Nordic Hydrology 3, 1972, 44–63
Published by Munksgaard, Copenhagen, Denmark

CHECKS ON THE WATER BALANCE OF A SMALL CATCHMENT

R. C. WARD

University of Hull, England

The paper discusses water balance data for a small (16 km^2) boulder clay catchment. In order to check the accuracy of the calculations, water balances are cast for different, overlapping periods of time within the same run of data (e.g. three-year, annual, seasonal, monthly, ten-day and storm-period). For each period the residual values are satisfactorily low (cf. 12 mm for the three-year balance and zero for the storm-period balance). A further series of checks is provided by rewriting the water equation in a number of different ways to enable estimated and measured values of certain water balance components to be compared. It is concluded that the measured values seem to be accurate and that the catchment appears to be watertight.

A previous article (Ward 1967) described the design and initiation of a small stream catchment experiment in East Yorkshire, Britain, whose preliminary objective is the solution of the water balance equation through the accurate measurement of the major water balance components. The experimental catchment (see Fig. 1) approximately 6 square miles (16 km^2) in area, is located on a boulder clay plain and has a total amplitude of relief of only 55 feet (18 m) so that most of the slopes are quite gentle. Almost the entire area is under mixed farming with a rotation of grass and corn crops.

Detailed measurements have now been in progress since October 1966, and sufficient data are available to permit a preliminary assessment of the success of this experiment and to bring to light discrepant data or data gaps which need urgently to be filled.

The water balance equation may be written as follows:

$$P - Q - E - \triangle S - \triangle G = 0$$

where P is precipitation, Q is streamflow, E is evapotranspiration and $\triangle S$ and $\triangle G$ are changes in soil moisture and groundwater storage respectively. If this equation can be solved, then it is likely that the measurements or estimations of the individual components of the water balance are satisfactory and that the stream catchment itself comprises a watertight hydrological unit in which all rain falling within the topographical drainage divides finds its way out of the catchment via the main stream or as evapotranspiration, and in which there is no consistent net gain or loss of water by soil moisture or groundwater seepage. Clearly these may be false suppositions if discrepancies in measurement are fortuitously complementary. It is, therefore, necessary to guard against this eventuality by casting water balances for different lengths of time within the same run of data and by re-writing the equation in a number of different ways.

If the equation cannot be solved, it must be determined whether certain components appear to have been consistently under- or overestimated, in which case basic assumptions may be in error, the catchment may not be watertight, or there may be a lack of coincidence between the topographic and groundwater catchments. Or there may be no apparent consistency in the ways in which the equation fails to solve, in which case gross errors of measurement may be suspected or a seasonal or periodic lack of watertightness. Again, overlapping time periods must be used and alternative balances cast before conclusions can be verified.

CALCULATION OF THE WATER BALANCE

Only a brief description of the methods of measurements of the principal water balance components will be given, together with an explanation of certain arbitrary assumptions which have been made in order to interpret the data on groundwater and soil moisture storage changes. Areal precipitation was originally calculated from the records of two tilting siphon gauges. From 1st February 1967, however, 4 tilting siphon gauges were used (see Fig. 1), the areal estimate being determined on the basis of the Thiessen polygon weightings for each gauge. Streamflow was measured by means of the wooden trapezoidal flume described by Ward (1967) and evapotranspiration by means of an evapo-

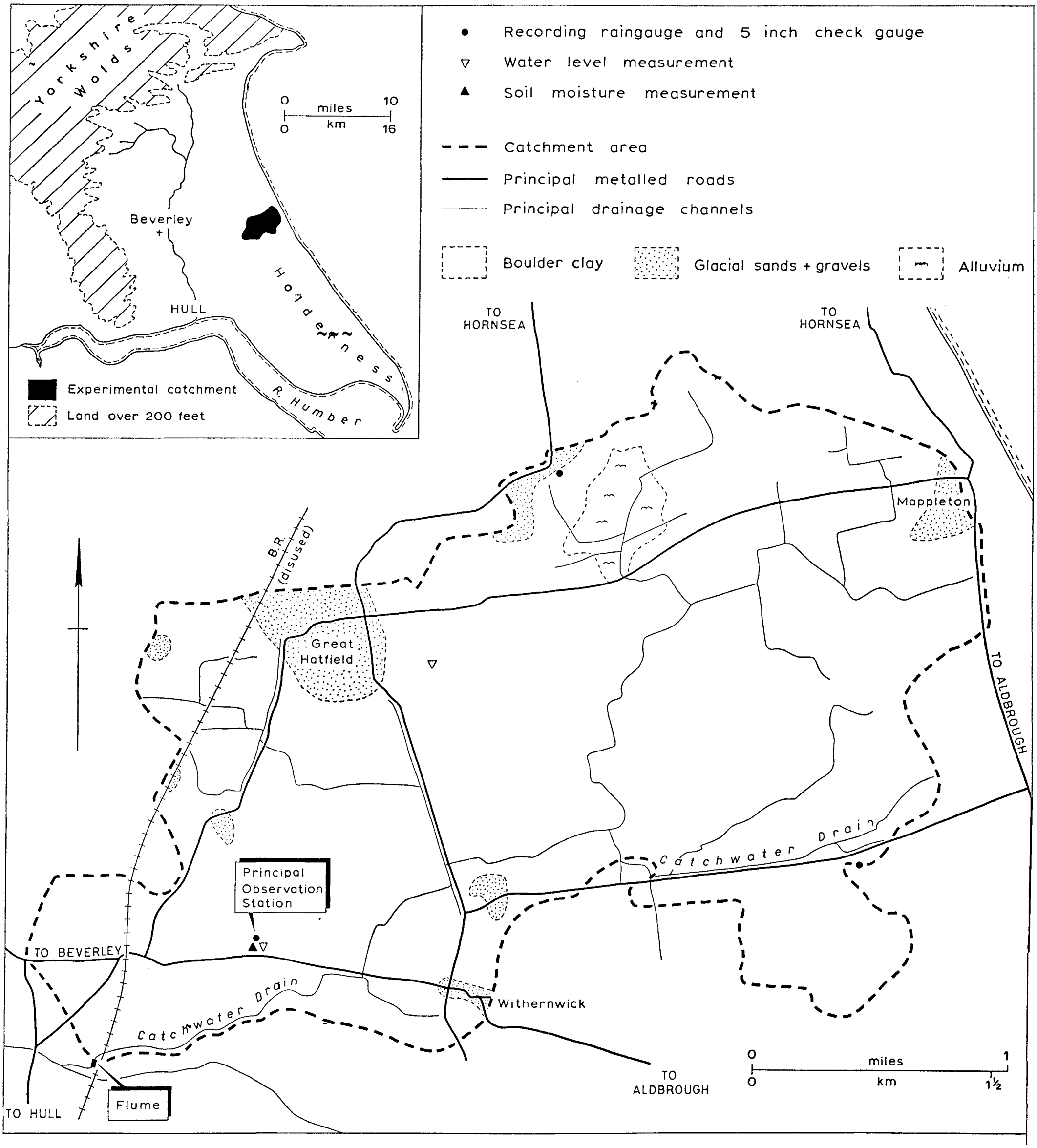


Fig. 1.

Map of the Catchwater Catchment, showing main features and location of hydrological measurements. Inset, location map.

transpirometer located at the main climatological station, again described by Ward (1963, 1967).

As will become apparent in the ensuing discussion, these 3 basic measurements seem to have been carried out satisfactorily during the initial study period. In relation to the measurement of storage changes, however, the situation appears to be less satisfactory. Thus, for the purposes of this study, groundwater storage changes were determined from observed levels in a well at the main climatological station except that during the final 3 months (i.e. July through September 1969), when a large-scale pumping test was carried out in this well, data from a nearby well of similar construction at Great Hatfield were used instead, care having been taken to verify that the water level variations in both wells were of similar magnitude throughout the preceding 6 months of 1969. In the absence of detailed information on particle size distribution, and porosity and permeability characteristics of the catchment soils and subsoil layers (N.B. assessments of these characteristics are currently in progress), the arbitrary assumption was made that the ratio between well water-level change and groundwater storage change was at all times 10:1, e.g. a well water-level decline of 10 cm represented a depletion of groundwater storage of 1 cm precipitation equivalent. This assumption was made on the basis of previous work by the author (Ward 1962) and general statements by Godwin (1931), who noted that the ratio of water-table rise to rainfall varies between 7:1 and 12:1 and by Nicholson (1951), who suggested that 1 inch of rain can raise the groundwater level 10 or 12 inches. It will be shown that this assumption seems reasonable in the light of the water balance calculations for the Catchwater Catchment.

Soil moisture storage was the least satisfactorily measured of the principal water balance components. Changes of soil moisture storage were determined from a battery of tensiometers at the climatological station. No data were available from October 1966 through January 1967. From February 1967 through May 1967 storage changes were estimated from daily tensiometer readings at 12 and 24 inches (30 and 60 cm) below the ground surface and from June 1967 for the remainder of the experimental period a third reading, at 9 inches (23 cm), was included in the profile mean. For the most part no attempt has been made to convert the tensiometer readings in cms of suction to a precipitation depth equivalent. Instead, water balance calculations are mainly presented disregarding soil moisture storage changes, although in most cases the recorded changes in tensiometer values are also given for the appropriate period and it is gratifying to note how frequently the measured difference has the right sign to improve the crude water balance calculation of $P - Q - E - \triangle G$. In passing, however, it is of interest to note that, using an early Thornthwaite

(Thornthwaite & Mather 1955) assumption that there will on average be 10 cm soil moisture storage readily available for evapotranspiration, together with the recorded range of tensiometer values from winter to dry summer conditions, a simple conversion of the mean tensiometer values

$$\triangle S \text{ (mm)} = \text{mean tensiometer value (cms)}$$

normally seems appropriate and has been incorporated into the water balance calculation of *E* in a later section of this report.

THE WATER BALANCE FOR DIFFERENT TIME INTERVALS

The water balance calculations for different time intervals within the experimental period of 3 consecutive water years, 1966/67 through 1968/69, will now be presented and discussed.

Three-year balance

The 3-year balance shown in Table 1 appears to be highly satisfactory, the residual of 12 mm representing only 0.6 % of the precipitation input during this period. No soil moisture storage change data are available for the complete 3-year period, although an assumption of $\triangle S = 0$ for such a length of time would be reasonable. It is interesting to compare the magnitudes of the principal measured components and to note that little more than 1/3 of the total precipitation appears as streamflow even in this relatively impermeable boulder clay area.

Table 1.
Three-year water balance data.

PERIOD	P (mm)	Q (mm)	E (mm)	△G (mm)	RESIDUAL P - (Q + E + △ G) (mm)	△ S tensiometers (cm)
Oct. 1966 - Sept. 1969	2073	785	1346	- 70	+ 12	no data

Annual balance

The annual balances shown in Table 2 appear less satisfactory, the residuals of 34, 52 and 6 representing 5.4, 7.5 and 0.8 % of the respective precipitation inputs for the 3 water years. The assumption of $\triangle S = 0$, although frequently made in such calculations for annual periods, is likely to be less reasonable than for the complete 3-year period and, in fact, for the 2 years in which tensiometer data are available it is seen that the balance would be (qualitatively) improved by incorporating $\triangle S$ values into the equation. When compared with the $\triangle G$ values, however, the residuals for 1966/67 and 1967/68 are large and presumably could not be fully accounted for by $\triangle S$, however accurately measured. It will be noted that the percentage of precipitation evacuated from the catchment area as streamflow varies widely from year to year (35.1, 27.9 and 49.3 % respectively) although the low precipitation value for 1966/67 may be suspect on the grounds that 2 gauges only were operational during the winter half of this year.

Seasonal balance

If balance, or the lack of it, is again judged in terms of the residual expressed as a percentage of the precipitation it will be seen from Table 3 that the seasonal values do not differ greatly from the annual values. The 6 seasonal residuals represented 4.3, 14.4, 18.0, 0.5, 3.0 and 4.6 % of the respective precipitation inputs. It is, however, clear that at this scale the role of soil moisture storage is much more important, as evidenced by the seasonal discrepancy be-

Table 2.
Annual water balance data.

PERIOD	P	Q	E	△G	RESIDUAL P = (Q + E + △G) (mm)	△S* tensiometers (cm)
	(mm)					
Water years						
1966/67	632	222	461	− 17	− 34	no data
1967/68	689	192	420	+ 25	+ 52	+ 7.8
1968/69	752	371	465	− 78	− 6	− 10.8

* negative and positive values in this column represent reduction and increase in soil moisture storage respectively, i.e. sign has been reversed for ease of comparison with residual.

Table 3.
Seasonal water balance data.

PERIOD *	P	Q (mm)	E	△G	RESIDUAL P - (Q + E + △G) (mm)	△S ** tensiometers (cm)
1966/67						
Winter	305	178	94	+ 20	+ 13	no data
Summer	327	44	367	- 37	- 47	- 26.9
1967/68						
Winter	279	135	66	+ 28	+ 50	+ 10.3
Summer	410	57	354	- 3	+ 2	- 2.5
1968/69						
Winter	381	277	78	+ 15	+ 11	+ 3.5
Summer	371	94	387	- 93	- 17	- 14.3

* Winter = Oct – Mar
Summer = Apr – Sept

** negative and positive values in this column represent reduction and increase in soil moisture storage respectively, i.e. sign has been reversed for ease of comparison with residual.

tween the high positive residuals during the winter periods and the high negative or low positive residuals during the summer periods. Except during the summer of 1967/68, when in any case the residual value and the indicated soil moisture storage change were both very low, the residual value would be substantially decreased by the incorporation of the soil moisture data. A comparison of the winter and summer magnitudes of the components of the water balance emphasises the close similarity which is found in most years between summer and winter precipitation over much of Eastern England and underlines the fact that seasonal contrasts in streamflow are largely the result of a marked seasonal change in the magnitude of evapotranspiration losses. The consistent seasonal contrast between large values of groundwater storage during the winter and groundwater depletion during the summer further emphasises the important role of subsurface moisture storage to which reference has already been made in connection with the estimated $\triangle S$ values.

Monthly balance

As might be expected, with a further reduction in the time period under consideration, the relative importance of moisture storages within the catchment increases (Table 4). Even so, although at this scale it is clearer than before that soil moisture effects cannot be ignored, it is nevertheless gratifying to note how many small monthly residuals exist even before the incorporation of estimated soil moisture in the water balance equation helps to further reduce the magnitude of these residuals. Thus 50 % of the monthly residuals were 1 cm or less, which represents approximately 17 % of the average monthly precipitation during the 3-year study period, and 72 % of the residuals were 1.5 cm or less. If a treatment of the tensiometer data similar to that suggested for other time periods is also used on a monthly basis these residuals are considerably reduced. This improvement is indicated in Fig. 2 in which graphs of the monthly water balance residual ($P-Q-E-\triangle G$) in mm and $\triangle S$ as indicated by the tensiometer values in cm may be compared for all except the first 5 months of the study period. In particular, attention is drawn to the fact that the two very substantial residuals for July 1967 (– 64 mm) and for August 1967 (– 41 mm) virtually disappear.

Ten-day balance

The graphical or tabular presentation of all the 10-day water balance data would clearly be unwieldy and potentially tedious. Two specimen periods have, therefore, been selected (see Table 5) to illustrate a number of salient points. The main reason for choosing these periods was that both are almost coincident with consecutive months having large and small residuals for the monthly partial water balance equation, i.e. $P-Q-E-\triangle G$. Thus during the first period the residuals for November and December 1967 were + 24 mm and – 3 mm respectively and during the second period, for July and August 1969, were + 3 mm and – 41 mm respectively. Examination of the 10-day data again emphasises how shorter-term data may indicate the complexities concealed by the longer-period values.

Referring to the 1967 data it is interesting that during the first three 10-day periods precipitation input is fairly precisely accounted for by the output of streamflow. The large positive residual for this 30-day period, therefore, seems to result almost entirely from the depletion of storage within the catchment as indicated by the negative $\triangle G$ values (no soil moisture data were available at this time). Possible explanations, upon which only speculation is possible at this stage, are that

1) the soil and subsoil layers above the water table stored a large proportion

Table 4.
Monthly water balance data.

MONTH	P	Q	E	ΔG	RESIDUAL P - (Q + E + ΔG) (mm)	ΔS* tensiometers (cm)
		(mm)				
1966						
O	71	30	27	+ 14	0	no data
N	58	34	9	+ 19	– 4	no data
D	46	35	6	– 6	+ 11	no data
1967						
J	39	30	0	+ 10	– 1	no data
F	53	33	13	+ 4	+ 3	no data
M	38	16	39	– 21	+ 4	– 1.5
A	31	4	34	– 8	+ 1	– 1.5
M	122	32	40	+ 32	+ 18	+ 2.3
J	14	5	78	– 47	– 22	– 15.8
J	28	1	103	– 12	– 64	– 31.4
A	83	1	72	+ 2	+ 8	+ 15.5
S	49	1	40	- 4	+ 12	+ 4.0
O	85	5	24	+ 39	+ 17	+ 7.1
N	59	36	0	– 1	+ 24	+ 1.4
D	47	23	0	+ 27	– 3	+ 3.2
1968						
J	31	38	6	– 18	+ 5	– 0.8
F	31	28	5	– 13	+ 11	– 0.2
M	26	5	31	– 6	– 4	– 0.3
A	55	3	51	– 6	+ 7	– 6.0
M	78	26	53	– 6	+ 5	+ 2.2
J	58	2	76	– 5	– 15	– 12.2
J	89	12	66	– 1	+ 12	+ 7.6
A	53	2	68	– 6	– 11	– 4.0
S	77	12	40	+ 21	+ 4	+ 9.8
O	59	23	24	+ 26	– 14	+ 1.0
N	79	47	7	+ 4	+ 21	+ 0.3
D	51	22	5	+ 5	+ 19	+ 0.7
1969						
J	66	101	0	– 16	– 19	– 1.0
F	58	36	18	+ 9	– 5	+ 2.5
M	68	48	24	– 13	+ 9	– 0.1
A	94	48	32	+ 22	– 8	+ 0.8
M	54	22	49	– 42	+ 25	– 2.0
J	72	17	72	– 8	– 9	– 0.5
J	80	4	103	– 30	+ 3	+ 1.4
A	16	1	84	– 28	– 41	– 22.8
S	55	2	47	– 7	+ 13	+ 8.9

* negative and positive values in this column represent reduction and increase in soil moisture storage respectively, i.e. sign has been reversed for ease of comparison with residual.

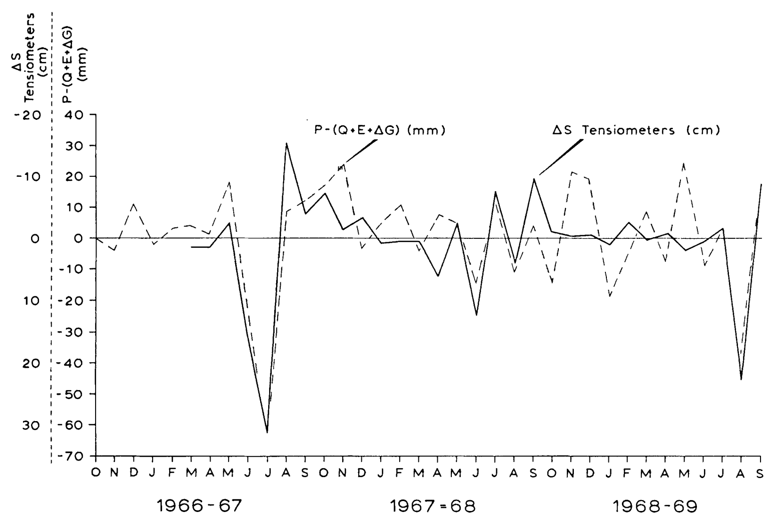


Fig. 2.

Comparative graphs of monthly water balance residuals with △ S as derived from tensiometers.

of the incoming precipitation, which slowly percolated through and showed as groundwater accretion during the 4th and 5th 10-day periods,

2) evapotranspiration losses from the catchment were substantially higher than those indicated, which would not be unlikely, and

3) that the groundwater depletion may be attributed to subsurface leakage from the catchment. During the last three 10-day periods of the 1967 data, streamflow accounts for a much smaller proportion of precipitation indicating that storage of moisture must have been an important factor. Again, however, this must have been largely above the water table since the increase in groundwater storage from 5th to 24th December has already been attributed to the downward percolation of precipitation from an earlier period.

In contrast, the 1969 summer data display a more coherent pattern. All the residuals are negative; in all but one of the 10-day periods evapotranspiration losses substantially exceeded precipitation input; and runoff was negligibly small. All of this implies large withdrawals of moisture from storage mainly to satisfy the evapotranspiration demand. Such withdrawals are indicated by the negative values af △G in all but the final 10-day period and by the indication of negative changes of soil moisture storage in all but one 10-day pe-

Table 5.
Ten-day water balance data.

TEN-DAY PERIODS	P (mm)	Q (mm)	E (mm)	$\triangle$G (mm)	RESIDUAL P − (Q + E + $\triangle$G) (mm)	$\triangle$S* tensiometers (cm)
1967						
Nov. 5 – Nov. 14	26	23	0	− 1	+ 4	no data
Nov. 15 – Nov. 24	3	3	0	− 17	+ 17	no data
Nov. 25 – Dec. 4	2	2	0	− 10	+ 10	no data
Dec. 5 – Dec. 14	22	4	0	+ 12	+ 6	no data
Dec. 15 – Dec. 24	9	6	0	+ 16	− 13	no data
Dec. 25 – Jan. 3	23	15	1	− 6	+ 13	no data
1969						
Jul. 7 – Jul. 16	10	1	28	− 11	− 8	− 6.1
Jul. 17 – Jul. 26	20	0	41	− 9	− 12	− 0.3
Jul. 27 – Aug. 5	49	3	29	− 4	− 21	+ 10.5
Aug. 6 – Aug. 15	1	0	31	− 10	− 20	− 9.5
Aug. 16 – Aug. 25	13	0	28	− 10	− 5	− 1.7
Aug. 26 – Sep. 4	2	0	21	+ 5	− 24	− 10.3

* negative and positive values in this column represent reduction and increase in soil moisture storage respectively, i.e. sign has been reversed for ease of comparison with residual.

riod. Irrespective of the correct numerical value which should be attributed to $\triangle S$, this was clearly a period in which a drying out of the catchment occurred and this, in turn, helps to explain the successive negative residuals.

Storm period balance

It must clearly be possible not only to cast and solve the water balance for any finite period such as those which have already been illustrated but also to solve the balance instantaneously through any period of time such as the duration of a storm or a precipitation-free period of moisture depletion. This more detailed approach demands more intensive and more accurate data and preferably continuous records of all water balance parameters at a large number of sites within the experimental catchment. Such data are not available for the Catchwater Catchment, but some indication of this approach is given by an examination of water balance conditions during a selected storm period in June 1969. Mass curves of the principal water balance components are shown in Fig. 3, and it will be observed that using the arbitrary assumptions about soil moisture and groundwater storage changes which have been used throughout this paper, the water balance equation $P = Q + E + \triangle G + \triangle S$ solves without residual, i.e. $29 \equiv 12 + 25 - 6 - 2 = 0$. In itself this is an extremely satisfactory situation, although examination of the individual mass curves indicates a number of discrepancies.

The mass curve of precipitation reflects the brief period of heavy rain during the night of 2nd – 3rd June, in the course of which 29 mm of precipitation occurred with no further increment before the end of the period under study. The resulting mass curve of runoff is of typical form and reflects a sharp-peaked hydrograph with steep rising limb and somewhat shallower falling limb. Total runoff during this period was 12 mm. Evapotranspiration losses were 25 mm, at a fairly uniform daily rate throughout the study period, so that by the end of the final day the mass $(Q + E)$ curve exceeded the P curve by

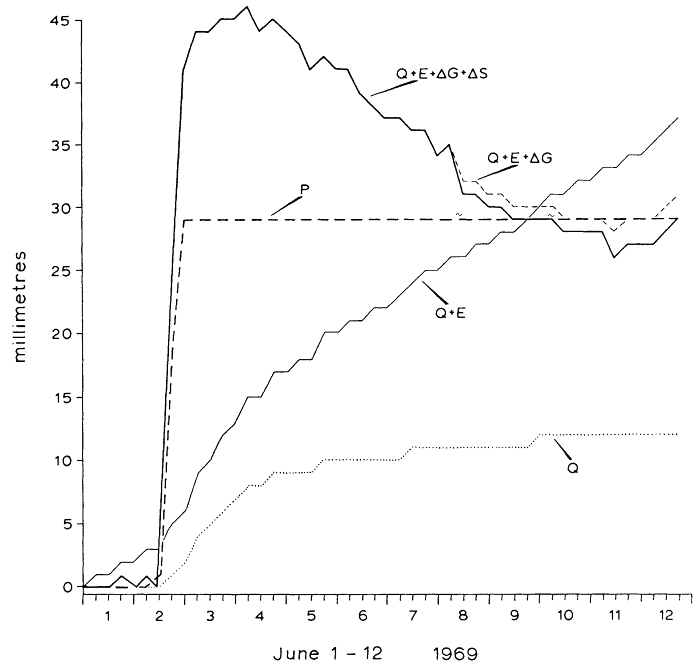


Fig. 3.

Mass curves of principal water balance components during a selected storm period.

8 mm, an amount which was precisely accounted for by a net soil moisture deficit of 2 mm and a net groundwater storage deficit of 6 mm through the period in question.

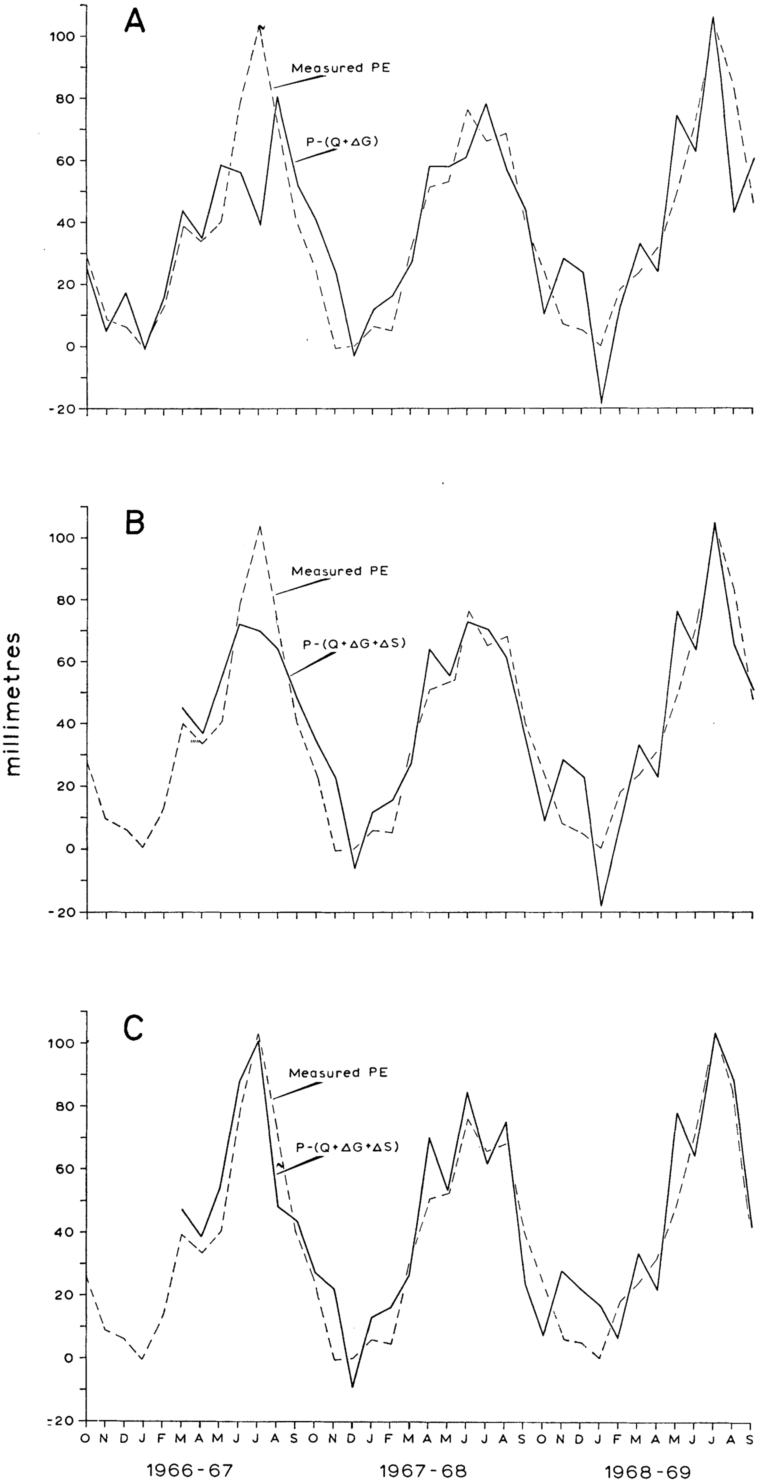
It will be noted that the combined $(Q + E + \triangle G)$ and the $(Q + E + \triangle Q + \triangle S)$ curves rise well above the mass curve of rainfall from the occurrence of rain until 9th June, seemingly indicating that the observed rise of water level in the well was not an entirely accurate reflection of groundwater storage changes but that it possibly incorporated an additional element of concentrated inflow to the well which took a little over one week to drain away. Only at the end of this drainage period, i.e. on 11th June, did the well water level again provide an accurate indication of groundwater storage.

ALTERNATIVE WATER BALANCE CHECKS

Apart from solving the water balance equation for varying, overlapping time periods, as has been illustrated above, additional checks on the accuracy with which measurements of individual water balance parameters have been made may be achieved by casting the water balance equation in modified forms. Thus, for example, instead of writing $P - Q - E - \triangle G - \triangle S \equiv 0$ it is possible to write $E \equiv P - (Q + \triangle G + \triangle S)$ and then to compare the value of E so derived with the value of E (potential evapotranspiration) measured at the climatological station within the catchment. A close similarity between the two values will provide further confirmation of the apparent accuracy of the potential evapotranspiration measurement whilst substantial discrepancies will suggest possible errors needing further investigation.

Three forms of this additional water balance check, applied to the monthly data for the duration of the study period, are illustrated in Fig. 4. In graph A) measured E values are compared with $P - (Q + \triangle G)$ and it will be observed that although there is general agreement between the two curves, there are also marked discrepancies at various times, particularly during the summer and autumn of 1967, the summer of 1969 and the winter of 1968–69. Such

Fig. 4.
Comparative graphs of measured potential evapotranspiration (PE) and evapotranspiration (E) calculated from the water balance equations. See text for full explanation.


A
Measured PE
P-(Q+ΔG)
B
Measured PE
P-(Q+ΔG+ΔS)
C
Measured PE
P-(Q+ΔG+ΔS)
millimetres
100
80
60
40
20
0
-20
O N D J F M A M J J A S O N D J F M A M J J A S O N D J F M A M J J A S
1966-67
1967-68
1968-69

discrepancies are to be expected for two main reasons. First, $\triangle S$ has not been accounted for but will probably have an important effect, especially in the summer months when the effectiveness of rainfall is decreased by the development of substantial soil moisture deficits. This effect is likely to be less important in the winter months when the variations of soil moisture storage are normally smaller. Secondly, the use of monthly data inevitably means that lag discrepancies will be introduced into the water balance estimate of E, particularly when rainfall occurs towards the end of the month. This will result in the estimated values of E being too high in the month in question and too low, because of the runoff generated by the previous month's rainfall, in the subsequent month. Lag discrepancies of this nature can only be overcome by shortening the water balance period. Graph B), however, indicates how the incorporation of $\triangle S$ helps to reduce discrepancies resulting from moisture storage in the soil zone. The situation is markedly improved in the summer and autumn of 1967 and in the late summer of 1969 by calculating $\triangle S$ on the arbitrary assumption, previously explained, that a change of 1 cm in the mean tensiometer readings represents a change in soil moisture storage of 1 mm.

Finally, graph C) shows that an even closer similarity between the measured *PE* curve and the water balance estimate of E can be obtained by calculating $\triangle S$ on the arbitrary assumption implicit in Fig. 2, namely that a change of 1 cm in the mean tensiometer reading represents a change in soil moisture storage of 2 mm. In this way the summer season discrepancies virtually disappear, leaving the majority of serious discrepancies confined to the winter period of 1968–69.

The validity of the water balance calculations can be further checked by applying aspects of the Thornthwaite water balance technique (Thornthwaite & Mather 1955) to the relevant data. Thornthwaite suggested that by keeping a running tabulation of precipitation and potential evapotranspiration and by making assumptions about the magnitude of soil moisture storage, quantitative estimates could be made of actual evapotranspiration, moisture deficit, soil moisture storage, runoff, and in appropriate conditions snow accumulation and melt. Comparison of each of these estimated values with actual measurements made in the catchment will constitute a further check on the accuracy of the latter. For convenience, in the present study no attempt has been made to calculate actual evapotranspiration; instead it has been assumed that evapotranspiration losses occurred always at the potential rate. Inevitably some discrepancy is likely to be introduced as a result, particularly in the dry summer periods, although other considerations of the data from the Catchwater Catchment (Pegg & Ward 1971) do much to substantiate the contention that actual evapotranspiration $\longleftrightarrow$ *PE*.

Table 6.
Modified Thornthwaite water balance estimate of runoff from the Catchwater Catchment.

LINE	ITEM					1966–67							
	(mm)	O	N	D	J	F	M	A	M	J	J	A	S
1	PE	27	9	6	0	13	39	34	40	78	103	72	40
2	P	71	58	46	39	53	38	31	122	14	28	83	49
3	Difference	44	49	40	39	40	-1	-3	82	-64	-75	11	9
4	△Storage	0	0	0	0	0	-1	-3	+4	-64	-75	+11	+9
5	Moisture Depletion	0	0	0	0	0	-1	-4	0	-64	-139	-128	-119
6	Moisture Surplus	44	49	40	39	40	0	0	78	0	0	0	0
7	Runoff *	26	40	40	40	40	16	6	49	20	8	3	1
8	Runoff * 1967–68	1	1	28	26	26	11	4	16	7	5	2	11
9	Runoff * 1968–69	26	53	49	59	48	46	55	25	10	4	2	1

* Estimated by assuming that 60 % of moisture surplus is rapidly evacuated as runoff whilst the remaining 40 % is held over in storage in the Catchment.

Since the measured soil moisture data were not considered sufficiently reliable to be used as a cross-check in this way, comparisons have been made only between the Thornthwaite water balance estimate of runoff and the measured runoff from the Catchwater Catchment, using monthly data for the 3-year period. To illustrate the simple calculations necessary in this modified approach the relevant data for 1966–67 are set out in Table 6. For the remaining 2 years, only the calculated runoff data are shown. The basic information on *PE* and precipitation (*P*) is set out in the first 2 lines of the table. The third line shows the difference between lines 1 and 2 and represents a series of additions to and subtractions from moisture storage in the catchment. A running check on moisture storage is maintained in lines 4, 5 and 6. When there is a soil moisture deficit, excesses of precipitation over *PE* are first used to bring the soil to "field capacity" and any remaining excess is then regarded as moisture surplus. If the soil is already at "field capacity" the whole of the excess of precipitation over *PE* is available as moisture surplus. When on the other hand, *PE* exceeds precipitation, moisture is withdrawn from storage, as is reflected in the values of moisture depletion given in the Table.

It is assumed that the moisture surplus represents that moisture which is available for streamflow but that because of storage effects within the catchment only part of the moisture surplus generated in any particular month will be evacuated from the catchment as streamflow during that month, the remainder being held over until the following month. Thornthwaite & Mather (1955) assumed, for convenience, that 50 % of the moisture surplus would runoff immediately and that the remaining 50 % would be held in storage but recognised that these percentage figures should be varied to suit the geological and hydrological conditions of the catchment in question. In the case of the Catchwater Catchment the assumption that 60 % of the moisture surplus will be evacuated rapidly and that 40 % will be held in storage seems an appropriate reflection of the physical characteristics of this boulder clay area, and has been used in the present calculations. Thus the 7th line of Table 6 indicates the moisture surplus distributed as runoff (*Q*) in this way for 1966–67 and lines 8 and 9 show the runoff similarly estimated for 1967–68 and 1968–69 respectively.

Fig. 5 shows comparative plots of the observed and estimated values of runoff for the 3-year study period. The general similarity between the two curves is immediately striking and is further emphasised by a comparison of the 3-year

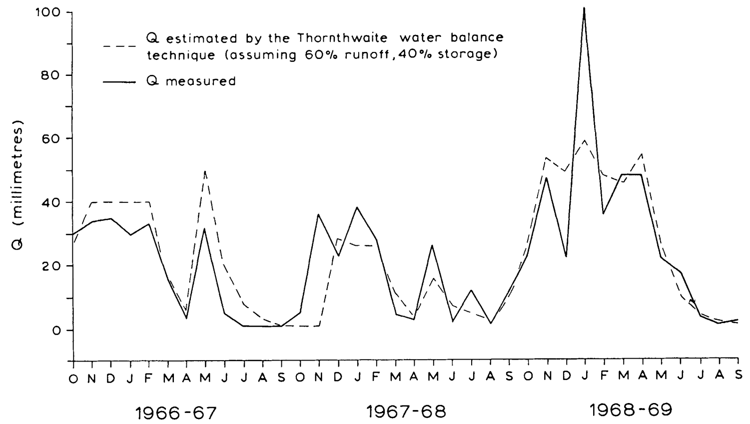


Fig. 5.

Comparative graphs of measured runoff and runoff estimated by the Thornthwaite water balance technique.

totals of 802 mm (Thornthwaite water balance) and 785 mm (Observed) and of the individual annual totals of 286, 138 and 378 mm (Thornthwaite water balance) and 222, 192 and 371 (Observed). This general similarity may be interpreted as still further substantiation of the overall reliability of the hydrological measurements made in the Catchwater Catchment and of the apparently successful water balance solutions previously discussed. On the other hand, Fig. 5 also indicates a number of striking discrepancies between the Thornthwaite water balance estimate and the observed runoff, particularly in the winter of 1968–69. A large part of the problem here may result from lack of sensitivity of the modified Thornthwaite technique used here in relation to snow storage effects. Precipitation falling as snow in one month will be held in storage until it melts, and unless allowance is made for this additional storage the water balance estimate of Q will be too high in the first month and too low in the second. This may partly explain the December 1968 and January 1969 discrepancies and it is interesting to note that the combined totals for these 2 months are not substantially different, i.e. 108 m (Thornthwaite water balance) and 123 mm (Observed).

CONCLUSIONS

General inferences which may reasonably be drawn from the foregoing discussions of water balance data from the Catchwater Catchment are that no one measurement of the principal components of the water balance seems to be consistently or greatly in error and that, related to this, there appears to be no persistent or significant leakage of subsurface water into or out of the catchment.

Examination of the data in this way does, however, raise a number of problems and indicate certain potentially useful lines of future investigation. An important question relates to the magnitude of the water balance residual which may be considered reasonable in the light of errors of measurement of the major water balance components. The percentage differences between the Thiessen polygon estimate of precipitation for the catchment and the arithmetic mean of the four gauge totals have been calculated, for the first 6 months of 1969. The Thiessen estimate has been used in all the calculations in this paper on the grounds that it is more likely to be accurate than the simple arithmetic mean. On the other hand, in an area so topographically subdued as the Catchwater Catchment, differences between the two methods might be expected to be relatively small and it is, therefore, somewhat disturbing to find differences of 6 % occurring in a random sample of 6 consecutive months. Errors of similar magnitude, but opposite sign, in the measurement of other water balance components could result in a situation where residuals of + or – 10 % of the precipitation input would fall within the margin of experimental error.

Clearly detailed investigations should be aimed initially at an improved understanding of hydrological processes within the catchment so that, in turn, more accurate data may be collected. Such detailed studies have been initiated as part of the long-term research plan of the experimental catchment and two, viz. an investigation of the accuracy of measurement of evapotranspiration and its role in the water balance of the catchment, and an investigation of the mode of occurrence and manner of movement of shallow groundwater, have been completed or are now nearing completion. Other going investigations are concerned with the accurate determination of soil moisture with particular reference to the use of a neutron probe and the relations between infiltration, groundwater response to precipitation and the movement of moisture through the soil profile; the character and mechanism of runoff from the catchment; and the patterns of rainfall, particularly storm rainfall, over the catchment and their effects on the hydrological response of the area as reflected in the stream hydrograph.

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Address:
Dr. R. C. Ward
The University, Hull
HU6 7RX England

Received 20 September 1971