Nordic Hydrology, 16, 1985, 79-88

The Role of Soil Moisture in the Water-Balance of a Small-Clay Catchment, 1967-75

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An eight year run of detailed soil moisture data has been incorporated into simple water balance calculations in an attempt to estimate actual evapotranspiration. The value of this data is shown when compared with estimates using only groundwater storage and its role during the autumn is particularly evident.

Introduction

The small experimental catchment established in 1965 by the Geography Department of Hull University (Fig. 1) has been shown to be a useful and reliable source of water-balance and other hydrological data. The aims and basic instrumentation of the project have been described in detail in a number of earlier papers by Ward (1967a, 1967b, 1972). The present author has shown that the simple water-balance approach can be used with success when attempting to evaluate actual evapotranspiration losses from the area (Pegg and Ward 1972, Pegg 1974). It is evident that the success of this approach is very dependent upon accurate and reliable data of changes in groundwater and soil moisture storage.

This short paper describes the nature of the soil moisture survey undertaken on the Catchwater Catchment between 1967 and 1975 inclusive. From these data estimates of actual evapotranspiration are developed and compared with that using groundwater fluctuations alone.

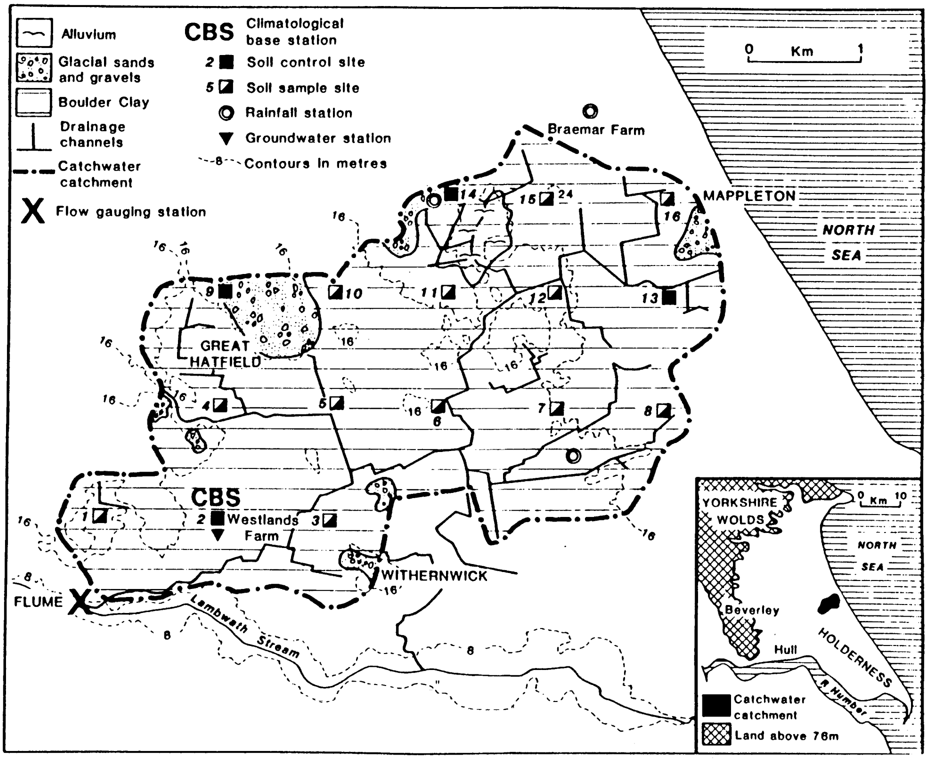

Fig. 1. Location of the Catchwater Drain Catchment showing the basic instrumentation and soil moisture sampling grid.

The Soil Moisture Survey

Soil moisture storage changes were carefully evaluated during the early years of the Catchwater Catchment study (Pegg 1970, 1974). The design of the sampling survey was conditioned by the following considerations:

a) the method of sampling should be reliable and accurate;
b) the sampling should be carried out as quickly and frequently as possible;
c) the evaluation of soil moisture conditions at several levels in the profile was desirable.
d) the sampling must be representative of the conditions over the whole catchment area.

Various methods of random sampling were considered, but in order to gain as much information as possible from the 15.4 km^2 area, a systematic sample at sixteen sites located at the intersections of the 1 km grid lines was used (Fig. 1).

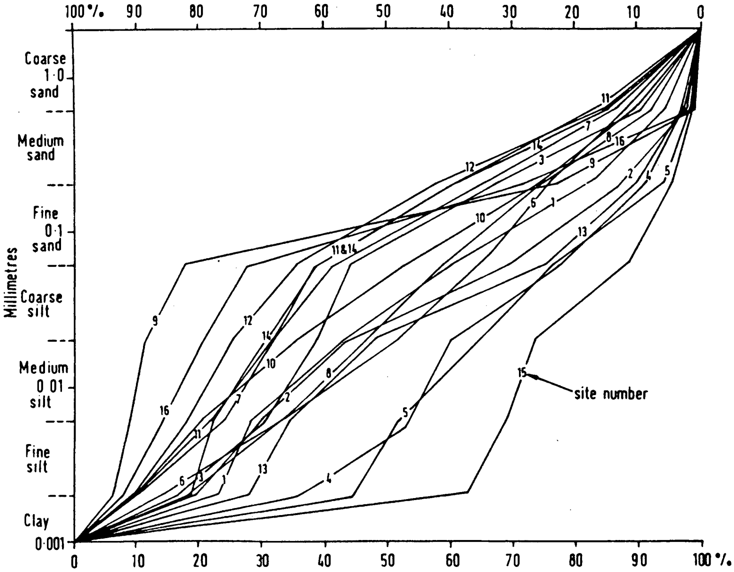

Fig. 2. The grain size characteristics of the sixteen soil sample sites. Samples shown from 30 cm depth.

Such a scheme gives a more precise estimate of the population mean than a random sample of the same size, however there is no valid estimate of error (Sampford 1962). A simple gravimetric method was used and replica samples collected from the surface; 15 cm, 30 cm and 60 cm below the surface. Initially all 16 sites were sampled on a weekly basis but once a consistent pattern began to emerge, the frequency of sampling was reduced to every four weeks and only 4 'control' sites sampled each week (Fig. 1). During the second year of study (1968) the control sites were sampled each week and the remaining sites every 13 weeks. In this way a reasonable estimate of storage conditions could be obtained without the complete destruction of the sites by over use of the gravimetric approach. During the extended period 1969-1975 the control sites were sampled every four weeks at the levels indicated earlier.

The information about soil structure, necessary for the conversion of percentage dry weight values of soil moisture to precipitation depth equivalents, was derived from a full analysis of all the soil samples collected from the various levels.

The range of soil types encountered in the sample network was considerable, ranging from the clays of sites 15 and 5 to the sand of site 9 (Fig. 2). In general clay content increased with depth. The data from the four control sites (Nos. 2, 9, 13 and 14) form the basis of the estimation of soil moisture storage changes. The range of values obtained from these sites is illustrated by the mean soil moisture content for 1967 shown in Table 1.

Table 1 – Mean soil moisture content – control sites – 1967

Level	Sites (% Dry weight) No 2	No 9	No 13	No 14	A mean n=4	B all sites mean n=16	C (B-A) mean n=12
Surface	25.5	24.7	24.9	34.8	27.5	33.4	36.0
	±3.6	±3.5	±2.6	±3.6	±1.0	±0.6	±0.8
15 cm	24.7	22.7	29.2	30.4	26.7	29.3	30.6
	±2.3	±1.8	±1.9	±3.0	±0.7	±0.4	±0.5
30 cm	23.7	20.6	25.1	23.5	23.2	26.5	27.7
	±1.8	±1.6	±1.3	±2.2	±0.5	±0.3	±0.3
60 cm	21.7	21.8	24.8	20.4	22.2	25.1	26.2
	±0.4	±1.2	±1.3	±1.8	±0.4	±0.2	±0.3
30 cm Profile	24.6	22.7	26.4	29.6	25.8	28.7	31.4
	±2.4	±1.9	±1.6	±2.8	±0.7	±0.4	±0.5
60 cm Profile	23.9	22.5	26.0	27.2	24.9	28.6	29.9
	±2.2	±1.7	±1.2	±2.4	±0.6	±0.4	±0.4

The relationship between the mean of the control sites (A in Table 1) and the mean of the remaining twelve sites (C) was investigated further by examining the correlation between them for actual soil moisture content and for the change in content between samples. The following results were obtained:

Correlation between the Control Sites and the Remaining Twelve Sites – 1967

Actual soil moisture content

Level	Surface	15 cm	30 cm	60 cm	30 cm Profile	60 cm Profile
r	0.79*	0.90*	0.84*	0.75*	0.91*	0.92*

Change in soil moisture content

r	0.75[1]	0.82*	0.46	0.44	0.83*	0.78[1]

where * = 0.1 level of significance and 1 = 1.0 level of significance.

The use of the change in soil moisture content is necessary in the water-balance calculations and the maximum degree of correlation was found with the 30 cm profile data. The estimated catchment soil moisture content for the complete period 1967-1974 is shown in Fig. 3 (samples were not taken for all of 1975 and it is therefore omitted). For comparative purposes the groundwater levels at the Climatological Base Station are also shown. This well level data has been used successfully by Tang and Ward (1982) to predict actual evapotranspiration. Their results, however, are only a rough estimate since it is quite possible for soil

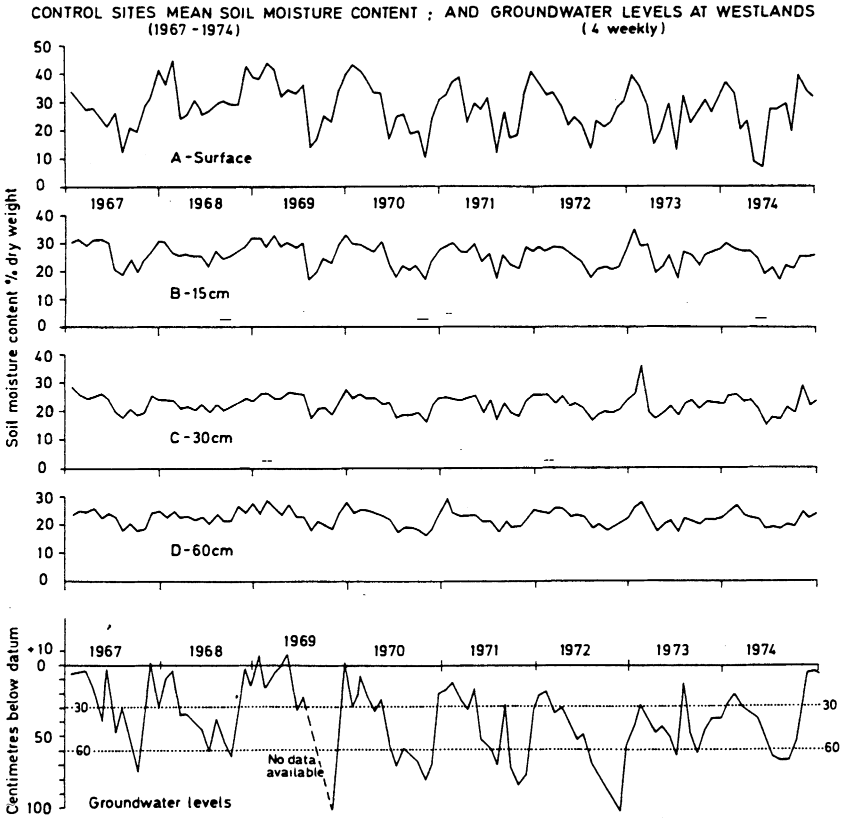

Fig. 3. The mean soil moisture content for the four control sites and associated groundwater levels at the C.B.S. 1967-1974.

moisture conditions to be changing out of phase with the groundwater regime. Close inspection of Fig. 3 shows that on a number of occasions the soil moisture content at the surface or 15 cm below is increasing when groundwater levels are falling.

The detailed relationship between soil moisture content and groundwater levels for the period 1967-1974 are shown in Fig. 4. It is clear that wide variations exist between the two variables and that although the groundwater table is very close to the surface, actual soil moisture data is necessary for an accurate evaluation of the waterbalance components.

Adjusting the data to calendar months and calculating the average conditions for the complete period makes it possible to compare soil moisture and groundwater more directly (Fig. 5). The difficulty of predicting one variable from the other is clearly evident. During the early autumn, or late summer period soil moisture responds to the recharge process in advance of the groundwater levels.

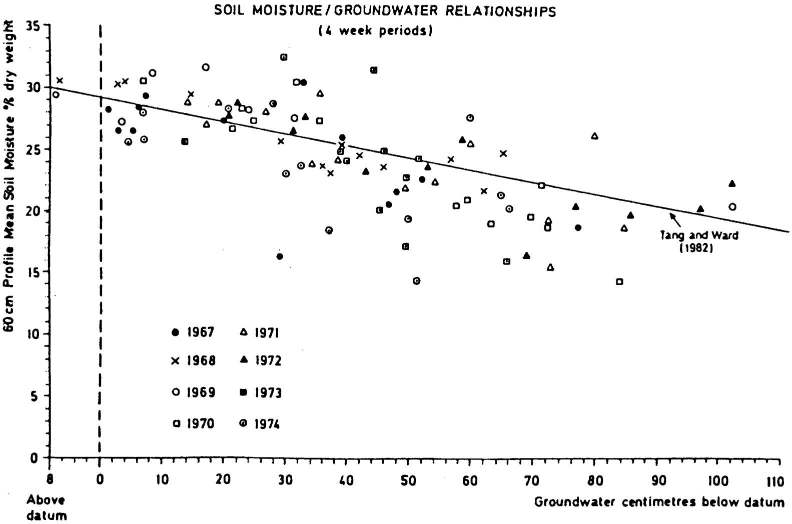

Fig. 4. Scatter diagrams showing the relationship between groundwater levels and soil moisture content.

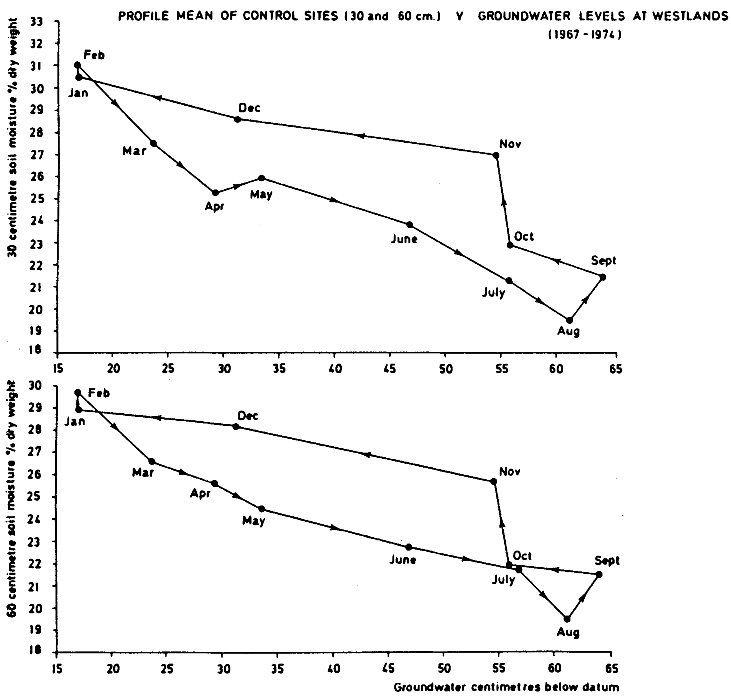

Fig. 5. Average groundwater/soil moisture content relationships for the shallow profile (30 cm) in upper diagram and deeper profile (60 cm) in the lower section.

The Application to the Water Balance

The soil moisture storage data can be applied to the simple waterbalance of the system for the period January 1967 to September 1975. The simple continuity equation has been used

$$P \equiv Q + E \pm \Delta G \pm \Delta S$$

where P – precipitation
Q – stream discharge
E – actual evapotranspiration
ΔG – change in groundwater storage
ΔS – change in soil moisture storage

To incorporate the percentage dry weight soil moisture data into the above equation it was necessary to convert it to actual water equivalents. Bulk density samples on a large scale would have destroyed the sites and were to be avoided. Therefore the average grain size characteristics of the soil samples were converted by assuming that under normal field conditions different soils have the dry weights indicated below:

Soil type	Dry Wt. Kgms/m^3
Fine sand	1602
Sandy loam	1362
Silt Loam	1202
Clay Loam	1121
Clay	1041

Soil dry weight under average field conditions (based on Hydrology Handbook No. 28. Am. Soc. Civil. Eng. 1949)

Using these data and the grain size distribution the rainfall equivalent of the 30 cm profile mean for the control sites of 25.8 % dry weight is equal to 109.1 mm of rainfall. This is a first approximation but seems reasonable when Penmans (1949) average root constant for shallow rooted vegetation such as grass is considered. He argued that 76 mm of water would be readily available and a further 25 mm could be used with difficulty. For long-rooted vegetation the root constant used by Penman (1949) was 203 mm which is close to the water equivalent for the 60 cm profile mean for 1967 of 24.9 % dry weight which converts to 209.9 mm of rainfall.

The mean monthly water-balance for the period January 1967 to September 1975 is shown in Table 2. The actual evapotranspiration estimate is derived from the solution of the continuity equation for all other variables i.e.

$$E60 \equiv P - Q \pm \Delta G \pm \Delta S60$$ (all the variables are as in Table 2)

Table 2 – Mean monthly values of waterbalance components for the Catchwater. Drain catchment using actual 60 cm profile mean soil moisture data (1967-75). Values shown in mm.

	J	F	M	A	M	J	J	A	S	O	N	D	Year
P	51.8	35.7	40.2	52.6	50.9	46.0	59.5	52.7	51.0	54.7	75.6	50.4	621.1
	±5.5	±5.4	±4.9	±8.1	±11.8	±5.8	±9.7	±11.9	±7.4	±12.9	±11.1	±4.2	±31.2
Q	44.5	26.1	17.4	17.1	11.9	3.6	2.7	1.2	3.5	22.4	25.3	30.0	205.7
	±8.9	±3.6	±4.7	±5.1	±4.2	±1.8	±1.3	±0.5	±1.3	±8.8	±6.1	±8.1	±23.3
△ G	−0.3	−8.0	−3.0	−5.5	−14.2	−9.7	−3.4	−5.3	+5.0	+4.2	+28.9	+8.2	−3.1
△ S60	+6.2	−26.2	−16.5	−1.6	−13.8	−8.5	−19.1	+16.1	+4.6	+31.6	+21.1	+6.2	0.1
E60	1.4	43.8	42.3	42.6	67.0	60.6	79.3	40.7	37.9	(−3.5)	0.3	6.0	418.4

where:

P – precipitation (Jan 1967-Sept 75 mean)*
Q – stream discharge (Jan 67-Sept 75 mean)*
$\triangle G$ – change in groundwater storage (Jan 67-Sept 75 mean)*
△S60 – change in soil moisture storage in the 60 cm soil profile (Jan 67-Jan 75 mean)
E60 – actual evapotranspiration using △ S60 in waterbalance

*(from Tang and Ward (1982)).

Examination of Table 2 shows the way that soil moisture content increases at the end of the summer before the upturn in groundwater levels. However, major problems are evident during October and November. The data using the 60 cm profile mean is presented as a first estimate since it is very likely that using this range of soil depth could possibly lead to double accounting. This is because with such shallow groundwater conditions the lower soil samples (60 cm) were taken from below groundwater level during wet periods in the autumn and winter. In particular problems occur in months with high water table and large changes in soil moisture content (i.e. October and November). The use of the 30 cm profile data in the continuity equation is preferred and the present author has demonstrated that the best estimate is obtained using this data for 1967 and 1968 (Pegg 1974). Inspection of the time series plot of the soil moisture data and groundwater levels shows the considerable period when the groundwater levels were within 60 cms of the surface (Fig. 3).

Applying the 30 cm profile soil moisture data to the water-balance equation for each month gives the results shown in Table 3. This shows the way that soil moisture conditions are much more variable than groundwater. In particular the tendency for soil moisture storage to increase in the period from August to November by a rather smaller amount than when the 60 cm profile is considered. This gives a rather more realistic estimate of actual evapotranspiration for these months. Tang and Ward (1982) have presented estimates of actual evapotranspiration for the same catchment area for the period January 1967 to September 1975.

Table 3 – The 30 cm moisture estimate of actual evapotranspiration 1967-75. Values shown in mm. (*P*, *Q* and $\triangle G$ in Table 2).

	J	F	M	A	M	J	J	A	S	O	N	D	Year
$\triangle$ S30	+2.1	−14.9	−9.9	+3.4	−9.3	−10.6	−7.5	+8.1	+6.3	+17.3	+6.5	+8.2	−0.3
E30	5.5	32.5	35.7	37.6	62.5	62.7	67.7	48.7	36.2	10.8	14.9	4.0	418.8
	(Tang & Ward (1982) for comparison)												
$\triangle$ S	0.0	−8.9	−2.5	−6.3	−14.5	−10.2	−3.6	−5.6	+5.3	+9.7	+30.5	+8.2	2.1
Et	7.7	26.4	28.3	47.3	67.7	62.4	59.1	64.1	37.1	19.4	4.2	4.0	427.7

Where

$\triangle$S30 – change in soil moisture storage in the 30 cm soil profile (Jan 67-Jan 75 mean)

E30 – actual evapotranspiration using $\triangle$ S30 in the water balance.

$\triangle S$ – change in soil moisture storage based on an estimate from groundwater levels as used by Tang and Ward (1982)

Et – evapotranspiration estimate using S in the waterbalance

They use an estimate of soil moisture storage based on the relationship between soil moisture and groundwater levels measured by the present author in 1967 and 1968. Their estimates for the longer period have been extrapolated from the groundwater record. The results of this are shown in Table 3 and Fig. 6 together with the estimate incorporating the soil moisture data.

It is clear from these data that the use of actual moisture data gives a more refined estimate of actual evapotranspiration. In particular the periods at the end of the summer when 'wetting' up quite obviously takes place from the surface downward so that potential evapotranspiration is established quickly once soil moisture storage has been recharged.

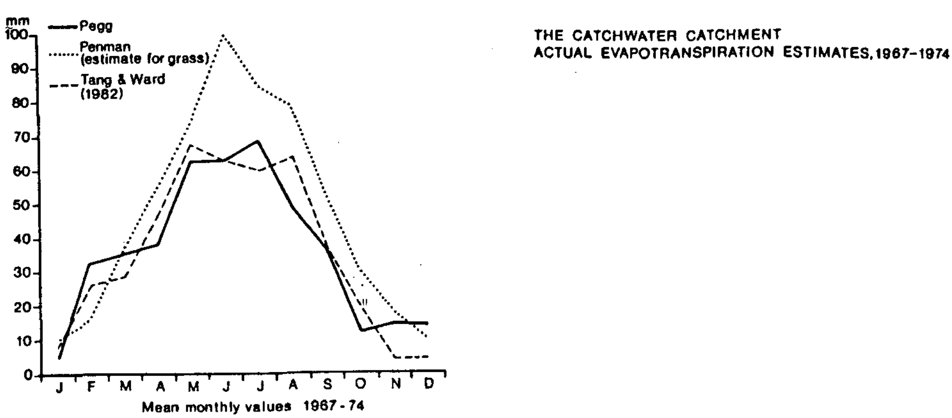

Fig. 6. Actual evapotranspiration estimates compared with Penman's (1948) potential evapotranspiration estimate for a grass surface (1967 to 74 mean).

Conclusions

Meaningful estimates of actual evapotranspiration have been derived from the hydrological measurements made during the Catchwater Catchment study for the period 1967-1975. However, misleading results can occur if groundwater levels alone are used to estimate changes in storage. This is particularly the case during the late summer and early autumn when the seasonal recharge process is commencing. It will also be a difficulty during a year with alternating wet and dry periods. In order to obtain effective estimates of actual evapotranspiration using the water-balance approach actual soil moisture storage data is needed. However, in an area where the groundwater table is near the surface the danger of double accounting must be recognized.

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First received 22 November, 1984
Revised version received: 4 March, 1985

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