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AN ASSESSMENT OF THE FSR RAINFALL-RUNOFF METHOD OF DESIGN FLOOD ESTIMATION

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ABSTRACT

The Flood Studies Report, FSR, and its Supplementary Reports provide widely used techniques for design flood estimation in UK catchments. There has been considerable debate on the accuracy of the various methods, but few of the objections have been substantiated. This report describes work aimed at providing authoritative comparisons between flood estimates derived from observed flood data and

- the original FSR rainfall-runoff method,
- the FSSR16 rainfall-runoff method,
- the FSSR16 method with observed data, and
- the FSR statistical method ($\bar{Q}$ equation plus regional growth curve).

The analysis was performed on a set of 88 catchments which had at least 15 years of annual maximum peak flow data (to generate the observed flood frequency relationships), and detailed rainfall and runoff data describing five or more flood events (to provide parameter estimates to replace those obtained from catchment characteristics). Comparisons were made for all catchments and all return periods (2, 5, 10, 25 and 50 years), for various subsets of catchments, and for return periods below a limit specified separately for each catchment. Results show that estimates made using the statistical method were unbiassed, while the rainfall-runoff methods, used without considering hydrological data recorded at the site, had a tendency to overestimate. This bias was reduced virtually to zero by including observed data (particularly percentage runoff). The largest overestimates tend to be on catchments on relatively permeable soils. Restricting comparisons further to consider the return periods within the specified limits rendered the estimates unbiassed.

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NOTATION

AREA	Topographic drainage area in km^2
EDF	Empirical Distribution Function
F	Non-exceedence probability
FSR	Flood Studies Report
FSSR	Flood Studies Supplementary Report
GEV	General Extreme Value
k	GEV shape parameter
M	Modified Anderson-Darling statistic
ML	Maximum Likelihood
MSL	Mainstream length in km
n	Number of catchments
N	Period of record in years
O	Observed non-exceedence probability
p	Exceedence probability
PMF	Probable maximum flood
PWM	Probability Weighted Moments
$\bar{Q}$	Mean annual flood
QT_i	Magnitude of T year flood on catchment i
QT_{ij}	Estimated value of T year flood on catchment i using method j
RMS	Root mean square
RT_{ij}	Relative error at return period T on catchment i using method j
S	Standard deviation
SAAR	Standard period annual average rainfall in mm
se	Standard error
SOILn	Fraction of catchment with soil (WRAP) type n
SPR	Standard percentage runoff
S1085	A mainchannel slope measure in m/km
T	return period
Tp	Unit hydrograph time to peak in hours
WRAP	Winter Rainfall Acceptance Potential (soil classification)
u	GEV location parameter
URBAN	Fraction of catchment cover by urban areas
α	GEV scale parameter
χ^2	Chi-squared goodness of fit statistic

Acronyms for flood estimation methods

FSR/STATS(CC)	FSR statistical method with catchment characteristics
FSR/RF-RO(CC)	FSR rainfall-runoff method with catchment characteristics
FSSR16(CC)	FSSR16 rainfall-runoff method with catchment characteristics
FSSR16(Tp&SPR)	FSSR16 rainfall-runoff method with model parameters Tp and SPR derived from observed data
FSSR16(Tp)	FSSR16 rainfall-runoff method with Tp derived from observed data
FSSR16(SPR)	FSSR16 rainfall-runoff method with SPR derived from observed data
DATA/STATS	Estimates from fitting a distribution to observed annual maxima; used as truth for assessment of other methods

1.0 INTRODUCTION

Estimating flood magnitudes of given probability or frequency of occurrence is an essential requirement for the design of drainage systems, bridges, flood protection works and other river engineering schemes. If sufficiently long records of river flow are available, the flood magnitude-frequency distribution can be estimated directly. However, the majority of sites have little or no information on previous flood flows, and the distribution has to be estimated indirectly.

The FSR[1] presents two indirect methods of flood estimation, which have been applied to a large number of catchments throughout the UK; firstly the statistical method, in which observed flood peaks are treated as random samples from some frequency distribution, and secondly the rainfall-runoff method, in which rainfall is treated as the statistical element and is converted to flow using a deterministic model of catchment response. In the rainfall-runoff method the estimated flood magnitude depends on several aspects of the input (eg. rainfall depth, duration, and profile, and catchment initial condition). A simulation exercise (FSR I.6.7, (437)) was undertaken to find a combination of inputs that would give a peak flow of the required return period. Appendix B describes this simulation exercise in some detail.

The statistical method estimates only peak flow, which may suffice for the design of culverts and bridges. However, the rainfall-runoff method synthesises the entire hydrograph and is therefore better suited to the design of flood storage or reservoir spillways. The rainfall-runoff method may also be preferred where the hydrologist has a feel for the parameter values (eg. the percentage of rainfall that runs off as flood flow). Adjusting such parameters to predict the effect of catchment changes (eg. field drainage, urbanisation) is intuitively easier than directly adjusting statistical parameters, such as mean annual flood.

With both methods, the various model parameters were related via multiple regression equations to the physical characteristics of the catchments, enabling flood quantiles to be estimated at sites without

[1] References to the Flood Studies Report are made as FSR volume.section(page); references to the Flood Studies Supplementary Reports (NERC,1977-1987) are made as FSSRnumber.

flow (or rainfall-runoff) data. These estimates might be improved using observed data from (or local to) the site of interest. The methods have been updated a number of times; of particular note here is the revision of the rainfall-runoff model presented in FSSR16.

Considering the wide application of the methods, there have been few studies comparing indirect flood estimates from the FSR methods with values obtained directly from flow data. One study, by Lynn (1978, unpublished), compared the statistical and rainfall-runoff methods (amongst others) with such direct estimates. He considered estimates of the mean annual flood (for 82 catchments), and the 10 year flood (for 39 catchments). However, he did not consider the effects of using observed data to refine the rainfall-runoff method estimates. Lynn found that the FSR statistical method underestimated the mean annual flood by 6% overall (15% in catchments less than 100 km^2), while the 10-year flood was underestimated by less than 1% overall. The rainfall-runoff model was more biassed, overestimating the mean annual flood by 13%, and the 10-year flood by 56%. Moreover, it gave a marked regional pattern of errors, overpredicting in eastern England and underpredicting in south and south-west England (a similar pattern to that found in the simulation study, FSR I.6.7.4(448)).

The somewhat disappointing performance of the rainfall-runoff model might be attributed to the design inputs derived from the simulation study, or to model deficiencies discussed in the FSR I.6.5.12(425), FSSR3 and elsewhere. Of these, the 5-fold classification of soil type (used to estimate the standard percentage runoff) is perhaps most culpable, particularly for classes 1 and 5. For example, Boorman (1980) found that too low a percentage runoff is predicted from soil type 5 in north-west England and that a soil type 6 might be a more appropriate classification in some areas. Reynolds (1981) suggested that a similar problem existed in northern Scotland. A recent study (Boorman et al, 1988) provides some support for this; small upland catchments in Scotland on soil type 5 were found to yield approximately 60% standard percentage runoff. The revised parameter estimation equations presented by Boorman (1985) go some way to rectifying the problems. These equations, summarised in FSSR16, provide more runoff from soil type 5 (SPR=53%) and reduce SPR to 10% (from 15%) on soil type 1. The requirement for even lower SPR in some chalk catchments (soil type 1) has been stated by Gurnell and Midgely (1987).

Errors in assessing response time or unit hydrograph shape may also be to blame for poor rainfall-runoff model performance. For example, Reed (1987) suggests that response time estimates for small catchments can be particularly poor. FSSR16 and Boorman (1985) also include a more robust formulation of the unit hydrograph time-to-peak equation, improving extrapolation to small catchments.

Archer (1980) examined the performance of the statistical method in north-east England and found that small-scale regional patterns in model error could be identified. However, in a reply, Beran (1981) argued that the patterns might be apparent rather than real, and could be due to sample bias in the observed data caused by large storms occuring over several catchments in an area. Archer and Kelway (1987) used observed flood frequency data from 46 catchments in the Northumbrian Water Authority area to compare the FSR statistical method with the FSR and FSSR16 rainfall-runoff methods. They found that overall the statistical method overpredicted the mean annual flood by 9.5%, and the 30-year flood by 5.5%. The rainfall runoff method underpredicted the mean annual flood by 4.4% but overpredicted the 30-year flood by 11.5%. A small-scale regional pattern of errors was found, similar to that for the statistical method. The use of observed rainfall-runoff data was not considered.

Other users of the FSR methods have made informal presentations at meetings and conferences suggesting unhappiness with certain aspects of the methods but these are frequently anecdotal and cannot be referenced or investigated.

This report aims to

- provide definitive comparisons of the various FSR techniques against observed data,

  test the effect of including various amounts of observed data,

  identify classes of catchment where the current rainfall-runoff method may be deficient (eg. size, urbanisation or soil type).

The criteria adopted in selecting the catchments used in the report are described in the next section. The derivation of floods of return period 2, 5, 10, 25, 50 and 100 years is described in Chapter 3, along with consideration of the maximum return period to which each catchment's observed flood frequency can be taken. A description of seven separate combinations of methods and observed data to be studied are given in Chapter 4. Chapter 5 describes the results, using different model and catchment subsets, while Chapter 6 presents results for a subset of six test catchments. Conclusions and recommendations are given in Chapters 7 and 8.

Appendix A contains full tables of results presented in summary form in the body of the report. Appendix B describes the FSR simulation exercise to define the combination of inputs required for the rainfall-runoff model to produce floods of designated return period. Appendix C contains details of a supplementary study which compares estimates of the probable maximum flood, PMF, using the FSR rainfall-runoff method, with maximum recorded historical floods in the UK.

2.0 STUDY CATCHMENTS

Catchments selected for this study had to pass four stages of quality control. Each catchment must:

have a reliable estimate of the true flood frequency curve against which to compare the various methods,

2. be suitable for application of the FSR procedures,

3. have numerous analysed individual flood events as a basis for the assessment of the usefulness of observed data, and

4. have a stable and natural hydrological regime.

The true flood frequency distribution for any catchment is of course unknown. The quantiles of the distribution may best be estimated from observed sequences of recorded data. The precision of each estimate depends primarily on the length of record, although other factors such as the accuracy of flow measurement are clearly influential. FSR I.2.11.2 recommends that only floods up to return periods of 2N years, where N is the number of years of record, should be estimated directly from at-site annual maximum data.

Figure 1 (from Lees, 1987) shows the number of stations with a given length of record held on the UK Surface Water Archive. The longest record is 105 years on the River Thames at Teddington. Therefore, even at this site only floods up to a maximum return period of 210 years should be estimated directly from the flood data. The original aim of this study was to estimate floods up to the 100 year return period; unfortunately there are only 12 stations in the UK whose records exceed 50 years. To obtain a more comprehensive and representative data set, the criterion was relaxed to include all catchments with at least 15 annual maximum flood events.

The FSR rainfall-runoff method assumes that the rainfall is evenly distributed over the catchment, therefore it is recommended for application on drainage areas up to 500 km^2. All but one of the catchments used in this study were smaller than this; the exception being the Usk at Llandetty which has an area of 544 km^2.

In order to test the utility of observed data when using the rainfall-runoff method, the number of catchments employed in the study was further restricted to include only those for which estimates of the unit-hydrograph model parameters had been derived for

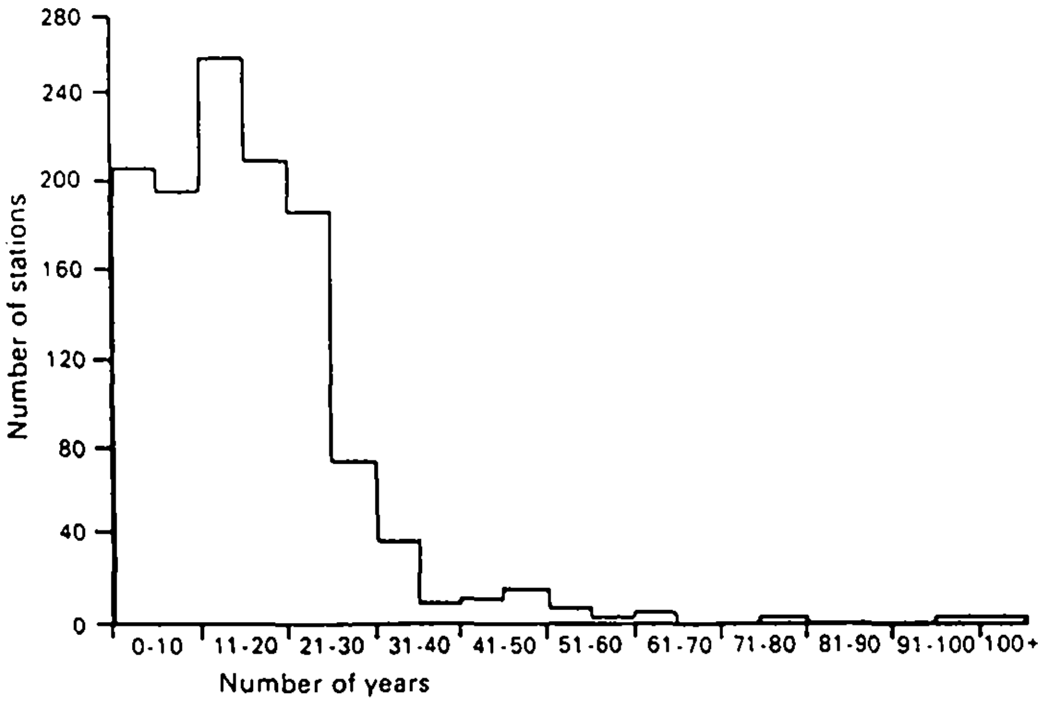

Figure 1. Record lengths for Surface Water Archive stations

at least five separate flood events. As part of the review of the FSR rainfall-runoff model parameter estimation equations (Boorman, 1985), rainfall and runoff data were collated for 210 catchments, of which 128 had five or more events. Ninety-one of these also had at least 15 years of annual maxima.

While these data had already been checked when collected, it was considered important to review their suitability for use in this study. For example, if a catchment had good quality event data for floods remaining in-bank, but the annual maximum flood series contained many out of bank flows, it would be unsuitable for this study.

At this stage of validation two stations were rejected from the study. The flow record for the River Isle at Ashford Mill gauging station shows that the highest five recorded annual maximum floods were all of similar magnitude (Figure 2). At this site a large volume of flood water is stored on the flood-plain immediately upstream of the station thereby attenuating flood peaks. The Ouzel at Willen was not included since floods are grossly attenuated by the Willen Lake as part of the flood alleviation scheme for Milton Keynes. Flows for the Tyne at Tarset are now influenced by the Kielder reservoir, which was commissioned in 1980; hence only data up to 1979 were used. For the same reason data for the Brenig at Pont-y-Rhuddfa were restricted to the period 1922-1974.

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Isle at Ashford Mill

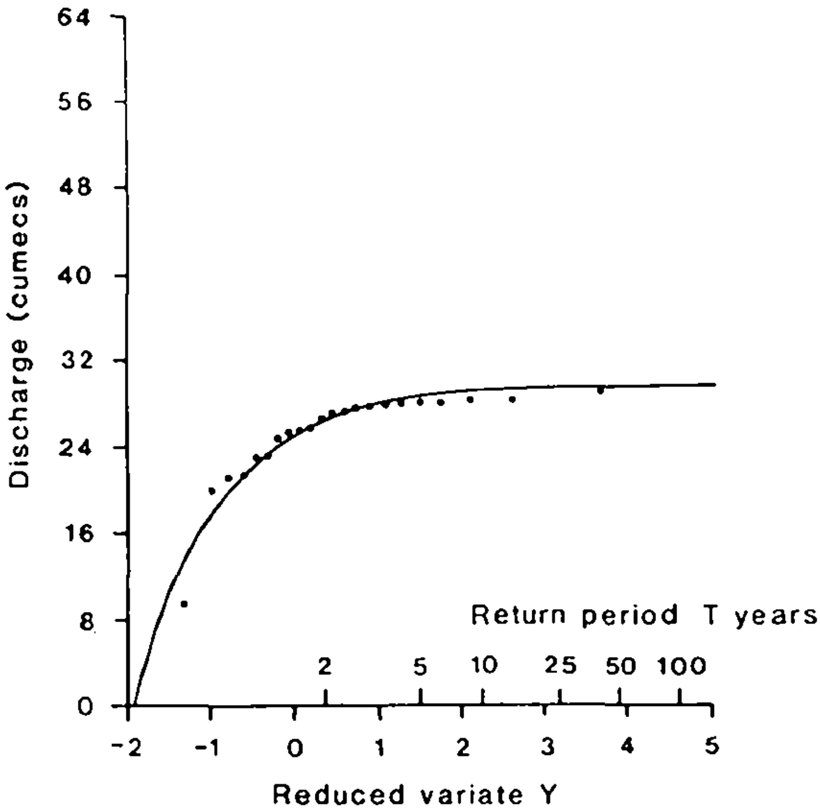


Figure 2. ***Flood frequency analysis for the Isle at Ashford***

Figure 3. Locations of catchments used in this study

Once unsuitable stations were rejected the number available was reduced to 88; the geographical location of each is shown in Figure 3. Unfortunately, for some areas of the country, no catchments were available for use. Therefore the sample set is not entirely representative of all types of catchment upon which the methods may be used in practice. In particular there are no catchments north of the Highland Boundary fault, in the Lake District or the Southern Uplands of Scotland. There are, however, a number of catchments from upland Wales, urbanised south-east England and low-lying East Anglia.

The range of physical characteristics encompassed by this sample of catchments is depicted in the histograms shown in Figure 4 and listed in Table 2.1 It can be seen that the sample contains a good range of drainage areas up to $400km^2$, there being only 8 larger catchments, and that about 75% of mainstream slopes (S1085) are below 10m/km. For over half of the catchments, the proportion of the drainage area urbanised is less than 0.04. Although not shown diagramatically, few of the catchments have more than 1% of their area draining through a lake. These diagrams do not, however, display the range of combinations of different characteristics, but there are certain combinations of characteristics which are more common than others. Small catchments tend to be steep, wet catchments tend to have impermeable soils, and urbanised catchments tend to be in areas of low average rainfall and to have permeable soils.

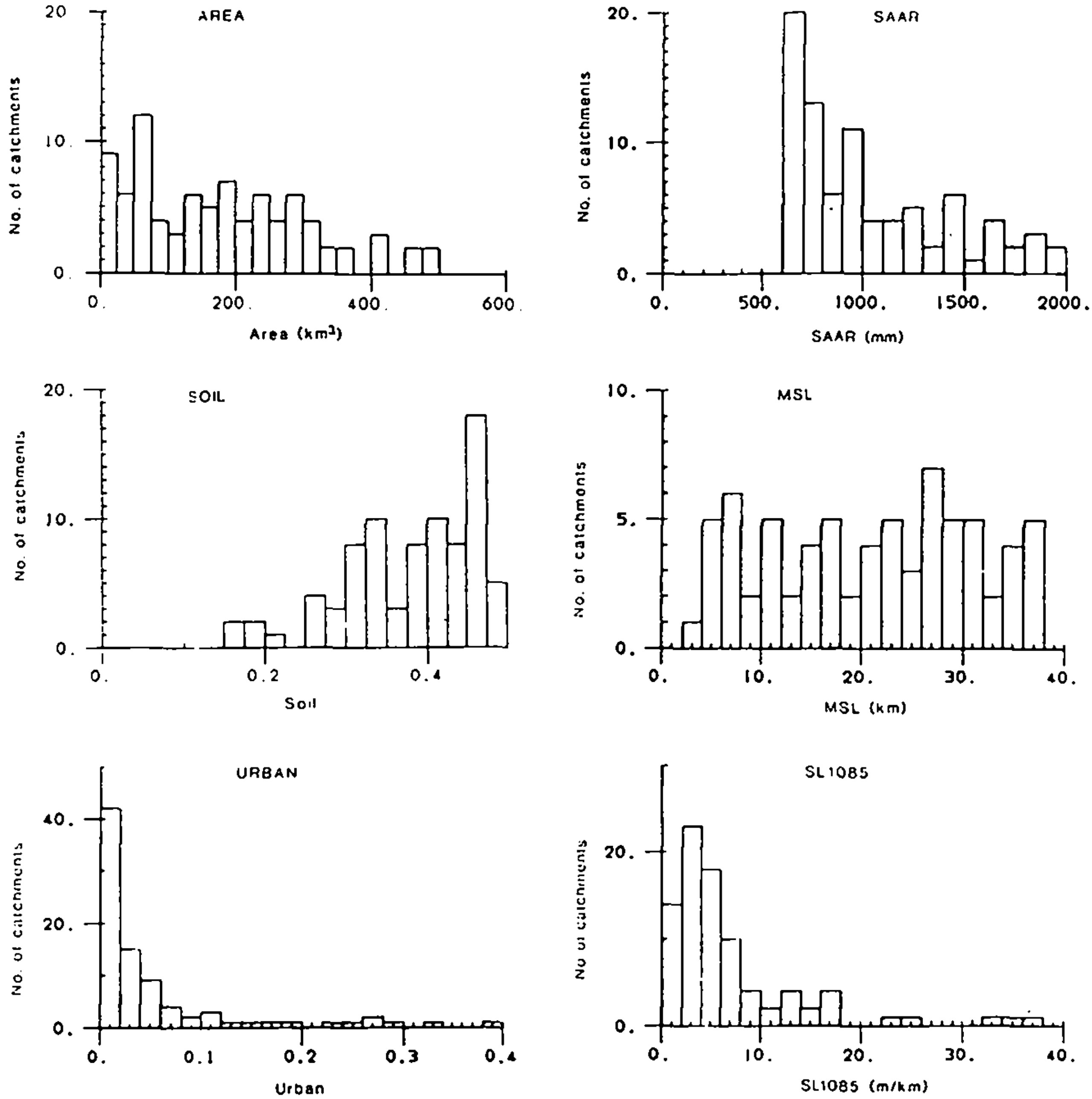


Figure 4. Histograms showing distribution of catchment characteristics

No	AREA	MSL	S1085	SAAR	SOIL1	SOIL2	SOIL3	SOIL4	SOIL5	URBAN
19001	369.0	42.0	5.81	914	0.000	0.000	0.000	0.800	0.200	0.110
19002	43.8	17.9	5.06	1024	0.000	0.000	0.000	1.000	0.000	0.070
19005	229.0	28.2	6.87	980	0.000	0.000	0.000	0.640	0.360	0.100
20001	307.0	31.9	6.08	736	0.050	0.000	0.220	0.720	0.020	0.020
23005	284.9	36.3	4.85	1322	0.000	0.000	0.000	0.000	1.000	0.000
24005	178.5	31.7	6.39	752	0.000	0.000	0.000	0.990	0.010	0.050
24007	44.6	11.9	14.89	797	0.000	0.000	0.000	0.930	0.070	0.000
27001	484.3	84.6	2.54	975	0.010	0.000	0.000	0.690	0.300	0.020
27035	282.3	31.7	4.47	1134	0.000	0.000	0.000	0.530	0.470	0.020
28070	9.1	4.2	35.95	985	0.000	0.100	0.000	0.000	0.900	0.000
29001	108.3	20.2	3.33	729	0.810	0.000	0.010	0.190	0.000	0.000
29004	54.7	12.1	1.98	630	0.510	0.080	0.000	0.420	0.000	0.000
30001	297.9	46.8	2.13	625	0.410	0.040	0.000	0.550	0.000	0.020
30004	61.6	15.1	3.26	697	0.000	0.000	1.000	0.000	0.000	0.000
31005	417.0	55.4	1.44	643	0.020	0.000	0.000	0.980	0.000	0.010
33014	272.0	29.9	2.24	609	0.550	0.000	0.450	0.000	0.000	0.020
33029	98.8	7.0	1.63	637	0.750	0.250	0.000	0.000	0.000	0.000
33045	28.3	7.8	3.26	627	0.000	0.000	1.000	0.000	0.000	0.000
34003	164.7	22.4	2.05	686	1.000	0.000	0.000	0.000	0.000	0.000
34005	73.2	22.7	1.73	647	0.080	0.000	0.920	0.000	0.000	0.000
35008	128.9	14.6	3.41	606	0.000	0.100	0.900	0.000	0.000	0.020
36008	224.5	37.9	1.71	606	0.000	0.070	0.930	0.000	0.000	0.010
37001	303.3	62.6	1.22	610	0.000	0.000	0.800	0.200	0.000	0.100
37007	136.3	26.9	1.85	606	0.000	0.030	0.900	0.070	0.000	0.130
38007	21.4	5.6	7.47	611	0.000	0.300	0.700	0.000	0.000	0.290
39004	122.0	2.4	4.36	764	0.900	0.100	0.000	0.000	0.000	0.390
39005	43.6	7.4	2.28	640	0.050	0.700	0.000	0.250	0.000	0.810
39007	354.8	32.3	0.98	710	0.250	0.140	0.350	0.260	0.000	0.330
39012	69.1	11.8	3.73	679	0.250	0.190	0.010	0.550	0.000	0.460
39022	164.5	22.1	1.62	751	0.350	0.000	0.000	0.650	0.000	0.020
39025	147.6	23.2	3.20	798	0.060	0.090	0.000	0.850	0.000	0.010
39026	199.4	27.9	2.10	700	0.060	0.000	0.000	0.940	0.000	0.020
39052	50.2	11.0	3.51	687	0.000	0.000	0.200	0.800	0.000	0.180
39053	89.9	14.6	2.25	825	0.000	0.000	0.000	1.000	0.000	0.090
40006	50.3	13.5	6.20	733	0.550	0.060	0.000	0.380	0.000	0.030
40009	136.2	19.4	3.24	808	0.000	0.000	0.000	1.000	0.000	0.010
40010	224.3	30.9	1.58	775	0.140	0.000	0.110	0.750	0.000	0.030
41005	180.9	26.7	2.10	835	0.000	0.000	0.000	1.000	0.000	0.040
41006	87.8	16.4	3.99	837	0.000	0.000	0.000	1.000	0.000	0.020
41007	403.3	44.8	1.50	755	0.040	0.000	0.000	0.960	0.000	0.010
41015	58.3	7.3	4.69	959	0.840	0.100	0.000	0.060	0.000	0.000
41028	24.0	10.0	4.88	842	0.000	0.000	0.000	1.000	0.000	0.010
45002	421.7	48.1	5.70	1420	0.000	0.870	0.000	0.020	0.120	0.000
45003	226.1	26.4	6.15	996	0.470	0.020	0.000	0.510	0.000	0.000

Table 2.1 Catchment characteristics.

No	AREA	MSL	S1085	SAAR	SOIL1	SOIL2	SOIL3	SOIL4	SOIL5	URBAN
45004	288.5	33.6	3.58	1052	0.500	0.000	0.150	0.350	0.000	0.010
46003	247.6	35.2	16.50	1696	0.260	0.240	0.000	0.000	0.500	0.000
46005	21.5	11.8	22.60	1987	0.000	0.000	0.000	0.000	1.000	0.000
47007	54.9	16.6	17.80	1477	0.140	0.500	0.000	0.000	0.360	0.000
48004	25.3	10.0	17.48	1533	0.000	0.250	0.000	0.000	0.750	0.000
48005	19.1	7.2	13.10	1121	0.000	1.000	0.000	0.000	0.000	0.060
52005	202.0	37.3	5.60	993	0.180	0.470	0.000	0.350	0.000	0.060
52006	213.1	16.7	5.50	907	0.300	0.000	0.450	0.250	0.000	0.050
52010	135.2	20.4	4.68	881	0.070	0.020	0.630	0.290	0.000	0.000
53005	147.4	24.6	3.00	972	0.600	0.000	0.100	0.300	0.000	0.050
53007	261.6	27.7	2.30	966	0.270	0.030	0.350	0.350	0.000	0.020
53009	72.6	16.1	8.15	1018	0.570	0.000	0.430	0.000	0.000	0.070
54004	262.0	28.8	1.92	691	0.030	0.000	0.000	0.970	0.000	0.250
54006	324.0	35.6	3.07	701	0.380	0.140	0.080	0.400	0.000	0.140
54011	184.0	26.9	4.85	675	0.420	0.000	0.010	0.570	0.000	0.030
54016	259.0	40.2	0.92	713	0.500	0.030	0.000	0.470	0.000	0.000
54019	347.0	56.7	1.40	692	0.300	0.000	0.700	0.000	0.000	0.040
54022	8.7	4.7	63.70	2235	0.000	0.000	0.000	0.000	1.000	0.000
55008	10.6	5.4	47.44	2401	0.000	0.000	0.000	0.000	1.000	0.000
55012	244.2	36.0	7.98	1643	0.000	0.630	0.000	0.000	0.370	0.000
56003	62.1	20.2	9.02	1260	0.000	0.780	0.000	0.000	0.220	0.000
56004	543.9	48.7	4.58	1488	0.000	0.600	0.000	0.000	0.400	0.020
56005	98.1	25.4	14.23	1469	0.000	0.250	0.300	0.000	0.450	0.160
56006	183.8	22.4	8.87	1661	0.000	0.530	0.000	0.000	0.470	0.000
57004	106.0	25.8	7.30	1759	0.000	0.000	0.300	0.000	0.700	0.040
57005	454.8	42.3	9.23	1863	0.000	0.000	0.400	0.000	0.600	0.050
58001	158.0	20.1	10.33	1839	0.000	0.140	0.430	0.000	0.430	0.040
58002	190.9	28.3	13.50	1981	0.000	0.000	0.100	0.000	0.900	0.010
60002	297.8	50.0	4.56	1637	0.000	0.630	0.000	0.000	0.370	0.000
61001	197.6	27.6	3.24	1282	0.000	0.950	0.000	0.000	0.050	0.000
61003	31.3	9.4	25.47	1474	0.000	1.000	0.000	0.000	0.000	0.000
64001	471.3	37.5	5.22	1836	0.000	0.500	0.000	0.000	0.500	0.000
65001	68.6	15.2	33.55	3030	0.000	0.020	0.000	0.000	0.980	0.000
66011	344.5	29.0	17.20	2162	0.000	0.510	0.000	0.000	0.490	0.000
67003	20.2	7.1	13.80	1308	0.000	0.000	0.000	0.000	1.000	0.000
67008	227.1	45.8	4.97	901	0.150	0.700	0.000	0.100	0.050	0.040
68006	150.0	30.9	10.03	1053	0.110	0.080	0.000	0.490	0.320	0.020
69027	150.0	41.4	5.62	1179	0.000	0.000	0.000	0.410	0.590	0.220
71003	10.4	5.2	37.80	1792	0.000	0.000	0.000	0.000	1.000	0.000
71004	316.0	37.1	5.02	1211	0.000	0.000	0.000	0.710	0.290	0.090
72002	275.0	34.2	7.74	1251	0.000	0.070	0.000	0.460	0.470	0.010
77002	495.0	53.4	3.69	1497	0.000	0.000	0.340	0.000	0.670	0.000
84008	51.3	18.9	13.45	1187	0.000	0.000	0.140	0.750	0.120	0.260
84012	227.2	61.2	6.62	1264	0.000	0.000	0.320	0.500	0.180	0.270

Table 2.1 (Continued) Catchment characteristics.

3.0 ESTIMATING T-YEAR FLOOD PEAKS FROM OBSERVED ANNUAL MAXIMA

3.1 INTRODUCTION

As described in the last section, the catchments chosen for analysis each had at least 15 years of observed annual maximum flood data. This section describes how floods of various return periods were estimated from these data, becoming the truth against which other methods of estimation would be compared. It had been intended to make such comparisons over a wide range of return periods, namely 2, 5, 10, 25, 50 and 100 years. However, inspection of the observed data for many catchments suggested that although values for the longer return periods might be adequate as best estimates for engineering design at that site, they were not reliable enough to be used as a basis for comparing other estimation methods. Thus, for each catchment, an upper limit on T was chosen by visual inspection of the plotted annual maximum data and fitted frequency curve. These "eyeball" limits of trustworthiness have been applied for most of the comparisons in Chapter 5. More objective ways of defining the limit were also investigated, including those based on goodness-of-fit and estimation errors. Although these techniques were not generally successful, they did improve consistency in the eyeball classification by focussing attention on those catchments where the techniques showed greatest discrepancy.

3.2 FITTING A FLOOD FREQUENCY DISTRIBUTION

The FSR presents a number of procedures for estimating T-year floods from annual maximum data; the choice of method depends on the required return period, T, and the number of years of data, N (see FSR I.2.11.2(243)). Thus, with N between 10 and 24, floods of return period up to 2N should be estimated using the EV1 (Gumbel) distribution (fitted by the method of maximum likelihood); with N of 25 or more, the GEV distribution should be used (again fitted by maximum likelihood). In each case, floods of return period beyond 2N should be found by scaling the observed mean annual flood, $\bar{Q}$, by the appropriate regional growth factor. FSSRs 13 and 14 contain modifications to this advice that affect the blending of flood frequency curves derived from data with regional and national growth curves. Firm guidance on how to assess the quality of derived flood frequency curves is not given; users are encouraged to use several methods, including examination of the plotted data.

The methods of estimating T-year floods adopted in this report depart from these recommendations in two ways.

Firstly, Hosking et al (1984) have suggested that more stable estimates of flood frequency are obtained when distributions are fitted by the method of probability weighted moments (PWM). For the GEV distribution, the probability, F, of an annual maximum value, x, being less than any value, X, is given by:

$$F(x<X) = \exp(-\{ 1 - k(X - u) /\alpha \}^{1/k}) \qquad (3.2.1)$$

This quantity F is usually called the non-exceedence probability. Hosking et al give the following parameter estimation equations:

$$k = 2.9554c^2 + 7.859c$$

$$\alpha = (2b_1-b_0)k/\{(1-2^{-k})\Gamma(1+k)\} \qquad (3.2.2)$$

$$u = b_0+ \alpha\{\Gamma(1+k)-1\}/k$$

where $c = (2b_1-b_0)/(3b_2-b_0)-\ln2/\ln3$

$$b_0= \sum x_i/N$$

$$b_1= \sum p_i x_i/N$$

$$b_2= \sum p_i^2 x_i/N$$

$$p_i=(i-0.35)/N$$

and i = ascending rank order of the annual maxima

The likely errors in estimating T-year floods using this method with 15 years of data are broadly similar to or better than those of using maximum likelihood with 25 years of data (Hosking et al, 1984, Table 6, page 15). Since the catchments used in this study had at least 15 years of data, it was considered reasonable to estimate T-year floods using the GEV distribution fitted by PWM throughout.

Secondly, the FSR recommendation to use regional growth factors in preference to the fitted distribution for return periods beyond 2N has not been followed. This is because the regional approach is intended to improve on uncertain estimates obtained from extrapolation of the at-site record, rather than to define the true value of the quantile.

For each catchment the GEV distribution was fitted by the PWM method and displayed with the annual maximum data on a graph of discharge versus return period. The non-exceedence probability of each flood was calculated using the Gringorten formula:

$$F = (i - 0.44) / (N + 0.12) \qquad (3.2.3)$$

Inspection of these frequency plots showed a number of catchments where the observed data gave an indistinct trend or where the distribution seemed to provide a poor fit. In such cases, the accuracy of the higher quantile estimates was considered to be poor and so a limit on return period was sought, below which the flood estimates could be trusted. Visual assessments of the plots were sensitive to:

1. departure of observed data from the fitted curve at high return periods (remembering though that the data points do not have constant variance and the return periods and magnitudes of the largest floods are poorly defined)

2. discontinuities in the observed data (suggesting changes in flow mechanism and/or compounded frequency distributions)

3. groups of data points at a certain discharge (suggesting overbank flow is limiting discharge at some point upstream)

4. downward curvature of the fitted GEV distribution implying an upper bound; this could result from overbank storage, which might fill eventually, and allow the flood frequency curve to resume upward curvature at higher return periods.

Reliance on visual definition using flood frequency plots can be criticised on the grounds of subjectivity. However, as discussed later in this section, more objective criteria based on the standard error of estimate gave limits which were often intuitively unacceptable.

Figure 5 gives twelve examples of the frequency plots and fitted GEV distributions (a further six examples are given in Chapter 6 of this report). Plots (a) to (c) show generally good fits where the eyeball limit was set at 25 years. Plot (d) shows a reasonable overall fit but contains large local departures (not uncommon with longer records); the 10-year limit seems appropriate particularly when it was found that fitting the GEV by maximum likelihood increased the 50-year estimate by 23%. Plots (e) and (f) show slightly inferior fit and were limited to 10 years (the downward curvature in (e) looked to be strongly influenced by the smallest flood). Plots (g) to (l) show poor fits, and were all limited to 5 years. Plots (g) and (h) indicate breaks in trend at about 5 years. Plots (i) and (j) exhibit downward curvature and the effect of the plotting position of the largest flood. Plots (k) and (l) exhibit groups of floods at similar discharges.

Table 3.1 gives, for each catchment, the length of record, the eyeball limit, and the 2- to 100-year estimates. Of the 88 catchments, 18 were given eyeball limits of 25 years, 53 were given 10 years, 14 were given 5 years, and three were given 2 years. In every case, the eyeball limit was considerably less than the FSR recommendation of 2N, and was often less than N/2 (see Figure 6). The effectiveness of these eyeball limits in filtering out poor quality quantile estimates is assessed in Chapter 5 of this report.

The remainder of this section describes investigations aimed at defining the eyeball limits more objectively, or at least ensuring that the limits were chosen consistently. It may be omitted by the more casual reader.

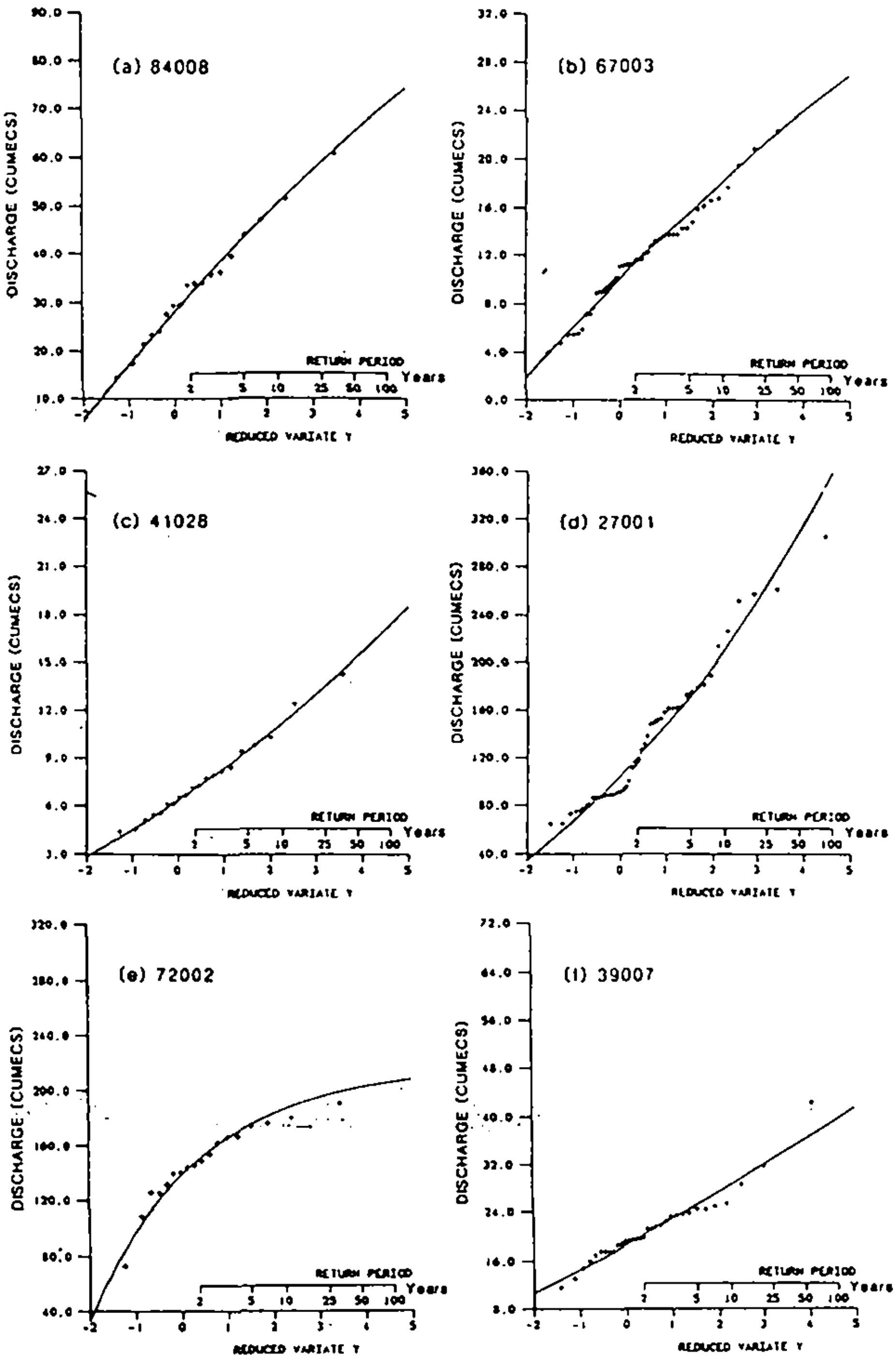
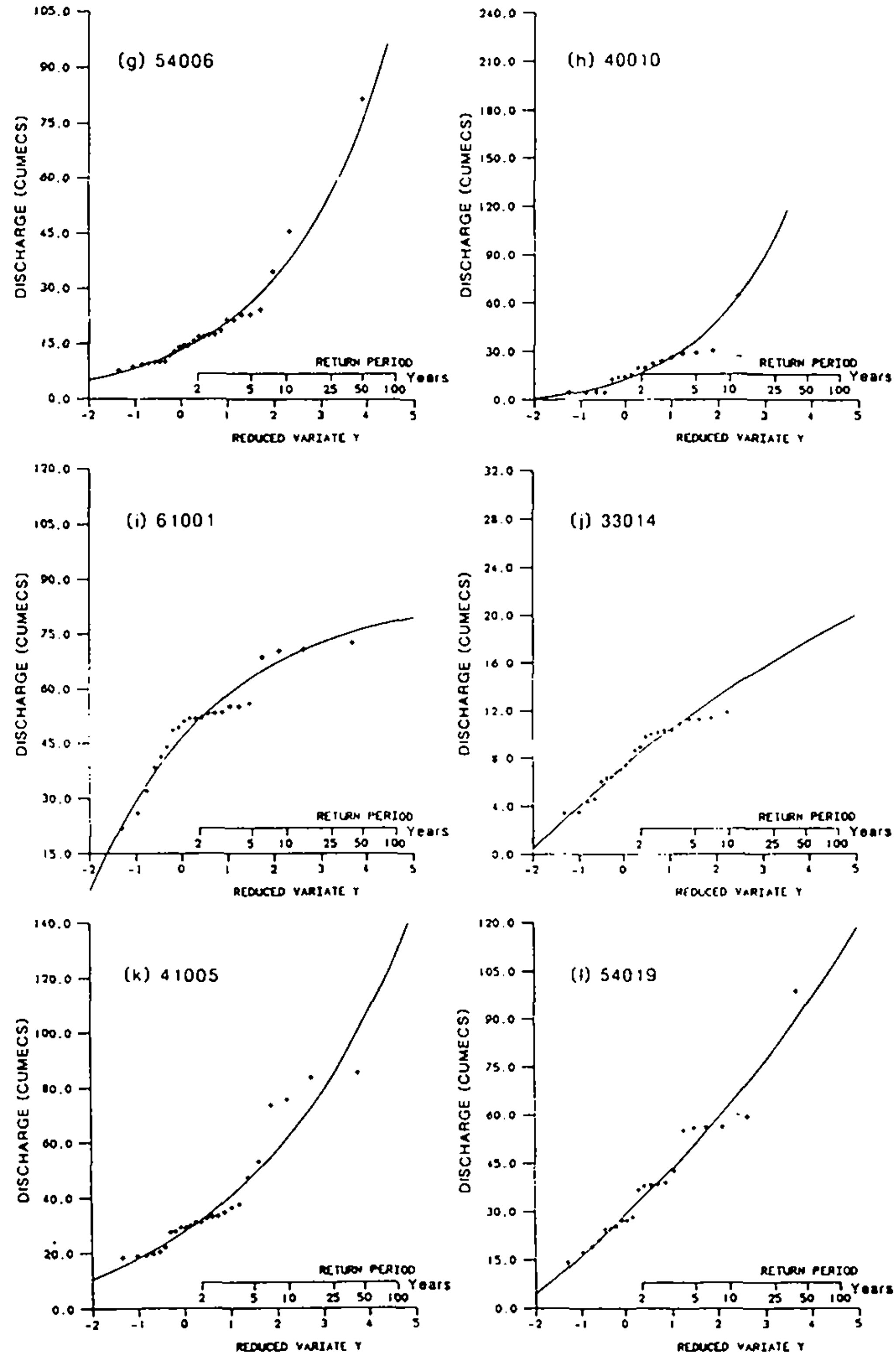


Figure 5. Example flood frequency curves


(g) 54006
(h) 40010
(i) 61001
(j) 33014
(k) 41005
(l) 54019
DISCHARGE (CUMECS)
RETURN PERIOD
Years
2 5 10 25 50 100
REDUCED VARIATE Y

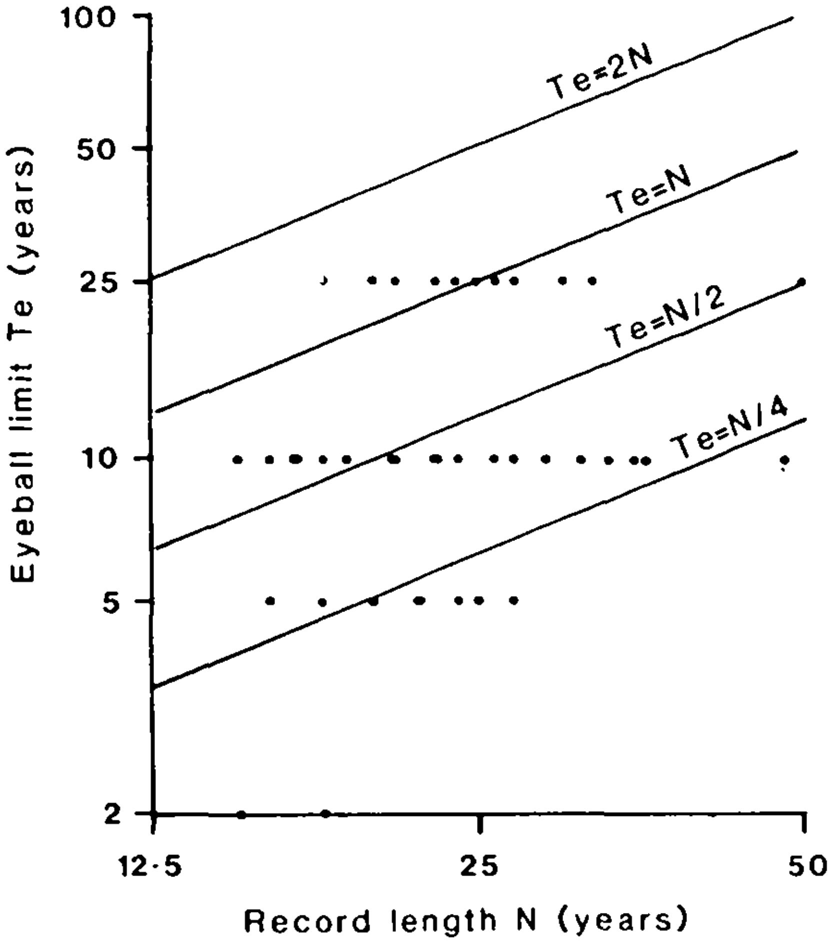


Figure 6. Eyeball limit plotted against length of record

Catchment	N	Eyeball limit	Return period of flood peak (years) 2	5	10	25	50	100
19001	29	10	114.6	154.8	178.1	204.2	221.4	236.9
19002	23	10	15.7	21.3	25.4	31.2	36.0	41.1
19005	23	10	86.3	117.9	138.8	165.2	184.8	204.2
20001	26	10	49.8	77.9	97.2	122.3	141.4	160.8
23005	20	10	224.4	282.4	318.0	359.8	388.7	415.8
24005	30	25	34.3	48.1	58.0	71.3	81.8	92.9
24007	15	10	12.3	17.9	22.1	28.2	33.2	38.7
27001	48	10	120.5	172.0	210.6	265.1	310.1	359.1
27035	15	2	60.0	68.8	74.4	80.9	85.4	89.7
28070	53	25	4.1	6.5	9.1	13.7	18.8	25.7
29001	26	25	2.2	3.4	4.3	5.4	6.3	7.2
29004	18	2	6.7	10.0	12.4	15.5	18.1	20.7
30001	27	10	16.6	25.1	30.5	37.0	41.5	45.9
30004	23	25	7.4	10.7	12.6	14.9	16.5	17.9
31005	24	10	32.9	51.9	66.5	87.6	105.4	125.1
33014	25	5	8.5	11.8	13.7	16.1	17.7	19.2
33029	17	10	3.1	4.1	4.5	4.9	5.1	5.3
33045	16	10	1.2	2.0	2.5	3.1	3.6	4.1
34003	24	10	6.1	9.2	11.4	14.2	16.3	18.5
34005	22	10	2.8	4.4	5.7	7.6	9.2	11.1
35008	19	10	14.0	22.0	27.1	33.4	37.9	42.2
36008	24	10	18.6	29.4	38.4	52.6	65.4	80.7
37001	35	10	22.1	31.0	37.1	45.1	51.2	57.4
37007	20	25	14.5	21.6	26.2	32.1	36.4	40.7
38007	35	10	7.1	10.1	11.9	13.8	15.1	16.3
39004	36	10	2.6	3.5	4.3	5.3	6.2	7.2
39005	19	10	11.3	15.5	17.9	20.5	22.2	23.7
39007	33	10	20.2	25.1	28.4	32.8	36.1	39.5
39012	27	10	12.6	17.0	19.8	23.2	25.6	27.8
39022	20	10	15.6	20.2	23.4	27.6	30.8	34.0
39025	18	25	16.1	21.2	25.0	30.5	34.9	39.8
39026	18	5	17.2	28.3	37.7	52.5	66.0	82.0
39052	27	10	7.8	11.3	13.9	17.4	20.1	23.1
39053	23	25	23.1	28.5	32.0	36.1	39.0	41.8
40006	16	5	5.4	10.0	15.4	26.9	40.9	62.2
40009	21	10	26.3	36.1	42.8	51.6	58.2	65.0
40010	18	5	17.0	36.4	57.8	101.5	152.6	227.5
41005	25	5	32.0	48.2	61.9	83.8	103.9	128.1
41006	21	10	34.6	47.3	55.4	65.3	72.4	79.4
41007	15	2	63.6	109.0	146.4	204.0	255.7	316.1
41015	18	5	1.6	2.6	3.4	4.7	5.8	7.0
41028	20	25	7.1	9.5	11.2	13.5	15.4	17.4
45002	24	5	142.3	190.7	223.0	264.2	295.0	325.8
45003	23	25	73.1	110.0	136.1	171.1	198.5	227.2

Table 3.1 Number of annual maxima, eyeball limit and GEV-PWM flood quantiles (m^3s^{-1}) for 88 catchments.

Catchment	N	Eyeball limit	Return period of flood peak (years) 2	5	10	25	50	100
45004	21	10	93.9	139.7	175.4	228.0	273.1	323.7
46003	27	5	212.8	282.6	332.6	400.4	454.4	511.1
46005	21	10	43.0	55.0	61.5	68.3	72.6	76.2
47007	23	10	21.7	24.6	25.9	27.0	27.7	28.1
48004	16	10	7.8	12.7	16.5	22.0	26.8	32.2
48005	17	10	5.2	7.5	9.3	12.0	14.3	16.9
52005	24	10	60.1	88.0	104.7	123.7	136.6	148.4
52006	23	25	51.0	82.6	110.1	154.8	197.0	248.5
52010	21	10	46.7	66.9	80.5	98.1	111.3	124.6
53005	48	10	28.5	39.7	47.1	56.6	63.6	70.7
53007	23	25	60.0	80.6	93.4	108.5	119.1	129.1
53009	18	10	13.8	19.7	24.0	30.1	35.0	40.3
54004	31	10	28.0	40.5	48.4	57.9	64.7	71.3
54006	27	5	15.7	26.3	36.7	55.9	76.3	103.9
54011	19	10	21.8	32.9	39.8	48.1	54.0	59.6
54016	23	10	14.3	18.9	22.2	26.6	30.0	33.6
54019	22	5	34.0	51.0	63.4	80.6	94.6	109.5
54022	32	25	12.7	16.9	20.1	24.7	28.6	33.0
55008	34	5	16.5	23.1	28.9	38.5	47.7	59.0
55012	17	10	184.3	232.4	257.4	283.0	298.3	311.1
56003	17	10	20.8	31.7	40.1	52.5	63.1	74.9
56004	19	10	302.5	430.9	533.3	686.4	820.1	972.6
56005	19	10	43.6	58.7	71.3	90.8	108.4	129.2
56006	21	25	148.4	207.6	250.4	308.9	355.8	405.5
57004	27	25	62.3	87.6	109.4	144.3	176.8	216.0
57005	17	10	260.6	348.4	422.8	540.6	649.2	779.0
58001	25	25	104.2	134.5	152.5	172.9	186.6	199.1
58002	18	10	174.1	228.2	266.7	318.5	359.4	402.3
60002	24	25	128.2	163.1	186.0	214.7	235.9	256.7
61001	22	5	51.3	63.0	68.5	73.6	76.5	78.7
61003	17	10	15.8	19.8	22.7	26.6	29.8	33.1
64001	19	10	307.8	363.5	389.0	412.3	424.9	434.5
65001	23	10	84.5	105.8	117.3	129.3	136.7	143.0
66011	21	10	363.4	440.3	488.5	546.2	587.0	625.8
67003	50	25	11.2	15.7	18.4	21.5	23.6	25.6
67008	20	5	23.3	30.1	35.8	44.8	53.1	62.9
68006	23	10	54.4	77.9	95.6	120.8	141.9	164.9
69027	31	10	81.5	108.9	126.1	146.7	161.3	175.2
71003	19	10	12.8	18.4	22.4	27.7	31.9	36.2
71004	22	5	147.3	201.1	254.5	352.5	456.4	596.4
72002	18	10	149.7	175.3	186.6	196.6	201.8	205.6
77002	21	10	384.3	488.2	559.2	651.6	722.2	793.9
84008	18	25	31.9	43.4	50.5	59.2	65.3	71.1
84012	22	10	117.8	144.4	158.5	173.2	182.3	190.0

Table 3.1 (Continued)

3.3 OBJECTIVE CRITERIA FOR SETTING RETURN PERIOD LIMITS

There is some chance, however small, that a particular sample of annual maxima could have come from any of a range of distributions, however unlike the population the sample might be. Thus, in evaluating the suitability of a particular distribution and parameter set, the following questions may be asked.

How likely is it that the sample comes from this distribution?

What is the likely error in T-year flood estimate if this distribution is adopted?

If these questions can be answered by quoting the value of a derived statistic, the same measure may be useful in helping to define the maximum trustworthy T.

3.3.1 Standard errors

It might seem that the above questions are answered by considering the standard error of estimation, both of the parameters of the distribution and the associated quantile estimates. The maximum trustworthy T could then be chosen as the return period at which the standard error reached some critical value. Unfortunately, estimates of standard errors are not obtained when fitting a distribution by probability weighted moments (PWM). However, fitting by maximum liklihood (ML) gives a variance-covariance matrix of parameters from which standard errors may be derived. The GEV distribution was therefore fitted again to each catchment, this time by ML, and the resulting standard errors were used to assess the goodness of fit of both the ML and the PWM fitted quantiles.

Unfortunately, these standard error limits were quite different from the eyeball limits. The standard errors seemed to relate more to the parametric form of the distribution than to any perceived lack of fit on the frequency plot. This was particularly true when the derived value for the GEV k parameter was positive (corresponding to downward curvature of the frequency plot with an upper limit on flood magnitude). In such cases the predicted errors might even reduce with rising T as the upper limit was approached. Flood frequency curves for two of the catchments seen in Figure 5 on page 17 are shown again in Figure 7; this figure shows both the PWM and ML curves and one standard error either side of the latter curve. The two catchments have similar record lengths, but catchment 41028 was given an eyeball limit of 25 years, while catchment 72002 was given a limit of ten years. In contrast, the standard error derived for the 10 year flood on catchment 41028 was 12%, while for catchment 72002 the standard error of the 100 year estimate was only 2.5% (which was considerably less than the difference between the PWM and ML curves).

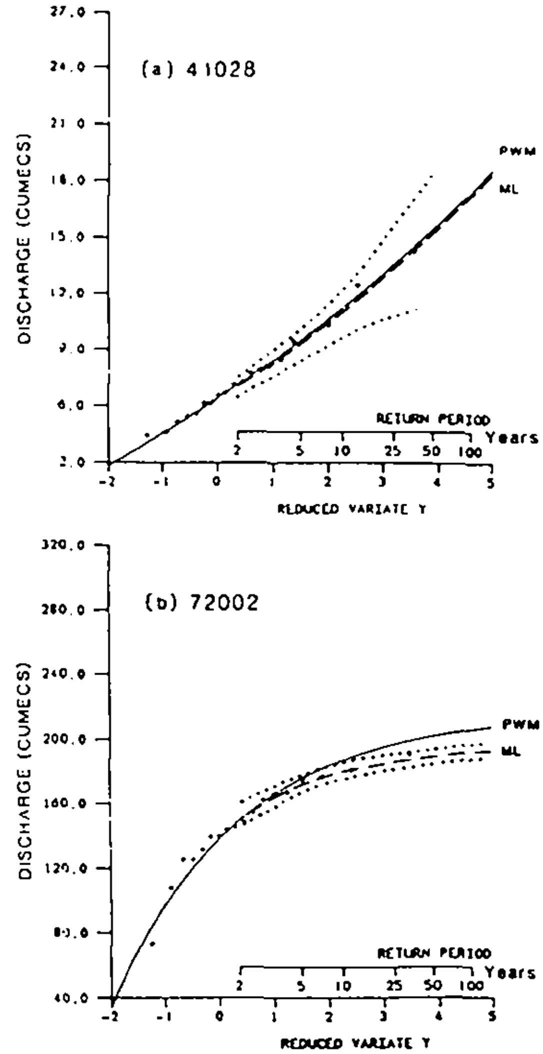


Figure 7. Maximum likelihood standard errors

Such problems associated with the estimation of standard errors were recognised in the FSR I.2.5.6(170), where a single 'practical' standard error formula was proposed:

$$se(Q(T)) = C / \sqrt{N} \qquad (3.3.1)$$

where C could be taken as 0.35 - 0.8 ln(-ln(1-1/T)). This depended only on the sample size and return period, and was therefore independent of distribution form and parameter values. However, standard errors which result from using this approach were still poorly correlated with the eyeball limits.

In an attempt to overcome these problems, standard errors were estimated by another method known as the jackknife (Miller 1974). The distribution is fitted N-times, omitting each data point in turn, thus giving N different estimates for the parameter and quantile values. The means (m) and standard deviations (S) of these N values may be used to correct bias and to predict standard errors (se) in the values derived from the full data set. Thus

$$QT = N\, QT_N - (N-1)\, m_T \qquad (3.3.2)$$

$$se = (N-1)\, S_T / \sqrt{N} \qquad (3.3.3)$$

where QT is the bias free estimate of the quantile, QT_N is the estimate based on all N years data, and m_T and S_T are the mean and standard deviation of the the N jackknifed estimates of QT each based on N-1 years of data.

This method would appear less sensitive to the presence (or otherwise) of outliers, but since the method samples (in effect) from within the available data, if those data are unrepresentative of the true flood distribution, then the jackknife estimates will also be unrepresentative. Note also that any outlier will appear in all but one of the N sub-samples.

Jackknife standard error estimates for the PWM fitting method were derived for each catchment and return period. Figure 8 shows the results for the same two catchments as shown in Figure 7 on page 23 Taken over all catchments the results seemed intuitively more realistic than either the ML values or those from Equation 3.3.1. However, they were still poorly correlated with the eyeball limits, giving higher limits to catchments with a downward curvature.

Despite these reservations, the jackknife error estimates were used to find the return period at which the standard error first exceeded X% of the corresponding flood estimate (with X = 10, 12.5, & 15). Of these, the 12.5% error seemed best correlated with the eyeball limits (though for some catchments even the 2-year flood failed the criteria, while for others the 100-year flood easily passed). For the example catchments seen in Figure 5 on page 17, jackknife limits corresponding to plots (a) to (f) were all 25 years or more, (100 years surprisingly for both (d) and (e)), 2 years for (g) and (h), and 10 years for (j) to (l). The limit corresponding to plot (i) was 100 years.

3.3.2 Goodness of fit

Since standard errors of estimate did not seem as sensitive as the eye to deviations from the fitted curve, an independent measure of goodness of fit was sought. In the Flood Studies Report, two goodness of fit indices were used (χ^2, Kolmogorov-Smirnov) but were found insufficiently powerful for the small samples typically available.

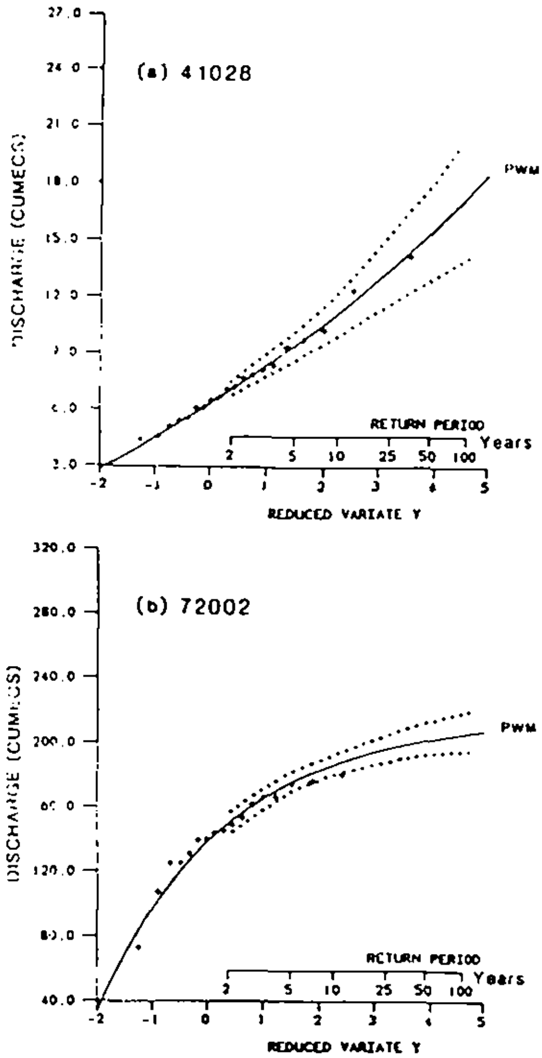


Figure 8. Jackknife standard errors

The *Kolmogorov-Smirnov* statistic is one of a number of so-called empirical distribution function (EDF) statistics which compare, at each data value (x), the observed non-exceedence probability (O=rank/number) with the expected value (F) derived from the chosen distribution. A more powerful EDF statistic is the Anderson-Darling, representing an integral weighted square error between O and F. Ahmad et al (1988) have recently studied a modified form (M) of this statistic with the weighting function (1-F(x)) biassed towards errors at high return period.

$$M = N \int_0^{\infty} \frac{(O(x)-F(x))^2}{(1-F(x))} \, dF(x) \qquad (3.3.4)$$

Integrating for constant $O(x)$ between x_i and x_{i+1}, and summing over the x_i gives the calculation formula:

$$M = N/2 - 2\sum_{i=1}^{N} F_i - (1/N)\sum_{i=1}^{N} \{(2i-1)\ln(1-F_i)\} \qquad (3.3.5)$$

In a series of simulation experiments, they derived samples from a known GEV parent distribution, fitted a GEV to the sample (to give F values), and derived the corresponding M values. In this way they built up a probability distribution for M, and then derived an equation for exceedance probability:

$$p(M) = \sin^2(h(M)) \qquad (3.3.6)$$

where $h(M) = -0.9394 + 0.9939M - 0.05411/M^{3/2} + 0.3476/M - 0.7785M/N^{1/2} + 0.05715/(MN^{1/2})$

Using this equation, it is possible to estimate the probability of a sample with a given M value coming from the fitted distribution.

Thus for each catchment, the M value of the fitted GEV was found and the corresponding probability derived. In general, these probabilities seemed well correlated with the trustworthiness of the T-year flood estimates, and indeed the three catchments given the lowest eyeball limit (27035,29004,41007) had the lowest probabilities (less than 0.5%). However, the correlation was not felt to be strong enough to provide a suitable objective method of setting maximum trustworthy T. In particular, long records were penalised where, although the distribution departed from the data, intuitively reasonable T-year estimates could still be obtained. For the example catchments in Figure 5 on page 17, plots (b) and (d) gave probabilities of 14% and 2%, while plots (a) and (c) gave probabilities of 95% and 98%. As expected, plots (e) and (f) gave lower probabilities of 35% and 15%, but unexpectedly similar values (44% and 23%) were given by plots (g) and (l). Plots (h) to (k) all gave 1% or less.

3.3.3 Combined standard errors and goodness of fit

From the analysis described in Sections 3.3.1 and 3.3.2 it seems that neither standard errors nor goodness of fit statistics alone can quantify the intuitive confidence a hydrologist has in flood frequency estimates based on visual inspection of flood frequency plots. Standard errors, in general, reduce with the length of record, but seem to be too closely associated with the form of the distribution rather than any apparent lack of fit. Goodness of fit generally gets worse with longer records where, although the overall fit may be adequate, small local departures are heavily penalised.

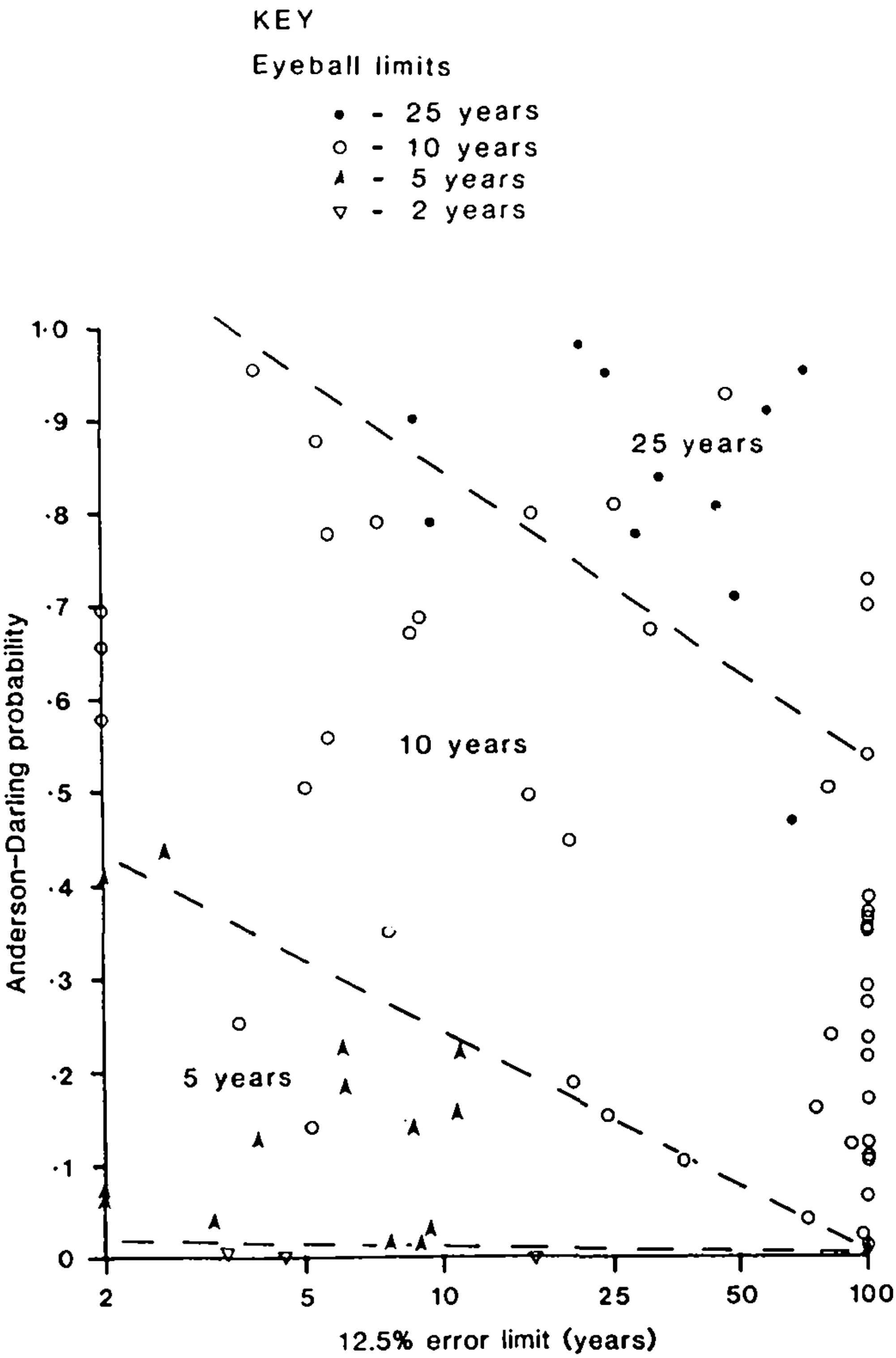


Figure 9. Comparison of assessment criteria

Since standard errors and goodness of fit are complementary, it was felt that a combination might be useful in defining the maximum trustworthy T. Figure 9 shows shows each catchment plotted on a graph of Modified Anderson-Darling probability (goodness of fit) against the jackknife (standard error) limit, with different symbols used to show the chosen eyeball limits. Overall, this figure seems to confirm that the eyeball limits combined both ideas. Furthermore, although the arguments are somewhat circular, the figure suggests that the eyeball limits have been applied in a reasonably consistent manner. Catchments which did not fit the trend were re-examined, but the eyeball limits were not redefined. The eyeball limits seemed consistent enough to use in the next stage of the comparisons.

A number of ideas for further work have been identified in the in the course of the investigations described in this chapter and are discussed in Chapter 8.

4.0 ESTIMATING T-YEAR FLOOD PEAKS BY INDIRECT METHODS

4.1 INTRODUCTION

The main objective of this study was to establish how well the FSR rainfall-runoff method of flood estimation works. This was achieved by comparing values calculated from flood data with estimates obtained using FSR methods. Chapter 3 described how "true" values were obtained as a basis for comparison. This section describes the various estimated values.

4.2 THE RAINFALL-RUNOFF METHOD

The FSR rainfall-runoff method can be applied at sites with no hydrological data by using estimates of model parameters based on catchment characteristics derived from maps. The details of this method are given in the FSR and are not repeated here. FSSR16 revised the parameter estimation equations, and therefore slightly different estimated flood peaks are obtained. Two sets of estimates corresponding to the FSR and FSSR16 model parameter estimation equations were calculated.

In both the FSR and FSSR16 it is recommended that, where possible, the model parameter values obtained from the regression equations are replaced with, or revised using, values from observed data. By analysing flood events, values of percentage runoff and unit hydrograph time-to-peak can be derived. Two types of data can be distinguished. Firstly, data collected at the site of interest, which may be called observed data. Since flood estimates are usually required at ungauged sites, this is rarely available. However, on large schemes there may be time to install equipment and collect data from at least a few storm events. The second type of data is usually referred to as local data, meaning that it has been collected at a station local to the site of interest. If the gauged catchment is sufficiently similar to that for which the estimates are required, information can be transferred between the sites. In this study only the utility of observed data was examined, and then only with the FSSR16 version since this is the currently recommended rainfall-runoff method.

Percentage runoff is not transferred directly from analysis to the design method, but is adjusted to a standard percentage runoff according to the catchment wetness and the rainfall depth. An adjustment is also made to remove the effect of urbanisation. Thus from an observed value of percentage runoff, PR, rural percentage runoff is calculated using the equation:

$$PR_{rural} = (PR - 21.0\ URBAN) / (1.0 - 0.3\ URBAN) \quad (4.1)$$

Standard percentage runoff (SPR) is calculated by subtracting two dynamic terms, DPR_{cwi}, *which is the dynamic contribution to percentage runoff* based on catchment wetness index (CWI), and DPR_{rain}, the dynamic term based on rainfall depth (P). Thus:

$$SPR = PR_{rural} - DPR_{cwi} - DPR_{rain} \quad (4.2)$$

where

$$DPR_{cwi} = 0.25 (CWI - 125) \quad (4.3)$$

in which

$$CWI = 125 + API - SMD \quad (4.4)$$

API is a 5-day antecedent precipitation index defined in FSR I.6.4.4, SMD is the estimated soil moisture deficit, and

$$DPR_{rain} = 0.45 (P - 40)^{0.7} \text{ for } P > 40mm \quad (4.5)$$

$$= 0 \quad \text{for } P \leqslant 40mm$$

It is recommended that SPR values should be calculated from at least five events. If they agree reasonably, then their average should be used in design flood calculations.

The observed event data can also be used to derive unit hydrographs. This can be done in two ways. The triangular FSR unit hydrograph can be replaced with an ordinate-by-ordinate representation, or the triangular form can be retained but with a time to peak derived from observed data. Only the latter form of modification was used in this study; again average values of time to peak were calculated from at least five events.

Revised T-year flood peak estimates were calculated using the FSSR16 method for four cases:

1. with model parameters estimated from catchment characteristics ("no data"),

2. with SPR from observed data,

3. Tp from observed data, and

4. with both observed SPR and Tp.

Some of the catchments available contained large urban areas. For such catchments it is recommended that the basic method of flood estimation is modified; the revised technique is described in FSSR5. The main difference between the FSR method and FSSR5 was the different way in which the increased runoff from urban areas was handled. However, FSSR16 uses the same urban correction as FSSR5. The methods for rural and urban flood estimation now differ only in the return period of the rainfall event required to estimate the flood of specifed return period, and the shape of the rainfall profile. This study was concerned only with the method for rural catchments; estimates calculated for catchments with large urban fractions use the rural method. It was hoped that these estimates would indicate the suitability of the method on urban catchments.

4.3 THE STATISTICAL METHOD

Although the primary aim of the study was to assess the performance of the rainfall-runoff method, estimates were also calculated using the FSR statistical technique based on catchment characteristics. Again the rural catchment method was applied to all catchments even where an urban adjustment was appropriate.

4.4 SUMMARY

"True" flood quantiles were calculated from observed annual maxima in Chapter 3. Six indirect methods of estimating flood magnitudes have been desribed in this chapter:

1. Using the FSR statistical method based on catchment characteristics: FSR/STATS(CC).

2. Using the FSR rainfall-runoff method based on catchment characteristics: FSR/RF-RO(CC)

3. Using the rainfall-runoff method based on catchment characteristics with FSSR16 modifications: FSSR16(CC)

4. As 3 but with observed data values of Tp and SPR: FSSR16(Tp&SPR)

5. As 3 but with observed data values of Tp: FSSR16(Tp)

6. As 3 but with observed data values of SPR: FSSR16(SPR)

5.0 RESULTS

5.1 INTRODUCTION

For each of the 88 catchments, floods of five return periods (2, 5, 10, 25 and 50 years) were estimated using the six different methods described in Chapter 4. These estimates were then compared with the respective flood quantiles derived from observed flow data as described in Chapter 3. Results are presented in two ways.

The accuracy of flood quantile estimates are compared across all catchments.

Flood frequency curves for each catchment are examined in terms of slope and index flood.

In order to assess the individual influence of particular catchments and ranges of catchment type (indexed by the physical characteristics), analyses were performed on various subsets of the 88 catchments. Some of these are described in detail in the text whilst the results from all subsets analysed are given in Appendix A.

5.2 PERFORMANCE STATISTICS

For each catchment a relative error was calculated for each of the 30 estimates (five return periods and six methods) using:

$$RT_{ij} = (QT_{ij} - QT_i) / QT_i \qquad (5.2.1)$$

where QT_{ij} is the T year return period flood quantile estimated on catchment i using method j and QT_i is the same flood quantile from the observed flow data at the gauging station. A positive value indicates that the method is predicting a peak flow greater than that observed, ie. overestimation, whereas a negative value indicates underestimation.

A residual statistic, defined in log space, was used by Lynn (1978) in his comparison of several flood frequency estimation methods.

$$RT'_{ij} = \log \ (QT_i / QT_{ij}) \qquad (5.2.2)$$

Rather confusingly underestimation results in negative value using Equation 5.2.1 but a positive value using Equation 5.2.2.

To examine how well the models performed over a range of catchments, these residuals were used to calculate two summary statistics.

$$\text{mean}_j = 1/n \sum RT_{ij} \qquad (5.2.3)$$

where the mean_j is the average value of the residual for return period T calculated using method j over all catchments 1 to n. This equation gives the mean residual, or bias, describing how well the method is doing, on average, over the range of catchments included in the calculation. The statistic indicates the expected accuracy of an estimate on a catchment chosen at random from the sample.

$$RMS_j = \sqrt{1/n \sum (RT_{ij}^2)} \qquad (5.2.4)$$

This equation provides the root mean square residual, RMS, indicating the variability of the estimates about zero rather than about the mean residual. This root mean square residual should only be used where the mean residual is close to zero.

5.3 THE STANDARD SET OF CATCHMENTS AND RETURN PERIODS

The full data set contained flood magnitudes from 88 catchments, 5 returns periods and 6 estimation methods. However, as already noted, some of these estimates come from urbanised catchments for which the methods are considered inappropriate, or are for return periods beyond our eyeball limit. A data set was identified that comprised those 74 catchments with less than 10% of the drainage area under urban development and with the quantiles restricted to those within the eyeball limits described in Chapter 3. This "standard data set" is used as the benchmark for many comparisons in the following sections. It is noteworthy that this set of 74 catchments contains quantiles up to the 25 year return period only, ie. no 50 year flood estimates were felt to be sufficiently reliable.

5.4 COMPARISON WITH RESULTS FROM LYNN (1978)

The residuals calculated for the 74 catchments, using the logarithm-based residual defined in Equation 5.2.2 for the 2 and 10 year return period floods were compared with the corresponding results reported by Lynn (1978). These two sets of statistics are given in the upper section of Table 5.4.1. They display a similar pattern of results ie. the statistical method is out-performing the rainfall-runoff method in terms of both mean and RMS residuals. The statistical method is almost unbiassed whereas the rainfall-runoff method overestimates, on average, both the 2 and 10 year floods. The RMS statistics are larger, in all cases for the Lynn data set. This may be partly due to the data sets comprising different catchments, but is more likely to result from exclusion of observed quantiles which were felt to be of poor quality in this study (Boorman, Acreman and Packman, abbreviated to BAP in Table 5.4.1). Shown in the lower half of Table 5.4.1 are the mean and RMS statistics based on the relative error (Equation 5.2.1). These show the same basic pattern of the rainfall-runoff model overestimation and the better performance of the statistical method in both bias and variability. It should come as no surprise that the statistical method performs better at low return periods since it has been calibrated directly against the mean annual flood.

The logarithm-based residuals have only been used to compare results with those reported by Lynn. In the remainder of the chapter comparisons are based on the relative error as given by Equation 5.2.1. However, Appendix A contains all four statistics for all subsets of catchments examined.

		n		RT'_{ij} mean		RMS	
		BAP	Lynn	BAP	Lynn	BAP	Lynn
2	1 FSR/STATS(CC)	74	43	0.01	0.05	0.16	0.21
	2 FSR/RF-RO(CC)	74	43	-0.05	-0.06	0.21	0.32
10	1 FSR/STATS(CC)	57	38	0.02	0.00	0.15	0.16
	2 FSR/RF-RO(CC)	57	38	-0.06	-0.19	0.19	0.35

	Method		RT_{ij} mean	RMS
2	1 FSR/STATS(CC)	74	0.06	0.43
	2 FSR/RF-RO(CC)	74	0.27	0.89
10	1 FSR/STATS(CC)	57	0.02	0.37
	2 FSR/RF-RO(CC)	57	0.28	0.72

Table 5.4.1 Statistics for return periods 2 and 10 years for the FSR statistical and rainfall-runoff methods for the standard catchment set used in this study (BAP) and those derived by Lynn (1978).

5.5 COMPARISON OF ORIGINAL FSR AND FSSR16 METHODS

As described in Chapter 1, Boorman (1985) found that the revisions to the FSR rainfall-runoff parameter estimation equations (FSSR16) in general left the flood estimates only slightly changed from those obtained using the orginal equations. Table 5.5.1 shows a comparison of results using the FSSR16 and the original FSR equations. It can be seen that overall the FSSR16 method performs slightly better than the original FSR method in terms of both mean and RMS relative errors, with both methods overestimating by, on average, 22-41%. The FSSR16 method is the current recommendation and hence the FSR method is not considered further in this chapter, although comprehensive results are given in Appendix A.

T		Method	n	RT_{ij} mean	RMS
2	2	FSR/RF-RO(CC)	74	0.27	0.89
	3	FSSR16(CC)	74	0.22	0.73
5	2	FSR/RF-RO(CC)	71	0.37	0.92
	3	FSSR16(CC)	71	0.34	0.77
10	2	FSR/RF-RO(CC)	57	0.28	0.72
	3	FSSR16(CC)	57	0.28	0.64
25	2	FSR/RF-RO(CC)	15	0.39	0.96
	3	FSSR16(CC)	15	0.41	0.83

Table 5.5.1 Statistics for return periods 2, 5, 10 and 25 years for the FSR/RF-RO(CC) and FSSR16(CC) methods.

5.6 USE OF MODEL PARAMETERS FROM FLOOD EVENT DATA

The FSR strongly recommends that values for the rainfall-runoff model parameters derived from flood events observed on the catchment should be used in preference to those values given by the catchment characteristic based equations. Flood estimates were derived using the FSSR16 model with parameters obtained from observed SPR and Tp data. The residuals were then compared with those from using the no-data equations in the same method. The results are given in Table 5.6.1. For all return periods the bias is reduced by using observed data; slightly when observed Tp is used, more so when observed SPR is used. Using both observed Tp and SPR makes a substantial improvement, for example, reducing the average overestimation of the 25 year flood from 41% to 11%. Using both observed Tp and SPR also reduces the

RMS residual. However, it can be seen that this decrease results *predominantly from using SPR, since using observed Tp alone increases* the variability of the estimates of all but the 10 year return period flood quantiles.

i		Method	n	RT_{ij} mean	RMS
2	3	FSSR16(CC)	74	0.22	0.73
	4	FSSR16(Tp&SPR)	74	-0.01	0.35
	5	FSSR16(Tp)	74	0.16	0.83
	6	FSSR16(SPR)	74	0.07	0.39
5	3	FSSR16(CC)	71	0.34	0.77
	4	FSSR16(Tp&SPR)	71	0.07	0.32
	5	FSSR16(Tp)	71	0.26	0.83
	6	FSSR16(SPR)	71	0.16	0.38
10	3	FSSR16(CC)	57	0.28	0.64
	4	FSSR16(Tp&SPR)	57	0.06	0.27
	5	FSSR16(Tp)	57	0.17	0.61
	6	FSSR16(SPR)	57	0.16	0.37
25	3	FSSR16(CC)	15	0.41	0.83
	4	FSSR16(Tp&SPR)	15	0.11	0.41
	5	FSSR16(Tp)	15	0.41	1.04
	6	FSSR16(SPR)	15	0.16	0.40

Table 5.6.1 Statistics for return periods 2, 5, 10 and 25 years comparing the utility of observed data.

Since observed Tp and SPR are usually available together and because using both gives the best estimates, further results obtained using methods FSSR16(Tp) and FSSR16(SPR) are not considered further in the body of this report but are contained in Appendix A. The remainder of this chapter considers the three methods:

1. FSR/STATS(CC),
3. FSSR16(CC) and
4. FSSR16(Tp&SPR)

5.7 RESULTS FROM THE STANDARD SET

Table 5.7.1 shows the statistics for return periods 2, 5, 10 and 25 years for the standard catchment set, for the three methods chosen for detailed analysis. The most striking result is that the majority of the values in the first column are positive indicating that the methods are, on average, over-estimating the flood peaks. Only for one method (FSSRTp&SPR) and one return period (2-years) is there, on average, underestimation. The figure of -0.01 indicates that on average this method is underestimating the 2-year return period flood peak by 1%. Both this and the statistical method show a small overall bias; only for the 25 year quantiles does it reach 10%. The RMS statistics are smallest for the statistical method for the 25 year quantile, but the FSSR16 method with observed data shows smaller variability in the 2, 5 and 10 year cases.

		Method	n	RT_{ij} mean	RMS
2	1	FSR/STATS(CC)	74	0.06	0.43
	3	FSSR16(CC)	74	0.22	0.73
	4	FSSR16(Tp&SPR)	74	-0.01	0.35
5	1	FSR/STATS(CC)	71	0.02	0.36
	3	FSSR16(CC)	71	0.34	0.77
	4	FSSR16(Tp&SPR)	71	0.07	0.32
10	1	FSR/STATS(CC)	57	0.02	0.37
	3	FSSR16(CC)	57	0.28	0.64
	4	FSSR16(Tp&SPR)	57	0.06	0.27
25	1	FSR/STATS(CC)	15	0.09	0.32
	3	FSSR16(CC)	15	0.41	0.83
	4	FSSR16(Tp&SPR)	15	0.11	0.41

Table 5.7.1 Statistics for return periods 2, 5, 10 and 25 years comparing the performance of three models on standard set of catchments.

It is necessary to remember the characteristics of the two methods when considering these results. FSR/STATS(CC) uses a regression of the mean annual flood on six catchment characteristics and a regionally based multiplier; it should therefore be expected that very good estimates of the 2-year flood are obtained. To estimate more extreme floods with this method a family of regional growth curves is used and the quality of the estimates will decrease. On the other hand the rainfall-runoff method uses catchment characteristics in a less direct fashion and contains no regionalisation. Estimates from FSSR16(CC) are therefore unlikely to be as good as those using FSR/STATS(CC) at low return periods. What might not have been anticipated is that the use of observed data in FSSR(Tp&SPR) improves results only to the same level as obtained with FSR/STATS(CC). It is, unfortunately, not possible to establish the relative performance of the methods at higher return periods.

5.8 RESULTS FROM THE FULL SET

Table 5.8.1 shows the statistics for return periods 2, 5, 10, 25 and 50 years using each of the three methods on all 88 catchments, thus relaxing the eyeball limits and including the more heavily urbanised catchments. The performance of the rainfall-runoff method is considerably worse than on the standard set, even with observed data. These results would seem to justify the need to have a specific method for urban catchments and to restrict the return periods to a reasonable limit.

Curiously the statistical method displays a smaller bias on this set of catchments than on the standard set, although the RMS is slightly worse.

				RT_{ij}	
		Method	n	mean	RMS
2	1	FSR/STATS(CC)	88	0.01 (0.06)	0.43 (0.43)
	3	FSSR16(CC)	88	0.34 (0.22)	1.13 (0.73)
	4	FSSR16(Tp&SPR)	88	0.10 (-0.01)	0.89 (0.35)
5	1	FSR/STATS(CC)	88	-0.02 (0.02)	0.39 (0.36)
	3	FSSR16(CC)	88	0.48 (0.34)	1.30 (0.77)
	4	FSSR16(Tp&SPR)	88	0.21 (0.07)	1.06 (0.32)
10	1	FSR/STATS(CC)	88	-0.02 (0.02)	0.38 (0.37)
	3	FSSR16(CC)	88	0.47 (0.28)	1.28 (0.64)
	4	FSSR16(Tp&SPR)	88	0.20 (0.06)	1.05 (0.27)
25	1	FSR/STATS(CC)	88	0.01 (0.09)	0.40 (0.32)
	3	FSSR16(CC)	88	0.46 (0.41)	1.31 (0.83)
	4	FSSR16(Tp&SPR)	88	0.20 (0.11)	1.04 (0.41)
50	1	FSR/STATS(CC)	88	0.05	0.46
	3	FSSR16(CC)	88	0.48	1.36
	4	FSSR16(Tp&SPR)	88	0.23	1.14

Table 5.8.1 Statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of three models on all 88 catchments. Statistics for the standard set are shown in brackets.

5.9 EXCLUDING CATCHMENT 39004

It was noted that from one catchment 39004, the Wandle at Beddington, the flood frequency curves generated by the rainfall-runoff methods provided very poor estimates of those derived from the observed data (Figure 10). Even when using observed flood event data, estimates of the percentage runoff were far too high. In contrast the FSR/STATS(CC) method performs well on this catchment. The River Wandle is underlain predominantly by chalk but has an urban fraction of 0.39, characteristics that together present particular problems for flood frequency estimation. In Chapter 6 details are presented of flood estimation problems on another catchment with a high proportion of WRAP type 1 soils, the Waithe Beck at Brigsley; the same problem occurs on the Wandle and it would be inappropriate to delve too deeply into causes for poor estimation on an individual catchment at this point. It is, however, worth noting that while observed SPR data does improve the estimates, using observed time to peak makes estimates worse. This is because the derived unit hydrographs have a very different shape to the triangular unit hydrograph used in making the flood estimates.

To test this catchment's influence on the overall results the statistics in Table 5.8.1 were recalculated after excluding this catchment. The results are shown in Table 5.9.1. A comparison of this table with Table 5.8.1 shows that, for the rainfall-runoff methods, the degree of improvement is marked. For each return period the bias is reduced by around 10% and the RMS is also significantly smaller, whereas the results for the statistical method are virtually unchanged. This demonstrates the considerable effects that a single poorly modelled catchment can have on the overall results. The comparison of Table 5.9.1 with the standard set given in Table 5.7.1 perhaps gives a more realistic impression of the effects of including the urban catchments and removing the quantile limit constraints. To aid this comparison the statistics for the standard set are given in brackets on Table 5.9.1. For the 5 and 10 year floods the bias and variability of both rainfall-runoff methods has increased by including the urban catchments and relaxing the return period limits. Results for the 2 and 25 year floods are about the same. It can be concluded that the overall performance of the model is not being unduly influenced by the inclusion of urban catchments or poorly estimated observed quantiles.

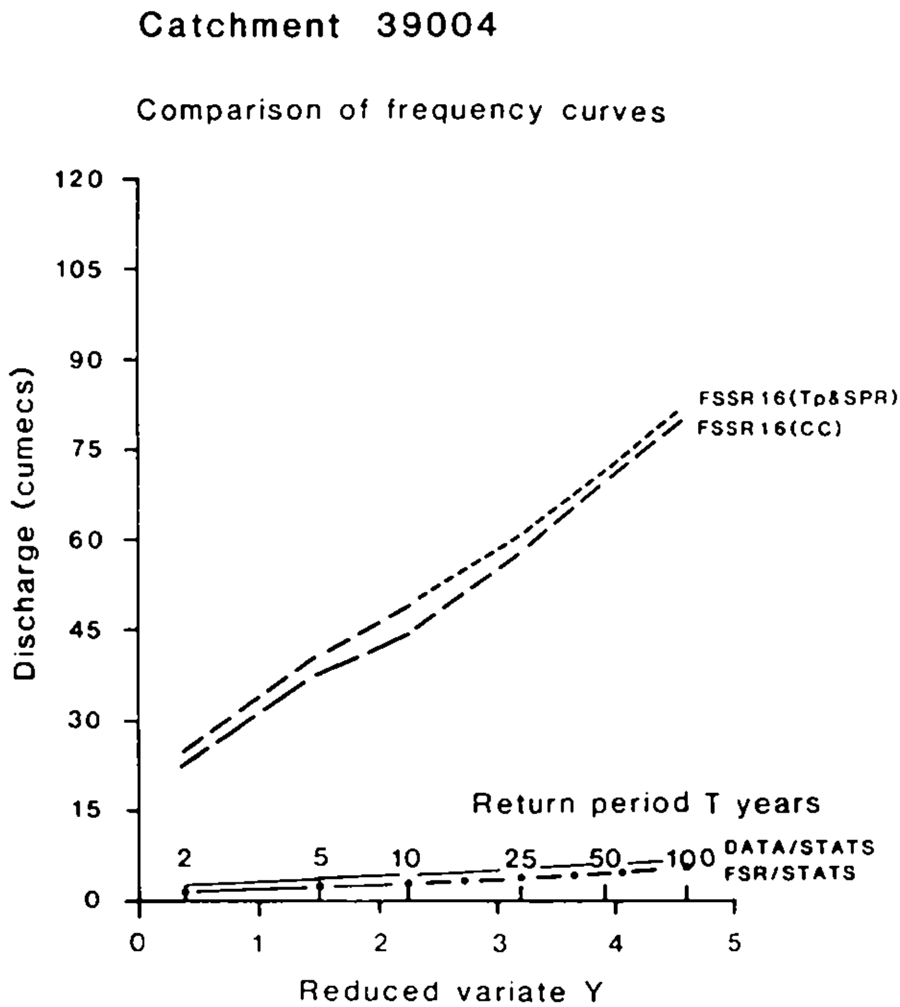


Figure 10. Flood frequency curves for the Wandle at Beddington (39004)

Return period		Method	n	RT_{ij} mean	RMS
2	1	FSR/STATS(CC)	87	0.02 (0.06)	0.43 (0.43)
	3	FSSR16(CC)	87	0.25 (0.22)	0.73 (0.73)
	4	FSSR16(Tp&SPR)	87	0.00 (-0.01)	0.34 (0.35)
5	1	FSR/STATS(CC)	87	-0.02 (0.02)	0.39 (0.36)
	3	FSSR16(CC)	87	0.38 (0.34)	0.79 (0.77)
	4	FSSR16(Tp&SPR)	87	0.10 (0.07)	0.34 (0.32)
10	1	FSR/STATS(CC)	87	-0.01 (0.02)	0.38 (0.37)
	3	FSSR16(CC)	87	0.37 (0.28)	0.78 (0.64)
	4	FSSR16(Tp&SPR)	87	0.10 (0.06)	0.36 (0.27)
25	1	FSR/STATS(CC)	87	0.02 (0.09)	0.40 (0.32)
	3	FSSR16(CC)	87	0.35 (0.41)	0.77 (0.83)
	4	FSSR16(Tp&SPR)	87	0.10 (0.11)	0.40 (0.41)
50	1	FSR/STATS(CC)	87	0.05	0.45
	3	FSSR16(CC)	87	0.37	0.81
	4	FSSR16(Tp&SPR)	87	0.12	0.46

Table 5.9.1 Statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of three models on all 88 catchments except 39004 the Wandle at Beddington. Statistics for the standard set are shown in brackets.

5.10 EXCLUDING CATCHMENTS UNDERLAIN BY WRAP TYPE 1 SOILS

The Wandle catchment is underlain by soils with a high Winter Rain Acceptance Potential. It was speculated that the rainfall-runoff models were performing relatively badly on other catchments with high proportions of WRAP type 1 soils. Table 5.10.1 shows the results from a set of catchments which have less than 20% WRAP type 1 soil. These figures can be compared with those from the standard set which are given in brackets. The FSR/STATS results are about the same, or slightly worse, suggesting that it is performing relatively well on the catchments underlain by WRAP type 1 soil. An improvement in the results is evident for FSSR16(CC), and, with FSSR16(Tp&SPR), the statistics are slightly better. This implies that the rainfall-runoff method is indeed working poorly on these catchments when no observed data are available and that observed Tp and SPR provide valuable information. It is noteworthy that on this set of catchments the rainfall-runoff model with observed data shows smaller variability than the statistical method and the bias is only greater for the 5 year return period floods. Furthermore, overestimation is, for this set, no greater than 12% for any return period, and is virtually unbiassed at the 2 and 10 year quantiles when observed data are employed.

		Method	n	RT_{ij} mean	RT_{ij} RMS
2	1	FSR/STATS(CC)	55	0.09 (0.06)	0.45 (0.43)
	3	FSSR16(CC)	55	0.17 (0.22)	0.54 (0.73)
	4	FSSR16(Tp&SPR)	55	0.02 (-0.01)	0.30 (0.35)
5	1	FSR/STATS(CC)	53	0.04 (0.02)	0.38 (0.36)
	3	FSSR16(CC)	53	0.28 (0.34)	0.56 (0.77)
	4	FSSR16(Tp&SPR)	53	0.07 (0.07)	0.26 (0.32)
10	1	FSR/STATS(CC)	44	0.04 (0.02)	0.39 (0.37)
	3	FSSR16(CC)	44	0.25 (0.28)	0.55 (0.64)
	4	FSSR16(Tp&SPR)	44	0.04 (0.06)	0.24 (0.27)
25	1	FSR/STATS(CC)	11	0.14 (0.09)	0.32 (0.32)
	3	FSSR16(CC)	11	0.37 (0.41)	0.53 (0.83)
	4	FSSR16(Tp&SPR)	11	0.12 (0.11)	0.31 (0.41)

Table 5.10.1 Statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of three models on standard set excluding catchments with more than 20% WRAP type 1 soils. Statistics for the standard set are shown in brackets.

5.11 AMOUNT OF AVAILABLE OBSERVED EVENT DATA

A further set of statistics were derived to investigate whether improved quantile estimates would result from increasing the amount of observed event data. This was achieved by reducing the standard set of catchments to include only those with at least 10 available events from which SPR and Tp had been derived. Results for this subset of catchments are given in Table 5.11.1. Clearly the no-data methods should give similar results if the two subsets contain the same range of catchments. This appears to be the case for the rainfall-runoff method since the results are not significantly different from those for the standard set, given in brackets. Conversely, the statistical method performs slightly worse all round, which is presumably a curiosity of the mix of catchments in the two sets. The most important statistics are those for the observed data method. Only for the 25 year quantiles is variability and bias smaller. This result is based on only 13 catchments but suggests that the value of increasing the number of events available is only important for higher return periods. Complementary to the findings in Section 5.6, the full version of Table 5.11.1 in Appendix A (Table A.5) shows that the type of observed data available may be important. In all cases the variability of estimates is greater using observed Tp than when using no observed data at all. On the other hand, estimates using only observed SPR have similar RMS values to the use of both types of observed data. This suggests that there are probably a few catchments for which the no-data estimates of Tp are much better that those derived from the available events. On average the performance of the unit hydrograph model is improved by increasing the numbers of events with estimates of percentage runoff.

		Method	n	RT_{ij} mean	RMS
2	1	FSR/STATS(CC)	58	0.09 (0.06)	0.44 (0.43)
	3	FSSR16(CC)	58	0.23 (0.22)	0.72 (0.73)
	4	FSSR16(Tp&SPR)	58	0.01 (-0.01)	0.38 (0.35)
5	1	FSR/STATS(CC)	55	0.05 (0.02)	0.37 (0.36)
	3	FSSR16(CC)	55	0.35 (0.34)	0.77 (0.77)
	4	FSSR16(Tp&SPR)	55	0.08 (0.07)	0.34 (0.32)
10	1	FSR/STATS(CC)	41	0.05 (0.02)	0.38 (0.37)
	3	FSSR16(CC)	41	0.27 (0.28)	0.60 (0.64)
	4	FSSR16(Tp&SPR)	41	0.05 (0.06)	0.27 (0.27)
25	1	FSR/STATS(CC)	13	0.11 (0.09)	0.34 (0.32)
	3	FSSR16(CC)	13	0.40 (0.41)	0.87 (0.83)
	4	FSSR16(Tp&SPR)	13	0.04 (0.11)	0.37 (0.41)

Table 5.11.1 Statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of three models on standard set excluding catchments with less than 10 events. Statistics for the standard set are shown in brackets.

5.12 THE NUMBER OF ANNUAL MAXIMA AVAILABLE

In addition to eyeball limits, the amount of data available for deriving observed flood frequency estimates may give an indication of their accuracy. To test this, statistics were derived for a further subset of the standard set of catchments with at least 25 annual maxima. The results are given in Table 5.12.1. For FSSR16(Tp&SPR)

the RMS statistic is smaller for the 2 and 5 year floods, though not significantly so. Results for the 10 and 25 year floods show a decline in performance but are based on only 11 and 6 catchments respectively. Surprisingly the bias is greater for FSR/STATS(CC) and FSSR16(Tp&SPR). With observed data there is little difference. Overall, these results suggests that the errors are not due to poorly defined observed flood frequency curves caused by too few annual maxima.

				RT_{ij}	
		Method	n	mean	RMS
2	1	FSR/STATS(CC)	16	0.16 (0.06)	0.30 (0.43)
	3	FSSR16(CC)	16	0.35 (0.22)	0.71 (0.73)
	4	FSSR16(Tp&SPR)	16	-0.03 (-0.01)	0.31 (0.35)
5	1	FSR/STATS(CC)	16	0.11 (0.02)	0.25 (0.36)
	3	FSSR16(CC)	16	0.47 (0.34)	0.80 (0.77)
	4	FSSR16(Tp&SPR)	16	0.05 (0.07)	0.27 (0.32)
10	1	FSR/STATS(CC)	11	0.12 (0.02)	0.27 (0.37)
	3	FSSR16(CC)	11	0.52 (0.28)	0.89 (0.64)
	4	FSSR16(Tp&SPR)	11	0.12 (0.06)	0.33 (0.27)
25	1	FSR/STATS(CC)	6	0.29 (0.09)	0.36 (0.32)
	3	FSSR16(CC)	6	0.71 (0.41)	1.14 (0.83)
	4	FSSR16(Tp&SPR)	6	0.20 (0.11)	0.50 (0.41)

Table 5.12.1 Statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of three models on standard set excluding catchments with at least 25 years annual maximum floods. Statistics for the standard set are shown in brackets.

5.13 SPATIAL DISTRIBUTION OF RESIDUALS

Figure 11 shows the spatial distribution of residuals from the FSSR16 observed data method for the standard set at the 2 year flood. These residual values are given in Table 5.13.1, and for the 10 year flood in Table 5.13.2. The model underestimates in south-western parts of England and Wales, and there is a tendency for overestimation in south-east England. The findings for south-west England reproduce those reported by Lynn (1978) which also coincide with the residuals mapped in the FSR I.6.7.4(448), reproduced as Figure 26 on page 105. However, both Lynn and the FSR found underestimation in south-east England. The mixture of over- and underestimation de-

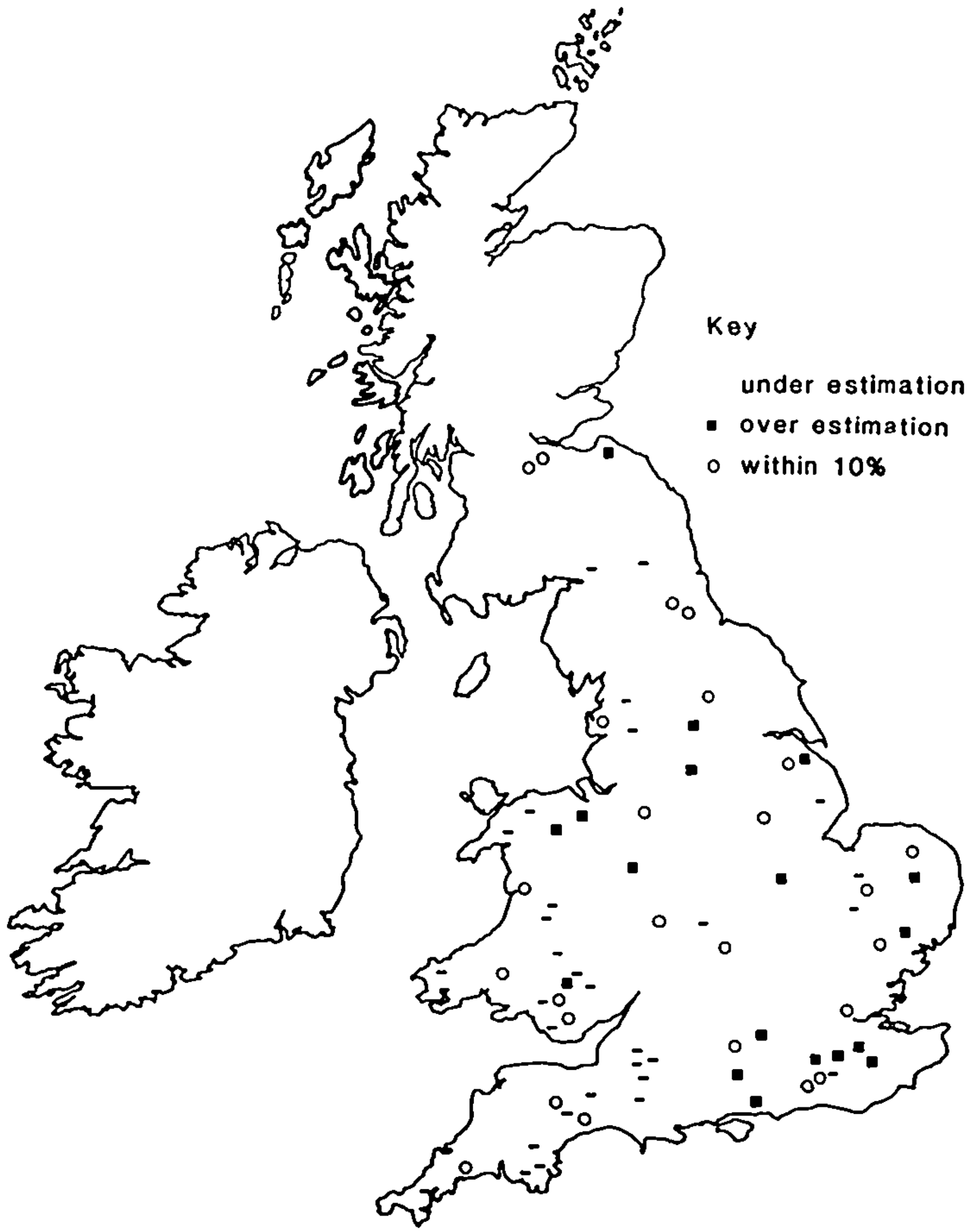


Figure 11. 2-year flood residuals using FSSR16(Tp&SPR)

picted in Figure 11 for the rest of the UK does not suggest regional patterns. However, it appears that underestimation dominates near to the west coast, with, generally, overestimation elsewhere.

The division line between these two regions follows, very roughly, the 800mm average annual rainfall isohyet. Table 5.13.3 shows that for catchments wetter than 800mm the average underestimation of the 2 year flood by the FSSR16 method using observed data is, on average, 6%. For catchments drier than 800mm the mean overestimation is 10%. The remainder of the table shows that the relative overestimation in the drier east of the UK is true also of the 5 and 10 year flood quantiles. Variability appears to be about the same in both regions.

It would be foolhardy to read to much into these results. Annual average rainfall is just providing a convenient way of splitting the catchments. The reason for the observed pattern of residuals is likely to be a combination of factors that will include soil type, topography and possibly design storm specification.

Catchment	Residual	Catchment	Residual
19002	0.09	46003	-0.45
19005	-0.08	46005	-0.45
20001	0.29	47007	-0.14
23005	-0.46	48004	0.04
24005	-0.08	48005	-0.43
24007	-0.06	52005	-0.23
27001	-0.02	52006	-0.19
27035	0.45	52010	-0.30
28070	0.36	53005	-0.31
29001	0.69	53007	-0.28
29004	-0.03	53009	-0.27
30001	0.05	54011	-0.02
30004	-0.19	54016	0.12
31005	0.22	54019	-0.37
33014	-0.48	54022	-0.17
33029	-0.25	55008	-0.22
33045	0.05	55012	-0.34
34003	0.00	56003	0.17
34005	0.12	56004	-0.20
35008	0.30	56006	-0.26
36008	0.09	57004	0.00
37001	-0.05	57005	0.04
39022	0.32	58001	-0.41
39025	-0.04	58002	-0.36
39026	0.02	60002	0.10
39053	0.16	61001	-0.17
40006	0.28	61003	-0.17
40009	0.29	64001	-0.04
40010	1.39	65001	-0.20
41005	0.03	66011	-0.12
41006	-0.29	67003	0.33
41007	0.30	67008	0.37
41015	1.67	68006	0.05
41028	0.06	71003	-0.18
45002	-0.03	71004	-0.19
45003	-0.19	72002	0.03
45004	-0.06	77002	-0.30

Table 5.13.1 Residuals for the 2 year return period showing the performance of the FSSR16(Tp&SPR) on the standard set. For example -0.02 indicates underestimation by 2%.

Catchment	Residual	Catchment	Residual
19002	0.10	48004	-0.09
19005	-0.06	48005	-0.40
20001	0.11	52005	-0.18
23005	-0.29	52006	-0.30
24005	0.05	52010	-0.25
24007	0.01	53005	-0.20
27001	0.04	53007	-0.14
29001	0.89	53009	-0.17
30001	0.15	54011	0.04
30004	-0.04	54016	0.34
31005	0.11	54022	-0.06
33029	0.21	55012	-0.14
33045	0.08	56003	0.18
34003	0.10	56004	-0.21
34005	0.08	56006	-0.19
35008	0.32	57004	-0.04
36008	0.02	57005	0.08
37001	0.08	58001	-0.24
39022	0.63	58002	-0.29
39025	0.17	60002	0.34
39053	0.57	61003	0.08
40009	0.50	64001	0.35
41006	-0.18	65001	-0.08
41028	0.27	66011	0.13
45003	-0.21	67003	0.50
45004	-0.07	68006	0.13
46005	-0.32	71003	-0.11
47007	0.38	72002	0.53
		77002	-0.21

Table 5.13.2 Residuals for the 10 year return period showing the performance of the FSSR16(Tp&SPR) on the standard set. For example -0.12 indicates underestimation by 12%.

		Method	n <	n >	RT_{ij} mean <800	RT_{ij} mean >800	RMS <800	RMS >800
2	1	FSR/STATS(CC)	24	50	0.08	0.05	0.40	0.44
	3	FSSR16(CC)	24	50	0.53	0.07	0.89	0.64
	4	FSSR16(Tp&SPR)	24	50	0.10	-0.06	0.37	0.34
5	1	FSR/STATS(CC)	23	48	0.03	0.01	0.29	0.39
	3	FSSR16(CC)	23	48	0.81	0.19	0.95	0.66
	4	FSSR16(Tp&SPR)	23	48	0.14	0.04	0.29	0.33
10	1	FSR/STATS(CC)	18	39	0.07	-0.00	0.30	0.40
	3	FSSR16(CC)	18	39	0.70	0.08	1.02	0.35
	4	FSSR16(Tp&SPR)	18	39	0.19	-0.01	0.30	0.26

Table 5.13.3 Statistics for return periods 2, 5, and 10 years comparing the performance of three models on standard set dividing the catchments into two groups on the basis of a threshold value of SAAR of 800 mm.

5.14 CATCHMENT SIZE

Further investigations were undertaken to examine whether the model performed better on large or small catchments. The standard set of 74 catchments was divided into two groups with AREA greater or less than 100 km^2. The resulting statistics for the two groups are given in Table 5.14.1. The statistical and no-data rainfall-runoff methods perform much better on the larger catchments in terms of both bias and variability for all but the 25 year floods, which are based on groups of only 5 and 10 catchments. In contrast, the rainfall-runoff method using observed data displays consistent performance for both groups of catchments. In can be concluded from these results that observed data are more beneficial on smaller catchments. This may result from the problem of accurately abstracting physical characteristics, such as soil type, on small catchments, whereas errors tend to average-out on larger catchments. Another possible explanation is that on small basins the response is dominated by the land phase of catchment response, which is difficult to model, whereas on larger basins response is dominated by the channel phase, which is relatively easy to model.

Return period		Method	n <	n >	RT_{ij} mean <100	RT_{ij} mean >100	RMS <100	RMS >100
2	1	FSR/STATS(CC)	25	49	0.24	-0.03	0.55	0.34
	3	FSSR16(CC)	25	49	0.42	0.12	1.00	0.54
	4	FSSR16(Tp&SPR)	25	49	0.01	-0.02	0.40	0.32
5	1	FSR/STATS(CC)	24	47	0.22	-0.09	0.47	0.29
	3	FSSR16(CC)	24	47	0.57	0.21	1.03	0.59
	4	FSSR16(Tp&SPR)	24	47	0.11	0.05	0.39	0.28
10	1	FSR/STATS(CC)	20	37	0.25	-0.10	0.48	0.28
	3	FSSR16(CC)	20	37	0.48	0.17	0.73	0.59
	4	FSSR16(Tp&SPR)	20	37	0.05	0.06	0.25	0.28
25	1	FSR/STATS(CC)	5	10	0.23	0.02	0.33	0.32
	3	FSSR16(CC)	5	10	0.46	0.39	0.46	0.96
	4	FSSR16(Tp&SPR)	5	10	0.28	0.03	0.40	0.41

Table 5.14.1 Statistics for return periods 2, 5, 10 and 25 years comparing the performance of three models on standard set dividing the catchments into two groups on the basis of a threshold value of area of 100 km^2.

5.15 COMBINING SUBSET SELECTION CRITERIA

There are a large number of possible combinations of restrictions which can be applied to produce subsets of catchments for comparison of the various techniques. In order to display the relative performance of the three primary methods on a number of subsets, a "bush diagram" was produced separately for each of four statistics, namely the 2 year mean and RMS and the 10 year mean and RMS. These are shown in Figure 12 to Figure 15. The diagrams contain a number of boxes each of which represents a combination of restrictions. Arrows leading to each box indicate the additional restriction imposed compared with the box from which the arrow originates. Hence the box at the extreme left contains the results for the full (88 catchment) data set, whereas the box on the far right contains the same statistics for a reduced set of catchments which satisfy all the restrictions imposed at once. In general, the numerical values decrease from left to right as the quality of the observed flood frequency curves increases and as the catchments on which the model performs poorly are omitted. Figure 12 shows that, in all subsets of the data, the basic rainfall-runoff model is, on average, over estimating the 2 year return period floods by around 20%. In contrast, when observed data are employed, this method displays little bias or slightly underestimates. This model performs predictably across the range of subsets. The bias reducing from 9% for all 88 catchments virtually to zero in many boxes on the right-hand side. Anomalies occur with the restriction on the number of annual maxima available. As indicated in Chapter 2, this is not a good indicator of the accuracy of observed quantiles. An explanation is that the subset of long record catchments just happens to include those on which the model performs relatively poorly. It may also be argued that this restriction reduces the number of catchments to a level where the results may be insignificant.

For the 10 year floods (Figure 14), both methods overestimate. This positive bias is small when observed data are used (less than 10%) but around 20-30% for the no-data case.

It is important to note that the number of catchments decreases from left to right. In the most restricted set only seven catchments remain, thus the sample is not very representative of the UK as a whole.

The RMS statistic for FSSR16(CC) decreases from over 70% on the left to just over 30% on the right for both the 2 and 10 year floods; the corresponding figures for FSSR16(Tp&SPR) are 22 and 11% respectively. In nearly all but the full 88 catchment set FSSR16(Tp&SPR) out-performs FSR/STATS(CC).

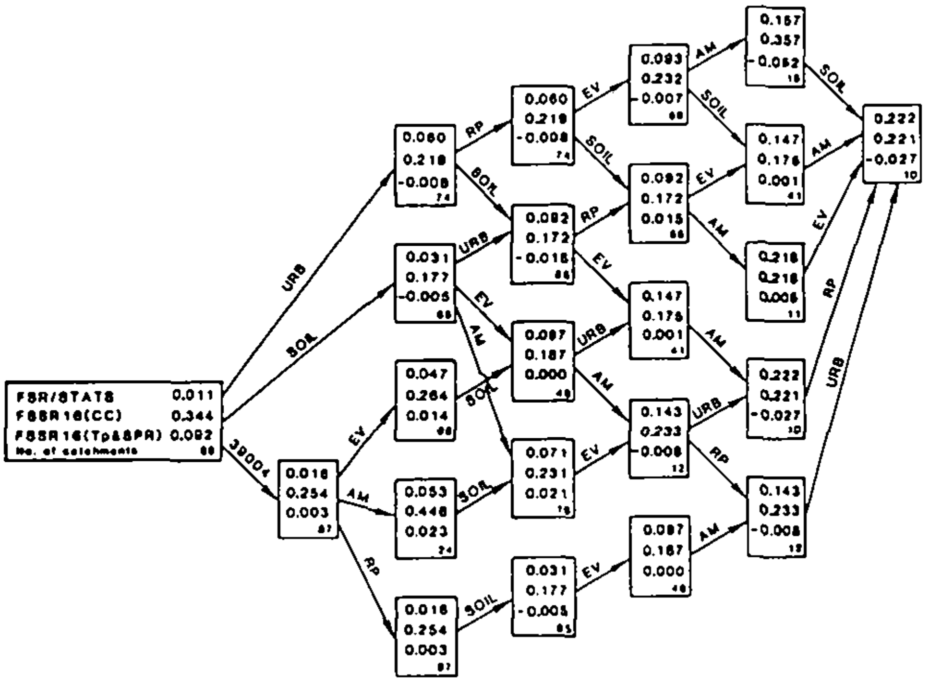


Figure 12. Bush diagram showing 2-year MEAN

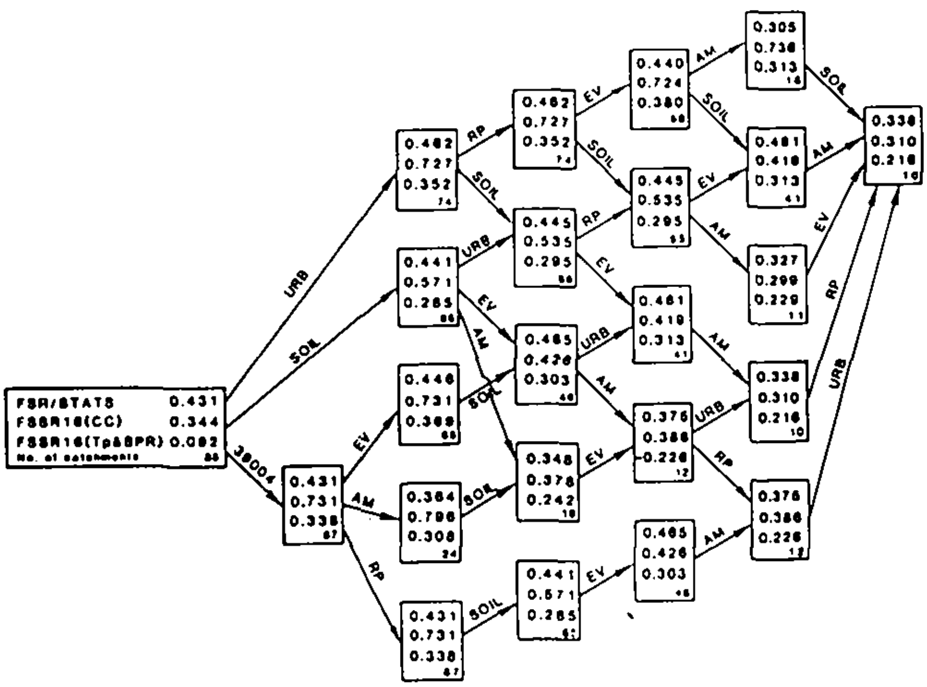


Figure 13. Bush diagram showing 2-year RMS

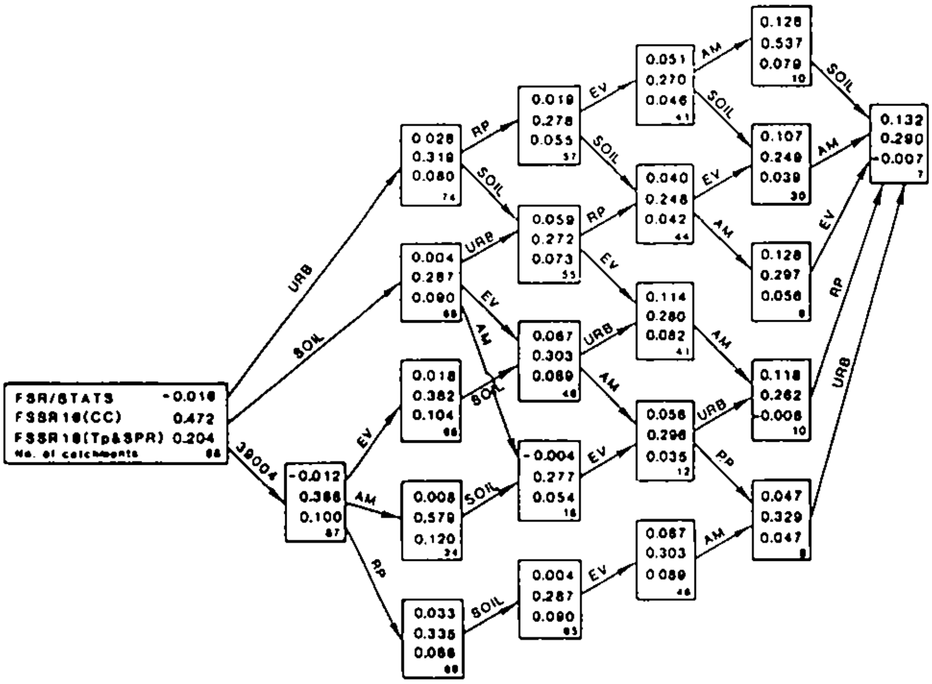


Figure 14. Bush diagram showing 10-year MEAN

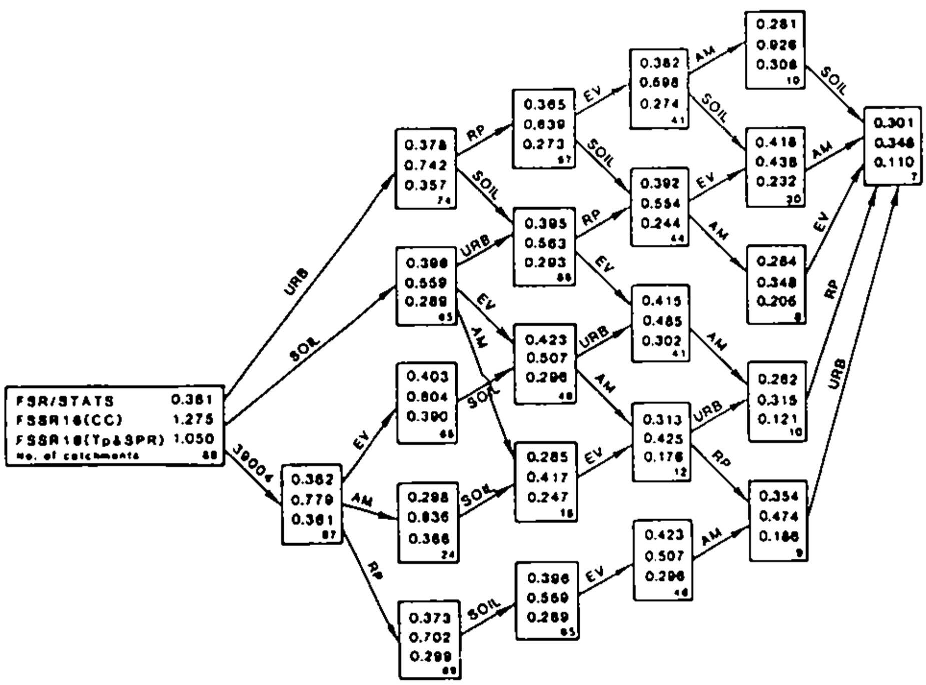


Figure 15. Bush diagram showing 10-year RMS

5.16 ASSESSING THE ENTIRE FLOOD FREQUENCY CURVE

The results presented so far have been in terms of the average error across all catchments in a set for individual quantiles. To examine the performance of the FSSR16 model (FSSR16(Tp&SPR)) on each catchment individually an index of the whole flood frequency curve was needed, indicating, for example, whether the estimated curves were too steep, too shallow, or about the right slope but always over- or underestimated. To achieve this objective the slope of the flood frequency curve was assumed to be adequately described by the slope of two segments of the curve

- the slope of the curve between the 2 and 10 year floods
- the slope of the curve between the 10 and 50 year floods.

In other words, how much larger is the 10 year than the 2 year return period flood, or the 50 year than the 10 year? The magnitude of the 10 year flood can be used to indicate the typical size of floods on the catchment and therefore fix the general location of the curve on the flood magnitude scale. In order to arrange the 88 curves into a small number of groups a 25-way classification system was devised. The slope of each segment was classified according to whether the value was

1.	a marked underestimate of that observed	< -20%
2.	a slight underestimate	-10% to -20%
3.	about the same	+10% to -10%
4.	a slight overestimate	10% to 20%
5.	a marked overestimate.	> 20%

Each of the 10 year flood indices was classified according to a similar 5-way scheme. Thus each catchment was assigned to one of 25 classes, each of which has a unique description eg. class two consists of those catchments where the slope of the curve is slightly underestimated and the index is markedly underestimated.

Table 5.16.1 shows the results of this 25-way classification as indexed by the 10 year return period flood and the ratio of the 10 and 50 year floods. Table 5.16.1 shows that the errors in both slope and index are not symmetrically distributed ie. there are relatively few catchments where the index or slope is slightly over- or under estimated, with the majority being either about right or very wrong. There are 26 (out of 78) catchments where the estimated flood frequency curve, between the 10 and 50 year floods, is too shallow and 30 where this slope is too steep. For 12 of these oversteep curves the index 10 year flood is also markedly overestimated.

Tables 5.16.2 and 5.16.3 show similar classifications for the 2 and 10 year return period floods, the former using the 10 year flood as the index, the latter using the 2 year flood. Table 5.16.2 shows that for 22 of the 88 catchments the slope is overestimated along with the 10 year flood. It is also noteworthy that in over half of the catchments (47) the ratio of 10 to 2 year flood has been overestimated by more than 20% and three-quarters by more than 10%. One possible explanation for these results is that the relationship between rainfall and flow return periods derived in the FSR simulation exercise (see Appendix B) is too steep.

The numbers in the right-hand boxes are reversed between Tables 5.16.2 and 5.16.3. This suggests that, for many catchments, the estimated flood frequency curves cross the observed, between the 2 and 10 year flood quantiles, thus the 2 year flood is underestimated and the 10 year flood is overestimated. The majority of catchments in Table 5.16.3 are still in the right-hand boxes indicating that the slope of the curve between the 2 and 10 year floods is markedly overestimated on as many catchments as the slope between the 10 and 50 year floods.

% ERROR RATIO OF 10 AND 50 YEAR FLOODS

% ERROR 10	<-20% Too flat	<-10%	-10% - +10% About right	>+10%	>+20% Too steep
<-20% Too small	*1 3	*2	*3 9	*4	*5 4
-20% - -10%	*6 3	*7	*8	*9	*10 1
-10% - +10% About right	* 11 9	*12 2	*13 7	*14 1	*15 2
10% - 20%	*16 1	*17 1	*18 4	*19 3	*20 1
>+20% Too big	*21 2	*22 1	*23 11	*24 4	*25 12

Number of catchments appears in centre of box.
Box number is in top left of box.

Box	Catchment numbers									
1	52006	55008	56004							
2	45003	54019	56006							
3	41006	46003	48005	52005	52010	53005	53009	58002	77002	
4	69027									
5	23005	33014	46005	58001						
6	39026	40006	71004							
7	56005									
8	71003									
9	53007									
10	55012									
11	34005	36008	41005	41007	45004	48004	54006	57004	57005	
12	27001	54022								
13	24005	24007	29004	33045	37001	54011	61003			
14	65001									
15	30004	38007								
16	31005									
17	68006									
18	19002	20001	37007	45002						
19	30001	34003	66011							
20	84012									
21	28070	40010								
22	56003									
23	19005	35008	39022	39025	39052	40009	41015	41028	54016	60002
	67008									
24	39004	54004	67003	84008						
25	19001	27035	29001	33029	39005	39007	39012	39053	47007	61001
	64001	72002								

Table 5.16.1 Classification of flood frequency curve estimates by method 5 (FSSR16(Tp&SPR)) according to the accuracy of estimation of the 10 year flood and ratio of 10 to 50 year floods as compared with observed data.

% ERROR RATIO OF 2 AND 10 YEAR FLOODS

% ERROR 10	<-20% Too flat	<-10%	-10% - +10% About right	>+10%	>+20% Too steep
<-20% Too small	*1	*2 0	*3 3	*4 5	*5 11
-20% - -10%	*6 2	*7 0	*8 0	*9 2	*10 3
-10% - +10% About right	*11 3	*12 2	*13 5	*14 4	*15 7
10% - 20%	*16 1	*17 1	*18 1	*19 3	*20 4
>+20% Too big	*21 2	*22 0	*23 5	*24 1	*25 22

Number of catchments appears in centre of box.
Box number is in top left of box.

Box	Catchment numbers								
1 52006									
3 45003	54019	56004							
4 48005	52005	52010	55008	56006					
5 23005	33014	41006	46003	46005	53005	53009	58001	58002	69027
77002									
6 39026	40006								
9 71003	71004								
10 53007	55012	56005							
11 41007	48004	54006							
12 36008	41005								
13 33045	34005	45004	57004	57005					
14 24007	27001	29004	54011						
15 24005	30004	37001	38007	54022	61003	65001			
16 20001									
17 31005									
18 19002									
19 30001	37007	68006							
20 34003	45002	66011	84012						
21 28070	40010								
23 19005	35008	41015	56003	84008					
24 19001									
25 27035	29001	33029	39004	39005	39007	39012	39022	39025	39052
39053	40009	41028	47007	54004	54016	60002	61001	64001	67003
67008	72002								

Table 5.16.2 Classification of flood frequency curve estimates by the method 5 (FSSR16(Tp&SPR)) according to the accuracy of estimation of the 10 year flood and ratio of 2 to 10 year floods as compared with observed data.

% ERROR RATIO OF 2 AND 10 YEAR FLOODS

% ERROR 2	<-20% Too flat	<-10%	-10% · +10% About right	>+10%	>+20% Too steep
<-20% Too small	*1	*2 0	*3 3	*4	*5 21
-20% - -10%	*6 0	*7 0	*8 0	*9 0	*10 2
-10% - +10% About right	*11 2	*12 2	*13 5	*14 7	*15 12
10% - 20%	*16 0	*17 0	*18 2	*19 0	*20 1
>+20% Too big	*21 6	*22 1	*23 4	*24 1	*25 11

Number of catchments appears in centre of box.
Box number is in top left of box.

Box	Catchment numbers									
1	52006									
3	45003	54019	56004							
4	48005	52005	52010	55008	56006	71003	71004			
5	23005	30004	33014	33029	38007	41006	46003	46005	53005	53007
	53009	54022	55012	56005	58001	58002	61001	61003	65001	69027
	77002									
10	47007	66011								
11	39026	48004								
12	36008	41005								
13	19002	33045	45004	57004	57005					
14	24007	27001	29004	30001	37007	54011	68006			
15	24005	34003	37001	39005	39012	39025	41028	45002	60002	64001
	72002	84012								
18	34005	84008								
20	54016									
21	20001	28070	40006	40010	41007	54006				
22	31005									
23	19005	35008	41015	56003						
24	19001									
25	27035	29001	39004	39007	39022	39052	39053	40009	54004	67003
	67008									

Table 5.16.3 Classification of flood frequency curve estimates by the method 5 (FSSR16(Tp&SPR)) according to the accuracy of estimation of the 2 year flood and ratio of 2 to 10 year floods as compared with observed data.

6.0 EXAMPLE CATCHMENTS

6.1 INTRODUCTION

In Chapter 5 results were given for the whole data set and for various subsets based on physical characteristics of the basins or the quantity and quality of hydrological data. In this section data and results are presented for six example catchments. These catchments are:

19001 Almond at Craigiehall
29001 Waithe Beck at Brigsley
39012 Hogsmill at Kingston
46003 Dart at Austins Bridge
54016 Roden at Rodington
55008 Wye at Cefn Brwyn

Three of these (19001, 39012 and 54016) were trial catchments in the FSR and therefore not used in developing the FSR regression equations or in the simulation exercise (Appendix B). These three catchments and 29001 were not used in the review of the FSR rainfall-runoff model parameter estimation equations on which FSSR16 is based. The extra two catchments are included to give a better distribution and range of catchment types. Values of catchment characteristics can be found in Table 2.1.

For each of the six catchments, two graphs are given comprising (a) the annual maximum data and the fitted curve, and (b) this curve plotted with the various estimated flood frequency curves. Beware of scale changes within each pair of figures.

Percentage runoff has already been identified as a most important variable to estimate well if accurate flood estimates are to be made. With this in mind, for some catchments, graphs are presented which illustrate how percentage runoff varies with rainfall for observed events, and how estimated percentage runoff increases using the FSSR16 model. Also shown in this figure is a curve that shows what percentage runoff would be required to estimate perfectly the fitted curve. The difference between this line and the FSSR16 model should not be viewed as the error in the PR model. Errors are obviously present at various stages of the estimation procedure. This perfect fit line gives a representation that assumes all such errors are in the PR term. If this line is quite different from the observed data it points to there being errors in some other part of the procedure.

6.2 19001: ALMOND AT CRAIGIEHALL

Period of record, N	:	29 years
Eyeball limit on return period	:	10 years
Return period for jackknife standard error of 12.5%	:	>100 years
Modified Anderson-Darling statistic	:	0.237

Firstly, consider the fit to the annual maximum data (Figure 16a). The fitted GEV has a positive k (0.14) and therefore curves downwards. The largest two peaks are well below the fitted line and are largely resposible for its downward curvature. Looking at the data points it might be thought that there is a kink at a return period of about 5 years (160 m^3/s). Such features in the plotted data can be caused by real catchment or hydraulic effects, or may be totally spurious. In a study involving so many catchments the data could not be investigated in detail. The authors would feel unhappy using the GEV curve to extrapolate beyond 10 years and would prefer to use an EV1 distribution. Below 10 years these two curves are very similar, hence the eyeball limit of 10 years. This is greatly less than the 60 years of the 2N rule. The modified Anderson-Darling statistic of 0.237 reflects the variation of the annual maxima about the fitted curve above 4 years. At first sight it seems surprising that the jackknife limit is greater than 100 years. This is because of the positive k; as return period increases the curve flattens and the standard deviation decreases.

From the estimated flood frequency curves (Figure 16b), it can be seen that the no data rainfall-runoff estimates are all too large and the curves too steep (hence the catchment appears at the bottom and to the right in the box diagrams in Tables 5.16.1, .2 & .3). Only four observed events were available but they gave model parameter values very similar to those obtained from regressions. These resulted in slightly larger estimated peaks. The statistical method underestimates the observed data.

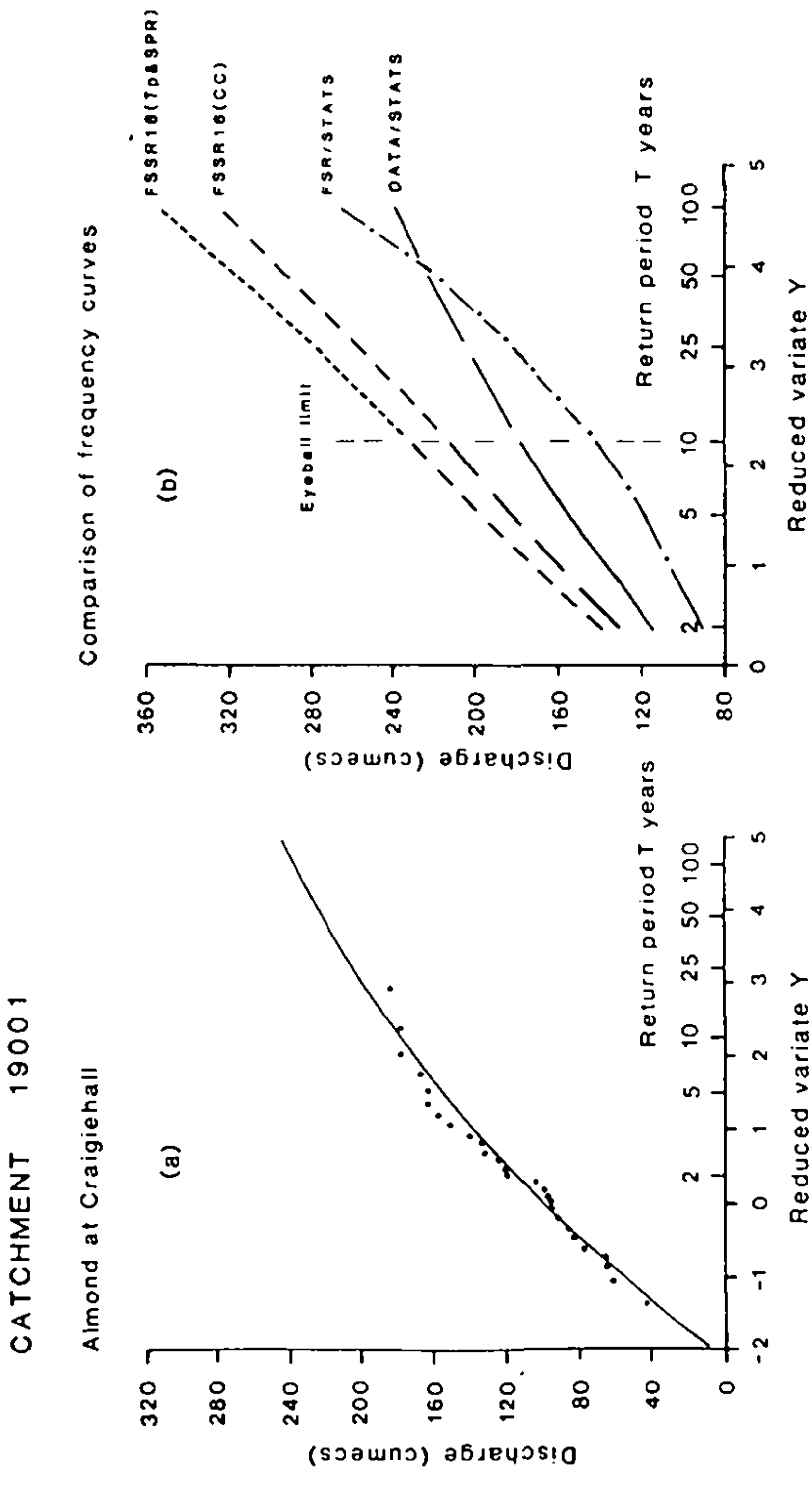


Figure 16. Almond at Craigiehall

6.3 29001: WAITHE BECK AT BRIGSLEY

Period of record, N	: 26 years
Eyeball limit on return period	: 25 years
Return period for jackknife standard error of 12.5%	: 8.2 years
Modified Anderson-Darling statistic	: 0.982

Figure 17a shows that 25 of the 26 annual maximum flows plot on a near perfect straight line; because the 26th plots well above this line the fitted GEV curves upwards (negative k). The modified Anderson-Darling statistic is 0.982, closer to a perfect fit of unity than might have been thought by inspection. Also surprising is that the return period corresponding to the jackknife limit is 8.2 years. The eyeball limit was 25 years, indicating that the data comprise one of the most consistent sets in the study. Note the scale of peak flow in the figure; the mean annual flood is about 2 m^3/s and the 25 year flood 4.5 m^3/s. The catchment has an area of 108 km^2 but has 80% WRAP type 1 soils.

FSSR16(CC) estimates are much too big but are greatly improved by using parameter estimates based on observed data. However, as the peaks are so small an estimated mean annual flood of 4 m^3/s represents a large error in percentage terms. The estimated curves are steeper than the observed one so the catchment is in the bottom right-hand corner of the box diagrams (Tables 5.16.1, .2 & .3)

It is worth looking slightly deeper at the percentage runoff values obtained from the events. Figure 18 shows all observed percentage runoffs were between 1.0% and 3.3%, yet when they were converted to SPR (as indicated by the arrows) a mean value of over 10% was obtained. The lower line representing the percentage runoff required for a perfect fit passes through the observed percentage runoff values, but the upper line, used in calculating the design flood peaks, is much higher. However, the absolute errors in estimating percentage runoff are small; at the 5-year level 4% is estimated when 2% is required for a perfect fit.

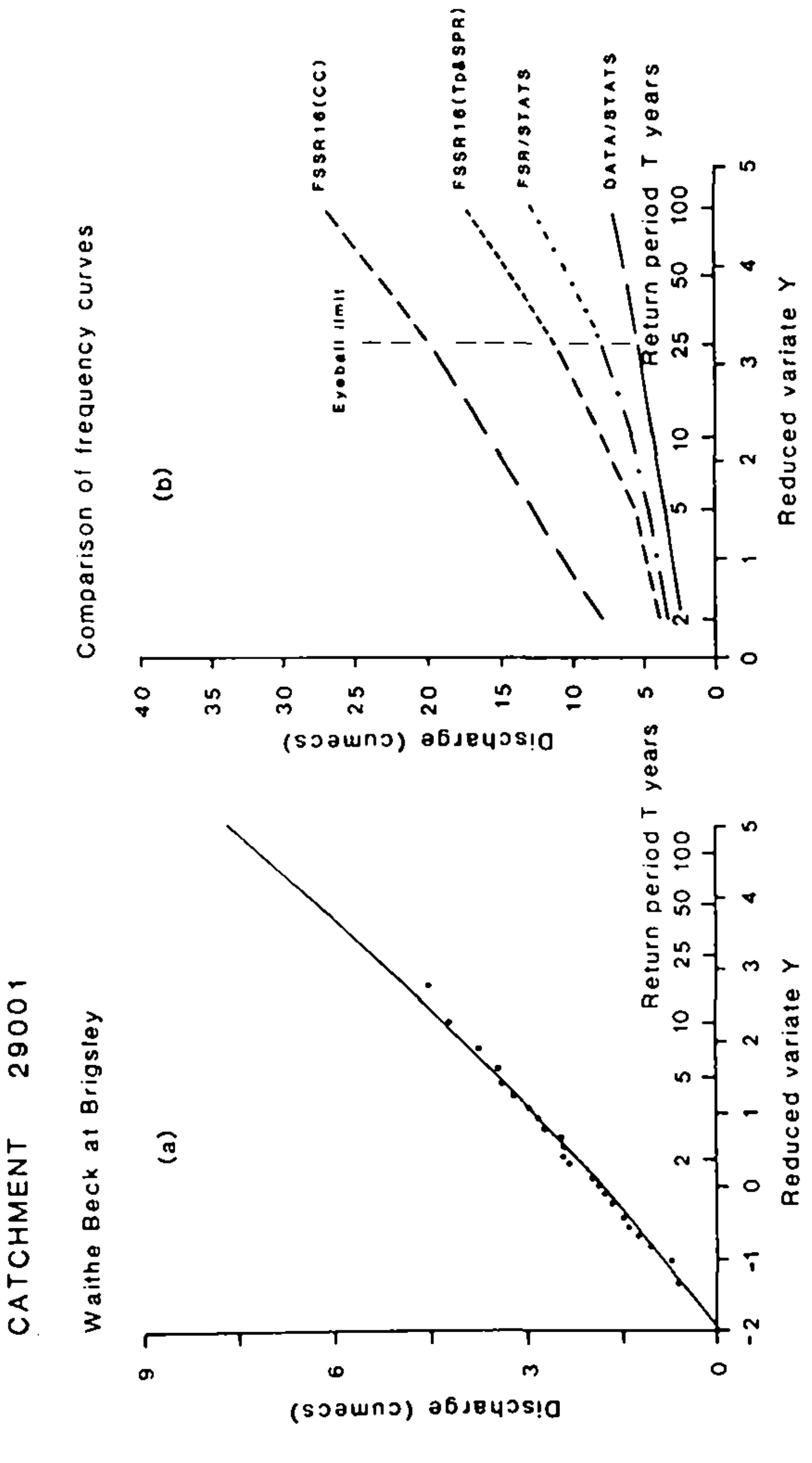


Figure 17. Waithe Beck at Brigsley (flood frequency curves)

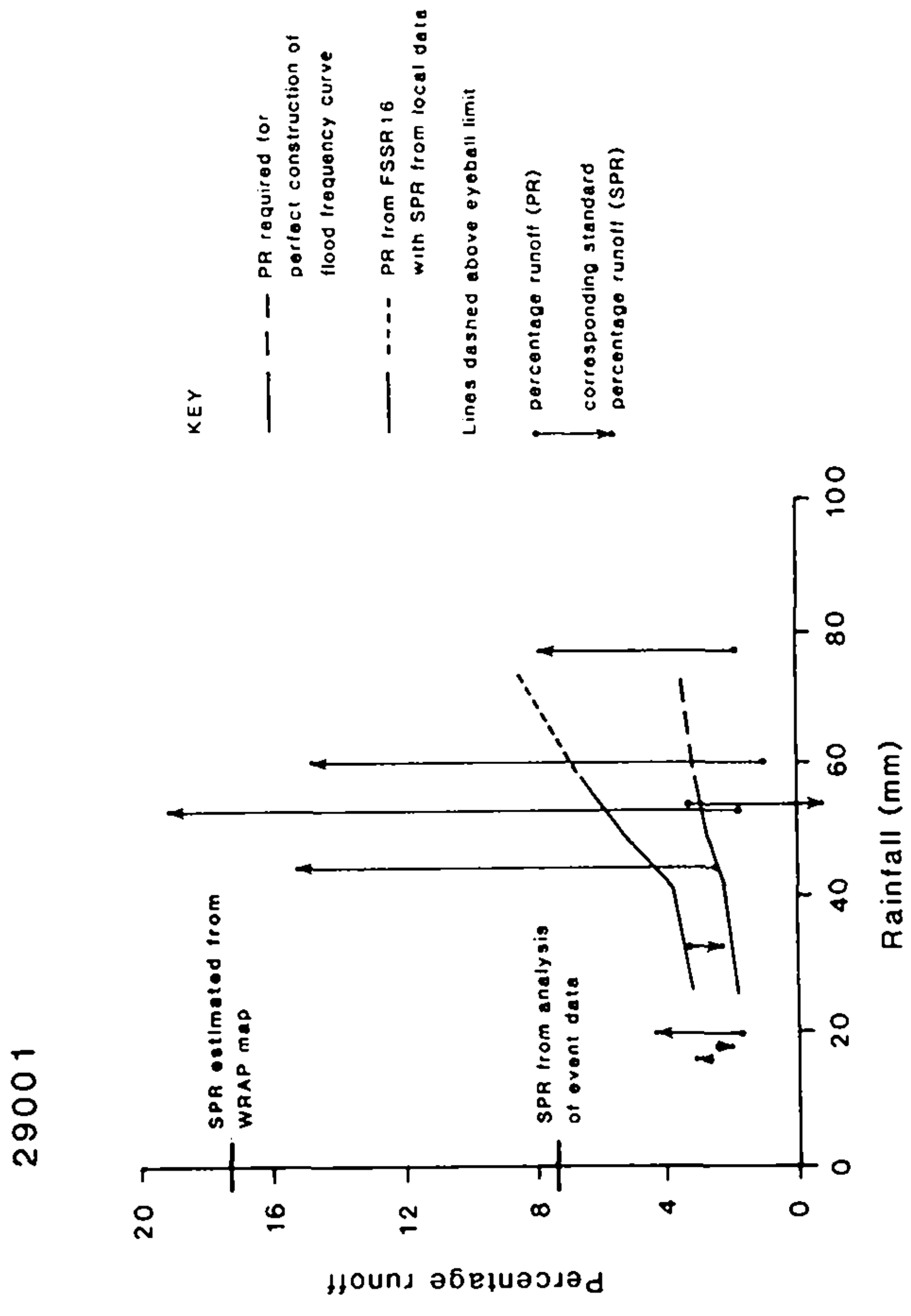


Figure 18. Waithe Beck at Brigsley (percentage runoff)

6.4 39012: HOGSMILL AT KINGSTON

Period of record, N	27 years
Eyeball limit on return period	10 years
Return period for jackknife standard error of 12.5%	10.9 years
Modified Anderson-Darling statistic	0.188

The plotted annual maxima (Figure 19a) show some deviations from the fitted GEV distribution, hence the low value of the modified Anderson-Darling statistic. The k value is very close to zero so the fitted distribution is very close to being an EV1. The eyeball and jackknife limits are both 10 years.

The FSSR16(CC) estimates are too large (see Table 6.1). Using observed data values of SPR and Tp gives the correct value for the 2-year flood, but the estimated flood frequency curve is too steep. The statistical method gives estimates that are too small.

However, both sets of estimates use the rural method although the catchment is 46% urbanised and the urban corrections to the methods should be applied. Table 6.1 gives the values using the urban methods.

Return Period	Data	Rainfall-runoff methods			Statistical method	
		Rural	Urban	Urban Tp+SPR	Rural	Urban
	DATA/STATS	FSSR16(CC)			FSR/STATS(CC)	
2	12.6	19.8	21.5	14.5	4.1	12.8
5	17.0	32.1	29.0	19.6	6.0	17.6
10	19.8	38.3	34.6	23.3	7.6	20.8
25	23.2	47.7	43.2	29.2	10.0	24.9
50	25.6	56.2	50.8	34.9	12.2	27.5
100	27.8	64.5	60.5	42.3	14.9	31.2

Table 6.1 Comparison of flood estimates using the rural method and the urban corrections.

The rainfall-runoff estimates have hardly changed as there is only a slight difference in profile shape and use of rainfall return period. The statistical method estimates have increased to be very close to the data. That the statistical method worked poorly before is not surprising as the method made no allowance for the urbanisation (unlike the rainfall-runoff method). The adjustment made in the statistical method is based on the model used in the rainfall-runoff method.

Again the catchment appears at in the bottom right hand corner of the box diagrams of Tables 5.16.1, .2 & .3.

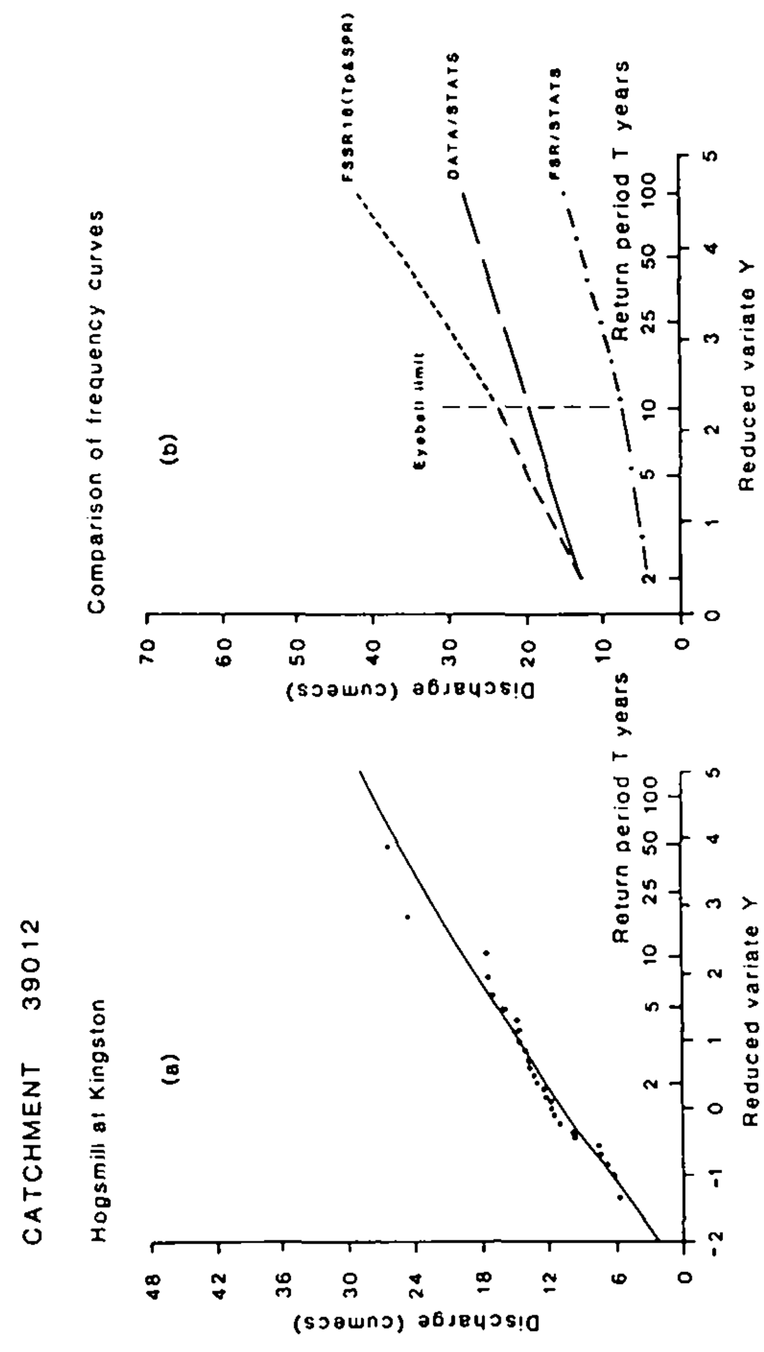


Figure 19. Hogsmill at Kingston

6.5 46003: DART AT AUSTINS BRIDGE

Period of record, N	:	27 years
Eyeball limit on return period	:	5 years
Return period for jackknife standard error of 12.5%	:	10.9 years
Modified Anderson-Darling statistic	·	0.221

As can be seen in Figure 20a there is one very large flood in the annual maximum series; it is almost twice the size of the next biggest. With such an extreme flood in the series, the fitted GEV of course curves upwards; without this flood it would have curved the other way. There is obviously some concern about the plotting position of this large flood. The authors made their eyeball limit 5-years, less than the 10 years jackknife limit. The modified Anderson-Darling statistic is relatively small.

Figure 20b shows that all the estimates are low; the statistical method is the best. Using model parameters based on event data has made the estimates worse, mainly by reducing the SPR value from about 36% to 30%. The revised value has come from 23 events distributed throughout the year. Figure 21 shows that the event rainfalls were generally between 20 and 60mm (one event had 122mm). This figure also shows that percentage runoffs varied between 17% and 42%, giving an average SPR of 30%. The large rainfall event has almost exactly this average SPR. The line plotted on the diagram to represent the PR needed to estimate perfectly the observed flood frequency curve is much higher than any of the event data which suggests strongly that an error in PR estimation is not the cause of the poor flood peak estimates.

That estimates should be so poor even though over 20 events are available is worrying and is the subject of further research. Apart from looking again at percentage runoff estimation, there are several other concerns that should be considered.

> The event flow peaks were between 60 and 200 m^3/s (ie. all less than the mean annual flood). Events with larger peak flows may give larger percentage runoffs.
>
> The triangular unit hydrograph may not be suitable for the catchment. A peakier unit hydrograph would give some increase in design flood peaks.
>
> The rainfall input is too low or the profile shape too diffuse.
>
> Rainfall depths may have been overestimated for the observed events.

It is most likely that a combination of factors is responsible.

The catchment appears in the top line of Tables 5.16.1, .2 & .3, which shows the magnitudes are underestimated, but in the centre and right hand columns indicating the slope of the estimated flood frequency curve is about right or too steep.

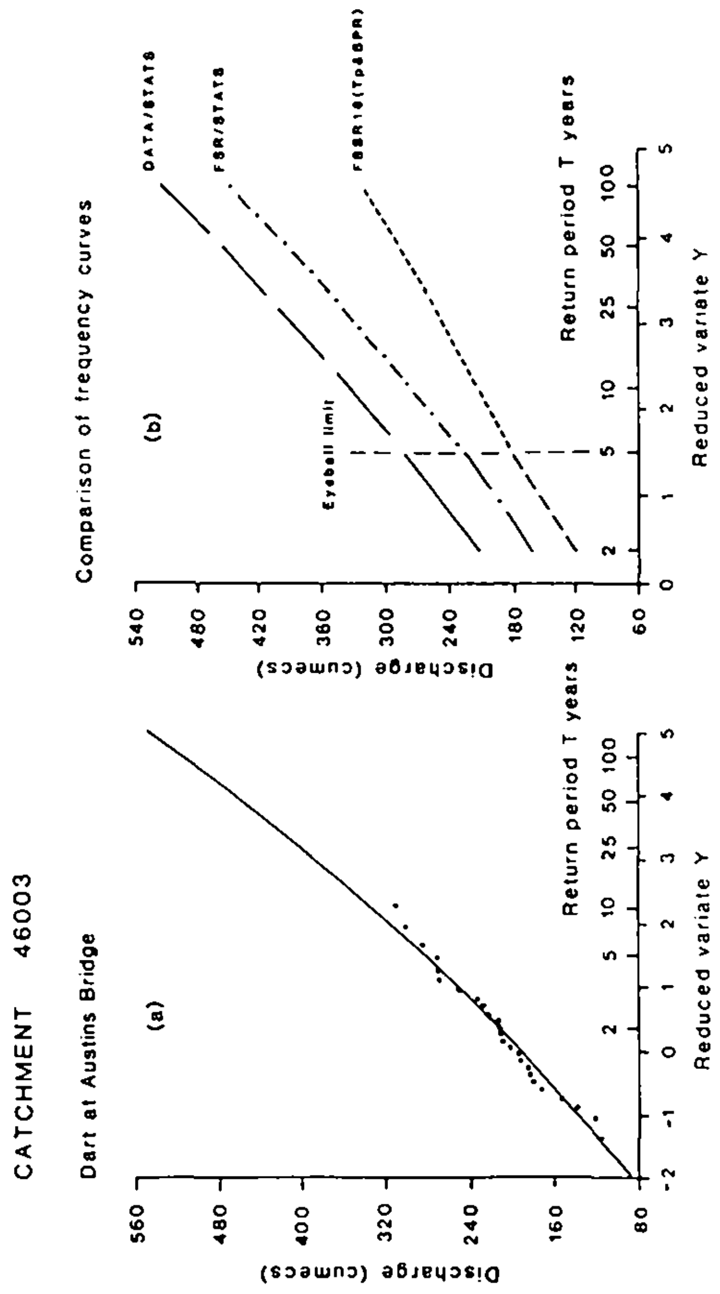


Figure 20. Dart at Austins Bridge (flood frequency curves)

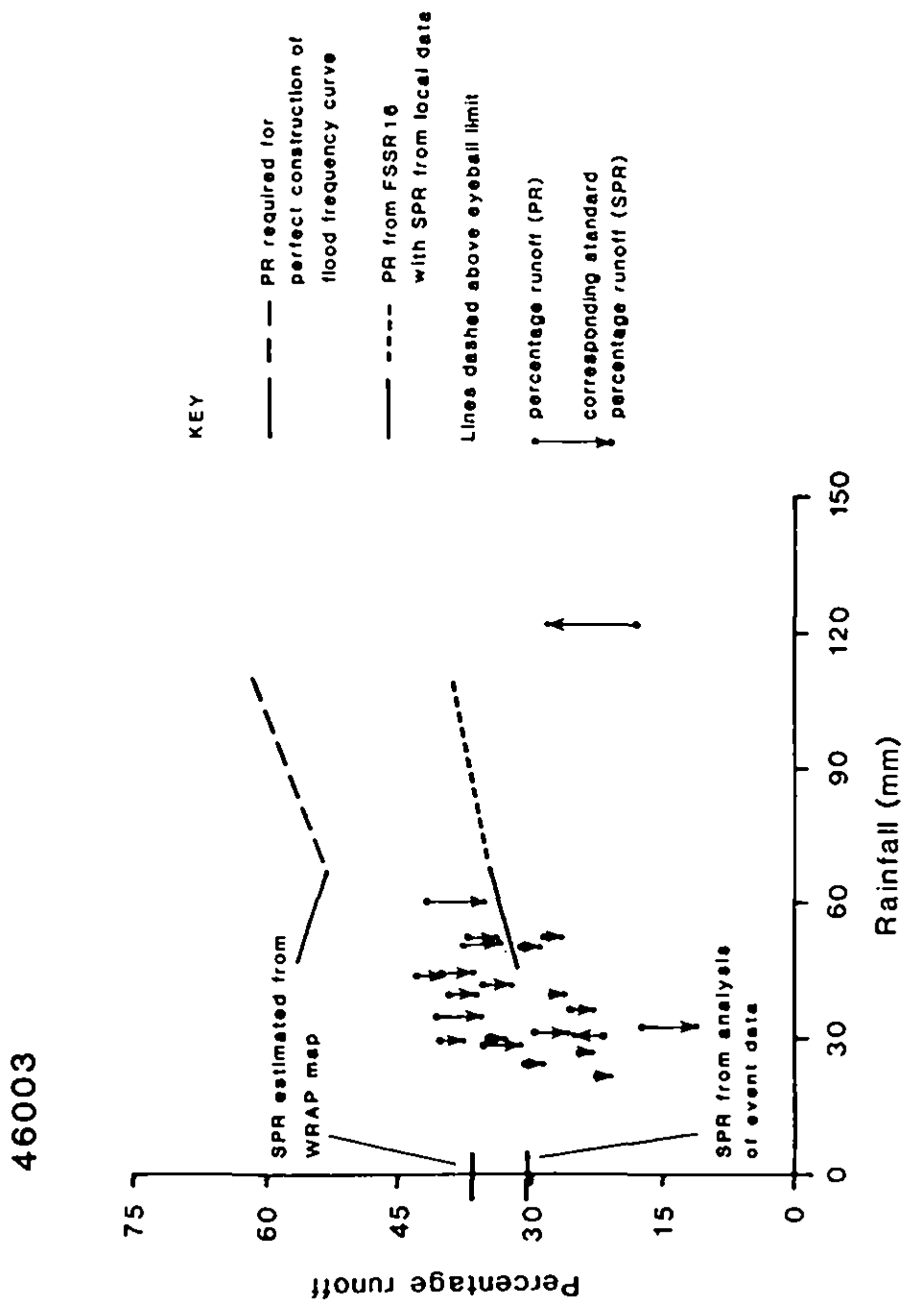


Figure 21. Dart at Austins Bridge (percentage runoff)

6.6 54016: RODEN AT RODINGTON

Period of record, N	. 23 years
Eyeball limit on return period	:·10 years
Return period for jackknife standard error of 12.5%	: 15.8 years
Modified Anderson-Darling statistic	: 0.496

The plot of annual maximum data has a strong trend but has two "waves" (see Figure 22a); the scatter about the fitted line is typical of a curve with a modified Anderson-Darling statistic of 0.5. The eyeball limit was 10 years, slightly less than the 16 years corresponding to the 12.5% jackknife standard error.

All the methods give peaks larger than the observed data (see Figure 22b). The performance of the rainfall-runoff method is improved by using observed data, but is still not as good as the statistical method which agrees well with the observed data at low return periods. The event data are from seven events, but they are all small (the largest is just over 11 m^3/s). Figure 23 shows that three events have SPR values greater than PR, arising as they do from events with large SMDs. As on catchment 29001, for the design case, using mean PR rather than mean SPR would give a better representation of the observed flood frequency curve.

The catchment falls in boxes 23, 25 & 20 of Tables 5.16.1, .2 & .3 indicating that the estimates and the slope of the estimated flood frequency curve are too large.

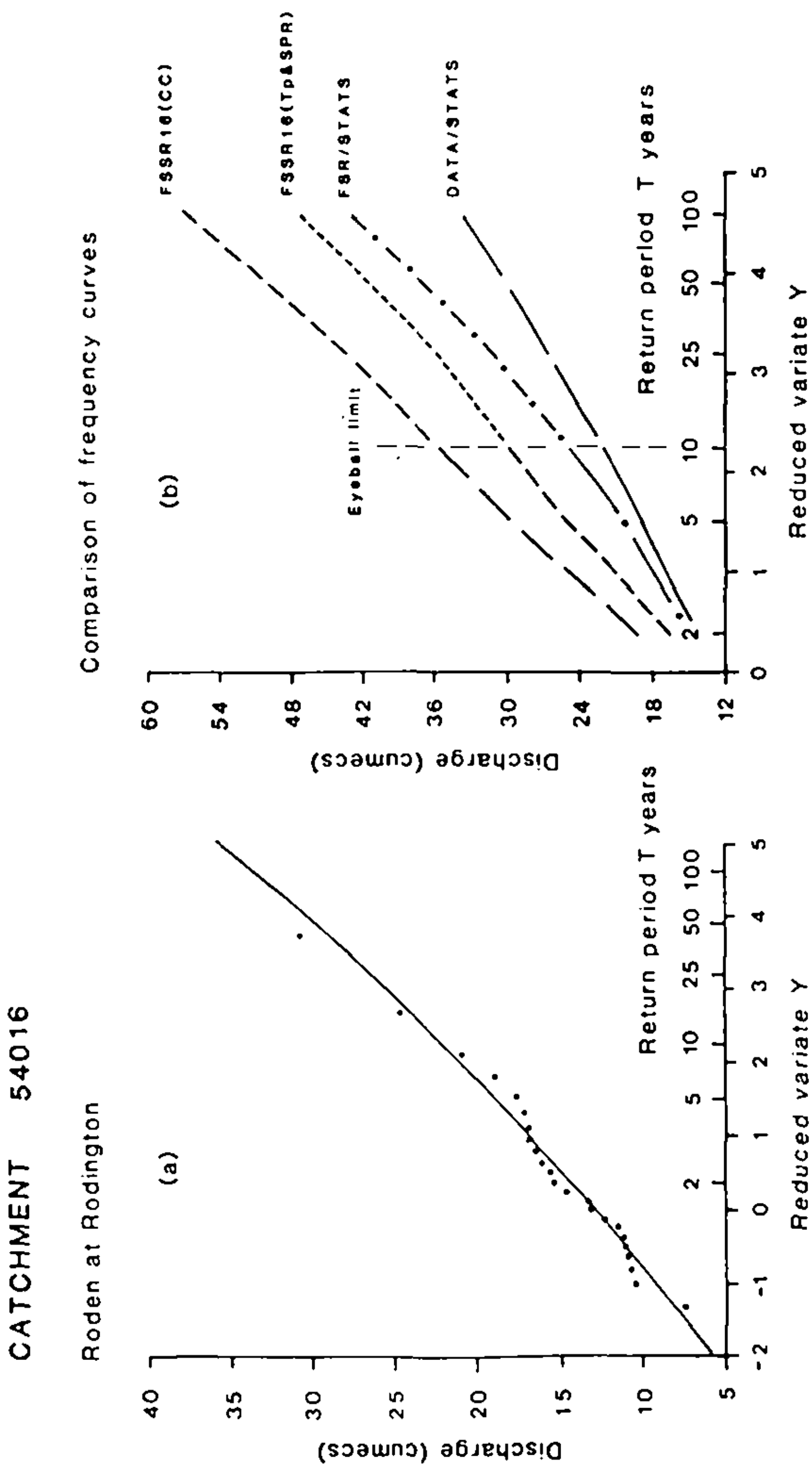


Figure 22. Roden at Rodington (flood frequency curves)

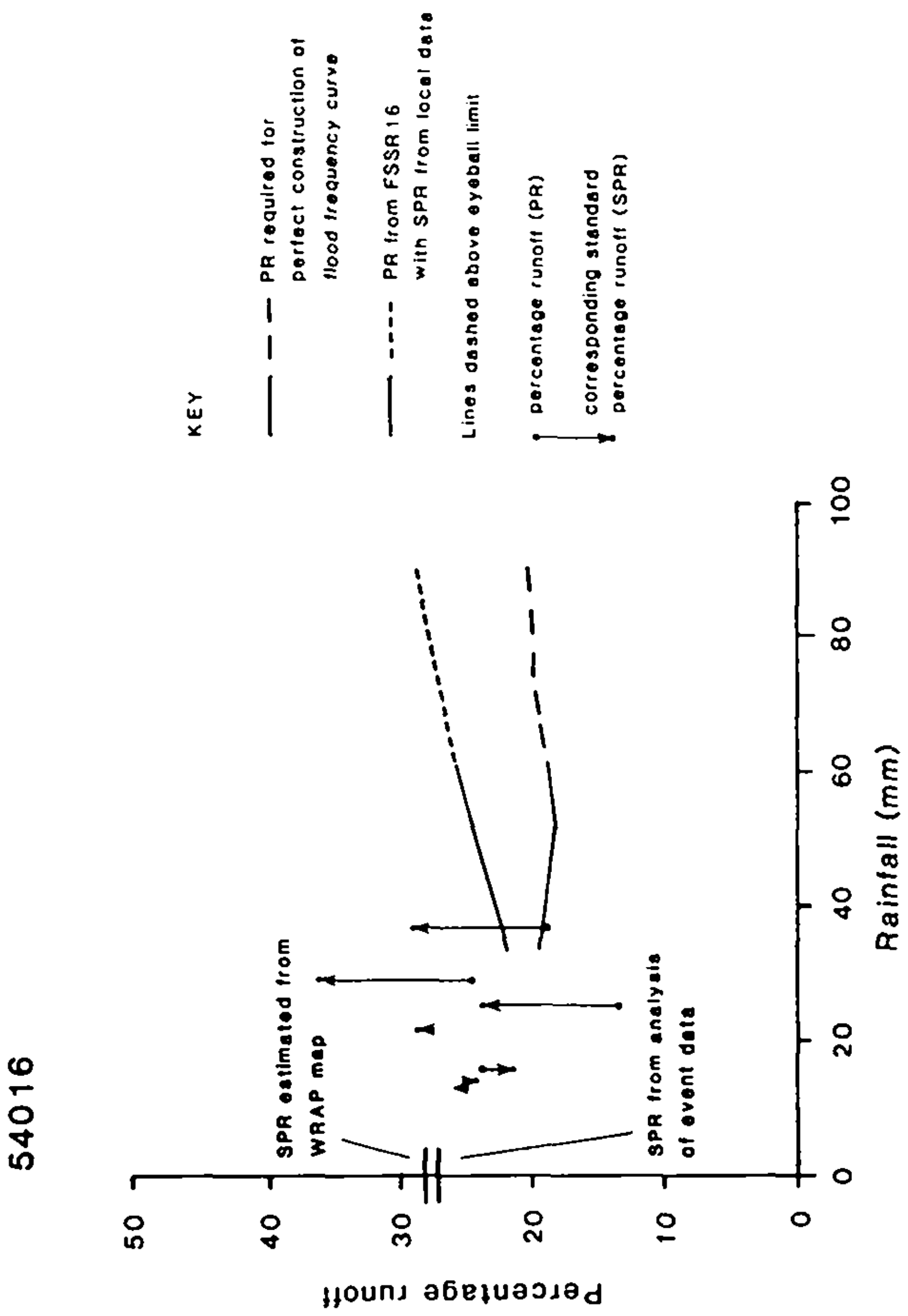


Figure 23. Roden at Rodington (percentage runoff)

6.7 55008: WYE AT CEFN BRWYN

Period of record, N		34 years
Eyeball limit on return period	:	5 years
Return period for jackknife standard error of 12.5%	:	9.4 years
Modified Anderson-Darling statistic	:	0.028

The GEV distribution fitted to the annual maxima has a large negative k (-0.31) and therefore curves steeply upwards as shown in Figure 24a. The figure also shows that the annual maxima are distinctly stepped and that there are two very large floods. The modified Anderson-Darling statistic is extremely low. The authors felt happy using the fitted curve only below 5 years despite 34 years of data. The return period corresponding to a jackknife standard deviation of 12.5% is slightly higher.

The FSSR16 no-data rainfall-runoff estimate agrees with the data at 2 years but is too big at 5 years. Incorporating observed data decreases the estimates to below the observed values. The statistical method over-estimates for low return periods but is then too flat so it intersects the observed curve at 10 years, as shown in Figure 24b. Figure 25 shows the event data represent a good range of rainfall depths and that variations in percentage runoff are roughly as predicted by the estimation equation.

The catchment appears in the top line of Tables 5.16.1, .2 & .3, which shows underestimation of magnitudes, but moves from the left to the right side of the table showing that the estimated flood frequency curve is too steep at low return periods and not steep enough for high return periods.

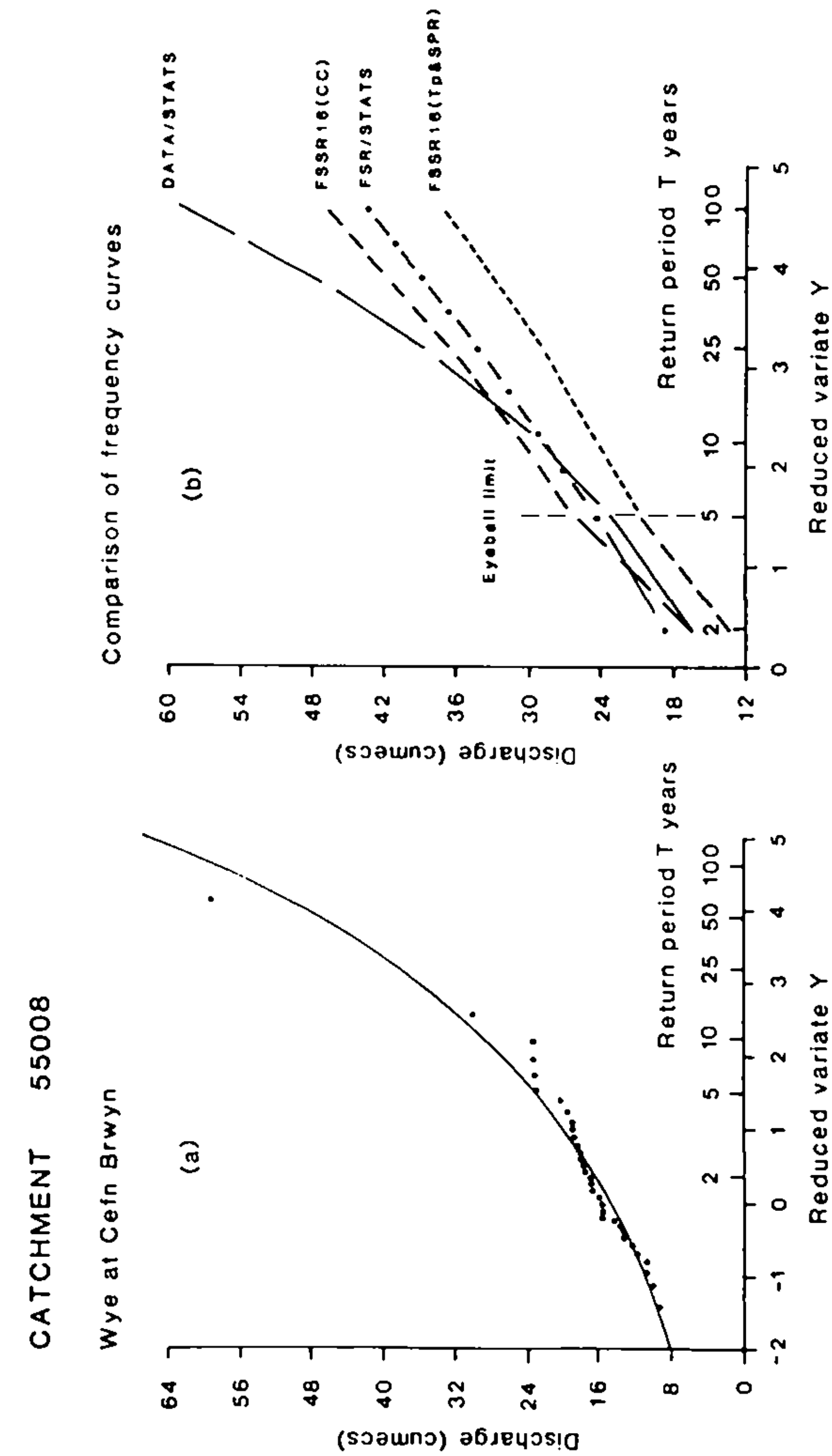


Figure 24. Wye at Cefn Brwyn (flood frequency curves)

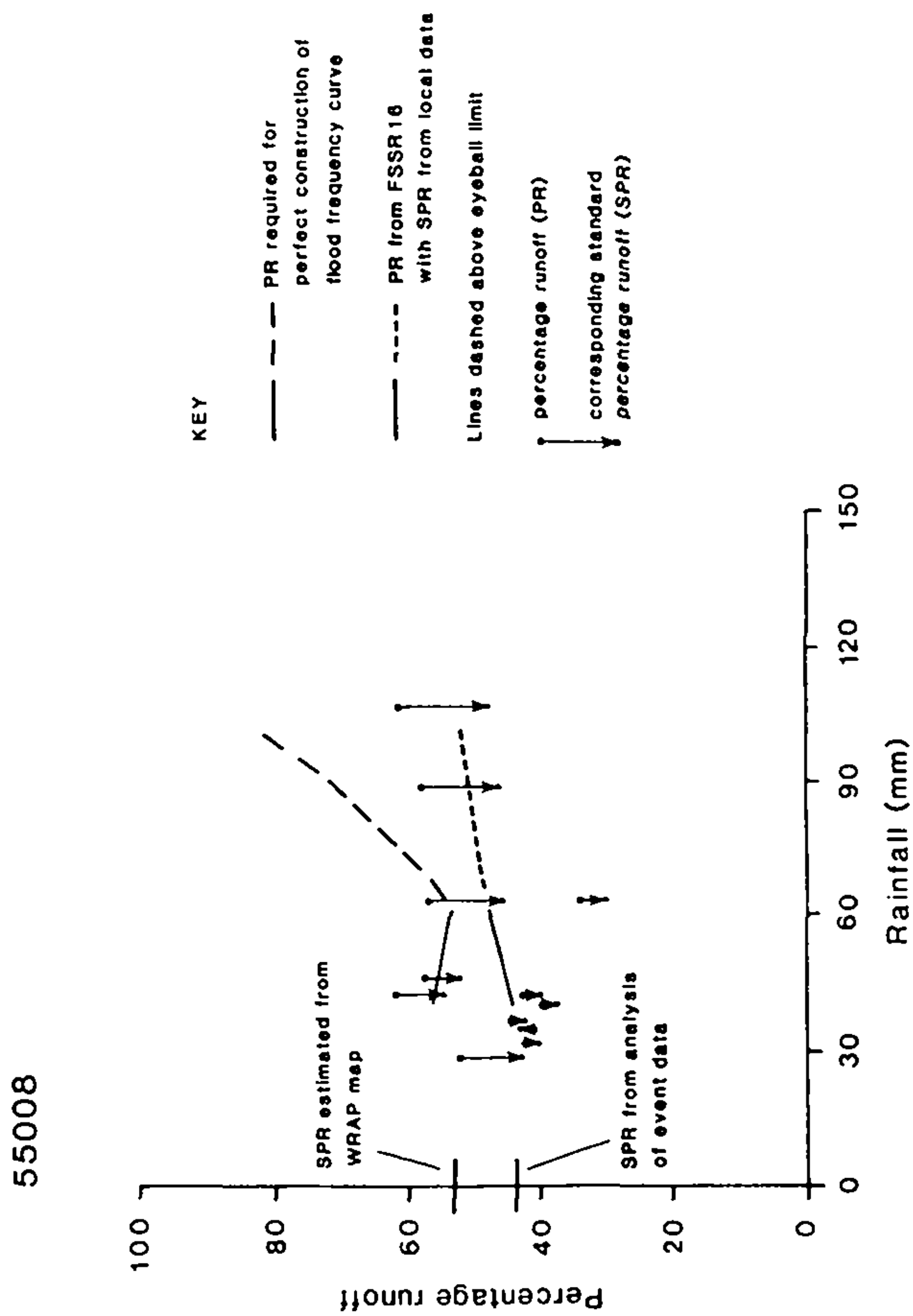


Figure 25. Wye at Cefn Brwyn (percentage runoff)

7.0 CONCLUSIONS

The objective of this study was to make a definitive assessment of flood estimates (up to return periods of 100 years) on rural catchments using the Flood Studies Report rainfall-runoff method. Many problems, both expected and unexpected, were encountered, but the study has provided a quantitative insight into how the FSR rainfall-runoff method performs and has indicated some of its potential weaknesses.

The first problem encountered was identifying a set of catchments for which flood quantiles could be calculated reliably, and for which flood event data were available to permit refinement of the rainfall-runoff model parameters. This latter consideration imposed the greater constraint as only 128 catchments had the required 5 events available. The original idea of trying to examine flood magnitudes up to the 100-year return period had to be modified as no catchment for which event data were available had sufficient annual maxima data to provide reliable estimates of the 100-year flood. Eighty-eight catchments were selected for study by lowering the requirement for annual maxima data to just 15 years. According to the "twice-the-period-of-record" rule-of-thumb it was anticipated that all catchments could have been used for a comparison of estimates up to 25 years, which would still have been a considerable improvement on results published from other studies.

In collating the true quantiles against which the estimates were to be compared, plots were produced showing the goodness of fit of the observed annual maxima to the fitted distributions. They showed very clearly the problem of trying to identify the true distributions from limited amounts of data. Some data sets plotted consistently and gave confidence in using quantiles from the distribution, but other data sets were very inconsistent and gave little confidence, even at return periods less than the period of record. A limiting return period was set by inspection (and termed an eyeball limit) to mark the maximum return period at which the fitted distribution was considered reliable. In all cases this was less than twice the period of record (2N), and usually less than N.

This comparision with the 2N rule is unfair as the rule gives a guide to the point at which a developed flood frequency curve should depart from the at-site line to the regional curve. The rule is concerned with how to get the best estimate of the T-year flood from observed annual maxima, rather than how to be sure that the estimate is accurate enough to be used as a benchmark for testing indirect methods of estimation. However, the comparison does serve as a reminder of how careful one must be in using at-site annual maximum data.

Considerable effort was expended in trying to replace the eyeball limit with a statistically derived one that could be applied objectively and, therefore, by anyone unfamiliar with the problems of fitting distributions to observed data. Some success was achieved by combining the modified Anderson-Darling statistic with a standard error from a jackknife analysis, but this is still far from being a standard technique that can be applied generally.

When catchments with urban areas greater than 10% were excluded, and the eyeball limits were applied, just 74 catchments were left on which to assess estimates of the 2 year flood. The number of catchments reduced as return period increased, so that only 15 catchments were available for comparison at the maximum return period of 25 years. These catchments are not well distributed geographically; there are none in Northern Ireland, none in Scotland outside the central lowlands, and none in the Lake District or northern Pennines. Comparisons using subsets of the data (eg. small or wet catchments) were based on very few catchments.

Using this standard data set, the no-data rainfall-runoff method, with parameters estimated by the FSSR16 regression equations, tended to over-estimate flood magnitudes. However, estimates were greatly improved when model parameters were derived from observed data; bias was then zero at the 2 year return period, increasing with return period to 11% at 25 years (the corresponding figures in the no-data case were 22% and 41%). It is reassuring that with parameters from observed data the method is seen to work fairly well. Values of standard percentage runoff were seen as particularly valuable in improving estimates. The statistical method, without observed data, performed as well as the rainfall-runoff method with data.

In the various subsets of catchments that were examined the performance of the rainfall-runoff method varied much as expected. Estimates were better at higher return periods if more events were available, they were worse on catchments with mainly permeable soils, and, in the no-data case, better on larger catchments. The variation in the performance of the statistical method was more random between these subsets. A plot of the residuals on a map of Britain showed general over-estimation in the south-east of England and under-estimation in south-west England and Wales; in other regions residuals were mixed. Dividing the catchments into those with more or less than 800mm average annual rainfall showed that the estimates tended to be better on wet catchments than on dry ones. The various derived statistics have been presented in three different ways in summary form in the body of the report, and comprehensively in an appendix.

This study has provided statistics describing the performance of the rainfall-runoff method of flood estimation. It is seen to work reasonably well in most cases where model parameter values can be derived from observed data. If such data are available, the method performs about as well as the statistical method without observed data, but has several advantages: it can provide a complete design hydrograph, it is based on a model of catchment response, and it performs in a predictable manner. However, several areas for further work remain and are described in the next chapter.

8.0 RECOMMENDATIONS

The lack of catchments available for this study clearly demonstrates the continuing need to gather both event data and annual maximum data. Such data underpins the design of land drainage schemes which accounted for £67M of Water Authority capital expenditure in 1986/7 (the last year for which figures are currently available, Water Authorities Association, 1987). Authorities measuring data must be made aware of the value of long records in estimating flood statistics; there is a national need for such data. There is a particular need for data from remote catchments in Scotland and Northern Ireland.

Work should continue on trying to identify measures of accuracy associated with fitting distributions to annual maxima. Perhaps an expert systems approach is needed to encode the principles used by the authors in fixing their eyeball limits.

The rainfall-runoff method with observed data is unbiassed overall, but there are particular catchments on which the flood frequency curve is poorly estimated. Since errors are not eliminated when observed model parameters are used, the method of defining the design inputs, or the way in which model parameters are assumed to vary on individual catchments, must be at fault. It is not acceptable to state that the method is unbiassed on average when errors on particular catchments can be large. A great deal of further work is required to improve the accuracy of estimation on all catchments.

The value of using local data (ie. data from a gauged catchment hydrologically similar to the site of interest) rather than data from the site of interest itself, should be considered, as it is this type of data which is normally available. The use of observed unit hydrographs instead of the triangular FSR one should be investigated; if this proves beneficial, the use of a more realistic unit hydrograph in the no-data situation should be considered. The type and quality of local data that give the greatest improvements should also be investigated since larger storms and floods may be found to be much more useful than smaller events.

While improving the quality of estimates obtained using the no-data equations is a valid objective, no flood estimate for a site in the UK should be made without some reference to local data. Estimating the variation in percentage runoff is of most importance. It is hoped that the existing project to replace the 5-class Winter Rainfall

Acceptance Potential map with a more detailed map with a greater number of classes will produce significant improvement in flood estimation. An important objective for research is the further development of methods of calibrating percentage runoff by reference to easily extracted measures of catchment response, such as base flow index.

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APPENDIX A. FULL TABLES OF COMPARISONS AND RESULTS

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	74	0.06	0.43	0.01	0.16
	2	FSR/RF-RO(CC)	74	0.27	0.89	-0.05	0.21
	3	FSSR16(CC)	74	0.22	0.73	-0.04	0.19
	4	FSSR16(Tp&SPR)	74	-0.01	0.35	0.03	0.14
	5	FSSR16(Tp)	74	0.16	0.83	-0.01	0.19
	6	FSSR16(SPR)	74	0.07	0.39	-0.00	0.14
5	1	FSR/STATS(CC)	71	0.02	0.36	0.02	0.14
	2	FSR/RF-RO(CC)	71	0.37	0.92	-0.09	0.21
	3	FSSR16(CC)	71	0.34	0.77	-0.09	0.20
	4	FSSR16(Tp&SPR)	71	0.07	0.32	-0.01	0.12
	5	FSSR16(Tp)	71	0.26	0.83	-0.05	0.19
	6	FSSR16(SPR)	71	0.16	0.38	-0.05	0.13
10	1	FSR/STATS(CC)	57	0.02	0.37	0.02	0.15
	2	FSR/RF-RO(CC)	57	0.28	0.72	-0.06	0.19
	3	FSSR16(CC)	57	0.28	0.64	-0.07	0.18
	4	FSSR16(Tp&SPR)	57	0.06	0.27	-0.01	0.11
	5	FSSR16(Tp)	57	0.17	0.61	-0.04	0.17
	6	FSSR16(SPR)	57	0.16	0.37	-0.05	0.13
25	1	FSR/STATS(CC)	15	0.09	0.32	-0.02	0.14
	2	FSR/RF-RO(CC)	15	0.39	0.96	-0.09	0.22
	3	FSSR16(CC)	15	0.41	0.83	-0.11	0.22
	4	FSSR16(Tp&SPR)	15	0.11	0.41	-0.02	0.15
	5	FSSR16(Tp)	15	0.41	1.04	-0.08	0.24
	6	FSSR16(SPR)	15	0.16	0.40	-0.05	0.14

Table A.1 Four statistics for return periods 2, 5, 10 and 50 years comparing the performance of six models on standard set of catchments.

		Method		RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	88	0.01	0.43	0.03	0.18
	2	FSR/RF-RO(CC)	88	0.38	1.23	-0.07	0.23
	3	FSSR16(CC)	88	0.34	1.13	-0.06	0.22
	4	FSSR16(Tp&SPR)	88	0.10	0.89	0.01	0.16
	5	FSSR16(Tp)	88	0.31	1.49	-0.03	0.22
	6	FSSR16(SPR)	88	0.15	0.69	-0.02	0.17
5	1	FSR/STATS(CC)	88	-0.02	0.39	0.04	0.17
	2	FSR/RF-RO(CC)	88	0.51	1.44	-0.11	0.24
	3	FSSR16(CC)	88	0.48	1.30	-0.11	0.23
	4	FSSR16(Tp&SPR)	88	0.21	1.06	-0.04	0.16
	5	FSSR16(Tp)	88	0.45	1.75	-0.08	0.23
	6	FSSR16(SPR)	88	0.27	0.78	-0.07	0.17
10	1	FSR/STATS(CC)	88	-0.02	0.38	0.04	0.18
	2	FSR/RF-RO(CC)	88	0.48	1.42	-0.10	0.24
	3	FSSR16(CC)	88	0.47	1.28	-0.11	0.23
	4	FSSR16(Tp&SPR)	88	0.20	1.05	-0.03	0.16
	5	FSSR16(Tp)	88	0.44	1.73	-0.07	0.23
	6	FSSR16(SPR)	88	0.26	0.77	-0.07	0.17
25	1	FSR/STATS(CC)	88	0.01	0.40	0.03	0.17
	2	FSR/RF-RO(CC)	88	0.45	1.38	-0.09	0.24
	3	FSSR16(CC)	88	0.46	1.31	-0.10	0.23
	4	FSSR16(Tp&SPR)	88	0.20	1.04	-0.03	0.18
	5	FSSR16(Tp)	88	0.42	1.68	-0.06	0.24
	6	FSSR16(SPR)	88	0.26	0.83	-0.06	0.17
50	1	FSR/STATS(CC)	88	0.05	0.46	0.02	0.18
	2	FSR/RF-RO(CC)	88	0.46	1.41	-0.09	0.25
	3	FSSR16(CC)	88	0.48	1.36	-0.10	0.24
	4	FSSR16(Tp&SPR)	88	0.23	1.14	-0.03	0.19
	5	FSSR16(Tp)	88	0.45	1.73	-0.07	0.25
	6	FSSR16(SPR)	88	0.29	0.85	-0.07	0.19

Table A.2 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on all 88 catchments.

		Method		RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	87	0.02	0.43	0.03	0.19
	2	FSR/RF-RO(CC)	87	0.29	0.87	-0.06	0.21
	3	FSSR16(CC)	87	0.25	0.73	-0.05	0.20
	4	FSSR16(Tp&SPR)	87	0.00	0.34	0.02	0.13
	5	FSSR16(Tp)	87	0.18	0.79	-0.02	0.19
	6	FSSR16(SPR)	87	0.09	0.39	-0.01	0.14
5	1	FSR/STATS(CC)	87	-0.02	0.39	0.04	0.18
	2	FSR/RF-RO(CC)	87	0.40	0.91	-0.10	0.22
	3	FSSR16(CC)	87	0.38	0.79	-0.10	0.21
	4	FSSR16(Tp&SPR)	87	0.10	0.34	-0.03	0.12
	5	FSSR16(Tp)	87	0.29	0.82	-0.06	0.19
	6	FSSR16(SPR)	87	0.20	0.41	-0.06	0.14
10	1	FSR/STATS(CC)	87	-0.01	0.38	0.04	0.18
	2	FSR/RF-RO(CC)	87	0.37	0.86	-0.09	0.21
	3	FSSR16(CC)	87	0.37	0.78	-0.10	0.20
	4	FSSR16(Tp&SPR)	87	0.10	0.36	-0.03	0.13
	5	FSSR16(Tp)	87	0.29	0.82	-0.06	0.20
	6	FSSR16(SPR)	87	0.20	0.41	-0.06	0.14
25	1	FSR/STATS(CC)	87	0.02	0.40	0.03	0.17
	2	FSR/RF-RO(CC)	87	0.34	0.83	-0.08	0.21
	3	FSSR16(CC)	87	0.35	0.77	-0.09	0.21
	4	FSSR16(Tp&SPR)	87	0.10	0.40	-0.02	0.14
	5	FSSR16(Tp)	87	0.26	0.81	-0.05	0.20
	6	FSSR16(SPR)	87	0.19	0.44	-0.05	0.15
50	1	FSR/STATS(CC)	87	0.05	0.45	0.02	0.18
	2	FSR/RF-RO(CC)	87	0.34	0.85	-0.08	0.22
	3	FSSR16(CC)	87	0.37	0.81	-0.09	0.22
	4	FSSR16(Tp&SPR)	87	0.12	0.46	-0.02	0.16
	5	FSSR16(Tp)	87	0.28	0.85	-0.05	0.22
	6	FSSR16(SPR)	87	0.21	0.49	-0.06	0.16

Table A.3 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on all catchments except 39004 the Wandle at Beddington.

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	55	0.10	0.45	-0.01	0.16
	2	FSR/RF-RO(CC)	55	0.14	0.54	-0.02	0.18
	3	FSSR16(CC)	55	0.17	0.54	-0.04	0.17
	4	FSSR16(Tp&SPR)	55	-0.02	0.30	-0.02	0.12
	5	FSSR16(Tp)	55	0.08	0.40	0.01	0.15
	6	FSSR16(SPR)	55	0.07	0.38	-0.00	0.14
5	1	FSR/STATS(CC)	53	0.04	0.38	0.01	0.15
	2	FSR/RF-RO(CC)	53	0.23	0.56	-0.06	0.17
	3	FSSR16(CC)	53	0.28	0.56	-0.08	0.17
	4	FSSR16(Tp&SPR)	53	0.07	0.26	-0.02	0.10
	5	FSSR16(Tp)	53	0.18	0.42	-0.05	0.15
	6	FSSR16(SPR)	53	0.15	0.35	-0.04	0.13
10	1	FSR/STATS(CC)	44	0.04	0.39	0.01	0.15
	2	FSR/RF-RO(CC)	44	0.19	0.54	-0.04	0.17
	3	FSSR16(CC)	44	0.25	0.55	-0.07	0.17
	4	FSSR16(Tp&SPR)	44	0.04	0.24	-0.01	0.10
	5	FSSR16(Tp)	44	0.13	0.37	-0.03	0.14
	6	FSSR16(SPR)	44	0.14	0.34	-0.04	0.13
25	1	FSR/STATS(CC)	11	0.14	0.32	-0.04	0.14
	2	FSR/RF-RO(CC)	11	0.28	0.46	-0.09	0.16
	3	FSSR16(CC)	11	0.37	0.53	-0.12	0.17
	4	FSSR16(Tp&SPR)	11	0.12	0.31	-0.04	0.12
	5	FSSR16(Tp)	11	0.30	0.44	-0.10	0.15
	6	FSSR16(SPR)	11	0.18	0.40	-0.06	0.14

Table A.4 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on the standard set with less than 20% SOIL1.

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	58	0.09	0.44	-0.01	0.16
	2	FSR/RF-RO(CC)	58	0.29	0.92	-0.06	0.20
	3	FSSR16(CC)	58	0.23	0.72	-0.06	0.18
	4	FSSR16(Tp&SPR)	58	0.01	0.38	0.02	0.14
	5	FSSR16(Tp)	58	0.19	0.91	-0.02	0.20
	6	FSSR16(SPR)	58	0.07	0.39	-0.01	0.14
5	1	FSR/STATS(CC)	55	0.01	0.37	0.00	0.14
	2	FSR/RF-RO(CC)	55	0.42	0.94	-0.10	0.20
	3	FSSR16(CC)	55	0.40	0.77	-0.10	0.19
	4	FSSR16(Tp&SPR)	55	0.11	0.34	-0.01	0.12
	5	FSSR16(Tp)	55	0.33	0.92	-0.06	0.20
	6	FSSR16(SPR)	55	0.20	0.37	-0.05	0.13
10	1	FSR/STATS(CC)	41	0.05	0.38	0.03	0.14
	2	FSR/RF-RO(CC)	41	0.27	0.68	-0.07	0.17
	3	FSSR16(CC)	41	0.27	0.60	-0.08	0.17
	4	FSSR16(Tp&SPR)	41	0.05	0.27	-0.01	0.11
	5	FSSR16(Tp)	41	0.18	0.66	-0.04	0.17
	6	FSSR16(SPR)	41	0.15	0.34	-0.04	0.12
25	1	FSR/STATS(CC)	13	0.11	0.34	-0.02	0.14
	2	FSR/RF-RO(CC)	13	0.41	1.03	-0.09	0.23
	3	FSSR16(CC)	13	0.40	0.87	-0.10	0.22
	4	FSSR16(Tp&SPR)	13	0.04	0.37	0.01	0.13
	5	FSSR16(Tp)	13	0.42	1.11	-0.08	0.25
	6	FSSR16(SPR)	13	0.07	0.30	-0.01	0.11

Table A.5 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on the standard set with at least 10 observed events.

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	16	0.16	0.30	-0.05	0.11
	2	FSR/RF-RO(CC)	16	0.44	0.99	-0.11	0.22
	3	FSSR16(CC)	16	0.35	0.71	-0.10	0.18
	4	FSSR16(Tp&SPR)	16	-0.03	0.31	0.04	0.15
	5	FSSR16(Tp)	16	0.31	0.92	-0.07	0.20
	6	FSSR16(SPR)	16	0.03	0.32	0.01	0.14
5	1	FSR/STATS(CC)	16	0.11	0.25	-0.04	0.09
	2	FSR/RF-RO(CC)	16	0.55	1.06	-0.14	0.23
	3	FSSR16(CC)	16	0.47	0.80	-0.14	0.20
	4	FSSR16(Tp&SPR)	16	0.05	0.27	-0.01	0.11
	5	FSSR16(Tp)	16	0.41	0.94	-0.11	0.20
	6	FSSR16(SPR)	16	0.14	0.35	-0.04	0.13
10	1	FSR/STATS(CC)	11	0.12	0.27	-0.04	0.10
	2	FSR/RF-RO(CC)	11	0.57	1.13	-0.15	0.23
	3	FSSR16(CC)	11	0.52	0.89	-0.15	0.21
	4	FSSR16(Tp&SPR)	11	0.12	0.33	-0.03	0.11
	5	FSSR16(Tp)	11	0.51	1.15	-0.13	0.23
	6	FSSR16(SPR)	11	0.21	0.42	-0.06	0.14
25	1	FSR/STATS(CC)	6	0.29	0.36	-0.11	0.13
	2	FSR/RF-RO(CC)	6	0.77	1.41	-0.18	0.28
	3	FSSR16(CC)	6	0.71	1.14	-0.19	0.26
	4	FSSR16(Tp&SPR)	6	0.20	0.50	-0.05	0.16
	5	FSSR16(Tp)	6	0.81	1.54	-0.18	0.29
	6	FSSR16(SPR)	6	0.23	0.49	-0.07	0.16

Table A.6 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on standard set of catchments which have at least 25 years of annual maximum data.

		Method	n	RT_{ij} mean	RMS	RT'_{ij} mean	RMS
2	1	FSR/STATS(CC)	50	0.05	0.44	0.01	0.16
	2	FSR/RF-RO(CC)	50	0.06	0.79	0.02	0.18
	3	FSSR16(CC)	50	0.07	0.64	0.01	0.17
	4	FSSR16(Tp&SPR)	50	-0.06	0.34	0.05	0.14
	5	FSSR16(Tp)	50	0.06	0.82	0.03	0.18
	6	FSSR16(SPR)	50	-0.03	0.32	0.03	0.13
5	1	FSR/STATS(CC)	48	0.01	0.39	0.02	0.15
	2	FSR/RF-RO(CC)	48	0.16	0.78	-0.02	0.18
	3	FSSR16(CC)	48	0.19	0.66	-0.04	0.17
	4	FSSR16(Tp&SPR)	48	0.04	0.33	0.00	0.12
	5	FSSR16(Tp)	48	0.17	0.81	-0.02	0.17
	6	FSSR16(SPR)	48	0.08	0.32	-0.02	0.12
10	1	FSR/STATS(CC)	39	-0.00	0.40	0.03	0.15
	2	FSR/RF-RO(CC)	39	0.02	0.32	0.01	0.14
	3	FSSR16(CC)	39	0.08	0.35	-0.01	0.13
	4	FSSR16(Tp&SPR)	39	-0.01	0.26	0.02	0.11
	5	FSSR16(Tp)	39	0.01	0.29	0.01	0.13
	6	FSSR16(SPR)	39	0.05	0.29	-0.01	0.11
25	1	FSR/STATS(CC)	11	-0.01	0.29	0.03	0.13
	2	FSR/RF-RO(CC)	11	0.03	0.25	-0.00	0.11
	3	FSSR16(CC)	11	0.12	0.32	-0.03	0.13
	4	FSSR16(Tp&SPR)	11	0.03	0.34	0.01	0.14
	5	FSSR16(Tp)	11	0.02	0.30	0.01	0.14
	6	FSSR16(SPR)	11	0.13	0.39	-0.32	0.13

Table A.7 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on standard set of catchments which have SAAR greater than 800 mm.

		Method	n	RT_{ij} mean	RMS	RT'_{ij} mean	RMS
2	1	FSR/STATS(CC)	24	0.08	0.40	-0.00	0.16
	2	FSR/RF-RO(CC)	24	0.68	1.07	-0.19	0.26
	3	FSSR16(CC)	24	0.53	0.89	-0.15	0.23
	4	FSSR16(Tp&SPR)	24	0.10	0.37	-0.02	0.13
	5	FSSR16(Tp)	24	0.36	0.85	-0.09	0.21
	6	FSSR16(SPR)	24	0.27	0.51	-0.08	0.16
5	1	FSR/STATS(CC)	23	0.03	0.29	0.01	0.13
	2	FSR/RF-RO(CC)	23	0.81	1.16	-0.22	0.28
	3	FSSR16(CC)	23	0.64	0.95	-0.18	0.24
	4	FSSR16(Tp&SPR)	23	0.14	0.29	-0.05	0.11
	5	FSSR16(Tp)	23	0.44	0.88	-0.12	0.22
	6	FSSR16(SPR)	23	0.35	0.49	-0.12	0.16
10	1	FSR/STATS(CC)	18	0.07	0.30	-0.01	0.13
	2	FSR/RF-RO(CC)	18	0.83	1.19	-0.23	0.28
	3	FSSR16(CC)	18	0.70	1.02	-0.20	0.26
	4	FSSR16(Tp&SPR)	18	0.19	0.30	-0.07	0.10
	5	FSSR16(Tp)	18	0.52	1.00	-0.14	0.23
	6	FSSR16(SPR)	18	0.38	0.50	-0.13	0.16
25	1	FSR/STATS(CC)	4	0.38	0.40	-0.14	0.14
	2	FSR/RF-RO(CC)	4	1.39	1.81	-0.34	0.38
	3	FSSR16(CC)	4	1.23	1.52	-0.32	0.36
	4	FSSR16(Tp&SPR)	4	0.32	0.54	-0.10	0.16
	5	FSSR16(Tp)	4	1.47	1.96	-0.35	0.39
	6	FSSR16(SPR)	4	0.26	0.44	-0.08	0.15

Table A.8 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on standard set of catchments which have SAAR less than 800 mm.

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	25	0.24	0.55	-0.06	0.19
	2	FSR/RF-RO(CC)	25	0.48	1.22	-0.10	0.25
	3	FSSR16(CC)	25	0.42	1.00	-0.10	0.23
	4	FSSR16(Tp&SPR)	25	0.01	0.40	0.02	0.14
	5	FSSR16(Tp)	25	0.34	1.13	-0.06	0.22
	6	FSSR16(SPR)	25	0.08	0.38	-0.01	0.14
5	1	FSR/STATS(CC)	24	0.22	0.47	-0.07	0.15
	2	FSR/RF-RO(CC)	24	0.62	1.23	-0.15	0.25
	3	FSSR16(CC)	24	0.57	1.03	-0.15	0.24
	4	FSSR16(Tp&SPR)	24	0.11	0.39	-0.24	0.13
	5	FSSR16(Tp)	24	0.46	1.12	-0.11	0.22
	6	FSSR16(SPR)	24	0.21	0.42	-0.07	0.14
10	1	FSR/STATS(CC)	20	0.25	0.48	-0.07	0.16
	2	FSR/RF-RO(CC)	20	0.46	0.76	-0.13	0.21
	3	FSSR16(CC)	20	0.48	0.73	-0.14	0.21
	4	FSSR16(Tp&SPR)	20	0.05	0.25	-0.01	0.10
	5	FSSR16(Tp)	20	0.26	0.46	-0.08	0.16
	6	FSSR16(SPR)	20	0.21	0.38	-0.07	0.14
25	1	FSR/STATS(CC)	5	0.23	0.33	-0.08	0.12
	2	FSR/RF-RO(CC)	5	0.36	0.38	-0.13	0.14
	3	FSSR16(CC)	5	0.46	0.46	-0.16	0.17
	4	FSSR16(Tp&SPR)	5	0.28	0.40	-0.09	0.14
	5	FSSR16(Tp)	5	0.37	0.43	-0.13	0.15
	6	FSSR16(SPR)	5	0.38	0.53	-0.12	0.17

Table A.9 Four statistics for return periods 2, 5, 10, 25 and 50 years comparing the performance of six models on standard set of catchments which have AREA less than 100 km^2.

		Method	n	RT_{ij} mean	RT_{ij} RMS	RT'_{ij} mean	RT'_{ij} RMS
2	1	FSR/STATS(CC)	49	-0.03	0.34	0.04	0.15
	2	FSR/RF-RO(CC)	49	0.1	0.66	-0.02	0.19
	3	FSSR16(CC)	49	0.12	0.54	-0.01	0.17
	4	FSSR16(Tp&SPR)	49	-0.02	0.32	0.03	0.13
	5	FSSR16(Tp)	49	0.06	0.62	0.02	0.18
	6	FSSR16(SPR)	49	0.06	0.39	-0.00	0.15
5	1	FSR/STATS(CC)	47	-0.09	0.29	0.06	0.14
	2	FSR/RF-RO(CC)	47	0.24	0.72	-0.05	0.19
	3	FSSR16(CC)	47	0.21	0.59	-0.05	0.17
	4	FSSR16(Tp&SPR)	47	0.05	0.28	-0.01	0.11
	5	FSSR16(Tp)	47	0.15	0.64	-0.02	0.17
	6	FSSR16(SPR)	47	0.14	0.36	-0.04	0.13
10	1	FSR/STATS(CC)	37	-0.10	0.28	0.07	0.14
	2	FSR/RF-RO(CC)	37	0.18	0.69	-0.03	0.18
	3	FSSR16(CC)	37	0.17	0.59	-0.03	0.17
	4	FSSR16(Tp&SPR)	37	0.06	0.28	-0.01	0.11
	5	FSSR16(Tp)	37	0.13	0.68	-0.01	0.17
	6	FSSR16(SPR)	37	0.13	0.36	-0.04	0.13
25	1	FSR/STATS(CC)	10	0.02	0.32	0.01	0.14
	2	FSR/RF-RO(CC)	10	0.41	1.14	-0.07	0.25
	3	FSSR16(CC)	10	0.39	0.96	-0.08	0.24
	4	FSSR16(Tp&SPR)	10	0.03	0.41	0.02	0.15
	5	FSSR16(Tp)	10	0.43	1.24	-0.06	0.27
	6	FSSR16(SPR)	10	0.06	0.32	-0.01	0.12

Table A.10 Four statistics for return periods 2, 5, 10 and 25 years comparing the performance of six models on standard set of catchments which have AREA greater than 100 km^2.

APPENDIX B. THE FSR SIMULATION EXERCISE

B.1 INTRODUCTION

The Flood Studies Report rainfall-runoff model provides a method of deriving a flood hydrograph from a single rainfall storm event. It is, of course, possible that different combinations of storm characteristics and catchment state produce flood peaks of the same magnitude, and it is to be expected that the magnitude of the derived flood peaks will be more sensitive to some of these variables than to others. For example, perhaps rainfall depth affects flood peaks more than the rainfall profile. A large number of computer simulations was performed to examine the way in which the return period of the peak flow was affected by these variables so that a single set of design inputs could be specified to generate a T-year flood peak. In fact the analysis had two stages. Firstly it had to be proven that the technique of using a set of design inputs and an event based model would work (ie. that it could reproduce observed flood frequency curves). Once this was established, the second stage was to formulate a way of selecting a single set of inputs that would give the flood peak of required return period. The following two sections review the two stages of the simulation exercise.

B.2 REPRODUCTION OF FLOOD FREQUENCY CURVES

The four variables that are required for design flood estimation using the rainfall-runoff method are:

1. rainfall storm duration,

2. rainfall profile shape,

3. rainfall storm depth (or return period), and

4. catchment wetness.

Each of these variables has a corresponding probability distribution and these can be combined to yield an overall probability distribution of peak flow (statistically they are the marginal distibutions of a joint probability surface). As the marginal distributions and their interdependence were known, numerical integration could be used to obtain the joint probability of particular combinations of inputs (for uncorrelated marginal distributions, A and B, $p(A \cap B)=p(A).p(B)$). The corresponding flow peak was derived from the rainfall-runoff model. The probability of obtaining a flood magnitude in the interval q_1 to q_2 was then found by summing all the joint probabilities for derived peaks in that interval. The flood frequency curve was built up by performing this summation over successive intervals and thereby covering the required range of flood peaks.

While this process was exhaustive in that all possible combinations of the four variables were considered, it was greatly simplified by defining just six to twelve sub-divisions to represent the entire range of each of the four variables.

Such simulations were carried out on 98 catchments for which rainfall-runoff model parameters, and a suitable length of annual maximum flows, were available. Seventeen catchments were later rejected because their response was too flashy for successful simulation based on hourly rainfall. General comparisons were made between the flood frequency curve derived from annual maxima and the the one resulting from the simulation exercise. However, subsequent analysis was restricted primarily to comparing observed and simulated values of the mean and 10 year floods.

In general, catchments with large floods were underestimated, but individual departures were worse on small and medium flood catchments. Figure 26 shows the pattern of residuals from a regression of the observed mean annual flood (BESMAF) on the simulated mean annual flood (SIMMAF), the latter having been adjusted by raising it to the power of 0.98

$$\text{BESMAF} \qquad \text{SIMMAF}^{0.98} \qquad \text{(B.1)}$$

The simulations tend to underestimate in the south and south-west, and to overestimate floods in East Anglia and on the east coast. The pattern resembles that of residuals from the regression of BESMAF on catchment characteristics, suggesting that the mean annual flood would be similarly over- or underestimated in the same areas by both the statistical method and full numerical integration of probabilities and simulation of peaks using the rainfall-runoff method.

The conclusion was that "the probability distributions of floods from real catchments can be adequately predicted by the simulation technique", FSR I.6.7.4(444).

B.3 CHOICE OF A SINGLE SET OF DESIGN INPUTS

The second stage of the analysis involved selecting a single choice of variables for each flood return period. This was achieved by choosing suitable fixed values of the three less important variables and then optimising the remaining variable such that the model reproduced the required flood magnitude. Since storm profile was found to be the least important variable it was fixed as the 75% winter profile, since this profile gave results closest to the average of

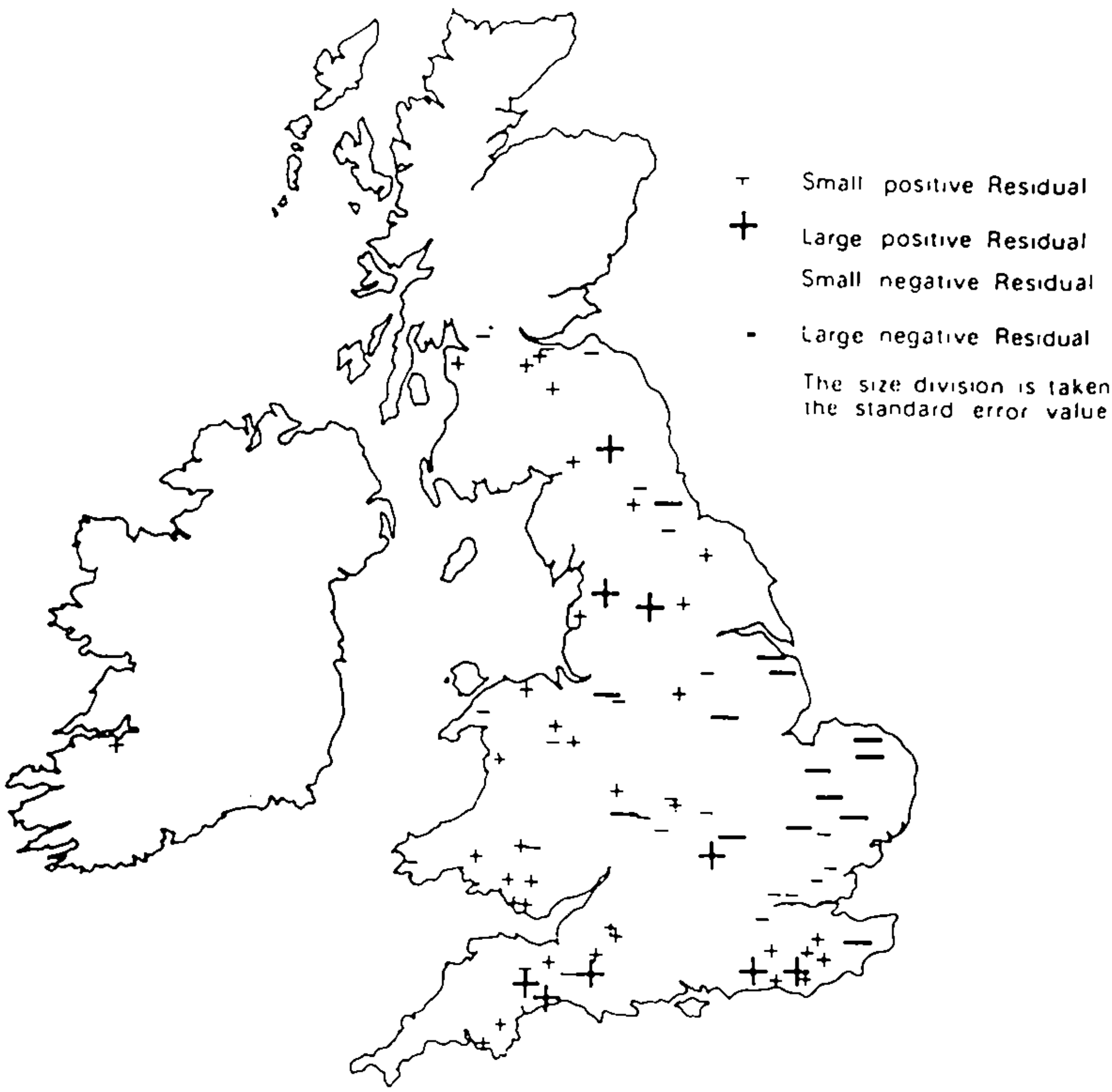

Figure 26. Residuals from estimating the mean annual flood

all profiles. It was found that flood magnitude was less sensitive to storm duration than to either of the remaining variables (ie. antecedent wetness and storm depth). Thus duration, D, was fixed by the equation

$$D = (1.0 + SAAR / 1000) Tp \qquad (B.2)$$

This equation was intended to estimate the duration giving the largest flood magnitude but, as curves of flood magnitude against storm duration are very flat, the choice of D is not critical. Antecedent wetness (CWI) and storm depth were found to be equally important in influencing flood peaks. When CWI was fixed, the relationship between flood return period and rainfall return period was similar between catchments. Conversely, fixing rainfall depth (by return period) led to inconsistent CWI values for different catchments. Therefore CWI was fixed and rainfall return period was chosen by optimisation. For each catchment the return period of rainfall required to produce floods of a range of return periods was evaluated. Curves depicting the relationships between the resulting return periods are given in FSR Figure I.6.54(456) for seven catchments. An average curve was recommended for selecting the appropriate storm return period to give the peak discharge of required return period when combined with the other variables.

Two points in particular may be made about the second stage of the analysis. Firstly, in selecting the single choice of variables, a match was sought with the simulated flood frequency curves, rather than those derived from observed data. Thus the regional deviations present in the simulations (see Figure 26) were built into the single choice of variables. Secondly, it is not clear how many catchments were used, and how much variability was present, when defining the relative return periods of design rainfall and peak flow. FSR Figure I.6.54(456) shows considerable scatter in the relationship for seven catchments where the rainfall return period varies from (i) 5 to 10 years for the 5 year flood, (ii) 12 to 27 years for the 10 year flood and (iii) 60 to 128 years for the 50 year flood. The corresponding recommendations of the FSR are 8, 17 and 81 years respectively.

APPENDIX C. ESTIMATION OF SOME EXTREME HISTORICAL UK FLOODS

C.1 NOTATION

A	cross-sectional area of river channel
AREA	catchment drainage area (km^2)
ARF	areal reduction factor
CWI	catchment wetness index
DPR_{cwi}	dynamic term of percentage runoff model controlled by catchment wetness
DPR_{rain}	dynamic term of percentage runoff model controlled by storm rainfall depth
MSL	mainstream length (km)
n	roughness coefficient in Manning equation
NMF	normal maximum flood (m^3/s)
PMF	probable maximum flood (m^3/s)
PMP	probable maximum precipitation (mm)
PR	percentage runoff
R	hydraulic radius of river channel
S	water surface slope (m/km)
S1085	slope of mainstream between 10% and 85% distance between outlet and source (m/km)
SAAR	average annual rainfall for the standard period 1941-1970 (mm)
SOIL1	proportion of drainage area underlain by soil of WRAP class 1
SPR	standard percentage runoff
Tp	mean time-to-peak of unit hydrograph (hr)
Tp	minimum time-to-peak of unit hydrograph (hr)
URBAN	proportion of catchment area urbanised
WRAP	winter rainfall acceptance potential

C.2 INTRODUCTION

Dam failures are amongst the most catastrophic calamities; a total of almost 350 people lost their lives in just three disasters in Britain (Bilberry in 1852, Dale Dyke 1864 and Dalgarrog in 1925). Gruner (1963) reported that a quarter of dam failures documented between 1799 and 1944 resulted from insufficient spillway capacity. The hydrologist therefore has an important role in developing design flood estimation techniques which accurately estimate the largest flood likely to be encountered, thus minimising the risk of catastrophe, whilst avoiding costly over-design.

It is fifteen years since the Flood Studies Report method (NERC, 1975) for estimating a maximum flood hydrograph was first applied in the UK. As a design tool it replaced some approximate rules-of-thumb with recommendations based on the first rigorous study of national rainfall and river flow data, though it too has been criticised for its simplistic assumptions. The question to be asked in 1989 is whether we can now do any better. A number of Flood Studies Supplementary Reports (NERC, 1977-1985) have been published refining the FSR procedure and many other papers have been written on this or closely related subjects; there should be, therefore, some new insights. On the other hand, as we are discussing maximum floods we do not expect much in the way of new data to prove or disprove the accuracy of our estimates. Indeed, if, in that space of time, we had had a major flood somewhere which equalled or exceeded our estimate, we would be concerned to say the least.

In normal estimation techniques it is intended that the best estimate is (roughly) equally likely to be under or over the true value. With maximum floods not only are we deprived (by definition) of the true value but even if we had some values that were close to being true we would not allow ourselves to underestimate any of them; we place all the error of estimate on one side. This is not like a factor of safety, applied as a multiplier to the final figure to reflect the lumped uncertainties; in the FSR procedure the approach is to maximise, or make the worst reasonable assumptions about, each component of the procedure as we go. In doing so, our estimates on many catchments may be greatly - perhaps an order of magnitude - in excess of any experienced flood. This paper compares some estimates of recorded floods with FSR maximum flood estimates made for the same catchments. It also examines the FSR procedure and suggests which aspects are most open to review.

C.3 SIGNIFICANT FLOODS IN BRITAIN

Records of historical flood events are available from many sources including water authority archives, newspapers and journals, some of which include photographic evidence and eyewitness accounts. For some other floods, the peak water levels are recorded as flood marks on bridges, walls and houses or as specially sited stones. A knowledge of the maximum recorded water level is only the first step in hydrological analysis; an estimate of the peak discharge is required if we are to estimate runoff potential and transfer our findings to other catchments.

Table C.1 contains a list of some major floods over the past 200 years with estimates of peak discharge. Also given is the method of estimation. The symbol G denotes a flow gauging station with an existing relationship between stage and discharge. This relationship will almost certainly have been extrapolated well beyond any flows used for its calibration. Uncertainty is compounded by the probability that the flow will have overtopped the measuring structure or river banks, and that the river bed may have been scoured during the flood, changing the stage-discharge relationship. Occasionally a gauging station is built at, or near, a site where a historical flood was recorded, such as on the Dee at Woodend (no 2 in Table C.1) where the peak discharge of the 1829 flood was estimated (NERC, 1975) by extrapolating the present stage-discharge relationship to the peak level given in the account of the floods by Lauder (1830).

The symbol SA in Table C.1 indicates that the discharge, Q, was calculated by the slope-area method eg. using the Manning equation

$$Q = A \; R^{2/3} \; S^{1/2} \; / \; n \qquad (C.1)$$

where A is the cross-sectional area, R is the hydraulic radius, n, the channel roughness and S, the water surface slope. The Manning equation was developed to describe flow in an infinite channel with constant cross-section, energy gradient and roughness; conditions rarely encountered in natural channels. Use of this retrospective discharge estimation technique relies on post-flood surveys to provide an accurate picture of the hydraulic properties of the channel at the peak of the flood. Critical to the calculation is the numerical value assigned to n. Text books provide suitable values for regular surfaces such as concrete, but suitable values for mixed surfaces including cobbles and grass containing fallen trees and supermarket trolleys are more difficult to determine. Despite these drawbacks, the technique has been widely used in the UK (see for example Acreman, 1983b for no 57 in Table C.1; Hydraulics Research, 1968 for nos 36-39; and Whiter, 1982 for nos 62-65).

Hydraulic equations can also be used to compute a minimum estimate of the peak flow by calculating the critical velocities needed to entrain material, such as large boulders, which were known to have been transported during the flood (see for example Metcalfe, 1979; Table C.1 no 91). Making certain assumptions about the hydraulic conditions, the difference in peak flows at two gauging stations (eg. Shenchie and Forres on the Findhorn, no 42) can give an estimate of the inflow from the intervening catchment (in this case the Divie and Dorback tributaries).

Techniques may be combined where the channel geometry and hydraulic conditions are complicated. Sargent (1982; no 12) calculated the peak flow for 1948 at Haddington using a back-water approach, to model the effects of weirs, combined with slope-area estimates where the water level was controlled by channel friction. A variety of other methods have been used; Dobbie and Wolf (1953; 19-23) built a scale model from paraffin wax to estimate the peak discharges of several streams around Lynmouth affected by the floods of 1952; Acreman (1986; nos 3 & 4) showed how a rating curve for the site of a historic peak level could be constructed using flow data from elsewhere on the same river; and erosion damage was used by Baxter (1949; no 14) to estimate the depth of water passing over a spillway. In each case the authors point out the uncertainties involved and would usually admit to errors of estimate of at least 20% and often much more.

Figure 27 shows the location of the sites mentioned in Table C.1. It can be seen that there are concentrations of flood events recorded in the highlands of Scotland, the Southern Uplands and south-west England. This pattern reflects, to some extent, the distribution of flood producing mechanisms. Floods result from a combination of intense rainfall falling on a responsive catchment. Thus the largest floods would be expected on steep, impermeable catchments, on small catchments in thunderstorm prone areas and on large catchments where long duration rainfalls are intense. However, the pattern of floods in Figure 27 is also partly due to the a geographical bias in available estimates of peak flows. The Hampstead storm of 14th August 1975 (Keers & Wescott, 1976), resulted in severe flooding of parts of north-west London but precise estimates of peak discharge are not available for the worst affected areas. (Binnie and Partners (1976) estimated the peak runoff from an area of 0.5 km^2 to be between about 2 and 7 m^3/s, lack of data precluded a more exact figure). A further example for which no flow data were recorded is the great Till flood of 1841 (Cross, 1967) which resulted from rain falling on frozen ground. Under normal conditions on this type of catchment, underlain by chalk, most of the rainfall would percolate into ground with only a low proportion producing stream-flow.

Despite some shortcomings these historical extreme events can be used to provide an indication of the likely maximum size of floods in the UK and their distribution. Figure 28 is a graph which shows each estimate from Table C.1 with its reference number attached. It also shows, with a + symbol, the maxima from each gauged catchment held on the Surface Water Archive (Institute of Hydrology, 1988). Figure 28 on page 113 also shows two lines. A-A defines the original Normal Maximum Flood, NMF (Institution of Civil Engineers, 1933) and B-B is the suggested spillway design flood curve for upland reservoirs which accompanied a later review (Allard et al, 1960). This latter line appears not to have formally superseded the earlier practice of taking some multiple ('at least twice') of the NMF as the spillway design (or 'catastrophic') flood.

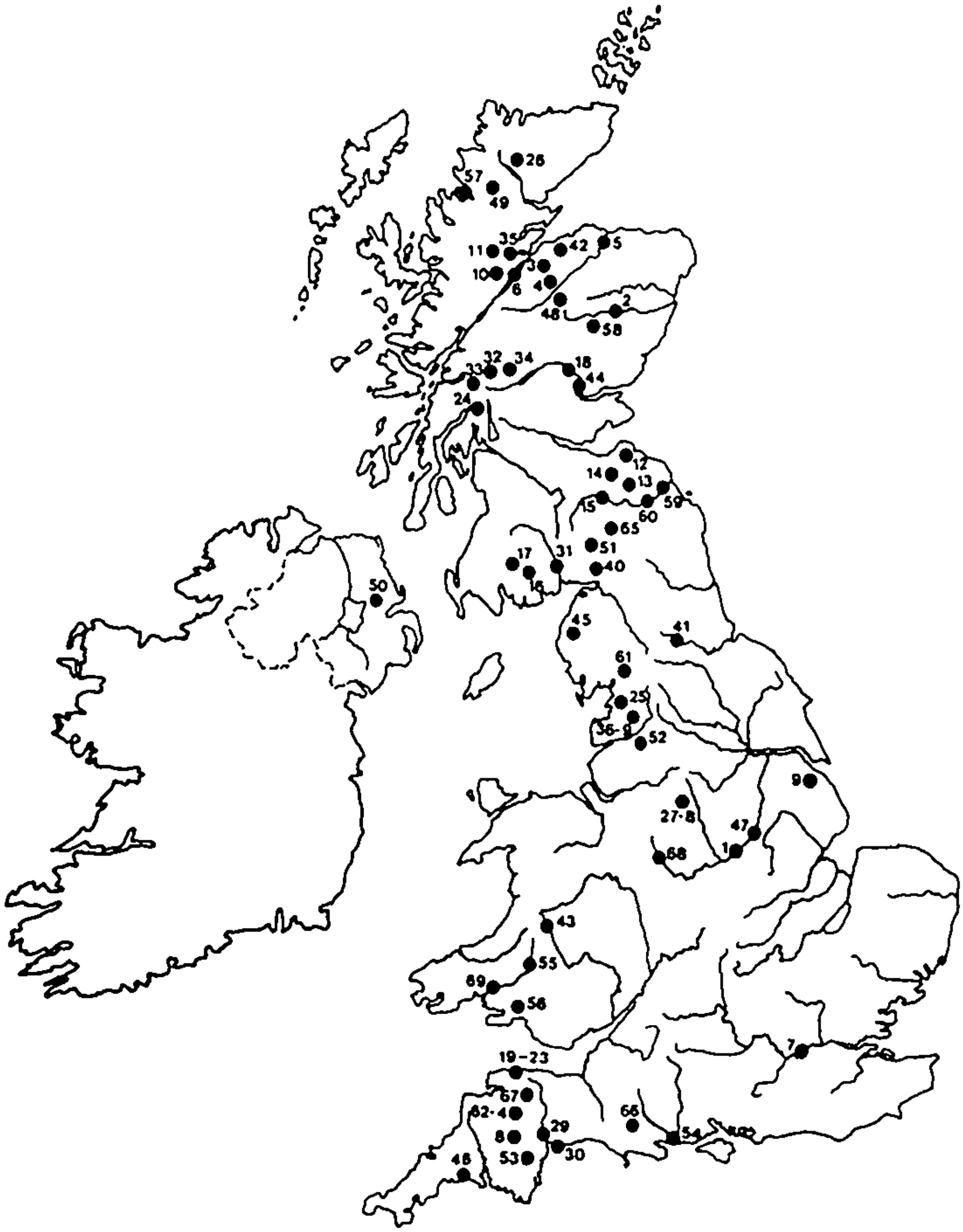

Figure 27. Location of sites in Table C.1

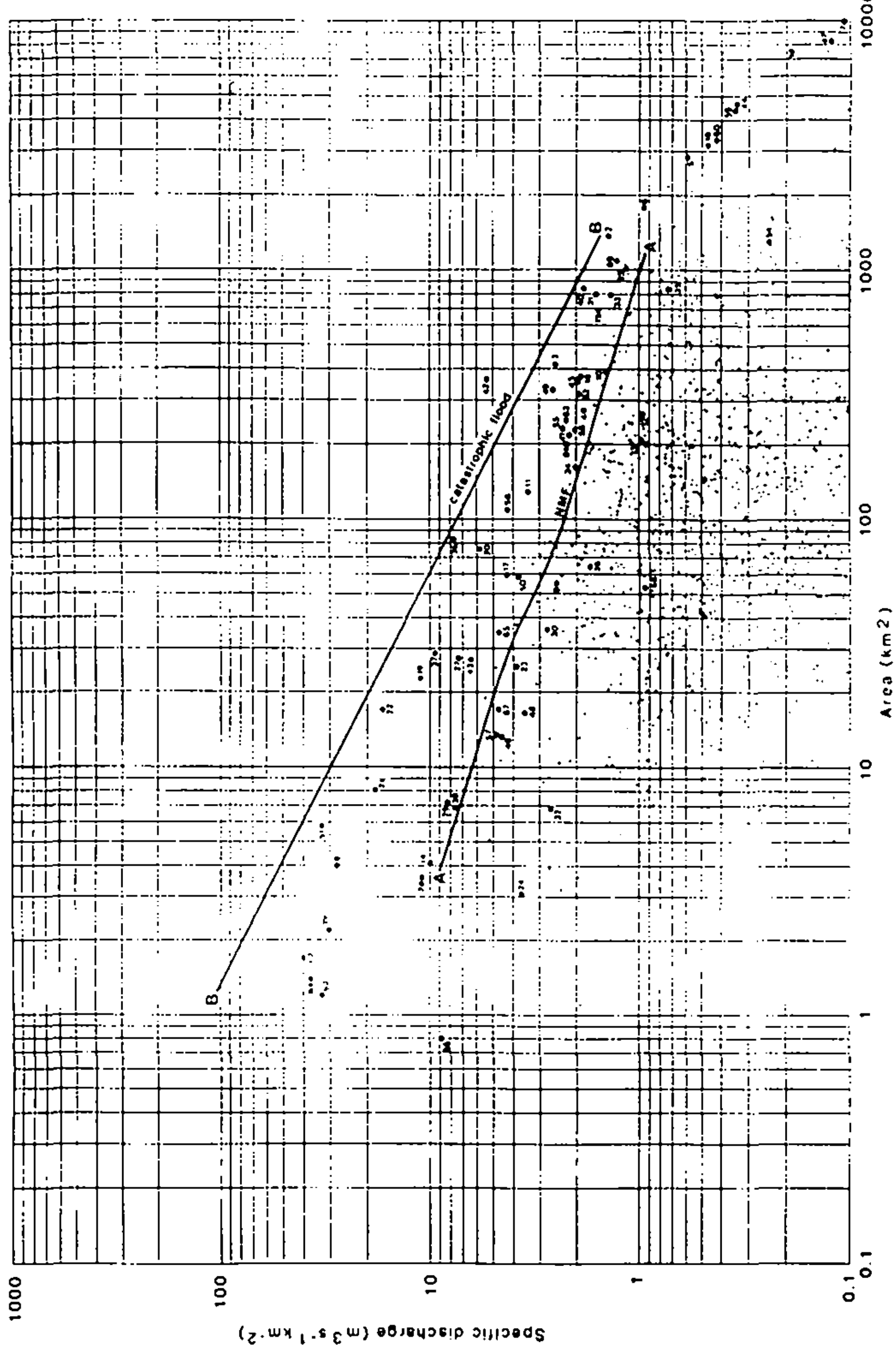

Figure 28. Observed magnitudes against catchment area

C.4 EXTRAPOLATE OR INTERPOLATE?

The presentation of maxima in Figure 28 allows the engineer to interpolate a value for his catchment. It is interpolation in the sense that recorded maxima are themselves being used directly to estimate similar maxima which might be expected at other and ungauged sites. It is implicit in such a use of envelope curves that the very highest floods, expressed in this case as runoff per unit area are the worst that our climate is capable of producing. We suggest later that, for larger catchments, this is a dubious proposition.

Interpolation can be supplemented by engineering judgment if conditions of the design catchment are significantly different from those of the observed sites. Clearly, a method of estimation based solely on catchment area, though attractively simple, is rather restrictive. However, this was not a problem when British design usage was dominated by upland reservoir construction. The post war development of lowland reservoirs and control of larger catchments, helped to highlight the need for new guidance where the allowances could be made explicit. Such guidance is provided in the Flood Studies Report.

Instead of drawing an envelope around recorded flow maxima, the FSR method of maximum flood estimation in effect draws the envelope around recorded rainfall maxima[2]. Rainfall is then converted to flow using a simple linear rainfall-runoff model. Model parameters were related to those physical characteristics of the catchment which quantify the upland v. lowland factor. The key difference between this technique and the one it has replaced is that the envelope method gains nothing from lesser flows recorded on the same catchment; the method relies on interpolation between observed maxima at all available sites. The rainfall-runoff methodology, on the other hand, uses data from a wider range of events, many of which are smaller - often much smaller - than those featuring in Table C.1; this method can be considered an extrapolation from recorded data on the same catchment.

C.5 PROBABLE MAXIMUM FLOODS

The FSR method transforms maximum rainfall estimates into flow hydrographs to produce the Probable Maximum Flood, PMF. This is achieved by assuming the worst possible conditions regarding antecedent wetness, design storm construction and speed of catchment response. One obvious test of the procedure is that its estimates

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[2] The term rainfall is used loosely here to include snowmelt. There is no doubt that snowmelt is a significant factor in many large floods, especially on large catchments, but, in this country, snowmelt alone can not generate flows in the PMF range.

should always be greater than any recorded maxima. These observed maxima, on the other hand, might be exceeded as time passes. At the time of publication of the FSR it was noted (Lowing, 1975) that the peak flow from the Red-a-ven event (Worth, 1930 no 8) had been estimated to be slightly higher than that given by the FSR procedure.

To test whether this was a unique occurrence, PMFs were calculated (using the Institute of Hydrology's micro-FSR computer package, developed by *Boorman*, 1988) for a selection of the catchments listed in Table C.1. Table C.2 provides the necessary catchment and climate characteristics required by micro-FSR. Boorman (1985) provides estimates of model parameters required for PMF estimation for a large number of catchments throughout the UK including the Tyne at East Linton (used for estimate 12). Boorman et al (1988) give values for several other catchments in Scotland. Table C.3 gives the results from the PMF procedure. These are shown in Figure 29 plotted against the maximum recorded floods. On the larger catchments (ie. those with larger *absolute flood peaks*), PMF *is around two and half times* the historical maximum. In addition to Red-a-ven, it can be seen that estimated flows at five sites (Stobshiel, no 14; Claughton, 39; Divie/Dorback, 42; Caldwell, 51; Chulmleigh, 62) exceeded the estimated PMF. To consider whether these exceedences pose a serious threat to the credibility of the PMF estimation procedure, we need to examine the estimates in a little more detail.

C.6 HOW CAN OBSERVED FLOODS EXCEED PMF?

There are a number of possible reasons why observed flood peaks might exceed PMF. The PMF model may be deficient in rainfall input, percentage runoff or unit hydrograph, or the model parameters may be inappropriate. Alternatively, the recorded flood peak may be in error.

C.6.1 *Rainfall input*

Unfortunately there are no short duration rainfall data for the largest event, the Caldwell Burn flood, although a professional meteorologist from Eskdalemuir Observatory, who was caught in the storm, estimated that the intensity probably equalled the 90 mm/hr which had been recorded in 1953 (Metcalfe, 1979). This is still far less than the 166 mm/hr probable maximum precipitation, PMP, used to estimate the PMF. There has been no definitive study comparing PMP and recent observed storms. However, the largest daily rainfall since the FSR data were collected, 238.4mm at Sloy Main Adit in January 1974 (Reynolds, 1982), is considerably less than the 300-350mm PMP for that site. Of the six historical floods which have exceeded PMF, *five are on small catchments* (< 10 km^2), *for which the* critical storm duration is much shorter than 24 hours. The Hampstead storm of 14th August 1975, during which 169 mm rainfall fell in two and a half hours (Keers & Wescott, 1976), is the closest to PMP re-

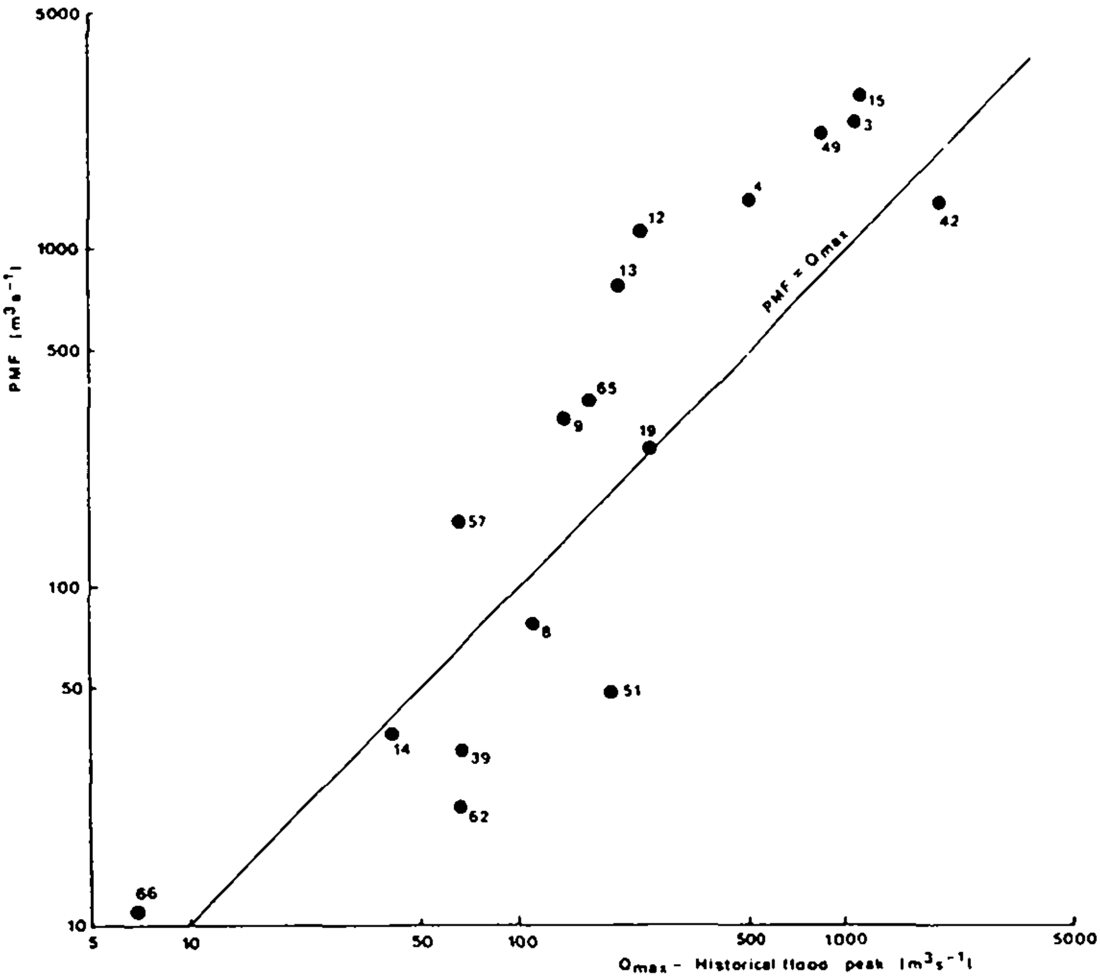

Figure 29. Observed magnitudes plotted against estimated PMF

cently recorded; the maximum two hour rainfall for this area is 190 mm. Table C.3 shows the peak runoff expressed in mm/hr over each catchment. Even during these six events runoff intensity was far less than the estimated PMP. This suggests that any deficiency in the PMF model is unlikely to arise from the rainfall input.

C.6.2 Percentage runoff

Henderson (1986) estimated that percentage runoff, PR, exceeded 90% in all parts (up to 107 km^2) of the Water of Leith catchment in Midlothian during the flood of November 1984, which was not influenced by snowmelt or frozen ground. However, it is not always clear that the methods used for the calculations are consistent with those specified in the FSR. A recent report by Welsh and Burns (1987) illustrates the sensitivity of PR estimates to the selected duration, showing that for small upland catchments in the south of Scotland PR can vary from around 40% for the first 5 hours of the storm to nearly 100% when calculated for the first 24 hours of the storm. Using the recommended procedure, Boorman et al (1988) confirmed that in small catchments underlain by impermeable soils (WRAP class 5), PR could be higher than given in the FSR. However, the PMP intensities are, in most cases, greater than twice the runoff rate recorded during the historic floods. Therefore even a PR as low as 50% would supply a sufficiently high runoff rate, suggesting that the percentage runoff part of the model is not inadequate.

C.6.3 Unit hydrograph

The FSR procedure uses a unit hydrograph to transform rainfall to runoff. The linear model has one parameter, its time to peak, Tp. For PMF estimation, Tp is reduced by one-third to simulate the worst possible conditions (this is the average ratio of minimum to mean Tp in the UK). This reduction may be inadequate to model the very rapid runoff experienced during extreme events. Alternatively, use of a linear model may not be appropriate. Nevertheless it is difficult to visualise what sort of model could reproduce the flood of 189 m^3/s estimated for the Caldwell Burn flood (no 51).

During some large floods the peak discharge results from a surge of water caused by the release of temporary blockages upstream. There is evidence that this occurred during the Lynmouth flood when a 15m high railway embankment collapsed on the River Heddon above Parracoombe (west of the Lyn); three people died (Delderfield, 1978). Such effects are not allowed for in the PMF model, but are usually short lived, and would not be important for spillway design as the peak would be attenuated when routed through the reservoir.

There are situations where the flood wave form and the channel geometry may combine to produce an unusual effect. Rather than attenuating as it moves downstream, the rising limb is steepened and the peak enhanced. This phenomenon may have occurred on the Findhorn in 1970 and would explain the large inferred flood peak for the intermediate catchment of the Divie/Dorback (no 42). If this was the case it would be wrong to take the difference in peaks as an estimate of the inflow from the extra contributing catchment area.

Whilst the FSR rainfall-runoff procedure may be deficient for intense rainfall events on small catchments, it may lead to overestimation of PMF on large catchments. When a large floodplain is involved, the flood wave travel time may be increased during large floods as the water spills into overbank storage and flow resistance increases.

C.6.4 Poor estimation of historical flood peaks

The method of flood peak derivation for the Red-a-ven flood is not clear from the article by Worth (1930). The floods at Chulmleigh, Forest of Bowland and Berryscaur were estimated by the slope/area method. As described above, even when the technique is applied by experienced hydraulic engineers, the accuracy of estimation can be poor, and the true peak may well have been closer to PMF. Apart from the doubts about inferring the peak discharge from the intervening area between two gauging stations, the Divie/Dorback flood discharge estimate relies heavily on the stage-discharge relationship at Forres gauging station. Previous to the flood, the highest current meter measurement used for the rating equation was around 2.1m. The flood peak stage was 4.71 m, thus the peak discharge was based on a large extrapolation. Futhermore, the control at the station is a gravel bar which suffered considerable scour and redeposition during the flood. Therefore, despite being recorded at a formal gauging station, the peak discharge may be a poor estimate.

There is a danger of dismissing all six of the estimated peaks which exceeded PMF. It is possible that some were underestimates. It is interesting that, with the exception of the Divie/Dorback - which is not a true catchment - the PMF exceedances all relate to catchments under 10 km^2. Indeed, only one of the events from such a small catchment (no 66) did not exceed PMF and this is underlain by chalk. Perhaps we would expect PMF to be approached more frequently on small catchments. The chance of maximum rainfall of small areal extent coinciding with a small catchment is much greater than a larger storm sitting squarely over a larger catchment. Even the Lynmouth storm was not centred over the Lyn catchment.

C.7 CONCLUSION

Extreme flood estimation is prone to uncertainty whether the estimate relates to an actual event or to a hypothetical design storm. The two design approaches - interpolating with an envelope curve or extrapolating with a model - are seen to have strengths and weaknesses, but the former still has a strong intuitive attraction which helps to aid interpretation of the latter. Recorded floods have highlighted the potential extreme response from small (<10 km^2) catchments.

	Date	Water course/site	Peak flow (m^3s^{-1})	Area (km^2)	Estimation method	Reference
1	Feb 1795	Trent, Nottingham	1416.0	7490.0	VA G	NERC (1975)
2	Aug 1829	Dee, Woodend (Aberdeenshire)	1900.0	1370.0	VA G	NERC (1975)
3		Findhorn, Shenachie (Morayshire)	1050.0	417.0	VA	Acreman (1986)
4		Dulnain, Balnaan Br (Morayshire)	500.0	272.0	VA	Acreman (1986)
5		Spey, Boat o'Brig	1665.0	2850.0	VA	Werritty & Areman (1985)
6	Jan 1849	Ness (Invernessshire)	1700.2	1792.3		Nairne (1895)
7	Nov 1894	Thames, Teddington	1059.0	9948.0	TH G	SWA
8	Aug 1917	Red-a-ven, Dartmoor	110.4	4.0		Worth (1931)
9	May 1920	Lud, Louth (Lincolnshire)	138.0	55.1		Crosthwaite (1921)
10	Dec 1936	Moriston, Invermoriston	557.5	391.0	VA G	Mclean (1945)
11	Nov 1947	Glen Cannich, Inverness	433.3	128.1	SA	Wolf (1952)
12	Aug 1948	Tyne, Haddington (East Lothian)	255.0	264.0	SA BW	Sargent (1982)
13	Aug 1948	Gala Water, Galashiels	200.0	207.0	VA G	NERC (1975)
14	Aug 1948	Tyne, Stobshiel (East Lothian)	40.8	4.1	TH	Baxter (1949)
15	Jan 1949	Tweed, Peebles	1079.0	694.0	SA G	NERC (1975)
16	Sep 1950	Ken, Earlston Dam (Galloway)	708.0	372.3	TH	Chapman & Buchanan (1966)
17	Sep 1950	Polharrow, Carsfad Dam (Galloway)	254.9	59.5	TH	Chapman & Buchanan (1966)
18	Nov 1951	Tay, Caputh	1481.0	3211.0	VA G	SWA
19	Aug 1952	West Lynn, Lynmouth	252.8	22.8	PM	Dobbie & Wolf (1953)
20		East Lynn, Lynmouth	436.1	76.0	PM	
21		Hoaroak Water, Lynmouth	148.7	8.1	PM	
22		Hoaroak Water, Lynmouth	286.0	17.0	PM	
23		Badgeworthy Water, Lynmouth	97.7	25.3	PM	
24	Sep 1953	Allt Uaine (Dumbartonshire)	11.3	3.1	TH	NERC (1975)
25	Dec 1954	Lune, Lancaster	1161.0	1011.7	VA G	Chapman & Buchanan (1966)
26	Jan 1955	Tirry, Rhian Bridge	110.9	64.2	VA	NERC (1975)
27	Aug 1957	Foston Brook (Derbyshire)	200.4	27.4	SA	Barnes & Potter (1958)
28		Snelston Brook (Derbyshire)	39.1	3.6	SA	
29	Sep 1960	Alphin Brook, Exeter	59.5	7.2	SA	Brierley (1965)
30	Oct 1960	Withycombe Brook, Exmouth	99.0	36.0	SA	Harrison (1961)
31	Jan 1962	Nith, Friars Carse	1274.0	799.0	VA G	SWA
32	Feb 1962	Allt Larig nan Lunn (Argyll)	18.1	6.8		Chapman & Buchanan (1966)
33	Feb 1962	Loch Awe (Argyll)	1076.2	797.0		Chapman & Buchanan (1966)
34	Feb 1962	Lyon (Perthshire)	324.3	161.5	VA G	Chapman & Buchanan (1966)
35	Feb 1962	Beauly, Erchless (Invernessshire)	608.8	841.8	VA G	Morgan (1966)
36	Aug 1967	Hindburn, Bowland Forest	637.0	83.4	SA	Hydraulics Rsearch (1968)
37		Dunsop Water, Bowland Forest	271.8	28.7	SA	
38		Blacko Water, Bowland Forest	52.3	6.9	SA	
39		Claughton Beck, Bowland Forest	66.5	2.2	SA	

	Date	Water course/site	Peak flow (m^3s^{-1})	Area (km^2)	Estimation method		Reference
40	Oct 1967	Esk, Netherby	1545.0	841.7	VA	G	SWA
41	Mar 1968	Tees, Dent Bank	467.5	217.3	TH	G	SWA
42	Aug 1970	Divie & Dorback (Morayshire)	1939.3	365.0	VA	G	NERC (1975)
43	Aug 1973	Wye, Pant Mawr	174.0	27.2	TH	G	SWA
44	Jan 1974	Tay, Ballathie (Perthshire)	1570.0	4587.1	VA	G	NERC (1975)
45	Jul 1976	Derwent, Ouse Bridge	696.9	363.0	VA	G	SWA
46	Sep 1976	Pol, Polperro (Cornwall)	60.0	13.2	SA		Kavanagh (1976)
47	Feb 1977	Trent, North Muskham	1006.0	8231.0	VA	G	SWA
48	Aug 1978	Allt Mor (Inverness-shire)	58.0	16.4	SA		McEwen (1981)
49	Oct 1978	Oykel, Easter Turnaig	847.5	330.7	VA	G	SWA
50	Dec 1978	Six Mile Water, Ballyclare	221.4	58.4	VA	G	SWA
51	Jun 1979	Caldwell B, Berryscaur (Dumfries)	189.0	5.8	SA	C	Metcalfe (1979)
52	Nov 1979	Calder, Whalley Weir	615.0	316.0	TH	G	SWA
53	Dec 1979	Dart, Austins Bridge	549.7	247.6	VA	G	SWA
54	Dec 1979	Stour, Christchurch (Hampshire)	310.0	1291.0	VA	G	Tyhurst (1981)
55	Dec 1979	Tywi, Dolau Hirion	533.8	231.8	VA	G	SWA
56	Dec 1979	Tawe, Ynystanglws	461.3	227.7	TH	G	SWA
57	Sep 1981	Ardessie B, Ardessie (Wester Ross)	65.0	13.5	SA		Acreman (1983b)
58	Oct 1981	Muick, Invermuick	470.6	110.0	VA	G	SWA
59	Jan 1982	Tweed, Norham	1518.0	4390.0	VA	G	SWA
60	Jan 1982	Tweed, Sprouston	1409.0	3330.0	VA	G	SWA
61	Jan 1982	Rawthey, Brigg Flatts	448.1	200.0	VA	G	SWA
62	Jul 1982	Chulmleigh (Devon)	68.0	1.7	SA		Whiter (1982)
63			39.0	1.2	SA		
64			51.7	1.4	SA		
65	Aug 1983	Hermitage Water (Roxburghshire)	165.0	35.0	SA		Acreman (1983a)
66	May 1986	West Stream, Lyons Gate (Dorset)	7.0	0.8	TH		Ian Howick Assc (1986)
67	Aug 1986	Crooked Oak, Knowstone (Devon)	80.0	17.0	SA		Horrocks (1986)
68	Aug 1987	Trent, Stoke-on-Trent	50.0	53.2	TH	G	Pirt (1987)
69	Oct 1987	Tywi, Carmarthen	1378.0	1088.0	VA	G	Frost(1988)

SWA Surface Water Archive, Institute of Hydrology
SA velocity from water surface slope, channel roughness and cross-sectional area
BW river level from back-water effect of weir
C critical velocity required to entrain transported material
VA velocity/area from current metering
PM physical model
TH theorectical calibration of hydraulic structure
G at formal gauging station

Table C.1 Peak discharge estimates for some documented floods since 1795

Site	Drainage area (km^2)	Stream slope ($m\ km^{-1}$)	Stream length (km)	Annual average rainfall (mm)	Urban area	Soil classification 1	2	3	4	5	Maximum rainfall 2 hr (mm)	24 hr (mm)
					(proportion of the catchment area)							
3 Shenachie	417.00	9.3	47.32	1337	0.00	0.00	0.00	0.00	0.00	1.00	129.0	305.0
4 Balnaan Br	272.00	9.94	37.43	1101	0.00	0.00	0.21	0.00	0.00	0.79	134.0	290.0
8 Red-a-ven	4.0	90.97	3.74	1690	0.00	0.00	0.00	0.00	0.76	0.24	165.0	370.0
9 Louth	55.1	6.12	7.45	677	0.00	1.00	0.00	0.00	0.00	0.00	165.0	280.0
12 Haddington	307.5	6.03	31.90	759	0.03	0.05	0.00	0.22	0.70	0.03	136.0	270.0
13 Galashiels	207.0	6.24	38.42	975	0.00	0.00	0.00	0.97	0.02	0.01	142.0	280.0
14 Stobshiel	4.1	45.3	1.75	800	0.00	0.00	0.00	1.00	0.00	0.00	138.0	270.0
15 Peebles	694.0	3.95	42.62	1252	0.01	0.00	0.00	0.88	0.00	0.12	141.0	305.0
19 Lynmouth	23.5	29.7	9.20	1500	0.00	0.00	0.60	0.00	0.00	0.40	160.0	340.0
39 Claughton Beck	2.25	85.88	2.95	1200	0.00	0.00	0.00	0.00	1.00	0.00	154.0	290.0
42 Dorback	365.0	9.75	37.60	790	0.00	0.00	0.39	0.00	0.00	0.61	133.0	261.0
49 Oykel	330.7			1967	0.00	0.00	0.00	0.00	0.00	1.00	118.0	280.0
51 Caldwell Burn	5.68	26.60	3.50	1180	0.00	0.00	0.00	1.00	0.00	0.00	141.0	290.0
57 Ardessie	13.5	80.49	7.53	1650	0.00	0.00	0.00	0.00	0.00	1.00	115.0	280.0
62 Chulmleigh	1.70	76.64	1.15	1050	0.00	0.23	0.23	0.00	0.00	0.54	170.0	270.0
65 Hermitage	35.9	10.75	22.88	1530	0.00	0.00	0.00	0.00	0.00	1.00	140.0	300.0
66 Lyons Gate	0.83	41.67	0.60	1010	0.00	0.50	0.00	0.00	0.00	0.50	162.0	310.0

Table C.2 Catchment characteristics for PMF estimation

	Site	Date of historical flood	Area	Estimated peak runoff		PMP maximum intensity	PR	PMF
			(km^2)	(m^{3}s^{-1})	(mm hr^{-1})	(mm hr^{-1})	%	(m^{3}s^{-1})
3	Shenachie	4-AUG-1829	417.0	1050.0	9.06	76.0	79.4	2400.
4	Balnaan Br	4-AUG-1829	272.0	500.0	6.62	82.3	73.4	1400.
8	Red-a-ven	17-AUG-1917	4.0	110.4	99.36	264.8	79.1	78.1
9	Louth	29-MAY-1920	55.1	138.0	9.02	114.6	34.3	317.
12	Haddington	12-AUG-1948	307.5	255.8	2.99	82.6	66.3	1150.
13	Galashiels	12-AUG-1948	207.0	200.0	3.48	89.2	61.4	782.
14	Stobshiel	12-AUG-1948	4.1	40.8	35.8	164.1	59.7	36.7
15	Peebles	7-JAN-1949	694.0	1079.0	5.60	78.4	64.8	2790.
19	Lynmouth	15-AUG-1952	23.5	252.1	38.6	167.0	68.5	258.
39	Claughton	8-AUG-1967	2.3	66.6	104.2	264.0	70.5	33.3
42	Dorback	16-AUG-1970	365.0	1939.3	19.12	79.4	66.5	1400.
49	Oykel	5-OCT-1978	330.7	847.5	9.23	51.9	85.2	2210.
51	Caldwell B	13-JUN-1980	5.7	189.0	119.4	166.0	62.2	49.6
57	Ardessie	25-SEP-1981	13.5	65.0	17.3	172.0	77.0	157.
62	Chulmleigh	12-JUL-1982	1.7	68.0	144.0	294.0	59.4	25.2
65	Hermitage	26-JUL-1983	35.9	165.0	16.5	141.6	79.1	362.
66	Lyons Gate	20-MAY-1986	0.83	7.0	31.5	286.0	56.7	10.8

Table C.3 PMF estimates for 17 UK catchments together with the peak flow for the largest recorded floods

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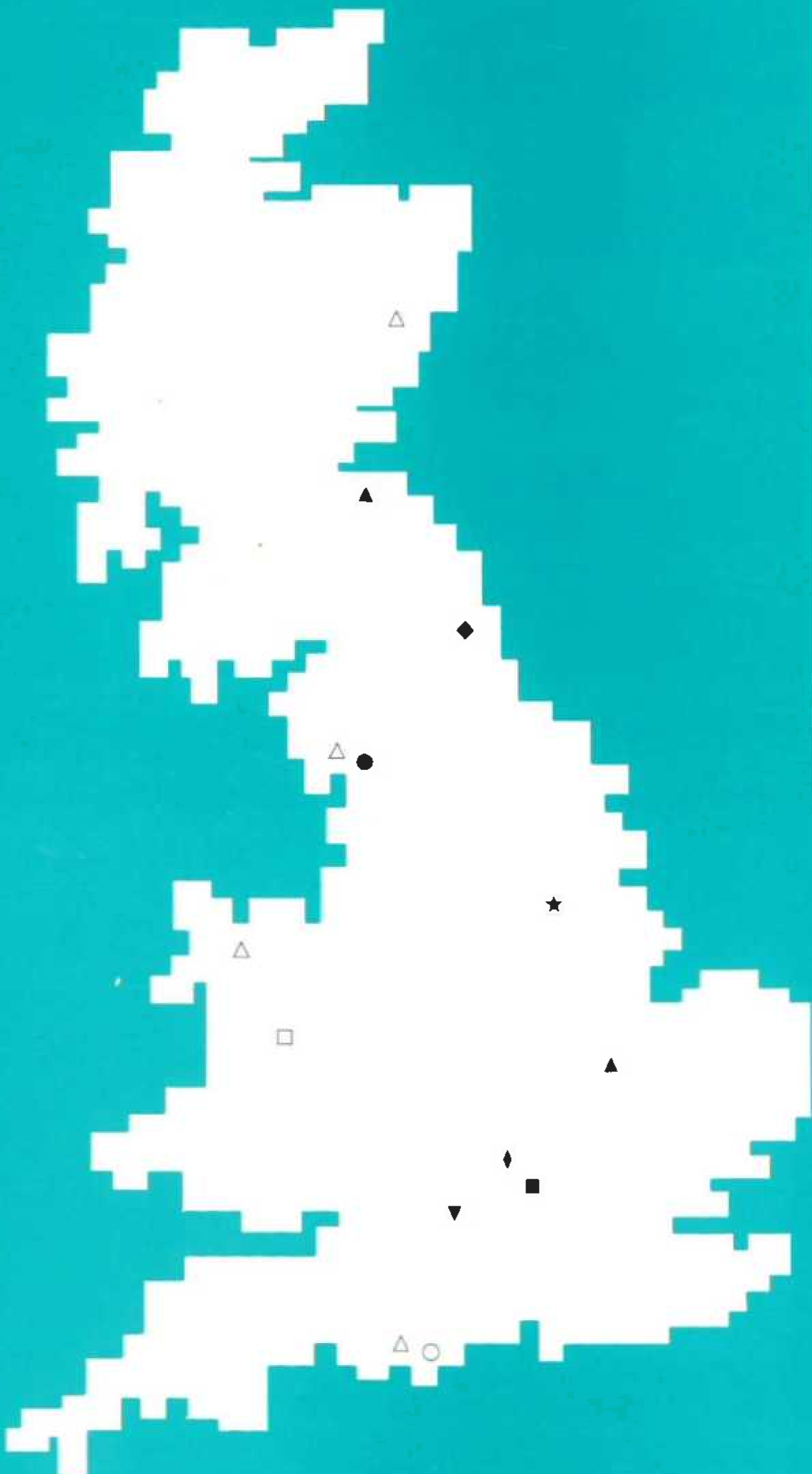

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