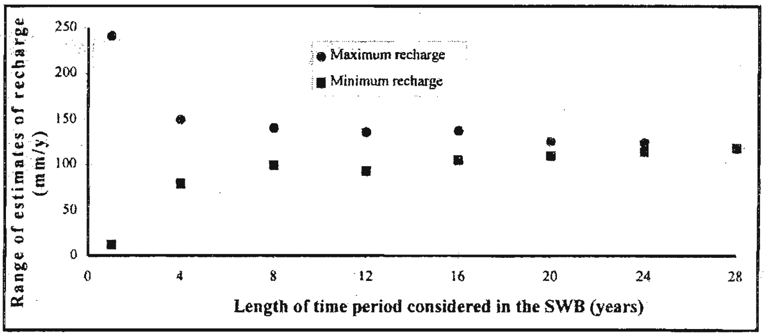

Figure 6: Range of estimates of recharge for different time periods considered in the soil water balance at Silsoe

Table 7: Estimates of recharge at Silsoe for the driest (1964), wettest (1979) and an average year (1980)

Year	Precipitation (mm)	Interception (mm)	Run off (mm)	ETp (mm)	ETa (mm)	Total Recharge (mm)
1964	402	28	0	549	357	17
1979	708	37	0	575	430	241
1980	578	33	0	516	432	113
Average recharge for the years considered						124

Table 6: Yearly estimates of recharge for Silsoe for the period 1962-1989

Year	Precipitation (mm)	Interception (mm)	Run off (mm)	ETp (mm)	ETa (mm)	Total Recharge (mm)
1962	453	28	0	500	365	60
1963	505	34	0	490	390	82
1964	402	28	0	549	357	17
1965	593	36	0	485	431	126
1966	674	38	0	494	454	183
1967	578	33	0	516	432	113
1968	577	36	0	473	440	102
1969	465	32	0	512	360	73
1970	568	33	0	535	390	145
1971	522	26	0	510	400	96
1972	460	32	0	528	345	83
1973	414	26	0	408	377	12
1974	694	34	0	560	430	229
1975	457	30	0	631	353	73
1976	429	27	0	662	300	102
1977	576	36	0	549	416	124
1978	532	33	0	554	401	98
1979	708	37	0	575	430	241
1980	584	33	0	558	458	93
1981	558	34	0	541	443	81
1982	655	34	0	596	437	184
1983	537	31	0	504	384	121
1984	584	31	0	502	387	166
1985	504	33	0	473	405	67
1986	575	36	0	491	386	153
1987	658	36	0	460	449	173
1988	606	33	0	539	448	125
1989	520	26	0	604	361	132
Average recharge for the years considered						116

CONCLUSION

In estimating recharge with a soil water budget in a particular location, climatic data for as many years as possible should be used for the location considered. As has been done in many studies, considering just one year's data (or even 2-3 years of data) will certainly not be sufficient and will lead to recharge estimates which can vary significantly. However, if this is not possible for some reason (for example, limited data availability or non availability of suitable computing capabilities), then at least a wet, dry and an average (normal) year (with respect to mean annual rainfall) must be considered in estimating recharge with the soil water budget method. The final value of recharge may be taken as the average of the recharge estimates for these wet, dry and the normal year.

References

1 Rushton K. R. & Ward C. (1979). The Estimation of Groundwater Recharge. *Journal of Hydrology*, **41**: 345-361.

2 Allison G. B., Gee G. W. & Tyler S. W. (1994). Vadose-Zone Techniques for Estimating Groundwater Recharge in Arid and Semiarid Regions. *Soil Science Society of America Journal*, **58**: 6-14.

3 De Silva R. P., (1998). A review of the methods of estimating groundwater recharge in relation to the dry zone of Sri Lanka. *The Open University Review of Engineering Technology Journal*, Vol : 4(2): 3-12, Open University of Sri Lanka.

4 Gee G. W. & Hillel D. (1988). Groundwater Recharge in Arid Regions : Review and Critique of Estimation Methods. *Hydrological Processes*, **2**: 255-266.

5 Lerner D. N., Issar A. S. & Simmers I. (1990). *Groundwater Recharge : A Guide to Understanding & Estimating Natural Recharge*. International Association of Hydrogeologists, Hannover.

6 Howard K. W. F. & Lloyd J. W. (1979). The Sensitivity of Parameters in the Penman Evaporation Equations and Direct Recharge Balance. *Journal of Hydrology*, **41**: 329-344.

7 De Silva R. P. (1996). *Estimating Groundwater Recharge with Limited Resources, with Special Emphasis on Spatial Variability: A Study in the Dry Zone of Sri Lanka*. Unpublished PhD Thesis, Silsoe College, Cranfield University, UK.

8 Doorenbos J. & Pruitt W. O. (1977). *Crop Water Requirements*. FAO, Rome.

9 Dharmasiri J. K. & Dharmawardena K. G. (1980). Recharge Measurements Using Tritium Tracer at Different Sites in Sri Lanka. *Interamerican Symposium on Isotope Hydrology*, Bogota, Columbia.

10 Irving W. M. (1982). Chloride Ion Concentration as an Aid to Estimating Recharge to the Woburn Sands. *Quarterly Journal of Engineering Geology*, **15**: 47-54.