I N S T I T U T E   O F   H Y D R O L O G Y

Report No 33 December 1976

WATER BALANCE OF THE HEADWATER CATCHMENTS

OF THE WYE AND SEVERN

1970-1975

ABSTRACT

The analyses described in this Report show that the mean annual loss (1970 - 1975) for the Wye catchment (hill pasture) - where loss is defined as the difference between precipitation and streamflow - is 18% of the mean annual precipitation of 2415 mm. The mean annual loss from the Severn catchment (about two-thirds of which is coniferous forest) is 30% of the mean annual precipitation of 2388 mm. Further, that if the mean annual loss from the Severn catchment is adjusted to allow for the unforested area in its upper reaches, the mean annual loss from the forested area of the Severn rises to about 38% of mean annual precipitation. The adjustment used in this calculation assumes that the rainfall-runoff relation for the unforested area of the Upper Severn is identical with that for the Wye catchment; the four months of runoff measurements from the Upper Severn that were available did not disprove this assumption, but more data are required before the assumption can be adopted with full confidence.

CONTENTS

1. OUTLINE OF THE STUDY

1.1 Historical background

The Institute of Hydrology's study of the headwater catchments of the Wye and Severn, like much other recent work on the losses of water from coniferous forest, has its origins in the meticulously executed study of Law (1956, 1957) on the Hodder Catchment in the Yorkshire Pennines. Concerned about the absence of research on the water balance of woodland, and about possible lower water yields from forested catchments than from catchments planted with short herbaceous vegetation, Law made a careful study of the water balance of a small (0.045 hectare) natural lysimeter in a plantation of Sitka spruce (*Picea sitchesis*) set in a slightly larger block of woodland (area 0.24 hectares). Based on measurements collected over the period 4 July 1955 to 8 July 1956, Law found that the precipitation above the forest canopy was 984 mm; of this, 630 mm reached the forest floor, from which 273 mm appeared as runoff. The total water loss was therefore 711 mm; over the remainder of the Hodder Catchment, however, the total water loss was 421 mm. Law concluded that the loss of water from the forested plantation was the greater by 290 mm.

Law's results attracted the attention of many research workers, and the scepticism of not a few: scepticism based upon the small size of the plantation used in his study which, it was argued, would have led to the introduction of edge effects in both radiative and aerodynamic aspects of vegetation. Rutter (1964), summarizing evidence from his own study of water relations of *Pinus sylvestris* under plantation conditions, from work reported by Deij (1956) on the Castricum lysimeters in the Netherlands, and from East African work by Pereira, Dagg and Hosegood (1962), observed that evaporation from forests had generally been found to lie between 0.8 and 1.0 times the Penman estimate of evaporation from an open-water surface (although, as Rutter states, Penman himself drew no such firm conclusion in his monograph 'Vegetation and Hydrology' (1963)). Rutter's own evidence suggested that actual evaporation from the plantation exceeded open-water evaporation by 10-20%, a high figure by comparison with most other results except those of Law. The main causes suggested for the high values of actual evaporation from forests were the smaller albedo of the vegetation, especially of conifers, giving greater absorption of energy; and greater aerodynamic roughness.

Law's result, if valid, was clearly of the greatest import at a time when water supply undertakings were being encouraged to afforest their water catchments; several industrial conurbations, such as those of the Midlands, draw water supplies from the wetter West and North of the United Kingdom, where the climate is such that land use is largely restricted to a choice between softwood production on the one hand and upland pasture of relatively low productivity on the other. Law's result suggested that extensive afforestation would result in reduced water yield in a period during which domestic consumption may be expected to rise from its present level of 168 litres (37 gallons) per head daily to 273 litres (60 gallons) by the year 2000, and during which industrial water demand for cooling and processing is likely to increase significantly. (Millis (1975) estimated that 44000 gallons, 30000 gallons and 44 gallons of water are required to produce one ton of steel, 1 ton of aluminium and 1 pint of beer respectively).

To attempt verification (or possibly, refutation) of Law's result, the Institute of Hydrology began a programme of research during the 1960s which consisted initially of two catchment studies. In the first, two adjacent catchments on the slopes of Plynlimon, in Central Wales, were intensively instrumented for the measurement of precipitation, river discharge, and soil moisture change; one of the catchments is the headwaters of the Wye (area 1055 hectares, almost entirely upland pasture) whilst the other is the headwaters of the Severn (area 870 hectares, of which slightly more than two-thirds is coniferous forest, principally Sitka spruce and Norway spruce, but with an admixture of Japanese larch). This study has two objectives, best formulated as questions: (i) is the mean annual loss (precipitation minus streamflow) greater for the forested Severn than for the hill pasture of the Wye, and if so, how far is the difference explicable in terms of different land-use? (ii) does the rapidity and magnitude of response to unit depth of precipitation differ for the two catchments, and if so, how far are the differences explicable in terms of different land-use?

The second of the two catchment studies mentioned above was set up on the small (area 152 hectares) moorland catchment of Coal Burn, a tributary of the Irthing in Northumberland. This catchment was ploughed in 1972 then planted with coniferous forest according to standard forestry practice; volume (and other characteristics) of streamflow in the years following ploughing are being compared with those observed in the five years preceding it.

This report gives results of analyses aimed at fulfilling the first of the above objectives, and is concerned exclusively with the analyses of data from the Wye and Severn catchments; results from the Coal Burn catchment will be presented elsewhere, and a later report will give results of analyses to determine the effects of alternative land-uses on the shape of the storm hydrograph (objective (ii) above).

1.2 Instrumentation and measurements

Accurate measurement of the components of the water balance, always a matter of the greatest difficulty, is even further complicated by the remoteness of the Plynlimon catchments, where problems of access and climate call not only for exceptional dedication from the field staff responsible for instrument maintenance and the collection of measurements, but also for instruments of extreme robustness to withstand the attentions of sheep, cattle, and in some cases, birds.

Similarly, stream gauging structures needed to be designed to withstand pounding by large boulders swept downstream in time of flood. Field staff stationed at Plynlimon are responsible for the following instrumentation:-

(i) Networks of raingauges, consisting of 20 ground-level monthly storage gauges in the Wye catchment and 18 monthly storage gauges in the Severn. Of the latter, 11 are at canopy level whilst the remainder are ground level gauges in the unforested part of the Upper Severn, or at Moel Cynnedd, a clearing in the forest at which a meterological station is also sited. In addition to networks of storage gauges, the Wye and Severn catchments each contain 3 Dines rainfall recorders, whilst a replicated network of Rimco raingauges with event recorder is being installed in each catchment. (See Figs. 1.2.1, 1.2.2.)

FIGURE 1.2.1

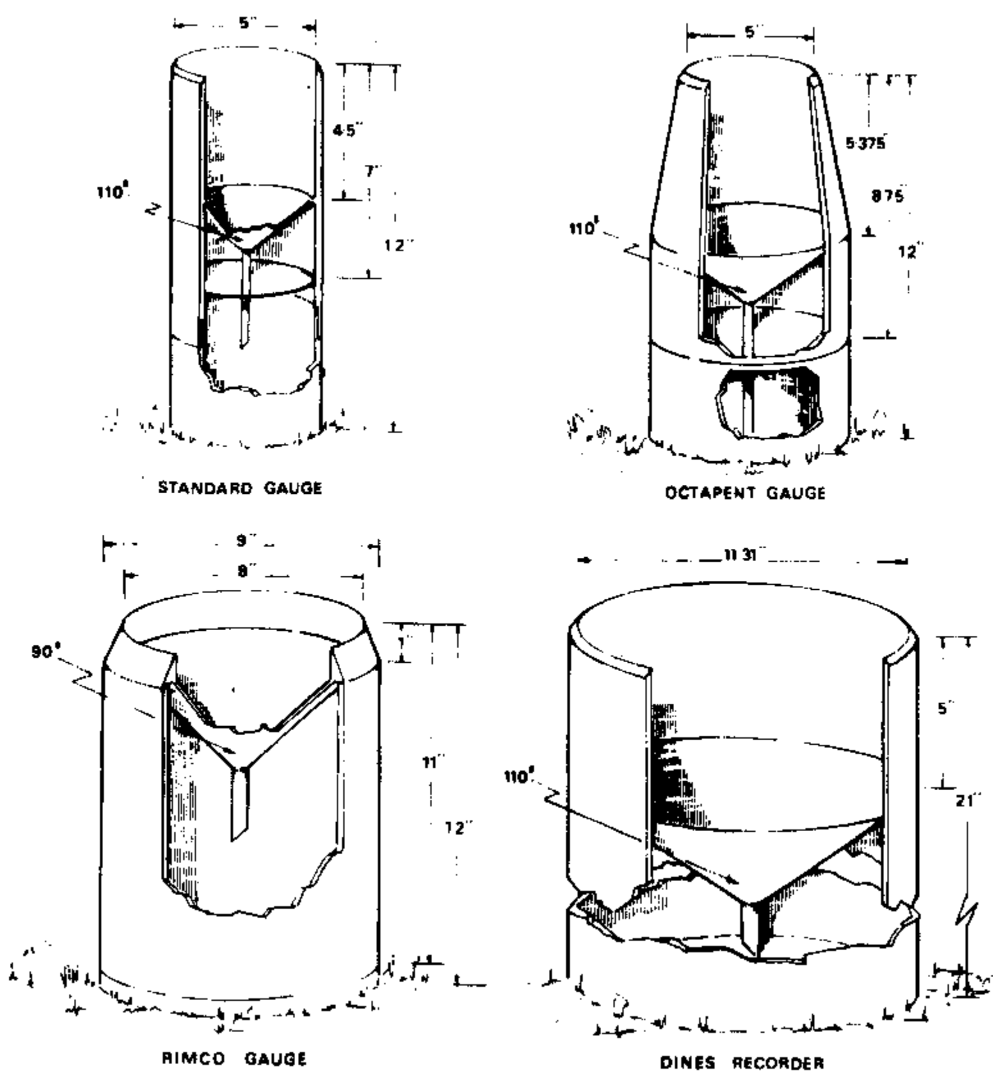


Figure 1.2.1 Types of raingauges in use at Plynlimon

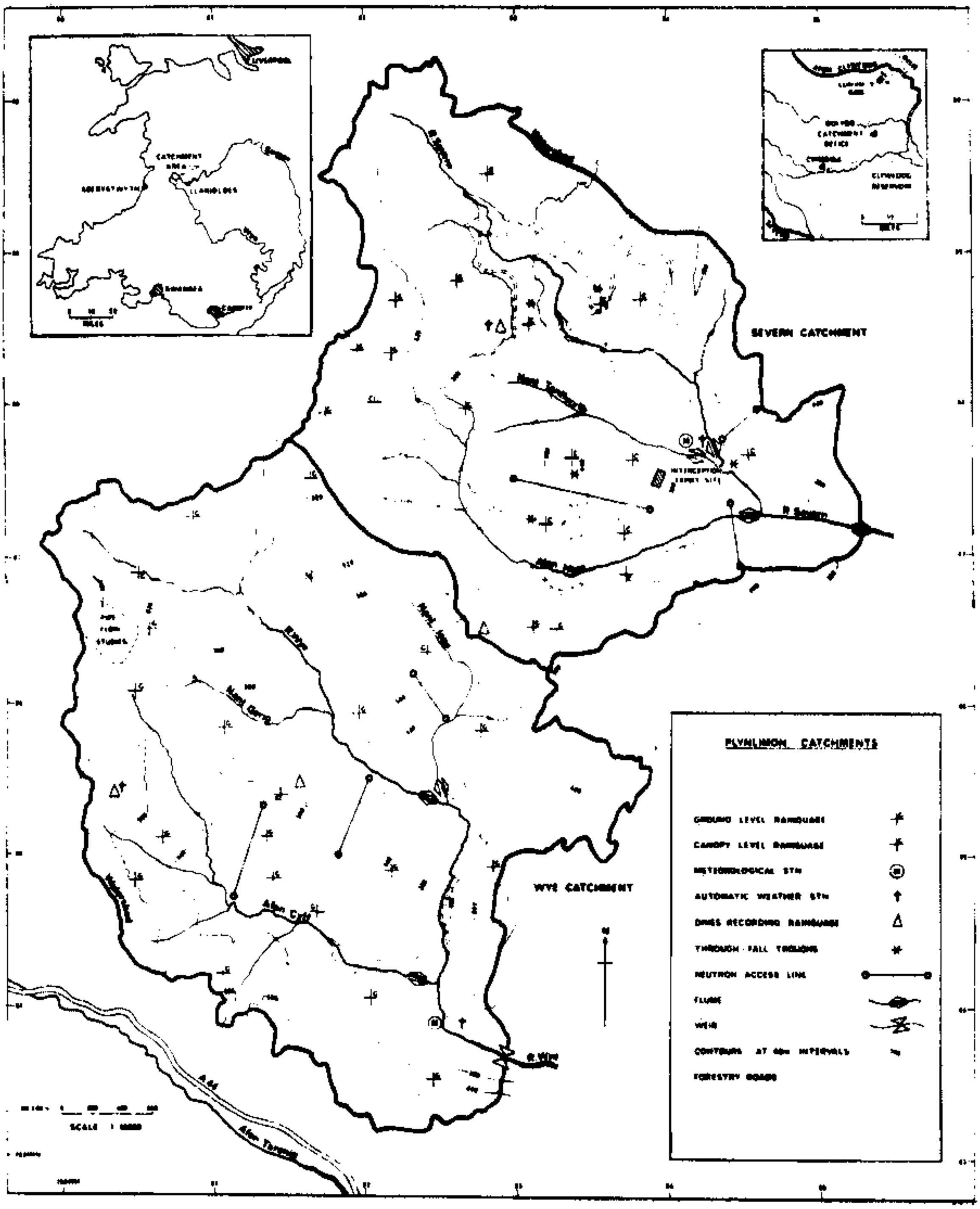


Figure 1.2.2   Map of the Plynlimon catchments

(ii) Stream gauging structures. Flow from the Wye is gauged by a modified Crump weir, and that from the Severn by a trapezoidal flume. Both Plynlimon catchments contain 3 sub-catchments, each of which is gauged by a specially-designed steep stream structure; the sub-catchments of the Wye are those of the Cyff, Gwy and Nant Iago tributaries, and those of the Severn are the Tanllwyth, Hafren and Hore. Stream stage is gauged by a Leupold-Stevens water level recorder, whilst each major catchment also has a Fischer-Porter punched paper tape recorder as a safeguard. (See Fig. 1.2.3)

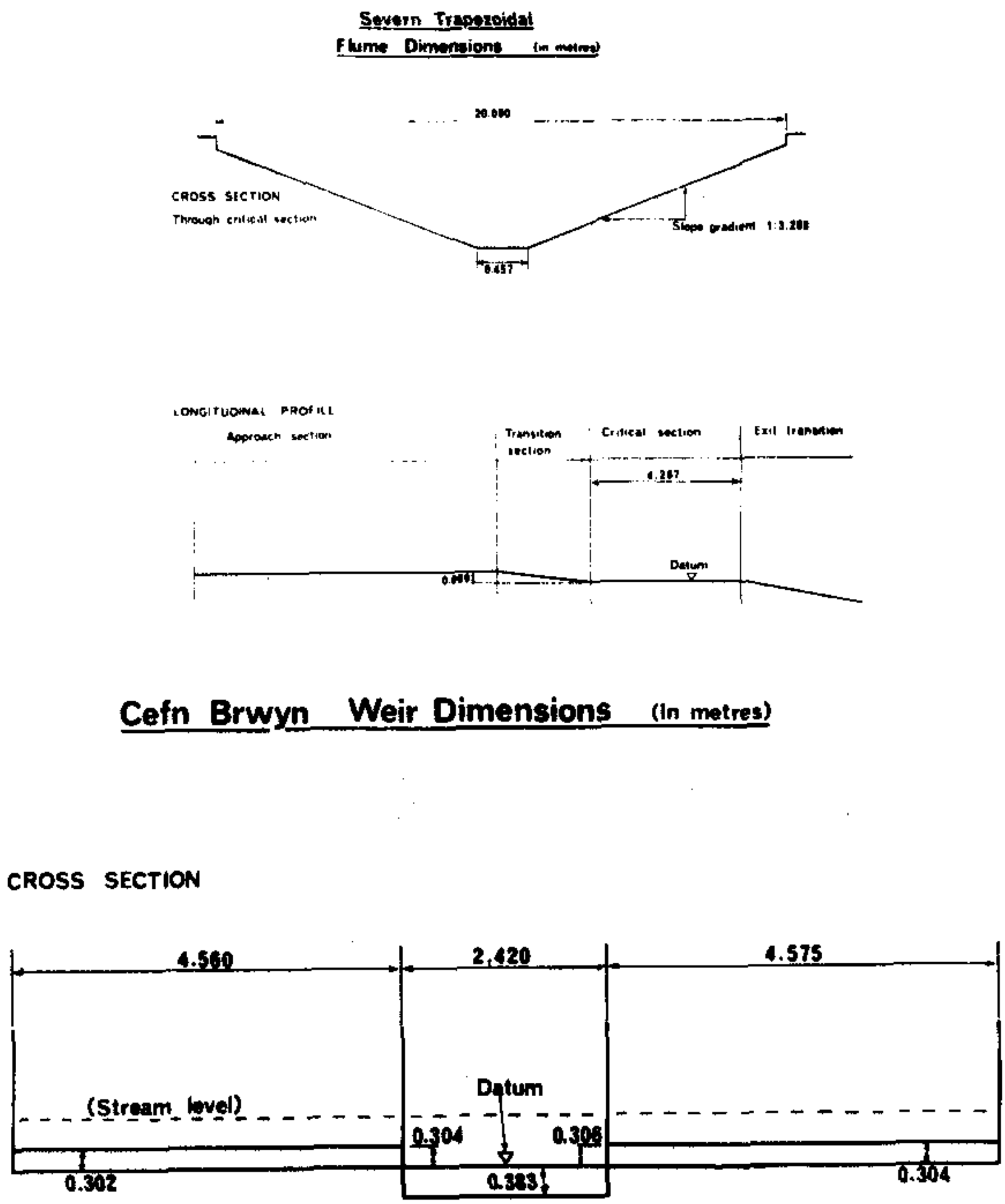


Figure 1.2.3 Severn and Wye stream gauging structures

(iii) Automatic weather stations (in addition to the meteorological station at Moel Cynnedd, mentioned above). Since an understanding of the energy balance may be important in interpreting the water balance data, each automatic weather station records net radiation (ie the balance between incoming and outgoing radiation, both short and long wave) and total solar radiation; variables also recorded are temperature, wet-bulb depression, rainfall, wind-run and wind-direction. All variables are recorded on magnetic tape at 5-minute intervals. (Fig. 1.2.4).

Figure 1.2.4 Institute of Hydrology Automatic Weather Station

(iv) Extensive networks of soil moisture access tubes (approximately 30 on each of the Wye and Severn catchments) at which soil moisture is recorded at 10 cm depth intervals throughout the soil profile by means of a neutron probe. Measurements are taken at roughly monthly intervals whilst for particular periods and purposes, daily readings have been taken. (Fig.1.2.2)

(v) Troughs (4 metres long x 10 cm wide) sited within the forest on the Severn catchment for the measurement of throughfall. (Fig.1.2.?)

In addition to (i) to (v) above, intensive studies of particular hydrological processes, notably interception of precipitation by the forest canopy and infiltration into the soil, have their own instrumentation at selected sites within the Wye and Severn catchments. Depth of snowfall, when it occurs, is measured by photogrammetric methods, supplemented by snow courses on which snow density is also measured. Water samples are also taken to assess natural water quality.

These sources supply data on field sheets, charts, punched paper tape or magnetic tape and data processing presents considerable logistic and computational problems. The suite of computer programs used to process the data is periodically updated as new instruments come into service (such as the auto probe, a device being developed for recording, on magnetic tape, moisture throughout the soil profile at frequent intervals). Full details of methods of computer processing of catchment data has been given in Institute of Hydrology Report No. 15.

1.3 Adequacy of instrument networks

The water balance equation

$$P = Q + \Delta S + AE \qquad \text{.......(1.3.1)}$$

where P, Q, ΔS and AE refer to precipitation, str amflow, soil moisture change, and actual evaporation respectively, (other losses from the catchment are assumed negligible) requires, as an ideal, accurate measurement of its component terms. Throughout the period covered by this report, however, no direct measurement of AE was possible, and an estimate of the actual evaporation loss from a catchment was provided by calculation of $P - Q - \Delta S$; the question may then be asked, 'with what accuracy are the quantities of P, Q and ΔS measured?'

Accurate measurement of any variable is beset with great difficulties, since the value recorded by an instrument is not necessarily the value which the measured variable would have assumed in the instrument's absence; the uncertainty principle, that a system cannot be measured without interfering with it, obtains in hydrology as in other sciences. However, provided that the inaccuracy of measurements is of the very simple kind described below, difficulties associated with accuracy of measurement are largely eliminated by working with differences between measurements, rather than with their absolute values; the problem then becomes the simpler one of assessing the <u>precision</u> of measurements, instead of their <u>accuracy</u>.

The simple case referred to in the last paragraph is the following. Suppose that we have a measurement x_{OBS} of a quantity whose true value is x_{TRUE}; x_{OBS} may be subject both to random errors of measurement, and a constant bias b, say. In symbols,

$$x_{OBS} = x_{TRUE} + b + \varepsilon \qquad \ldots\ldots\ (1.3.2)$$

where ε is a random error of measurement. If we have $x^{(1)}_{OBS}$ and $x^{(2)}_{OBS}$ from catchments 1 and 2 respectively, so that

$$x^{(1)}_{OBS} = x^{(1)}_{TRUE} + b + \varepsilon^{(1)}$$

$$x^{(2)}_{OBS} = x^{(2)}_{TRUE} + b + \varepsilon^{(2)}$$

then the difference between observations

$$x^{(1)}_{OBS} - x^{(2)}_{OBS} = x^{(1)}_{TRUE} - x^{(2)}_{TRUE} + \varepsilon^{(1)} - \varepsilon^{(2)}$$

is an unbiased estimate of the true difference. We need therefore consider only the precision of this estimate, as described by the variance of $\varepsilon^{(1)} - \varepsilon^{(2)}$.

The above justification for working with differences, as a means of avoiding difficulties of accurate measurement, is invalid if the inaccuracy of observation is other than a constant bias. If, for example,

$$x^{(1)}_{OBS} = \beta\, x^{(1)}_{TRUE} + \varepsilon^{(1)}$$

$$x^{(2)}_{OBS} = \beta\, x^{(2)}_{TRUE} + \varepsilon^{(2)}$$

then the difference between observations $x^{(1)}_{OBS} - x^{(2)}_{OBS}$ is no longer an unbiased estimate of $x^{(1)}_{TRUE} - x^{(2)}_{TRUE}$. Biases of this form (with observations proportional to their true values) may be detectable if all four components in the water balance equation (1.3.1) are measured since the relation between the observed components then becomes

$$P_{OBS} = \left(\frac{\beta_Q}{\beta_P}\right) Q_{OBS} + \left(\frac{\beta_{\Delta S}}{\beta_P}\right) \Delta S_{OBS} + \left(\frac{\beta_{AE}}{\beta_P}\right) AE_{OBS}$$

and significant departure fron unity of the partial regression coefficients when P_{OBS} is regressed (through the origin) on Q_{OBS}, ΔS_{OBS}, and AE_{OBS} as independent variables would cast light on which observations, if any, have proportional biases. The interpretation of the partial regression coefficients in this way is very much open to doubt, however, if there is any possibility that terms may have been improperly omitted from the water balance equation (if, for example, losses from the catchment by deep percolation were appreciable, but had been assumed negligible).

On the assumption that inaccuracies are of the 'constant bias' type illustrated in equation (1.3.2), attention may then be concentrated on the precision of estimates as measured by their reproducibility about a central value, and this is considered in the following subsections.

1.3.1. Precision of the estimate of mean areal precipitation

The precision of mean areal precipitation has been considered in Institute of Hydrology Report No 27: Analysis of data from Plynlimon raingauge networks: April 1971-March 1973. On the assumption that precipitation y_{ijk} recorded by a monthly storage gauge in altitude class i, slope class j, and aspect class k, could be adequately represented by a linear statistical model of the form

$$y_{ijk} = \mu + a_i + s_j + l_k + \varepsilon_{ijk} \qquad \text{.........(1.3.1.1.)}$$

in which ε_{ijk} is a random variable with zero mean and constant variance σ_e^2, then the constants μ, a_i, s_j and l_k were estimated by least squares, and the residual variance σ_e^2 estimated. The coefficient of variation $(100\hat{\sigma}_e/\bar{y})$ was, on average, about 7% for the Wye and 10% for the Severn; with the further assumption that mean areal precipitation could be adequately estimated by the arithmetic mean $\bar{y}$ of all gauges within a catchment, a crude estimate of the number of gauges required if the calculated mean is to lie within d% of the true mean was obtained from:

$$n = 4(CV)^2/d^2 \qquad \text{..........(1.3.1.2)}$$

where CV is the coefficient of variation. This calculation showed the numbers of gauges required on the catchment were as shown in Table 1.3.1.1.

Table 1.3.1.1 Numbers of period (storage) gauges required to estimate mean monthly precipitation with given precision

	Estimate to lie within d% of the true areal mean: d=20%:	d=10%:	d=5%:	d=2.5%:	d=1%:
Approximate number of gauges:					
Wye:	1	2	8	31	196
Severn:	1	4	16	64	400

It will be recalled that the Wye and Severn catchments contain 20 and 18 monthly storage gauges respectively; comparison of these values with the numbers shown in Table 1.3.1.1 suggests that the existing networks estimate mean areal precipitation to within rather less than 5% of the true areal mean (as measured by an infinitely dense network of gauges).

1.3.2 Comparison of catches of canopy level and ground-level gauges

Eleven of the eighteen gauges in the Severn catchment are mounted on masts to canopy level; the remaining seven, and all the gauges in the Wye catchment, are at ground level. The difficulties of measuring precipitation over a forest are well known (Mill (1900); Law (1957); Penman (1965)), and analysis to estimate the possible magnitude of the difference in catch between ground-level and canopy level gauges was therefore necessary.

Attention was restricted to the eighteen gauges in the Severn catchment and to the analysis of monthly precipitation for the period April 1971 to March 1973. The Severn gauges are, of course, distributed throughout a range of altitudes, aspects and slopes, allocation being by means of a domain theory described at length in Institute of Hydrology Report No. 27. This report had showed that aspect and slope effects, on monthly storage gauge catch, were small, and of the order of sampling error; altitude effects, however, were considerable in most months. To assess the differences between catches by ground level and canopy level gauges, catches were therefore adjusted for altitude differences, but no attempt was made to adjust for differences in slope or aspect.

To separate the effects of ground level and canopy level gauges, after adjustment for altitude differences, a statistical model of the following form was used:-

$$y_{ijk} = \mu + a_i + l_j + \varepsilon_{ijk} \qquad \qquad ....(1.3.2.1)$$

where i = A, B, C or D is a suffix referring to the altitude class; j = 1 for ground level gauges, j = 2 for canopy level gauges; and y_{ijk} is the catch of the k^{th} gauge in the i^{th} altitude class and j^{th} level. If μ is the true mean areal precipitation for the entire catchment, the catch by a gauge in altitude class i will deviate from μ by an amount a_i which measures the extent to which gauges in that altitude class tend to catch more (or less) than the true areal mean. Clearly the sum of the a_i over all the gauges in the network must be zero, because the areal mean is μ. The gauge under consideration may be either a ground level gauge or a canopy level gauge, and the possibility of differential catch is allowed for in the model by the term l_j. (l_1 is the deviation from the true areal mean μ that is appropriate to ground level gauges, l_2 is the deviation appropriate to canopy level gauges). As before, the sum of the l_j over all gauges in the network must be zero.

With the above statistical model, a test was made of the hypothesis that catches by ground level and canopy level gauges do not differ, apart from random variation. (In the terminology, the null hypothesis is given by $H_o: l_1 = l_2 = 0$, to be tested against the alternative $H_1: l_1, l_2 \neq 0$). The calculation was set out in tabular form in which the total sum of squares of deviations from the estimated arithmetic mean μ for the whole catchment is divided into three components: one corresponding to differences between altitude classes, ignoring the effect of differences between the gauge levels; another corresponding to the difference between gauge levels, eliminating the effects of differences between altitude divisions; and a third yielding an estimate of the variance of residuals ε_{ijk}. The analysis of variance table was therefore as follows

	df
Between altitude classes (ignoring gauge level)	3
Between gauge levels (eliminating altitude effects)	1
Residual	13
Total	17

The null hypothesis of no difference between levels was tested by comparing the ratio (mean square between levels, eliminating altitude effects/residual mean square) with tabulated values of the F statistic for 1 and 13 degrees of freedom.

Table 1.3.2.1 shows the values of the 'level' constants l_1, l_2 (free *from altitude effects) obtained month by month for the period* April 1971-March 1973, together with the arithmetic mean of all 18 gauges. In 13 of the 24 months, ground level gauges caught more than the overall mean (since the values of l_1 were positive in 13 months of the 24); in the remaining 11 months they caught less. On average, over all 24 months, ground level gauges caught 2.8 mm more than the monthly mean (174.4 mm) and the canopy level gauges caught 1.8 mm less (7 x 2.8 + 11 x -1.8 = 0, apart from rounding error). Table 1.3.2.1 also shows that significant ($P < 0.05$) departures from zero of the level constants, l_1 and l_2, occurred in only 3 months of the 24 (February and March 1972, February 1973). All three were months when snow fell at the Moel Cynnedd meteorological station: the table also shows the number of days on which snow fell there. If means are taken over all months when snow fell, gauges at ground level caught 7.3 mm more precipitation over a month than the mean for all gauges, and those at canopy level about 4.6 mm less.

The conclusion of this analysis is as follows. In months free of snowfall, differences in catch between ground level and canopy level gauges are likely to be no greater than site to site variation in the same altitude class. In months when much precipitation falls as snow, the catch by ground level gauges may well be significantly greater than catch by canopy level gauges. This may be because turbulence at canopy level causes mast head gauges to undercatch, or because snow drifting into ground level gauges causes them to overcatch.

Whatever the explanation, the analysis suggests that the difference in catch is no more than a very few percent in months when snow days are few. It is fortunate that snow constituted only a small part of precipitation in the 5 years covered by this report.

Table 1.3.2.1 Parameters l_1, l_2 representing the difference between ground-level and canopy-level gauge catch, April 1971-March 1973

	Mean all gauges	Ground level (l_1) millimetres	Canopy level (l_2)	Snow days Moel Cynnedd†
Apr. 1971	71.2	+ 0.8	- 0.5	0
May 1971	75.2	+ 2.1	- 1.3	0
June 1971	192.4	+ 2.4	- 1.6	0
July 1971	71.1	+ 1.2	- 0.7	0
Aug. 1971	217.8	- 1.3	+ 0.8	0
Sept. 1971	89.7	+ 1.5	- 1.0	0
Oct. 1971	211.2	+ 6.9	- 4.4	0
Nov. 1971	307.9	+ 8.9	- 5.7	7
Dec. 1971	127.9	- 0.6	+ 0.4	3
Jan. 1972	227.6	+10.1	- 6.4	8
Feb. 1972	145.9	+18.6*	-11.8*	6
Mar. 1972	213.2	+21.1*	-13.4*	3
Apr. 1972	301.2	+18.8	-12.0	0
May 1972	145.8	- 6.5	+ 4.1	0
June 1972	198.1	-15.9	+10.1	0
July 1972	141.0	- 6.4	+ 4.1	0
Aug. 1972	123.8	- 5.0	+ 3.2	0
Sept. 1972	62.0	- 2.4	+ 1.5	0
Oct. 1972	81.1	- 1.6	+ 1.0	0
Nov. 1972	328.5	- 3.5	+ 2.2	1
Dec. 1972	254.8	- 5.5	+ 3.5	1
Jan. 1973	176.4	+ 5.7	- 3.6	4
Feb. 1973	283.4	+26.7*	-17.0*	9
Mar. 1973	138.6	- 8.4	+ 5.4	1
Overall mean	174.4	+ 2.8	- 1.8	
Mean, months when snow fell	220.4(10)	+ 7.3	- 4.6	
Mean, months when no snow fell	141.5(14)	- 0.4	+ 0.2	

* Denotes statistical significance ($P<0.05$).

† National Grid Reference SN 843877

1.3.3 Precision of the estimate of mean areal soil moisture change, ΔS

The Wye and Severn catchments each contain three 'lines' of access tubes perpendicular to the contour pattern; there are also other tubes which are read less frequently than the tubes sited in lines. The lines in the Wye catchment are named the Wye, Nant Iago and Cyff lines, and contain six, seven and seven tubes respectively; those in the Severn are named the Hore, Moel Cynnedd and Y Foel lines, and contain six, eight and eight tubes respectively.

To examine the loss of precision resulting from possible reduction in network density on the estimate of mean change in soil moisture, subnetworks containing varying numbers of access tubes were selected at random from the existing networks. The value of $\bar{\Delta}S$ (ie the sample arithmetic mean of the changes in soil moisture, throughout the profile, for the tubes in the subnetwork) was computed, together with the variance $s^2(n)$ amongst the estimates $\bar{\Delta}S$ from subnetworks of the same size (n tubes); this variance was then plotted as a function of n to examine how rapidly it increased as n decreased.

Data were abstracted from the record for intervals at the beginning and end of which all access tubes in the networks (29 tubes on the Severn catchment, 30 on the Wye) had been visited, so that the soil moisture change ΔS_i for the i^{th} access tube was available for the complete network. The data used were the following

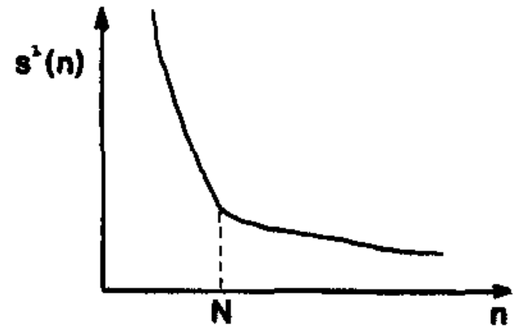
Severn:	2. 5.1969 to 30. 5.1969
	4. 1.1971 to 25. 4.1971
	29. 5.1971 to 22. 6.1971
	28.10.1971 to 25.11.1971
	23. 3.1972 to 27. 4.1972
	27. 7.1972 to 8. 9.1972
	25. 4.1973 to 31. 5.1973
Wye:	1. 5.1969 to 29. 5.1969
	22. 6.1971 to 6. 8.1971
	23. 3.1972 to 27. 4.1972
	25. 4.1973 to 31. 5.1973

For each catchment, non-overlapping subnetworks of sizes 2, 3, 4, 5, 6, 7, 8 and 9 access tubes were constructed from the complete networks of 29 and 30 tubes, so that the number of subnetworks were as follows

n:	2	3	4	5	6	7	8	9
Severn:	14	9	7	5	4	3	3	3
Wye:	15	10	7	6	5	4	3	3

For the denser subnetworks, therefore the variance $s^2(n)$ was calculated from a few values only, and is therefore subject to greater uncertainty than the values of $s^2(n)$ calculated for small n.

It was expected that the plot of $s^2(n)$ against n would show the following pattern:-



As the number of tubes in the subnetwork increases to N, the variance $s^2(n)$ reduces rapidly so that a relatively small increase in network density corresponds to a relatively large increase in precision of the mean areal estimate $\bar{\Delta}S$. As n increases beyond N, however, the increase in precision corresponding to an increase in n becomes much less; in a rather loose sense, therefore, N (the value of n at which the curve's "elbow" occurs) is an optimum density for the network. The purpose of the calculations was to estimate the value of N for each catchment.

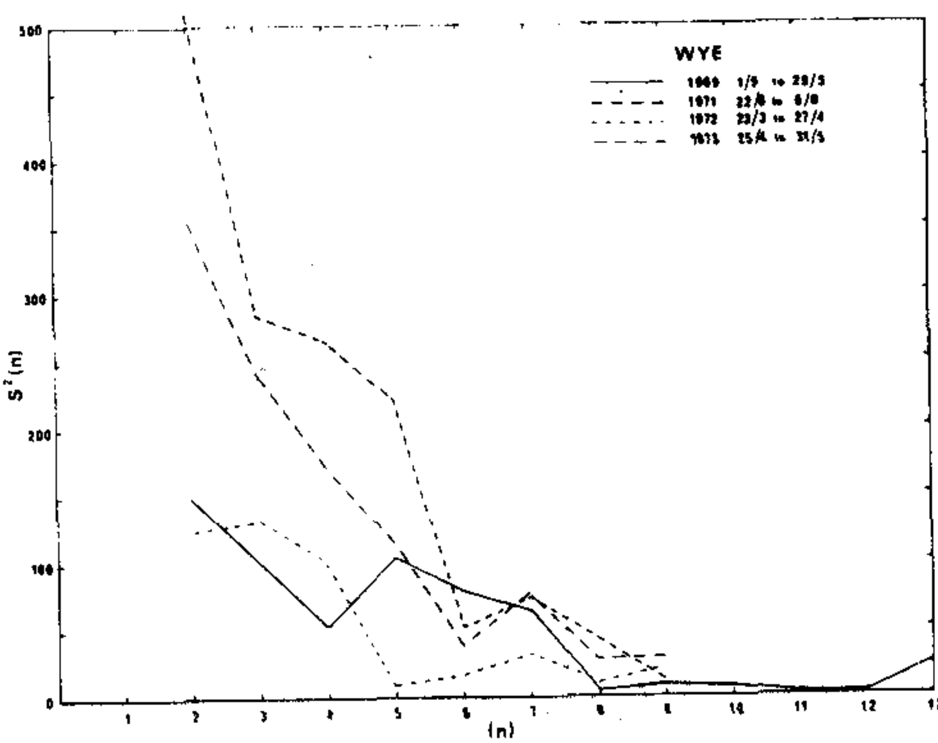


Figure 1.3.3.1 Variance of $\bar{\Delta}S$ for neutron access tube networks of size n tubes: Wye catchment

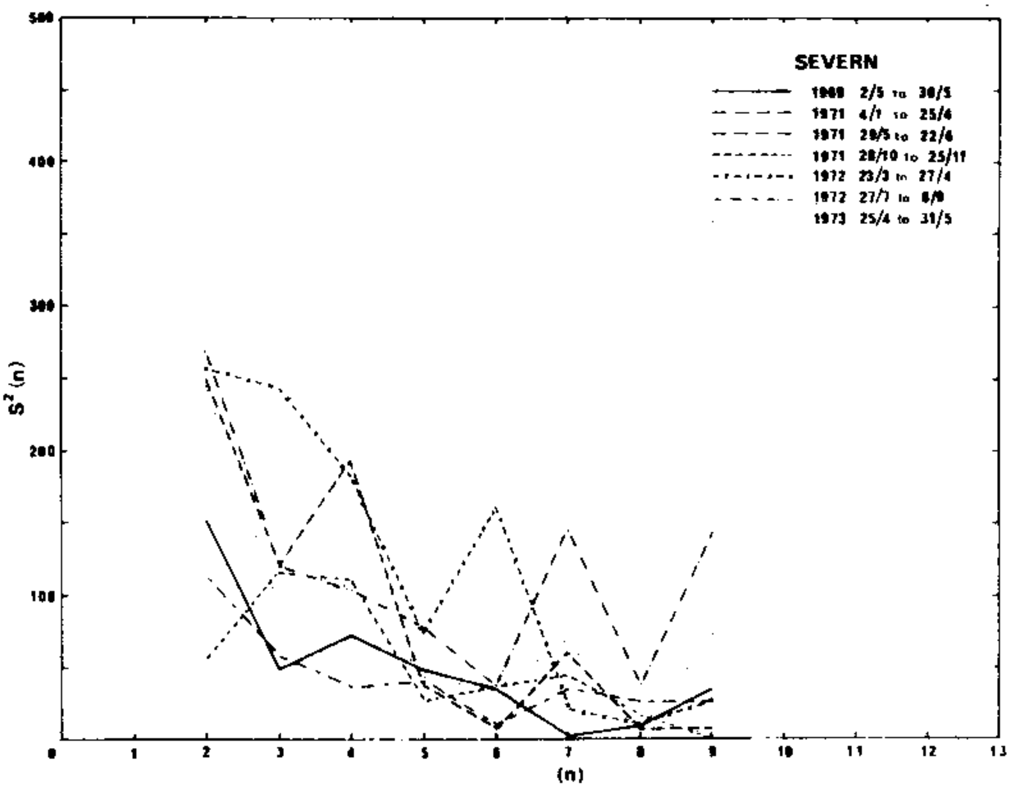


Figure 1.3.3.2 Variance of $\bar{\Delta}S$ for neutron access tube networks of size n tubes: Severn catchment

Figures 1.3.3.1 and 1.3.3.2 show the plots of $s^2(n)$ against n for the periods given above. As the number of access tubes in the sub-network decreases from 10 to about 5, there is, in general, but little loss of information as measured by the increase in $s^2(n)$; for subnetworks of five tubes or fewer, $s^2(n)$ increases more rapidly. For the periods considered, therefore, it seems likely that a network of about eight or ten tubes would have provided almost as much precision as a network of greater density.

1.3.4 <u>Duplication of raingauge network</u>

The observations recorded by a single raingauge network represent but one sample of points on the rainfall surface spanning the catchment (when the rainfall surface is that obtained by plotting precipitation depth as a co-ordinate in a space in which grid co-ordinates - eastings and northings - of gauges provide the x and y co-ordinates). If a functional representation can be assumed for this surface, and if a probabilistic structure for the deviations of observations from it can be assumed, then an "internal" estimate of error is possible and the precision of a mean areal estimate can be assessed. The precision quoted will, however, be critically dependent upon the assumptions implicit in the assumed probabilistic structure; an alternative means of determining the precision with which mean areal precipitation is estimated is by superimposing a second network of raingauges on the catchment, to examine the differences in mean areal estimates given by the two networks.

Accordingly a duplicate network of 8 gauges was set up for a short period within one subcatchment (Cyff) of the Wye, and of 6 gauges within one subcatchment (Hafren) of the Severn for a similar period. The gauges used were distributed over the subcatchments according to domain theory (see IH Report No. 27), and were not at the same sites as the existing storage gauges. Moreover, they were of tipping-bucket type (Rimco) with their orifices horizontal, but with the orifice centre mounted at ground level; the duplicate gauges were surrounded by anti-splash grids, identical with those surrounding the monthly storage gauges. The gauges of the duplicate network differed in at least three ways from the existing gauges, (in addition to the differences in recording method): (i) their orifices were horizontal; (ii) their orifices were larger; and (iii) the funnel angle was less. Furthermore, the Rimcos give continuous rainfall records measured by the occurrence of tips printed on magnetic tape, whilst the storage gauges gave only monthly totals. After each tip, the catch of each Rimco bucket was collected in a plastic drum, and the total collected in the two drums (one for each bucket) was used to check the total catch for the month recorded by the Rimco.

Table 1.3.4.1 Comparison of catches by replicated network of Rimco gauges with those of existing storage gauges: Cyff

	Mean catch (mm):			
	Rimco:	Storage:	Difference R-S):	CV%
January 1975	433.4	435.0	-1.6 ± 27.8	14
February	69.8	69.6	+0.2 ± 1.6	6
March	134.8	140.0	-5.2 ± 5.4	10
April	220.3	249.0	-28.7 ± 11.9	12
May	68.1	62.8	+5.3 ± 2.6	11
	926.4	956.4	-30.0 ± 30.9	10.6%

Table 1.3.4.1 shows the arithmetic mean of the monthly catches of both Rimco and storage gauges on the Cyff, together with the mean difference and its standard error as calculated by a paired sample t-test. Despite the relatively large difference in April 1975, the areal means given by the two networks did not differ significantly ($P > 0.05$): in the remaining months, the absolute values of differences between catches were very much smaller. Even when the large April difference is included, the total catch for the 5-month period January-May 1975 differed by only 3%.

Table 1.3.4.2 shows the corresponding areal means for the period August 1975 to March 1976 on the Hafren subcatchment. With the exception of December 1975 and January 1976, when Rimco gauges caught significantly less than the monthly storage gauges, agreement between the two areal means is good. A snow diary for the catchment records intermittent snowfall and lying snow for the period 15 December 1975 to 4 February 1976, with falls variable over the

Table 1.3.4.2 Comparison of catches by replicated network of Rimco gauges with those of existing storage gauges: Hafren

August 1975	91.7	89.3	+2.4 ± 5.3	14
September	275.8	279.8	-4.0 ± 20.5	15
October	123.4	116.6	+6.8 ± 7.2	13
November	243.5	242.2	+1.3 ± 15.8	16
December	221.7	249.3	-27.6 ± 6.1	6
January 1976	238.0	276.5	-38.5 ± 4.9	4
March	113.8	124.8	-11.0 ± 4.1	8
Total (Excluding Dec-Jan)	848.2	852.7	-4.5 ± 27.7	13.2%
Total (all months)	1307.9	1378.5	-70.6 ± 28.8	10.8%

Conclusion

1. Excluding results for December 1975 and January 1976, no significant difference between Rimco and storage gauges
2. Snow diary reports snowfall and lying snow from 15 December 1975 to 4 February 1976; fall variable over catchment. Heavy falls on 24-26 January 1976 inclusive. At Dolydd, 6cm on 24 January, 5cm on 25 January and 4cm on 26 January 1976.

catchment; heavy falls were recorded on 24 to 26 January, whilst at the Dolydd office some miles from the catchment, and at lower altitude, 6 cm, 5cm and 4 cm were recorded on each of those days. Rimco gauges are notoriously unreliable in periods of snowfall, when the tipping mechanism may become frozen or clogged; there appears therefore, to be adequate reason for discarding the observed results for the Hafren subcatchment. If these are set aside, the totals for the five-month period August to March 1976, differ by less than 1%; even if they are included, totals for the seven month period differ by no more than 5%.

To summarize, agreement between monthly catches by the two networks appears to be satisfactory, except in months of snowfall, and the resultant effect of differences between gauge dimensions and exposures is small for the length of period considered in the analysis.

1.3.5 Accuracy and precision of streamflow measurements

As stated in Section 1.2, stream stage was measured on the Wye catchment with both a Leupold-Stevens and a Fischer-Porter water-level recorder mounted over the stilling well adjacent to a modified Crump weir; on the Severn catchment, stage was again measured with Leupold-Stevens and Fischer-Porter recorders, adjacent to a critical depth flume of trapezoidal cross-section. The Leupold-Stevens recorder provides a visible trace, of value both for permitting visual inspection to ensure that the device is functioning correctly, and for examining the hydrograph immediately following a heavy storm; it has therefore been regarded as the primary recording instrument, with the Fischer-Porter used as a standby in case of failure. At a later stage (1975), the Fischer-Porter recorder on each structure was replaced by water level recorders developed by the Institute which use magnetic tape loggers.

Rating curves for all eight gauging structures in the catchments were calculated from hydraulic theory, using the finished structure dimensions (Hydraulics Research Station, Report No. EX 335; British Standards Institution Report BS 3680 Part 4C: June 1974). The theoretical rating curves were verified, in most cases, by dilution gauging and current metering; the report describes the results obtained from the main catchments, however, so that this section presents only an account of current metering and dilution gauging on the Severn trapezoidal flume (the modified Crump weir at Cefn Brwyn on the Wye, being of long-established design, was considered to be less in need of field confirmation than the Severn trapezoidal of more recent design). Moreover, the hydraulic theory used to compute the theoretical rating could not be considered reliable for stages less than about one-twentieth of the throat length of the Severn trapezoidal (ie, less than about 210 mm); alternative methods for deriving a rating were therefore required for the range 0-210 mm, in addition to the need for a check on the theoretical rating over the whole range.

The current metered rating curve was calculated using 36 measured discharges spanning a wide range of stages from about 100 mm to 1500 mm. At each metering, stage measurement was taken from the Leupold-Stevens recorder; discharge was obtained from measurements collected by a battery of five miniature Braystoke meters mounted on a vertical rod lowered into the water at 12 points across the width of the structure at the tapping point. Counts of propeller revolutions were converted to discharge estimates by the Hydraulics Research Station, who also computed a theoretical rating curve independently by their own computer program.

Using the 36 stage-discharge values recorded on the Severn trapezoidal, a rating curve of the form

$$Q = \alpha H^{\beta}$$

was calculated by least squares after logarithmic transformation; the curve obtained had $\hat{\alpha} = 1.68 \times 10^6$, $\beta = 2.1692$. Alternative ratings of the form

$$Q = \alpha(H-y)^{\beta}$$

were also fitted, but the additional sum of squares of direction accounted for by the inclusion of the third parameter y was trivial (for $Q = \alpha H^{\beta}$, the value of r^2 was 0.9995, and the inclusion of $\hat{y}$ affected the fifth decimal place); the above numerical values of $\hat{\alpha}$ and $\hat{\beta}$ were therefore used with $y = 0$.

Dilution gauging was used to obtain a reliable rating at low stages. Discharge was calculated for 13 gaugings, again with stage measurements taken from the Leupold-Stevens recorder. Continuous injection of sodium iodide was used with water samples taken in the structure when concentration was judged to have reached its 'plateau' level; this procedure followed standard Institute practice. Measurements from thirteen gaugings spanning a range of stages from 70 mm to about 600 mm, were used to calculate a best-fitting rating curve by least squares for which the rating was

$$Q = 10^6 \times 4.81H^{2.0009} \quad (r^2 = 0.995)$$

a curve of marginally poorer fit than that obtained by current metering. This rating was extrapolated beyond the range of stages used in fitting it, and, as a means of comparing the effects of alternative ratings on the catchment water budget, the monthly streamflow was computed by each for the period mid-May-December 1975; this period was selected because the Severn trapezoidal flume received a major overhaul in early May 1975, and at the time at which the comparison was made, data were available for this period only.

Table 1.3.5.1 Severn trapezoidal: monthly flows following May 1975 using a dilution gauging rating curve

Rating curve by dilution gauging: $\log_e Q = -12.245 + 2.0009 \log_e H$; $r^2 = 0.995$
$(\pm 0.2342)(\pm 0.94245)$

	Q (Dilution gauging):	Q (Theoretical):	Q (Current metering):
May 1975 (12 days only)	49mm	48mm	49
June	16	12	13
July	57	49	52
August	30	22	24
September	150	144	148
October	107	93	99
November	196	184	192
December	194	206	200
	799	758	777

$(Q_{DG} - Q_{TH})/Q_{TH}\% = 5.4\%$

	Wye:	Severn:
P: (June to Dec.1975)	1160	1184
Q:	902	710 (Theoretical) 728 (Current metering) 750 (Dilution gauging)
P-Q: June to Dec.1975 inclusive)	258	474 (Theoretical) 456 (Current metering) 434 (Dilution gauging)

Using the three rating curves (theoretical, current metering and dilution gauging) the monthly streamflows were as shown in Table 1.3.5.1. This table also shows the total rainfall (P) for the period June-December 1975, and the total rainfall minus streamflow, P-Q, for both Wye and Severn basins. These values are not strictly the actual evaporation losses, because no account has been taken in their calculation of soil moisture change ΔS; however, it is most improbable that inclusion of ΔS would significantly affect the magnitude of the difference in P-Q between the two catchments. The table shows that the total streamflow as estimated using the dilution gauging rating curve is 5.4% greater than that obtained using the theoretical rating curve. This represents a 'worst case' in the sense that this discrepancy was obtained by extrapolating the dilution gauging rating far beyond the range of stages used in fitting it. The streamflow for the period May-December as estimated by the current metering rating curve (fitted using a much wider range of stages) differed from the estimates given by the theoretical rating by the much smaller quantity of 2.5%.

On the basis of this evidence, therefore, the error in streamflow estimation does not appear to be large enough to place in doubt the conclusions drawn later in this report regarding the differential water loss from the two main catchments.

2. BETWEEN YEAR WATER BALANCE OF THE WYE AND SEVERN CATCHMENTS

2.1 Annual water balance using data from periods without stream gauging complications

Table 2.1.1 shows values of annual precipitation P (calculated as a Thiessen mean areal estimate) and annual streamflow Q for each of the years 1970-75 (Wye) and 1972-75 (Severn). Also shown are the differences P-Q and the Penman estimates of annual potential evapotranspiration E_T, calculated from (i) solar radiation, recorded by Kipp solarimeter at the Dolydd office, some miles from the catchments; (ii) sunshine hours recorded at Dolydd, for the estimation of net long wave radiation; (iii) maximum and minimum air temperatures, wet and dry bulb temperatures, and wind run measured at the Moel Cynnedd meteorological station in the Severn catchment.

Table 2.1.1 Annual values of P, Q, P-Q and E_T, Wye and Severn catchments (units : mm)

Year:	P:		Q:		P-Q:		E_T:	
	Wye:	Severn:	Wye:	Severn:	Wye:	Severn:	Wye:	Severn:
1970	2869	2689	2415	-	454	-	485	567
1971	1993	1948	1562	-	431	-	468	548
1972	2131	2221	1804	1567	328	654	423	494
1973	2606	2504	2164	1823	442	681	436	510
1974	2794	2848	2320	2074	474	774	406	476
1975	2099	2121	1643	1406	456	715	435	511
	2415(6)	2388(6)	1985(6)		431(6)		442(6)	518(6)
	2408(4)	2424(4)	1983(4)	1718(4)	425(4)	706(4)	425(4)	498(4)

Before October 1971, the streamflow record from the Severn catchment was possibly affected by shoaling in the trapezoidal flume used to gauge flow; a later section examines the earlier record and concludes that the effect of shoaling on flow estimates was probably small (Section 2.2). After October 1971, when a sediment trap was installed above the trapezoidal flume and cleaned regularly, the streamflow record is known to be reliable, and it is this that was used to compute the entries in Table 2.1.1.

Of particular interest for discussion of the annual water balance is the magnitude of $P_S-Q_S-P_W + Q_W$ (= D, say) where the subscripts S and W refer to the Severn and Wye catchments respectively; this measures the difference between the annual losses (P-Q) from the two catchments. As stated in Section 1.3, the importance of D is two-fold; first, because it affords some protection against possible biases in the measurement of mean annual precipitation P and streamflow Q (a constant bias in the measurement of Q, for example, will cancel out when D is calculated, provided that it is equal for both the catchments), and second, because it affords some protection against unmeasured losses from deep percolation, although evidence suggests that such losses are negligible for both catchments. Table 2.1.2 shows the annual values of D, together with their mean and standard error.

Table 2.1.1 shows that precipitation measured on the Wye agrees well with that measured over the Severn by the 11 canopy-level gauges and 7 ground-level gauges; streamflow from the two catchments, however, is considerably different, such that the mean difference between the losses (ie, the mean of the annual values $P_S - Q_S - P_W + Q_W$) is +281 ±20 mm. On the evidence of these rather limited data, therefore, there is a clear difference in the water losses from the two catchments, the loss from the Severn being significantly greater.

Table 2.1.2 Annual values of $P_S - Q_S - P_W + Q_W$ (mm)

Year:	$P_S - Q_S - P_W + Q_W$:
1972	+ 326
1973	+ 239
1974	+ 300
1975	+ 258
Mean:	+ 281 ± 20

Comparison of the annual losses P-Q with the calculated potential evapotranspiration E_T shows that the loss on the Wye is slightly less than E_T (mean loss 431 mm, mean E_T 442 mm) whilst for the Severn the mean annual loss is considerably more (mean loss for 1972-75 is 706 mm; mean E_T is 498 mm). The difference in annual E_T for the Wye and Severn catchments is accounted for by the different albedos used (0.15 for the Severn catchment, 0.25 for the Wye).

2.2 Extension of streamflow record on the Severn: 1970-1971

The last section mentioned that a sediment trap was installed above the Severn trapezoidal flume in October 1971 to deal with the problems of shoaling (accumulation of sediment); the purpose of this section is to justify the use of streamflow record for the period preceding that date.

Using monthly precipitation P and streamflow Q from the Severn catchment for the 30 months following January 1972, the following regression equation was found to express Q in terms of P:

$$Q = -34.57 + 0.90P \quad (r^2 = 0.8989;\ r = 0.95) \quad \ldots\ldots\ldots (2.2.1)$$

Using this equation, and the Thiessen estimates of mean areal precipitation for each month, estimates of streamflow were obtained for each month of the years 1970 and 1971 (together, also, with the months beginning August 1969 when streamflow records began). Denoting flows estimated from equation (2.2.1) by $\hat{Q}$, the estimated annual flows, together with the measured flows from the Fischer-Porter water level recorder then in operation were as follows:

	$\Sigma\hat{Q}$ (estimated flow):	ΣQ (from Fischer-Porter):	ΣP (cumulative areal precipitation):
1969 (Aug-Dec)	672 ± 63	692	946
1970	1991 ±109	1963	2690
1971	1328 ±108	1196	1948

Inspection of the above results shows that, whilst the observed total annual flow in each of the years 1970 and 1971 is less than that estimated on the basis of data following January 1972, in neither year does the measured streamflow lie more than two standard errors distant from the estimated flow. It therefore seems improbable that the effect of shoaling in the Severn trapezoidal flume before October 1971 was sufficient to warrant the rejection of these data; if they are accepted, the annual water balance for the years 1970-75 inclusive is as shown in Table 2.2.1.

Table 2.2.1 Annual values of P, Q and P-Q: Wye and Severn catchments years 1970-75 (units:mm)

	P:		Q:		P-Q:		$P_S-Q_S-P_W+Q_W$:
Year:	Wye:	Severn:	Wye:	Severn:	Wye:	Severn:	
1970:	2869	2690	2415	1963 (1991)*	454	727 (699)*	+ 273 (+ 245)*
1971:	1993	1948	1562	1196 (1328)*	431	752 (620)*	+ 321 (+ 189)*
1972:	2131	2221	1804	1567	328	654	+ 326
1973:	2606	2504	2164	1823	442	681	+ 239
1974:	2794	2848	2320	2074	474	774	+ 300
1975:	2099	2121	1643	1406	456	715	+ 258
Mean:	2415	2388	1985	1672 (1698)*	431	717 (690)*	286

* Values shown in brackets are those derived from estimated streamflows on the Severn catchment for the years 1970-71.

2.3 Annual water balance after adjustment for unforested area of the Upper Severn

A considerable part of the Severn catchment is unforested. This unforested area, which constitutes approximately 331 hectares of its total area of 870 hectares, lies principally at the higher altitudes; it has higher rainfall and contributes more streamflow, per unit area, than the forested part of the catchment. To adjust the Severn streamflow for the contribution from the unforested area (which, although ungauged, may be considered to behave like the neighbouring Wye catchment, and its flow contribution estimated accordingly) the precedure described later on in this report was adopted (see Section 3.2). The resulting adjusted annual precipitation P, and streamflow Q from the forested area of the Severn are shown in Table 2.3.1, together with the corresponding values from the Wye for comparison.

Table 2.3.1 Annual values of P, Q and P-Q: Wye and forested area of the Severn catchment only, years 1970-75 (units:mm)

	P:		Q:		P-Q:		$P_S-Q_S-P_W+Q_W$:
Year:	Wye:	Severn:	Wye:	Severn:	Wye:	Severn:	
1970:	2869	2485	2415	1636	454	849	+ 395
1971:	1993	1762	1562	797	431	965	+ 534
1972:	2131	2124	1804	1342	328	782	+ 454
1973:	2606	2380	2164	1581	442	799	+ 357
1974:	2794	2703	2320	1785	474	918	+ 444
1975:	2099	2035	1643	1213	456	822	+ 366
Mean:	2415	2248	1985	1392	431	856	425

The result of adjustment for the unforested Upper Severn on the difference between the annual losses is considerable. The mean annual loss from the Wye is about 18% of the precipitation input, whilst the unadjusted mean annual loss for the Severn is 30%; after adjustment, however, the mean annual loss for the Severn rises to 38% of the mean annual precipitation input.

3. WITHIN YEAR WATER BALANCE OF THE WYE AND SEVERN CATCHMENTS

3.1 The value of soil moisture data for the within-year water balance calculation

Cumulative totals of precipitation P, streamflow Q and change in soil moisture ΔS are shown in Table 3.1.1. Also shown is the Penman (1956) estimate of potential evapotranspiration E_T for comparison with the measure of actual evaporation loss $P-Q-\Delta S$.

It will be seen that the periods over which P, Q and E_T have been accumulated are of irregular length determined by the dates when soil moisture was measured by neutron probe. Inspection also shows that the soil moisture changes ΔS are usually small in absolute magnitude, compared with the totals of P and Q. It is therefore of interest to determine whether ΔS contributes significant information to the within-year water balance study; if it does not, subsequent analysis could be simplified by restricting it to P and Q accumulated over calendar-monthly intervals.

The value of the measure ΔS was therefore determined for the Wye and Severn catchments by (i) calculating the regression of Q on P for the intervals determined by the dates of soil moisture measurement; (ii) calculating the regression of Q on both P and ΔS for the same intervals; (iii) determining whether the inclusion of ΔS significantly reduced the residual (unexplained) variance, using a variance ratio test. For the Severn, analysis of data from the 30 periods between 29.10.71 and 21.6.74 (see Table 3.1.1) showed that the regression

$$Q_S = -26.95 + 0.85\,P_S - 1.16\,\Delta S \quad (R^2 = 0.948) \quad \ldots\ldots\ldots(3.1.1)$$
$$(\pm 9.54) \quad (\pm 0.04) \quad (\pm 0.35)$$

gave a significantly better fit than

$$Q_S = -15.78 + 0.80P_S \quad (r^2 = 0.927) \quad \ldots\ldots\ldots(3.1.2)$$
$$(\pm 10.42) \quad (\pm 0.04)$$

Similarly, for the Wye, analysis of data for the 57 periods between 3.1.69 and 21.6.74 showed that the regression

$$Q_W = -16.86 + 0.90\,P_W - 0.89\,\Delta S_W \quad (R^2 = 0.976) \quad \ldots\ldots\ldots(3.1.3)$$

gave a significantly better fit than

$$Q_W = -13.30 + 0.88\,P_W \quad (r^2 = 0.969) \quad \ldots\ldots\ldots(3.1.4)$$
$$(\pm 6.18) \quad (\pm 0.02)$$

For both catchments, therefore, knowledge of ΔS contributes significantly to the estimation of Q, suggesting that the water balance should indeed be computed over the intervals defined by soil moisture measurements, and should include, where possible, the measure ΔS despite their relatively small numerical values. Details of the

Table 3.1.1 Wye catchment: monthly water balance (mm)

Period: From:	To:	P:	Q:	ΔS:	$P-Q-\Delta S$:	E_T:
3. 1.69	30. 1.69	302	262	+ 4	36	3
31. 1.69	27. 3.69	289	210	-17	97	13
28. 3.69	1. 5.69	270	229	- 1	42	50
2. 5.69	29. 5.69	223	164	+ 1	59	55
30. 5.69	2. 7.69	134	98	- 7	42	114
3. 7.69	6. 8.69	82	39	- 4	47	105
7. 8.69	27. 8.69	144	93	+ 8	43	44
28. 8.69	3.10.69	160	136	+13	12	44
4.10.69	4.11.69	142	135	0	7	17
5.11.69	26. 2.70	1068	956	-10	123	22
27. 2.70	25. 3.70	211	195	+ 9	7	20
26. 3.70	29. 4.70	417	346	+10	62	50
30. 4.70	29. 5.70	34	42	-38	29	71
30. 5.70	1. 7.70	133	37	+10	87	110
2. 7.70	23. 7.70	142	93	+17	32	65
24. 7.70	4. 9.70	292	247	- 9	54	99
5. 9.70	28. 9.70	134	123	- 9	20	31
29. 9.70	26.10.70	213	159	+24	30	13
27.10.70	7.12.70	703	663	+ 6	34	10
8.12.70	4. 1.71	46	69	-11	-12	2
5. 1.71	25. 4.71	686	550	+ 6	130	68
26. 4.71	29. 5.71	75	30	-19	64	83
30. 5.71	22. 6.71	165	120	+ 7	38	52
25. 6.71	6. 8.71	151	77	- 6	80	150
7. 8.71	1. 9.71	170	128	+ 5	38	47
2. 9.71	29. 9.71	96	56	- 1	41	37
30. 9.71	28.10.71	208	189	- 3	23	19
29.10.71	25.11.71	288	245	+15	28	6
26.11.71	6. 1.72	159	159	- 5	5	4
7. 1.72	27. 1.72	216	184	+15	17	3
28. 1.72	24. 2.72	133	138	-10	5	2
25. 2.72	23. 3.72	57	81	-15	-9	16
24. 3.72	27. 4.72	396	327	- 4	73	50
28. 4.72	2. 6.72	225	136	+20	69	74
3. 6.72	27. 6.72	170	146	-12	36	55
28. 6.72	27. 7.72	111	124	-19	7	76
28. 7.72	8. 9.72	193	103	- 7	97	100
9. 9.72	28. 9.72	18	19	+ 5	-5	24
29. 9.72	24.10.72	31	14	- 5	22	13
25.10.72	30.1172	343	256	+48	39	6
1.12.72	6. 1.73	251	285	-10	-24	4
7. 1.73	27. 1.73	159	127	+10	21	2
28. 1.73	1. 3.73	371	306	- 2	68	8
2. 3.73	5. 4.73	248	236	- 3	15	35
6. 4.73	25. 4.73	42	40	- 8	11	30
26. 4.73	31. 5.73	220	171	+15	34	82
1. 6.73	9. 7.73	65	45	-37	58	108
10. 7.73	7. 8.73	348	240	+34	74	62
8. 8.73	30. 8.73	54	52	-21	23	47
31. 8.73	4.10.73	257	204	+19	34	41
5.10.73	2.11.73	216	206	- 9	18	12
3.11.73	29.11.73	278	238	+17	23	6
30.11.73	28. 1.74	625	518	+ 1	106	8
29. 1.74	28. 3.74	407	356	-15	66	23
29. 3.74	25. 4.74	11	18	-25	18	38
26. 4.74	23. 5.74	102	23	+26	53	56
24. 5.74	21. 6.74	148	91	0	57	84
22. 6.74	18. 7.74	204	152	+ 4	48	59
19. 7.74	15. 8.74	221	177	+ 5	39	58
16. 8.74	12. 9.74	246	207	+ 3	36	43
13. 9.74	11.10.74	226	207	- 4	23	25
12.10.74	28.11.74	430	415	0	15	11
29.11.74	21.12.74	374	325	+13	36	3
22.12.74	16. 1.75	283	231	-14	66	3
17. 1.75	14. 2.75	306	238	+ 7	75	4
15. 2.75	14. 3.75	109	92	0	17	6
15. 3.75	18. 4.75	217	150	- 3	70	28
19. 4.75	16. 5.74	157	129	- 1	29	46
17. 5.75	1. 6.75	6	13	-32	25	44
2. 6.75	1. 7.75	36	15	-45	66	98
2. 7.75	1. 8.75	159	73	+29	57	81
2. 8.75	1. 9.75	87	35	- 8	60	75
2. 9.75	1.10.75	269	192	+51	26	35
2.10.75	17.11.75	213	198	- 7	22	13
18.11.75	15.12.75	270	278	- 8	0	1

Table 3.1.1 Severn catchment: monthly water balance (mm) (Months approximate only)

Period: From:	To:	P:	Q:	ΔS:	P-Q-ΔS:	E_T:
29.10.71	25.11.71	276	209	+12	56	7
26.11.71	6. 1.72	172	138	- 4	38	5
7. 1.72	27. 1.72	217	150	+ 5	63	3
28. 1.72	24. 2.72	133	125	- 3	11	4
25. 2.72	23. 3.72	49	62	- 8	-5	19
24. 3.72	27. 4.72	413	298	0	116	58
28. 4.72	2. 6.72	222	104	+21	98	86
3. 6.72	27. 6.72	190	118	-27	98	62
28. 6.72	27. 7.72	109	102	- 3	9	86
28. 7.72	8. 9.72	167	87	-13	93	119
9. 9.72	28. 9.72	53	17	+ 1	34	28
29. 9.72	24.10.72	30	10	- 2	23	17
25.10.72	30.11.72	355	222	+40	94	8
1.12.72	6. 1.73	270	268	- 7	10	5
7. 1.73	27. 1.73	134	102	0	31	2
28. 1.73	1. 3.73	320	260	+16	44	10
2. 3.73	5. 4.73	250	202	-10	57	42
6. 4.73	25. 4.73	40	31	-12	22	35
26. 4.73	31. 5.73	206	125	+ 7	74	94
1. 6.73	9. 7.73	72	35	-31	67	126
10. 7.73	7. 8.73	350	203	+33	115	72
8. 8.75	30. 8.73	54	43	-24	34	55
31. 8.73	4.10.73	255	166	+19	70	49
5.10.73	2.11.73	213	176	+ 3	33	15
3.11.73	29.11.73	257	190	+ 7	60	7
30.11.73	28. 1.74	666	557	+ 5	104	9
29. 1.74	28. 3.74	384	309	-15	90	28
29. 3.74	25. 4.74	14	15	-19	18	45
26. 4.74	23. 5.74	98	14	+13	71	64
24. 5.74	21. 6.74	151	60	+ 8	83	97
22. 6.74	18. 7.74	209	130	+ 2	77	69
19. 7.74	16. 8.74	235	144	+ 5	86	69
17. 8.74	12. 9.74	268	193	- 1	76	49
13. 9.74	11.10.74	354	249	0	105	35
12.10.74	28.11.74	426	347	+ 5	74	13
29.11.74	21.13.74	366	289	+11	66	4
22.12.74	16. 1.75	291	236	- 9	64	4
17. 1.75	14. 2.75	334	280	- 6	60	4
15. 2.75	14. 3.75	112	78	+ 8	26	8
15. 3.75	18. 4.75	177	105	+ 9	89	34
19. 4.75	16. 5.75	164	107	-13	70	55
17. 5.75	1. 6.75	7	8	-28	27	51
2. 6.75	1. 7.75	41	12	-33	62	113
2. 7.75	1. 8.75	163	50	+14	99	94
2. 8.75	1. 9.75	87	22	- 5	70	87
2. 9.75	1.10.75	274	148	+35	91	42
2.10.75	17.11.75	216	176	- 3	43	17
18.11.75	15.12.75	261	237	+ 5	19	1

variance ratio tests leading to this conclusion are shown in Table 3.1.2.

Table 3.1.2 Value of ΔS for estimating streamflow Q from the Severn catchment

	df	MS	F
Regression of Q on P alone	1	368 093	
Using ΔS	1	8 417	11.08**
Regression of Q on P and ΔS	2	188 255	
Residual	27	760	

Value of ΔS for estimating streamflow Q from Wye catchment

	df	MS	F
Regression of Q on P alone	1	1 529 637	
Using ΔS	1	10 677	15.17**
Regression of Q on P and ΔS	2	770 157	
Residual	54	704	

Examination of equations (3.1.1) and (3.1.3) shows that the coefficients of P depart significantly from unity (0.85 ± 0.04 and 0.90 ± 0.02 for the Severn and Wye respectively). The explanation of this apparently anomalous result is that the remaining variable, actual evaporation AE, is not included in the right-hand sides of the equations (it is of course, not measured directly). It is well known that the omission of one independent variable from a multiple regression equation leads to biased estimates of the remaining coefficients, and this could be an explanation of the departures observed. When direct measures of actual evaporation become available, using eddy correlation methods, it will be of interest to include AE as a third independent variable; if it were then found that any coefficient departed significantly from its theoretical value of ± 1, this would indicate either (i) that some component of the water balance (such as deep percolation, assumed negligible in the Plynlimon catchments) was not being measured, and was large; or (ii) that the measurements of some component(s) of the water balance was subject to consistent bias.

It is of interest to examine whether the coefficients in equations (3.1.1) and (3.1.3) for the Severn and Wye differ significantly. Table 3.1.3 tested whether the regression coefficients differed significantly for the two catchments, and it was concluded that they did not; if streamflow Q is to be estimated from precipitation P and soil moisture change ΔS by means of a multiple regression equation, the regression planes for the Wye and Severn can be assumed parallel.

Table 3.1.3 Test of significance of differences between regression coefficients Wye and Severn catchments

	df	MS	F
Pooling regression coefficients of P, ΔS	2	957 644	1326.38***
Differences between regression coefficients Wye and Severn	2	268	<1
Pooled error	81	722	

Table 3.1.4 Test of significance of differences between intercepts Wye and Severn catchments

	df	MS	F
Combined regression of Q on P, ΔS	2	968 410	1341.29***
Differences between regression coefficients	2	268	<1
Differences between intercepts	1	8 161	11.30**
Pooled error	81	722	

Table 3.1.4 confirms that, whilst the regression coefficients are not significantly different, the intercepts are; using the pooled regression coefficients, equations for estimating Q from P and ΔS are therefore

$$Q_S = -33.83 + 0.89\ P_S - 1.02\ \Delta S_S$$

for the Severn, and

$$Q_W = -14.70 + 0.89\ P_W - 1.02\ \Delta S_W$$

for the Wye.

If the same precipitation over both Wye and Severn catchments were able to give the same change in soil moisture in each, the resultant streamflow from the Severn would therefore be about 19 mm (33.83 - 14.70) less than that from the Wye.

For the within-year balance, therefore, ΔS contributes significant information for both Wye and Severn, despite its relatively small absolute numerical value.

3.2 Adjustment of the Severn streamflow for the unforested part of the Upper Severn

Although most of the 870-hectare Severn catchment is forested, a considerable proportion (0.38 of the total) is pasture and peat hag. This area lies mainly in the upper part of the catchment and in appearance and hydrological behaviour is probably much like the Wye. On the assumption that the unforested Upper Severn behaves like the Wye catchment, streamflow from the Severn may be adjusted by subtracting the contribution from the unforested part, leaving the streamflow contributed solely by the forested area. Ideally, the adjustment procedure would be as follows:

(i) Calculate the (Thiessen) mean areal precipitation P for the unforested Upper Severn.

(ii) Calculate the mean soil moisture change ΔS, using data from all tubes in the unforested Upper Severn.

(iii) Substitute P and ΔS in equation (3.1.3) to obtain the estimated depth of streamflow (mm) contributed by the Upper Severn.

(iv) Multiply this depth by the unforested area, giving the volume of streamflow (units m^3) contributed by the Upper Severn, and subtract from the volume of streamflow for the entire Severn catchment.

(v) Divide the resulting difference by the forested area of the Severn, giving depth of streamflow.

A difficulty arises with the procedure at step (ii). There are four access tubes in the Upper Severn (tubes with index numbers 43, 47, 53 and 54 in the Institute's computer summary listings), but soil moisture records from them are far from complete; of the 24 intervals between 29.10.71 and 2.11.73, changes in soil moisture at each of the four tubes can be calculated for only five, whilst for one interval ΔS cannot be calculated for any tube. Because of this sparseness of soil moisture data, the equation used to estimate the streamflow contribution from the Upper Severn was not equation (3.1.3), but the equation

$$Q = -9.02 + 0.861P \qquad \text{..................(3.2.1)}$$

Using this equation, the Upper Severn streamflow contribution was calculated monthly. The adjusted streamflow from the forested area of the Severn, together with its mean areal precipitation, are shown in Table 3.2.1; it will be seen that the result of adjusting both streamflow and precipitation for the unforested Upper Severn is to increase the estimate of annual water loss associated with the coniferous forest. Thus, the mean annual loss for the three years, 1972-74 was 703 mm for the entire Severn catchment; after adjustment this estimate was increased to 833 mm. The corresponding mean loss for the Wye catchment was 415 mm.

To check the validity of the assumption that the unforested Upper Severn can be treated like the Wye catchment, the two principal streams (Nant Arwystli and the Upper Hafren) draining it were gauged

Table 3.2.1. Adjusted streamflow from the Severn catchment: contribution from the unforested Upper Severn removed

		P^1 (Upper Severn):	estimated $Q^{(1)}$ [2] (Upper Severn):	$Q^{(2)}$ (whole catchment):	Q^3 (forest only):	P^4 (forest only):
1970	J	174	141	167	183	156
	F	354	296	243	210	252
	M	250	206	142	103	164
	A	414	347	262	210	316
	M	40	25	32	36	34
	J	128	101	25	-22	112
	J	229	188	110	62	180
	A	196	160	118	92	159
	S	241	198	133	93	192
	O	397	333	256	209	352
	N	446	375	356	344	417
	D	154	124	119	116	151
					1636	2485
1971	J	315	262	164	104	220
	F	282	234	121	52	135
	M	177	143	87	53	116
	A	74	55	42	34	69
	M	81	61	22	-2	70
	J	218	179	106	61	174
	J	79	59	24	3	64
	A	230	189	117	73	207
	S	101	78	44	23	80
	O	228	187	150[5]	127	204
	N	332	277	209	167	293
	D	133	105	103	102	130
					797	1762
1972	J	256	211	186	171	219
	F	175	142	107	86	120
	M	253	209	129	80	190
	A	304	253	246	242	304
	M	147	118	76	50	149
	J	201	164	135	117	191
	J	149	119	92	75	131
	A	127	100	80	68	120
	S	63	45	22	8	63
	O	87	66	18	-11	77
	N	357	298	224	179	308
	D	263	217	254	277	252
					1342	2124

Table 3.2.1. (continued)......

		P^1 (Upper Severn):	estimated $Q^{(1)}$ [2] (Upper Severn):	$Q^{(2)}$ (whole catchment):	Q^3 (forest only):	P^4 (forest only):
1973	J	187	152	138	129	166
	F	341	284	218	177	236
	M	147	118	130	137	126
	A	200	163	127	105	174
	M	206	168	121	92	191
	J	59	42	31	24	57
	J	192	156	91	51	190
	A	262	216	161	127	228
	S	243	200	154	126	236
	O	226	186	186	186	207
	N	279	231	195	173	245
	D	360	301	272	254	324
					1581	2380
1974	J	406	340	308	288	335
	F	240	198	198	198	222
	M	160	129	87	61	95
	A	24	12	14	15	24
	M	107	83	19	-20	99
	J	170	137	65	21	151
	J	350	292	200	144	324
	A	130	103	88	79	128
	S	399	334	285	255	381
	O	225	185	166	154	223
	N	360	301	243	207	274
	D	510	430	401	383	447
					1795	2703
1975	J	497	380	351	333	424
	F	88	59	93	114	73
	M	135	95	64	45	112
	A	245	179	135	108	201
	M	75	49	53	55	64
	J	47	32	12	0	49
	J	169	131	49	-1	159
	A	88	66	22	-5	86
	S	279	223	145	97	264
	O	117	89	93	95	112
	N	260	205	184	171	241
	D	263	211	205	201	250
					1213	2035

[1] Thiessen estimates of 7 gauges

[2] Estimated as $Q = -9.02 + 0.861P$

[3] $Q = \{870\ Q^{(2)} - 331\ Q^{(1)}\}/539$

[4] $P = \{870\ P - 331\ P^*\}/539$, where P is Thiessen areal estimate for entire catchment

[5] Flows after this month are derived from Leupold-Stevens water level recorder; previously, flows were derived from a Fischer-Porter recorder

from October 1975 onwards. At the time of reporting, only three months of this record (October-December 1975) are available; Table 3.2.2 shows the monthly streamflow (averaged over both catchments) together with the streamflow from the unforested Severn as estimated using the regression calculated from Wye data. The table shows that the regression estimate in all three months was lower than that measured, but these data are insufficient to justify any firm conclusions. If further records showed that the regression consistently underestimated streamflow from the Upper Severn, streamflow from the forested Severn would be consistently over-estimated, and the water loss from the forest under-estimated.

Table 3.2.2 Observed and estimated streamflow (mm) from the unforested Upper Severn: October-December 1975

	OCT:	NOV:	DEC:	TOTAL:
Observed runoff: (Mean, Nant Arwystli and Upper Hafren):	156	257	251	664
Estimated runoff: (using Wye regression):	99	220	210	529

3.3 The seasonal discrepancy between actual evaporation AE and potential evaporation E_T

Comparison of $P-Q-\Delta S$ with the Penman estimate of potential evapotranspiration from the Wye reveals an apparently consistent seasonal discrepancy between them. Table 3.1.1 shows that, of the 57 intervals there listed, 25 lay between October and March; in 19 of these the actual evaporation loss $P-Q-\Delta S$ exceeds E_T. Of the 32 intervals between April and September inclusive, only 5 are such that $P-Q-\Delta S$ exceeds E_T. Expressed as a table, the pattern is as follows:

	$P-Q-\Delta S>E_T$:	$P-Q-\Delta S<E_T$:	
October-March	19	6	25
April-September	5	27	32
	24	33	57

The large number of intervals between April and September for which actual evaporation $P-Q-\Delta S$ is less than potential evapotranspiration E_T is surprising, particularly since in 26 of the 32 intervals total precipitation P exceeds total E_T, suggesting that the catchment is less often in deficit than the above table indicates. Furthermore, for 19 of the 25 intervals between October and March $P-Q-\Delta S$ exceeds E_T; during this part of the year evapotranspiration should be at the potential rate, and if E_T and $P-Q-\Delta S$ estimated the same quantity, the probability that the latter should exceed the former in 19 of the 25 intervals is very small (0.005). The conclusion must therefore be either that E_T under-estimates the loss of water from the catchment during periods between October and March, or that P-Q-ΔS over-estimates it; the converse holds between April and September.

A similar seasonal discrepancy has been observed on the Institute's experimental catchment on the River Ray at Grendon Underwood; there Penman's E_T tended to be higher than P-Q-ΔS in summer months, and lower in winter months. A similar seasonal discrepancy was reported by Ward (1963) following a study of evapotranspirometer data from the Thames basin; Ward wrote: "On theoretical grounds, it would seem to be reasonable to expect that Penman's formula will tend to over-estimate E_T during the spring, and to underestimate it during the autumn, since no direct allowance is made in the formula for the heating of the soil by part of the incoming radiation. Generally speaking, in the spring, soil temperatures are initially low as a result of previous winter conditions, whilst after the summer months soil temperatures are initially high despite the fact that the amount of incoming radiation is similar in both seasons. Accordingly, a larger proportion of the incoming radiation will be required to heat the soil in the spring than in the autumn, and the proportion available for evaporation will be correspondingly lower."

To examine whether the data from the Wye conflict with Ward's hypothesis, they were abstracted for the periods March-April-May and September-October-November, giving the following table:

Number of intervals with:	Period: March-April-May	September-October-November	
P-Q-ΔS>E_T:	2	9	11
P-Q-ΔS<E_T:	11	5	16
Total:	13	14	27

If the frequency with which E_T exceeds P-Q-ΔS were equal - apart from sampling errors - for both spring and autumn, the probability of a distribution of the 27 intervals as extreme as, or more extreme than, that shown above is rather small ($P<0.05$; $\chi^2_{(1)} = 4.80$, using Yates' correction), suggesting that P-Q-ΔS is less likely to exceed E_T in spring than in autumn. The data therefore do not conflict with Ward's hypothesis, although other explanations may be equally valid.

3.3.1 The spatial variability in the estimates of E_T

Before attempting to enlarge upon the explanation given above for the seasonal discrepancy between E_T and P-Q-ΔS (and before alternative explanations are advanced), some account is required of the method by which the estimates E_T were calculated.

There is but one meteorological station on the Wye and Severn catchments, situated at Moel Cynnedd in the Severn. Measurements taken at this station, and at the catchment office at Dolydd, some miles from either catchment, were used to calculate the estimates given in Table 3.1.1. Since there was no net radiometer at either site, net radiation was estimated using records from a Campbell-Stokes sunshine recorder and Kipp radiometer at Dolydd, taking albedos of 0.15 for the Severn catchment and 0.25 for the Wye. Wind run and wet bulb depression measurements were taken at the Moel Cynnedd site, together with daily maximum and minimum temperatures (for the estimation of mean daily air temperature, and the calculation of Δ, the slope of the saturation vapour pressure curve).

Table 3.3.1.1 Estimates of E_T obtained (i) using Moel Cynnedd meteorological station data; (ii) using data from 2 AWS at Eisteddfa Gurig; (iii) using one AWS at Carreg Wen (iv) using 2 AWS at Moel Cynnedd. (P-Q-ΔS, for the Wye is also shown); (Data from 2.3.73 to 21.6.74)

	P-Q-ΔS: (Wye)	E_T: (Moel Cynnedd)	Using data from AWS: EG1:	EG2:	CW2:	MC1:	MC2:
October-March	228	84 (±20)	82	106	137	104	132
April-September	362	548 (±27)	591	589	572	547	447
Total: (2.3.73 to 31.6.74)	590	632 (±34)	673 (±34)	695 (±34)	709 (±34)	651 (±34)	579 (±34)
			684 (±24)			615 (±24)	

Estimates of E_T obtained (i) using Moel Cynnedd meteorological station data; (ii) using data from 2 AWS at Eisteddfa Gurig; (iii) using 2 AWS at Carreg Wen; (iv) using 2 AWS at Moel Cynnedd. (P-Q-ΔS, for the Wye, is also shown; data from 29.1.74 to 21.6.74)

	P-Q-ΔS: (Wye)	E_T: (Moel Cynnedd)	Using data from AWS: EG1:	EG2:	CW1:	CW2:	MC1:	MC2:
October-March	66	23	21	22	37	43	21	38
April-September	128	178	190	210	238	224	199	148
	194	201 (±16)	211 (±16)	238 (±16)	275 (±16)	267 (±16)	220 (±16)	186 (±16)
			224 (±11)		271 (±11)		203 (±11)	

From 1972 onwards, automatic weather stations (AWS) have been sited at two points within each of the Wye and Severn catchments. On the former, AWS were installed at Eisteddfa Gurig and at Cefn Brwyn; on the latter, at CarregWen and Moel Cynnedd. Eisteddfa Gurig and CarregWen are high altitude sites, whilst Cefn Brwyn and Moel Cynnedd are at low altitude. Because of instrumental difficulties, particular with the net radiometers, the early AWS data are of questionable reliability; the later data, however, may be used to compare the estimates E_T, calculated by the above procedure, with those calculated using the net radiation measurements from the AWS. Since all AWS, including those in the Severn, are sited over grass (those at Moel Cynnedd are in a large clearing, whilst those at Carreg Wen are above the tree line), the AWS estimates of E_T may be compared directly with those calculated for the Wye; Table 3.3.1.1 shows the values of E_T obtained.

The most striking feature of this table is the large difference between P-Q-ΔS and the E_T estimate, whether from the Moel Cynnedd meteorological station or from AWS; clearly, differences of such magnitude cannot be accounted for by any spatial variability in the E_T estimates, despite the large differences both between and within sites. The last line of Table 3.3.1.1 shows that there is good agreement between the total E_T computed from the Moel Cynnedd meteorological station data and the total E_T computed from the two AWS in the same clearing, and an analysis of variance (Table 3.3.1.2) shows that, whilst there are significant differences in total E_T from the three AWS sites, there is on average no significant difference between the E_T totals computed from the two AWS in each pair. Despite the crude method used to estimate net radiation in the earlier years of the study, there is nothing in the AWS data collected subsequently to suggest that E_T calculated from the Moel Cynnedd meteorological station data is greatly in error; nor can such crudities explain the large discrepancies between P-Q-ΔS and E_T for the Wye catchment.

Table 3.3.1.2 Comparison (by analysis of variance) of E_T as estimated (i) at Moel Cynnedd meteorological station; (ii) by AWS at Eisteddfa Gurig; (iii) by AWS at Careg Wen; (iv) by AWS at Moel Cynnedd

A. For the 14 periods between 2.3.73 and 21.6.74 (a 'period' is determined by the dates on which soil moisture was measured)

Source of variation:	df	MS	F	
Between periods	13	4641.86		
Manual station v automatic weather stations	1	51.45	<1	(N.S.)
Between AWS sites (EG v CW v MC)	2	271.18	3.27*	(P<0.05)
Between duplicate AWS within sites	2	101.21	1.22	(N.S.)
Residual	65	82.98		
Total	83			

Total E_T for periods between 2.3.73 and 21.6.74 (mm):

Moel Cynnedd:	EG1:	EG2:	CW2:	MC1:	MC2:
632 (±34)	673 (±34)	695 (±34)	709 (±34)	651 (±34)	579 (±34)
(CV = 19%)	684 (±24)			615 (±24)	

B. For the 4 periods between 29.1.74 and 21.6.74 (during which 2AWS were operating at each of the sites, EG, CW, MC

Source of variation:	df	MS	F	
Periods	3			
Manual station v Automatic weather stations	1	217.15	3.33	(N.S.)
Between AWS sites EG v CW v MC	2	604.04	9.27**	(P 0.01)
Between duplicate AWS within sites	3	81.21	1.25	(N.S.)
Residual	18	65.16		
Total	27			

Total E_T for periods between 29.1.74 and 21.6.74 (mm)

Moel Cynedd:	EG1:	EG2:	CW1:	CW2:	MC1:	MC2:
201 (±16)	211 (±16)	238 (±16)	275 (±16)	267 (±16)	220 (±16)	186 (±16)
	224 (±11)		271 (±11)		203 (±11)	

(CV = 14%)

4. ASPECTS OF THE ENERGY BALANCE OF THE WYE AND SEVERN CATCHMENTS

4.1 Annual energy balance

If the annual losses P-Q are assumed to be due solely to evaporation from the catchment, these losses can be expressed in terms of the quantities of energy required to account for them. The energy required to evaporate 1 mm of water is slightly dependent upon temperature, but deviates little from 2.47×10^6 Jm^{-2} over the range of temperatures encountered at Plynlimon; hence 2.47 (P-Q) MJm^{-2} is approximately the energy required to effect the evaporative losses observed, and it is of interest to determine what fraction of the net radiation R_N this accounts for.

Net radiation was not measured on the Wye and Severn catchments until the advent of the automatic weather stations, whilst sensor difficulties following their installation were such that reliable records of R_N do not begin until about 1973. However, total solar radiation R_S has been reliably measured by Kipp solarimeter at the Dolydd catchment office since 1969, and Figure 4.1.1 shows the high correlation between daily R_N (MJm^{-2}) at the Moel Cynnedd meteorological station (measured by automatic weather station there) and daily R_S (MJm^{-2}) at the Dolydd office for the year 1974. Using such data, a regression equation was calculated which allowed R_N to be estimated, given R_S, for the period preceding installation of the automatic weather stations. This regression was:

$$R_N = -0.820 + 0.50\,R_S \quad \text{(units } MJm^{-2}\text{)}$$
$$(r^2 = 0.9158;\; r = 0.96) \qquad \text{........(4.1.1)}$$

approximately, where R_N and R_S in equation (4.1.1) refer to the mean values, over each month, of net and solar radiation respectively; using this relation, mean daily R_N (MJm^{-2}) was then estimated with a standard error of approximately ± 0.88 MJm^{-2}.

Equation (4.1.1) gave estimates of total annual net radiation at Moel Cynnedd as shown in Table 4.1.1. The R_N so calculated is taken to be that appropriate to grass, since the automatic weather station

Table 4.1.1 Estimated annual net radiation R_N for the Wye catchment and energy required to account for observed evaporative loss

Year:	R_N (MJm^{-2}):	(P-Q) mm:	Energy equivalent (MJm^{-2})	Proportion of R_N:	B:
1970:	1373	454	1122	0.82	0.22
1971:	1344	431	1063	0.79	0.26
1972:	1331	328	812	0.61	0.64
1973:	1352	442	1093	0.81	0.23
1974:	1294	474	1172	0.91	0.10
1975:	1379*	456	1126	0.82	0.22
	1345±13	430±21	1065±53	0.79 ± 0.040	0.28 ± 0.076

* Calculated from the regression using Moel Cynnedd solar radiation

Calculated from the regression ($R_N = -0.82 + 0.5R_S$) using the sum of all 6 AWS

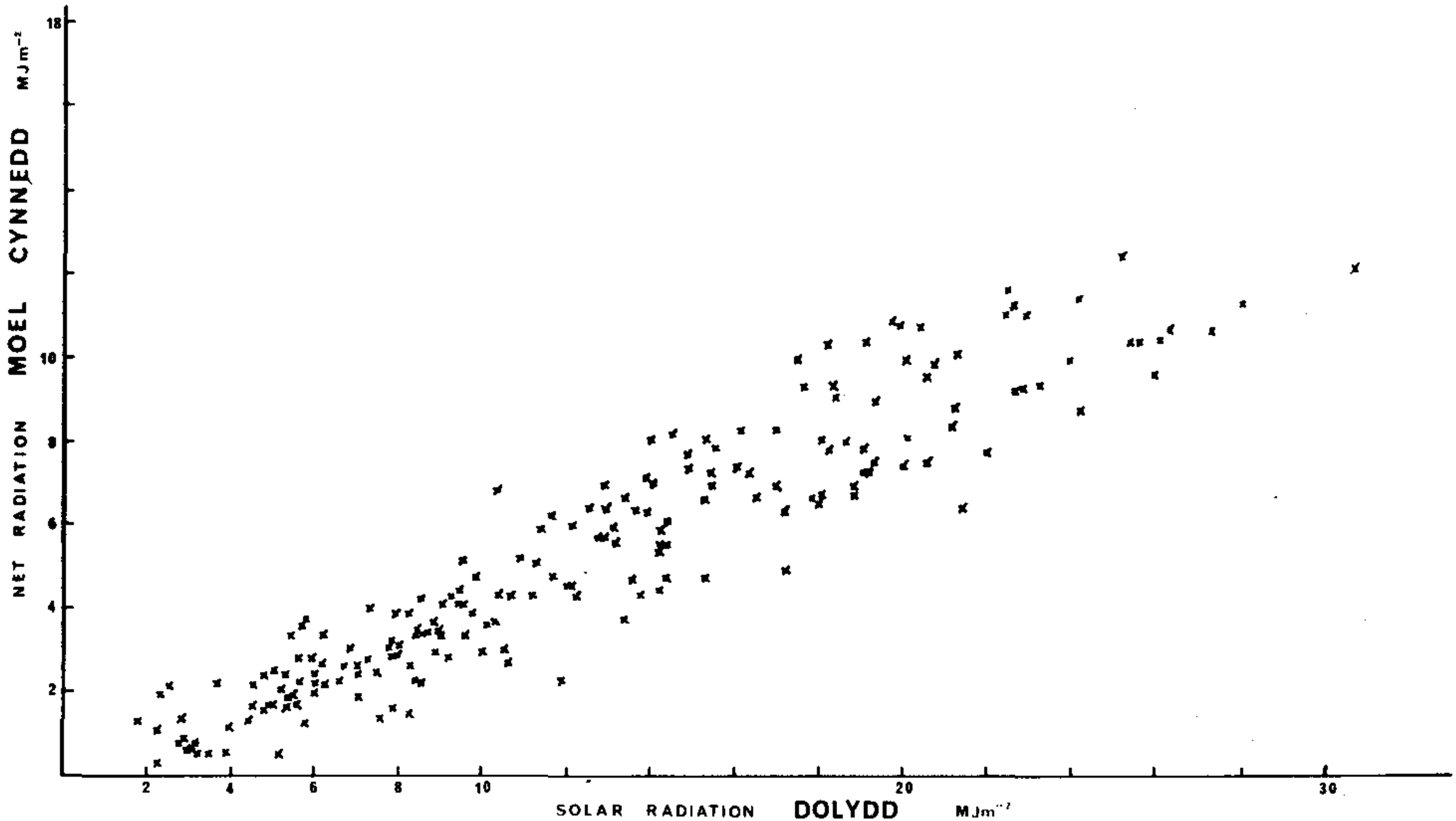


Figure 4.1.1 Daily R_n at Moel Cynnedd plotted against daily R_s at Dolydd (11 April 1974 - 31 October 1974 less dates when AWS was not working)

giving the record from which equation (4.1.1) was calculated is sited in a large grassy clearing within the forest. Also shown in Table 4.1.1 are the values of P-Q for the Wye catchment, and the energy needed to account for this evaporation loss; on average, approximately 79% of the total net radiation throughout the year is required to account for the observed losses from the Wye catchment. If the reasonable assumption is made that the annual total soil heat storage is negligible, the remaining 21% of net radiation is accounted for by sensible heat flux.

For the forested part of the Severn catchment, energy balance considerations require a measure (or failing that, an estimate) of net radiation over the forest. This quantity was estimated by assuming (i) that incoming solar radiation R_S is equal for both Wye and Severn catchments; (ii) that the net long wave radiation R_L is equal for both catchments. The relations between R_N, R_S and R_L are then

$$R_N^{GRASS} = (1-\alpha^{GRASS})\, R_S - R_L$$

$$R_N^{FOREST} = (1-\alpha^{FOREST}) R_S - R_L,$$

whence the estimate of R_N^{FOREST} is given by

$$R_N^{FOREST} = R_N^{GRASS} + (\alpha^{GRASS} - \alpha^{FOREST})\, R_S \qquad \ldots\ldots.(4.1.2)$$

The quantities α in equation (4.1.2) refer to albedo.
Using equation (4.1.2), the annual total R_N over the forested Severn is as shown in Table 4.1.2.

Table 4.1.2 Estimated annual net radiation R_N for the Severn catchment, and energy required to account for observed evaporative loss

Year:	R_N (MJm^{-2}):	(P-Q)mm:	Energy equivalent (MJm^{-2}):	Proportion of R_N:	B:
1970:	1712	727(699)	1796(1725)	1.05(1.01)	-0.05(-0.01)
1971:	1675	752(620)	1859(1532)	1.11(0.92)	-0.10(+0.08)
1972:	1658	654	1616	0.97	+0.03
1973:	1687	681	1683	1.00	0.00
1974:	1604	774	1913	1.19	-0.16
1975:	1744[1] 1719[2] 1697±97[3]	715	1766	1.01	-0.01
Mean:	1680 (±20)	717(690) (±18)(±22)	1772(1696) (±45)(±53)	1.06(1.02) ±0.033(±0.037)	-0.06(-0.02) ±0.029(±0.033)

[1] measured at Moel Cynnedd
[2] estimated by $R_N^{FOREST} = R_N^{GRASS} + (\alpha^{GRASS} - \alpha^{FOREST})R_S$
[3] mean of 6 AWS; 2 at each of Eisteddfa Gurig, Moel Cynnedd and Carreg Wen

For the Severn catchment, therefore, the table suggests that the energy equivalent of the observed mean value of (P-Q)mm is slightly greater (1.06 $\pm$ 0.033) than the total net radiation R_N for the year at the Moel Cynnedd meteorological station. This result is modified if it is remembered that a proportion 0.62 of the total Severn area is under forest, with the remainder as rough pasture and peat bog; if the total net radiation is therefore taken as

$$0.62R_N^{FOREST} + 0.38R_N^{GRASS}$$

with R_N^{FOREST} as given by equation (4.1.2), then the values of Table 4.1.2 become adjusted as shown in Table 4.1.3. The adjustment appears not unreasonable, since the losses (P-Q)mm are those for the whole catchment.

Adjustment for the unforested Severn therefore reduces the total R_N for the whole catchment, so that the energy required to account for the observed loss (P-Q)mm increases to (1.14 $\pm$ 0.04)R_N, the coefficient 1.14 being significantly greater than unity. The same calculation may be carried out by a second method: if the losses (P-Q)mm adjusted for the unforested Severn, which are shown in Table 2.3.1, are expressed in terms of the energy required to evaporate them, this energy requirement is on average equal to (1.12$\pm$ 0.05) R_N, where R_N is now the unadjusted total net radiation for the forest as calculated by equation (4.1.2).

Table 4.1.3 Estimated total annual net radiation R_N(adjusted) for the Severn catchment, adjusted for the unforested upper Severn, and energy required to account for the observed evaporative loss.

Year:	R_N(adj.) (MJm^{-2}):	(P-Q)mm:	Energy Equivalent (MJm^{-2}):	Proportion of R_N:	β:
1970:	1583	727(699)	1796(1725)	1.13(1.09)	-0.12(-0.08)
1971:	1549	752(620)	1859(1532)	1.20(0.99)	-0.17(+0.01)
1972:	1534	654	1616	1.05	-0.05
1973:	1560	681	1683	1.08	-0.07
1974:	1486	774	1913	1.29	-0.22
1975:	1605	715	1766	1.10	-0.09
Mean:	1553 ±17	717(690) ±18(±22)	1772(1706) ±44(±53)	1.14(1.10) ±0.04(±0.04)	-0.12(-0.08) ±0.026(±0.031)

The magnitude of this coefficient merits some comment, and there are several possible explanations for the result. These include the following:-

(a) The annual loss (P-Q) mm is over-estimated. This may arise because:

- (i) mean areal precipitation P is too large;
- (ii) annual streamflow Q is under-estimated by the gauging structure;
- (iii) there is a loss of water from the catchment by deep percolation.

Earlier sections of this report have described the work undertaken to check the measurements of P and Q and it appears reasonable to rule out (i) and (ii) as possible explanations of Table 4.1.2. A loss of water from the catchment by deep percolation cannot be ruled out, however, but the impermeability of the Ordovician and Silurian mudstones and shales underlying the catchment suggests that leakage is unlikely.

(b) R_N is underestimated. This may arise because:-

- (i) radiometers on the Moel Cynnedd automatic weather stations are incorrectly calibrated, are shaded, or are tilted relative to the vertical;
- (ii) R_N^{GRASS}, measured over the grass at the Moel Cynnedd meteorological station, underestimates R_N for a (hypothetical) Severn catchment under grass: see equation (4.1.2);
- (iii) the difference $\alpha^{GRASS} - \alpha^{FOREST}$, the difference between albedos, is underestimated: see equation (4.1.2);
- (iv) R_S, measured by the Moel Cynnedd automatic weather stations, underestimates the spatially-averaged short-wave radiation received by the catchment as a whole;
- (v) the net long-wave radiation R_L emitted by the forested Severn is less than the net long-wave R_L emitted by the Wye, so that R_L does not vanish when the radiation balance equations which lead to equation (4.1.2) are subtracted.

The possibility of calibration errors or tilt ((b)(i)) cannot be eliminated entirely, although automatic weather station radiometers are mounted by specialists from the Institute's Instrument Section, and are replaced annually by newly calibrated instruments.
The possibility of shading can be ruled out; for each automatic weather station site, a plot is made of the angle defined by the horizon and the horizontal at each compass point, and this angle is everywhere much smaller than the angle to the midday-sun even at the winter solstice. The possibility of shading at the ends of the day can also be eliminated (see later discussion).

Explanation (b) (iii), that of underestimating the albedo difference $\alpha^{GRASS} - \alpha^{FOREST}$ (which, for the derivation of R by equation (4.1.2), was used with $\alpha^{GRASS} = 0.25$, $\alpha^{FOREST} = 0.15$, values quoted by Penman (1963)) was eliminated by a study reported in full elsewhere (Roberts G., Baty A.J.B., and Hill P.,: Albedo measurements over a spruce forest and at various domains in a grassland area: 1975). In this study, two Kipp and Zonen solarimeters were mounted over the forest on a rod protruding from an aluminium tower, one solarimeter facing vertically upwards, the other down; the mean albedo, calculated from many measurements at the one site in the forest, was 11.4 $\pm$ 0.2%. The same solarimeter device was also mounted at several sites in the Wye catchment, the sites being selected by the "domain theory" used when selecting raingauge sites; in two successive years, the mean albedo over grass was found to be 20.0$\pm$ 0.4% and 19.1$\pm$ 0.4% with the first value derived from observations at 28 sites, the second from 34. These results suggest that the albedo difference, taken as 0.10 (= 0.25-0.15) may have been over-estimated, rather than underestimated, and if the observations of Roberts et al. had been used to give an albedo difference of 19.5 - 11.4 = 8.1%, then the coefficient of R_N would have been increased from 1.14 to some higher value. The possibility of differential albedo over the Wye catchment is also eliminated by their study; in a careful analytical search for possible associations between Wye albedo and aspect, altitude and slope of the measurement sites, no such association was found).

Explanation (b) (v) of different net long-wave radiation from the Wye and Severn catchments, has not been checked; although there is evidence of a degree or so difference in mean air temperatures recorded at Moel Cynnedd and at Carreg Wen at the higher altitude, it seems unlikely that differences in surface temperature between forest and pasture would be large enough to cause significant differences between their black-body radiations.

There remains the possibilities that R_N and R_S measured at the Moel Cynnedd meteorological station (altitude 358m), may be biased estimates. A preliminary comparison of total net radiation for the five-month period of 1974 as measured at Moel Cynnedd, Eisteddfa Gurig (altitude 500m) and Carreg Wen (altitude 575m) suggested an association between R_N and altitude; since automatic weather stations at all three sites are mounted over grass, and since analysis had already shown no evidence of association between albedo and altitude, the explanation was sought in the variation of solar radiation R_S with altitude.

Table 4.1.4 shows the monthly total R_S received at Moel Cynnedd and at Carreg Wen, throughout 1974; these sites are the lowest and highest altitude sites for automatic weather stations at Plynlimon. The values shown in Table 4.1.4 were assembled, not by the authors of this report, but by I.C.Strangeways of the Institute's Instrument Section, who has been in charge of automatic weather station development from its very beginning: he derived the Table entirely independently of this report, and before it was drafted, by selecting what he considered to be the most appropriate values from either or both automatic weather stations at each site. Inspection of Strangeways' data shows a clear and consistent difference between the solar radiation recorded at Carreg Wen and at Moel Cynnedd.

A possible explanation is the decreasing density of aerosol at higher altitudes, although work by Unsworth and Monteith (1972), who measured solar radiation at 200m intervals during an ascent of Ben Nevis on a cloudless day (20 August 1971) giving results which would imply a considerably smaller increase in total solar radiation with altitude than that suggested by the Table 4.1.4; however, their relation between the attenuation coefficient for aerosol τ_a and altitude was derived from observations collected on but one day, for part of which their radiometer read erratically. They also noted that their observed changes in turbidity with height were rather less than those shown by workers in the Alps and in continental air masses. There must be a possibility, therefore, that the magnitude of the difference in total solar radiation observed at Moel Cynnedd and Carreg Wen is real.

Net radiation values R_N were assembled by Strangeways in the same manner; these are shown in Table 4.1.5, and are derived from net radiometers mounted at the end of the automatic weather station b om (the solar radiometer is mounted at the top of its mast). Strangeways selected the data shown in Tables 4.1.4 and 4.1.5 from one or both automatic weather stations at each of the two sites, Moel Cynnedd and Carreg Wen, the selection being based upon long experience of when such data are reliable and when they may be suspect; to quantify the variation between the two individual automatic weather stations at each site, and to compare this variation with variation between sites, the reliable data from each station was assembled for Eisteddfa Gurig (altitude 500m) as well as the two sites Carreg Wen and Moel Cynnedd. Where, for reasons such as instrument failure, a month's data were incomplete, the missing data were estimated by setting the total radiation for each missing day equal to the mean daily total radiation for all days of that month that yielded data; a corrected monthly total was then computed. Table 4.1.6 shows the analysis of variance in which variation between sites is compared with variation between automatic weather stations within sites; Table 4.1.7 shows the annual totals for R_S at the three sites.

Table 4.1.6 suggests that the apparent relation between solar radiation and altitude is maintained by the inclusion of data from the Eisteddfa Gurig automatic weather stations, when a method differing slightly from that of Strangeways is used to compute monthly totals. The Table also shows that the regression of R_S on altitude, although based on observations at three sites only, shows no significant departure from linearity; further calculation shows that annual total R_S increases by about 141 ±21 MJm^{-2} per 100m of altitude.

Despite the apparent significance of the R_S-altitude relation, there must still be some doubt about the reality of its magnitude. The difference between the annual totals from the Moel Cynnedd stations is considerable, though not statistically significant, and the strength of the R_S-altitude relation could be accounted for to a large extent by station 1 at Moel Cynnedd (which gave a low annual total) and the single automatic weather station at Carreg Wen (which gave a high annual total). Further analysis is required to confirm or disprove the R_S-altitude relation suggested by the 1974 data.

Table 4.1.4 (Data supplied independently by I.C. Strangeways). Total monthly solar radiation R_S (MJm^{-2}) at Moel Cynnedd (altitude 358m) and Carreg Wen (altitude 575m): 1974

	Carreg Wen:	Moel Cynnedd:	Moel Cynnedd low by:
January 1974	57 (MJm^{-2})	50 (MJm^{-2})	12%
February	107	96	10%
March	277	199	28%
April	440	342	22%
May	470	408	13%
June	553	479	13%
July	476	406	15%
August	425	358	16%
September	240	216	10%
October	189	149	21%
November	74	57	23%
December	32	27	16%
Total:	3340	2787	17%

Table 4.1.5 (Data supplied by I.C. Strangeways). Total monthly net radiation R_N (MJm^{-2}) at Moel Cynnedd (altitude 358m) and at Carreg Wen (altitude 575m): 1974

	Carreg Wen:	Moel Cynnedd:
January 1974	-1 (MJm^{-2})	10 (MJm^{-2})
February	30	37
March	99	64
April	194	120
May	256	189
June	303	206
July	272	221
August	225	196
September	134	99
October	75	78
November	18	15
December	-1	-7
Total:	1604	1228

Moel Cynnedd low by 23% over the year

Table 4.1.6 Analysis of variance, total monthly solar radiation R_S for months of 1974. Data were used from two automatic weather stations at Moel Cynnedd, two at Eisteddfa Gurig, and one at Carreg Wen

Source of variation:	df	MS	F
Months	11	143 560	
Between automatic weather stations	4	4 239	
Between sites	2	7 831	12.24***
Linear regression on site altitude	1	15 285	23.88***
Quadratic regression on site altitude	1	377	<1 (N.S.)
Between stations at Moel Cynnedd	1	1264	1.98(N.S.)
Between stations at Eisteddfa Gurig	1	31	<1 (N.S.)
Residual	44	640	
Total:	59		

Table 4.1.7 Annual totals, R_S, for 1974 (units MJm^{-2}).

Site:	Station:	R_S:	Mean R_S:
Moel Cynnedd	1	2726	2814 ±62
	2	2901	
Eisteddfa Gurig	1	2937	2950 ±62
	2	2964	
Carreg Wen	1	3342	3342 ±88

Table 4.1.8 shows, for total net radiation R_N, the analysis of variance corresponding to Table 4.1.6. Net radiation observations at Eisteddfa Gurig were suspect for much of January and February 1974 so that the analysis is confined to period March-December; however, since both net radiometers at Carreg Wen functioned satisfactorily for that period (although one of the solar radiometers did not) some replication was possible at that site. Table 4.1.9 shows the totals for R_N recorded by each automatic weather station for the period March-December.

Table 4.1.8 confirms the increase in altitude of R_N, and shows some similarities with Table 4.1.6. Analysis shows that total R_N received during the March-December period of 1974 apparently increased by 137 MJm^{-2} per 100 metres of altitude, a value agreeing closely with the apparent increase in R_S (see above: 141 MJm^{-2} per 100 metres of

Table 4.1.8 Analysis of variance, total monthly net radiation R_N for months March-December 1974. Data were used from two automatic weather stations at Moel Cynnedd, two at Eisteddfa Gurig and two at Careg Wen.

Source of variation:	df	MS	F
Between months	9	59419	
Between automatic weather stations	5	3375	
Between sites	2	6204	13.54
Linear regress on site altitude	1	9226	20.14
Quadratic regression on site altitude	1	3182	6.95
Between stations at Moel Cynnedd	1	4307	9.40
Between stations at Eisteddfa Gurig	1	15	<1 (N.S.)
Between stations at Carreg Wen	1	146	<1 (N.S.)
Residual	45	458	
Total:	59		

altitude). Nevertheless, the R_N data require even greater care, and raise even greater questions, than the R_S data; the period totals R_N recorded by the two automatic weather stations at Moel Cynnedd differed significantly, and no explanation was apparent. Furthermore, there is evidence of curvature in the apparent relation between R_N and altitude.

The above rather lengthy discussion presents evidence, although not conclusive evidence, of a relation between R_S and altitude, and between R_N and altitude, that are rather more pronounced than earlier publications would suggest. Until these relations become modified by analysis of subsequent data, they are taken here as indications of a need to make adjustment to the net radiation R_N at Moel Cynnedd. By calculating the mean catchment altitude and the slope of the derived relation between R_N and altitude, a provisional result was obtained which suggested that R_N at Moel Cynnedd should be adjusted upwards by a factor of 1.2. If this factor is used to decrease the estimated R_N for both Wye and Severn catchments, Tables 4.1.1 and 4.1.2 then become (if the unforested upper Severn is ignored) as shown in Tables 4.1.10. and 4.1.11.

On average, therefore, 0.66 of the annual total R_N is required to account for the observed annual loss (P-Q) mm for the Wye catchment whilst for the Severn, the fraction is significantly greater at $(0.88 \pm 0.03) R_N$.

This section has concentrated on discussion of the extent to which R_N and R_S at Moel Cynnedd are representative, and of how far their possibly unrepresentative nature might account for the large energy requirement needed to account for the mean annual loss (P-Q)mm for the Severn catchment. There is a further possible explanation of the size of the factor $1.14R_N$ needed to account for the Severn loss; namely, the advection of additional energy from areas upwind. This phenomenon has undoubtedly been observed at the Institute's study site in the Thetford forest, and it seems probable from the results given in the next section, that energy advection accounts for a considerable part of the winter evaporative loss from the forested Severn.

Finally, the hourly R_S (and R_N) totals were examined for a sample of cloud-free days at Plynlimon; such days are rather infrequent. When R_S was plotted against time, it was often found that the hourly R_S values at Moel Cynnedd lay below the corresponding values at the higher altitude sites, particularly in the mid-day period 1000-1400hrs; differences were negligible in the early morning or late evening.

Table 4.1.9 Total R_N for period March-December 1974 (Units:MJm^{-2})

Site:	Station:	R_N:	Mean R_N:
Moel Cynnedd	1	1431	1284 ±48
	2	1137	
Eisteddfa Gurig	1	1352	1343 ±48
	2	1334	
Carreg Wen	1	1587	1614 ±48
	2	1641	

Table 4.1.10 Estimated annual net radiation calculation R_N for the Wye catchment (after provisional adjustment for altitude) and energy required to account for observed evaporative loss

Year:	R_N(adj) (MJm^{-2}):	(P-Q) mm:	Energy Equivalent (MJm^{-2}):	Proportion of R_N:	β:
1970	1648	454	1122	0.68	0.47
1971	1613	431	1063	0.66	0.52
1972	1597	328	812	0.51	0.96
1973	1622	442	1093	0.67	0.49
1974	1553	474	1172	0.75	0.33
1975	1655	456	1126	0.68	0.47
Mean:	1614 ±16	430 ±21	1065 ±53	0.66 ±0.03	0.54 ±0.09

Table 4.1.11 Estimated annual net radiation R_N for the Severn catchment (after provisional adjustment for altitude) and energy required to account for observed evaporative loss

Year:	R_N(adj) (MJm^{-2}):	(P-Q) mm:	Energy equivalent (MJm^{-2})	Proportion of R_N:	β:
1970	2054	727(699)	1796(1725)	0.87(0.84)	0.15(0.19)
1971	2010	752(620)	1859(1532)	0.92(0.76)	0.09(0.32)
1972	1990	654	1616	0.81	0.23
1973	2024	681	1683	0.83	0.20
1974	1925	774	1913	0.99	0.01
1975	2093	715	1766	0.84	0.10
Mean:	2016	717(690)	1772(1706)	0.88(0.84)	0.14(0.19)
	23	±18(±22)	±45(±53)	±0.03(±0.03)	±0.03(±0.04)

4.2 Within-year energy balance

4.2.1 Within-year energy balance of the Wye catchment

If P-Q-ΔS is assumed to measure the actual evaporation between the dates on which soil moisture was measured by neutron probe, a calculation similar to that of the preceding section can be made, showing the within-year energy balance. Table 4.2.1.1 shows, for the Wye catchment, the mean daily values of E_T and $_{AE}$ = P-Q-ΔS; their corresponding energy equivalents; and the estimated net radiation R_N. The latter is obtained, as before, by use of the high correlation between net radiation at Moel Cynnedd and the solar radiation at the Dolydd office, and the values of R_N shown are adjusted upwards by a factor of 1.2 to allow for the deviation of Moel Cynnedd altitude from the mean altitude for the catchment.

It is of interest to examine the mean value of the proportion of R_N necessary to account for the observed evaporative loss from the catchment, and to compare this mean value computed (i) for the periods between October and March, with that computed (ii) for periods between April and September inclusive. For the former, Table 4.2.1.1 shows that about 0.92 times the net radiation is required to account for the evaporative loss; for the latter, the figure is 0.43.

Table 4.2.1.1 Wye catchment: E_T (mm day^{-1}); actual evaporation (mm day^{-1}) equivalent energy (MJm^{-2}); R_N (MJm^{-2}); and the ratio (equivalent energy/R_N)

Period:	Number of days:	E_T (mm day^{-1}):	E_a ($P-Q-\Delta S$) mm day^{-1}:	Total Equivalent energy (MJm^{-2}):	Total R_N (MJm^{-2})	Ratio:
3. 1.69-30. 1.69	28	0.11	1.28	88.9	28.1	3.2) Oct-Mar
31. 1.69-27. 3.69	56	0.23	1.73	239.6	149.4	1.6)
28. 3.69- 1. 5.69	35	1.43	1.20	103.7	272.4	0.4
2. 5.69-29. 5.69	28	1.96	2.11	145.7	220.6	0.7
30. 5.69- 2. 7.69	34	3.35	1.24	103.7	416.2	0.2
3. 7.69- 6. 8.69	35	3.00	1.34	116.1	359.6	0.3
7. 8.69-27. 8.69	21	2.09	2.05	106.2	155.2	0.7
22. 8.69- 3.10.69	37	1.19	0.32	29.6	183.5	0.2
4.10.69- 4.11.69	32	0.52	0.22	17.3	99.2	0.2) Oct-Mar
5.11.69-26. 2.70	114	0.19	1.08	303.8	187.7	1.6)
27. 2.70-25. 3.70	27	0.74	0.26	17.3	171.3	0.1
26. 3.70-29. 4.70	35	1.43	1.77	153.2	241.7	0.6
30. 7.70-29. 5.70	30	2.37	0.97	71.6	256.7	0.3
30. 5.70- 1. 7.70	33	3.33	2.64	214.9	371.1	0.6
2. 7.70-23. 7.70	22	2.95	1.45	79.0	226.9	0.3
24. 7.70- 4. 9.70	43	2.30	1.26	133.4	360.8	0.4
5. 9.70-28. 9.70	24	1.29	0.83	49.4	122.6	0.4
29. 9.70-26.10.70	28	0.46	1.07	74.1		)
27.10.70- 7.12.70	42	0.24	0.81	84.0		) Oct-Mar
8.12.70- 4. 1.71	28	0.07	-0.43	-29.6	36.8	)
5. 1.71-25. 4.71	111	0.61	1.17	321.1	367.7	0.9)
26. 4.71-29. 5.71	34	2.44	1.88	158.1	347.8	0.4
30. 5.71-22. 6.71	24	2.17	1.58	93.9	197.4	0.5
23. 6.71- 6. 8.71	45	3.33	1.78	197.6	501.9	0.4
7. 8.71- 1. 9.71	26	1.86	1.46	93.9	180.9	0.5
2. 9.71-29. 9.71	28	1.32	1.46	101.3	184.9	0.5
30. 9.71-28.10.71	29	0.66	0.79	56.8	110.9	0.5)
29.10.71-25.11.71	28	0.21	1.00	69.2	59.4	1.2) Oct-Mar
26.11.71- 6. 1.72	42	0.10	0.12	12.4	35.2	0.4)
7. 1.72-27. 1.72	21	0.14	[illegible]	42.0	22.6	1.9)
28. 1.72-24. 2.72	28	0.07	[illegible]	12.4	42.6	0.3)
25. 2.72-23. 3.72	27	0.57	[illegible]	-22.2	121.4	)
24. 3.72-27. 4.72	35	1.43	2.06	180.3	253.4	0.7
28. 4.72- 2. 6.72	36	2.06	1.92	170.4	302.0	0.6
3. 6.72-27. 6.72	25	2.20	1.44	88.9	213.2	0.4
28. 6.72-27. 7.72	30	2.53	0.23	17.3	289.8	0.1
28. 7.72- 8. 9.72	43	2.32	2.26	239.6	397.8	0.6
9. 9.72-28. 9.72	20	1.20	-0.25	-12.4	118.5	
29. 9.72-24.10.72	26	0.50	0.85	54.3	94.7	0.6)
25.10.72-30.11.72	37	0.16	1.08	98.8	62.6	1.6)
1.12.72- 6. 1.73	37	0.11	-0.65	-59.3	33.1	) Oct-Mar
7. 1.73-27. 1.73	21	0.10	1.00	51.9	20.8	2.5)
28. 1.73- 1. 3.73	33	0.24	2.06	168.0	77.8	2.2)
2. 3.73- 5. 4.73	35	1.00	0.43	37.0	217.0	0.2
6. 4.73-25. 4.73	20	1.50	0.55	27.2	153.7	0.2
26. 4.73-21. 5.73	36	2.28	0.94	84.0	334.6	0.2
1. 6.73- 9. 7.73	39	2.77	1.49	143.3	407.9	0.4
10. 7.73- 7. 8.73	29	2.14	2.55	182.8	234.5	0.8
8. 8.73-30. 8.73	23	2.04	1.00	56.8	188.5	0.3
31. 8.73- 4.10.73	35	1.17	0.97	84.0	190.5	0.4
5.10.73- 2.11.73	29	0.41	0.62	744.5	82.8	0.5)
3.11.73-29.11.73	27	0.22	0.85	56.8	55.0	1.0) Oct-Mar
30.11.73-28. 1.74	60	0.13	1.77	261.8	61.9	4.2)
29. 1.74-28. 3.74	59	0.39	1.12	163.0	181.9	0.9)
29. 3.74-25. 4.74	28	1.36	0.64	44.5	212.6	0.2
26. 4.74-23. 5.74	28	2.00	1.89	130.9	229.4	0.6
24. 5.74-21. 6.74	29	2.90	1.96	140.8	329.9	0.4
22. 6.74-18. 7.74	27	2.18	1.78	118.6	241.0	0.5
9. 7.74-15. 8.74	28	2.07	1.39	96.3	224.4	0.4
16. 8.74-12. 9.74	28	1.54	1.28	88.9	185.2	0.5
13. 9.74-11.10.74	29	0.86	0.79	54.8	143.9	0.4

Mean ratio (energy equivalent/R_N), Oct-Mar period: 0.92

Mean ratio (energy equivalent/R_N), Apr-Sept period: 0.43

4.2.2 Within-year energy balance of the Severn catchment

Table 4.2.2.1 shows the mean daily values of E_T and AE = P-Q-ΔS, in units of mm day^{-1}, together with the corresponding energy equivalents, and the net radiation R_N corrected to mean catchment altitude. The foot of the table shows that an energy requirement considerably in excess of daily net radiation is needed to account for the observed evaporation loss during the months October to March (1.44 times R_N); in the months April to September, about half (0.57) of the net radiation R_N would be required to account for the mean daily evaporation loss.

Table 4.2.2.1 Severn catchment: E_T (mm day^{-1}); actual evaporation (mm day^{-1}); equivalent energy (W m^{-2}); R_N (W m^{-2}); and the ratio equivalent energy/R_N

Period:	Number of days:	E_T (mm day^{-1}):	E_a (P-Q-ΔS) mm day^{-1}:	Total Equivalent energy (MJm^{-2}):	Total R_N (MJm^{-2}):	Ratio:
29.10.71-25.11.71	28	0.25	2.00	138.3	71.5	1.9)
26.11.71- 6. 1.72	42	0.12	0.90	93.9	42.5	2.2)Oct-Mar
7. 1.72-27. 1.72	21	0.14	2.00	155.6	27.3	5.7)
28. 1.72-24. 2.72	28	0.14	0.39	27.2	51.3	0.5)
25. 2.72-23. 3.72	27	0.70	-0.18	-12.4	145.8	-0.08)
24. 3.72-27. 4.72	35	1.66	3.31	286.5	304.3	0.9
28. 4.72- 2. 6.72	36	2.39	2.72	242.1	362.6	0.7
3. 6.72-27. 6.72	25	2.48	3.92	242.1	256.0	0.9
28. 6.72-27. 7.72	30	2.69	0.30	22.2	348.0	0.1
28. 7.72- 8. 9.72	43	2.77	2.16	229.7	477.5	0.5
9. 9.72-28. 9.72	20	1.40	1.70	84.0	142.4	0.6
29. 9.72-24.10.72	26	0.65	0.88	56.8	113.9	0.5)
25.10.72-30.11.72	37	0.22	2.54	232.2	75.4	3.1)
1.12.72- 6. 1.73	37	0.14	0.27	24.7	39.8	0.6)
7. 1.73-27. 1.73	21	0.10	1.48	76.6	25.2	3.0)Oct-Mar
28. 1.73- 1. 3.73	33	0.30	1.33	108.7	93.5	1.2)
2. 3.73- 5. 4.73	35	1.20	1.63	140.8	260.6	0.5)
6. 4.73-25. 4.73	20	1.75	1.10	54.3	185.7	0.3
26. 4.73-31. 5.73	36	2.61	2.06	182.8	401.8	0.4
1. 6.73- 9. 7.73	39	3.23	1.72	165.5	489.6	0.3
10. 7.73- 7. 8.73	29	2.48	2.97	284.1	281.6	1.0
8. 8.73-30. 8.73	23	2.39	1.48	84.0	226.4	0.4
31. 8.73- 4.10.73	35	1.40	2.00	172.9	228.8	0.8
5.10.73- 2.11.73	29	0.52	1.14	81.5	99.6	0.9)
3.11.73-29.11.73	27	0.26	2.22	148.2	66.3	2.2)Oct-Mar
30.11.73-28. 1.74	60	0.15	1.73	256.9	74.4	3.4)
29. 1.74-28. 3.74	59	0.47	1.52	222.3	218.4	1.0)
29. 3.74-25. 4.74	28	1.61	0.64	44.5	255.3	0.2
26. 4.74-23. 5.74	28	2.28	2.54	175.4	275.4	0.6
24. 5.74-21. 6.74	29	3.34	2.86	205.0	296.1	0.5
22. 6.74-18. 7.74	27	2.56	2.85	190.2	298.3	0.6
19. 7.74-16. 8.74	29	2.38	2.97	212.4	269.5	0.8
17. 8.74-12. 9.74	27	1.81	2.81	187.7	222.4	0.8

Mean ratio (energy equivalent/R_N), Oct-Mar: 1.44

Mean ratio (energy equivalent/R_N), Apr-Sept: 0.57

The values obtained in this section and section 4.2.1 are conveniently displayed as a table of the radiation required to account for the losses observed:

	Wye:	Severn:
October-March:	0.92 R_N	1.44 R_N
April-September:	0.43 R_N	0.57 R_N

4.2.3 Energy aspects of the seasonal differences between E_T and $P-Q-\Delta S$

The seasonal difference between actual evaporation $P-Q-\Delta S$ and potential evaporation as estimated by E_T has been mentioned earlier in this report: $P-Q-\Delta S$ commonly exceeds E_T during winter months, and is less than E_T when the catchment is in deficit, the regular distribution of precipitation throughout the year suggests that deficit conditions occur infrequently at Plynlimon; less frequently, certainly, than the differences between summer E_T and $P-Q-\Delta S$ would indicate.

To account for the winter excess of $AE = P-Q-\Delta S$ over E_T on the Wye catchment, either some additional energy flux is required, or else some seasonal bias is suggested in the variables from which E_T is calculated. These two possibilities are now considered further.

An additional source of energy for evaporation in winter months could be provided by a soil heat store, or by downward flux of sensible heat from the air. To examine the likely magnitude of the contribution from a soil heat store, the expression for net radiation R_N used in the Penman formula for E_T ($R_N = (1-r)R_S - R_B$, where R_S and R_B are the incoming short-wave radiation and net long-wave radiation respectively, and r is the albedo of the surface) was modified as:

$$R_N = (1-r)\ R_S - R_B + \alpha\cos 2\pi t/365 + \beta\sin 2\pi t/365 \quad ....(4.2.3.1)$$

The harmonic terms in this expression integrate to zero over the year, satisfying the condition that annual soil heat storage should be negligible. If α, β are chosen such that the sum of squares of differences between $E_a = P-Q-\Delta S$ and E_T is minimized (ie, chosen to bring the calculated values E_T most nearly in line with observed evaporative losses) it is found that the values of α, β (in units of mm of water) are:

$$\alpha = 2.04$$

$$\beta = 0.37.$$

These values would suggest that soil heat flux (if that be the additional energy source required) must account for an evaporative loss of about 1.3 mm day^{-1} throughout the winter months; the soil would be releasing heat from early October until mid-March, with the maximum flux occurring about 10 January. Table 4.2.3.1 shows, for the Wye catchment, the totals of $E_a = P-Q-\Delta S$, of E_T as calculated by the Penman formula, and by the Penman formula incorporating the adjustment to the radiation term shown in equation (4.2.3.1). Those periods for which $P-Q-\Delta S$ was negative were omitted from the calculation.

It appears improbable that an energy flux of this magnitude could be supplied from soil heat storage; the flux required to explain it is certainly considerably greater than the measured values for soil heat flux recorded in Thetford Chase. It would not appear, either, that a seasonal variation in albedo of the Wye catchment could be a possible explanation; Table 4.2.3.1 shows values E_T** obtained by allowing albedo to vary harmonically throughout the year, about a mean value of 0.25. The coefficients of the harmonic terms were

$$\alpha = -0.34$$

$$\beta = -0.07$$

and the sum of squares of deviations of E_T** from $P-Q-\Delta S$ is large (40564.3, whilst the "no-model" sum of squares is 46661.5).

Table 4.2.3.1 Values of E_T, $P-Q-\Delta S$, and modified E_T values (denoted by E_T*, E_T**, obtained by allowing a harmonic addition to the radiation term; a harmonic variation in albedo

29. 1.74-28. 3.74	23	66	60	35
29. 3.74-25. 4.74	38	18	38	39
26. 4.74-23. 5.74	56	53	41	43
24. 5.74-21. 6.74	84	57	55	47
22. 6.74-18. 7.74	59	48	27	26
19. 7.74-15. 8.74	58	39	25	27
16. 8.74-12. 9.74	43	36	20	24
13. 9.74-11.10.74	25	23	18	20

E_T*: calculated as for E_T, but with $R_N = (1-0.25)R_S - R_B + 2.0406\cos\frac{2\pi t}{365} + 0.3717\sin\frac{2\pi t}{365}$

E_T**: calculated as for E_T, but with $R_N = (1-0.25 + 0.3416\cos\frac{2\pi t}{365} + 0.0729\sin\frac{2\pi t}{365})R_S - R_B$

$$\Sigma(P-Q-\Delta S - \overline{P-Q-\Delta S})^2 = 46661.5$$

$$\Sigma(P-Q-\Delta S - E_T^*)^2 = 23206.8$$

$$\Sigma(P-Q-\Delta S - E_T^{**})^2 = 40564.3$$

Period:	E_T:	P-Q-ΔS:	E_T*:	E_T**:
3. 1.69-30. 1.69	3	36	30	7
31. 1.69-27. 3.69	13	97	44	22
28. 3.69- 1. 5.69	50	42	49	50
2. 5.69-29. 5.69	55	59	38	40
30. 5.69- 2. 7.69	114	42	77	63
3. 7.69- 6. 8.69	105	47	60	52
7. 8.69-21. 8.69	44	43	22	25
22. 8.69- 3.10.69	44	12	25	32
4.10.69- 4.11.69	17	7	22	18
5.11.69-26. 2.70	22	123	110	38
27. 2.70-25. 3.70	20	7	32	27
26. 3.70-29. 4.70	50	52	49	50
30. 4.70-29. 5.70	71	29	52	53
30. 5.70- 1. 7.70	110	87	73	64
2. 7.70-23 7.70	65	32	38	33
24. 7.70- 4. 9.70	99	54	54	55
5. 9.70-28. 9.70	31	20	19	23
5. 1.71-25. 4.71	68	130	127	83
26. 4.71-29. 5.71	83	64	64	61
30. 5.71-22. 6.71	52	38	29	30
23. 6.71- 6. 8.71	150	80	93	77
7. 8.71- 1. 9.71	47	38	22	27
2. 9.71-29. 9.71	37	41	22	24
30. 9.71-28.10.71	19	23	21	19
29.10.71-25.11.71	6	28	21	9
26.11.71- 6. 1.72	4	5	41	8
7. 1.72-27. 1.72	3	17	23	5
24. 3.72-27. 4.72	50	73	51	51
28. 4.72- 2. 6.72	74	69	52	53
3. 6.72-27. 6.72	55	36	29	30
28. 6.72-27. 7.72	76	7	38	34
28. 7.72-28. 9.72	124	92	73	71
29. 9.72-24.10.72	13	22	14	13
25.10.72- 6. 1.73	10	15	63	17
7. 1.73-27. 1.73	2	21	21	4
28. 1.73- 1. 3.73	8	68	34	14
2. 3.73- 5. 4.73	35	15	49	45
6. 4.73-25. 4.73	30	11	28	29
26. 4.73-31. 5.73	82	34	61	61
1. 6.73- 9. 7.73	108	58	63	56
10. 7.73- 7. 8.73	62	74	26	29
8. 8.73-30. 8.73	47	23	24	24
31. 8.73- 4.10.73	41	34	24	29
5.10.73- 2.11.73	12	18	16	13
3.11.73-29.11.73	6	23	21	9
30.11.73-28. 1.74	8	106	63	14

5. INTERCEPTION OF PRECIPITATION BY THE SEVERN FOREST

In September 1972, six interception troughs (length: 4 m; breadth: 10 cm; depth: 30 cm) were sited beneath the forest canopy of the Severn catchment, each adjacent to a canopy level storage gauge. A further trough of similar dimensions had been placed under the canopy near the Dolydd office in February 1972: initial data from the latter trough were not always reliable, however, and the trough was later removed to the Moel Cynnedd meteorological station. Catch by the latter trough has been recorded daily; catches from the former six have been recorded at monthly intervals or more frequently. Sites at which troughs were installed were as follows:

Catchment:	Domain:	Exact catch area (cm^2):	Percentage of 4000 cm^2
Upper Severn	B2X	3995.2	99.9
Lower Severn	A1Y	4000.8	100.0
Nant Tanllwyth	B2W	4010.0	100.3
Afon Hore	A1X	3978.9	99.5
Afon Hore	B2X	4004.0	100.1
Upper Severn	C2W	3998.4	100.0

Stemflow was not recorded: the catch by each trough was compared with the catch of the adjacent canopy storage gauge; where trough catches were measured at other than calendar monthly intervals, the precipitation was estimated using (a) the catch from the raingauge read daily at Moel Cynnedd meteorological station; (b) the catches for the appropriate calendar months from the storage gauges adjacent to each trough.

Taking an average over all troughs and all periods, the mean throughfall was 55 ±4.5% of incoming precipitation. Figure 5.1 shows no apparent seasonal variation in throughfall percentage, and Figures 5.2 to 5.7 show the relation between measured throughfall and precipitation (in adjacent storage gauge) for each trough. Inspection shows that this relation is roughly linear for each trough and that the slope for trough A1X (Afon Hore) tends to be rather greater than that for the other five.

5.1 A crude estimate of stemflow

Although stemflow was not measured, a crude estimate of the magnitude of the stemflow component may be obtained as follows: The monthly streamflow from the forested part of the Severn is estimated as in section 3.2. (This requires (i) the calculation of mean areal precipitation on the unforested part of the Severn; (ii) the assumption that the linear regression, calculated from Wye catchment data, which expresses depth of streamflow Q in terms of precipitation, P, applies equally to the unforested part of the Severn catchment; (iii) the use of this linear regression to calculate the contribution to streamflow from the unforested part of the Severn). With the streamflow from the unforested Severn so estimated, the depth of streamflow from the forested part may be

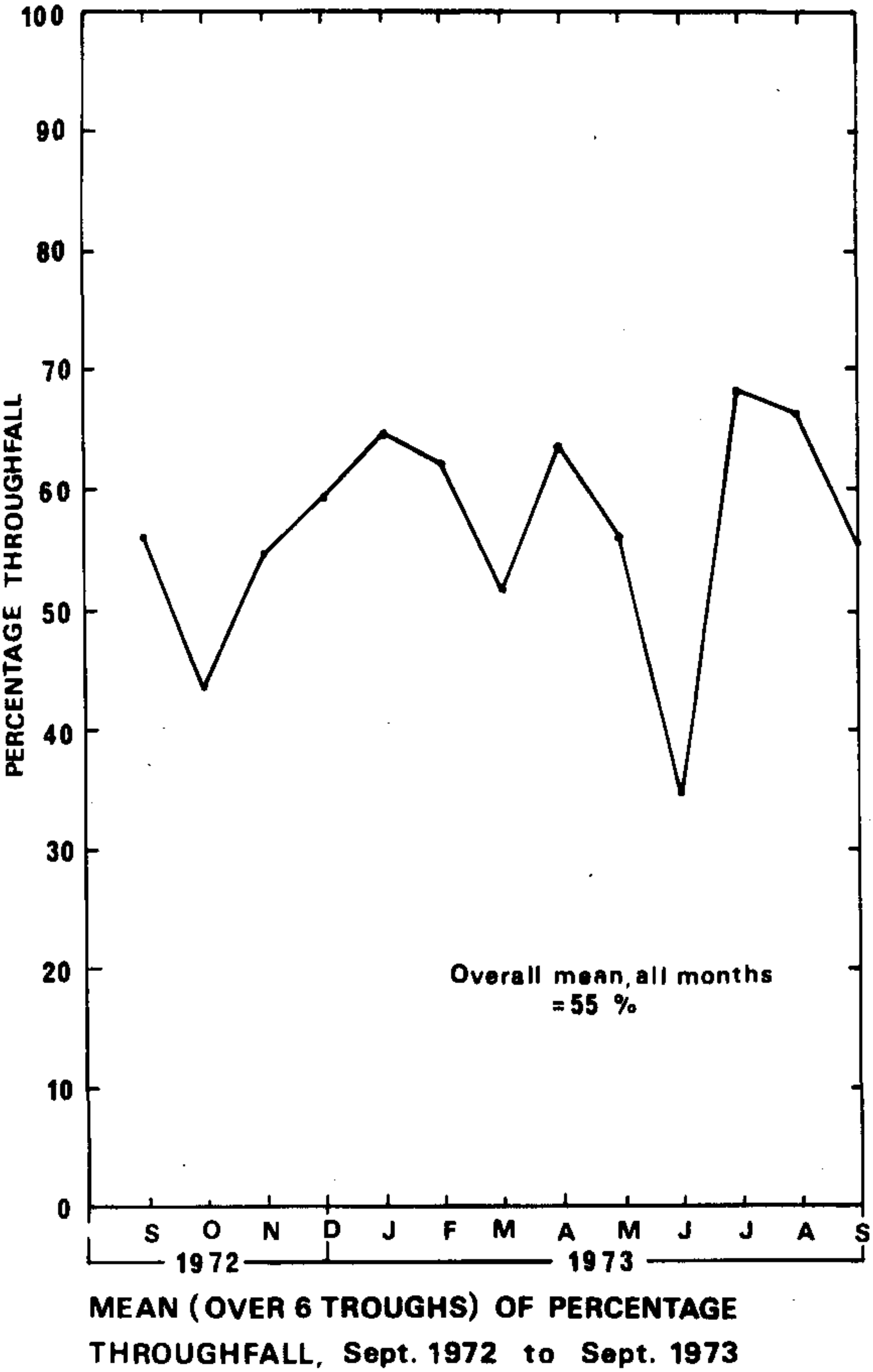
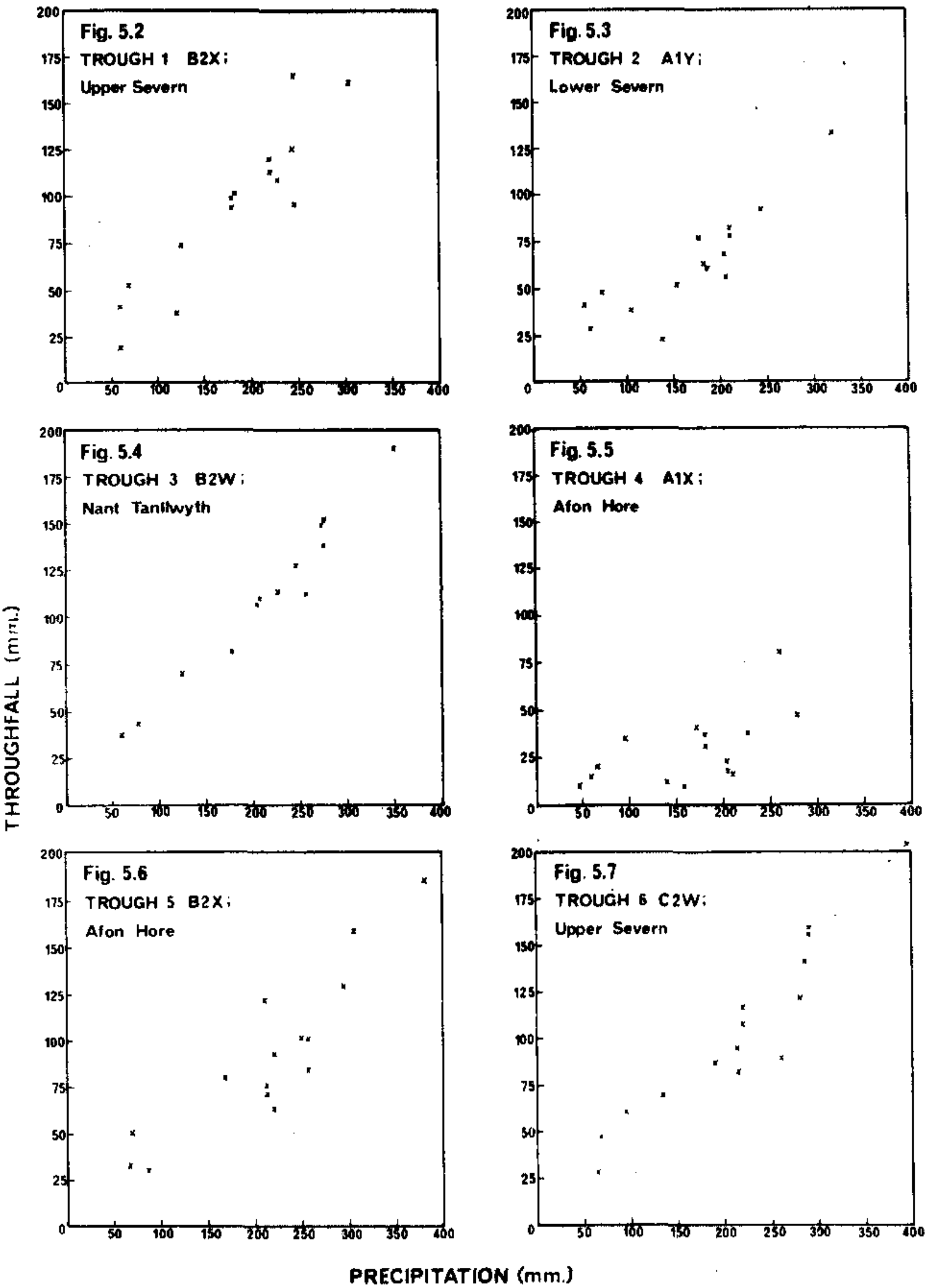


Figure 5.1 Seasonal percentage throughfall



Figures 5.2 - 5.7 Relationship of measured throughfall and precipitation

calculated if the unforested and forested areas are known.

For winter months, when both change in soil moisture (ΔS) over a month and the actual transpiration (tr) are both small, the water balance equation for the forested part of the Severn

$$\text{Throughfall} + \text{stemflow} = Q + Tr + \Delta S \qquad \text{.........(5.1.1)}$$

becomes approximately

$$\text{Throughfall} + \text{stemflow} = Q \qquad \text{.........(5.1.2)}$$

Substitution of the measured throughfall (calculated as a mean of all troughs), and the estimated streamflow from the forested area of the Severn, in equation (5.1.2) gives an estimate of depth of water reaching the soil surface as stemflow.

Table 5.1.1 shows details of this calculation for the calendar years 1973 and 1974. The total of the differences between streamflow and throughfall for months between October and March inclusive is 260 + 425 = 685 mm, whilst the total precipitation is 1293 + 1624 = 2917 mm; the crude estimate of stemflow, expressed as a percentage of incoming precipitation, is therefore 685 x 100/2917 = 23%. Roughly, therefore, 55% of precipitation drips through the canopy; 23% reaches the soil surface as stemflow; and the remaining 22% is intercepted by the canopy and thence evaporated. This figure agrees reasonably well with one derived from Table 2.3.1 (not entirely independently): after adjustment, of the Severn losses for the unforested Upper Severn, the mean (5-years) loss from the Severn is 437 mm greater than that from the Wye, with a mean (adjusted, 5-year) precipitation for the Severn catchment of 2291 mm; if the additional loss from the Severn were accounted for entirely by interception loss, this latter would be estimated as 100 x 437/2291 = 19% of incoming precipitation. If data are used solely from the years 1970-72 shown in Table 2.3.1 and again assuming that the additional loss from the Severn is accounted for by interception loss, the agreement is even better: the mean additional loss due to interception is (395 + 534 + 454)/3 mm, from a mean precipitation of (2485 + 1762 + 2124)/3 mm, this representing 22% of the incoming precipitation, which agrees exactly with the estimate obtained from the 1973-74 data using the above crude argument.

The figure of 23% for stemflow loss is considerably higher than that reported in the literature. Law (1957), working with a small Sitka spruce plantation, found that stemflow accounted for only 7% of incoming precipitation over a period of 18 months. Law's plot contained 95 trees on an area of 0.045 ha, representing a density of 1 tree per 4.74 m^2; on the Severn catchment, the density of trees is greater, at approximately 1 tree per 2.36m^2, although it does not follow, necessarily, that greater density of stems is associated with greater stemflow. Law's figure of 7% for measured stemflow is subject to some uncertainty, also; the coefficient of variation calculated from the five stemflow gauges used was 49% (c.f. a coefficient of variation of 41% obtained by Dr I Calder, using 3 stemflow gauges).

Table 5.1.1 Comparison of throughfall and adjusted streamflow from the Severn catchment (forest only)

Month:	Precipitation P, Upper Severn only (mean of 5 gauges):	Streamflow, Q, Upper Severn only (Q= -9.02 + 0.861 P):	Q entire Severn catchment:	Q_F, from forested area only:	Th (Throughfall):	Th-Q_F:	P_F (forest precipitation, estimated):	Estimated stem-flow (see text):
Jan 73	190	154 (+- 31)	138	128	109	- 19	166	+ 19
Feb	348	291	218	173	157	- 16	236	+ 16
Mar	157	126	130	132	64	- 68	126	+ 68
April	204	167	127	102	116	+ 14	174	
May	208	170	121	91	107	+ 16	191	
June	60	43	31	24	19	- 5	57	
July	195	159	91	49	114	+ 65	190	
Aug	263	217	161	127	152	+ 25	228	
Sept	243	200	154	126	141	+ 15	236	
Oct	225	185	186	187	127	- 60	207	+ 60
Nov	277	229	195	174	141	- 33	245	+ 33
Dec	360	301	272	254	190	- 64	324	+ 64
1. 1.74 - 31. 1.74	397*	333	308**	292	167	-125	340	+125
1. 2.74 - 28. 2.74	249	205	197	192	110	- 82	217	+ 82
1. 3.74 - 27. 3.74	128	101	85	75	66	- 9	115	+ 9
28. 3.74 - 24. 4.74	11	0	16	25	6	- 19	16	
25. 4.74 - 22. 5.74	104	80	12	- 30	32	+ 62	94	
23. 5.74 - 19. 6.74	171	138	56	6	77	+ 71	150	
20. 6.74 - 17. 7.74	227	186	136	105	117	+ 12	198	
19. 7.74 - 31. 7.74	157	126	82	55	82	+ 27	139	
1. 8.74 - 14. 8.74	87	66	55	48	43	- 5	80	
15. 8.74 - 31. 8.74	46	30	33	35	18	- 17	46	
1. 9.74 - 11. 9.74	233	192	163	145	123	- 22	202	
12. 9.74 - 20. 9.74	188	153	122	103	96	- 7	165	
1.10.74 - 10.10.74	68	50	54	56	35	- 21) - 37	65) 215	+ 37
11.10.74 - 31.10.74	171	138	112	96	80	- 16)	150)	
1.11.74 - 27.11.74	286	237	215	201	172	- 29) - 40	247) 292	+ 40
28.11.74 - 30.11.74	45	30	28	27	16	- 11)	45)	
1.12.74 - 19.12.74	297	247	219	202	137	- 65) -132	257) 445	+132
20.12.74 - 1. 1.75	216	177	182	185	115	- 67)	188)	

* Estimated as (Upper Severn rainfall) = - 4.75 + 1.11 (Severn mean areal rainfall)

** Obtained from daily summary listings

Stemflow percentage: $\frac{(19 + 16 + 68 + 60 + \ldots + 132)100}{(166+236 + \ldots + 445)} = \frac{68500}{2928}$

= 23%

. CONCLUSIONS

The analyses described in the above sections lead to the following conclusions.

(i) The mean annual loss (1970-75) for the Wye catchment (hill pasture) - where loss is defined as the difference between annual precipitation P and annual streamflow Q - is 18% of the mean annual precipitation P which is 2415 mm. The mean annual loss from the Severn catchment (about two-thirds of which is coniferous forest) is 30% of mean annual precipitation P, which is 2388 mm.

(ii) If the mean annual loss from the Severn catchment is adjusted to allow for the unforested area in its upper reaches, the mean annual loss from the forested area of the Severn rises to about 38% of mean annual precipitation. The adjustment used in this calculation assumes that the rainfall-runoff relation for the unforested area of the Upper Severn is identical with that for the Wye catchment; the four months of runoff measurements from the Upper Severn that were available did not disprove this assumption, but more data are required before the assumption can be adopted with full confidence.

(iii) The energy required to account for the observed mean annual loss P-Q from the Wye catchment is 66 $\pm$ 3% of the total annual net radiation R_N; the energy required to account for the observed mean annual loss from the Severn is 88 $\pm$ 3% of its total annual net radiation R_N. These values are calculated on the assumption that solar radiation R_S (and hence net radiation R_N) measured at the Moel Cynnedd meteorological station underestimates the solar radiation (and net radiation) received by the catchment as a whole; the R_S and R_N for Moel Cynnedd have therefore been adjusted upwards by a factor of 1.2.

(iv) On the basis of one year's observations of R_S from solarimeters at the Moel Cynnedd, Carreg Wen and Eisteddfa Gurig automatic weather station sites, it appeared that annual solar radiation R_S increased with altitude by about 141 MJm^{-2} per 100 m of altitude. Using data from the net radiometers mounted on the automatic weather stations, it appeared that annual net radiation total R_N increased by 137 MJm^{-2} per 100 m of altitude. Analysis of data from subsequent years is required before these radiation-altitude relations can be used with confidence.

If the within-year energy balance is considered, the energy required to account for the losses from the Wye catchment in the winter months from October to March (where loss is now defined as P-Q-ΔS, with ΔS the mean change in soil moisture storage over the catchment) is about 92% of the total net radiation R_N; for the Severn catchment, the energy required to account for the losses between October and March is 144% of R_N.

A possible explanation for the magnitude of the latter figure (and one that is supported by the Institute's study of the evaporation losses from tall conifers in Thetford Chase, Norfolk) is that the additional energy requirement in excess of R_N is supplied by a downward flux of sensible heat from air passing over the forest canopy.

(vi) Still considering the within-year energy balance, the energy required to account for the losses P-Q-ΔS from the Wye catchment in summer months (April to September) is 43% of the net radiation R_N; the corresponding figure for the Severn is 57%.

(vii) Preliminary analysis of throughfall data from the Severn catchment suggests that 55% of the incident precipitation falls through the canopy. Of the remaining 45%, possibly 23% flows down the stems and 22% may be evaporated from the canopy.

(viii) For the Wye catchment, Penman's E_T underestimates the actual evaporation losses (P-Q-ΔS) in winter months October to March; in summer months, E_T exceeds the actual evaporation loss more frequently than the catchment is likely to be in deficit.

(ix) The seasonal discrepancy between Penman's E_T and actual evaporation from the Wye catchment cannot be accounted for by the neglect of soil heat storage, nor by any seasonal variation in albedo of the catchment.

(x) The results of dilution gauging and current metering studies on flow through the Severn trapezoidal flume suggest that measured flows from the Severn catchment can be used with full confidence.

(xi) In months free of snowfall, statistical analysis gives no evidence that catches by canopy-level gauges in the Severn differed significantly from catches by ground-level gauges. However, in months when snow fell, there was evidence that canopy-level gauges sometimes recorded a significantly lower catch than ground-level gauges at the same altitude.

7. REFERENCES

Law, F	1956	The effect of afforestation upon the yield of water catchment areas. *J. Brit. Waterworks Ass.*, 38, 489-494.
Law, F	1957	Measurement of rainfall, interception and evaporation losses in a plantation of Sitka spruce trees. IUGG/IASH: Gen. Assembly, Toronto, II, 397-411.
Millis, L W F	1975	Water and water management: the developing philosophy. IHD/ICE/IH Conf: Engineering Hydrology Today, 3-9.
Rutter, A J	1964	Studies on the water relations of *Pinus sylvestris* in plantation conditions. II The annual cycle of soil moisture change and derived estimates of evaporation. *J. appl. Ecol.*, 1, 29-44.
Deij, L J L	1956	Contribution to a discussion on evaporation. *Neth. J. agric. Sci.*, 4, 92.
Pereira, H C, Dagg, M & Hosegood, P H	1962	The development of tea estates in tall rain forest: the water balance of both treated and control valleys. *E. Afr. agric. For. J.*, 27, 36-40.
Penman, H L	1963	Vegetation and hydrology. Tech. Comm. 53, Commonwealth Bureau of Soils: Commonwealth Agricultural Bureaux, Farnham Royal, Bucks.