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THE

PLYNLIMON FLOODS OF AUGUST 5th/6th 1973

by

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ABSTRACT

Too often flood analyses have to be performed with scanty or unreliable data. In this case the severe storm event centred over the Institute's experimental catchments in Mid-Wales, with their dense network of instruments recording rainfall and streamflow. The storm produced the highest flood peaks ever recorded for the catchments. Using provisional results from the Institute's Flood Studies, the return period of the estimated peaks and of the rainfall was determined. Catchment response during the event was compared with that predicted by previous unit hydrograph analysis. The spectacular geomorphological effects of the flood are described with particular emphasis on slope failure as the result of subsurface flows. The effects of the localised Plynlimon flood wave on the River Wye downstream are treated as an example of channel routing by the Hydraulics Research Station. Subsequent effects of the flood are hypothesized and discussed and the concluding section returns to the adequacy of flood data from the experimental network.

CONTENTS

FIGURES

TABLES

PLATES

INTRODUCTION

The United Kingdom Flood Studies revealed how valuable accurate runoff data are for floods of high return periods, especially in the relatively rare cases in which they are accompanied by data from a dense network of rainfall recorders. Thus the largest flood ever recorded in a densely-instrumented experimental catchment is of more than ordinary importance. The flood described herein occurred in the Institute's Upper Wye and Upper Severn catchments in Mid-Wales (Plynlimon) and were recorded by perhaps the densest concentration of hydrological instruments in the British Isles. Since the purpose of the twin catchment configuration is to compare the hydrological effects of forest and grassland land usage, the biggest flood event is also important in terms of land-use effects on extremes (which might not have been recorded during the life of the experiment but for chance).

The flood occurred during the completion of the Flood Studies at the Institute and the treatment here also reflects the use to which early data were put in testing empirical relations discovered by the Study. Particularly useful were the probability analyses of peak flows and average unit hydrographs already available for the two main catchments (three tributaries in each catchment have been gauged since 1970 but their records were too short for the Flood Study to consider).

The following topics appeared worthy of special attention:

1. Synoptic conditions connected with the heavy rainfall and their probable frequency;
2. The distribution, spatially and temporally, of storm rainfall in a hilly area of dense instrumentation;
3. The return period of rainfall depths, intensities and of peak flood discharges as established from available data;
4. The nature of catchment response to a 'rare' event with particular reference to the sensitivity of time parameters of outflow;
5. Geomorphological effects of the flood and new exposures of the relationship between superficial deposits and subsurface flow;
6. Effects of a fairly localized flood input to the main rivers Severn and Wye;
7. Subsequent effects of the flood on runoff and sediment yield in the experimental catchments;
8. The performance and adequacy of the instrument network for the analysis of severe floods.

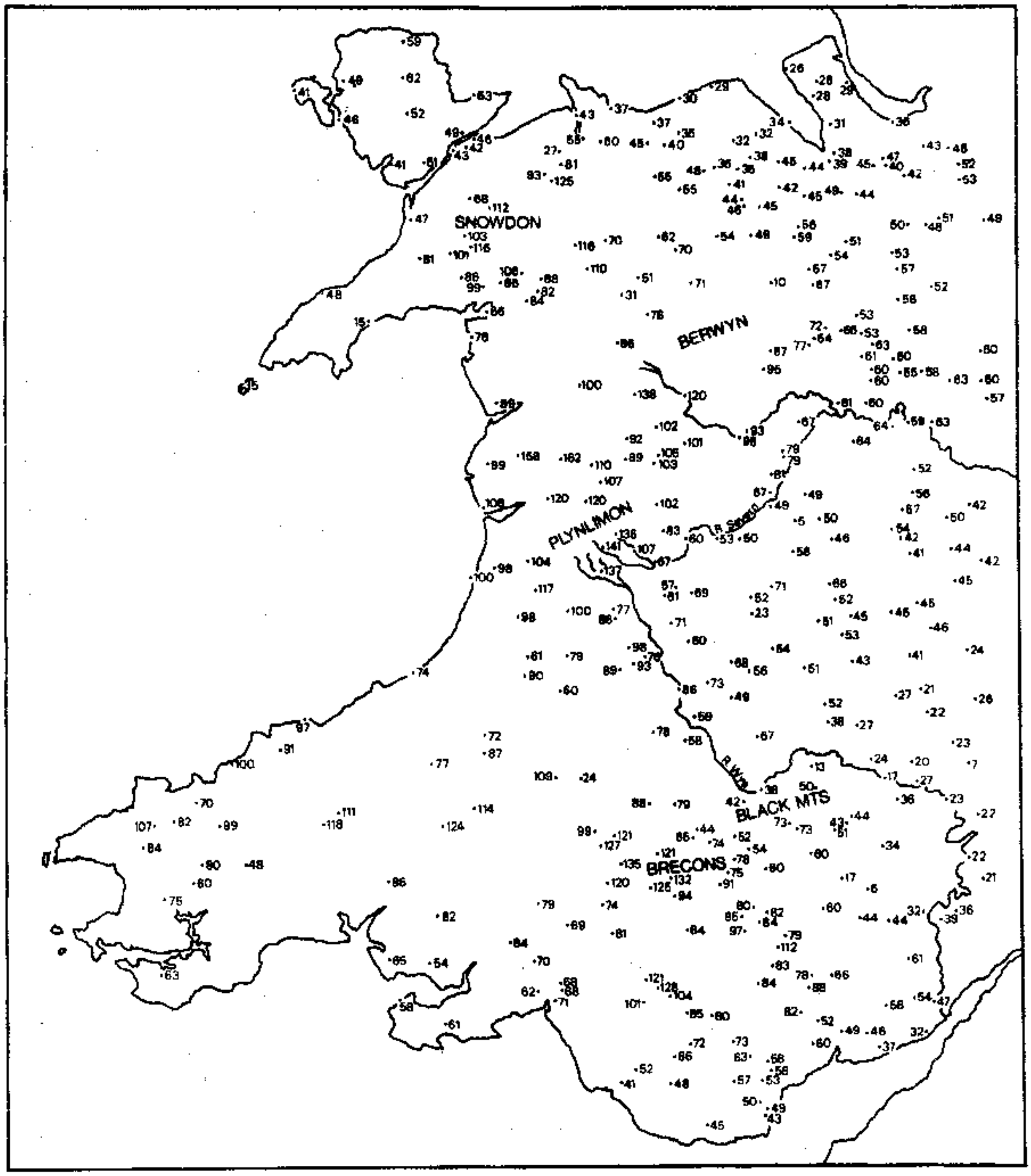


Figure 1. Rainfall totals for Wales, 48 hours commencing 0900 GMT, 4/8/73, based on information supplied by the Meteorological Office.

SUMMARY OF THE FLOOD

The first five days of August 1973 were the wettest for twelve years at Newtown in the Upper Severn valley and the weekend of 4th/5th August saw the cancellation through rain of several outdoor shows and sports fixtures (County Times and Express, 11.8.73). Table 1 shows the 28-day antecedent rainfall at Tanllwyth (Moel Cynnedd) in the Severn catchment prior to the storm recorded on the 5th (100.6 mm). It can be seen that 59.6 mm of rain had fallen since 25th July when the Meteorological Office estimated zero soil moisture deficit for the Plynlimon area, a figure described as 'remarkably low for the end of July' in the S.M.D. Bulletin. Over 40 mm fell over the catchments on the day before the flood; such an amount in winter would normally by itself suggest flood alert situations at Plynlimon.

In the early hours of 6.8.73 a six-hour period of intense rainfall affected the Plynlimon massif, the Berwyns to the north, parts of Snowdonia and the Brecon Beacons. The rainfall for Wales for the 48 hours following 0900 GMT on 4.8.73 is shown in Figure 1; virtually all of the totals shown fell in the storm described and its precursor on the 4th. The maximum (six-hour) spell of rainfall over Plynlimon occurred between 2300 on the 5th and 0500 on the 6th (all times GMT for catchment data). During this spell 70 mm or more fell. Unfortunately, because of the rapid response of upland catchments and the timing of the storm, there are no eye-witness observations of the flood peak from the Institute's catchments. The flood waters caused severe damage, mainly to farmland and camp sites on the Severn at Llandinam and tributaries at Trefeglwys, Meifod and Manafon. The River Dovey also badly flooded whilst an eighty-year-old at Llangurig had never seen the Wye so high.

SYNOPTIC CONDITIONS AND THE AUGUST FLOODS

In spite of its westerly location (where winter rainfalls would be anticipated as the cause of the highest floods) this event followed almost exactly 17 years after the previous most severe flood in the area, recorded at the Plynlimon Weir and Cefn Brwyn (Surface Water Survey, 1961) and in British Rainfall for 1957. The latter is worthy of full quotation:

> 'On the 4th (August 1957) the storms were confined to Wales, where at Marteg in the Upper Wye Valley, sheep and cattle were washed away and drowned as streams rose rapidly following exceptionally heavy rain .... A "very rare" fall (Bilham's classification, British Rainfall, 1935) is believed to have occurred at Llangurig (Llugnant) Montgomeryshire on the 5th when about 4 inches (101.6 mm) fell in 120 minutes: it was also reported that upstream of Llangurig the River Wye reached its highest level for 40 years. Llanidloes, Montgomeryshire, about 4 miles to the north-east of Llangurig, suffered heavy damage as two streams burst their banks following a storm of "remarkable" intensity (again Bilham classification - 2.72 inches were recorded in 2 hours 50 minutes at Hillfield, Llanidloes). A main road was flooded to a depth of three feet and many houses and shops were flooded and damaged'.

TABLE 1. 28-day antecedent rainfall for Moel Cynnedd prior to 5.8.73

August	5th	-	100.6 mm
"	4th	-	40.3 mm
"	3rd	-	1.3 mm
"	2nd	-	1.9 mm
"	1st	-	0.1 mm
July	31st	-	4.6 mm
"	30th	-	7.2 mm
"	29th	-	4.2 mm
"	28th	-	-
"	27th	-	-
"	26th	-	-
"	25th	-	-
"	24th	-	0.3 mm
"	23rd	-	0.3 mm
"	22nd	-	13.4 mm
"	21st	-	4.2 mm
"	20th	-	17.7 mm
"	19th	-	17.3 mm
"	18th	-	14.1 mm
"	17th	-	0.5 mm
"	16th	-	11.8 mm
"	15th	-	28.8 mm
"	14th	-	36.0 mm
"	13th	-	0.8 mm
"	12th	-	0.9 mm
"	11th	-	0.9 mm
"	10th	-	2.8 mm
"	9th	-	3.3 mm
"	8th	-	-

The coincidence of dates for the 1957 and 1973 floods is less surprising when Lamb's remarks (1950) about climatic singularities are quoted:

> '23-30 July and following week:
>
> Thundery, cyclonic weather over Europe and the British Isles. Stagnant depressions common. Cyclonic type approaching its greatest frequency of the year in Britain 4 - 8 August.'

Lamb also remarks that the peak of the year's mean temperature curve also occurs in the week 30th July to 6th August; possibly this aggravates any convectional activity during this unstable spell.

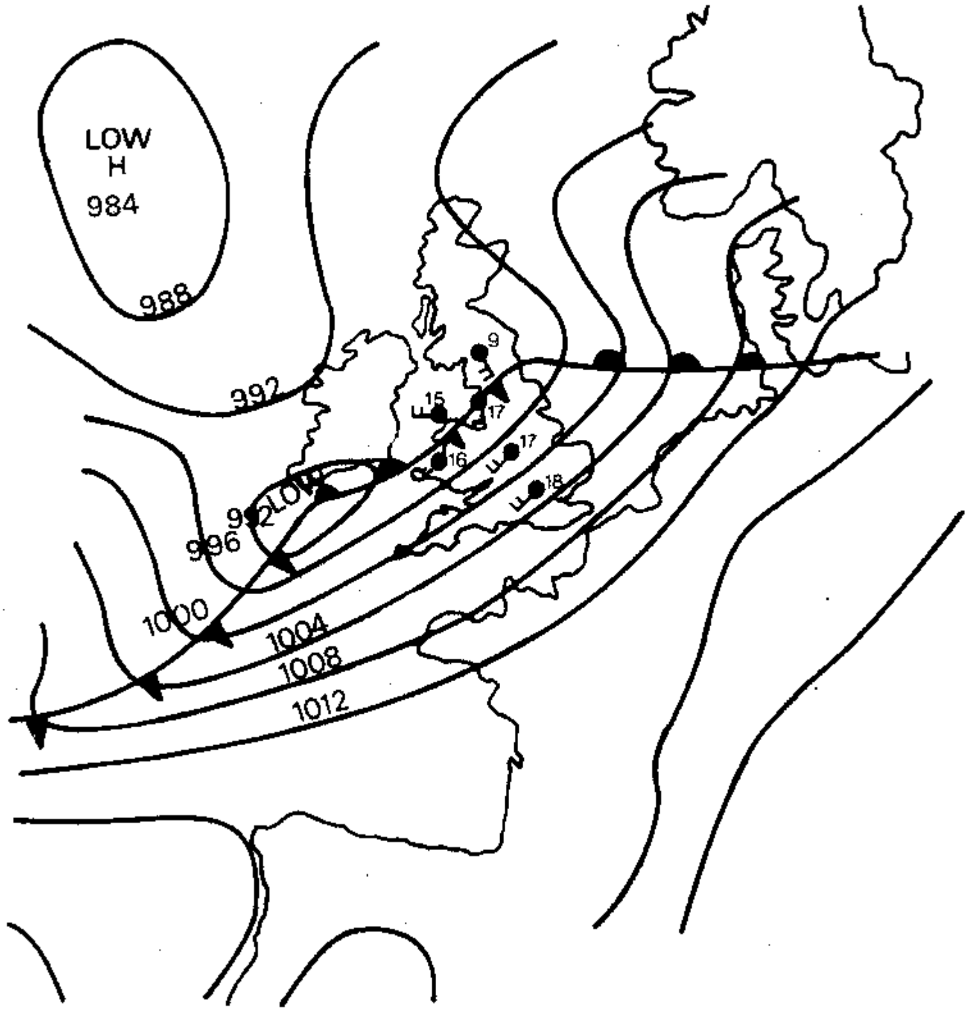
The weather chart for 1200 GMT on 5.8.73 shows a complex low pressure area stretching from Iceland to Scandinavia and the British Isles. A series of fronts forms part of the system and a small wave depression developing off the west coast of Ireland is seen to deepen and move rapidly into western Britain by midnight on the 5th (See Figure 2). The cold front section of the wave brought the heavy rainfall in the early hours of the 6th. The effects of the passage of this front can be gauged from the increase of windspeed and veering of wind direction recorded by the automatic weather stations on the catchments; a fall of around 2^{o}C in air temperature also marks the change from warm sector air to a colder, northern airstream.

The synoptic characteristics and storm profiles of heavy rainfalls over the Plynlimon catchments form part of the Institute's work on streamflow modelling of the flood hydrograph. Meteorologists have already carried out such studies and results from Snowdonia to the north suggest what the pattern may be. Matthews (1972) demonstrates the significant association of synoptic categories and rainfall intensities for Valley and Cwm Dyli. Cold fronts are notably more important in producing high intensity falls (3.1 mm/hr is quoted as an average) over North Wales than in the Midlands. Similarly, Lowndes (1968, 1969) and Holgate (1973) report the importance of the cold front type for daily totals in the area. The uniformity of rainfall over the Plynlimon area during the storm in question is less surprising in view of the conclusions of Harrold (culminating in his 1973 paper) that warm front and warm sector rainfall is far more variable and more susceptible to orographic influence than that from cold fronts.

RAINFALL ANALYSES

The instrument network of the Plynlimon catchment is shown in Figure 3; the raingauge network is basically monthly-read (for details see Clarke, Leese and Newson, In press). The monthly totals for August 1973 are shown in Figure 4 and hand-drawn isohyets have been superimposed to emphasize the generally uniform distribution of falls over the two catchments. The isohyetal average for the two catchments differs by 2.9 mm, the arithmetic average by 2.2 mm and the Thiessen polygon average by 0.1 mm. Only the arithmetic average gives the Severn more rainfall and it is concluded that the storm rainfall, which composed almost half the monthly total, fell uniformly over the two catchments.

This conclusion can be supported by using rainfall recorders at six sites



SYNOPTIC SITUATION AT 00hrs GMT, 6/8/73

Figure 2. Synoptic situation at 0000 GMT, 6/8/73, showing the cold front over North Wales. Reproduced from the Meteorological Office daily weather report.

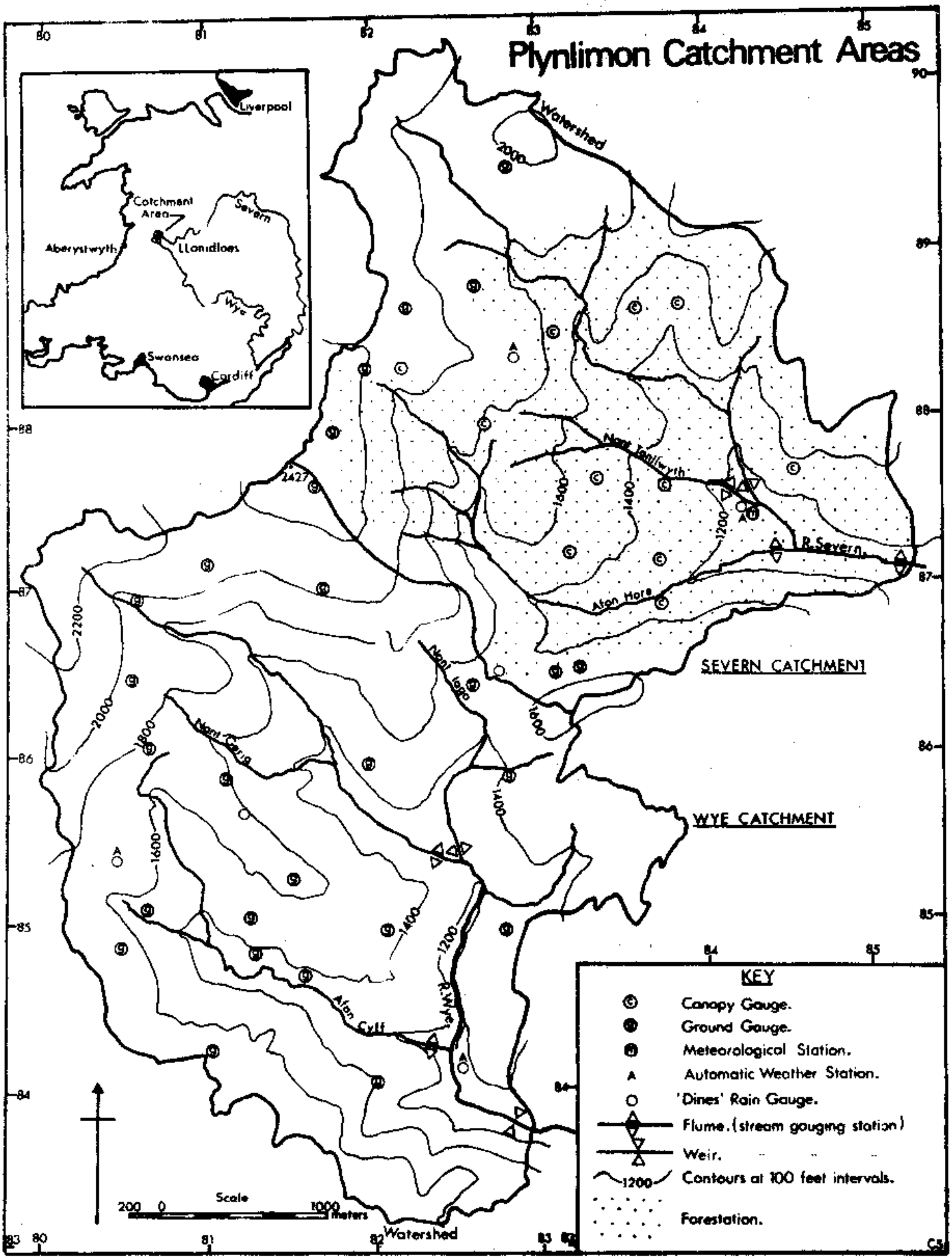


Figure 3. Plynlimon experimental catchments - instrument network

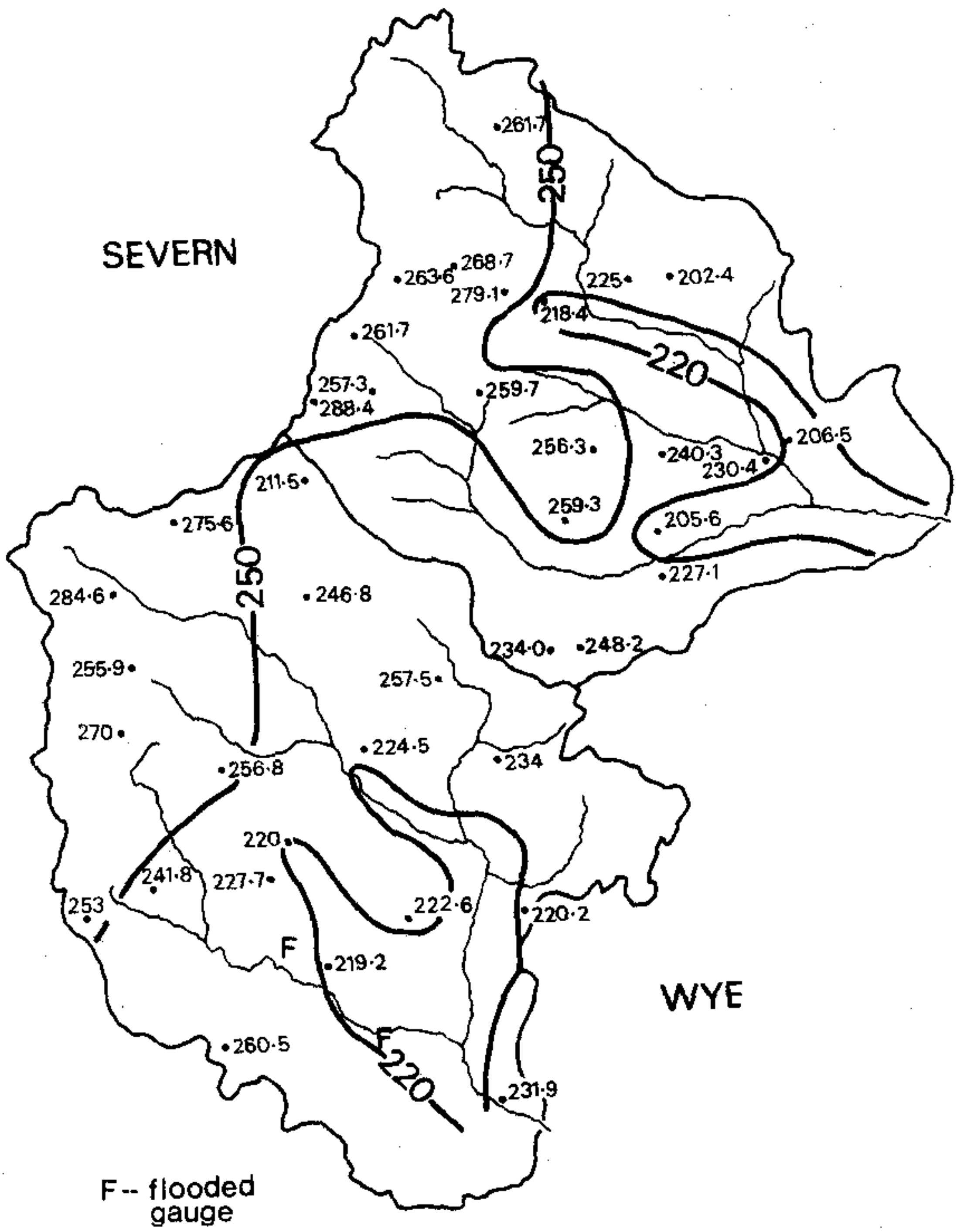


Figure 4. Monthly rainfall totals for August 1973, Plynlimon catchments (mm).

in the catchments; at four of these sites the Dines tilting syphon recorder is supplemented by a tipping-bucket gauge which forms part of the automatic weather station. The differences between these two types of gauge with regard to hourly falls are shown in Figure 5 (the Dines is continuously recording rainfall increments whereas a tipping-bucket gauge only records in half-millimetre units, logged every five minutes). No large or consistent differences are indicated although the tipping-bucket gauge is at ground-level and tends to catch more. However, there are virtually no points on the line of equality and the two types of data should be used with care. Totalled to give the daily fall for 0900 5th - 0900 6th August and plotted against altitude, the recording raingauge records again show only slight differences between the two catchments, (Figure 6). The Esgair y Maen gauge developed a fault and can be discounted. Daily totals in all cases show the higher catch of the ground-level tipping bucket gauge; the exposure of the Dines is considerable in comparison.

The recording gauges also provide information on the temporal profile of the storm and on storm movement. The basic profile is shown in Figure 7 which shows the daily-read Dines recorder chart for Tanllwyth (Moel Cynnedd). The storm peaked late, possibly a factor in the flooding which followed since a large area of the catchments would be contributing flow by the time the 'core' of the storm arrived. At Tanllwyth almost 50% of the total storm rainfall had fallen before the two-hour "core" between 0100 and 0300 on the 6th. It is possibly critical for catchment response too that two hours is approximately the lag-time of the catchments; during these two hours nearly 50 mm of rain were recorded simultaneously at all stations on the catchments. Figure 8 shows, from automatic weather station data, that little or no storm movement occurred across the catchments (Carreg Wen's early peak has been traced to a B.S.T./G.M.T. error in the start time). The absence of storm movement makes comparison of catchment response between the Severn and Wye much more valid, especially times to peak discharge, whilst areal uniformity allows easier comparisons of peak flows and rates of runoff.

Rainfall and peak flow return periods

Because of the relative uniformity of rainfall over the catchments it is possible to use the daily Dines recorder chart for Tanllwyth (Moel Cynnedd) as a basis of frequency assessments for the August storm. Several authors were consulted and the tabulated estimates are shown in Table 2. The chosen durations are the standard rainfall day, six hours - representing the main core of the August storm, and two hours - the approximate time of concentration of the main catchments.

When considering the return period of the daily total for the storm it should be borne in mind that on the previous day a fall of 40.3 mm of rain represents a fall equalled or exceeded less than once a year on average (it is given a return period of between 2 and 5 years by Holland, 1968). The two-day total of 143.6 mm has a return period of 10-20 years. As a consequence, the catchments were thoroughly wet prior to the main flood even though the previous day's flood hydrographs had completed half of their recession curve. It is the author's opinion that such

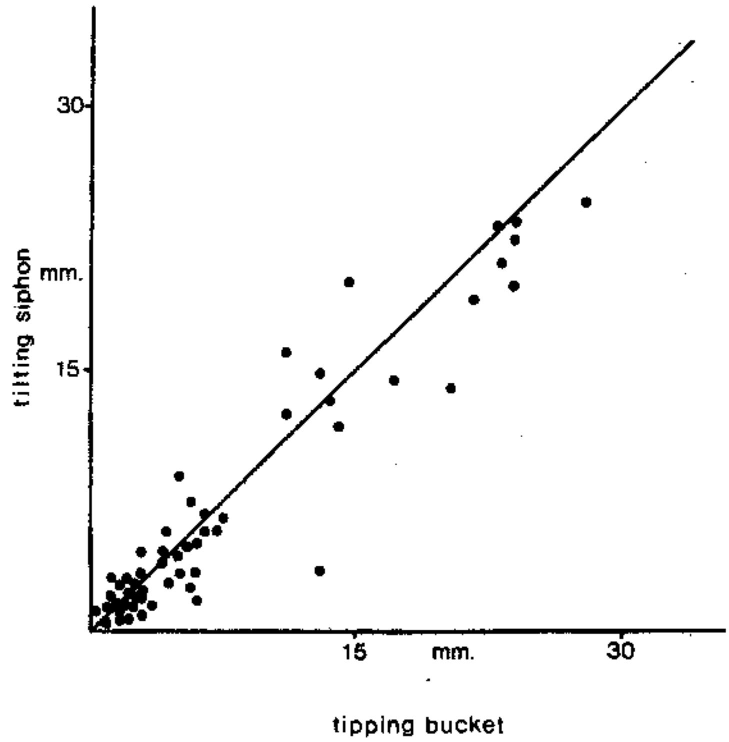


Figure 6. Daily fall for 0900 GMT 6th August, totalled from rain recorders. Dines tilting siphon recorders: circled dot, tipping-bucket recorders: dot, the one standard daily gauge: cross.

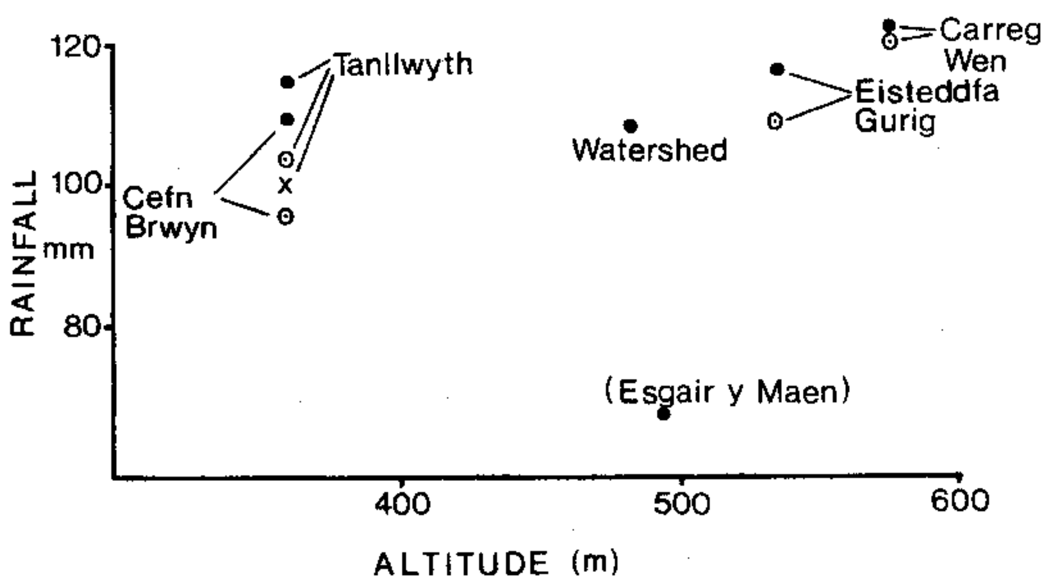


Figure 5. Comparative hourly totals for 5th/6th August at sites where tilting siphon (Dines) and tipping bucket (automatic weather station) gauges are present.

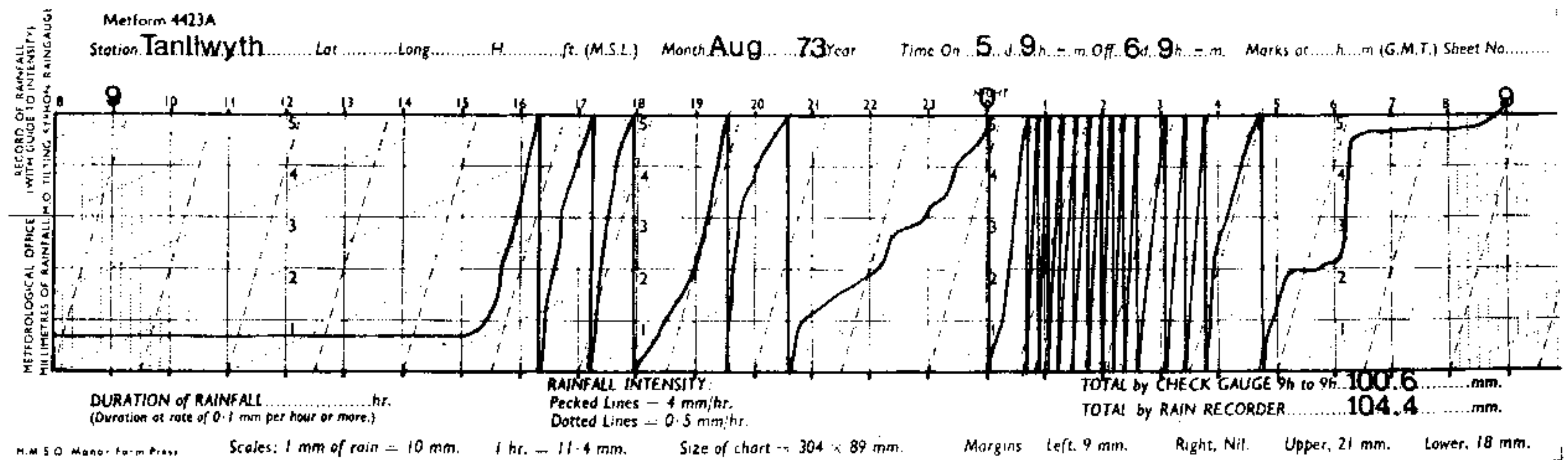


Figure 7. Daily-read Dines recorder chart for Tanllwyth (Moel Cynedd), Severn catchment.

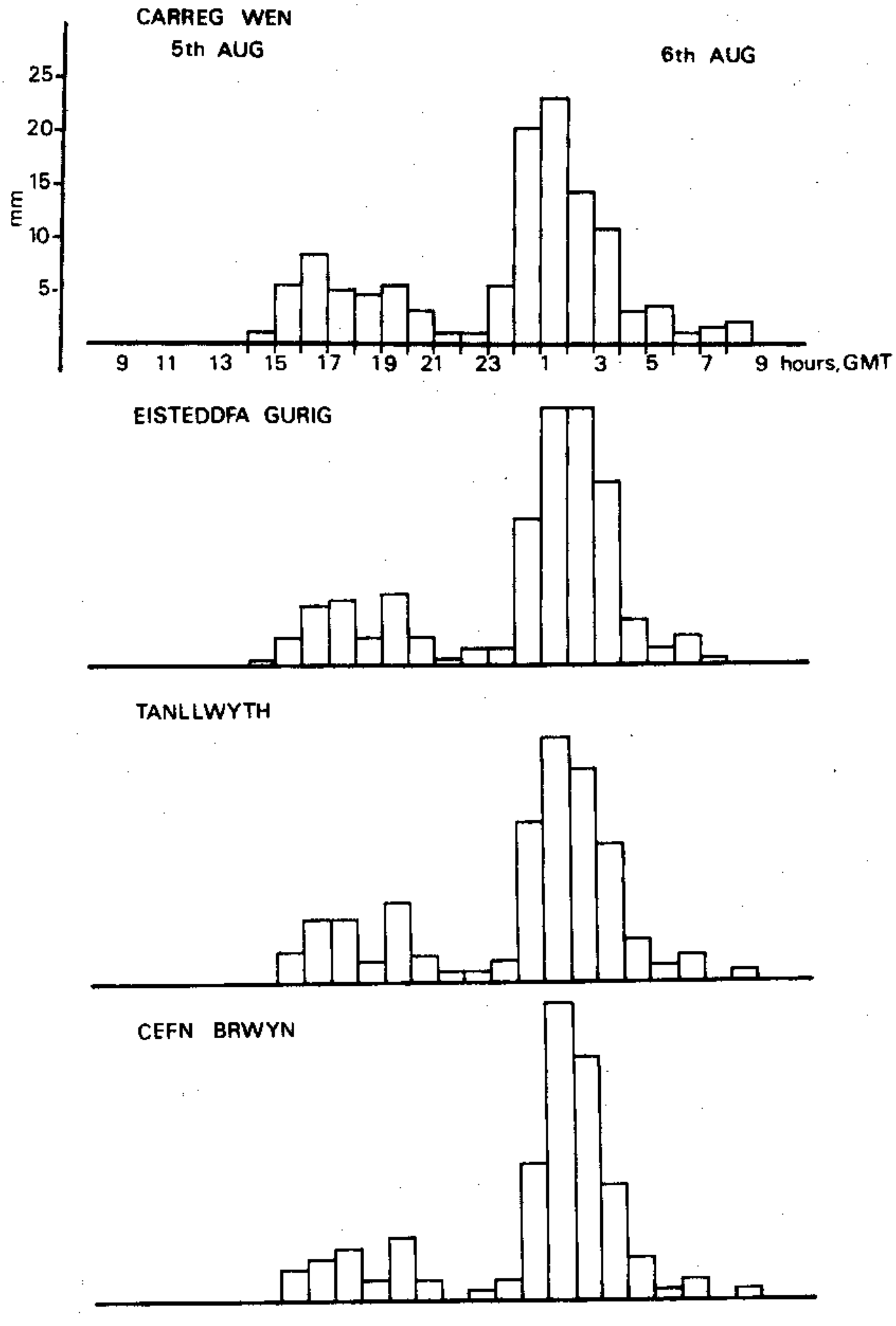


Figure 8. Storm rainfall profiles from automatic weather stations, 5th/6th August.

wet antecedent conditions are of especial importance on the Plynlimon catchments where the response of the plateau peat deposits is critical for runoff. That the peat areas did respond dramatically to the main storm is a conclusion obtainable from the erosion survey.

TABLE 2 Rainfall frequencies based on the Dines daily chart for Tanllwyth, 5 - 6.8.73

Data

Daily fall	=	103.3 mm
Max 6 hours	=	72.7 mm
Max 2 hours	=	46.0 mm
Max intensity	=	20 mm/hr for 2 hours

103 mm in 24 hours

Met Office Flood Study	approx 4 year return period
Met Office Memo 33 (Bilham)	approx 50 year return period
Rodda (Inst. Br. Geogrs.)	approx 10 year return period

72.7 mm in 6 hours

Met Office Flood Study	approx 16 year return period
Met Office Memo 33	approx 50 - 100 year return period

46.0 mm in two hours

Met Office Flood Study	approx 16 year return period
Met Office Memo 33	approx 20 - 50 year return period

Rainfall intensity

Met Office Memo 33	approx 20 - 50 year return period
Met Office Flood Study	approx 9 year return period

Turning to the probability of the recorded river flow peaks, it became obvious that field survey of the peak levels would be required for two reasons:

a. Data on peak flows was required in advance of the monthly removal of recorder charts and paper tapes, followed by computer processing; in two cases, recorders had malfunctioned; in several cases calibrations were not then available for the flow structures,

b. It was clear from inspection that most flow structures had been filled or overtopped by the flood peak.

TABLE 3. Slope area estimates of peak flow made at sections nearby IH flumes

Catchment	Area(km^2)	x-sect. (m^2)	perim. (m)	slope	Manning n	Q est. m^3/s	Max flume cap. m^3/s (design)
WYE							
Cyff*	3.13	5.22	12.5	0.02	0.05*	11.10	9.9
Gwy*	3.98	6.50	14.63	0.03	0.05*	16.87	17.83
Nant Iago	1.02	2.16	6.10	0.07	0.05	5.65	3.96
(Lower Wye)	2.42					(10.60**)	Ungauged
					total	44.22	
Cefn Brwyn	10.55	21.25	14.86	0.02	0.04	56.40	52.35 †
SEVERN							
Hafren	3.67	5.46	9.75	0.03	0.05	12.60	10.19
Hore	3.08	8.55	9.75	0.02	0.05	23.12	14.15
Tanllwyth	0.89	-	-	-	-	(2.16) ←	2.16
(Lower Severn)	1.0					(5.11**)	Ungauged
					total	42.99	
Severn Flume	8.70	-	-	-	-	(41.03) ←	41.03 †

*For these sections the cross-sectional area was divided between the channel proper, with a high roughness and the grassy banks, with a low roughness, ('n' = 0.035). For other sections this was not considered necessary. The final value is independently almost identical to that chosen by other experienced surveyors during the design of the flumes

** Estimates here assume areal equality of runoff and extrapolation of the slope area figures for the three preceding stations.

† Recorded flows Wye 57.30 cumecs
Severn 26.50 cumecs

Conventional survey methods were used to obtain cross-sections and the slope of rack marks on each side of the stream. The first available uniform reach was chosen upstream of the structure but outside its ponding influence. Because of the careful siting of the flumes, such a reach is frequently available and has no significant tributaries joining within it.

In one case, the Hafren, survey downstream of the flume was necessary because of the dense forest upstream. In each case two cross-sections were levelled, at either end of the rack mark survey lines (which were surveyed for between 100 and 300 metres). Abney level measurements were also made for comparison and photographs taken upstream, downstream and also of the channel sections. The plentiful dead grass and Juncus rush at that time of year made the marks exceptionally clear (see Plate 1). For selection of Manning's 'n' values, the photographic work of the United States Geological Survey (Barnes, 1967) was discussed. Only the Tanllwyth and Severn flumes were not surveyed because marks were consistent with both structures being filled but not overtopped. The full capacity of each flume was known from design. Further, in both cases the forestry upstream and downstream made survey of little benefit.

At the Tanllwyth flume both the Leupold and Stevens chart recorder and an experimental magnetic-tape device failed; at the Hafren the recorder jammed whilst the Cyff's record is of little use because the by-pass channel was open for alterations at the time of the flood. Subsequent observations prove that the Cyff flume overtops at high flows, as may do the Gwy flume.

The tributary structures at Plynlimon are comparatively recent and their records have yet to be used for flood frequency analyses. Thus it can only be claimed that they experienced their highest flows so far. Extensive damage was caused by overtopping at two of them; when built they were designed to measure up to the estimated 10-year peak discharge (Herbertson, 1968).

Estimated discharges for main catchments and tributaries are shown in Table 3. For Cefn Brwyn the estimate at the site is closer to the recorded flow than totalling the tributary estimates. For the Severn flume the tributary estimates closely match the maximum design capacity but the recorded flow is much lower. This point will be taken up later.

During 1973 the historical flow records for the Wye at Cefn Brwyn and for the Severn flume (preceded by the older Severn Weir) were used by the U.K. Flood Study for flood frequency and unit hydrograph analyses. Table 4 shows the tabulated data on annual peaks and estimates of return periods. It can be seen that the estimated peaks of 6th August 1973 have a return period of between 100 and 1000 years (Wye) and between 1000 and 10000 years (Severn). The latter range reduces to 25 - 100 years if recorded flow is used. Using the regional frequency curve for Wales in order to give a wider data base we find that the estimated Wye flood was 3.39 times the mean annual flood (recurrence interval: > 1000 years) whilst the Severn's factor was 3.04 (recurrence interval: ≤ 1000 years) based on estimation, (3.38 and 1.96 respectively if based on recorded flows). The only other comparative work is on the Wye at Cefn Brwyn which was used as an example by the Transport and Road Research Laboratory (Young and Prudhoe, 1973) whose best fit line for recorded flows shows a similarly high return period for the August flood but whose calculated flood frequency based on rainfall probabilities is more likely to extrapolate to around 100 years for the event. The discrepancy between the rainfall and flow-based estimates will be returned to; it is most likely connected with the previous day's heavy rain and in this context the total for the two days (140.9 mm) has a return period of only 5 years.

TABLE 4. Flood frequency analyses for the Wye and Severn main streams

Annual maxima for stations 54/22 and 55/8 - m^3/s

	Severn	Wye
1952	10.93	15.73
1953	10.63	15.73
1954	10.63	19.05
1955	9.58	13.47
1956	9.58	13.75
1957	23.69*	48.76*
1958	13.18	12.42
1959	8.85	10.18
1960	23.08	18.30
1961	16.97	22.97
1962	14.77	17.63
1963	8.67	10.74
1964	12.34	11.92
1965	20.72	19.58
1966	17.48	18.11
1967	12.34	9.26
1968	15.80	10.90
1969	8.24	16.82
1970	9.32	16.02
1971	11.33	23.39

*The 5th August flood of 1957 was reputedly the highest for 40 years on the Upper Wye in response to a similar rainfall to that of 5th August 1973 but concentrated into 2 hours!

(last year considered for)
(Flood Study analyses.)

Gumbel distribution estimates - m^3/s

	t(yrs)	2.33	10	25	100	1000	10000
WYE		16.91	28.11	34.35	43.76	59.14	74.45
	(standard error)	1.96	4.1	5.53	7.71	11.34	15.00
SEVERN		13.51	19.91	23.47	28.84	37.63	46.37
	(standard error)	1.12	2.34	3.16	4.4	6.47	8.57

UNIT HYDROGRAPH ANALYSES - CATCHMENT RESPONSE

The recorded stage hydrographs for all available sites are shown in Figure 9. The unit hydrograph analyses, prepared for the Wye and Severn by the Flood Study at Wallingford as part of a study of over a hundred catchments (Lowing and Newson, 1973), were compared with those of the event in question. This provided useful information on the possible change in unit hydrograph parameters for the larger events, a problem which affects use of the technique. The average unit hydrograph prepared for the two catchments was also used as a further means of estimating the peak flows by convolution with the known rainfall. The results of using the average and most severe analysed hydrographs with the Tanllwyth rainfall record and assuming 100% runoff, produce underestimates compared with those made by flume capacity and field survey; so too does the non-linear model produced by A. N. Mandeville (see Figure 10). However, all three methods produce peaks which exceed or equal the recorded peak at the Severn flume. When the data for the event itself were subjected to unit hydrograph processing the following results were derived (the average parameters for over 20 unit hydrographs for each catchment are shown in brackets):

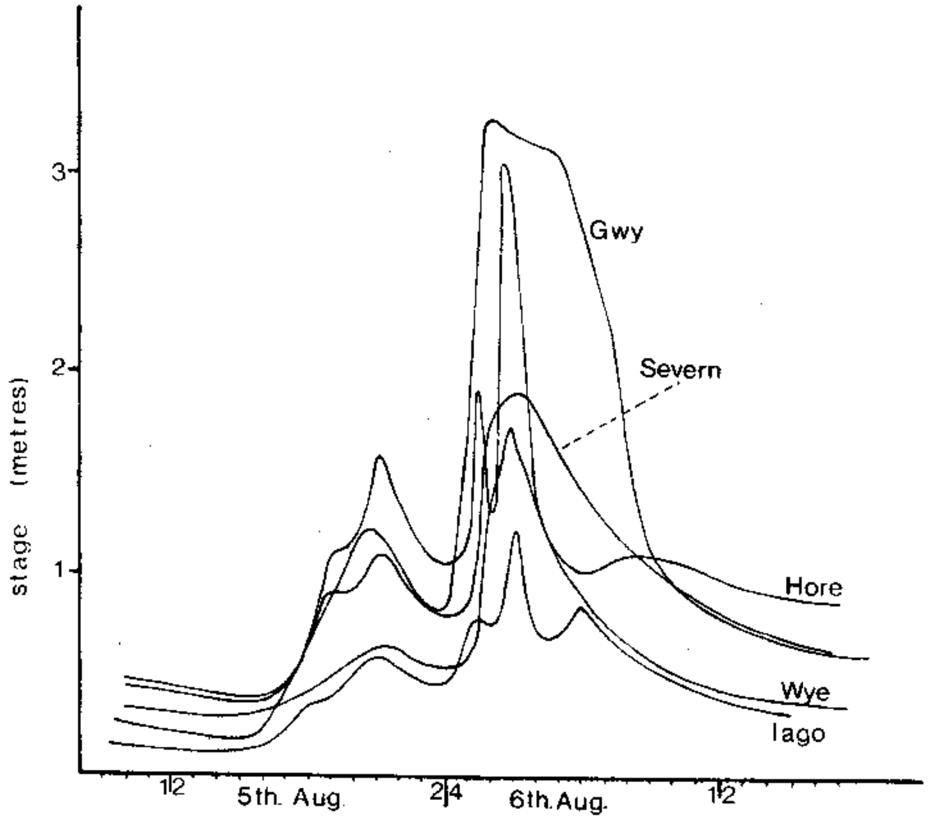


Figure 9. Stage hydrographs available for Plynlimon main streams (Wye and Severn) and tributaries. N.B. these represent flow through various geometric structures and are not comparable in this form.

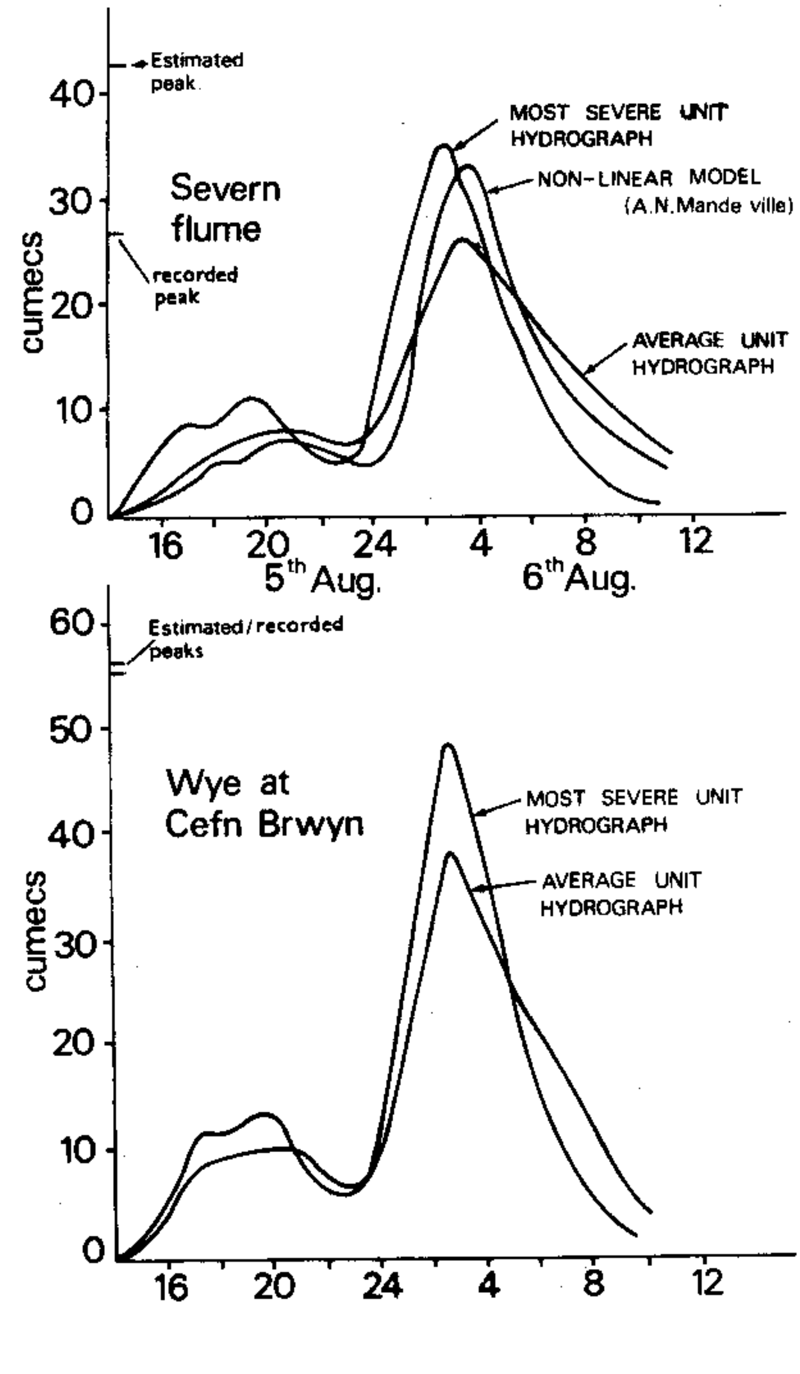


Figure 10. Use of unit hydrographs and predictive model to estimate peak flows with recorded rainfall (allowing 100% runoff).

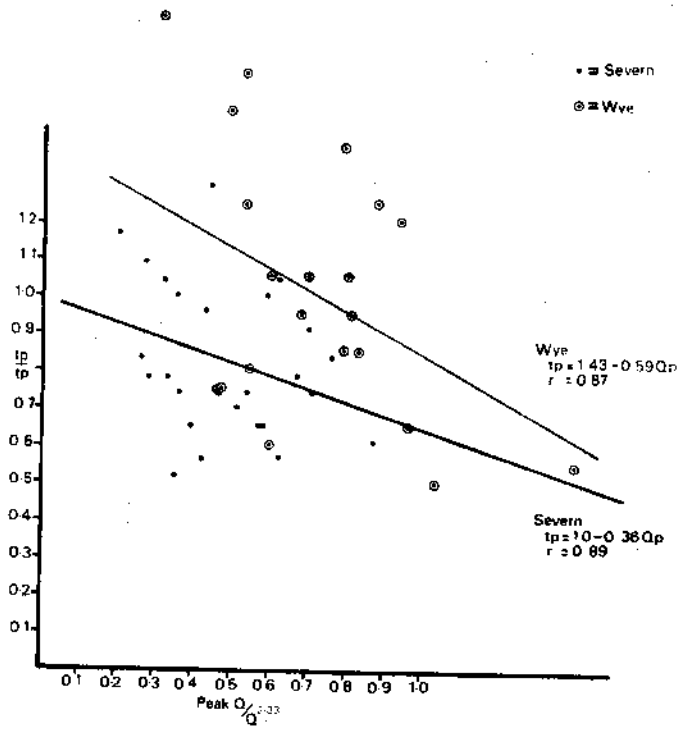


Figure 11. Decline in time-to-peak with increasing peak discharge, Plynlimon catchments (data from U.K. Flood Study).

WYE AT CEFN BRWYN

Time to peak ..... 2.5 hours (2.0 hours)
Peak runoff ..... 100.4 cumecs per 100 km^2 72.3)
Percentage runoff . 78.2% (48.9%)

SEVERN FLUME*

Time to peak ..... 2.3 hours (2.3 hours)
Peak runoff ..... 88.8 cumecs per 100 km^2 (58.3)
Percentage runoff . 61.0% (43.8%)

It can be judged that the time-to-peak is not lower than average although the peak rate of runoff is significantly larger than average. The percentage runoff is much higher than average. The 'normal' time-to-peak is particularly of interest since the Plynlimon catchments had earlier proved to be unusual amongst the national sample of catchments in that time-to-peak did decline with the increasing size of event. Figure 11 shows peak flows indexed by comparison with the mean annual flood and time-to-peak by comparison with the average; the August 1973 flood clearly does not follow the trend and is therefore more noteworthy from the point of view of amounts of runoff rather than timing, a point which is a corollary of the wet antecedent conditions rather than rainfall intensity or channel developments.

*Remarks concerning the accuracy of the Severn flume are made in a later section.

GEOMORPHOLOGICAL EFFECTS OF THE FLOOD

Geomorphologists now frequently accept the view that under most climatic regimes the 'catastrophic' or rare event does not contribute as much to the long-term development of landforms as seems to be the case on inspection shortly after it occurs; the more frequent moderate event, e.g. bankfull discharge, is credited with being more effective (see Wolman and Miller, 1960). However, the low frequency event produces a set of datable features whose future modification can be studied and the fact that the features, particularly on slopes, are formed in locations which are the most active under normal conditions, allows an appreciation of the processes involved. Normally the processes are hidden from view or are too slow to perceive.

It quickly became clear that all round the Plynlimon area the flood of 5th/6th August had moved large amounts of channel and slope material. Although Slaymaker (1972) concludes that the Upper Wye catchment shows an approximate balance between supply and removal of sediment, this was upset and slope changes were far more extensive than channel changes. Much of the debris supplied to channels by slope failures is still in the same channel reach (not only large boulders but also peat rafts and finer regolith). Where material did not reach the channel it has shown little subsequent modification and during the growing season of 1974 has become colonised by mosses, grasses and rushes.

The most graphic slope failures provided not only fresh exposures of the glacial, periglacial and creep deposits of the catchment but indicated a very clear association between the subsurface movement of water and slope development.

The location of the major sites of activity within the Institute's catchments is shown in Figure 12; Figure 13 is included because the Llwyd provided more spectacular examples at closer quarters (the Llwyd is the stream which flows past the Dolydd Office). Checks were made in all cases with the 1967 aerial survey of the area, but generally the features were so fresh as to be obviously datable to the August 1973 event; clear evidence of older but similar features was obtained but as mentioned above, one or more growing seasons covers the scars with young vegetation. Data are also available for the University College, Aberystwyth, experimental catchment on a tributary of the Rheidol (western slope of Plynlimon) where geomorphological action was also spectacular.

A library of photographs was built up but there is only opportunity here to show examples of the main types of flood erosion.

Apart from the basic classification into channel and slope activity, of which the latter was dominant, the slope failures may also be classified according to slope element location, the deposits involved and the part played by subsurface water flow. Provisionally the following are defined:

Figure 12. Sites of geomorphological action, 5 - 6 August, Plynlimon catchments. S = slide, B = burst, G = gullying, X = major site of deposition.

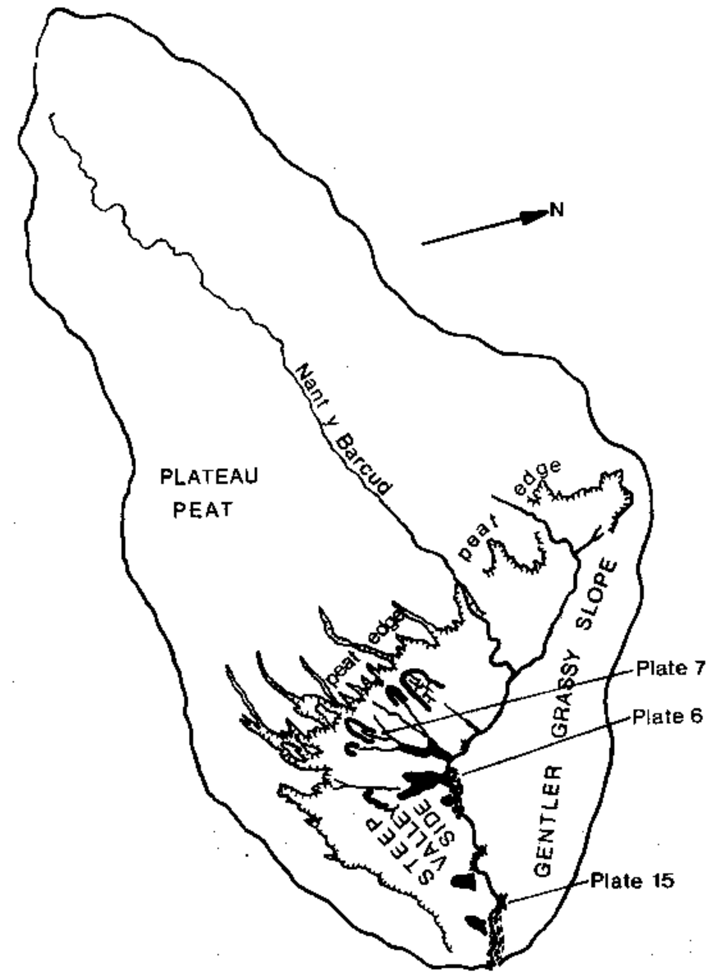


Figure 13. Slope failure and channel adjustments, Upper Llwyd catchment.

a. 'bursts'

b. slides

c. gullies

Bursts

Part of the invisible channel network in the Plynlimon catchments (although modified by the forestry in the Severn) consists of 'perennial pipes' (Gilman, 1972) flowing beneath peat-filled rushy flushes which link the peaty areas on the interfluves with the valley-bottom mires. It is not clear whether the peat infilling has come from the interfluves as part of the erosion of those areas into haggs or whether it has developed in situ as a corollary of the rapid vegetative growth of Juncus effusus. The long profile of the flushes and the intermittent potholes through the peat to the stream below suggest that the peaty infill is moving, almost glacier-like, down the bedrock gully particularly during flood events. As a result the perennial pipe is quite frequently constricted or even entirely blocked, whereupon the stream resurges to the surface for some distance until another open pothole conducts it underground again. Under the conditions of the August flood it is clear that the capacity of the pipes was exceeded and evidence of flow on the surface can be seen around many of the potholes. Peaty and gravelly debris was deposited and this may also help to explain the bulges in the long profile so characteristic of these features. The most graphic of the erosion features of the flood occurred where the peat infill became completely ruptured and slid in a series of huge 'rafts' down to the valley bottom. The causes would seem to be complete saturation of the peat from above and below, high pressures within the pipe (with possible backing up behind obstructions) and frequent rupturing of the infill around the pothole features. Because of the presence of the pipe the term "burst" is preferred although the peat was not liquified, a reason for Crisp et al. (1964) to prefer the term "slide" for similar movements in the Pennines.

Subsequent fieldwork has demonstrated that the most spectacular burst flushes occurred where the contained pipe drained one of the main channels conducting water from the area of peat haggs to the edge of the valleyside proper. This is true of the Upper Gwy left bank burst (Cerrig-yr-wyn) and a further significant factor in this case is the presence of the old mining leat towards the top of the slope, providing a line of weakness along which failure subsequently occurred. Figure 14 shows the plan and elevation of the feature whilst Plates 2 & 3 were taken shortly after the flood. The bedrock exposed by the burst has clearly been gullied during an era of more active surface drainage (possibly periglacial). The gully was then infilled by coarse-textured brown peat drained by the pipe at the peat/bedrock contact. In one location the presence of bands of shale debris in the peat (see Plate 4) demonstrates the spilling action of big floods in the past and it is hoped eventually to obtain a pollen dating for these horizons. There were no eye-witnesses to the burst but the evidence is that it occurred rapidly rather than gradually - fragments of shale and peat were discovered on the opposite bank of the Gwy 3 m above the stream. There is no obvious hiatus in the flow record for

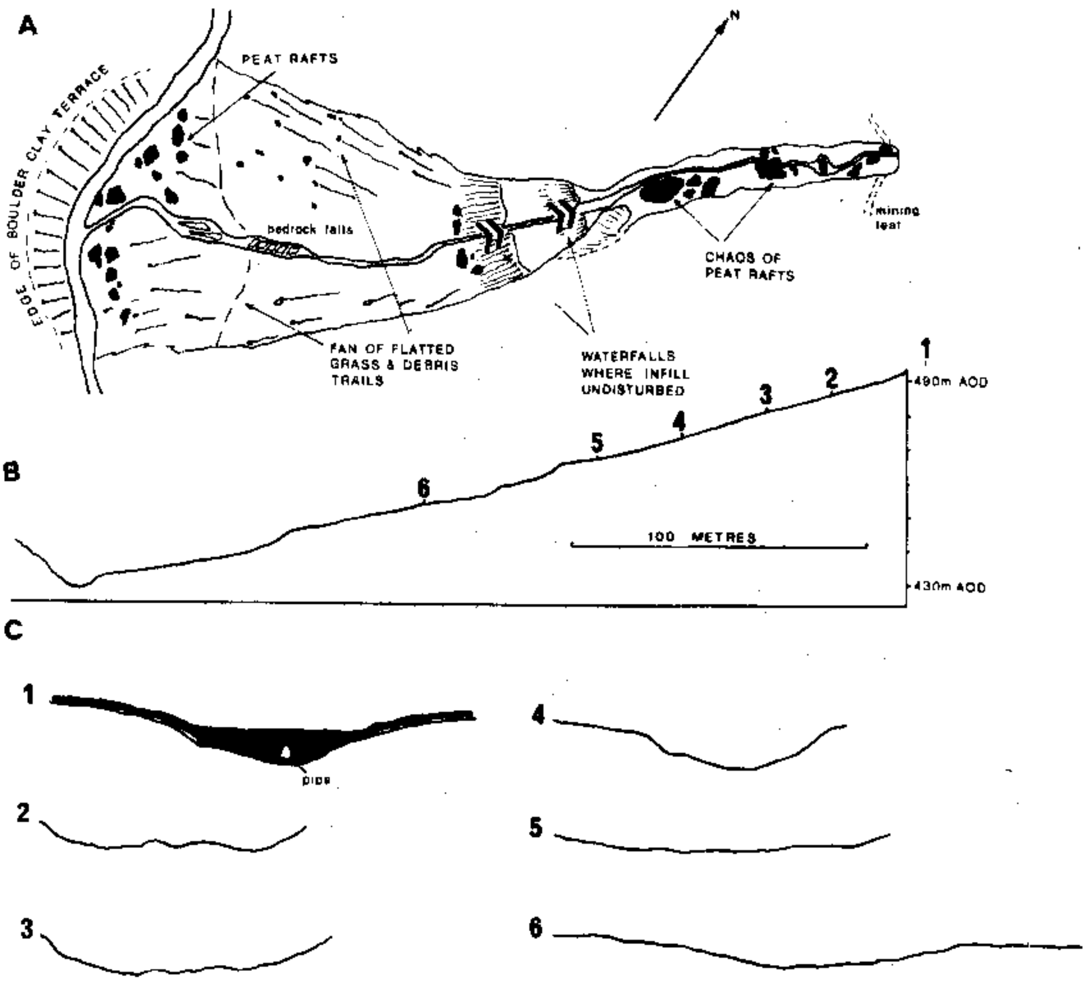


Figure 14. Burst flush feature, left bank of Gwy. A. Plan (tape and compass survey), B. Longitudinal section (Abney level) and C. cross-sections at points numbered on (B).

the Gwy flume, just over a kilometre downstream; consequently it is assumed that the failure of the peat was not associated with the immediate release of ponded water. Thus the tracks left at the base of the flush which indicated a flow of several cumecs must represent more in the way of a peaty avalanche or mudflow than the rack marks of a torrent of water.

A feature identical to the Cerrig-yr-wyn burst caused the destruction of the road to the Institute's weather stations at Eisteddfa Gurig (see Plate 5); again an area of peat hagging discharged into the top of the flush and this was also the case in the Upper Llwyd.

Slides

Another class of erosion scars was produced on straight slopes by the sliding of soil and superficial deposits along a lubricated stratum where subsurface drainage occurs in intermittent pipes or more generally along the interface of the two materials. The two main types were sliding of weathered boulder clay (brownish yellow) over fresher boulder clay (blue) at the edge of the boulder clay terraces immediately adjacent to the stream and sliding of a mixed mass of slope deposits and boulders over bedrock, occurring much nearer the top of the valley sides. In both cases even 48 hours after the flood peak these sites were glistening with water from along the lubricated stratum.

Both types (see Plates 6, 7, and 8) are well demonstrated on the right bank of the Upper Wye and the right bank of the upper Llwyd. In both cases the slopes are between 20 and 25° for boulder clay slides and nearer 30° for colluvium slides. Peat covers the interfluve above the slope and the streamward edge of the boulder clay terrace shows plentiful signs of previous failure (Plate 9). The pipes and seepage lines which lubricated the slides are less regular than either the perennial pipes of the rush flushes or the intermittent pipes of the peaty podsols elsewhere. Particularly in the colluvium slides they appear to form around lines of higher concentrations of stones or where tearing has occurred through creep under normal conditions (see Plate 10). Thus, as in all other cases, the subsurface movement of water and the mass movement of slopes are inseparable.

Gullies

The deposits known as stratified scree (Watson, 1965) are very easily eroded and although many of the densely grouped gullies in the material have a grass cover now (e.g. those being studied above the Gerig/Gwy confluence and in the Colwyn tributary of the Cyff) in others the loose material is exposed (see Plate 11). On the right bank of the upper Hore in the Severn catchment there was rapid downcutting in the floor of the gullies and deposition of the scree material lower down the slope in fans, particularly where slope angle lessened, for example on the top of the soliflucted boulder clay terrace. It becomes easier to see how extensive deposits of this material occur elsewhere at lower levels (e.g. beneath the Dolydd Office) with a relatively lower angle of dip (around 15°) and with interactions of finer material.

Quite large deposits could be formed in a short time under more severe conditions.

Other sites of activity

Whilst the network of ephemeral pipes in the peaty gley profiles typifying the middle slopes in the catchments did not lead to sliding, they clearly carried large quantities of peaty material during the flood and large areas of black stains could be seen around the bursts in the system (frequently the result of sheep treading). Fine shale debris was present with the peat in some cases. In one notable case (Plate 12) a large pipe yielded a large debris fan below a burst. Apart from the naturally vegetated right bank of the Upper Hore and the peat hagged area of the Upper Severn, the Severn catchment was not the site of much slope development. At one stage it was thought that a wash-out of trees along the road known as F11 (now R11) had been solely caused by the flood (Plate 13) but the Forestry Commission have since pointed out that this feature developed during road construction. It clearly points out that the root mat does lead to greater slope stability until such time as a break occurs (as in road construction) when the entire slope beneath the break falls along the smooth bedrock contact. A corollary is that the interruption of flow in the stream at the base of the slope is more serious when an extensive mat of trees and regolith falls into the channel than with grassland. It is clear that parts of the network of forest drains were subjected to larger flows than at any stage since their construction and erosion in some cases was severe as in Plate 14 (although no records are available for the pre-flood situation, forest drains are at various standard depths and widths). Similarly, culverts under forest roads became insufficient and there were wash-outs of road material into drains.

Channel erosion

Only two main situations produced clear effects of channel erosion: reaches bordered by steep peat blanks and minor channel diversions caused by adjacent slope failures. The mechanism for the failure of peat banks appears fairly clear in that arc-shaped blocks of peat, undercut on the outside of bends and heavy from their soaking by the flood peak merely slump into the channel. This is common in the Upper Gwy and the Llwyd (Plate 15). In both cases this is the first erosion of the peat banks for approximately 5000 years since the birch forest layer has been exposed by the slump. Where the forest layer occurs in the Upper Llwyd it is at one point buried beneath at least 3 m of soliflucted boulder clay, indicating the reactivation of mass movement following the forest clearance. The fact that quite deep deposits of this nature can be quite recent adds to the difficulties in classifying and dating the superficial deposits on the catchments; the fans of stratified scree could also be quite young (see above).

Although the Cyff and Tanllwyth catchments are being used to measure bedload movement with channel-bed traps, in both cases the capacity of the trap was exceeded and much material was missed. It was recorded that the calibre of bed load had coarsened during the flood and as usual

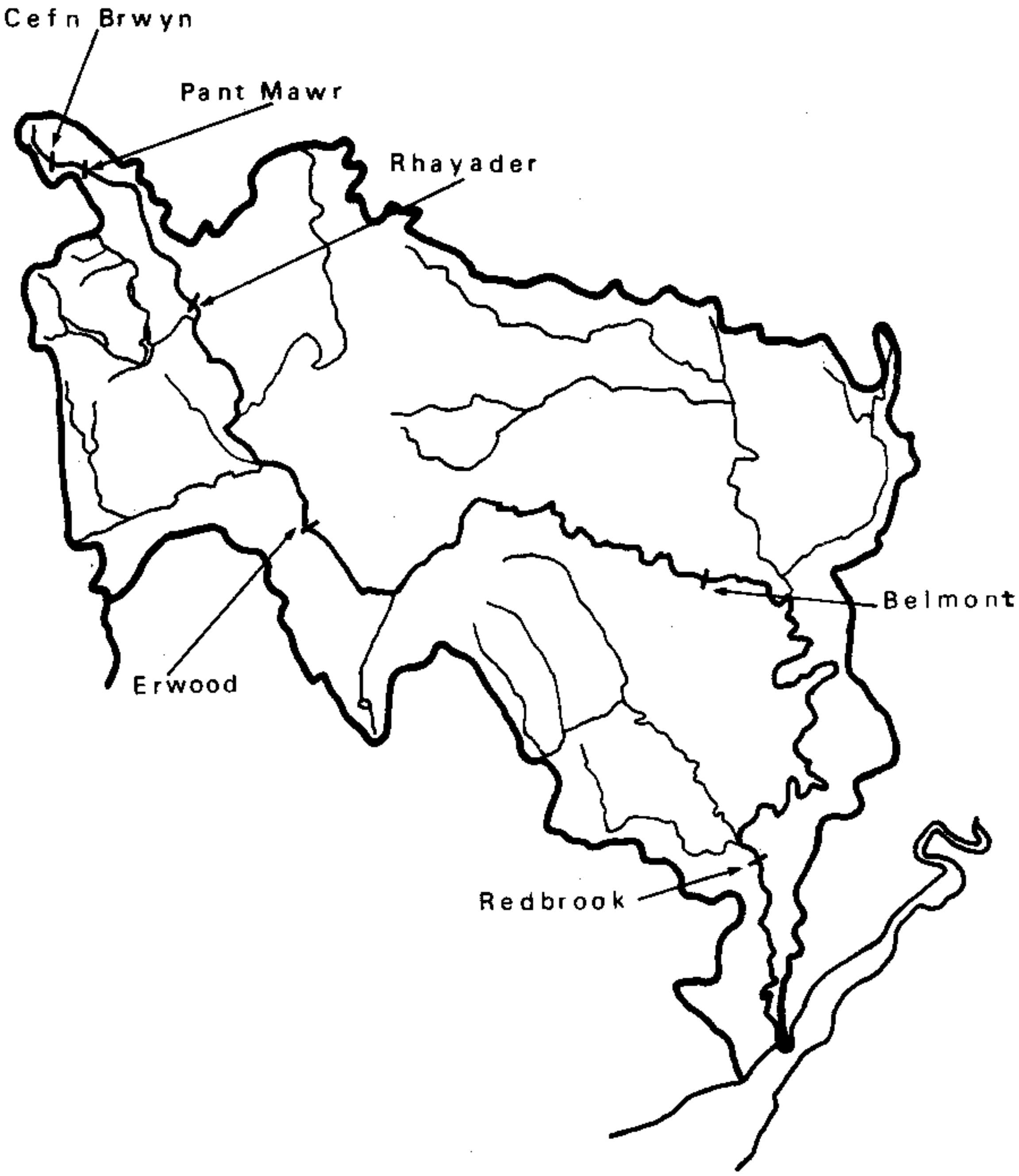


Figure 15. Gauging stations along the Wye.

after such an event there were individual cases of very large boulders having moved (see Plate 16). Velocity estimates performed as part of peak discharge estimates are between 2.13 m/sec and 2.70 m/sec, quite sufficient for material of over 10 cm in diameter to be moved. Since the Plynlimon channels contain numerous huge glacially-derived boulders, there is no shortage of all sizes of material already in the channels. Neither the largest boulders nor bedrock exposures in the channels showed any effects of the flood except for losing their upper covering of moss and lichen. In the finer size ranges the main contribution of tributary streams (see Plate 17) and forest drains/roads seems to have been of gravel and small cobbles. Unlike boulders on the one hand or fines on the other, which move respectively too slowly and too fast to be of nuisance, it was shoals of this size range taking a period of weeks after the flood to move out of the catchments which caused most problems at the flumes (see below).

THE EFFECTS OF THE PLYNLIMON FLOOD ON THE SEVERN AND WYE MAIN RIVERS

Whilst the Upper Severn received flood discharges from most of its upland Welsh catchments (especially the Vyrnwy and Tern), the narrower configuration of the Upper Wye and the fact that the storm was insignificant over the Lower Wye, meant that a flood wave passed down the valley with little effect from tributary inflow. Data was kindly supplied from five other gauging stations downstream of Cefn Brwyn (see Figures 15 and 16). The Hydraulics Research Station used this data in their study of flood routing for the United Kingdom Flood Studies and Dr R K Price has kindly supplied the following comments:

'The flood of August 1973 produced a discharge hydrograph which, at Erwood, had a peak discharge of 625 m^3/s and a curvature at the peak of about $- 3.9 \times 10^{-6}$ m^3/s^3. This value for the curvature is the largest for any recorded overbank flood. The next highest recorded value is for the flood of December 1965 which had a curvature at the peak of $- 2.2 \times 10^{-6}$ m^3/s^3.

Because of the large curvature it can be anticipated that the attenuation of the flood wave along the river would be large. Figure 17 shows the recorded discharge hydrographs at Erwood and Belmont with the predicted hydrograph at Belmont using the variable Parameter Diffusion method to route the flood along the reach. The data for the $\bar{c}$ and α curves was the same as that used by Price (1973). There is reasonable agreement between the time of occurrence and the value of the peak discharge at Belmont, though there is some distortion of the predicted hydrograph.'

Although flow hydrographs were provided by the Severn River Authority, HRS had not included the Severn in their previous analyses and the complication of tributary inflow makes attenuation less obvious. It is sufficient to list the peak levels and timing down the Severn as far as Shrewsbury where flooding was averted by 6 inches. A danger warning was issued on the 6th - the system of flood hazard protection in the town is described by Harding and Parker (1973). This flood provides an example of the capacity of the Clywedog Reservoir to reduce flood levels: it did not spill.

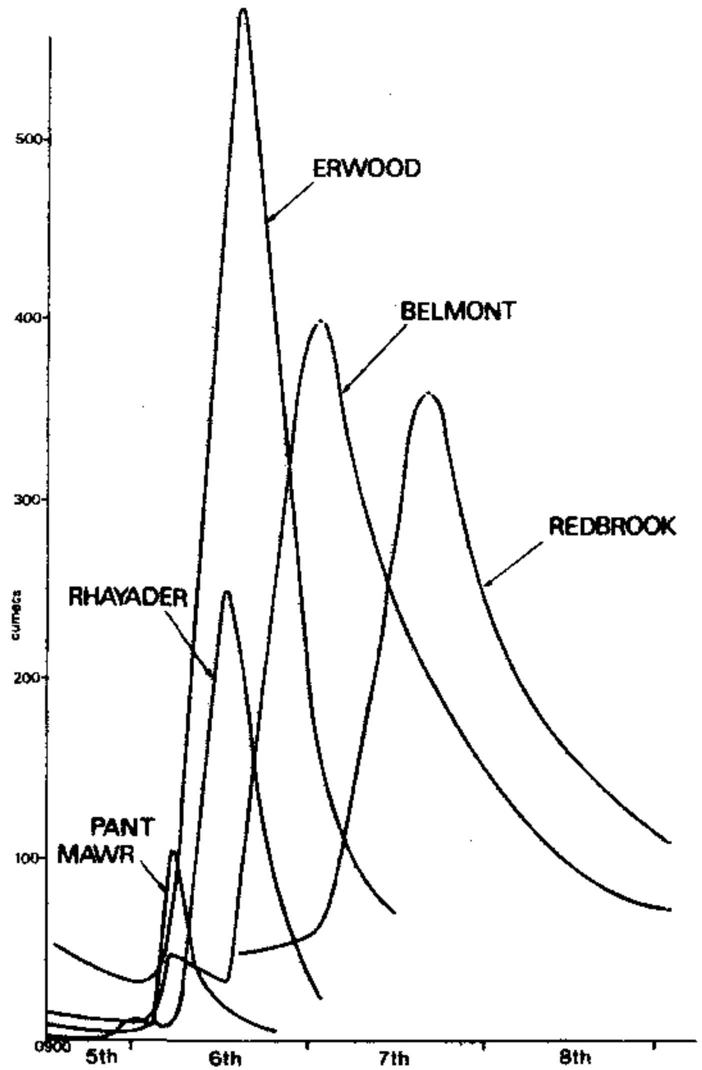


Figure 16. Flow hydrographs downstream from Cefn Brwyn.

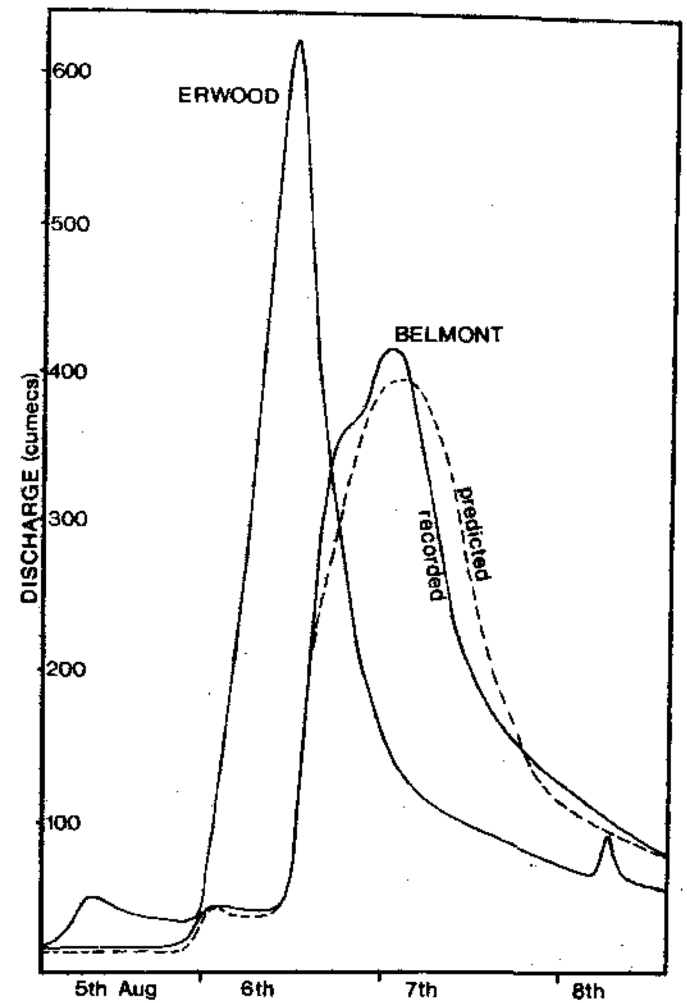


Figure 17. Flood routing on the Wye, Erwood to Belmont, used as trial of method used by Dr R K Price Hydraulics Research Station (his illustration).

Llanidloes	8' 5"	0530	6th August
Caersws	9' 9"	0900	6th August
Abermule	12' 9"	1515	6th August
Llandrinio Br ...	19'10"	0430	7th August
Montford G.S. ...	19' 5"	1600	7th August
Shrewsbury Welsh Br.	12' 9"	2300	7th August

SUBSEQUENT EFFECTS OF THE FLOOD

Two corollaries to the geomorphological action accompanying the flood are being investigated: the gradual transport of eroded material by stream channels and the possible changes in response time as a result of channel exposure by slope failure.

The first topic has proved a difficult problem at the Institute's gauging stations, especially in the Severn catchment. As mentioned above, shoals of gravel sized material have been moving slowly down the catchment and for winter of 1973-74 it is fair to say that the largest flood of each calendar month caused extensive deposition in the Severn flume (see Plate 18) and the old Severn weir which is operated as a sediment trap because of previous problems with the flume downstream. However, such regular clearance by excavator have never been necessary before and similarly the crump weir on the Wye at Cefn Brwyn required clearing during the winter, the first time since 1969. It is fortunate that two of the steep-stream gauging structures are equipped with sediment traps for the bed-load study and are largely free from trouble; the other structures have kept largely free of sediment although there has been drowning downstream of the Hafren (Plate 19) and Hore by shoals of cobbles and gravel. It is of little surprise in view of the observed erosion of roads and drains that the Severn catchment has a greater sediment problem (see also Painter et al. 1974).

There is no evidence so far to suggest that lag times for the catchments have been significantly altered as the result of channel development in August 1973. Whilst the flood of 16th/17th June 1974 showed rise times of much less than two hours it is thought that this was due to a rainfall intensity alone, since winter flooding was not accelerated.

PERFORMANCE OF THE PLYNLIMON HYDROLOGICAL NETWORK UNDER SEVERE FLOOD CONDITIONS

It has already been noted that the flood provided a test for both data analysis and data collection at Plynlimon. The following conclusions can now be made on the advantages and shortcomings of Plynlimon data for flood studies:

(i) The capacity of six out of eight streamflow gauges was exceeded; this is a corollary of the design return period for these structures (ten years - based on channel dimensions and flow data). It is, however, satisfying that not more damage was done by an event of such rarity: only the Hafren was badly damaged, although the concrete of the Severn flume was abraded and the Gwy recorder hut undermined (Plate 20). Other damage was restricted to fill material (Hore and Hafren). Smaller weirs and rated sections used for process studies in the Gerig were extensively damaged. Sedimentation was not a problem in the steep-stream structures since these transport gravelly and finer material quite well. Only boulders accumulate at the base of the entry ramp (see Plate 21) and whilst these no doubt affect the accuracy of calibration during the flood they do not cover the tapping point and make level records inaccurate. The Severn flume, however, develops shoals of finer material which block the tapping point and it should be borne in mind that the recorded flow for the August flood is considerably lower than that estimated by slope area surveys on the tributaries or from rack marks at the flume itself. Silt was removed from the tapping pipe after the flood and the anomalous shape of the flood peak suggests that blockage had occurred. At Cefn Brwyn the situation is simpler: both estimated and recorded floods are slightly in excess of the structure's capacity and this supports observations on site. A further problem concerns the uncertainty of calibration for the Plynlimon structures: at the time of the flood, theoretical calibrations did not exist for the steep-stream structures and none of the now-available calibrations has been checked at full capacity. The bypassing of the Gwy and Cyff structures produces a broad hydrograph peak and is of uncertain effect on the calibration: the relatively low bypasses were introduced to prevent the flumes flowing at full depth.

(ii) The Leupold and Stevens chart recorders worked well at five out of eight sites, jamming occurring during the steep rise of stage at the Hafren, Tanllwyth and Cefn Brwyn sites. At Cefn Brwyn the value of a back-up recorder (Fischer and Porter punched paper tape) was demonstrated. Unfortunately a back-up magnetic tape recorder at Tanllwyth did not operate successfully. The close agreement of stage levels at the Severn flume between chart and punched tape lends further weight to the hypothesis that the stilling well was not responding accurately to water level changes.

(iii) The raingauge network at Plynlimon is not at present immediately suited to flood analyses and in this respect the planned replication of the network of monthly gauges with recording gauges will be a distinct improvement. A number of calculations were needed on the basis of the one Dines chart available the next day, its check gauge, automatic weather station data and further long-period Dines recorders before storm depths and intensities were determined as approximately uniform over the two catchments. One long-period Dines recorder malfunctioned during the storm and at the end of the month two accumulating raingauges from the network were found to be flooded. At least one of each pair of automatic weather stations yielded a full record although an operator timing error (BST/GMT) is suspected at one station. It is probable that a meteorologist could make more use of the associated data from these stations in connection with the meteorological conditions associated with the storm.

(iv) Soil moisture data is currently being studied in relation to calibrating antecedent conditions for floods. Data from the neutron probe recordings made monthly have not been used here since Soil Moisture Deficit and antecedent rainfalls are of more immediate use for such analyses as the unit hydrograph technique.

CONCLUSIONS

General

The flood runoff of 5th/6th August was the result of a combination of rainfall of a moderately high return period and extremely wet antecedent conditions. Response times for the main catchments were normal but both the peak rate and proportion of runoff were high. The influence of peat hydrology is especially marked under these conditions as witnessed by the erosional effects where subsurface flows are fed from the edge of the blanket peat areas. Subsurface flow was associated with almost every case of mass movement. Slope activity was greater than channel alterations. Sediment problems have resulted, particularly in the Severn catchment. Some short-comings are suggested in the available data from the network of instruments.

The influence of land-use on the flood

Unfortunately our uncertainties over the actual peak discharge at the Severn deny us an unequivocal conclusion regarding the influence of the mature Hafren forest on rare flood flows. Since, however, recorded and estimated flows correlate quite well at Cefn Brwyn and at the minor structures and because the two methods of estimation for the Severn flume peak flow are closer to each other than to the recorded flow, it is felt that the full flume capacity of 41.03 cumecs was filled. Using this figure the respective areal runoff figures for the peaks at Cefn Brwyn and the Severn flume are 5.43 cumecs/km^2 and 4.72 cumecs/km^2, showing the higher runoff from the grassland catchment. Both figures are much higher than shown in a graph by Rodda (1974) of 22 events at Plynlimon. No relationship is plotted by Rodda and so a further 23 events have been added to his sample to produce Figure 18. Figure 18 and its equation do not include the August 1973 flood and it can therefore be used to predict what the rate of peak runoff was in the Severn on that occasion. The answer is 3.66 cumecs/km^2, compared with 4.72 estimated and 3.05 recorded; perhaps the true discharge was therefore around 32 cumecs at the peak of the hydrograph. The deviation of the data from the line of equality is clear - the Wye normally produces a higher peak runoff rate than the Severn.

A comparison of peak runoff rates at the tributary structures, based on the indirect estimates also points to a higher rate of runoff by the Wye tributaries, except for the Hore (which has the steepest slopes in the Severn and a considerable amount of grassland too).

Rodda (1974) also shows a graph of time to peak for the Severn and Wye (in fact the parameter, L_2, used is perhaps better described as rise time since unit hydrograph analysis was not involved). Of 23 events plotted, 16 show a longer rise time for the Severn than the Wye. The delaying effect of mature forest on runoff is the more remarkable because the data are uncorrected for size and slope; the Severn catchment is smaller and has a steeper main channel slope. Rodda's rise time analysis is confirmed by the unit hydrograph results already mentioned which demonstrated an average 2 hour time-to-peak in the Wye and 2.3 hours in the Severn. The individual results of unit hydrograph analysis for the two catchments were scrutinized in order to make comparisons for the larger floods (only these were chosen for analysis) and floods for which other data were available. Eventually it was decided to restrict the treatment to those events which occurred in response to the same storm (although no investigation of storm timing or movement has yet been possible). Thus ten paired events were subjected to 't' tests of the differences between the mean values of unit hydrograph parameters and, more reliably, to 't' tests of the differences between paired values (Chatfield, 1970). Parameters tested were 'tp' (time-to-peak), 'tw' (width of hydrograph in hours at half peak), Qp (peak runoff) and 'perc' (percentage direct runoff). The results are shown in Table 5 below:

TABLE 5. 't' test results for unit hydrograph parameters from ten identical events, Plynlimon catchments

Differences of mean values (two-tailed test)

	Severn	Wye	't'	Significance
$\overline{tp}$	1.61	2.12	1.82	significant at 0.01
$\overline{tw}$	2.90	2.70	0.63	not significant
$\overline{Qp}$	66.40	80.80	1.92	significant at 0.01
$\overline{perc}$	46.20	47.90	0.26	not significant

Differences between pairs of values (one-tailed test)

	mean difference		
tp	0.51	6.85	significant at 0.001
tw	0.20	0.59	not significant
Qp	14.40	2.27	significant at 0.025
perc	1.70	0.71	not significant

Whilst the most significant difference is that in times-to-peak, it should be noted that for these data the Severn's response is significantly

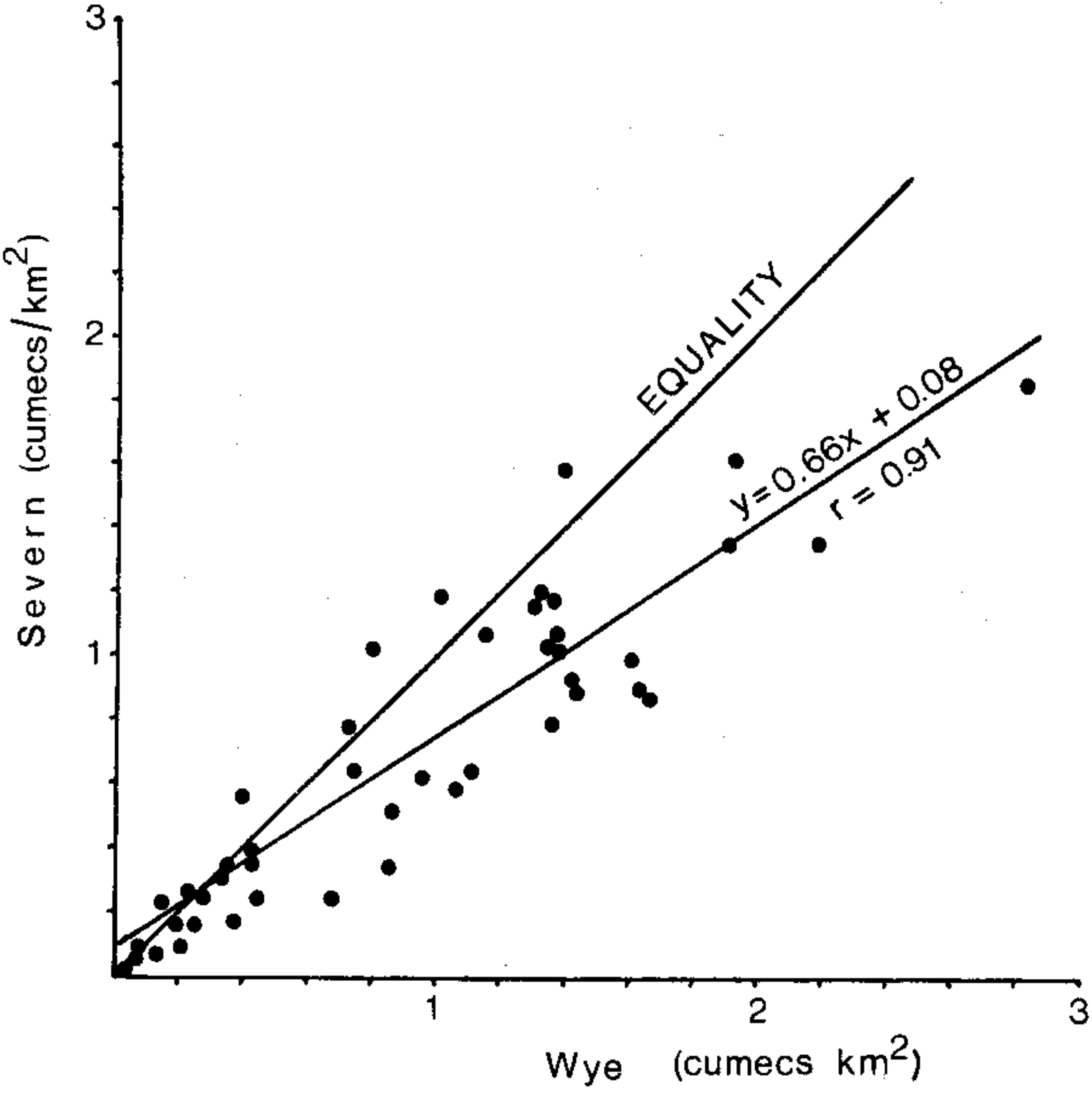


Figure 18. Peak discharge rates for Severn and Wye, 1970-73, standardized by catchment area.

faster than that of the Wye. Peak discharges are significantly different in the Wye's favour but the other two parameters are not significant. It should be noted that for the flood in question the Severn responded slightly faster and had a much lower Qp and perc value than the Wye although the recorded data are suspect. Clearly more analyses are required and from October 1973 onwards hydrograph data have been carefully collated for Plynlimon, particularly with regard to solving the time-to-peak question.

Acknowledgements

This report series provides an excellent outlet for detailed treatment of particular research topics of the Institute. The author is grateful for help in preparing it to J.D.G. Smart for field survey, A. J. Bucknell, P. J. Hill and R. A. Davis for their observations concerning the flood, S. W. Smith and his staff for collating much of the data, Julia Tucker and M. J. Lowing for unit hydrograph analyses, Elaine Bishop and R. C. Jones for peak flow data, J. C. Mosedale for sediment data and many more from within the Institute who helped with the production of the report.

From other organisations I should like to thank J. R. Calder of the Meteorological Office, R. Goodhew of the Severn River Authority, I. Fox of the Wye River Authority (now respectively Severn/Trent and Welsh Water Authorities) and R. K. Price of the Hydraulics Research Station.

Plate 1. Rack marks on the left bank of the Cyff, upstream of the flume.

Plate 2. Lower end of burst flush, Cerrig-yr-wyn, Wye catchment.

Plate 3. Upper end of Cerrig-yr-wyn brust.

Plate 4. Shale bands in the peat infill of the Cerrig-yr-wyn flush.

Plate 5. Lower end of burst flush which disrupted the Eisteddfa Gurig road (Tarenig catchment).

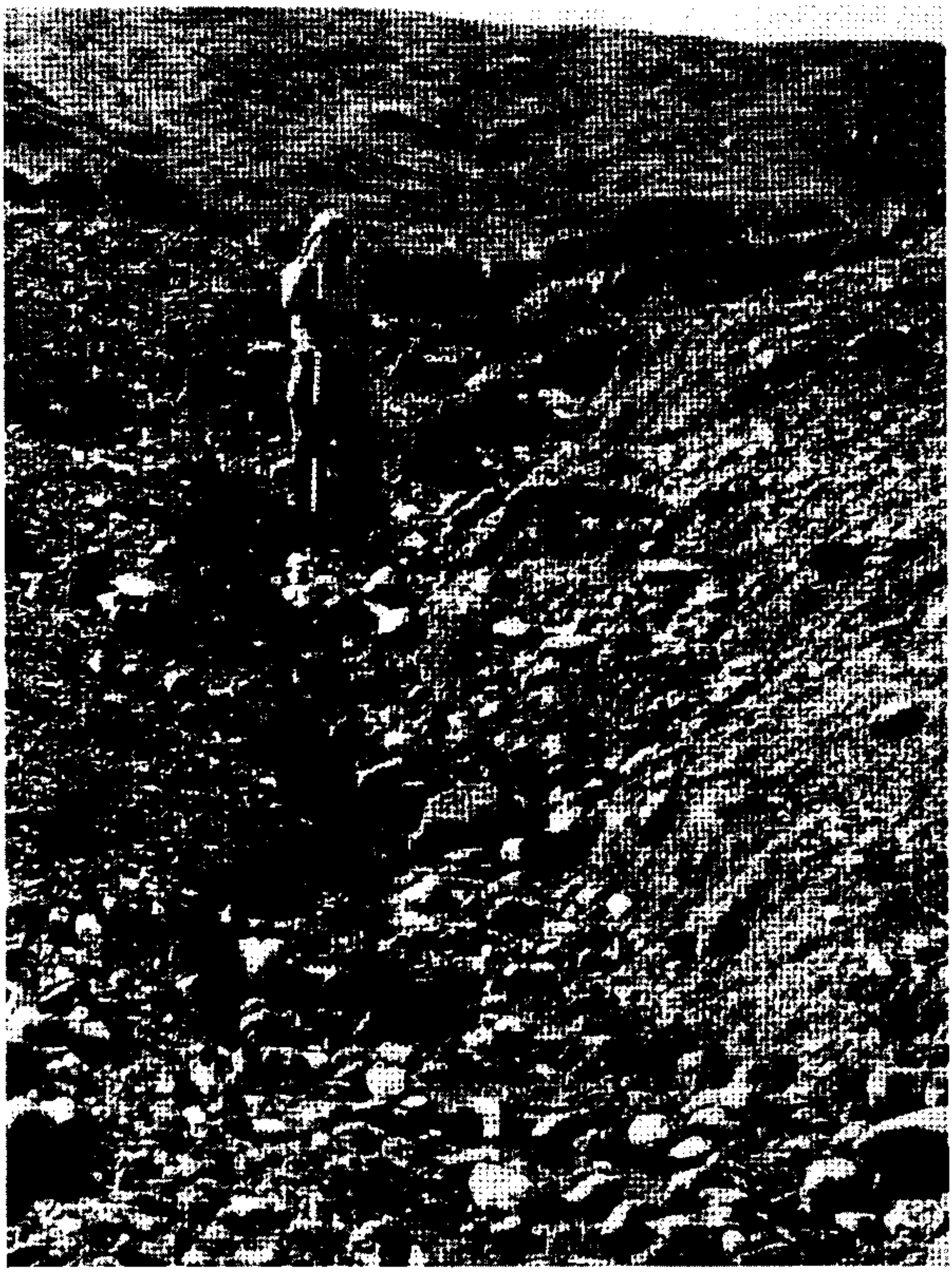


Plate 6. Slide of weathered over unweathered boulder clay, Upper Llwyd. Note water flowing in foreground.

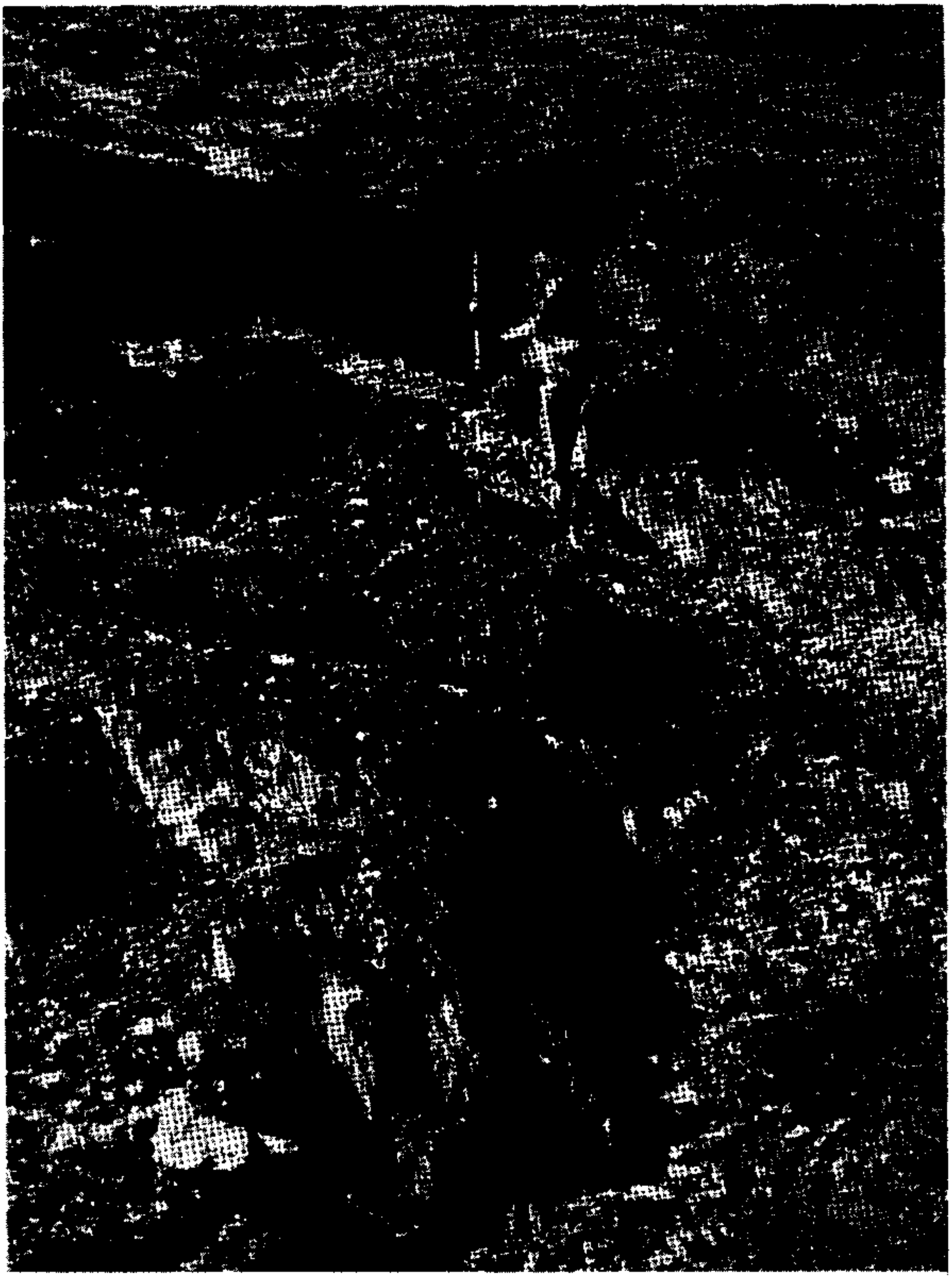


Plate 7. Slide of slope-waste on bedrock, Upper Llwyd.

Plate 8. Boulder clay slide, Upper Gwy, left bank.

Plate 9. Vegetated slide scar in boulder clay terrace, Upper Gwy, right bank.

Plate 10. Pipe flow at silt/boulder clay junction, Upper Gwy, right bank.

Plate 11. Gullied stratified scree (and slope-waste) below Eisteddfa Gurig road.

Plate 12. Large pipe burst on Cerrig-yr-Wyn (Wye catchment).

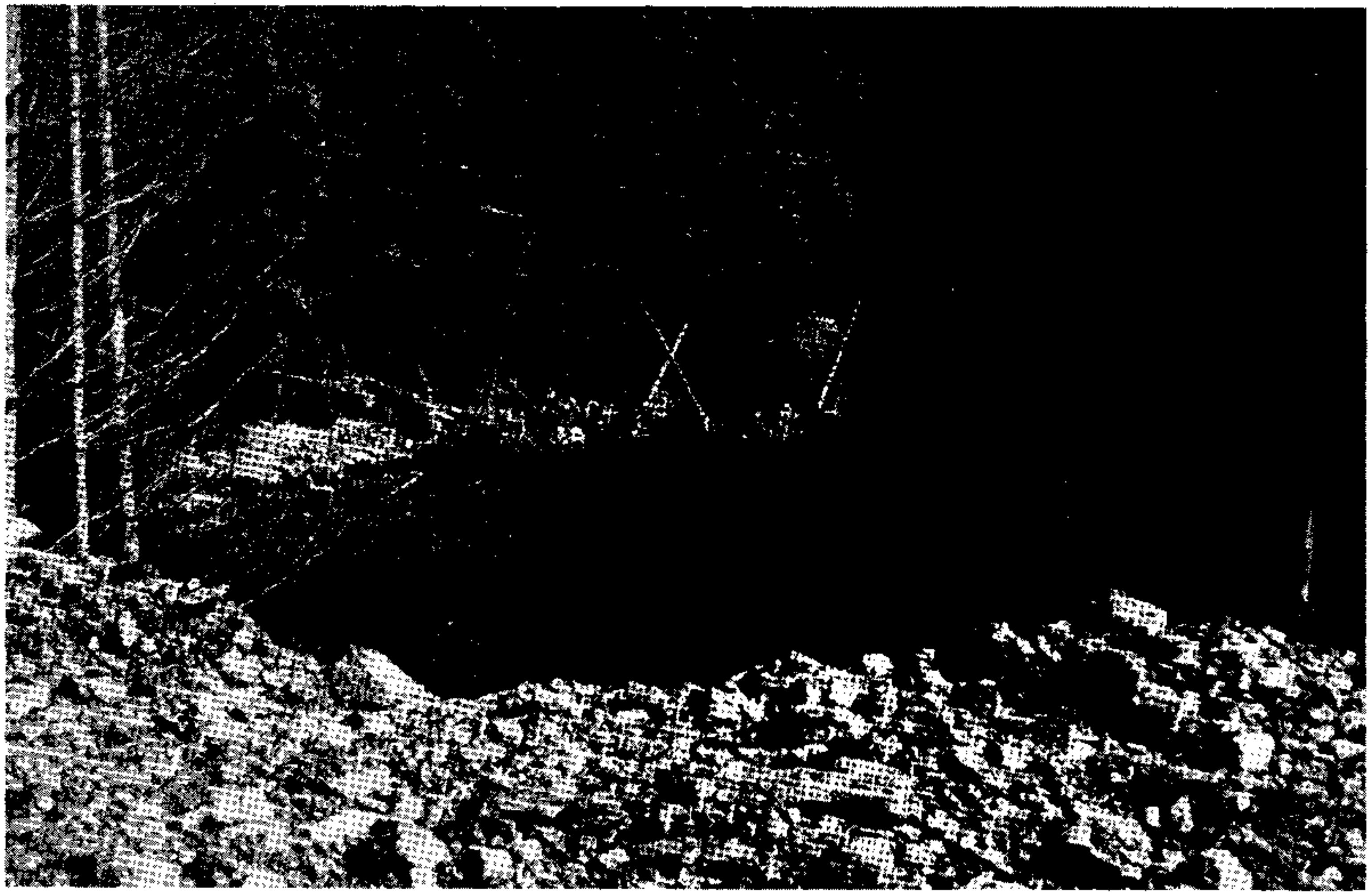


Plate 13. Slide of superficial material and trees into the Upper Hafren.

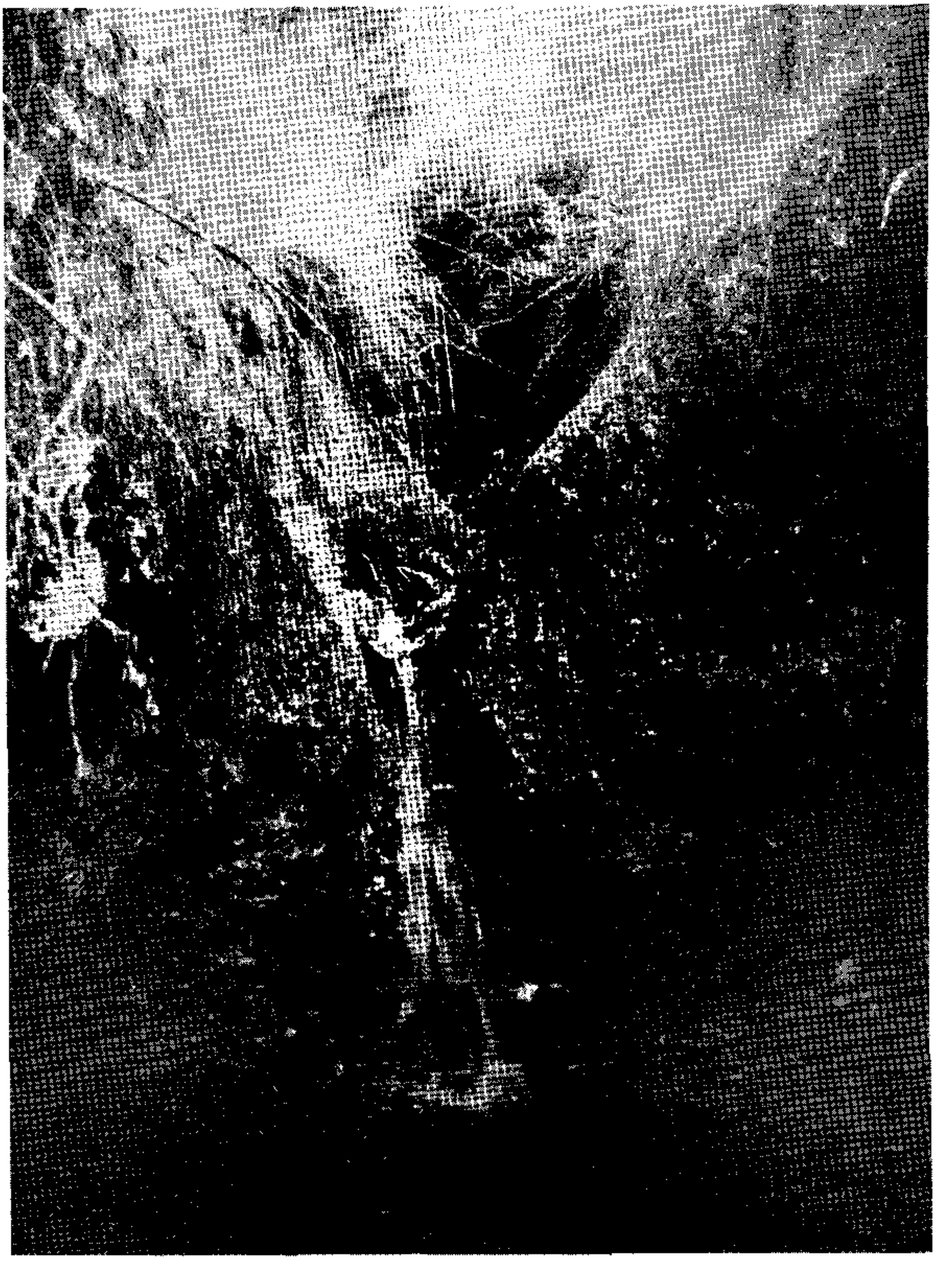


Plate 14. Badly-eroded forest ditch, Hafren catchment.

Plate 15. Bank slipping of peat, Upper Llwyd, showing exposure of woody layer.

Plate 16. Boulder movement at the Gwy flume. The boulder being measured apparently passed through the flume.

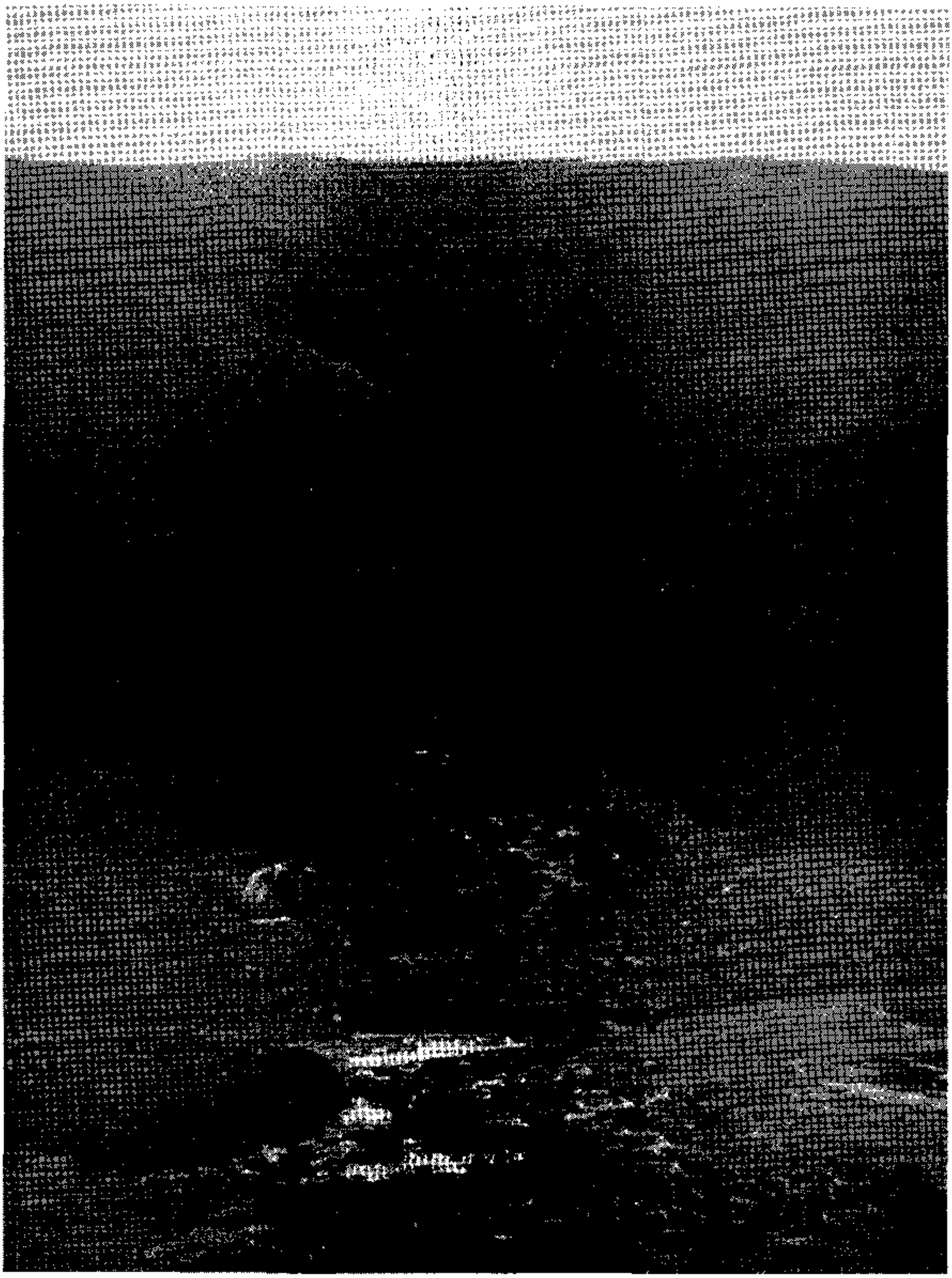


Plate 17. Cobbles and gravel deposited at a Wye right bank tributary junction.

Plate 18. Shoal of gravel in entrance to Severn flume.

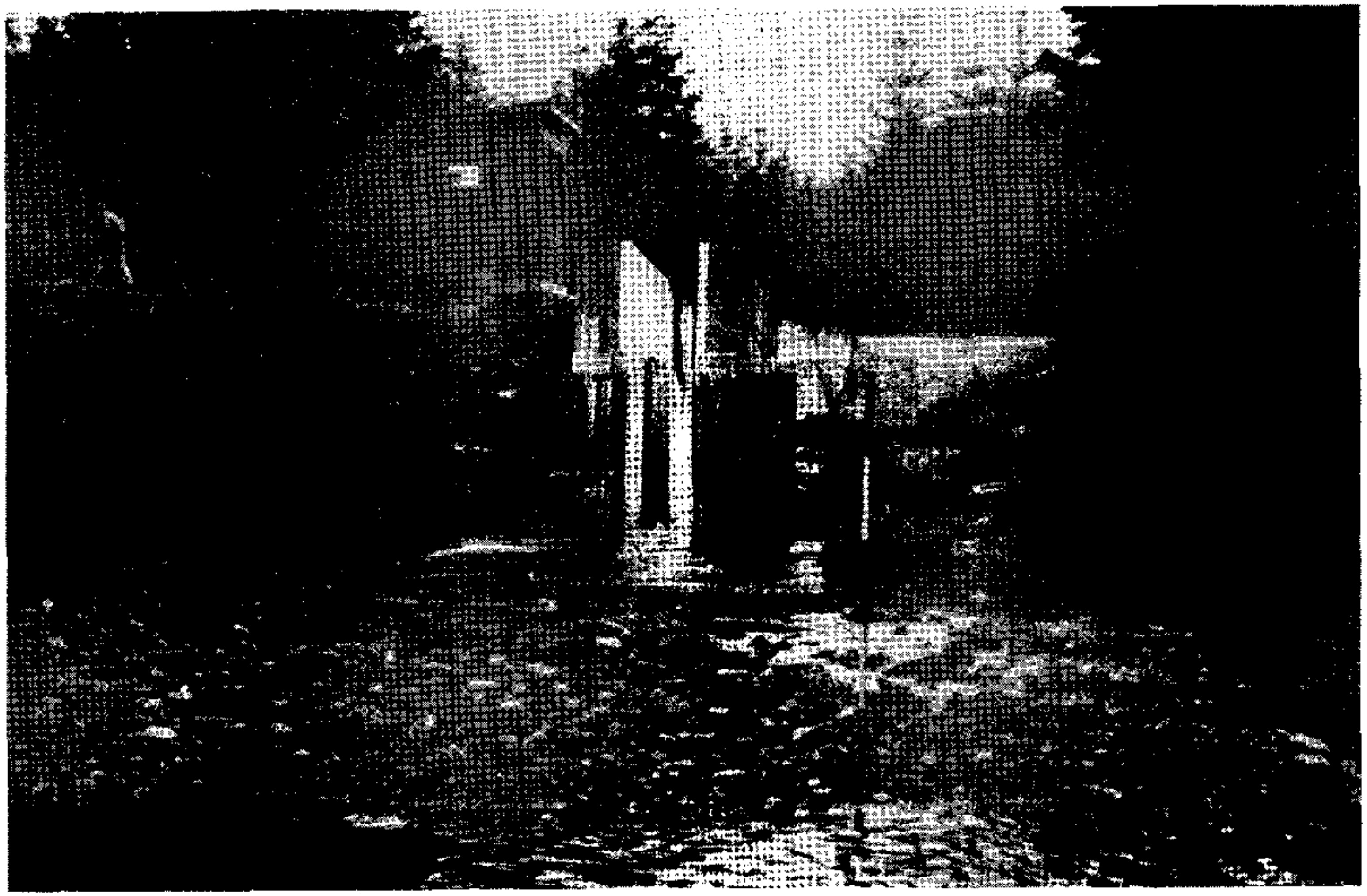


Plate 19. Downstream drowning of the Hafren control by shoal of cobbles and gravel. Note washed out fill on each side of flume and badly eroded by-pass channel (near figure to left).

Plate 20. Undermining of Gwy flume hut by overtopping flood waters.

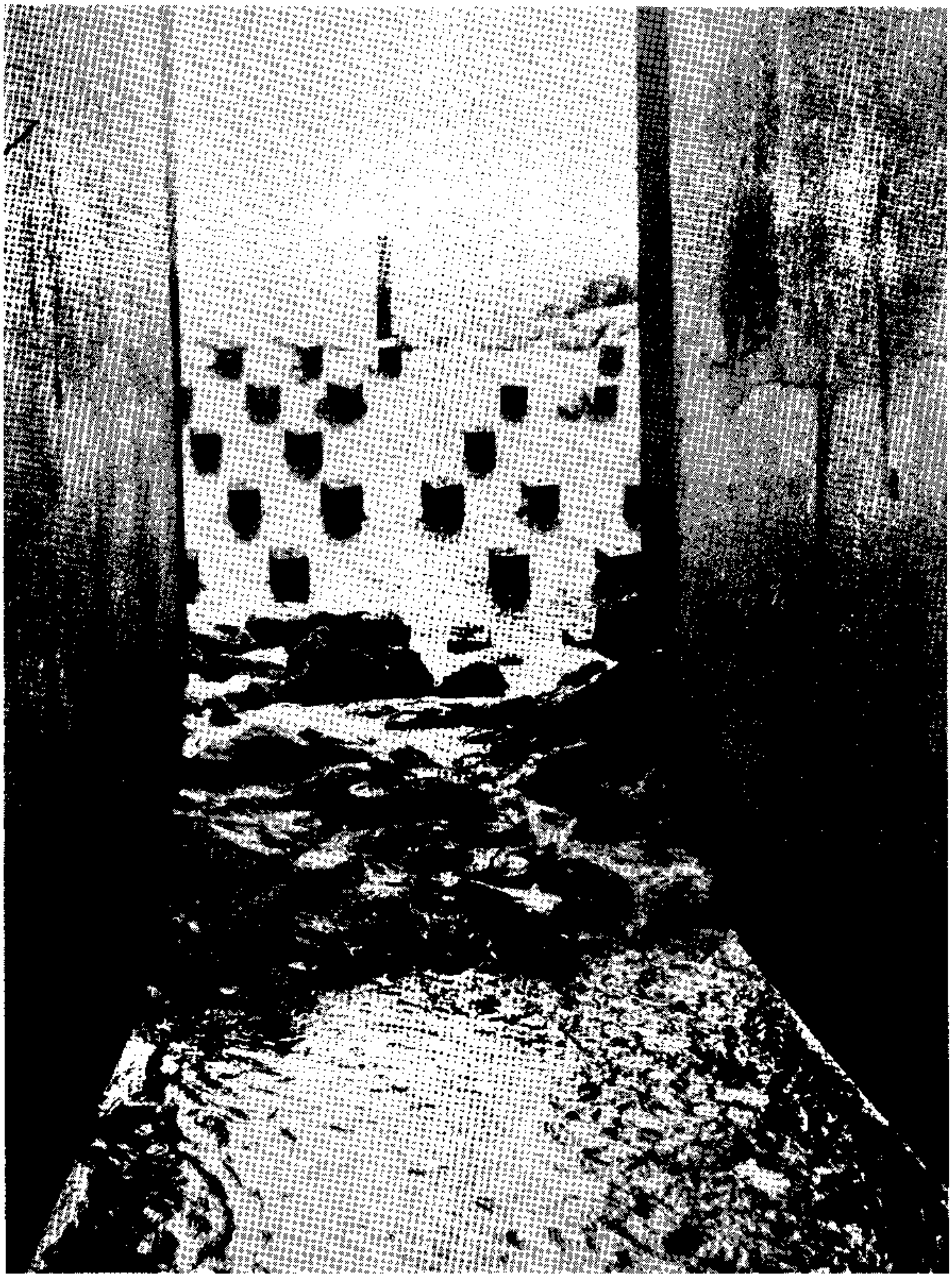


Plate 21. Bed load deposition at base of entry ramp, Gwy flume.

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