1988/040

DESIGN FLOOD HYDROGRAPHS FOR THE AVON AT BATHFORD

D. W. Reed

Report to Sir Alexander Gibb & Partners
June 1988

Contents

DESIGN FLOOD HYDROGRAPHS FOR THE AVON AT BATHFORD

1. Background

The Department of Transport is considering a Bath Eastern Bypass. The proposed route crosses the Avon flood plain close to Bathford. Design hydrographs are required for detailed investigation by Sir Alexander Gibb & Partners of the possible effect of structural changes to the flood plain on the frequency of floods in Bath.

2. Method

The requirement for design flood hydrographs (rather than just peak flow estimates) is usually met by adopting a rainfall-runoff method of flood estimation such as that specified in Volume I, Chapter 6 of the Flood Studies Report (Natural Environment Research Council, 1975) and revised in Flood Studies Supplementary Report No. 16 (Institute of Hydrology, 1985). There are two reasons why this is inappropriate to flood estimation on the Avon at Bath.

Firstly, the physical characteristics of the various tributaries of the Avon are diverse, notably in terms of geology. (Fig. 2.1.) Thus a rather detailed approach would be necessary: calibrating rainfall-runoff models for perhaps eight subcatchments and constructing a flood routing model of the main Avon. This would be a lengthy and expensive analysis although it might be possible to adapt Wessex Water's flood forecasting model of the Avon for design use (Evans, 1987).

Secondly, the availability of extensive records of flood levels and flows at Bath makes it desirable that flood estimates be based directly on these data. Consequently a hybrid method has been adopted in which design hydrographs have been constructed from a statistical analysis of peak flows and a special analysis of hydrograph "widths", the width being defined as the duration for which the flow in a particular event exceeds half its peak value. (Fig. 2.2.)

Historical flood data for the Avon at Bath refer to flows and/or levels at St James' Bridge, close to the main railway station. More recent data are for a primary gauging station at Bathford. The proximity of this gauging station to the proposed highway crossing is an asset in deriving the necessary design flood estimates but it is unfortunate that there was no period of overlap between gaugings at St James and gaugings at Bathford.

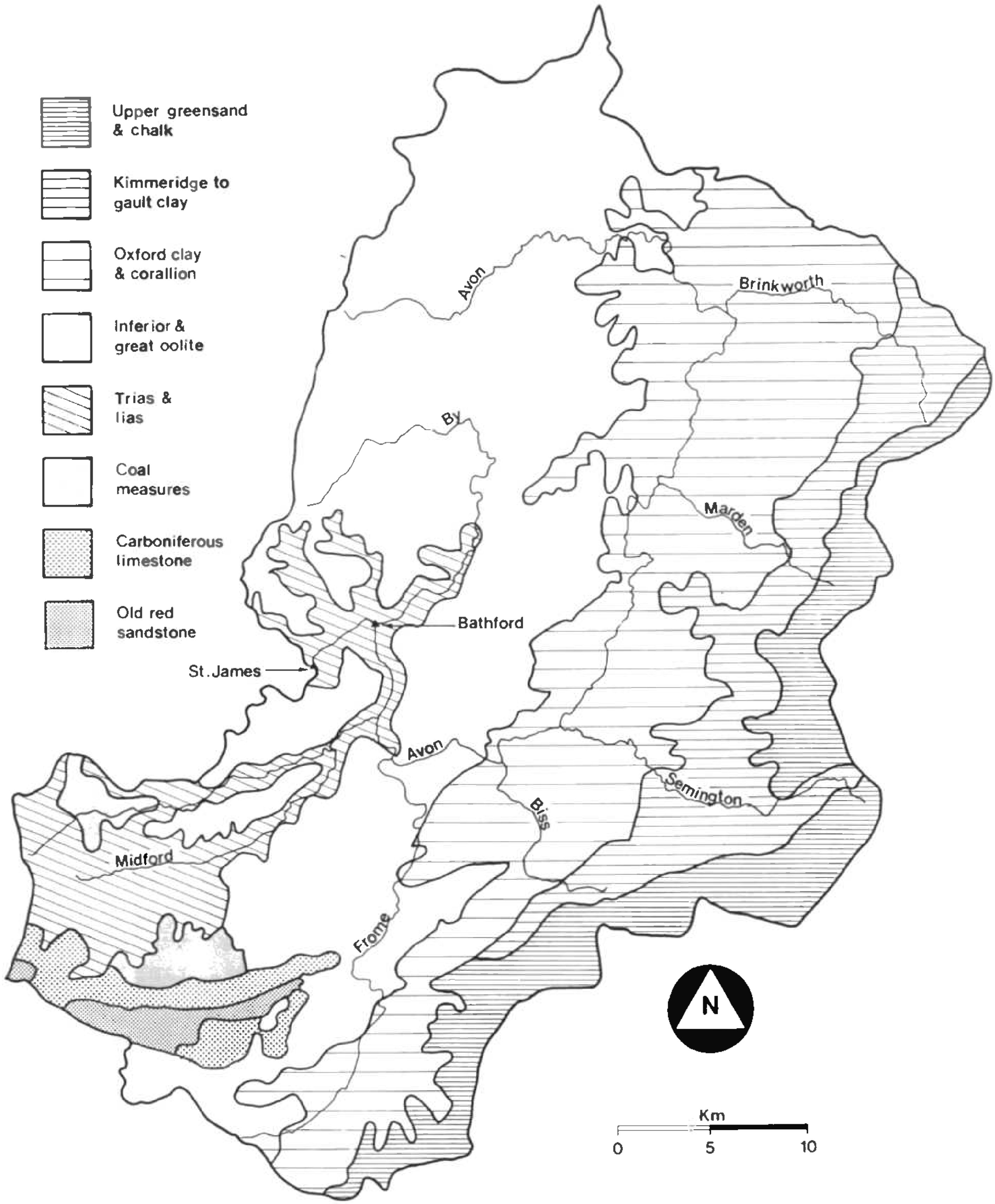

FIG. 2.1 Avon catchment to Bath - river network and geology

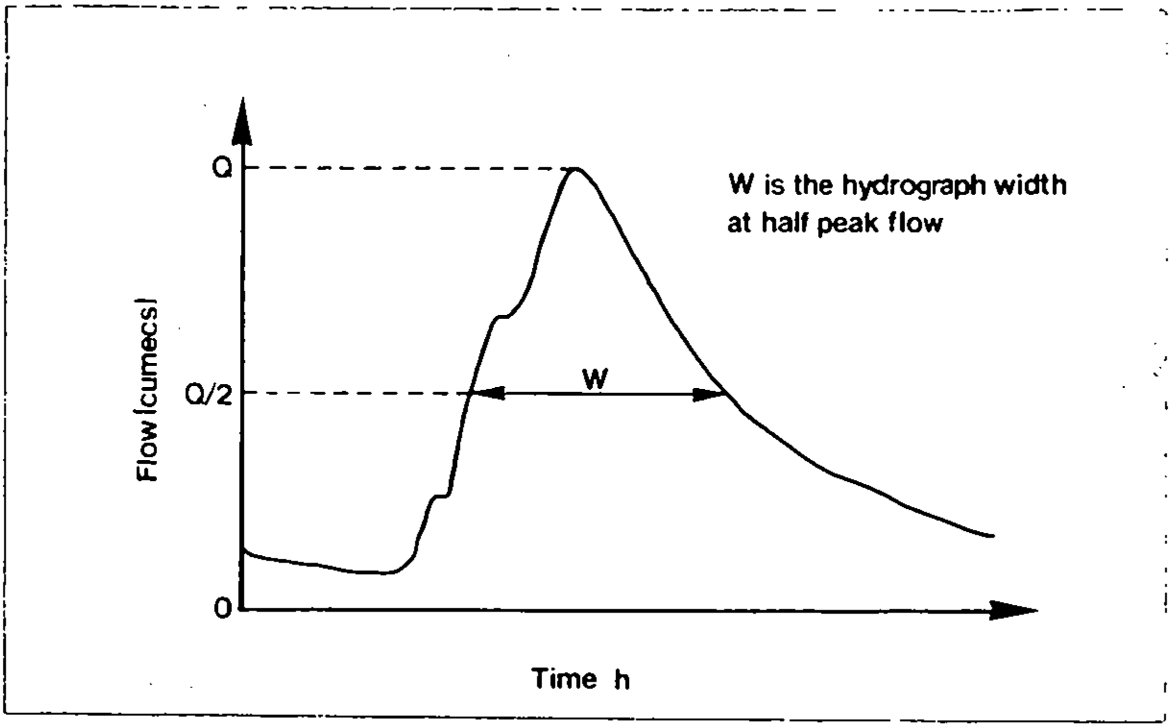

Fig. 2.2 Definition of hydrograph width, W

3. Analysis of Avon at Bathford flood data (1969-1987)

3.1. RATING EQUATION

The Avon at Bathford gauging station was established in December 1969. It is located immediately downstream of the outfall of the By Brook, some 6 km upstream of Bath City Centre. The catchment area is 1552 km^2. Wessex Water carry out current meter gaugings to monitor the relationship between levels and flows but were unwilling to release these data at the time of the study. It was therefore not possible to verify that the supplied rating:

$$Q = 52.7\ (H - 0.6)^{1.3992}$$

is appropriate throughout the period of analysis. Here Q is flow in cumecs and H is water level in metres relative to a datum of 18.0 mAOD. The rating equation was therefore taken to be correct, despite unspecified misgivings intimated by Wessex Water.

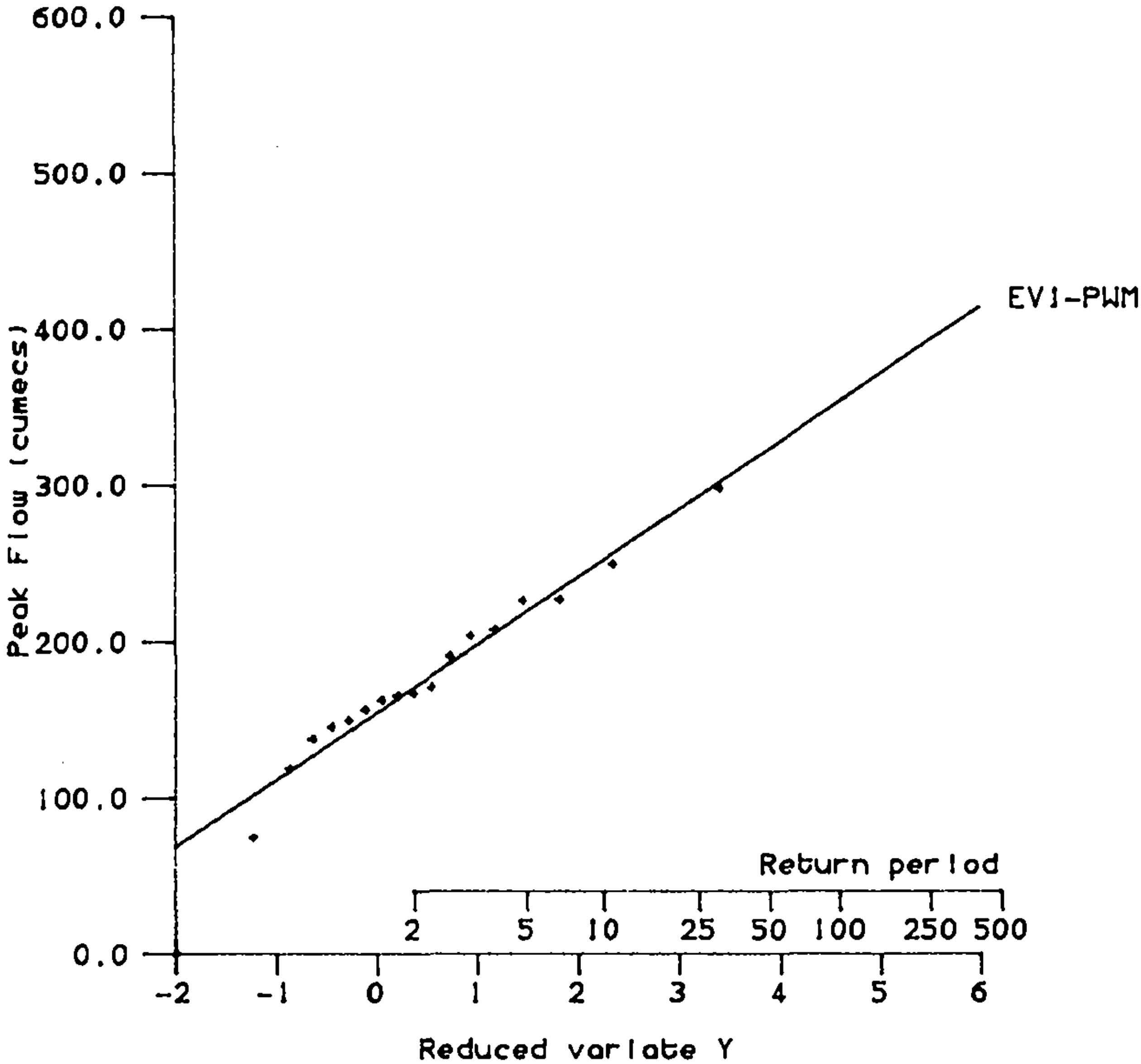

Fig. 3.1 Flood frequency - Avon at Bathford

3.2 ANNUAL MAXIMUM (AM) ANALYSIS

Annual maximum flows were abstracted for 17 water years and are given in Table 3.1. The arithmetic mean annual flood (AMAF) is 180 cumecs, with a coefficient of variation (CV) of 0.29. The annual maximum flows conform reasonably to an Extreme Value type 1 (EV1) distribution fitted by the method of Probability Weighted Moments (PWM), as shown in Fig. 3.1. This yields an estimate of 293 cumecs for the 25-year flood. Because of the relatively short period of record it is inappropriate to consider a General Extreme Value (GEV) distribution.

3.3 PEAKS OVER THRESHOLD (POT) ANALYSIS

An initial threshold of 19.9 mAOD was selected and independent peaks abstracted from the chart records. Although there were no gaps in the record of monthly maximum flows (held in the Surface Water Archive maintained at the Institute), charts were not available for several periods. This led to a loss of nearly 3 years in the effective length of record available for the POT analysis. With an adjusted threshold of 20.3 mAOD (corresponding to 110.7 cumecs), the mean annual flood, POTMAF, was calculated to be 171 cumecs. The same model (Flood Studies Report, Equation 1.2.7.5.3) yielded an estimate of 266 cumecs for the 25-year flood.

TABLE 3.1 Annual maximum flood series - Avon at Bathford

Date	Peak level mAOD	Peak flow Q cumecs	Hydrograph width W hours
1/ 2/71	20.87	165.9	44
4/ 2/72	*	204.2	*
7/12/72	*	208.0	*
9/ 2/74	*	226.5	*
28/ 1/75	20.67	145.9	29
25/ 9/76	*	74.3	*
30/11/76	20.84	162.9	52
28/ 1/78	20.59	138.0	40
30/ 5/79	21.44	227.0	36
28/12/79	22.05	298.1	50
11/ 3/81	20.92	171.1	79
16/ 3/82	21.11	191.0	42
31/ 1/83	20.78	156.8	32
16/ 1/84	20.88	167.0	33
21/ 1/85	20.71	149.8	39.5
26/12/85	21.64	249.7	80
19/11/86	20.39	119.0	44

* Original charts unavailable for these events

TABLE 3.2 Peaks over threshold series - Avon at Bathford

Date	Peak level mAOD	Peak flow Q cumecs	Hydrograph width W hours
22/ 1/71	20.54	133.2	42
24/ 1/71	20.57	136.1	60
2/ 2/71	20.87	165.9	44
27/ 4/71	20.47	126.5	36
12/ 6/71	20.83	161.9	44
19/ 6/71	20.44	123.7	44
27/ 9/74	21.00	179.4	40
22/11/74	20.49	128.4	52
27/12/74	20.48	127.5	39
20/ 1/75	20.52	131.3	34
28/ 1/75	20.67	145.9	29
9/ 3/75	20.33	113.5	32
1/12/76	20.84	162.9	52
14/ 1/77	20.33	113.5	38
10/ 2/77	20.43	122.8	47
21/ 2/77	20.52	131.3	48
11/12/77	20.51	130.3	51
24/ 1/78	20.31	111.6	40
28/ 1/78	20.59	138.0	40
1/ 2/79	20.78	156.8	44
30/ 5/79	21.44	227.0	36
27/12/79	22.05	298.1	50
5/ 2/80	20.55	134.2	40
11/ 3/81	20.92	171.1	79
14/ 3/81	20.83	161.9	70
15/12/81	20.51	130.3	43
30/12/81	20.67	145.9	58
10/ 3/82	20.66	144.9	28
16/ 3/82	21.11	191.0	42
10/12/82	20.70	148.8	44
19/12/82	20.51	130.3	28.5
8/ 1/83	20.34	114.4	27
1/ 2/83	20.78	156.8	32
3/ 1/84	20.40	119.9	44.5
13/ 1/84	20.35	115.3	21.5
17/ 1/84	20.88	167.0	33
23/11/84	20.38	118.1	96
22/ 1/85	20.71	149.8	39.5
9/ 2/85	20.49	128.4	48
26/12/85	21.64	249.7	80
10/ 1/86	20.44	123.7	32
29/ 1/86	21.12	192.1	44
19/11/86	20.39	119.0	44
21/11/86	20.32	112.6	40
15/12/86	20.30	110.7	46

Note Significant missing periods. Effective length of record is 15 years 2 months.

3.4 HYDROGRAPH WIDTHS

Using the definition of hydrograph "width", W, indicated in Fig. 2.2, values were derived for the 45 independent events in the POT data series. (Table 3.2.) A correlation analysis revealed no significant chronological trend in the peak flows or widths. The mean value of W was 44.5 hours, with a coefficient of variation of 0.32. There was a slight tendency for higher peaked events to have longer widths but the correlation was not significant at the 5% level (r=0.24 for n=45).

4. Analysis of Avon at St. James flood data (1939-1969)

4.1 RATING EQUATIONS

The Avon at Bath gauging station was established in November 1939, with a nominal catchment area of 1600 km^2. The flow gauging record - hereafter referred to as St James - was a composite of water level measurements approx. 75 metres upstream of St James' Bridge and current meter gaugings at Grove Street. These sites were respectively approx. 475 metres downstream and 180 metres upstream of Pulteney Weir. Within the scope of the present study it was impractical to investigate the basis of these old ratings in any great detail. Thus the flood data were taken as published in Volume IV of the Flood Studies Report but with two important corrections. Firstly, a small but systematic error in application of the piecewise rating equations was rectified. Secondly, a false peak on 12/6/1955 was deleted. The resultant annual maximum flood series is summarized in Table 4.1.

4.2. ANNUAL MAXIMUM (AM) ANALYSIS

The arithmetic mean annual flood calculated from 30 water years is 160 cumecs, with a coefficient of variation (CV) of 0.45. This represents a greater degree of variability than evident in the recent record at Bathford (Section 3.2). Reference to the map of CV values published in the Flood Studies Report (Fig. I.4.22) suggests that the Bathford value (0.29) is unusually low for gauging stations in the Bristol Avon hydrometric area. The annual maximum flows do not conform particularly closely to an EV1 distribution and a General Extreme Value (GEV) distribution was therefore also fitted. (Fig. 4.1.) That based on a Probability Weighted Moments (PWM) fit has a 'k' parameter of -0.23 and yields estimates of 322 cumecs for the 25-year flood and 467 cumecs for the 100-year flood. (See Hosking et al, 1984).

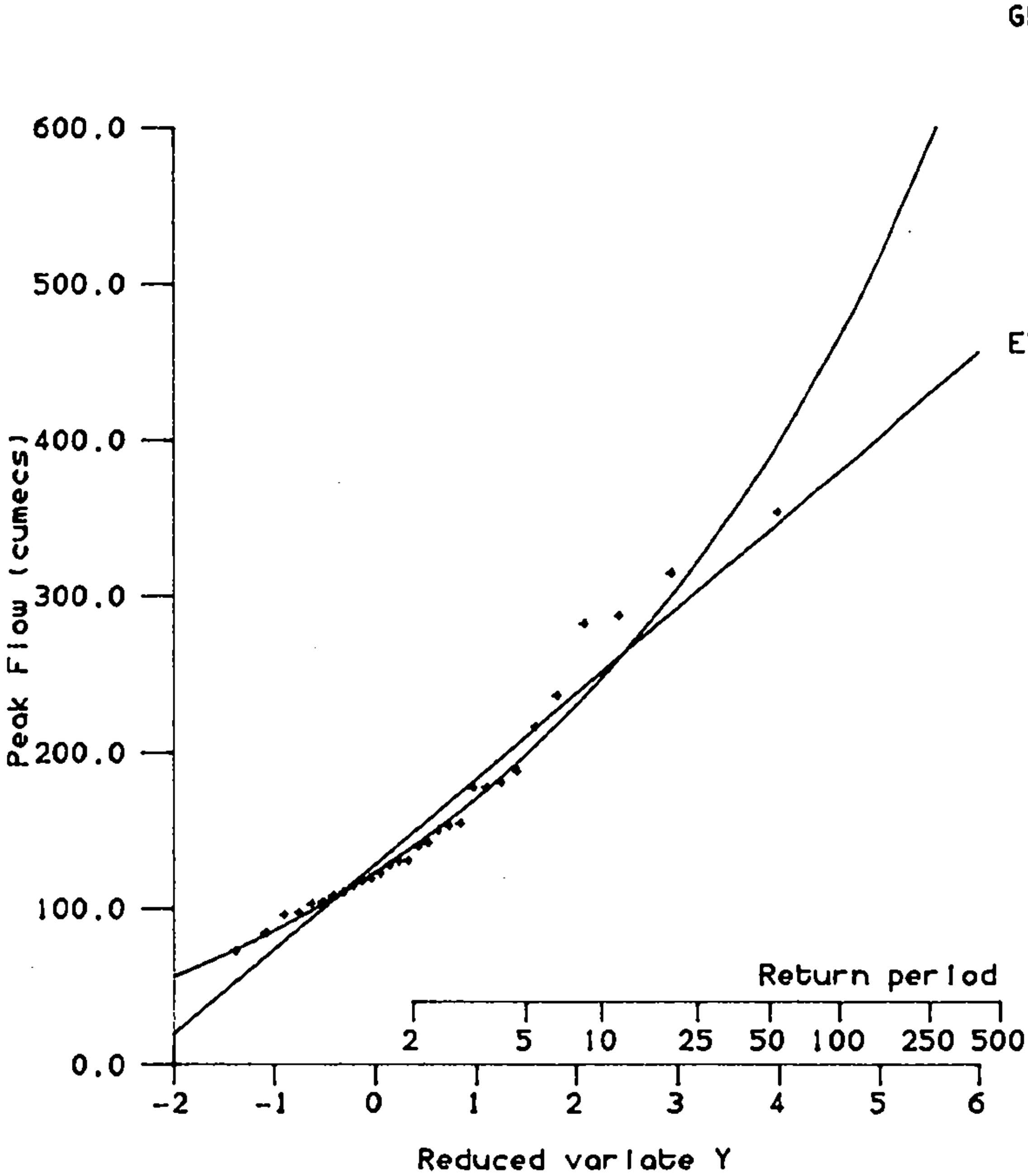

Fig. 4.1 Flood frequency - Avon at St. James

TABLE 4.1 Annual maximum flood series - Avon at St. James

Date	Peak level mAOD	Peak flow Q cumecs	Hydrograph width W hours
4/ 2/40	18.43	150.3	67
14/11/40	18.46	153.4	47
24/ 1/42	17.51	84.4	63
1/ 2/43	18.47	155.0	85
24/12/43	17.21	72.7	46
18/11/44	18.11	119.5	96
4/ 2/46	18.23	130.8	63
13/ 3/47	19.96	287.7	54
13/ 1/48	17.84	97.5	106
12/12/48	17.93	104.1	51
6/ 2/50	18.05	114.6	121
21/11/50	19.36	236.5	48
9/11/51	18.32	140.2	55
21/12/52	18.09	117.9	59
13/ 6/54	17.80	96.0	70
16/ 1/55	19.13	217.0	37
31/ 1/56	18.22	130.5	48
8/ 2/57	17.98	108.2	69
25/ 2/58	18.35	142.3	50
22/ 1/59	18.68	178.0	84
24/ 1/60	18.68	178.0	50
4/12/60	20.70	354.0	47
22/ 1/62	18.14	122.8	61
18/ 3/63	17.92	103.3	126
25/11/63	19.90	282.4	55
3/ 8/65	18.01	110.8	22
9/12/65	18.78	188.3	37
5/11/66	18.71	181.4	27
11/ 7/68	20.27	314.9	45
25/12/68	18.20	127.9	40

4.3 PEAKS OVER THRESHOLD (POT) ANALYSIS

Because of the longer period of record available, a POT analysis is inappropriate.

4.4 HYDROGRAPH WIDTHS

Typical hydrograph widths were investigated by reference to the annual maximum series. The hydrograph widths had a mean value of 61.0 hours and a CV of 0.41. Slight chronological trends towards shorter widths (r=-0.30) and higher peaks (r=0.32) were noted but neither correlation is significant at the 5% level.

5. Comparisons between Bathford and St James' analyses

5.1 CATCHMENTS

The absence of overlap in the periods of record at Bathford and St James hampers comparisons. The area draining to St James is some 48 km^2 (about 3%) greater than the 1552 km^2 catchment to Bathford. That the extra area has a notable urban component (ie. much of the city) is probably of little consequence; both catchments are still predominantly rural in character. One might expect flows to be slightly larger at St James (because of the larger area); however, the flood plain intervening between Bathford and St James may compensate by attenuating major flood peaks.

5.2 DIFFERENCES IN MEAN ANNUAL FLOOD

A test was made for a difference in means between the Bathford and St James' annual maxima. The test (based on the Z-statistic) assumes that the samples are drawn from a normal distribution. This is reasonable for flood maxima if a logarithmic transform is first applied. The test indicates that the difference in means is not significant at the 5% level.

5.3 DIFFERENCE IN HYDROGRAPH WIDTHS

The distributions of hydrograph widths (Sections 3.4 and 4.4) were found to be slightly skewed. Applying the Z-test as before to logarithmically transformed values, the mean hydrograph widths at Bathford (44.5 hours) and St James (61.0 hours) were found to be very significantly different. The analyses were somewhat inconsistent in the use of the POT series at Bathford and the AM series at St James. As a precaution, it was decided to investigate hydrograph widths for the Bathford AM series also.

As referred to in Section 3.3, some of the Bathford charts were not available. Thus hydrograph widths could only be abstracted for 13 of the 17 annual maximum events. These show a mean width of 46.2 hours and a coefficient of variation of 0.35. Although less different than before, the Z-test indicated that the Bathford and St James' mean hydrograph widths were still significantly different.

5.4 DISCUSSION

The conclusion that the mean annual floods at Bathford and St James are similar but that their hydrograph widths are significantly different is a little worrying. One interpretation is that the flood plain between Bathford and Bath attenuates and delays the flood hydrograph but that the additional catchment area to St James negates any reduction in peak flows. If this is the case we might expect the difference in hydrograph widths to be more marked for major events than for minor events. This was tested by splitting the Bathford and St James' annual maximum flood data at their median values.

The analysis was limited by the relatively short AM series available for Bathford. It indicated a marked difference in hydrograph widths for minor events (mean of 39 hours at Bathford compared to 69 hours at St James) and typically no difference for major events (mean of 52 hours at both sites). The subdivision indicated that the chronological trend to shorter hydrograph widths at St James is more marked for major events (r=-0.461) than for minor events (r=-0.204) but neither correlation is significant at the 5% level.

The lack of concurrent data for Bathford and St James makes it difficult to judge the significance of the flood plain in attenuating flooding in Bath. An

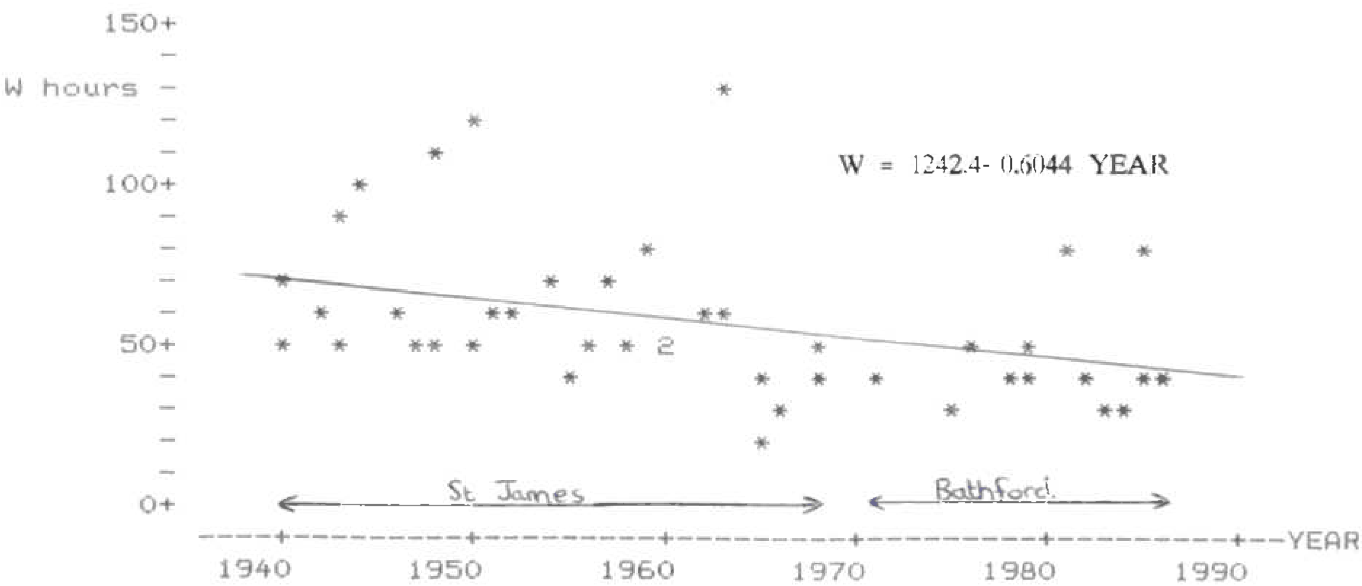

FIG. 5.1 Chronological trend in hydrograph widths

alternative explanation is that the shorter hydrograph widths seen in the Bathford record may stem from a long-term trend to shorter hydrograph widths for Avon floods. If the St James and Bathford annual maximum data are combined and treated as a single homogeneous record of Avon flood peaks, the chronological trend in hydrograph widths is highly significant (r=-0.368 for 43 observations). Figure 5.1 summarizes the hydrograph width data and provides a simple regression model.

A possible explanation of the trend in hydrograph widths is that developments in the catchment - notably, improvements in field and arterial drainage, and creeping urbanization - have accelerated the catchment response to heavy rainfall. Under such circumstances one might expect a long-term trend to higher peak flows but the evidence for this was relatively weak. It is of course possible that the trend in Fig. 5.1 is spurious, arising perhaps from shifts in rainfall frequency, deficiencies in the rating equations, or a lack of homogeneity between the St James and Bathford records.

5.5 CONCLUSION

It was judged that best use of the available data would be to combine the Bathford and St James data and to treat them as a single homogeneous record of flood peaks on the Avon in the vicinity of Bath.

6. Preferred peak flood estimates

6.1 HISTORICAL FLOOD DATA

The Flood Studies Report lists data for a number of historical floods on the Avon at Bath, the highest being a peak flow at St James of 375 cumecs on 15 November 1894. These flood estimates are based on inscribed flood marks beneath St James' Bridge and take into account the slight difference in water levels between St James' Bridge and the site of the St James water level recorder.

Leese (1973) assesses that systematic marking of floods probably commenced with construction of the bridge in 1863. Contentiously, she judges that the lack of flood marks subsequent to the 25/1/1925 event infers that systematic marking ceased in 1925. This assumption was reviewed by examining a long-term daily rainfall record at Batheaston (see below).

Of recent floods in the instrumental period since November 1939, those on 4 December 1960 (354 cumecs), 11 July 1968 (315 cumecs) and 28 December 1979 (298 cumecs) are of particular note.

Although no evidence was found that a large flood passed unrecorded in the period 1925 to 1939, it was judged that only the ten largest floods in Table 6.1 reliably represent the highest annual maxima in the 125-year period (1863 to 1987). These are events with estimated peak flows in excess of 250 cumecs.

Published accounts (eg. Greenhalgh, 1974) refer to earlier floods at Bath, notably those of 1809 and November 1823. However, recorded peak levels for these events relate to Pulteney Weir and, it seems, have never been satisfactorily converted to estimates of peak flow. It is said that the November 1823 event was comparable with the November 1894 event only because of a blockage at the Old Bridge, subsequently demolished.

6.3 ANALYSIS

The gauged annual maxima at St James and Bathford were combined to form a single series of 47 annual maxima for the Avon in the vicinity of Bath. EV1 and GEV distributions were considered and both Maximum Likelihood (ML) and Probability Weighted Moments (PWM) estimates derived. Figure 6.1 illustrates the fit provided by the PWM methods if the annual maxima are plotted according to Gringorten's formula. (FSR I.1.3.4)

When data for the ten largest annual maximum floods are superposed (Fig. 6.2) - plotted as the ten largest in a sample of 125 years - a preference emerges for the EV1 representation. Consequently the preferred flood frequency relationship is the EV1-PWM distribution with parameters:

$u = 137.2$ and $a = 51.9$

This leads to estimates of 303 cumecs for the 25-year flood and 376 cumecs for the 100-year flood.

6.4 COMPARISON WITH LEESE'S ESTIMATES

The above flood estimates are about 9% greater than those derived by Leese (1973) and reproduced as an example in the Flood Studies Report (I.2.8.2). The explanation for the slightly higher values lies partly in the correction of the error in applying the piecewise rating equation to the St James water level data (Section 4.1) and partly in the relatively high incidence of moderately large floods in the additional period of gauged record. (Compare Tables 3.1 and 4.1.) The slightly different interpretation of the historical data has had no effect on the flood estimates. They have been plotted on Fig. 6.2 for information only; the preference for the EV1/PWM fit would have remained had they been plotted as the ten largest annual maximum floods in 110 years rather than 125 years. Formal techniques are available for joint fitting of gauged and historical annual maximum data (eg. Leese, 1973), based on a Maximum Likelihood approach.

6.2 LARGEST FLOODS IN 125 YEARS OF RECORD

Combining the historical floods with the gauged records for St James and Bathford, it would appear that estimates are available of all annual maxima in the period 1863 to 1987 in excess of 200 cumecs. (Table 6.1.) The only anomaly in ranking between Table 6.1 and the inscribed flood marks at St James' Bridge is that the March 1947 and December 1900 floods are transposed. Within the scope of the present study it was impractical to re-open estimation of flood flows ascribed to specific historical events.

TABLE 6.1 Censored annual maximum flood series - Avon at Bath (1863-1987)

Rank i	Date	Peak flow Q_i cumecs	Gringorten plotting position y_i	Growth factor Q_i / QBAR
125	15/11/1894	375	5.41	2.24
124	25/10/1882	362	4.38	2.17
123	4/12/1960	354	3.88	2.12
122	11/ 7/1968	315	3.55	1.88
121	31/12/1900	302	3.29	1.81
120	28/12/1979	298	3.09	1.78
119	13/ 3/1947	288	2.92	1.72
118	25/11/1963	282	2.78	1.69
117	9/ 3/1889	264	2.65	1.58
116	25/ 1/1925	255	2.53	1.53
	26/12/1985	250		
	16/ 2/1900	239		
	21/11/1950	236		
	-/ 3/1867	228		
	30/ 5/1979	227		
	9/ 2/1974	226		
	-/11/1875	218		
	16/ 1/1955	217		
	7/12/1972	208		
	-/ 1/1866	206		
	4/ 2/1972	204		

An independent check was made by reference to annual maximum 4-day rainfalls at Batheaston, focussing particular attention on the 1925-1939 period. The degree of correspondence between point rainfalls and catchments flows is naturally rather limited. The rainfall search revealed a severe storm on 25 June 1935 which affected much of the Avon catchment and led to exceptional flash flooding on tributaries in and around Melksham and Bath. Contemporary reports (British Rainfall, 1935) indicate that the Avon at Bath responded very rapidly to the rainfall (123 mm at Batheaston, mainly in about 3.5 hours) but imply that the event did not lead to flooding from the Avon proper.

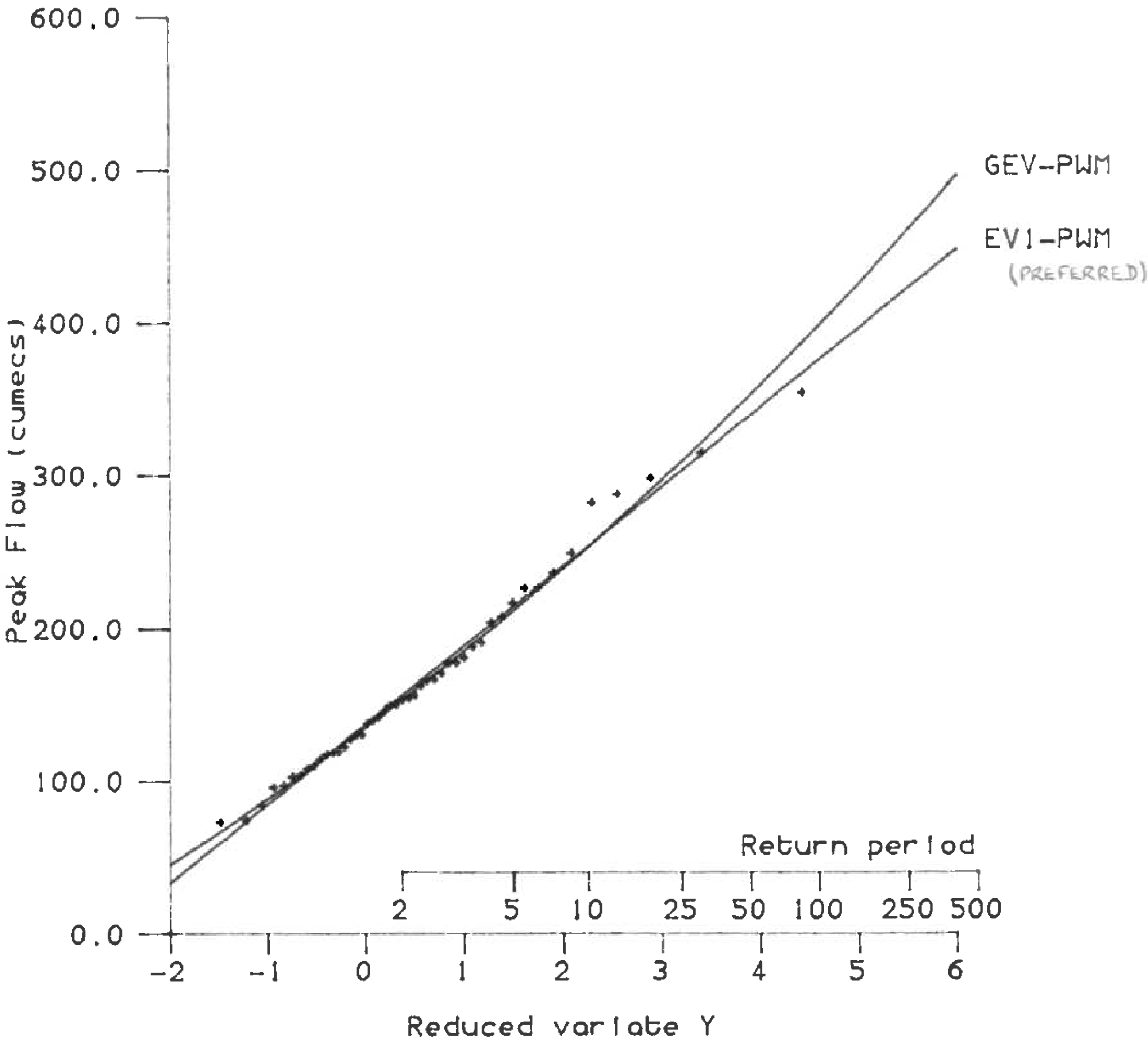

Fig. 6.1 Preferred flood frequency relation - Avon in the vicinity of Bath

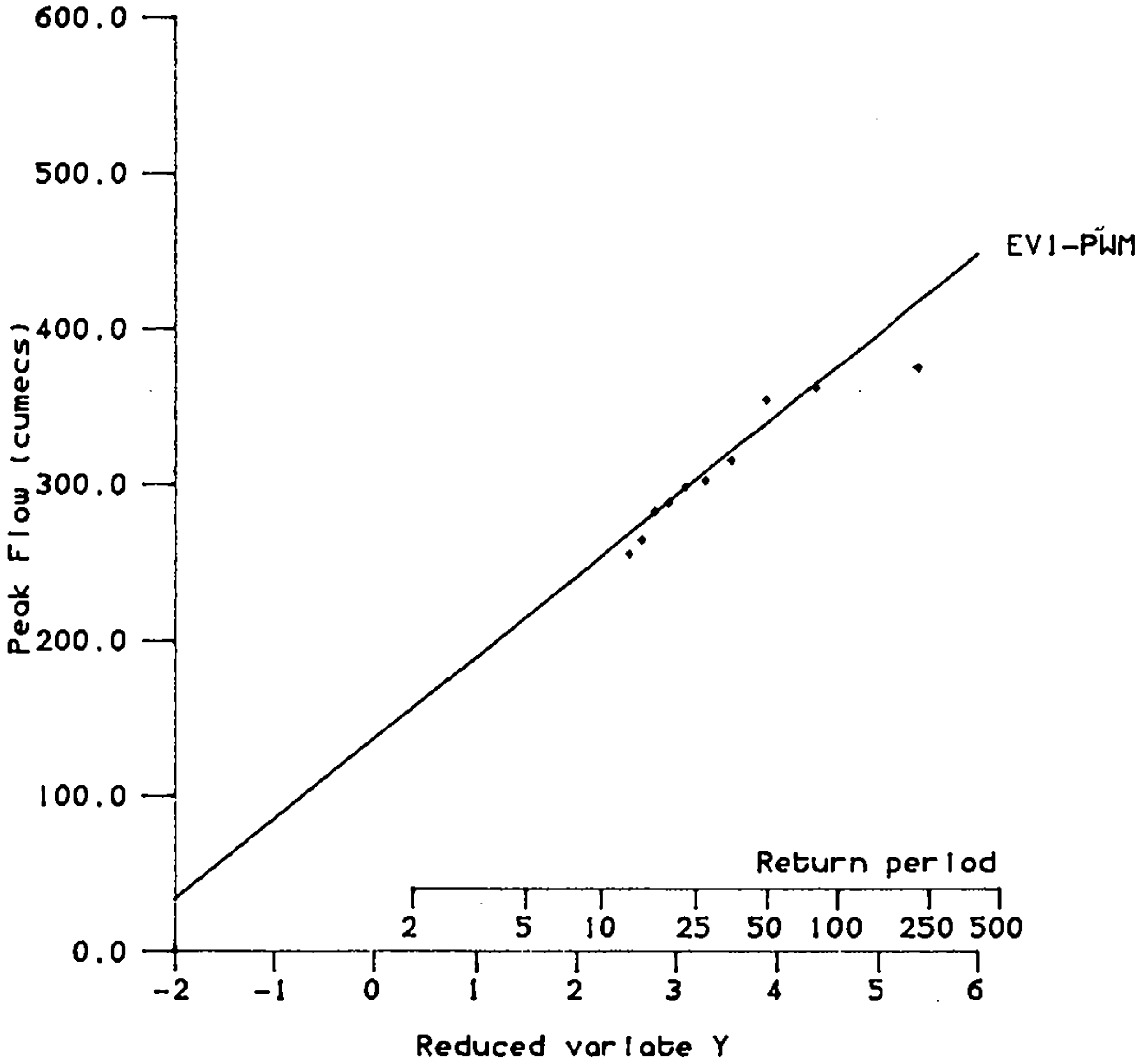

Fig. 6.2 Comparison with ten largest annual maxima in period 1863 to 1987.

6.5 COMPARISON WITH REGIONAL FLOOD GROWTH CURVE

Application of the Flood Studies Report regional growth curve to the Avon mean annual flood of 167 cumecs (obtained by combining the Bathford and St James records) yields estimates of 307 cumecs for the 25-year flood and 404 cumecs for the 100-year flood. The latter is appreciably higher than the preferred estimate derived above. However, while adoption of a GEV distribution with k=-0.10 (as in the Region 8 flood growth curve) would accord reasonably well with a GEV fitted to the Bathford and St James' 47 year record (k=-0.07 by both ML and PWM methods), it would conform less well with the historical flood data for Bath. It would infer that the flood peak of 375 cumecs on 15 November 1894 had a return period of about 65 years. There is only a 1 in 7 chance of 125 years elapsing with no exceedances of the 65 year event. This reasoning is simplistic but serves to illustrate that application of the regional growth curve is difficult to support in this instance.

6.6. SUMMARY

Peak flood estimates are summarized in Table 6.2, where the preferred estimates are highlighted. Although Greenhalgh (1974) was rather vague about his estimate of the 100-year flood (368 cumecs and 365 to 420 cumecs are mentioned), it is reassuring to note that the present estimates are not seriously different from those assumed in the design of the Bath flood protection scheme.

Table 6.2 Summary of peak flood estimates

Data	Years of record	Method	Q_{25} cumecs	Q_{100} cumecs
Bathford	17	EV1-PWM	293	354
St. James	30	GEV-PWM	322	467
Bathford + St. James	**47**	**EV1-PWM**	**303**	**376**
Barnford + St. James	47	QBAR plus FSR region 8 curve	307	404
St. James + historical	~90	See Leese (1973)	278	344

7. Design flood hydrographs

The preferred flood frequency relationship is the EV1-PWM line shown in Fig. 6.2. The approach taken to deriving design flood hydrographs is to invoke aspects of the FSR rainfall-runoff method, utilizing the information about hydrograph widths derived earlier.

In view of the apparent chronological trend to shorter hydrograph widths - and because the design hydrographs are nominally required for the Bathford site - it is appropriate to use the mean hydrograph width observed from the Bathford annual maximum series. This is a width at half peak flow of 46 hours.

A preliminary action in constructing the design hydrographs is to evaluate the baseflow component using Fig. 1 of Flood Studies Supplementary Report No. 16 (Institute of Hydrology 1985). Knowledge of the average annual rainfall (SAAR) and the catchment area is all that is required, yielding an estimate for the Avon at Bathford of 39 cumecs.

The steps of the procedure by which the design hydrograph is constructed are illustrated in Fig. 7.1 for the 100-year event. The first step is to choose a dimensionless shape from the standard hydrographs given in Fig. 3 of Flood Studies Supplementary Report No. 9 (Institute of Hydrology, 1979). For a catchment with a SAAR of 865 mm we adopt a dimensionless shape corresponding to a value of D/Tp of (1+SAAR/1000) or 1.865. [Step 1]

The standard hydrograph is dimensionless both in time units and flow units. It is convenient first to scale the hydrograph by the relevant peak response runoff. This is defined as the peak flow less the baseflow. To obtain the 100-year response hydrograph the ordinates of the dimensionless hydrograph are multiplied by (376-39) = 337. [Step 2] Then the baseflow allowance is restored by adding 39 cumecs to all the ordinates. [Step 3]

The final step is to adjust the temporal scale of the design hydrograph. This is done simply by applying a time factor so that the width at half peak flow is the required 46 hours. [Step 4]

Ordinates of the 100-year Bathford hydrograph are given in Table 7.1.

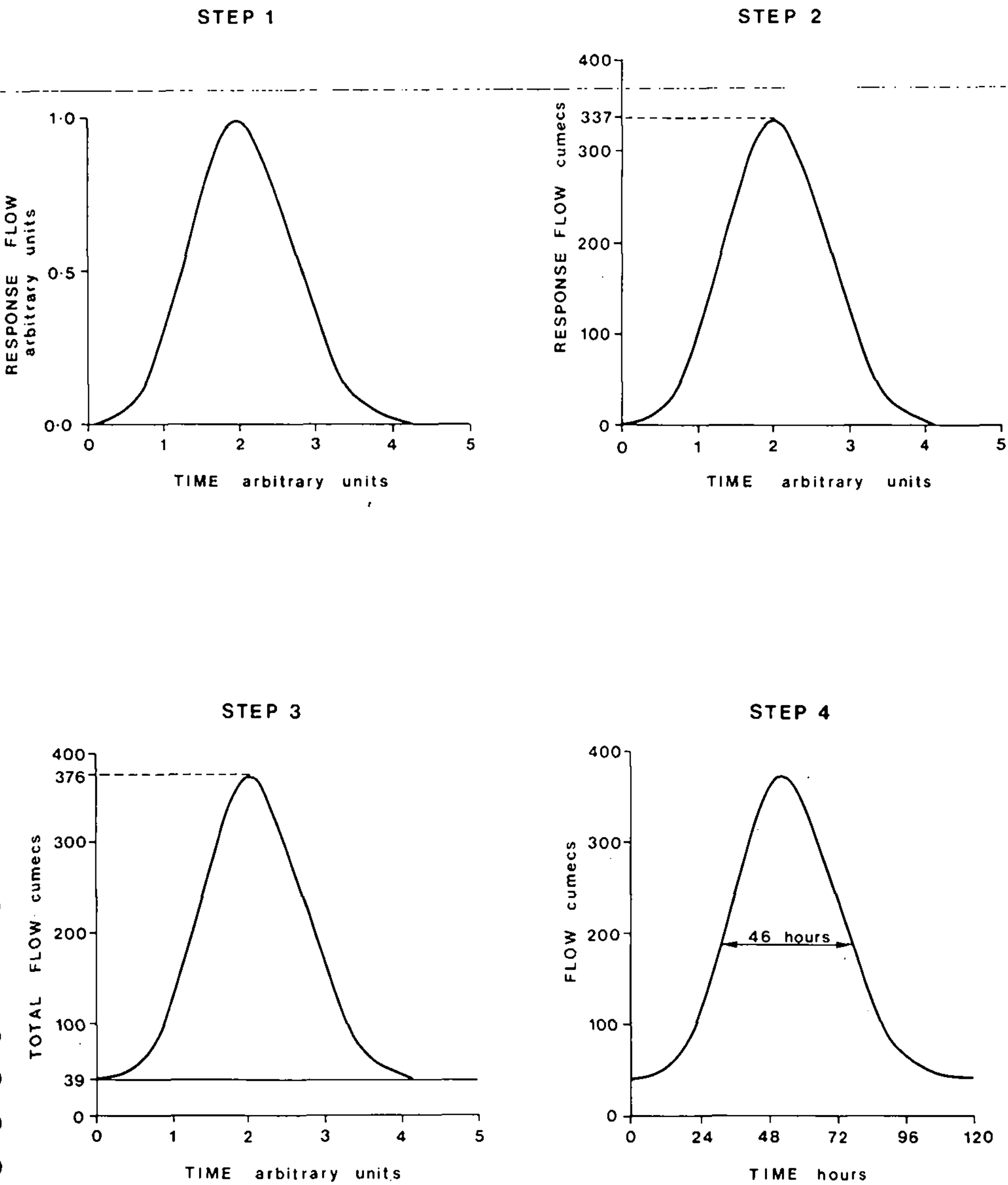

Fig. 7.1 Procedure for constructing design hydrograph (illustrated for 100-year event)

Table 7.1 100-year flood hydrograph - Avon at Bathford

Time (hours)	Flow (cumecs)	Time (hours)	Flow (cumecs)
0	39	66	287
6	40	72	232
12	50	78	177
18	70	84	122
24	120	90	80
30	180	96	59
36	250	102	49
42	322	108	42
48	367	114	40
54	371*	120	39
60	336		

* Peak of 376 cumecs at 51.5 hours

8. Summary

8.1. FLOOD FREQUENCY

Peak flow estimates have been derived by combining flow data from the Bathford and St James (Bath) gauged records. Some minor errors in the St James' annual maximum data have been corrected. The preferred estimates (Fig. 6.1) are based on an Extreme Value type 1 (EV1) distribution, fitted to the annual maximum flows by the method of Probability Weighted Moments (PWM). The estimates have been tested against additional historical flood data for Bath (Fig. 6.2). The preferred estimate of the 100-year peak flow is 376 cumecs.

8.2 DESIGN HYDROGRAPHS

A procedure has been developed for converting the peak flow estimates to design hydrographs - nominally at Bathford - by a novel study of hydrograph widths and inferences from the Flood Studies Report rainfall-runoff method. This has been illustrated for the 100-year event. Additional work would be needed to produce design hydrographs for other return periods, following the graphical procedure illustrated in Fig. 7.1 or by tailoring a computer program.

8.3 TENTATIVE CONCLUSIONS ABOUT SIGNIFICANCE OF FLOOD PLAIN STORAGE AND LONG-TERM TRENDS IN CATCHMENT RESPONSE

The study has been hampered by the lack of overlap between the St James and Bathford records and by unspecificied uncertainty in the Bathford rating equation supplied by Wessex water. Some tentative conclusions have nevertheless been drawn about the relationship between Bathford and St James floods, and thus the possible significance of the intervening catchment and flood plain storage.

The gauged mean annual floods at Bathford (180 cumecs) and St James (160 cumecs) are not significantly different in statistical terms. This suggests that the additional runoff from the 48 km^2 intervening area is at least balanced by a modest attenuation of floods due to channel and flood plain storage between Bathford and St James.

After considering several hypotheses that might explain the shorter hydrograph widths found in the Bathford record, it was concluded that there is some evidence of a progressive acceleration in flood response in the Avon catchment. Possible causes are advanced and appear plausible but the lack of consistent long-term flow records limits confidence in these conjectures.

8.4 SUGGESTION FOR ASSESSMENT OF SIGNIFICANCE OF AVAILABLE FLOOD PLAIN STORAGE

The above analysis has not quantified the extent to which the flood plain storage between Bathford and St James limits flooding problems in Bath. What evidence the study of flood peaks and hydrograph widths has produced suggests that the effect may be little greater than to counterbalance the increased catchment area to St James.

It would be of interest to compare the volume of flood plain inundation in the December 1960 or December 1979 flood as a percentage of the overall flood hydrograph volume. Similarly, the volume of available flood plain storage evaluated from survey might be compared with the volume of design hydrographs, from which it may be possible to judge the significance of any possible erosion of storage by highway or other developments.

8.5 RARITY OF DECEMBER 1960 FLOOD PEAK

From Table 6.1 and Fig. 6.1, the return period of the December 1960 flood peak is assessed to be about 65 years.

Acknowledgements

The Institute acknowledges the cooperation of Wessex Water in supplying water level charts for the Bathford gauging station and in providing additional historical and general information about Avon floods. Jonathan Parker (on placement from Sheffield City Polytechnic) carried out the analysis of hydrograph widths and produced the extreme value plots.

References

Evans, N.A. (1987) A review of the flood warning scheme in the Bristol Avon catchment. Unpublished M.Sc. project, Dept. of Civil Engineering, Univ. of Birmingham.

Greenhalgh, F. (1974) *Bath flood protection scheme.* Wessex Water.

Hosking, J.R.M., Wallis, J.R. and Wood, E.F. (1984) Estimation of the generalised extreme-value distribution by the method of probability weighted moments. Institute of Hydrology Report No.89.

Institute of Hydrology — Flood Studies Supplementary Reports:
No. 9 1979 — Short cut to convolution
No. 16 1985 — The FSR Rainfall-runoff model parameter estimation equations updated.

Leese, M.N. (1973) Use of censored data in the estimation of Gumbel *distribution parameters for annual maximum flood series.* Water Resources Research, 9, 6: 1534-1542.

Natural Environment Research Council (1975) Flood Studies Report, 5 volumes, NERC.