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ESTIMATION OF THE MAGNITUDE AND FREQUENCY OF FLOODS IN THE CATCHMENT OF NANT Y MOCH RESERVOIR

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Executive Summary

Powergen PLC operates Nant y Moch reservoir as part of the Rheidol Hydro-electric Power Scheme. The operating rules for the reservoir were inherited from earlier operators of the system and are based on the safety requirements of the Dam Safety Inspectorate with regard to the likelihood of occurrence of rare and destructive floods. Hydrometric data in the catchment was scarce during the design phase of the scheme and it is believed that regional estimates may have overestimated the risk and led to the operation of the scheme at less than optimum water level in the reservoir.

Hydrometric data collected in the area since the scheme was started forms the basis of this study which has the aim of making a better assessment of the magnitude of floods with specified return periods. A model relating rainfall distribution to altitude and longitude has been developed to estimate catchment annual rainfall, which has then been distributed to daily rainfall using the ratio of annual catchment rainfall to annual rainfall measured at the Moel Cynnedd climate station in the Plynlimon catchments. Ranking analysis suggests that the 1 day rainfall with a 5 year return period for Nant y Moch is 80.8mm, and regional growth curves related to 1D-M5 suggests the probable maximum daily precipitation is 350mm.

Catchment characteristics have been derived for the main and subcatchments at Nant y Moch and the regression equation from the Flood Studies Report (1975) used to predict the mean annual flood. The best estimate of MAF for the 54.94 km^2 catchment is 65.22 $m^3.sec^{-1}$. Sensitivity analysis using various different options for catchment characteristics suggests that the estimate of MAF is particularly affected by the stream slope used (S1085), especially in multi-limbed catchments like Nant y Moch where the estimate can be ambiguous. Stream network density also significantly affects the MAF, but its derivation for Nant y Moch is less ambiguous than S1085. In general the regression method seems to be more affected by characteristics that describe the routing of the flood than by those (AREA and 1D-M5) that dictate the volume of flood flow.

A second approach, using data from tributaries of the Rheidol, the 56 ha Maesnant and the 80 ha Maesnant Fach, has been to develop a rainfall-runoff model based on the unit hydrograph approach, and to compare the results with the FSR regression approach of calculating unit hydrograph parameters. The use of the unit hydrograph technique has drawn attention to the importance of timing of flood peaks generated in the various subcatchments, and the wide variation in catchment characteristics. Extrapolation of the UH parameters derived on these small catchments to the much larger Nant y Moch catchment raises questions of their applicability even to nearby catchments with very different characteristics. However, a procedure combining the salient features of the regression method of estimating the MAF with the temporal resolution of the unit hydrograph method has provided useful corroboration of the whole-catchment approach, leading to an estimate of the MAF of 58.8 $m^3.sec^{-1}$. This is less than the whole-catchment estimate but is logical in that the structure of the catchment is such as to generate sub-catchment flood peaks that do not concentrate in a typical way.

Regional growth curves, updated in the FSR supplementary reports, have been used to estimate long return period floods up to T10,000. The regional growth factor technique does not lend itself to estimation of the probable maximum flood. Where suitable data exists, the FSR recommends use of the unit hydrograph rainfall-runoff approach to convert the PMP to the PMF, which in the case of Nant y Moch yields an estimate of 820 $m^3.sec^{-1}$. The next best method recommended by the FSR is a regression equation related to catchment characteristics which gives an estimated PMF of 650 $m^3.sec^{-1}$.

The report has only concerned itself with routing floods through the reservoir to the spillway in so far as the reservoir area has been included as an attenuating influence in the regression to estimate MAF. No allowance has been made for the present control rules which may determine that at the time of any serious flood the water level is below the spillway and capable of reducing the flood volume at the spillway. Depending on the width of the flood hydrograph and the persistence of flows near the peak levels, this extra storage may not have much impact in any case on the peak flow to be accommodated by the spillway.

Recommendations are made for the improvement of the hydrometric network with a view to further refinement of the flood estimates.

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1. Introduction

Nant y Moch Reservoir was built on the Afon Rheidol in the 1960s to provide storage for power generation by the Rheidol Power Station at Capel Bangor near Aberystwyth. The prime purpose of the reservoir is to feed the downstream Dinas Reservoir to enable this to be used as a constant head device for the turbines. Water released from Nant y Moch as compensation flow and to maintain the levels in Dinas is also used to generate electricity, thus the water level in Nant y Moch reservoir has an important bearing on the generating potential of the system.

The operating rules of Nant y Moch reservoir, now run by Powergen PLC, are based on the need to maintain the maximum water level commensurate with the minimum spare capacity required to enable the spillway and reservoir storage to cope with extreme floods. The reservoir was built in an era of lower national demand for power than present, and at a time when there was less environmental and resource pressure to provide alternative sources of energy to conserve fossil fuels and reduce carbon dioxide emissions. As a result there has been little need until now for the system to run with optimum efficiency. Powergen are of the opinion that the reservoir may currently be operating at a lower average water level than is strictly necessary to comply with reservoir safety standards, largely because the predictions made for return periods of floods in the catchment may err too far on the side of caution. The guidelines used for the design of the scheme may have overestimated flood risk in the area.

At the time the scheme was being designed, the engineers concerned would not have had the benefit of the Flood Studies Report (NERC, 1975) or subsequent updates to this (NERC, 1985; Reed & Field, 1992). The Flood Studies Report (FSR) was able to bring together a vast amount of relevant data on rainfall and flows, to allow regionalisation of the rainfall-runoff relationships and to allow prediction of flood flows and return periods in ungauged catchments using local or regional rainfall records and catchment characteristics. Since the FSR was published there has also been considerable development in rainfall-runoff models for prediction of flows in catchments with rainfall records but no long term flow data.

The purpose of this investigation is to assess the techniques and information now available, and to use these where appropriate to estimate better the flood risk at Nant y Moch. Limited recommendations for reservoir control will be made where this will help Powergen to re-assess the operating rules for Nant y Moch and to determine whether there is a case for the spillway to be redesigned.

2. Hydrometric Data Availability

The catchment of Nant y Moch reservoir covers the headwaters of the Afon Rheidol, rising at its highest point on Plynlimon Fawr (752m). The reservoir has flooded the site of the original confluence of the Upper Rheidol's four main arms, the Hyddgen, the Hengwm, the Llechwedd Mawr, the Rhuddlan, and also that of the minor tributaries (figure 2.1). As a typical western margin catchment with a marked temperate marine climate it lies in an area influenced by incoming depressions laden with warm moist air that cools rapidly and condenses as it rises over the Plynlimon range. There are thus clear gradients of rainfall across the catchment, increasing west to east, largely as a result of altitudinal change but also affected by topography and distance along the track of the weather systems. The prediction of floods in the catchment is not a simple task of using the maps in the FSR to derive data for inputting to the predictive equations given, mainly because of interpolation problems in an area of steep environmental gradients. It has been necessary to collect together as much existing hydrometric data as possible to facilitate the investigation.

2.1 Streamflow

The major problem with any hydrological study of a specific area is the lack of available data in the catchment being studied. Ideally, long term streamflow records are available that can be used to derive suitable flood statistics, the longer the data sequence, the more confidence can be placed in the predictions of rare events. For the Upper Rheidol there is no long term streamflow gauging station that can be used to derive these flow statistics, the nearest ones being on the adjacent Afon Ystwyth at Tan y Castell near Aberystwyth (Howe & Rodda, 1960), and the stations run by the Institute of Hydrology in the Plynlimon catchments (Kirby et al., 1991). Unfortunately, neither data set is strictly relevant to Nant y Moch because it is in an area of considerable spatial variation in rainfall and topography. It is precisely this combination of hydrological variability and lack of local data that has left Powergen in the position of having some doubts as to the validity of existing flood estimates for the catchment.

One bright spot is the existence of a short period rainfall and flow record from two tributaries of the Upper Rheidol, the Maesnant and the Maesnant Fach, which rise on Plynlimon on the south eastern side of the catchment and run directly into the reservoir (see figure 2.1). Between May 1984 and May 1990 streamflow measurements were carried out as part of an Institute of Hydrology study of the effects of grassland improvement in the Maesnant Fach (Roberts et al., 1990). Although this was essentially a hydrochemical study, the streamflow structures were designed and built to a sufficiently high standard, and data collected at a sufficiently frequent (15-minute) time interval, to allow water balances to be

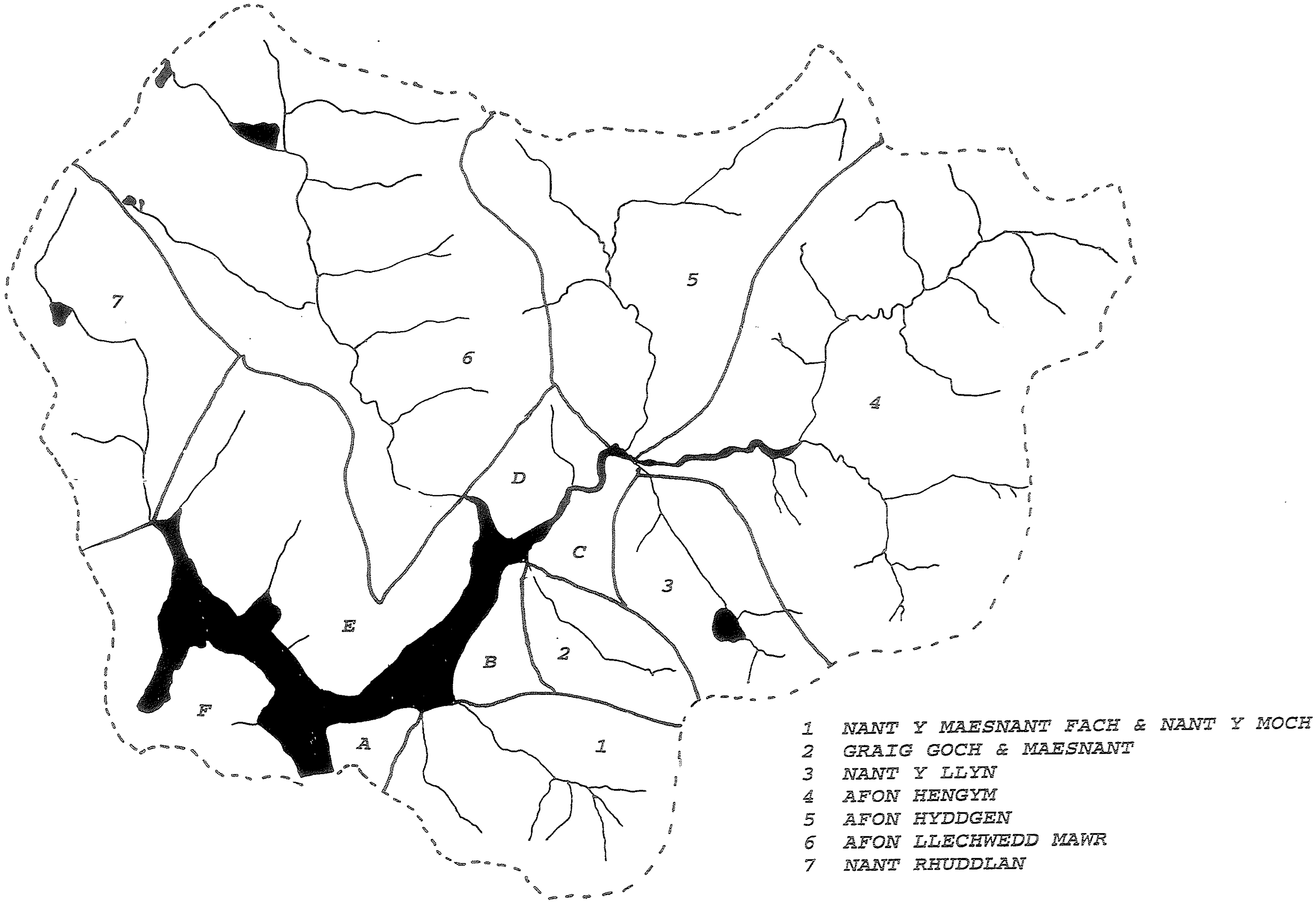


Figure 2.1. The Nant y Moch catchment, its major subcatchments and the main stream network.

produced and estimates to be made of extreme flows over the study period.

The water balances derived suggested that the catchment area of the Maesnant has been reasonably well defined at 56ha. However, there are a number of uncertainties regarding the Maesnant Fach catchment boundary that makes it difficult to have absolute confidence in this catchment for the purposes of this flood study. Nevertheless, relationships derived between the Maesnant Fach and Maesnant flow data have been found to be useful as an aid to quality control and as means of infilling missing data in the Maesnant. For the infrequent periods when both gauges are out of commission the most appropriate Plynlimon gauge, the Gwy in the Wye, has been used to infill the flow records.

Using this six-year sequence of flow data it is possible to define rainfall-runoff relationships and to use the models derived to predict hydrograph behaviour in the adjacent ungauged tributaries feeding into Nant y Moch reservoir.

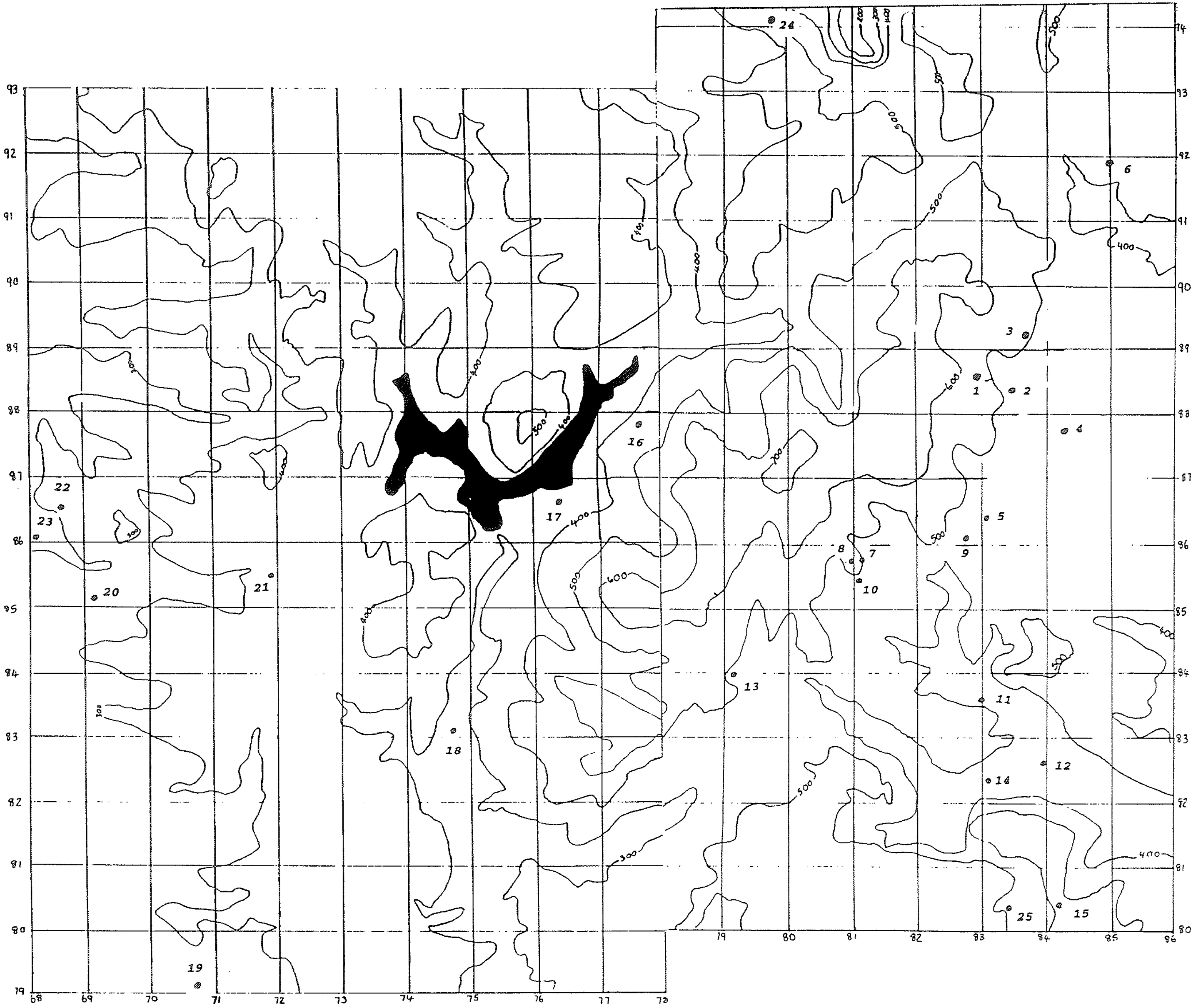
2.2 Rainfall

At the time Nant y Moch reservoir was designed and built, few rainfall records will have been available for assessing flood risk. The situation at present is still not good, there being only short periods of high frequency i.e. hourly or daily, rainfall records available for the catchment itself. For estimating return periods of floods it is therefore necessary to look at the regional rainfall distribution and to interpolate for the catchment itself on the basis of isolating the major controls on rainfall. Fortunately during the last 30 years the number of period raingauges in the area has increased, even if the records from these are only available intermittently at some sites. Interrogation of the National Water Archive has revealed 25 gauges within a 20km grid square centred on the Nant y Moch dam wall, although these are largely clustered to the south and at a lower altitude than the catchment, with an obvious lack of gauges in the unpopulated northern area of the catchment. The gauges are listed in table 2.2 and shown on the map in figure 2.2.

Ideally for flood studies in ungauged catchments a long sequence of short time interval rainfall (hourly or sub-hourly) is required. This can be input to catchment rainfall-runoff models enabling production of a synthetic sequence of flows, providing the parameters of these models have been optimised previously on flow data from the same or a similar catchment. The only hourly rainfall data available for Nant y Moch is the six year sequence from the Maesnant and Maesnant Fach that was obtained during the grassland improvement study (Roberts et al., 1990). Conceptual rainfall-runoff models, such as HYRROM (see Institute of Hydrology, 1986; Blackie & Eeles, 1985) are either too coarse in their output (HYRROM gives daily flows from daily rainfall inputs) or, in the case of more sophisticated distributed models such as the Institute of Hydrology Distributed Model (IHDM) or

Table 2.2 Details of the raingauges used in the initial spatial rainfall analysis.

Raingauges	Altitude	Grid Reference		Aspect	slope	MAR	SAAR
		Eastings	Northings				
Carreg Wen	576	2829	2885	84	9.6	2670	2624
Blaen Hafren	439	2835	2884	165	30.0	2415	2497
Tor Glas	543	2836	2893	143	5.7	2543	2484
Moel Cynnedd	358	2843	2877	90	4.8	2330	2366
Esgair y Maesnant	475	2831	2864	340	0.1	2603	2649
Cefyn-llwyd	439	2850	2919	65	0.1	2236	2259
Esgair y Maen	442	2812	2858	142	30.0	2634	2665
Esgair y Maen	488	2810	2858	165	30.0	2749	2678
Nant Iago	397	2827	2862	230	7.2	2207	2166
Esgair y Maen	502	2811	2855	225	14.5	2662	2699
Cefn-brwyn	343	2830	2837	45	14.5	2233	2264
Manod	320	2840	2827	55	5.7	2081	2096
Plynlimon	488	2791	2839	50	6.4	2247	2268
Pant Mawr	335	2831	2825	10	7.2	2084	2144
Cefn Hendre	495	2843	2804	2	30.0	2459	2268
Maesnant	434	2776	2878	45	16.6	2169	2095
Nant y Moch(upper)	380	2764	2867	312	5.2	2008	2034
Dinas	275	2747	2831	335	5.7	1786	1638
Cwm Rheidol	53	2706	2792	239	30.0	1333	1293
Bontgoch	290	2693	2851	218	2.4	1344	1342
Craigypistyll	310	2719	2855	313	14.5	1867	1546
Elerch	195	2688	2866	213	7.2	1386	1358
Bontgoch W.T.Works	174	2683	2861	346	8.2	1418	1358
Rhiw-Gam	381	2798	2942	305	19.5	1921	1920
Nant Rhys	480	2834	2804	0	3.2	2342	2325



1	CARREG WEN
2	BLAEN HAFREN
3	TOR GLAS
4	MOEL CYNNEDD
5	ESGAIR Y MAESNANT
6	CEFYN-LLWYD
7	ESGAIR Y MAEN
8	ESGAIR Y MEAN
9	NANT IAGO
10	ESGAIR Y MAEN
11	CEFN-BRWYN
12	MANOD
13	PLYNLIMON
14	PANT MAWR
15	CEFN HENDRE
16	MAESNANT
17	NANT Y MOCH (UPPER)
18	DINAS
19	CWM RHEIDOL
20	BONGOCH
21	CRAIGYPISTYLL
22	ELERCH
23	BONTGOCH W.T.WORKS
24	RHIW-GAM
25	NANT RHYS

Figure 2.2. The raingauge network used for the study and the distribution of altitudes within the catchments.

the Système Hydrologique Européen (SHE), require more information about the hydrological characteristics of a catchment than is usually available in non-experimental catchments. Hourly rainfall data can be used however for optimisation of an hourly or sub-hourly rainfall-runoff model of Nant y Moch for this six year period using the unit hydrograph approach as recommended by the FSR. However it remains difficult to extend the sequence for a longer period because of the lack of hourly data elsewhere within the Nant y Moch area.

The next best option is to distribute catchment daily rainfall using typical storm profiles to give the hourly distribution required for the rainfall-runoff model, and hence estimate peak daily flows from the daily flow volumes derived. A search on the National Water Archive database revealed only two gauges in the region where long-term daily rainfall data is available, at Cwm Rheidol Power Station and at the Institute of Hydrology's Moel Cynnedd Climatological Station. Of these, Cwm Rheidol experiences much lower rainfall (SAAR of 1293mm) compared to the likely rainfall in the catchment (>2000mm), whereas Moel Cynnedd, although on the lee side of the Plynlimon Massif, and therefore experiencing slightly different weather patterns, comes closer in terms of annual rainfall amounts (2366mm). The gross assumption has had to be made, therefore, that the distribution of daily rainfall at the two sites is similar to the distribution of annual rainfall, enabling Moel Cynnedd daily rainfall to be used to distribute monthly or annual estimates for the Nant y Moch catchment into daily values.

3. Rainfall Distribution in the Catchments

3.1 Spatial distribution of rainfall in the Nant y Moch area

The advantage of using the National Water Archive as a source of rainfall data is that whatever the number of years of record available, the data has been standardised to the average annual rainfall for a standard period - 1941 to 1970. This enables an assessment of the spatial pattern of rainfall within and around the catchments to be made independently of the temporal variation and a model of spatial rainfall variation to be established. From known characteristics of the whole Nant y Moch catchment and its major subcatchments it is then possible to estimate annual or daily rainfall into these using the model. It is recognised that the factors that control the spatial variation in annual rainfall totals may not be the same as those controlling daily or sub-daily totals, or at least do not act to the same degree. Daily maxima will tend to be controlled more by randomly-occurring, anticyclonic, convectional storms, mainly affecting the summer months, while the variation in annual totals is dependent on the more predictable cyclonic rainfall patterns. In the absence of direct daily rainfall data it has to be assumed that the two are controlled by the same spatial distribution.

An initial assessment of annual rainfall totals across the region (table 2.2) indicates that distance from the coast and altitude are the dominant controls. This would support the model of Johnson et al., (1990) for the Balquhidder catchments in central Scotland, where altitude and longitude were found to explain most of the variance in rainfall totals, but not that of Kirby et al., (1991) for the Plynlimon catchments. Here, altitude was also found to be dominant, but the 'a priori' hypothesis of aspect and slope effects that had dictated the rainfall sampling strategy was also found to hold. Longitude effects were also evident at Plynlimon, not as expected as an overall west-east gradient but as windward and leeward anomalies.

The model of spatial variability in SAAR derived for Nant y Moch was based initially on a multiple regression of rainfall as a function of altitude, aspect, ground slope, and longitude. Altitude explains most of the variance, giving the highest correlation coefficient for a single variable, but inclusion of longitude significantly improves the model fit. The independent variables are not entirely orthogonal, however, as altitude and longitude are themselves correlated to some extent, the more inland gauges obviously tending to be at the higher altitude of the Plynlimon range, but inclusion of longitude allows for the fact that the altitude effect is not unique. Two distinct populations are represented, as shown in figure 3.1. These can be defined by longitude, in that those gauges on the windward side of Plynlimon have a steeper increase in rainfall with altitude than those on the leeward side in the Plynlimon catchments. If taken as one population, the increase in rainfall with altitude becomes non-linear at the low altitude and the high altitude end of the range. For the purposes of the rainfall model it was decided to ignore gauges at the extreme ends of the altitude range as neither are strictly relevant to Nant y Moch catchment itself (see table 3.1.1). The lowest point of the catchment at 350m and the highest point on Plynlimon at 752m represent only a small portion of the catchment and are not in any case well described by rainfall amounts across the watershed in the Plynlimon catchments. The resultant linear relationships are shown in table 3.1.2. in the following form:

$$\text{RAINFALL} = x + y*\text{ALTITUDE} + z*\text{LONGITUDE} \qquad \text{.......Eq. 3.1}$$

3.2 Derivation of annual maximum daily catchment rainfall

The most significant variable in the Flood Studies Report (FSR) method is the daily rainfall with a 5 year return period (1D-M5). The FSR actually recommends that the 2D-M5 rainfall is used, primarily because the 2-day period is considered to be more likely to cover the whole of a single rainfall-flood event in most medium to large catchments. In catchments experiencing an SAAR of between 2000 and 2800mm

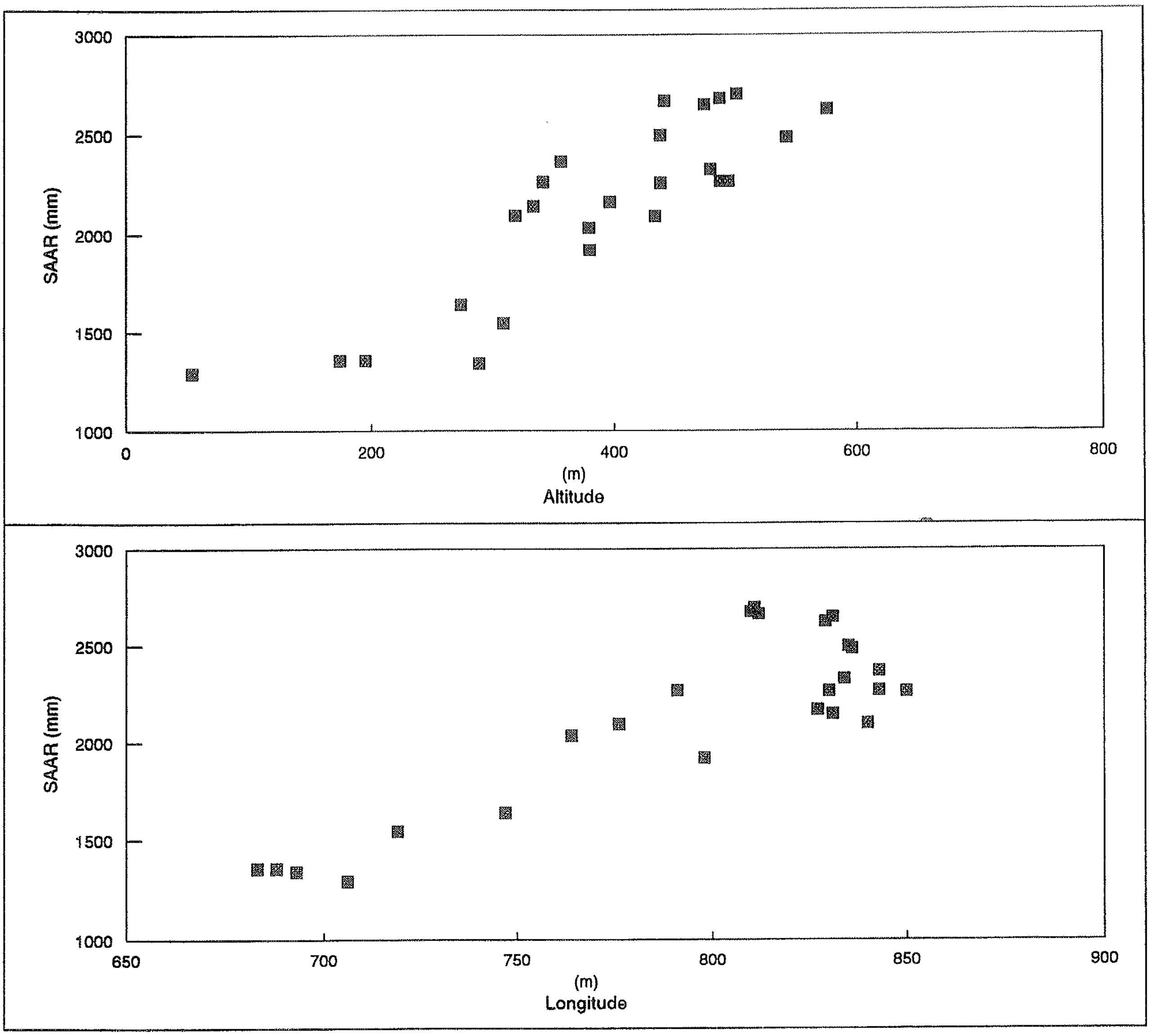


Figure 3.1. Relationship between annual rainfall and altitude and longitude in the Nant y Moch area.

Table 3.1.1 Details of Gauges used in the Final Regression Analysis for Spatial Model Development

Rain Gauge	Altitude (m)	Longitude (km)	MAR (mm)	SAAR (mm)
Blaen Hafren	439	83.5	2415	2497
Tor Glas	543	83.6	2543	2484
Moel Cynnedd	358	84.3	2330	2366
Cefyn-llwyd	439	85	2236	2259
Nant Iago	397	82.7	2207	2166
Cefn-brwyn	343	83	2233	2264
Manod	320	84	2081	2096
Plynlimon	488	79.1	2247	2268
Pant Mawr	335	83.1	2084	2144
Cefn Hendre	495	84.3	2459	2268
Nant Rhys	480	83.4	2342	2325
Maesnant	434	77.6	2169	2095
Nant y Moch(upper)	380	76.4	2008	2034
Dinas	275	74.7	1786	1638
Cwm Rheidol	53	70.6	1333	1293
Bontgoch	290	69.3	1344	1342
Craigypistyll	310	71.9	1867	1546
Elerch	195	68.8	1386	1358
Bontgoch W.T.Works	174	68.3	1418	1358
Rhiw-Gam	381	79.8	1921	1920

Table 3.1.2 Linear Regressions Forming the Basis of the Spatial Rainfall Model

SAAR		
Constant		-2075.89
Std Err of Y Est		107.06
R Squared		0.94
No. of Observations		20
Degrees of Freedom		17
	Altitude	*Longitude*
X Coefficient(s)	1.19	4.62
Std Err of Coef.	0.30	0.61

MAR		
Constant		-1382.63
Std Err of Y Est		105.56
R Squared		0.93
No. of Observations		20
Degrees of Freedom		17
	Altitude	*Longitude*
X Coefficient(s)	1.48	3.65
Std Err of Coef.	0.30	0.60

(Q3+Q4)/2		
Constant		*-81.81*
Std Err of Y Est		4.22
R Squared		0.94
No. of Observations		20
Degrees of Freedom		17
	Altitude	*Longitude*
X Coefficient(s)	0.05	0.18
Std Err of Coef.	0.01	0.02

the 1D-M5 is then taken as 79% of this value .

The 2D-M5 can be read straight from the FSR map, or interpolated as a function of SAAR from a look up table in the FSR. However, the steep rainfall gradients across the Nant y Moch catchment make it difficult to interpolate the value between the 100 and 150mm contours on the map. The logical approach is a linear interpolation estimating the rainfall at the centroid of the catchment, and this gives a 2D-M5 of 120mm and therefore a 1D-M5 of 94.8mm. For the purposes of estimating catchment rainfall this value needs to be reduced by an areal reduction factor of 0.85 (FSR Supplementary Report No. 1, 1977) to allow for the difference between point and areal storm rainfall, giving a 1D-M5 of 80.6mm.

A more accurate and reliable method has been to use the daily rainfall records available from the Moel Cynnedd site, adjusted proportionally according to the ratio of SAAR estimated for the main and sub-catchments at Nant y Moch and SAAR at Moel Cynnedd. The analysis requires the series of annual maximum daily or two-daily rainfalls shown in table 3.2.1.

A comparison of the two methods (1D versus 2D) is shown for the sequence of annual maximum daily rainfall at Moel Cynnedd in figure 3.2. This indicates considerable spread around the 1:1 line with some evidence of net deviations from the line at both low and high maximum daily rainfalls, clearly due to the carry over of some storms from one 9am-9am standard rainfall day to the next. However it is also clear that in the area of the predicted 1D-M5 value the two methods agree well. This is probably one of the reasons M5 is chosen as a standard return period - because it is not sensitive to the method chosen for estimating 1D rainfall. The actual 1D/2D factor calculated for the data set is 0.766, which is close to the FSR recommendation of 0.79. There is no justification for preferring the calculated factor over the FSR ratio, which is based on a much larger data set.

Statistical analysis of the results gives a good indication of the likely return periods of rainfall up to 10 years, as shown in table 3.2.2 as a function of the quartile distribution. The 1D-M5 value estimated in this way, 80.8mm, is remarkably close to the interpolation of the FSR map contours which gives 80.6mm.

3.3. Estimating extreme daily rainfall values

Within a set of rainfall data such as is available for Nant y Moch i.e 25 years, it is possible but unlikely that any extreme rainfalls (T>50 years) will have occurred; it would in fact be impossible to recognise their existence if such a rainfall had occurred. Clearly, the shorter the length of the data series available, the less confidence can be had in the extension of that series to predict extreme events. Fortunately the FSR analysis of extreme events indicated that, for sites with long

Table 3.2.1.a-c. Ranking analysis of 25 annual daily rainfall maxima for gauges in the Nant y Moch area between 1969-1994.

Year	Moel Cynnedd	Carreg Wen	Blaen Hafren	Tor Glas	Esgair y Maesnant	Cefyn-llwyd	Esgair y Maen	Esgair y Maen	Nant Iago
1984	125.5	139.2	132.4	131.8	140.5	119.8	141.4	142.0	114.9
1982	113.2	125.5	119.5	118.8	126.7	108.1	127.5	128.1	103.6
1987	110.6	122.7	116.7	116.1	123.8	105.6	124.6	125.2	101.3
1969	102.8	114.0	108.5	107.9	115.1	98.2	115.8	116.4	94.1
1976	100.0	110.9	105.5	105.0	112.0	95.5	112.6	113.2	91.5
1985	98.0	108.7	103.4	102.9	109.7	93.6	110.4	110.9	89.7
1978	84.5	93.7	89.2	88.7	94.6	80.7	95.2	95.6	77.4
1972	82.9	91.9	87.5	87.0	92.8	79.2	93.4	93.8	75.9
1989	82.5	91.5	87.1	86.6	92.4	78.8	92.9	93.4	75.5
1970	77.5	86.0	81.8	81.4	86.8	74.0	87.3	87.7	70.9
1993	75.9	84.2	80.1	79.7	85.0	72.5	85.5	85.9	69.5
1988	75.0	83.2	79.2	78.7	84.0	71.6	84.5	84.9	68.7
1974	74.2	82.3	78.3	77.9	83.1	70.8	83.6	84.0	67.9
1990	73.0	81.0	77.0	76.6	81.7	69.7	82.2	82.6	66.8
1981	71.8	79.6	75.8	75.4	80.4	68.6	80.9	81.3	65.7
1971	68.6	76.1	72.4	72.0	76.8	65.5	77.3	77.6	62.8
1992	65.0	72.1	68.6	68.2	72.8	62.1	73.2	73.6	59.5
1983	63.8	70.8	67.3	67.0	71.4	60.9	71.9	72.2	58.4
1980	63.6	70.5	67.1	66.8	71.2	60.7	71.6	72.0	58.2
1977	60.9	67.5	64.3	63.9	68.2	58.1	68.6	68.9	55.8
1979	58.0	64.3	61.2	60.9	64.9	55.4	65.3	65.6	53.1
1975	53.9	59.8	56.9	56.6	60.3	51.5	60.7	61.0	49.3
1973	53.2	59.0	56.1	55.9	59.6	50.8	59.9	60.2	48.7
1986	52.5	58.2	55.4	55.1	58.8	50.1	59.1	59.4	48.1
1991	44.0	48.8	46.4	46.2	49.3	42.0	49.6	49.8	40.3

Table 3.2.1.b

Esgair y Maen	Cefn-brwyn	Manod	Plynlimon	Pant Mawr	Cefn Hendre	Maesnant	Nant y Moch(upper)	Dinas	Cwm Rheidol
143.2	120.1	111.2	120.3	113.7	120.3	111.1	107.9	86.9	68.6
129.1	108.3	100.3	108.5	102.6	108.5	100.2	97.3	78.4	61.9
126.2	105.8	98.0	106.0	100.2	106.0	97.9	95.1	76.6	60.4
117.3	98.4	91.1	98.5	93.2	98.5	91.0	88.4	71.2	56.2
114.1	95.7	88.6	95.9	90.6	95.9	88.5	86.0	69.2	54.6
111.8	93.8	86.8	93.9	88.8	93.9	86.8	84.2	67.8	53.6
96.4	80.9	74.9	81.0	76.6	81.0	74.8	72.6	58.5	46.2
94.6	79.3	73.4	79.5	75.1	79.5	73.4	71.3	57.4	45.3
94.1	78.9	73.1	79.1	74.8	79.1	73.1	70.9	57.1	45.1
88.4	74.2	68.7	74.3	70.2	74.3	68.6	66.6	53.7	42.4
86.6	72.6	67.2	72.8	68.8	72.8	67.2	65.2	52.5	41.5
85.6	71.8	66.4	71.9	68.0	71.9	66.4	64.5	51.9	41.0
84.6	71.0	65.7	71.1	67.2	71.1	65.7	63.8	51.4	40.5
83.3	69.9	64.7	70.0	66.2	70.0	64.6	62.8	50.5	39.9
81.9	68.7	63.6	68.8	65.1	68.8	63.6	61.7	49.7	39.2
78.3	65.6	60.8	65.8	62.2	65.8	60.7	59.0	47.5	37.5
74.1	62.2	57.6	62.3	58.9	62.3	57.6	55.9	45.0	35.5
72.8	61.0	56.5	61.2	57.8	61.2	56.5	54.8	44.2	34.9
72.6	60.9	56.3	61.0	57.6	61.0	56.3	54.7	44.0	34.8
69.5	58.3	54.0	58.4	55.2	58.4	53.9	52.4	42.2	33.3
66.2	55.5	51.4	55.6	52.6	55.6	51.4	49.9	40.2	31.7
61.5	51.6	47.7	51.7	48.8	51.7	47.7	46.3	37.3	29.5
60.7	50.9	47.1	51.0	48.2	51.0	47.1	45.7	36.8	29.1
59.9	50.2	46.5	50.3	47.6	50.3	46.5	45.1	36.3	28.7
50.2	42.1	39.0	42.2	39.9	42.2	39.0	37.8	30.5	24.0

Table 3.2.1.c

Bontgoch	Craigypistyll	Elerch	Bontgoch W.Works	Rhiw-Gam	Nant Rhys
71.2	82.0	72.0	72.0	101.8	123.3
64.2	74.0	65.0	65.0	91.9	111.2
62.7	72.3	63.5	63.5	89.8	108.7
58.3	67.2	59.0	59.0	83.4	101.0
56.7	65.3	57.4	57.4	81.1	98.3
55.6	64.0	56.2	56.2	79.5	96.3
47.9	55.2	48.5	48.5	68.6	83.0
47.0	54.2	47.6	47.6	67.3	81.5
46.8	53.9	47.4	47.4	66.9	81.1
44.0	50.6	44.5	44.5	62.9	76.2
43.1	49.6	43.6	43.6	61.6	74.6
42.5	49.0	43.0	43.0	60.9	73.7
42.1	48.5	42.6	42.6	60.2	72.9
41.4	47.7	41.9	41.9	59.2	71.7
40.7	46.9	41.2	41.2	58.3	70.6
38.9	44.8	39.4	39.4	55.7	67.4
36.9	42.5	37.3	37.3	52.7	63.9
36.2	41.7	36.6	36.6	51.8	62.7
36.1	41.6	36.5	36.5	51.6	62.5
34.5	39.8	35.0	35.0	49.4	59.8
32.9	37.9	33.3	33.3	47.1	57.0
30.6	35.2	30.9	30.9	43.7	53.0
30.2	34.8	30.5	30.5	43.2	52.3
29.8	34.3	30.1	30.1	42.6	51.6
25.0	28.8	25.3	25.3	35.7	43.2

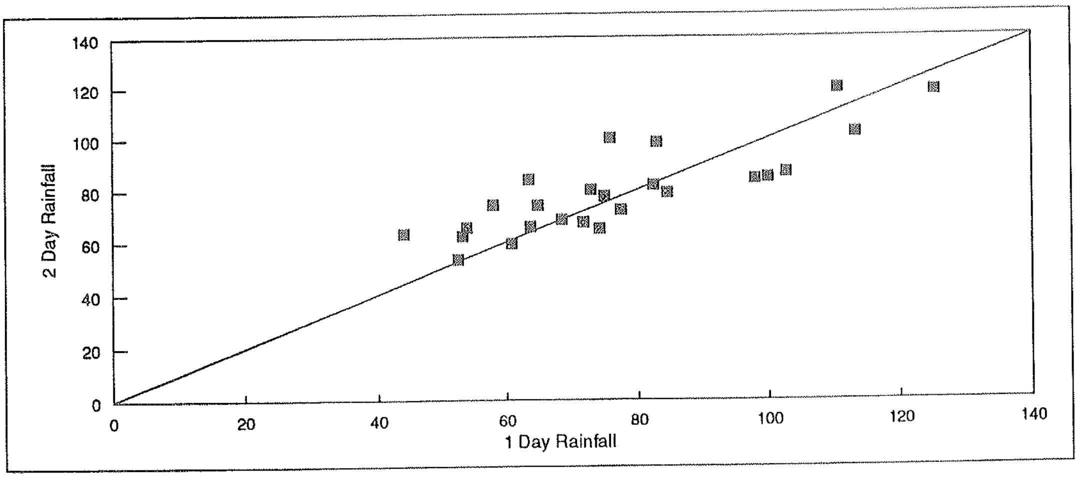


*Figure 3.2. A comparison of methods of calculation of the maximum 1-day rainfall at Moel Cynnedd: 1D and 2D*0.79.*

Table 3.2.2. Return periods of daily catchment and subcatchment rainfall (mm) related to quartile statistics.

Catchment	Mean Altitude	Mean Longitude	Q1	(Q1+Q2)/2	Q2	(Q2+Q3)/2	Q3	(Q3+Q4)/2	Q4
	(m)	(Km)	Twice Yearly		M1	M2		M5	M10
1	491.5	775	47.89	54.16	60.43	65.19	69.95	82.47	94.99
2	535.6	778	49.40	55.87	62.34	67.25	72.16	85.08	97.99
3	545.3	790	50.94	57.61	64.27	69.34	74.40	87.72	101.04
4	512.8	805	51.64	58.40	65.16	70.30	75.43	88.93	102.43
5	495.2	785	49.04	55.47	61.89	66.76	71.64	84.46	97.28
6	416.4	755	43.72	49.45	55.17	59.52	63.87	75.30	86.73
7	410.5	735	41.45	46.88	52.30	56.42	60.54	71.38	82.22
a	375.0	760	43.13	48.77	54.42	58.71	62.99	74.27	85.55
b	398.5	770	44.83	50.69	56.56	61.02	65.47	77.19	88.91
c	405.6	773	45.34	51.27	57.21	61.71	66.22	78.07	89.92
d	501.8	775	48.17	54.47	60.78	65.57	70.35	82.95	95.54
e	400.0	757	43.49	49.18	54.88	59.20	63.52	74.90	86.27
f	400.0	740	41.69	47.15	52.61	56.75	60.90	71.80	82.70
Mean values			46.21	52.26	58.31	62.90	67.50	79.58	91.66
Catchment as a Whole	455.0	775	46.89	53.03	59.17	63.83	68.49	80.75	93.01

records, the growth factor MT/M5 tended to be consistent within a particular region. These regions were delineated grossly in the main edition of the FSR as: (1) England & Wales, and (2) Scotland & Northern Ireland. Thus, because it is possible to estimate M5 with a relatively short record, these regional growth factors can be used to extrapolate with some confidence to extreme rainfalls, and these are shown for Nant y Moch in table 3.3.

Table 3.3 Estimates of extreme 1D rainfalls related to an M5 for Nant y Moch of 80.8mm.

Return Period	Growth Factor (MT/M5)	1-day rainfall (mm)
M5	1.0	80.8
M10	1.14	92.1
M20	1.28	103.4
M50	1.5	121.2
M100	1.69	136.6
M1000	2.49	201.2
M10000	3.7	299.0
PMP	4.45	359.6

It is interesting to note that the probable maximum daily precipitation estimated this way is very close to the value derived from the map in the FSR (1975) which suggests a value of 350mm for the centroid of the catchment.

4. Flood Estimation

4.1 Derivation of catchment characteristics for flood estimation

There is no gauging station on the Rheidol that has a record sufficiently long to be used to estimate flow statistics in the Nant y Moch catchment. One approach that can be taken is to use Flood Studies Report techniques (NERC, 1975) to estimate the frequency of flood flows likely to be encountered. The main FSR method for use in ungauged catchments is based on flood relationships with catchment characteristics, as follows:

$$MAF = k * AREA^{0.94} * STRMFRQ^{0.27} * S1085^{0.16} * SOIL^{1.23} * RSMD^{1.03} * (1+LAKE)^{-0.85} \quad .....Eq.\ 4.1.1$$

where: MAF is the Mean Annual Flood ($m^3.sec^{-1}$), equivalent to a return period of 2.33 years.
k is a regional constant (0.0213 for Wales)
AREA is the catchment area (km^2)
STRMFRQ is the drainage density (junctions.km^{-2})
S1085 is a measure of channel slope from 10% to 85% of the channel length upstream from the gauging station (m. km^{-1})
SOIL is an areally-weighted, dimensionless index of the winter rain acceptance potential (infiltration capacity) of the soils in the catchment
RSMD is the effective annual maximum daily rainfall of 5-year return period after average winter soil moisture deficit has been satisfied (mm)
LAKE is the proportion of the catchment covered by open water.

Some of these parameters can be interpolated from FSR maps e.g. SOIL, SMD, 1D-M5, while others are taken from OS maps, e.g. AREA, LAKE, S1085, STRMFRQ. The catchment characteristics, with the sub-catchment characteristics estimated on an individual basis, are shown in Table 4.1.1.

Strictly, the regression method is designed for one-limbed catchments (classic dendritic drainage) of which Nant y Moch is not a good example, having four approximately equal limbs, the Hengwm, the Hyddgen, the Rhuddlan and the Llechwedd Mawr, and three limbs which are minor in terms of area but important in terms of generating flood peaks because of their higher rainfall and steeper slopes. This affects the estimation of drainage density and channel slope, which are both important sources of variance in the regression model adopted by FSR and cannot therefore be lightly ignored. The basic choice is between considering the catchment as one unit or a number of subcatchments whose floods must be added together.

AREA

Catchment area is a crucial component of the equation and has been estimated using a number of different methods - planimetry of the whole catchment on 1:50,000 maps, planimetry of the subcatchments and sub areas on 1:25,000 maps, area integration on 1:25,000 maps using the trapezium method and also by the paper weighing method. The catchment area, including the reservoir, is 54.94km^2 by planimetry, of which only 2.11km^2 (3.8%) is the reservoir itself. It covers a large geographical area in a region of considerable hydrological variability and would be classed as a large catchment by FSR standards (>20km^2), although

Table 4.1.1 Values used in the FSR equation to estimate the Mean Annual Flood

		Catchment Area (Km)	S1085 to lakeside	S1085 to dam base	Stream Junctions	STMFRQ with lake	SOIL	1DM5 (mm)	RSMD (mm)
1	Nant y Maesnant Fach & Nant y Moch	4.16	83.33		22	4.07	0.5	82.5	79.5
2	Graig Goch & Maesnant	1.99	157.74		6	2.32	0.5	85.1	82.1
3	Nant y Llyn	2.33	85.11		6	1.98	0.5	87.7	84.7
4	Afon Hengwm	12.87	20.14	16.31	44	2.63	0.5	88.9	85.9
5	Afon Hyddgen	6.95	24.92		14	1.55	0.5	84.5	81.5
6	Afon Llechwedd Mawr	11.73	10.53		25	1.64	0.5	75.3	72.3
7	Nant Rhuddlan	3.52	19.55		9	1.97	0.5	71.4	68.4
a	-	0.25			1	3.12	0.5	74.3	71.3
b	-	0.46			1	1.68	0.5	77.2	74.2
c	-	0.49			1	1.58	0.5	78.1	75.1
d	-	1.10			1	0.70	0.5	83.0	80.0
e	-	4.87			27	4.27	0.5	74.9	71.9
f	-	2.10			7	2.56	0.5	71.8	68.8
Nant y Moch Reservoir		2.11			22	0.49		79.58	76.58
	Small Lakes								
3	Llyn llygad	0.08							
6	Plas y Mynydd	0.07							
6	Llyn Dwfn	0.03							
Average values for the Sub-Catchments		54.94	57.33		13	2.31	0.5	79.58	76.58
Catchment Treated as a Whole		54.94	20.88	16.31	164	2.3	0.5	80.75	77.75

its component subcatchments if treated separately would be classed as small catchments.

1D-M5

Calculation of the 1D-M5 rainfall relies on the multiple regression equation 3.1 and table 3.1.2. which relates rainfall to the longitudinal centroid of the catchment and the areally-weighted mean altitude (the hypsometric analysis used is shown in table 4.1.2 and the predicted 1D rainfall for the main and subcatchments shown in table 4.1.3).

S1085

Although rainfall and area are clearly the most important variables in the equation, effectively circumscribing the volume input to the catchment, the description of the channel network ie. its density and slope, controls the time distribution of that flow volume and hence the magnitude of the flood peak. The method is therefore sensitive to the, often ambiguous, estimates of stream network density (STRMFRQ) and slope (S1085). S1085 is particularly important, as it can be a small or large number with a reasonably high exponent (0.16), yet because it is not an easy task to decide on the best method of calculation this can result in a wide range of options.

When the catchment is taken as one unit, the FSR recommends that the stream slope (S1085) is taken from the most important limb. As can be seen from figure 2.1, this is difficult to define at Nant y Moch, as the longest limb is the Llechwedd Mawr, but if taken as true dendritic drainage in a symmetrical lenticular catchment, the axis of symmetry is along the Hengwm. At Nant y Moch the catchment is lop-sided, with the largest subcatchments all lying on the right bank of the main limb (adopted as the Hengwm) and characterised by shallow stream gradients, while the smaller catchments draining off the slopes of Plynlimon all lie on the left bank and are characterised by steep stream gradients. An analysis of the effect of progressively accumulating the S1085s together to provide a mean S1085 weighted by stream length (a surrogate for catchment area) indicates that in spite of their small size catchments 1 to 3 have the effect of doubling the stream slope from 18 m km^{-1} to 38 m km^{-1}, which translates into a 10% increase in the MAF calculated. One advantage of splitting the catchment into component subcatchments (see figure 2.1), is that each of these has a drainage network that approximates more closely to the classic pattern.

STRMFRQ

The estimation of STRMFRQ is less controversial, the one problem being that the original equation was optimised using network characteristics derived from the old version of the 1:25,000 maps, which showed fewer streams than the latest version of the map. As the new maps have been used for deriving data for this report, a correction factor of 0.74 has been introduced as recommended in FSR

Table 4.1.2 Hypsometric analysis to give areally-weighted mean altitude for the catchments.

	Sub-Catchments													
Altitude Range	1	2	3	4	5	6	7	a	b	c	d	e	f	Whole Catchment
350-450	0.045	0.01	0.012	0.08	0.115	0.222	0.16	0.015	0.02	0.017	0.02	0.67	0.85	2.236
450-550	0.056	0.024	0.045	0.415	0.8	0.05			0.001	0.001	0.015			1.407
550-650	0.032	0.017	0.048	0.162	0.1						0.021			0.38
650-750	0.001	0.008	0.008	0.001										0.018
Total	0.134	0.059	0.113	0.658	1.015	0.272	0.16	0.015	0.021	0.018	0.056	0.67	0.85	4.041
Mean Altitude														
400	18	4	4.8	32	46	88.8	65.68	5.625	8	6.8	8	268	340	894.4
500	28	12	22.5	207.5	400	24.45			0.368	0.5	7.5	0		703.5
600	19.2	10.2	28.8	97.2	56.6						12.6	0		228
700	0.667	5.4	5.52	0.752								0		12.6
Hypsometric Altitude	**491.5**	**535.6**	**545.3**	**512.8**	**495.2**	**416.4**	**410.5**	**375.0**	**398.5**	**405.6**	**501.8**	**400.0**	**400.0**	**455.0**

Table 4.1.3. Predicted mean annual rainfall and 1D-M5 rainfall for the main and subcatchments at Nant y Moch

Catchment		Mean Altitude	Mean Longitude	MAR (predicted)	1 day Rainfall (predicted)
1	Nant y Maesnant Fach & Nant y Moch	492	775	2178.2	82.5
2	Graig Goch & Maesnant	536	778	2254.5	85.1
3	Nant y Llyn	545	790	2312.8	87.7
4	Afon Hengwm	513	805	2319.4	88.9
5	Afon Hyddgen	495	785	2220.1	84.5
6	Afon Llechwedd Mawr	416	755	1993.5	75.3
7	Nant Rhuddlan	411	735	1911.8	71.4
a	-	375	760	1950.4	74.3
b	-	398	770	2021.8	77.2
c	-	406	773	2043.3	78.1
d	-	502	775	2193.4	83.0
e	-	400	757	1976.6	74.9
f	-	400	740	1914.5	81.8
Mean Values		-	-	2099.2	79.6
Catchment as a Whole		455	775	2123.9	80.8

Supplementary Report No. 11 (NERC, 1985).

SUBCATCHMENTS
The subcatchment approach is problematical when attempting to estimate the total input to the reservoir, as there remains a number of polygonal contributing areas each with no obvious drainage pattern. It is difficult to use the conventional FSR equation for these areas because no stream slope value can be measured, but as their total area represents a significant part of the catchment area neither can they be ignored. Simply increasing the flood peak proportionally according to area does not give the same answer as the estimate for the whole catchment because this effectively reduces the estimate of drainage density for the whole catchment. An approach has been adopted whereby the S1085 is set at the same value as for the main catchment, and the stream junction count is set to unity; each polygon is then treated as a normal catchment. The problems introduced are as follows:

(1) It is difficult to apply the stream frequency correction of 0.74 to a catchment with no stream junctions, and logically there will always be the catchment exit on both versions of the map. The correction for catchments containing streams has thus been introduced into the formula as:

$$STRMFRQ = (1+(0.74*JUNCTIONS))/AREA \quad ...Eq.\ 4.1.2$$

(2) The summing of the subcatchment values relies on the assumption that the flood peaks will all coincide as they enter the reservoir. This will clearly not be the case as the sub-catchments vary considerably in size and therefore time to peak. In contrast this variation in time to peak response is implicit in the calculation of MAF for the whole Nant y Moch catchment. All other parameters remaining equal, the result must be that the whole catchment approach will inevitably produce a lower estimate than the lumped subcatchment approach. This is confirmed in table 4.1.4 where the MAF for the lumped subcatchments at 73.52 $m^3.sec^{-1}$ is 12.7% higher than the estimate of 65.22 $m^3.sec^{-1}$ for the whole catchment, while the areal correction method on the sum of the main subcatchments gives 81.7 $m^3.sec^{-1}$ an overestimate by 25.2%. This problem is further dealt with by reference to the unit hydrograph method in section 4.3.

4.2 Flood levels from catchment characteristics

Substituting the 'preferred' values of catchment characteristics into the FSR (equation 4.1.1) gives a mean annual flood (MAF) of 65.22 $m^3.sec^{-1}$. Floods with longer return periods can be estimated using regional growth curves, as described in the FSR (NERC, 1975) and subsequently updated in FSR Supplementary

Table 4.1.4 Mean annual flood (MAF) calculated from the subcatchments and the main catchment

		Nant y moch		Catchment 1		Catchment 2		Catchment 3		Catchment 4		Catchment 5		Catchment 6		Catchment 7	
Area		54.96	43.21	4.16	3.82	1.99	1.91	2.33	2.22	12.87	11.04	6.95	6.19	11.73	10.12	3.52	3.27
STMFRQ		2.21	1.24	3.98	1.45	2.36	1.26	2.01	1.21	2.55	1.29	1.63	1.14	1.60	1.14	1.96	1.20
S1085		16.31	1.56	83.33	2.03	157.74	2.25	85.11	2.04	20.14	1.62	24.92	1.67	10.53	1.46	19.55	1.61
SOIL		0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43
RSMD		77.75	88.60	79.47	90.62	82.08	93.68	84.72	96.79	85.93	98.21	81.46	92.95	72.30	82.21	68.38	77.62
LAKE		0.04	0.97		1.00		1.00	0.08	0.93		1.00		1.00	0.10	0.92		1.00
REGION	0.0213																
MEAN ANNUAL FLOOD			65.22		9.26		4.60		4.48		20.49		9.97		11.49		4.45

	Catchment a		Catchment b		Catchment c		Catchment d		Catchment e		Catchment f	
Area	0.25	0.27	0.46	0.48	0.49	0.51	1.10	1.10	4.87	4.43	2.10	2.01
STMFRQ	4.05	1.46	2.18	1.23	2.05	1.21	0.91	0.97	4.16	1.47	2.59	1.29
S1085	16.31	1.56	16.31	1.56	16.31	1.56	16.31	1.56	16.31	1.56	16.31	1.56
SOIL	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43	0.50	0.43
RSMD	71.27	81.00	74.19	84.42	75.07	85.45	79.95	91.18	71.90	81.74	68.80	78.11
LAKE		1.00		1.00		1.00		1.00		1.00		1.00
REGION												
MEAN ANNUAL FLOOD		0.45		0.71		0.75		1.38		7.55		2.88

MEAN ANNUAL FLOOD (Sum of Sub-Catchments) 78.47

Report No. 14 (NERC, 1983). These estimates are shown in table 4.2, however it should be noted that confidence can be placed only in the calculation of return periods up to T1000. Greater return periods should ideally be calculated using the Unit Hydrograph Losses Model (see section 4.3), but can also be approximated using an equation of the form:

$$QT / MAF = 0.85 + (0.222(1 - e^{0.12y})) / - 0.12 \qquad \text{...Eq. 4.2.1}$$

where the relationship between y and the return period T is inferred from the Gumbel Extreme Value distribution.

Table 4.2 Estimated magnitude of floods of various return periods in hydrometric areas 55-67 & 102.

Return period	**Reduced Variate (y)**	**Factor**	**Flow ($m^3 sec^{-1}$)**
2.33 years (mean annual flood)		1.0	65.22
5 years		1.21	78.92
10 years		1.42	92.61
50 years		1.94	126.53
100 years		2.18	142.18
500 years		2.86	186.53
1000 years		3.19	208.05
5000 years	8.52	4.14	270.01
10000 years	9.21	4.59	299.36
Half PMF		PMF/2	326.4
PMF			652.8

Table 4.2 also includes an estimate of the probable maximum flood (PMF) associated with the probable maximum precipitation (PMP), and also that of the half-PMF. The PMP has been derived from the FSR by interpolating between the isohyets on the appropriate map, and also by using the regional growth curve for 1-day rainfall (see table 3.3). Ideally the PMF should be calculated by convoluting the PMP with the unit hydrograph having allowed for losses, but an initial crude

estimate can be gained using a regression equation related to catchment characteristics referred to in the FSR but improved by the incorporation of data from 80 catchments by Reed & Field (1992).

$$PMF = 0.881\ AREA^{0.925}\ S1085^{0.291}\ RSMD^{0.547}\ (1+URBAN)^{2.16}\ SOIL^{0.472}\ \ldots\ \text{Eq. 4.2.2}$$

Unfortunately, the presence of the reservoir also creates a problem with the FSR method. Being a controlled reservoir rather than a natural lake it is not always in a state to be considered within the FSR equation in the traditional way, i.e as an agent of attenuation for the flood peak. To do this, the worst case scenario for the reservoir has to be assumed, that of being full to maximum capacity, the antecedent flows already spilling and the release valves closed, in which case the reservoir will behave like a lake and can be treated as such in the FSR equation. This gives an MAF of 65.22 $m^3.sec^{-1}$ for the whole catchment, which compares with an estimate 67.23 $m^3.sec^{-1}$ for the whole catchment when it is assumed that the reservoir does not exist. For this latter estimate, the catchment characteristics have been adjusted to allow for the rainfall falling on the surface of the lake, for the contribution to S1085 made by that part of the stream channel under the lake, but not for the stream junctions hidden under the lake. Certain other assumptions have also been made: that no tributaries are completely hidden by the lake, and that a linear interpolation of stream altitude is reasonable. The existence of the lake can be seen, in the worst case, to reduce the flood peak by only 3% of its pre-reservoir value.

4.2.1. Sensitivity of MAF to variations in catchment characteristics.

The most critical parameter controlling the MAF is S1085. The best estimate for the main catchment has been taken as 16.31 m km^{-1}, the value for the Hengwm limb from source to the base of the dam wall. Clearly the other options shown in table 4.2.1 using various combinations of the main tributaries down to the lake are steeper and also vary markedly between 18.39 and 38.67 m km^{-1}. The sensitivity of the MAF estimate is considerable, table 4.2.2 indicating that the 'best estimate' MAF of 65.22 $m^3.sec^{-1}$ increases to 74.88 $m^3.sec^{-1}$ if the weighted mean of all the subcatchments is used. This is probably unrealistically high for the FSR method which was developed using slope data from the main limb of catchments and, although the value adopted is low for the type of topography under study, the combination of the alternative main limbs raises the slope to only 22.48 m km^{-1} which results in a MAF of 68.66 $m^3.sec^{-1}$, only 5% higher than the accepted value.

Of the other characteristics, (tables 4.2.3 and 4.2.4) the methods of calculation of both catchment area and, particularly, stream frequency can have a significant effect on MAF, however in the case of Nant y Moch the estimation of both of these is less contentious than for S1085.

Table 4.2.1 Alternative S1085 calculations

Catchment	Mean Stream Length (To Lakeside)	Altitude (10%)	Altitude (85%)	Change	L(1085)	Gradient
1	2.000	360	485	125	1.500	83.33
2	1.775	360	570	210	1.331	157.74
3	2.350	370	520	150	1.763	85.11
4	5.630	360	445	85	4.220	20.14
5	5.350	360	460	100	4.013	24.92
6	5.700	345	390	45	4.275	10.53
7	3.750	355	410	55	2.813	19.55

Catchment	Mean Stream Length (To base of Dam)	Altitude (10%)	Altitude (85%)	Change	L(1085)	Gradient
4	10.630	305	435	130	7.970	16.31

Mean Values of S1085 (Length weighted)

4	85	4.220	20.14
4+5	185	8.230	22.48
4+5+6	230	12.505	18.39
4+5+6+7	285	15.318	18.61
4+5+6+7+1+2+3	770	19.912	38.67

Table 4.2.2 Mean annual flood estimates using alternative values of S1085.

Sensitivity Analysis for Changes in S1085

Changes in S1085 (calculated from main sub-catchment value)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		20.14	1.62
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			67.46

Changes in S1085 (calculated from main+secondary sub-catchment values)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		22.48	1.65
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			68.66

Changes in S1085 (calculated from main+secondary tertiary sub-catchment values)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		18.39	1.59
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			66.49

Changes in S1085 (calculated from main+secondary tertiary+quaternary sub-catchment values)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		18.61	1.60
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			66.61

Changes in S1085 (calculated from all sub-catchment values)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		38.67	1.79
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			74.88

Changes in S1085 (calculated from the (Main Limb to base of dam)

AREA		54.96	43.21
STMFRQ		2.21	1.24
S1085		16.31	1.56
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		0.04	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			65.22

Table 4.2.3 *Mean annual flood estimates using alternative values of AREA.*

Sensitivity Analysis for Changes in Area

Nant y Moch (Planimetered)			
AREA		*54.96*	43.21
STMFRQ		2.21	1.24
S1085		16.31	1.56
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE			1.00
REGION	0.0213		
MEAN ANNUAL FLOOD			67.34

Nant y Moch (Integration Method)			
AREA		*53.71*	42.29
STMFRQ		2.26	1.25
S1085		16.31	1.56
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE			1.00
REGION	0.0213		
MEAN ANNUAL FLOOD			66.31

Nant y Moch (excluding area of the reservoir)			
AREA		*52.83*	41.64
STMFRQ		2.30	1.25
S1085		16.31	1.56
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE			1.00
REGION	0.0213		
MEAN ANNUAL FLOOD			65.58

Nant y Moch (Planimetered but including Reservoir Area)			
AREA		*54.96*	43.21
STMFRQ		2.21	1.24
S1085		16.31	1.56
SOIL		0.50	0.43
RSMD		77.75	88.60
LAKE		*0.04*	0.97
REGION	0.0213		
MEAN ANNUAL FLOOD			65.22

Table 4.2.4 *Mean annual flood estimates using alternative values of STRMFRQ*

Sensitivity Analysis for Changes in STMFRQ

Nant y Moch (Assuming No Junctions under lake)				***Nant y Moch (Assuming Junctions under lake)***			
AREA		54.96	43.21	AREA		54.96	43.21
STMFRQ		*2.21*	1.24	STMFRQ		*2.50*	1.28
S1085		16.31	1.56	S1085		16.31	1.56
SOIL		0.50	0.43	SOIL		0.50	0.43
RSMD		77.75	88.60	RSMD		77.75	88.60
LAKE			1.00	LAKE			1.00
REGION	0.0213			REGION	0.0213		
MEAN ANNUAL FLOOD			67.34	*MEAN ANNUAL FLOOD*			69.57

Nant y Moch (No Junctions but influenced by the lake)				***Nant y Moch (Junctions under the lake and influenced by the lake)***			
AREA		54.96	43.21	AREA		54.96	43.21
STMFRQ		*2.21*	1.24	STMFRQ		*2.60*	1.29
S1085		16.31	1.56	S1085		16.31	1.56
SOIL		0.50	0.43	SOIL		0.50	0.43
RSMD		77.75	88.60	RSMD		77.75	88.60
LAKE		*0.04*	0.97	LAKE		*0.04*	0.97
REGION	0.0213			REGION	0.0213		
MEAN ANNUAL FLOOD			65.22	*MEAN ANNUAL FLOOD*			68.10

4.3 Flood characterisation using the unit hydrograph method

The unit hydrograph method offers a relatively simple simulation technique for the prediction of the complete flood hydrograph and especially the timing and magnitude of the peak (FSR 1975). The approach depends upon the separation, by an objective technique, of quick response flow, which is the direct consequence of recent rainfall, from baseflow, which is sustained by slower flow pathways. For suitable events, typically those where the flow rises from baseflow in response to a short duration rainstorm and falls again to baseflow, the recession being uncomplicated by succeeding rain events, a linear relationship is then established between the quick response flow and the effective rainfall. The computation of the time distribution of effective rainfall through the allocation of "losses" from the measured or predicted rainfall is a difficult problem, but the detail is generally of little significance for small catchments and short-duration high-magnitude rainfall events. Deviations from linearity for particularly large flows have been postulated on hydraulic principles (FSR, p381), but non-linearities have proved difficult to identify in field data (FSR, pp403-405).

Two distinct unit hydrograph approaches are possible for the Nant y Moch catchments: the estimation of unit hydrograph parameters from catchment characteristics, following the recommendations of the FSR, and the derivation of unit hydrographs from local information, i.e. the rainfall and flow data from IH experimental catchments, the Maesnant and Maesnant Fach.

4.3.1 Unit hydrograph parameters predicted by the FSR

The unit hydrograph is the response of a catchment to a given quantity of effective rainfall, usually normalised to 10 mm, falling over a short period conveniently chosen to match the rainfall or flow data interval, for instance one hour. By applying mathematical arguments, it is also possible to define an instantaneous unit hydrograph (IUH), which is the response to an instantaneous input of rainfall. The IUH can be regarded as the limit of a sequence of unit hydrographs with successively shorter time periods. Although the IUH is scientifically more elegant, for practical purposes the finite-period unit hydrograph is an appropriate choice. In the application of the unit hydrograph to flood prediction, the FSR recommends working on a time interval that is less than one-fifth of the time-to-peak of the unit hydrograph. In the case of the Nant y Moch catchments it has been convenient to set the time interval, and hence the period of the unit hydrograph, for various purposes to 1 hour, 0.5 hour or 0.25 hour.

Unit hydrographs invariably have a skewed form, with a short rising limb reflecting the slight delay in the initiation of the flood-generation processes of overland flow and throughflow and the travel time of the flood wave in stream channels, a single well-defined peak, and a slower recession that results from the slow drainage of flow pathways (Figure 4.3.1). Characterisation of the form of the unit hydrograph by a limited number of parameters is necessary both for the development of empirical equations describing the dependence of the unit hydrograph, for example, on the physical dimensions of the catchment, and for the eventual use of unit hydrograph techniques in ungauged catchments. For practical reasons the number of parameters is reduced to as few as possible: the FSR recommends the use of a triangular unit hydrograph defined by three parameters, of which the most important are the time to peak Tp and the peak discharge Qp. The need to assign a value to a third parameter, the timebase Tb, is eliminated by the observation, from a large number of such hydrographs, that the recession limb can be assumed to be 1.52 times as long as the rising limb. The second parameter Qp is defined by the convention that the unit hydrograph represents the catchment response to a standard quantity (10 mm) of effective rainfall.

Thus there remains one parameter Tp, which can be estimated from catchment characteristics by an empirical equation (Floods Studies Supplementary Report 16, 1985):

$$Tp(0) = 283.0\ (S1085)^{-0.33}\ (1+URBAN)^{-2.2}(SAAR)^{-0.54}(MSL)^{0.23} \qquad \text{... Eq. 4.3.1}$$

where Tp(0) is the time-to-peak of the IUH
S1085 is the 10-85% stream slope ($m\ km^{-1}$)
URBAN is the urban fraction (zero for Nant y Moch catchments)
SAAR is the standard period average annual rainfall (mm)
and MSL is the main stream length (km) .

The time-to-peak of the T-hour unit hydrograph is approximately

$$Tp(T) = Tp(0) + T/2 \qquad \text{... Eq. 4.3.2}$$

The usual convention is to compute a unit hydrograph for 10 mm of effective rainfall, and to adopt a standard value of 2.52 for Tb/Tp, fixing the skew of the hydrograph. In this case the time-base of the hydrograph is then given by

$$Tb(T) = 2.52\ Tp(T) \qquad \text{... Eq. 4.3.3}$$

and the peak discharge (expressed as cumec per 100 $km^{2)}$ of the unit hydrograph is

$$Qp(T) = 220/Tp(T) \qquad \text{... Eq. 4.3.4}$$

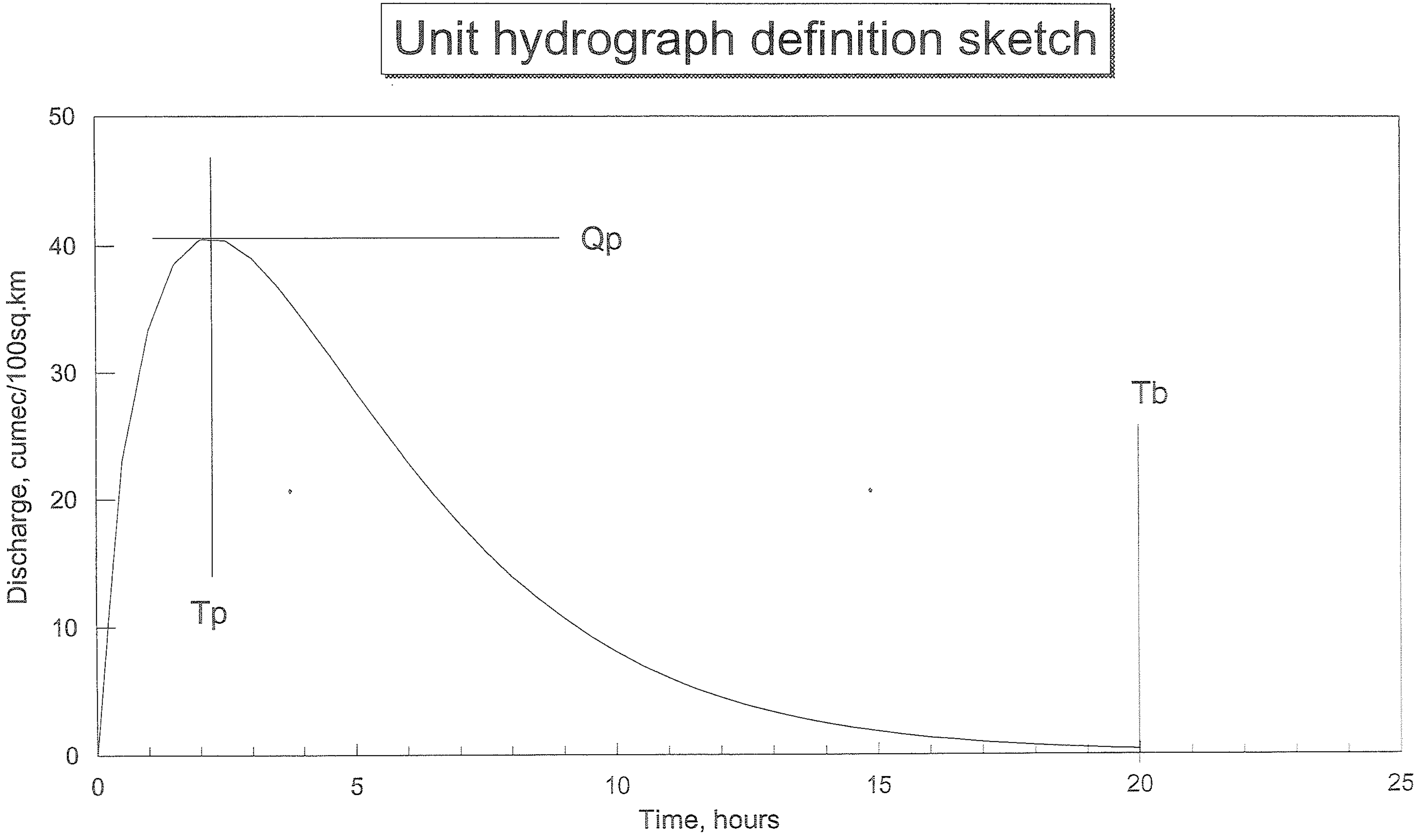


Figure 4.3.1. Definition sketch for the unit hydrograph.

Table 4.3.1 shows the result of applying these relationships to the seven subcatchments and six minor contributing areas of the Nant y Moch catchment to compute the 0.25-hour unit hydrograph. The final row in the table shows the 0.25-hour unit hydrograph parameters obtained for averaged characteristics for the whole Nant y Moch catchment.

An alternative method is to compute a cumulative hydrograph for a 10 mm storm, weighting the contributions from each subcatchment according to its area (subcatchment areas are presented in Table 4.2.1). Figure 4.3.2 shows unit hydrographs for a selection of the larger subcatchments and contributing areas, along with the triangular unit hydrograph computed for the whole catchment and the cumulative (weighted mean) unit hydrograph. As the weighted mean unit hydrograph is the sum of a number of different triangles with varying times to peak, it has started to acquire a curvilinear and skewed shape similar to that of Figure 4.3.1. The short time-to-peak of the weighted mean unit hydrograph is a consequence of the early arrival of flood peaks generated on subcatchments 1 to 3 and contributing area 'e', with short channels feeding directly into the reservoir. Although the timing of the peaks of the two hydrographs for the whole catchment differ, their peak discharges are very similar (see also Table 4.3.2).

4.3.2 Derivation of unit hydrographs from IH catchments

The IH experimental catchments of Maesnant and Maesnant Fach were operated between May 1984 and May 1990. Data sets of hourly rainfall from a rainfall recorder in each catchment, and discharges at quarter-hourly intervals from flow gauging stations were available for the derivation of unit hydrographs. After inspection of the flow record, nine rainfall events were selected for detailed analysis. Two of these events were found to be unsatisfactory for the purpose probably because of input to the stream from unmeasured snowmelt, and the rainfall record for a third event may have been incomplete.

For the analysis of the remaining six events, a method by Nash (1958) was adopted, as it is easily implemented using a spreadsheet package. Nash proposed an IUH function based on the response of a number of storage reservoirs in series, generalised into a 2-parameter formula which can reproduce a unit hydrograph form of arbitrary skewness. The general form of the Nash IUH is shown in Figure 4.3.1: broadly the parameter k is a time factor that largely controls the time-to-peak, while the second parameter n controls the skewness. In the Nash IUH formula:

$$Q(0) = \frac{10}{0.036k\Gamma(n)} e^{-t/k} \left(\frac{t}{k}\right)^{n-1} \qquad \text{... Eq. 4.3.5}$$

Table 4.3.1 FSR 0.25-hour unit hydrograph parameters estimated from catchment characteristics

	Subcatchment	Channel slope m/km S1085 (*)	Annual rainfall mm MAR	Stream length km MSL (+)	Time to peak h Tp(0.25)	Peak discharge cu.m/s per 100sq.km Qp(0.25)	Time base h Tb(0.25)
1	Nant y Maesnant Fach & Nant y Moch	83.33	2178	2.00	1.34	164.18	3.38
2	Graig Goch & Maesnant	157.74	2255	1.78	1.07	206.57	2.68
3	Nant y Llyn	85.11	2313	2.35	1.34	164.51	3.37
4	Afon Hengwm	20.14	2319	5.63	2.51	87.79	6.32
5	Afon Hyddgen	24.92	2220	5.35	2.37	92.79	5.97
6	Afon Llechwedd Mawr	10.53	1994	5.70	3.33	65.98	8.40
7	Nant Rhuddlan	19.55	1912	3.75	2.56	86.08	6.44
a		16.31	1950	0.25	1.49	147.21	3.77
b		16.31	2022	0.25	1.47	149.85	3.70
c		16.31	2043	0.25	1.46	150.64	3.68
d		16.31	2193	0.25	1.41	156.00	3.55
e		16.31	1977	0.25	1.48	148.19	3.74
f		16.31	1915	0.25	1.51	145.87	3.80
	Whole catchment	16.31	2124	5.63	2.80	78.52	7.06

* Channel slope for small contributing areas estimated as equal to overall catchment slope.

\+ Mean stream length for small contributing areas estimated at 250 m.
Mean stream length for Afon Hengwm used as an estimate for MSL of whole catchment.

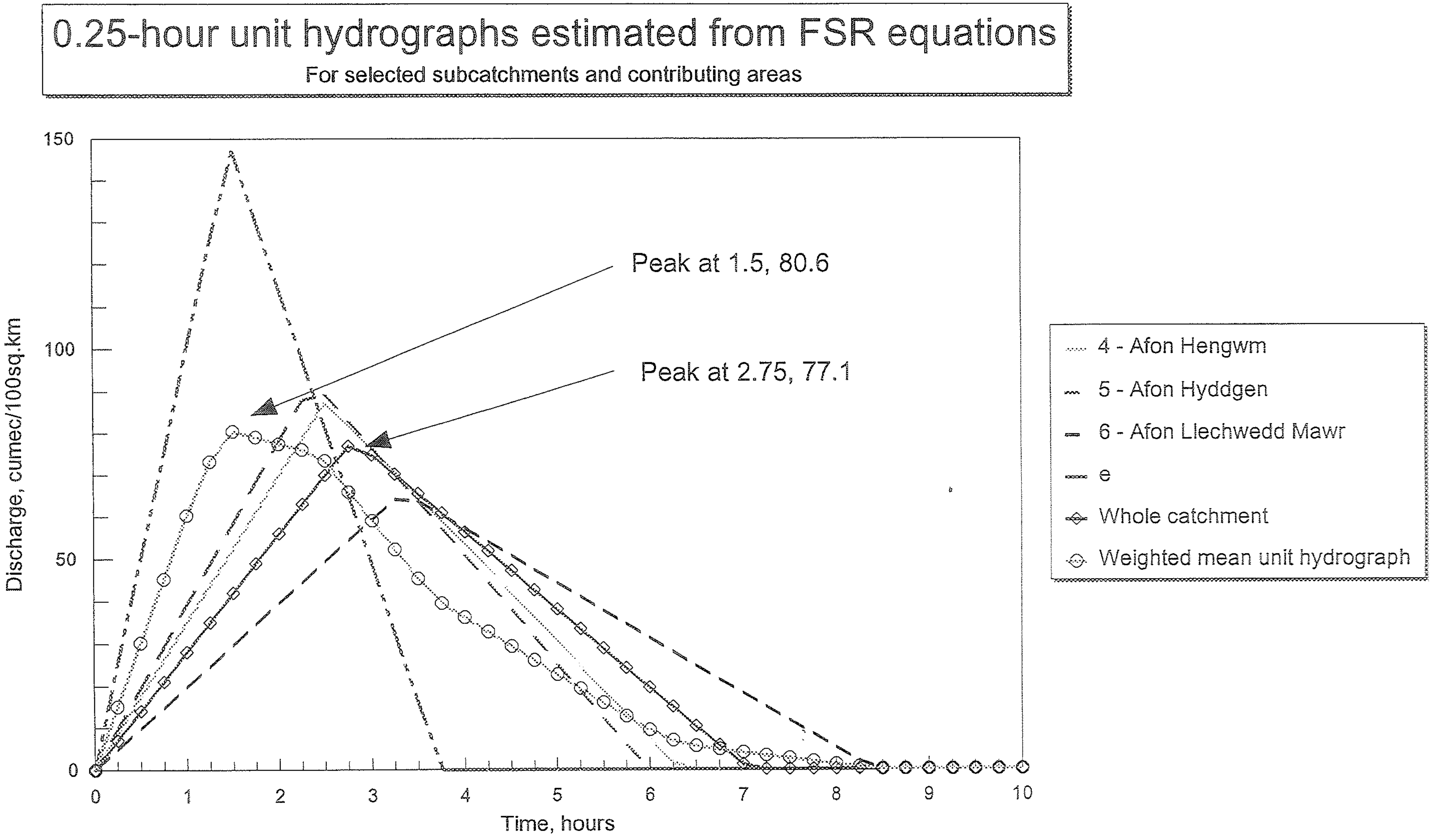


Figure 4.3.2. Unit hydrographs for the Nant y Moch catchment and subcatchments derived from the FSR triangular unit hydrograph.

Table 4.3.2 *Ordinates for 0.25-hour unit hydrographs of Nant y Moch catchment*

Time	Triangular unit hydrograph for whole catchment	Weighted average unit hydrograph
h	cu.m/s per 100 sq.km	cu.m/s per 100 sq.km
0.00	0.00	0.00
0.25	7.01	15.09
0.50	14.01	30.19
0.75	21.02	45.28
1.00	28.02	60.37
1.25	35.03	73.22
1.50	42.03	80.57
1.75	49.04	79.12
2.00	56.04	77.61
2.25	63.05	76.11
2.50	70.06	73.50
2.75	77.06	66.00
3.00	74.87	59.09
3.25	70.26	52.19
3.50	65.65	45.32
3.75	61.04	39.50
4.00	56.43	36.02
4.25	51.82	32.68
4.50	47.21	29.34
4.75	42.60	26.00
5.00	37.99	22.65
5.25	33.39	19.31
5.50	28.78	15.97
5.75	24.17	12.62
6.00	19.56	9.37
6.25	14.95	6.87
6.50	10.34	5.50
6.75	5.73	4.78
7.00	1.12	4.06
7.25	0.00	3.33
7.50	0.00	2.61
7.75	0.00	1.89
8.00	0.00	1.17
Maximum	77.06	80.57

the time-to-peak is equal to

$$Tp(0) = k\,(n - 1) \qquad \text{... Eq. 4.3.6}$$

The parameters were obtained by a moments method originally intended for manual tabulation but ideally suited to the spreadsheet method (Nash 1958). Table 4.3.3 sets out the calculations involved for one event. The steps were as follows:

(a) the quarter-hourly flow record was converted to hourly (to match the rainfall record) using Simpson's rule.

(b) for each point in the flow record, the ratio of Q(t) to Q(t-1) was calculated. When these ratios are plotted against time, it is usually possible to detect a point at which the quick response flow gives way to baseflow (Figure 4.3.3). This point (N) is highlighted by a change in gradient (Wilson 1990, p156).

(c) the baseflow was assumed to rise linearly from the point at which the flow begins to rise up to the point N. The quick response flow (column 3) is the difference between the total flow and the baseflow, and is zero at the start of the rising limb and at point N.

(d) the effective rainfall was calculated by subtracting a "loss rate" which is inversely proportional to the catchment wetness index (CWI). The constant of proportionality, by which column 6 must be multiplied to obtain the loss rate, was initially set by dividing the difference in the sums of columns 4 and 3 by the sum of column 6.

The catchment wetness index

$$CWI = 125 + API5 - SMD \qquad \text{... Eq. 4.3.7}$$

where API5 is the 5-day antecedent precipitation

$$API5 = 0.5^{1/2}\,(P_{d-1} + 0.5\,P_{d-2} + 0.5^2\,P_{d-3} + 0.5^3\,P_{d-4} + 0.5^4\,P_{d-5}) \qquad \text{... Eq. 4.3.8}$$

P_{d-i} is the daily precipitation for each of the 5 preceding days

and SMD is the soil moisture deficit.

(e) for several storms, it was necessary to make minor iterative adjustments to the proportionality coefficient for the loss rate to bring the total effective rainfall more closely into line with the total of the quick response flow.

Table 4.3.3 *Implementation of method of moments to derive parameters of Nash (1958) IUH*

1	2	3	4	5	6	7	8	9	10	11	12
	Total flow	Quick response flow	Rainfall	CWI	Loss rate (1/CWI)	Eff.rainfall	Elapsed time	Time x flow	Time x effective rainfall	Time.sq x flow	Time.sq x rainfall
Day no	mm/hr	mm/hr	mm	mm		mm	hr	mm	mm	mm x hr	mm x hr
28.92	0.16	0.00	0.5	129.6	0.0077	0.00	1	0.00	0.00	0.00	0.00
28.96	0.16	0.00	1.5	129.6	0.0077	0.59	2	0.00	1.19	-0.01	2.38
29.00	0.17	0.01	1.0	135.3	0.0074	0.13	3	0.03	0.40	0.10	1.20
29.04	0.21	0.05	1.5	135.3	0.0074	0.63	4	0.21	2.53	0.82	10.13
29.08	0.27	0.10	0.0	135.3	0.0000	0.00	5	0.51	0.00	2.57	0.00
29.13	0.31	0.15	0.5	135.3	0.0074	0.00	6	0.88	0.00	5.29	0.00
...	...	...	...	...	...	...	...	...	...	...	...
30.42	0.29	0.14	0.0	159.1	0.0000	0.00	37	0.00	0.00	186.82	0.00
30.46	0.28	0.12	0.0	159.1	0.0000	0.00	38	4.59	0.00	174.35	0.00
30.50	0.26	0.11	0.0	159.1	0.0000	0.00	39	4.16	0.00	162.27	0.00
Totals		26.21	43.5		0.1473	27.22		523.00	383.76	11433.84	5913.93
Moments								19.9523	14.0971	436.1964	217.2403

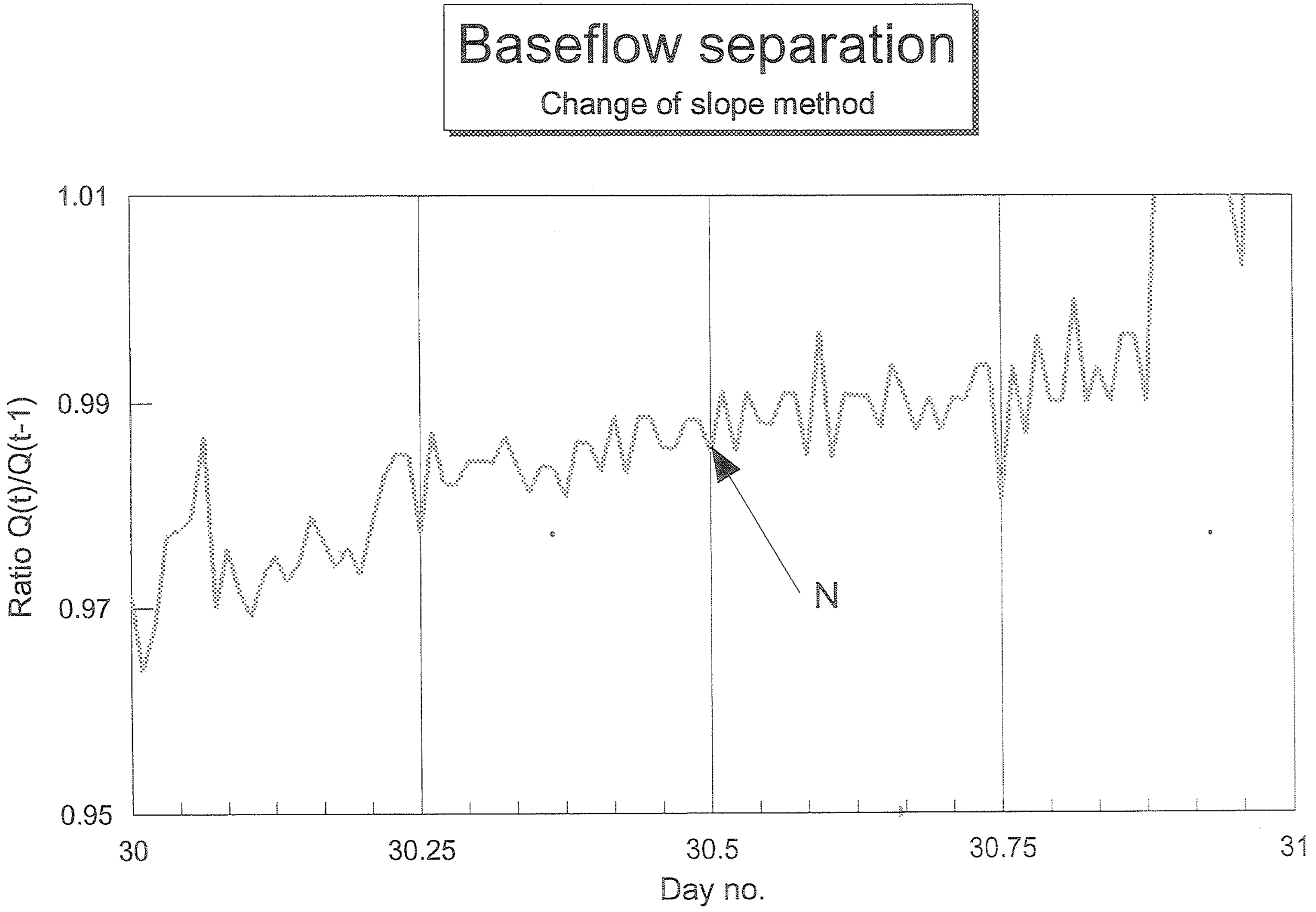


Figure 4.3.3. Baseflow separation by the changing gradient method.

(f) columns 9 to 12 were obtained by computing the products of the effective rainfall and the quick response flow with elapsed time and the square of the elapsed time (e.g. column 12 is equal to the product of column 7 and the square of column 8).

From the totals of the columns, the first and second moments of effective rainfall P and quick response flow Q were computed as:

$m_1(P)$ = sum(column 10) / sum(column 7)
$m_2(P)$ = sum(column 12) / sum(column 7)
$m_1(Q)$ = sum(column 9) / sum(column 3)
$m_2(Q)$ = sum(column 11) / sum(column 3)

The properties of the Nash IUH function are such that

$$nk = m_1(Q) - m_1(P) \qquad \text{... Eq. 4.3.9}$$

$$n(n+1)k^2 = m_2(Q) - m_2(P) - 2\,nk\,m_1(P) \qquad \text{... Eq. 4.3.10}$$

The results for the six events are presented in Table 4.3.4. The time to peak Tp was computed from the parameters k and n (Eq. 4.3.6), and the peak discharge Qp was calculated by setting t equal to Tp in Eq. 4.3.5.

The IUH derived for each event was used in the computation of the one-hour unit hydrograph, which is given by

$$Q(1) = \frac{10}{0.036}\left\{\Gamma(n, \tfrac{t}{k}) - \Gamma(n, \tfrac{t-1}{k})\right\} \qquad \text{... Eq. 4.3.11}$$

where $\Gamma(n, t/k)$ is the incomplete Gamma function.

The time to peak Tp of the one-hour unit hydrograph is given by

$$Tp(1) = \frac{e^{1/k(n-1)}}{e^{1/k(n-1)} - 1} \qquad \text{... Eq. 4.3.12}$$

For each of the six event hydrographs, the appropriate one-hour unit hydrograph

Table 4.3.4 Parameters of Nash instantaneous unit hydrograph for the Maesnant and Maesnant Fach catchments, obtained by the method of moments

Maesnant

Date	k	n	Sum of squares	Time to peak Tp hrs	Peak discharge Qp cu.m/s per 100sq.km
Jan 85	2.727	1.933	0.0301	2.54	38.58
Apr 85	3.291	1.418	0.0102	1.38	43.54
Sep 85	2.155	2.492	0.0977	3.22	39.84
Oct 85	1.483	3.944	0.0741	4.37	42.34
Apr 87	4.228	1.089	0.2530	0.38	50.7
Dec 88	5.344	1.352	0.0342	1.88	28.41
Weighted mean	3.047	1.641		1.95	40.18

Maesnant Fach

Date	k	n	Sum of squares	Time to peak Tp hrs	Peak discharge Qp cu.m/s per 100sq.km
Jan 85	2.757	1.801	0.0272	2.21	40.64
Apr 85	2.702	1.794	0.0214	2.15	41.61
Sep 85	2.925	1.757	0.0733	2.21	39.19
Oct 85	2.088	2.583	0.0471	3.31	40.05
Apr 87	3.646	1.307	0.0423	1.12	43.51
Dec 88	5.497	1.167	0.0283	0.92	34.19
Weighted mean	3.125	1.615		1.92	39.81

was applied to the effective rainfall to predict the quick response flow. Figure 4.3.4 shows the typical level of agreement between observed and predicted flows. The sum of squares of the deviations between observed and predicted flow, a measure of the closeness of fit, was then used in the calculation of weighted averages of Tp and Qp, the weight attached to each value being inversely proportional to the sum of squares of deviations. It should be noted that the IUH was not itself found using a least-squares method.

A "backsolver" routine of the spreadsheet package, which solves implicit equations iteratively, was then used to estimate the values of parameters k and n which matched the weighted average Tp and Qp. This procedure, which follows in principle the recommendation of Wilson (1990, p166), was found to give values of k and n which were in keeping with the observed distribution of individual k and n values (Figure 4.3.5).

For flood predictions on the Nant y Moch catchment using the "design storm" approach, it was decided to use a time interval of 0.5 hour, and for this the 0.5-hour unit hydrograph was required.

The Nash 0.5-hour unit hydrograph function is

$$Q(0.5) = \frac{10}{0.036 \times 0.5}\left\{\Gamma(n, \tfrac{t}{k}) - \Gamma(n, \tfrac{t-0.5}{k})\right\} \qquad \text{... Eq. 4.3.13}$$

with time to peak given by

$$Tp(0.5) = 0.5\frac{e^{0.5/k(n-1)}}{e^{0.5/k(n-1)} - 1} \qquad \text{... Eq. 4.3.14}$$

The ordinates of the weighted mean IUH's and 0.5-hour unit hydrographs for the Maesnant and Maesnant Fach catchments are presented in Table 4.3.5. Figures 4.3.6 and 4.3.7 show the IUH's for the six rainfall events, and the weighted IUH's for the two catchments. Note that the time to peak of the 0.5-hour unit hydrograph is approximately 0.25 hours longer than that of the IUH. This is consistent with the approximate rule given in the FSR. Figure 4.3.8 presents the data contained in Table 4.3.5 in graphical form.

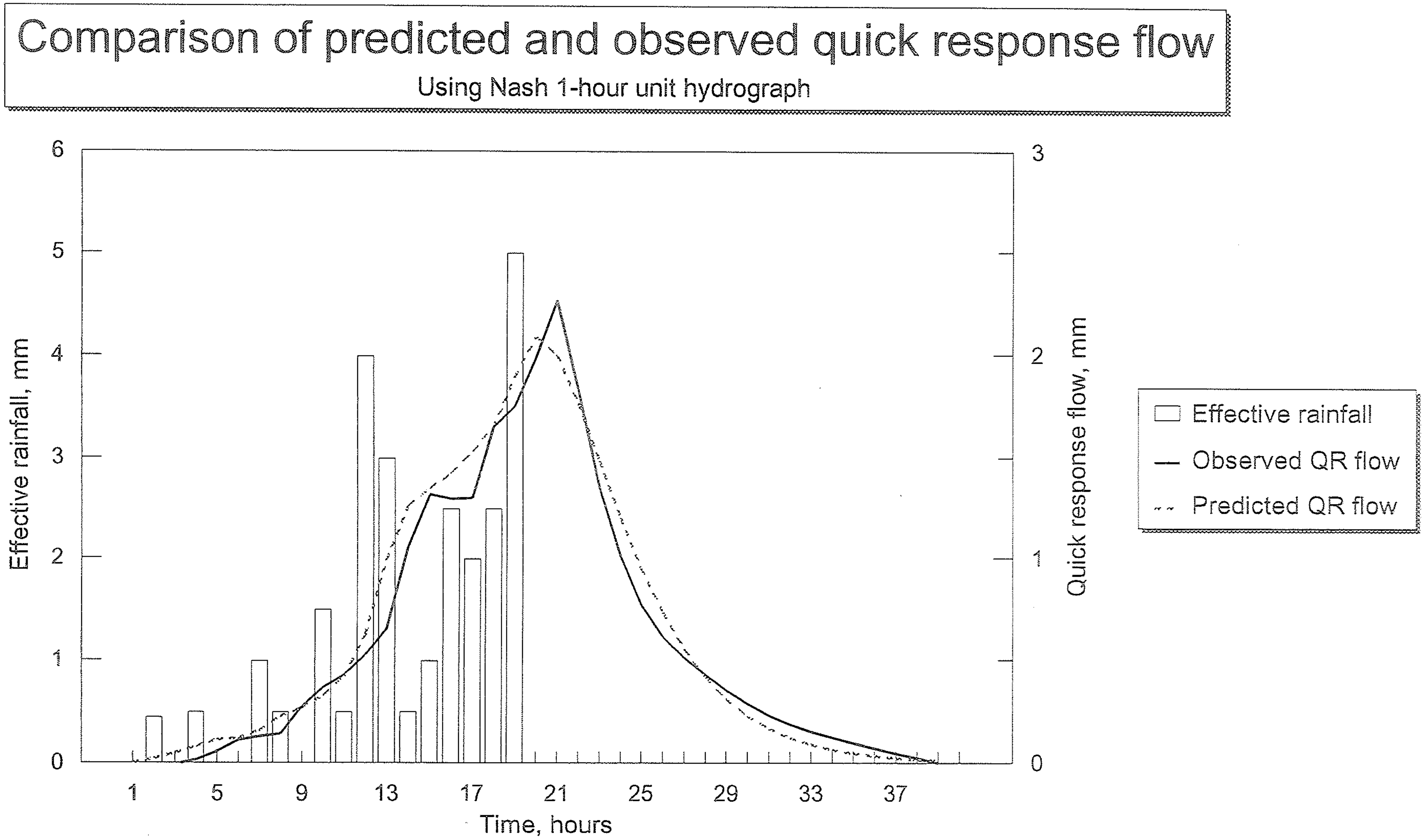


Figure 4.3.4. Comparison of observed and predicted flows for a typical rainfall event on the Maesnant subcatchment.

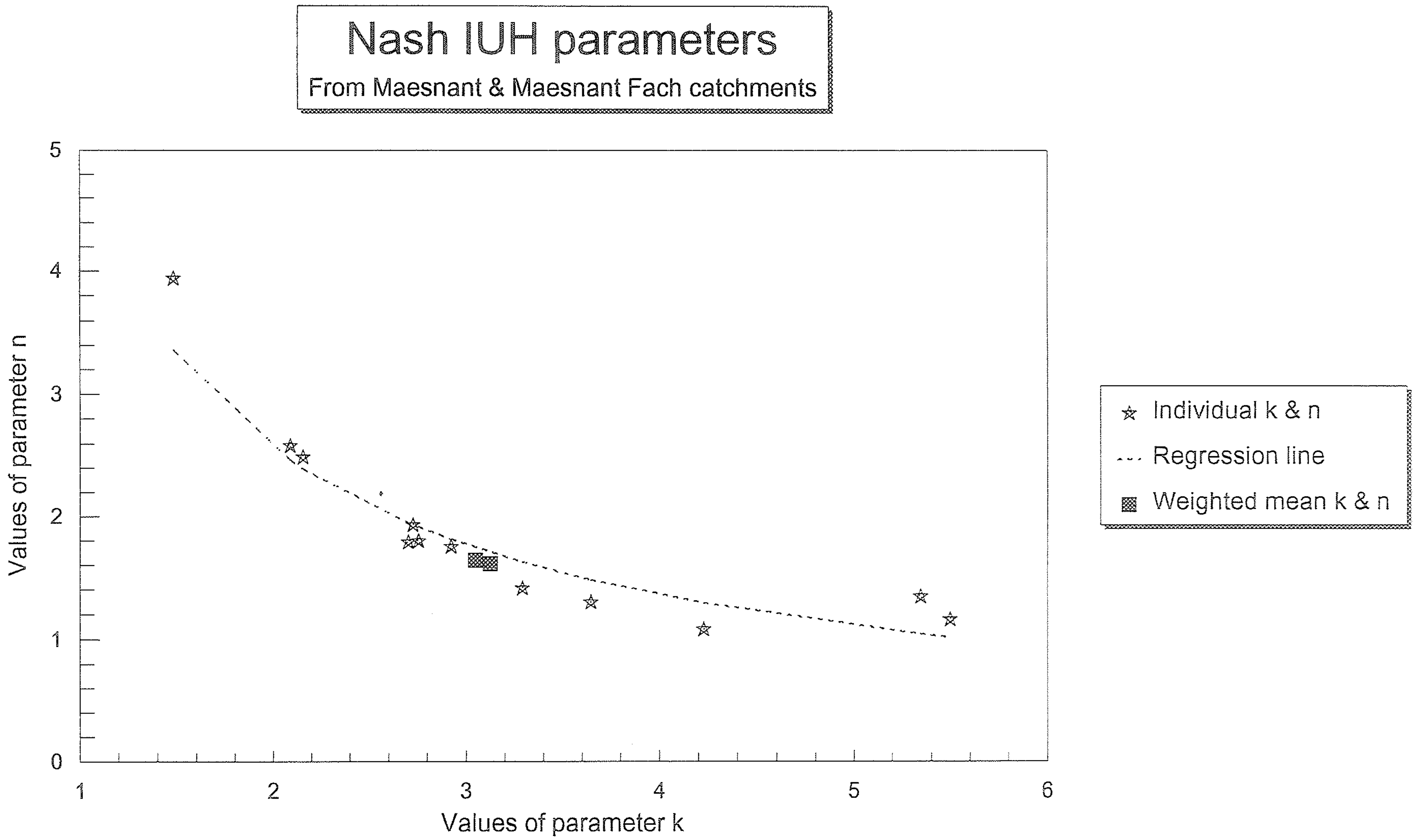


Figure 4.3.5. The range of parameter values for the Nash instantaneous unit hydrograph.

Table 4.3.5 *Ordinates of Nash IUH's and 0.5-hour unit hydrographs for the Maesnant and Maesnant Fach catchments*

Time hrs	IUH		0.5-hour unit hydrograph	
	Maesnant	Maesnant Fach	Maesnant	Maesnant Fach
0.00	0.00	0.00	0.00	0.00
0.25	18.80	19.40	5.91	6.20
0.50	27.02	27.42	17.53	18.07
0.75	32.28	32.48	26.54	26.94
1.00	35.76	35.79	31.99	32.19
1.25	38.01	37.89	35.56	35.59
1.50	39.36	39.13	37.86	37.75
1.75	40.03	39.71	39.25	39.02
2.00	40.17	39.79	39.94	39.62
2.25	39.91	39.49	40.10	39.73
2.50	39.33	38.89	39.86	39.44
2.75	38.52	38.07	39.29	38.85
3.00	37.52	37.07	38.49	38.04
3.25	36.38	35.95	37.50	37.05
3.50	35.15	34.73	36.37	35.93
3.75	33.84	33.45	35.14	34.72
4.00	32.50	32.13	33.84	33.44
4.50	29.74	29.43	31.12	30.78
5.00	27.00	26.76	28.37	28.09
5.50	24.36	24.18	25.67	25.46
6.00	21.86	21.74	23.10	22.95
6.50	19.53	19.46	20.68	20.58
7.00	17.38	17.35	18.44	18.39
7.50	15.42	15.43	16.38	16.38
8.00	13.64	13.68	14.51	14.54
8.50	12.03	12.10	12.82	12.88
9.00	10.59	10.68	11.30	11.38
9.50	9.30	9.41	9.94	10.03
10.00	8.16	8.27	8.72	8.83
11.00	6.25	6.37	6.69	6.81
12.00	4.76	4.88	5.10	5.22
13.00	3.61	3.72	3.87	3.99
14.00	2.72	2.72	2.93	3.03
15.00	2.05	2.05	2.20	2.30
Time to peak	1.95	1.92	2.21	2.18
Peak discharge	40.18	39.81	40.04	39.68

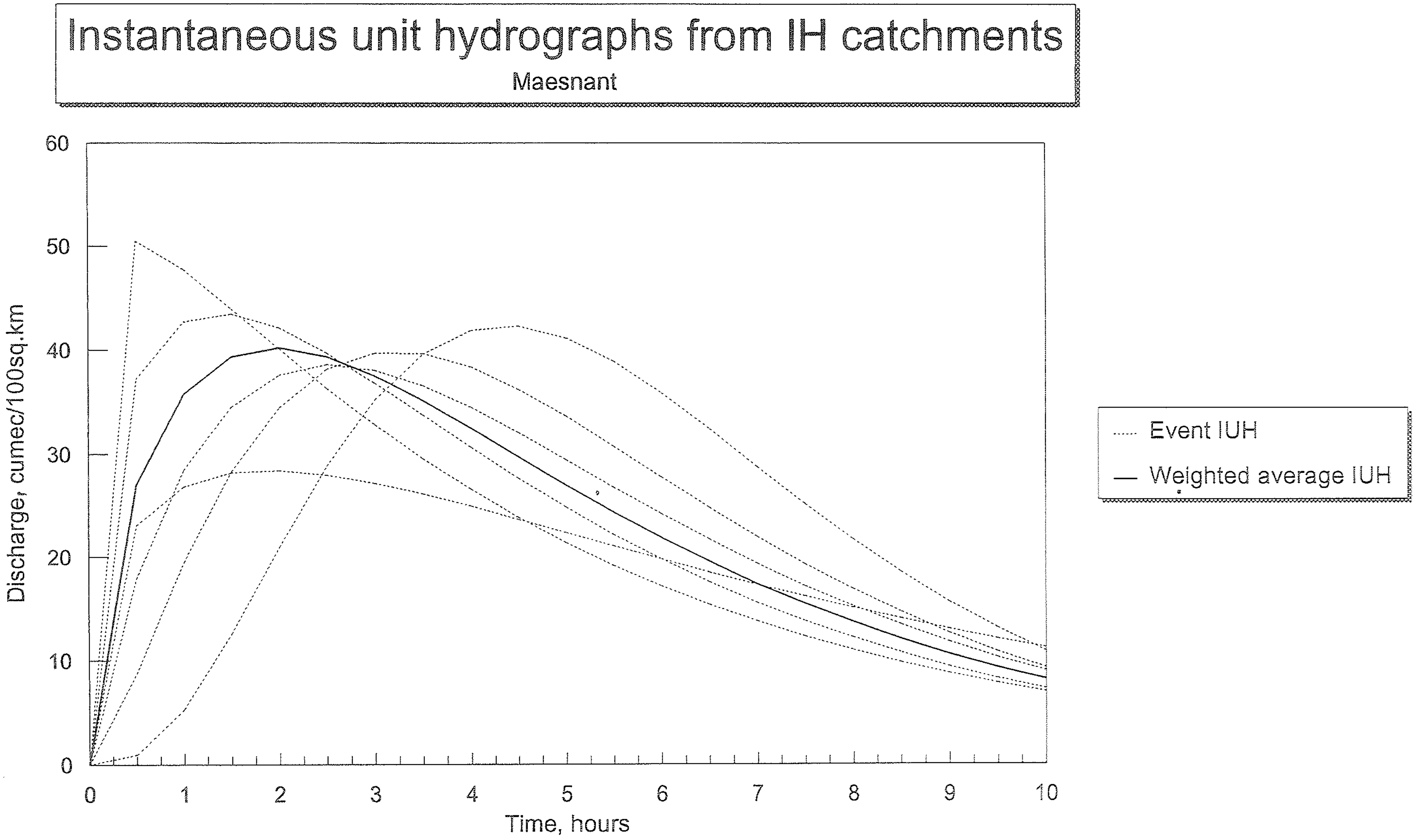


Figure 4.3.6. Instantaneous unit hydrographs for the Maesnant catchment.

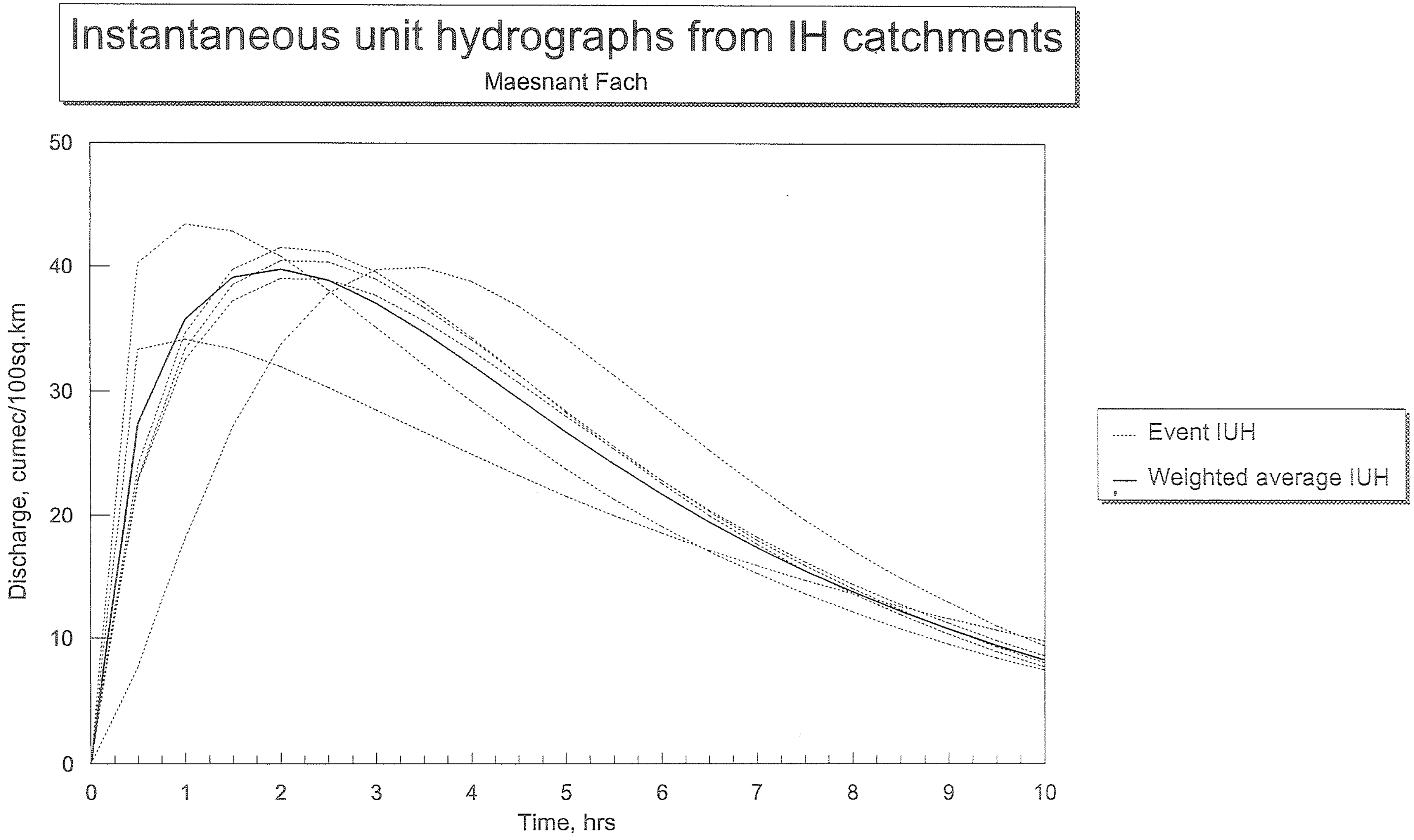


Figure 4.3.7. Instantaneous unit hydrographs for the Maesnant Fach catchment.

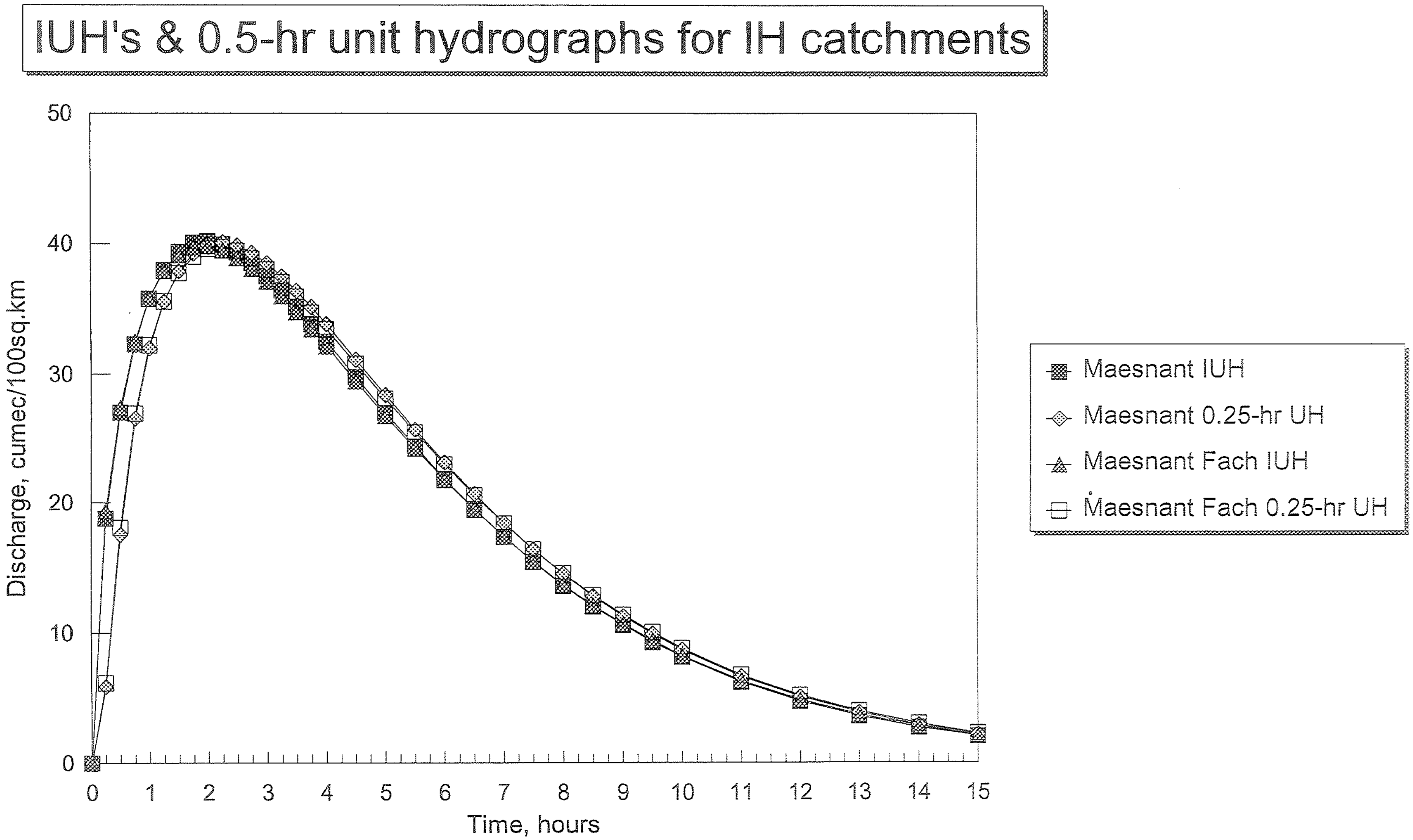


Figure 4.3.8. Comparison of the IUH and the 0.5-hour unit hydrographs for the Maesnant and Maesnant Fach.

4.3.3 Extension to the other Nant y Moch subcatchments

To extend the results of the previous section to ungauged catchments, a simple method is required relating the unit hydrograph parameters to suitable catchment characteristics. It was decided to use the empirical FSR equation expressing the time to peak in terms of the stream slope, the rainfall and the stream length (Eq. 4.3.1), modifying the coefficient 283.0 to match the results of the analysis of the IH catchment data. In this way it was possible to go some way towards incorporating the local data into the prediction process.

Applying the FSR equation to the Maesnant and Maesnant Fach catchments (Table 4.3.6), the required values of the coefficient are found to be

283 x 1.95/0.907 = 608, using the Maesnant time-to-peak as a standard

or 283 x 1.92/0.990 = 549, using the Maesnant Fach.

It is clear at this stage that flood discharges estimated using the Nash unit hydrographs will be smaller than those estimated from the triangular unit hydrographs, which have a shorter time-to-peak and less skew.

Based on the time-to-peak calculated for the Maesnant catchment, and on the computation of the time-to-peak of the FSR triangular unit hydrograph calculated from Equation 4.3.1, it is possible to make an estimate of the time-to-peak of the Nash IUH and T-hour unit hydrograph for each of the subcatchments and contributing areas of the Nant y Moch catchment. Table 4.3.7 shows the time-to-peak of the 0.5-hour Nash unit hydrograph for each of the subcatchments and contributing areas, based on the assumption that the Nash Tp(0) is proportional to the time-to-peak calculated from Equation 4.3.1, and that the time-to-peak of the Nash 0.5-hour unit hydrograph is 0.25 hours longer than that of the IUH.

To compute the ordinates of the Nash 0.5-hour unit hydrograph, it is necessary to have estimates of the parameters k and n, but these can be obtained only by making a further assumption. In the absence of better information, it was assumed that the parameter n, which is an expression of the skewness of the hydrograph, does not change across the Nant y Moch catchment, and hence the value of n derived for the Maesnant catchment was used throughout. For each subcatchment and contributing area the parameter k of the Nash 0.5-hour unit hydrograph was adjusted iteratively so that the time-to-peak computed from Equation 4.3.14 matched Tp(0.5) as derived from Equation 4.3.1 and modified in the light of the Maesnant data.

Table 4.3.8 presents the results of basing the same calculations on the Maesnant

Table 4.3.6 *Empirical FSR equation (4.3.1) applied to Maesnant and Maesnant Fach catchments to determine parameters of triangular IUH for the two IH experimental catchments*

Subcatchment	Channel slope	Annual rainfall	Stream length	Time to peak	Peak discharge	Time base
	m/km	mm	km	h	cu.m/s per 100sq.km	h
	S1085	MAR	MSL	Tp	Qp	Tb
Maesnant	126.8	2267.3	1.125	0.907	242.60	2.29
Maesnant Fach	113.3	2089.1	1.175	0.990	222.22	2.49

Note: to match the time-to-peak determined using the Nash unit hydrograph analysis, the coefficient in equation 4.3.1 would have to be increased from 283 to 608 (Maesnant) or 549 (Maesnant Fach), and the peak discharge estimated by this method is several times the peak value of the Nash 0.5-hour unit hydrograph.

Table 4.3.7 0.5-hour Nash unit hydrograph parameters estimated from FSR time-to-peak, using Maesnant as a basis

	Subcatchment	FSR time-to-peak Tp(0)	Estimated time-to-peak of Nash 0.5-hour unit hydrograph	Parameters of Nash 0.5-hour unit hydrograph	Peak discharge of Nash 0.5-hour unit hydrograph
				n = 1.615	
				k=	
1	Nant y Maesnant Fach & Nant y Moch	1.22	2.87	4.24	29.29
2	Graig Goch & Maesnant	0.94	2.01	2.84	43.75
3	Nant y Llyn	1.21	2.59	3.79	32.75
4	Afon Hengwm	2.38	5.11	7.89	15.75
5	Afon Hyddgen	2.25	4.82	7.42	16.76
6	Afon Llechwedd Mawr	3.21	6.89	10.8	11.52
7	Nant Rhuddlan	2.43	5.22	8.07	15.41
a		1.37	2.93	4.35	28.6
b		1.34	2.87	4.25	29.22
c		1.34	2.86	4.23	29.4
d		1.29	2.75	4.05	30.68
e		1.36	2.91	4.31	28.83
f		1.38	2.96	4.39	28.28

Table 4.3.8 0.5-hour Nash unit hydrograph parameters estimated from FSR time-to-peak, using Maesnant Fach as a basis

	Subcatchment	FSR time-to-peak Tp(0)	Estimated time-to-peak of Nash 0.5-hour unit hydrograph	Parameters of Nash 0.5-hour unit hydrograph	Peak discharge of Nash 0.5-hour unit hydrograph
				n = 1.641	
				k=	
1	Nant y Maesnant Fach & Nant y Moch	1.22	2.61	3.66	33.37
2	Graig Goch & Maesnant	0.94	1.83	2.45	49.87
3	Nant y Llyn	1.21	2.36	3.28	37.31
4	Afon Hengwm	2.38	4.63	6.82	17.94
5	Afon Hyddgen	2.25	4.37	6.41	19.08
6	Afon Llechwedd Mawr	3.21	6.24	9.33	13.12
7	Nant Rhuddlan	2.43	4.72	6.97	17.55
a		1.37	2.66	3.75	32.58
b		1.34	2.61	3.67	33.28
c		1.34	2.6	3.65	33.5
d		1.29	2.5	3.5	34.95
e		1.36	2.65	3.72	32.84
f		1.38	2.69	3.8	32.22

Fach catchment characteristics and Nash parameters.

The values of k and n for each subcatchment and contributing area (two series based on the Maesnant and Maesnant Fach) were used in Equation 4.3.13 to provide 0.5-hour ordinates of a Nash 0.5-hour unit hydrograph for each subcatchment and contributing area. For each of the two series of parameter values, these hydrographs were then used in the computation of a weighted mean unit hydrograph for the whole Nant y Moch catchment. The two resulting 0.5-hour unit hydrographs are shown in Figure 4.3.9.

4.3.4 Prediction of flood peaks using the triangular unit hydrograph

For the whole Nant y Moch catchment, the triangular unit hydrograph shown in Figure 4.3.2 was used to simulate the quick response flow generated by a design storm of various magnitudes, to develop a sequence of peak discharges for given return periods. The procedure used was laid down by the FSR (pp458-469).

Time to peak of 0.25-hour unit hydrograph: 2.75 hours

Data interval (must be less than Tp/5): 0.5 hours

Design storm duration : (1 + SAAR/1000)Tp
= 8.59 hours
Take nearest odd integer multiple of Tp: 8.5 hours

For computation of 50-year flood, use the 8.5-hour rainstorm of 80-year return period (FSR provides graphical basis for this stage on p464, Wilson 1990 gives a clearer graph on p182).

For the Nant y Moch catchment, the ratio r of 60-minute M5 rainfall to 2-day M5 rainfall is taken from the map in the FSR.

$$r = 19\%$$

The ratio of 8.5-hour M5 rainfall to 2-day M5 rainfall is found by entering Table II.3.10 of the FSR or Wilson's (1990) Table 2.9 with this value of r.

Ratio 8.5-hour M5 to 2-day M5: 48.6%

2-day M5 rainfall: 120 mm (see section 3.2)

8.5-hour M5 rainfall: 48.6 x 120 / 100 = 58.3 mm

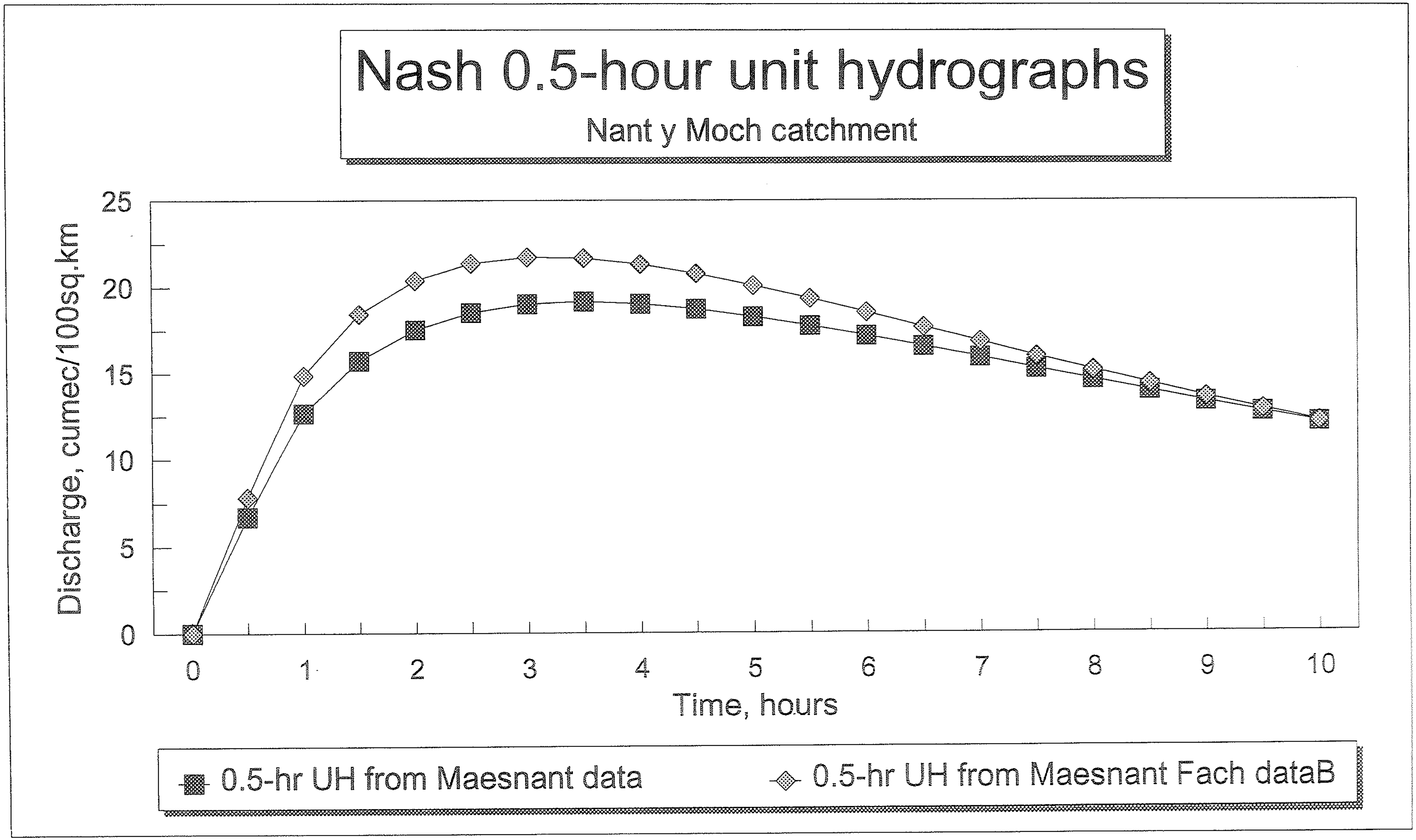


Figure 4.3.9. Unit hydrographs for the Nant y Moch catchments.

Growth factor M80/M5
(from FSR Table II.2.7 or Wilson Table 2.6: 1.67

8.5-hour M80: 97.4 mm

Areal reduction factor (for duration 8.5 hours
and a catchment area of 54.94 sq.km): 0.92

Total rainfall for design storm (P): 89.6 mm

Catchment wetness index (CWI): 127 mm
(from FSR Figure I.6.62)

Soil index (SOIL): 0.5

Standard percentage runoff (SPR): 95.5 SOIL + 0.12 URBAN
= 47.8%

Runoff percentage for design storm: SPR + 0.22(CWI - 125) + 0.1(P - 10)
= 47.8 + 0.22(127 - 125) + 0.1(89.6 - 10)
= 56.2%

Net rainfall: 89.6 x 56.2 / 100 = 50.3 mm

The design storm is derived from the 75% winter storm profile (FSR Figure I.6.65 or Wilson Figure 2.17). This is a symmetric profile of net rainfall which is on average more peaked than 75% of all winter storm profiles.

For an 8.5-hour storm, the rainfall in half-hour increments is given in table 4.3.9.

The catchment's response to the design flood is obtained by convoluting the design rainfall with the 0.5-hour unit hydrograph:

$$Q(t) = \sum_{0}^{\infty} P(t-\tau)U(\tau) \qquad \text{... Eq. 4.3.15}$$

where P(t) is rainfall
U(t) is the unit hydrograph
and Q(t) is the quick response flow.

Table 4.3.9. Distribution of net rainfall into half-hourly increments for an 8.5-hour design storm.

Time	Rainfall
0.5	0.50
1.0	1.01
1.5	1.26
2.0	1.51
2.5	2.52
3.0	3.02
3.5	4.53
4.0	6.79
4.5	8.05
5.0	6.79
5.5	4.53
6.0	3.02
6.5	2.52
7.0	1.51
7.5	1.26
8.0	1.01
8.5	0.50

The results of the computation outlined above are presented in Figure 4.3.10. The peak discharge for the 50-year flood is 137.9 cumecs, to which should be added an average non-separated flow of

$$\begin{aligned} & 0.00033\ (\text{CWI} - 1125) + 0.00074\ \text{RSMD} + 0.003\ \text{cumec/sq.km} \\ = \quad & 0.0030 \times 54.94\ \text{cumec} \\ = \quad & 3.36\ \text{cumec} \end{aligned}$$

The 50-year flood is therefore

$$137.9 + 3.36 \qquad = \qquad 141.3\ \text{cumec}$$

4.3.5 Prediction of flood peaks using other unit hydrographs

The procedure of the previous section was followed for the weighted mean unit hydrograph derived in section 4.3.1 from the FSR triangular unit hydrographs for

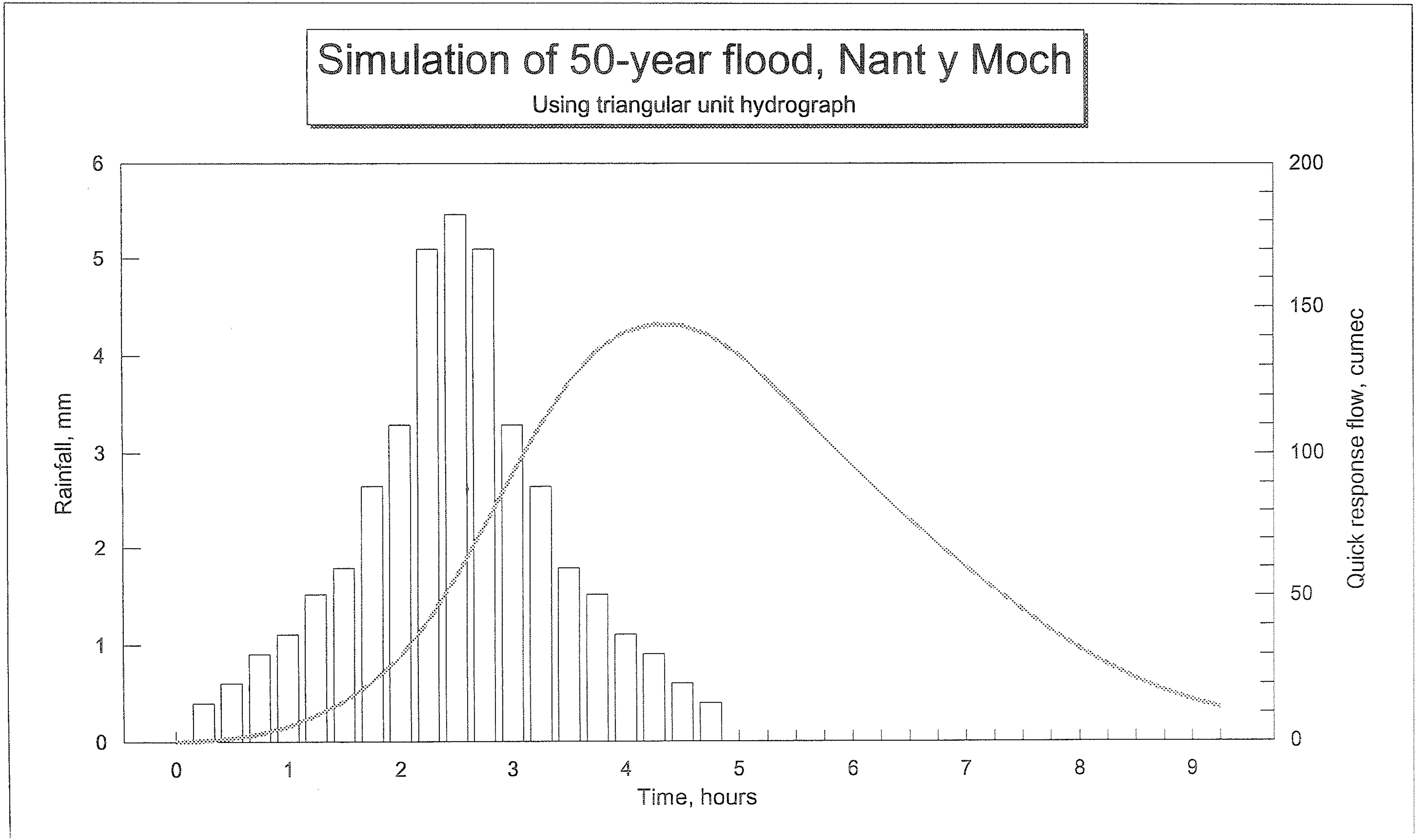


Figure 4.3.10. 50 year flood simulated using the triangular unit hydrograph.

each subcatchment (Table 4.3.2), using a time interval of 0.25 hours, and for the weighted mean Nash unit hydrographs (Figure 4.3.9) using a time interval of 0.5 hours. The results, in the form of estimates of flood magnitudes for a range of return periods, are presented in Table 4.3.10. For the triangular unit hydrograph only, the PMF was estimated by convoluting the design storm with a total rainfall equal to the PMP (Table 3.3) with a modified unit hydrograph whose time-to-peak was two thirds of the value computed from equation 4.3.1.

Table 4.3.10 Estimated magnitude of floods of various return periods

Return period	Peak discharge, cumec			
	0.25-hour triangular UH	0.25-hour weighted mean UH	Nash 0.5-hour UH	
	Computed from FSR formula (Eq. 4.3.1)	Computed from subcatchment triangular UH's	Computed from Maesnant catchment data	Computed from Maesnant Fach catchment data
5 years	85.8	87.1	34.7	36.6
10 years	104.2	105.1	41.5	44.1
50 years	141.3	147.4	54.6	58.7
100 years	154.8	161.5	59.5	63.8
500 years	189.0	201.3	72.2	77.7
1000 years	243.8	263.5	91.7	99.0
5000 years	315.8	347.6	117.2	127.3
10000 years	413.8	392.9	151.4	165.8
Half PMF				
PMF	822.7			

4.4 A comparison of estimates of flood return periods

As flow data is only available for the Maesnant and Maesnant Fach, a direct comparison of the unit hydrograph method of flood estimation with the catchment characteristics regression method is possible for this small area only. To put this in context, the Maesnant covers only 1% of the Nant y Moch catchment and, even then, is only truly representative of the steeper catchments draining from Plynlimon. It is thus unwise to use the unit hydrograph parameters derived from Maesnant to extrapolate directly to the whole of the Nant y Moch catchment. The difficulty is highlighted in table 4.3.10, where the unit hydrograph based on real flow data is in both cases giving a flow at Nant y Moch for a given return period approximately 40% of that using the FSR unit hydrograph methods.

The reason for this lies in the length of the tail of the unit hydrographs derived for the IH catchments, which has the effect, for a given volume of flow, of reducing the peaks to compensate. It is not altogether clear why the quickflow response should be so much slower than would be predicted by the FSR equations, but it may be linked to the deeper than average soils for a catchment of this type, the prevalence of soil piping which contributes to flow resistance, and to the channels themselves which are characterised by a stepped profile of riffles or waterfalls and pools which can contribute substantially to flow resistance particularly for the moderate floods experienced during the study period. Flow resistance will decline during higher floods but as these did not occur during the study period the derived unit hydrograph parameters will have been biassed towards smaller floods with high flow resistance.

A comparison with results from the Cefn Brwyn gauging station on the River Wye (catchment area 10.5 km^2), taken from the FSR Volume IV (Hydrological Data), suggests that the long tail of the unit hydrograph may be a feature of steep mountain catchments. The Wye experimental catchment upstream of Cefn Brwyn has an S1085 of 36.3 $m.km^{-2}$ (Kirby et al 1991), and shows a unit hydrograph time-to-peak of around 2 hours with a peak unit hydrograph discharge of 66.3 cumec/100 km^2 (Table 4.3.11). The timebase of the unit hydrograph is about five times the time-to-peak, compared with the factor of 2.52 built into the FSR triangular unit hydrograph.

It has also been possible to use a combination catchment characteristics and unit hydrograph approach to interpret the difference between the whole catchment and lumped subcatchment estimates of MAF given in section 4.2. If it is assumed that the peak flows derived for each subcatchment are the best estimates available, and that the time of arrival at the reservoir of each flood peak is well described by the unit hydrograph lag, T(p), it is possible to determine a MAF from a weighted mean of the subcatchment unit hydrographs. This weighted mean estimate of the MAF takes into account the phase differences between flood waves generated by the various subcatchments:

$$MAF = Max \sum (Q_i / q_{pi}) \, q_i(t) \qquad \text{...eq. 4.4}$$

where: Q_i is the MAF for subcatchment i
$q_i(t)$ is the unit hydrograph flow at time t for subcatchment i
q_{pi} is the unit hydrograph peak flow for subcatchment i

Table 4.3.11 *Unit hydrograph data for River Wye at Cefn Brwyn (FSR Volume IV)*

Date of event	UH peak discharge cumec/100sq.km	UH time to peak hours	UH width at 0.5 peak hours	UH timebase hours
12.5.68	56.6	2.4	3.9	11.8
24.5.68	54.0	4.5	4.3	12.0
24.6.68	77.0	2.3	3.5	7.4
26.6.68	66.0	2.3	3.1	10.6
2.7.68	58.0	1.9	3.1	13.0
19.9.68	61.0	1.5	2.8	12.6
28.9.68	83.0	1.6	1.8	9.8
2.10.68	64.0	1.7	2.9	11.6
22.11.68	68.0	1.2	3.2	10.0
26.11.68	58.6	2.5	2.8	13.4
19.12.68	56.0	1.5	3.0	13.9
19.1.69	48.0	1.5	4.5	14.2
30.3.69	70.0	1.3	2.4	11.1
10.4.69	85.0	2.2	2.4	8.3
14.4.69	64.0	2.4	3.0	11.4
25.4.69	56.6	1.8	2.9	13.8
2.6.69	64.0	1.8	2.8	11.8
10.9.69	74.0	2.7	2.7	9.6
21.9.69	100.0	1.3	2.2	6.7
19.2.70	48.0	3.0	5.5	12.2
5.4.70	73.0	1.7	2.8	9.6
21.4.70	56.5	2.1	3.6	12.5
15.8.70	76.4	1.8	2.5	9.6
9.9.70	88.0	1.7	1.9	8.8
27.10.70	63.0	1.9	2.7	12.3
1.11.70	55.0	1.4	2.9	14.4
Mean	66.3	2.0	3.0	11.2

gives an MAF of 58.8 m^3 sec^{-1}, which is much less than the direct sum of the MAF's for the subcatchments (78.5 m^{3}sec^{-1}), and even less than the estimate of 65.2 m^3 sec^{-1} from the whole catchment regression equation. Thus the varying lags of the subcatchments allow the peak discharges from the steep but small subcatchments and polygonal contributing areas to be routed through the lake before the main combined peak from the larger but flatter northerly catchments arrives. This attenuation effect is of course already implicit in the whole-catchment approach because it is based on empirically-derived relationships obtained from real flow data, which will tend to have come from symmetrical and lenticular catchments.

5. Conclusions and Recommendations

Using rainfall data collected since Nant y Moch reservoir was constructed, as part of the Rheidol scheme, it has proved possible to re-assess the return periods of rainfall and, hence, floods entering the reservoir from the Nant y Moch catchment. A rainfall model, developed by relating rainfall distribution to altitude and longitude, has been shown to estimate catchment annual rainfall and also daily rainfall effectively. Ranking analysis suggests that the 1 day rainfall with a 5 year return period (1D-M5) for Nant y Moch is 80.8mm, which agrees almost exactly with the figure from the Flood Studies Report 2D-M5 when this is converted to 1D-M5 and an areal reduction factor applied. Regional growth curves related to 1D-M5 suggest that the probable maximum daily precipitation is 350mm. There is little evidence therefore that the Flood Studies Report estimates are significantly improved by introducing local rainfall data.

Floods in the main and lumped sub-catchments have been estimated using the FSR regression method on catchment characteristics. Sensitivity analysis using various different options for catchment characteristics suggests that the estimate of MAF is sensitive to the stream slope used (S1085), particularly in multi-limbed catchments like Nant y Moch where the estimate from the main limb can be ambiguous. Stream network density (STRMFRQ) also significantly affects the MAF, but its derivation for Nant y Moch is less ambiguous than S1085. In general the regression method seems to be more affected by characteristics that describe the routing of the flood than by those (AREA and 1D-M5) that dictate the volume of flood flow.

The best estimate of MAF for the 54.94 km^2 catchment is 65.2 m^3 sec^{-1}. This value is considered to be a more realistic estimate than the arithmetic lumping of subcatchments because the latter cannot allow for non-coincidence of flood peaks from the subcatchments as they enter the lake. However, it has been possible using a combined approach to offset the peak discharges for the subcatchments derived from the FSR regression method using the triangular unit hydrograph time to peak values for the same catchments. When the hydrographs are added, this gives a peak flow of 58.8 m^3 sec^{-1}, which is reasonably close to the whole catchment estimate.

The rainfall-runoff modelling approach has also been adopted where data availability permits, i.e. the 0.56 km^2 Maesnant catchment and the 0.80 km^2 Maesnant Fach, but it is felt that the huge discrepancy in areas (each catchment covers only about 1% of the Nant y Moch catchment and is not representative of the low gradient streams which comprise most of the catchment) make it impractical to use the unit hydrograph parameters derived to predict floods directly in the main catchment. Furthermore, a comparison of the FSR unit hydrograph parameter prediction method, using catchment characteristics, with the real analysis of Maesnant and Maesnant Fach data suggests that local flow processes in these steep catchments may result in more delay in runoff than is typical of the remainder of the Nant y Moch catchment. Only the installation of a gauging station on one of the more important tributaries would resolve this question. It is probable that the unit hydrograph parameters estimated from the FSR equations are reasonable for the other subcatchments, but data from the upper Wye catchment indicate that the simple triangular unit hydrograph with its pre-defined skewness may not be an appropriate choice.

The use of updated regional growth factors from FSR supplementary reports related to MAF indicates that the 10 year, 100 year, and 1000 year floods are 92.6, 142.2 and 208.1 $m^3.sec^{-1}$ respectively. The regional growth factor technique does not lend itself to estimation of the probable maximum flood. A regression equation is recommended by the FSR as a crude first estimate, and this gives an estimated PMF of 650 $m^3.sec^{-1}$. Using the unit hydrograph rainfall-runoff approach indicates that a value of 820 $m^3.sec^{-1}$ may be more appropriate.

No attempt has been made at this juncture to route these floods through the reservoir, either by incorporating a lag to the unit hydrograph, or by introducing flow over the existing spillway. It has been a policy within this study to give Powergen the benefit of independent estimates of flood return periods that are not coloured by a prior knowledge of the flood estimates used for the original design of the scheme, by the present control rules or by the operation and rating of the existing spillway. Philosophically, this would be best treated as a separate investigation which will require modelling of the floods through the reservoir. This would involve an iterative optimisation of spillway size and drawdown recommendations that will depend heavily on the shape of the hydrograph at the reservoir, i.e. the persistence of peak or near-peak flows, as well as volume flow and absolute peak flow.

It has become apparent in the course of this study that a considerable improvement in the reliability of flood estimates could be secured by improvements to the hydrometric networks within the catchment. In particular, we would strongly recommend the installation of a recording raingauge near the centroid of the catchment and a flow gauging structure on one of the larger tributaries. A relatively short run of data from a new gauging station and a re-instated Maesnant structure would help to define the spatial variation in unit hydrograph parameters, and provide a firm basis for further refinement of the flood estimates.

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