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Maidenhead, Windsor and Eton Flood Study

Stage 2

Hydrology Report

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1. Introduction

1.1 SCOPE OF STUDY

The work described in this report is in pursuance of Section 2 "Terms of Reference" of the sub-consultant agreement for hydrological investigation. The study objectives were determined after consideration of Chapter 6 of the "Final Report" by M Beran (Assessment of Consultant Report "Maidenhead Flood Study", 27th November 1986). In summary the objectives are:

a) preparation of a flood frequency relationship for the Thames at Maidenhead, including assessment of the return period of the 1947 flood peak and the duration of flooding over bench levels;

b) *investigation of a time trend and non-stationarities in the data;*

c) preparation of a flow duration curve for the Thames at Maidenhead.

The first objective provides the main design parameters for remedial works and is described in Section 3. The 1947 flood has particular importance as it is likely to be adopted as the design standard to be accommodated by the proposed scheme. Although the peak flood level is the variable of prime importance in controlling the flood losses, aspects of the benefit evaluation performed by Middlesex Polytechnic's Flood Hazard Research Centre require knowledge of the duration of inundation (Section 5). Objective b relates to suspicions that have been voiced about changes in the climate and hydrological regime and concerns about the applicability of recent flood experience to long term behaviour (Section 6). Work related to objective c was in fact carried out first (Section 7) and provided information needed by Hydraulics Research Ltd in sedimentation studies.

1.2 PAST STUDIES

The hydrology of the Maidenhead area was considered in the Maidenhead Flood Study Stage One Final Report using three sources of information: rainfall records, level records and flow records. The main emphasis was on flood level records which were used to obtain flood level frequency curves for head and tail water at locks along the Thames. Chronological plotting of head and tail water levels for navigation locks in the Maidenhead area suggested that the severity and frequency of high flood stages in the Thames has diminished in recent times. Level and flow records were used to obtain a range of flood frequency curves from which it was concluded that the upper limit of design flow should be 500 m^3/s. In contrast to the Stage One Final Report the work described below has given more attention to flood discharge records than flood level records.

Several reports have been published on past flooding of the Thames. Symons and Chatterton (1895) and Symons (1894) describe the levels reached and the areas affected along the Thames by the flood of November 1894. Griffiths (1969) lists flooding events for over 1000 years. Floods in the Thames Valley have been analysed in several reports of the Thames Conservancy notably in 1914 and 1947, although these concentrated more on flood stage than on corresponding discharge.

2. Data

2.1 Flood discharge and stage

Stage records for head and tail water are available for all Thames locks with many having almost 100 years of record. Level duration listings give durations in days above various bench levels for each flood that attained or exceeded typical low flood level. Sources and examples are shown in Section 6.6 of the Final Report.

The availablity of discharge data is shown in Table 2.1 and the location of gauging stations is shown in Figure 2.1. Teddington daily mean discharges prior to 1974 were determined from weir calculations when the flow was less

Table 2.1 Discharge data

River	Gauging station	Station number	Grid reference	Catchment area (km^2)	Daily mean flows
Thames	Teddington/ Kingston	39001	TQ 177698	9948.0*	1883-1985 naturalised and gauged
Thames	Bray	39009	SU 909797	6915.3	1960-1974#
Thames	Royal Windsor	39072	SU 982773	7046.0	1979-1985+
Thames	Day's Weir	39002	SU 568935	3444.7	1938-1985
Thames	Eynsham	39008	SP 445087	1616.2	1951-1985
Colne	Denham	39010	TQ 052864	743.0	1980-1985
Wey	Tilford	39011	SU 874433	396.3	1980-1985
Mole	Castle Mill	39068	TQ 179502	316.0	1980-1985

* This catchment area has been recomputed by Thames Water and differs from that used in the Stage One Final Report

\+ Contains many missing values - 24 complete months available

\# Data from Surface Water Archive, Institute of Hydrology - used only to assist with determination of the Maidenhead flow duration curve than 85 m^3/s. Higher flows (which include all annual maxima) were based on stage readings taken twice a day at low tide and converted to discharge using a downstream rating. Since 1974 daily mean flows have been based on the 15 minute readings from the Kingston ultrasonic gauge.

On installation in 1979 the Royal Windsor gauge was a single path ultrasonic station; at the time of writing it is in the process of being upgraded to multi-path. A correction factor has been applied to the previously published Windsor flows post February 1982 since current meterings and other experience had revealed a drift in the calibration that was giving rise to overestimation of discharges. Bray Weir discharge computation made use of the upstream level, head loss, and weir openings and characteristics. There was no separate rating for the high flow range based on downstream levels as at other sites. Although the station is now discontinued charts continued to be installed and have been made available to the study.

The other tabulated stations were used for particular aspects; their data were obtained from the Surface Water Archive at the Institute of Hydrology.

2.2 TAILWATER RATING FOR BRAY WEIR

Because of uncertainties in the high flow computation of Bray flows, and to make use of the much longer lock keeper's records, it was decided to try to employ Bray tailwater levels as a gauging station. A rating curve was determined for Bray tailwater based on high flow events from the period 1979 to 1987 when chart records of stage were available at Bray and flow records were available from the ultrasonic gauge at Windsor to give the stage and discharge at the hydrograph peaks. Events with a peak discharge over 90 cumecs gave the relationship:

$$Q = 1.344(H-58.399)^{2.049}$$

where Q = discharge (m^3/s)
H = stage above OD Newlyn (feet)
(Note the use of mixed units to accord with basic data that are available).

This represents within-bank (or extended above on a similar geometry) discharge and although all discharge is confined to a limited number of openings through the railway bridge upstream there would be some out of bank contribution which would lead to underestimation at the larger events. For example the 1947 flood inundation map indicates a flood plain width of 2 km in the vicinity of Bray.

The effect of the flood plain is discussed in outline in Section 5 of the Stage One Final Report. Based upon that information supported by anomalous results which ensue in the statistical analysis if the within bank rating is continued to high stage it was decided to branch to a high flow rating to represent out-of-bank conditions. This departs from the lower rating at Q=255 m^3/s (highest calibration point) and passes through the previously assumed discharge and level of the 1947 flood (510 m^3/s, pro-rated from 500 m^3/s at Maidenhead as assumed in the Stage One Final Report). The rating for discharge above 255 m^3/s is:

$$Q = 0.5240(H-58.399)^{2.4165}$$

where Q = discharge (m^3/s)
H = stage above OD Newlyn (feet)

The rating curve is shown in Figure 2.1. Strictly the data derived from this rating curve should be associated with the Windsor site, this being the location of discharge observation. However, in order to distinguish it from the Windsor ultrasonic station the station has been labelled Bray/Windsor in this report. In order to apply the Bray/Windsor discharge values to Maidenhead a factor of 0.98 is applied to allow for the small catchment area difference.

3. Flood Frequency Analysis

3.1 GENERAL

The flood frequency relationship is required for the Maidenhead study site. Three sources of information were initially considered in constructing a single curve:

(a) annual maximum series at Bray/Windsor (Section 3.2)

(b) the Teddington/Kingston flood frequency curve with a correction factor (Section 3.3)

(c) regional estimators of mean annual flood and flood frequency curve. (Section 3.4)

Method (c) was judged to be considerably more uncertain than the other two so the final curve (Section 3.7) was computed from the results of methods (a) and (b) only.

3.2 ANNUAL MAXIMUM ANALYSIS OF BRAY/WINDSOR DATA

The extended annual maximum series shown in Table 3.1 has been produced for Bray/Windsor using the tailwater rating curves derived in Section 2.2.

The tabulated annual maximum discharges from 1979 to 1985 were obtained from the Windsor ultrasonic gauge. For the period before 1979 the Bray/Windsor rating equation was applied to annual maximum levels determined from the following sources:

1. 1972 - 1978 Bray tailwater stage charts
2. 1959 - 1971 and 1956 Bray stage charts corrected from OD Liverpool to OD Newlyn [$OD_N = OD_L - 0.92$ (feet)]
3. 1892 - 1958 Level duration listing for Bray tailwater. For those years

Table 3.1 Bray/Windsor annual maxima 1892 - 1985

Water year	discharge (m^3/s)	Water year	discharge (m^3/s)	Water year	discharge (m^3/s)
1892	261.15	1924	414.27	1956	237.28
1893	185.30	1925	349.20	1957	224.23
1894	533.80	1926	298.84	1958	358.43
1895	202.85	1927	393.69	1959	256.83
1896	398.62	1928	171.18	1960	341.24
1897	196.79	1929	419.35	1961	252.71
1898	285.95	1930	176.82	1962	203.21
1899	435.46	1931	247.11	1963	244.73
1900	227.65	1932	409.22	1964	139.27
1901	157.95	1933	90.91	8965	225.37
1902	398.62	1934	147.39	1966	234.17
1903	435.46	1935	353.80	1967	231.09
1904	211.93	1936	335.06	1968	240.79
1905	188.05	1937	163.05	1969	172.17
1906	182.56	1938	349.20	1970	261.63
1907	383.33	1939	378.52	1971	244.73
1908	142.55	1940	261.15	1972	188.39
1909	209.00	1941	233.79	1973	241.97
1910	393.69	1942	330.06	1974	327.29
1911	363.69	1943	96.96	1975	85.29
1912	273.38	1944	199.99	1976	271.90
1913	230.71	1945	185.30	1977	207.55
1914	419.35	1946	509.90	1978	254.32
1915	368.39	1947	179.51	1979	228.25
1916	277.37	1948	227.65	1980	218.45
1917	358.43	1949	250.30	1981	233088
1918	335.06	1950	277.37	1982	221.02
1919	243.55	1951	237.28	1983	182.66
1920	214.88	1952	193.97	1984	178.11
1921	155.12	1953	168.55	1985	249.18
1922	209.00	1954	344.07		
1923	273.38	1955	211.93		

Water year 1892 = October 1892 - September 1893

when the annual maximum was below the typical low flood level the value was taken from Bray tackle sheets.

For the period 1959 to 1979 it was found that the peak levels obtained from the level duration listing were higher than those from the stage charts. The average difference between the listing and chart value remained consistent over the common period at 0.21 feet so this figure was used as a correction factor to reduce the gauge read annual maximum levels between 1892 and 1958 to their equivalent chart values. Possible explanations for this difference are a difference in datum, a bias in reading the staff gauge in turbulent conditions, or a pressure reduction within the pipe to the float well.

The double mass plot of Bray/Windsor annual maxima against Teddington annual maxima is shown in Figure 3.1. The double mass plot shows a reasonably consistent gradient back to the early 1940s but increasing curvature beyond. The annual maxima series was hence divided into four subsets for trial flood frequency analysis:

1. 1979 - 1985 Windsor ultrasonic gauge
2. 1959 - 1985 Windsor ultrasonic gauge and Bray charts
3. 1940 - 1985 Period over which record seems homogeneous from double mass plot
4. 1892 - 1985 Extended annual maximum series.

Figure 3.2 shows the frequency plots obtained from the four subsets of the annual maxima series. Inspection of these plots reveals a tendency towards an EV3 form of distribution although reducing in intensity with increased record length. Such a form is not conceivable in the light of experience generally and it is assumed that the effect is due to sampling error.

3.3 FLOOD FREQUENCY BASED UPON TEDDINGTON/ KINGSTON DATA

Figure 3.3 shows the fitted flood frequency curve to Teddington/Kingston daily maximum discharges. As explained in Section 2.1 these "daily" values represent, for the most part, the average of two point estimates made at low tide. The data appear well described by an EV1 fit. There is a very large disparity between the distribution fitted to the instrumental record at Teddington and that implied by the Region 6/7 flood frequency curve from the Flood Studies Report (FSR). One source of difference is the use made of historical data (flood marks etc collected prior to the start of the conventionally gauged record) when constructing the FSR region curves. A considerable amount of historical information is available for the Thames (Griffiths, 1969) and this was used where applicable to augment the 103 year Teddington record.

Since 1673 three floods have been established as having magnitudes similar to or greater than the 1894 event: 1774, 1809 and 1821. The 1821 event is considered to have exceeded the severity of the 1894 flood by a considerable margin; the other two are thought to have been of generally similar magnitude to the 1894 flood.

The method of maximum likelihood can be used to incorporate such historical information. In addition to the 103 fixed data points from the gauged record there are three further data points in which 789 m^3/s, the magnitude of the 1894 flood, was known to have been exceeded (as well as 206 points where it is known not to have been exceeded) .

The likelihood function then has the form:

$$L = \prod_{i=1}^{103} (p(x_i)) \cdot \prod_{i=1}^{3} (1-F_{789}) \cdot \prod_{i=1}^{206} (F_{789})$$

where p is the probability of x_i recorded point
F_{789} is the non-exceedance probability of 789 m^3/s
L is the likelihood of the sample

This function is controlled by the parameters u, a and k of the GEV distribution and values of those parameters are found which maximise L (hence "maximum likelihood"). The first product term alone is used to find the corresponding fit when historical data are excluded.

Table 3.2 Comparison of GEV fits with and without historical data

Variable	Without historical data		With historical data		FSR national
u	269.6		269.5		
a	96.3		99.0		
k	0.022		-0.038		-0.20
	m^3/s	Q(T)/QBAR	m^3/s	Q(T)/QBAR	Q(T)/QBAR
QBAR	323.1	1.00	330.4	1.00	1.00
Q(5)	438.7	1.36	422.3	1.28	1.22
Q(10)	481.1	1.49	502.0	1.52	1.48
Q(20)	546.6	1.69	580.8	1.76	1.77
Q(25)	567.1	1.76	606.0	1.83	1.88
Q(50)	629.8	1.95	685.7	2.08	2.22
Q(60)	646.1	2.00	707.1	2.14	2.32
Q(100)	691.1	2.14	766.8	2.32	2.61
Q(200)	751.2	2.32	850.3	2.57	3.06
Q(500)	829.1	2.57	962.7	2.91	3.76
Q(1000)	887.0	2.75	1051.5	3.18	4.38

QBAR is mean annual flood; Q(T) is T year flood

As indicated by Figure 3.4 and the value of a in Table 3.2 the main effect of historical data is to increase the gradient of the fitted line. However, it also converts the fit from one with small positive to one of small negative k although both being close to zero they would accord closely with EV1 fits as previously determined by the Figure 3.3 procedure. Despite the addition of historical data the frequency curve remains far different from the all-country fit of the FSR as shown in Table 3.2, and further still from the all-region fit as shown in Figure 3.5.

Nevertheless, the impact on quantile estimation is quite substantial leading to an 11% increase at the 100 year return period. Consequently the effect on implied return periods is also quite large. For example the recorded data imply a return period of 130 years for the 1947 flood but when set in the longer historical context this reduces to 64 years.

These values require adjustment for the difference in catchment to

Maidenhead. To establish a conversion factor information was assembled on low return period floods. Table 3.3 shows the comparison between three methods of estimating the mean annual flood at Bray/Windsor and Teddington.

Table 3.3 Mean annual flood (m^3/s) at Bray/Windsor and Teddington

	DATA		CALMAF	FSR
	1940-1985	1892-1985		
Bray/Windsor	236.2	262.9	203.0	214.2
Teddington	331.3	331.0	295.0	289.9
Bray/Windsor :Teddington ratio	0.713	0.794	0.688	0.739

The "FSR" and "CALMAF" methods are based on catchment characteristics (Flood Studies Report, chapters 4 and 5 respectively, NERC, 1975). The "FSR" results use the six variable equation for the East Anglia region advocated in Flood Studies Supplementary Report 5 for less urbanised catchments in the Thames basin. The mean annual calendar day flood (CALMAF) is determined from a four variable equation. The "DATA" results are obtained as the arithmetic average of the annual maxima daily mean discharge data. There is good general agreement between the estimates, the regression based no-data equations underestimating the data based estimates by 10% which is well within the normal range of difference for this method.

For a case such as this data based-estimators would be preferred so the regression results are presented as confirmation only and to assist with assessing the ratio at the mean flood level between Bray/Windsor and Teddington discharges. The Table 3.3 ratios are also in tolerable agreement with the value previously adopted for the ratioing of the flow duration curve (Section 7). It was concluded from the various considerations above that there is no discernible trend in the ratio with discharge magnitude, that the data based estimate for the recent period would be more reliable than the earlier data, and finally that the factor used for the flow duration curve would serve also for flood frequency. The Teddington flood frequency curve was therefore adjusted by a factor of 0.73 to estimate the flood frequency relationship at Maidenhead.

3.4 REGIONAL ESTIMATION

The objective of a regional estimation technique is to bring data from surrounding stations to bear on a site estimation problem. Its role diminishes as the quantity and quality of the local data increases. In general terms the

Thames is a very well monitored river, nevertheless uncertainties exist which justified the trial use of regional procedures in the early stages of the Maidenhead study:

(a) closest gauging station (Bray) is of poor quality and the next closest (Windsor) is of short duration

(b) most data relates to daily mean discharge while instantaneous peak values are of most interest

(c) considerable overbank flow for even moderate sized floods.

A procedure was adopted similar to that recommended in the FSR for sites with an intermediate amount of data. In view of uncertainties with the Bray/Windsor record the following steps were used:

1. EV1 fit to 1959 - 1985 Bray/Windsor data
2. Extrapolation to 10 years
3. Further extension using multipliers from FSR region 6/7 flood frequency curve
4. As an alternative to step 3 a "Thames River" dimensionless regional flood frequency curve was constructed by pooling annual maxima series for Bray/Windsor (1940 - 1985), Day's Weir (1938 - 1985) and Teddington (1883 - 1985).

Table 3.4 Regional flood frequency curves for Bray/Windsor site

Q(T)	Region 6/7 curve m^3/s	"Thames River" curve m^3/s
Q(2)	219.4	219.4
Q(5)	265.2	265.2
Q(10)	295.4	295.4
Q(25)	390.2	347.6
Q(50)	477.7	387.8
Q(60)	503.4	398.4
Q(100)	581.7	428.0
Q(200)	703.1	466.2

3.5 FLOOD FREQUENCY RELATIONSHIP ALONG THE COURSE OF THE THAMES

As a final check on the coherence of the flood estimates, at least at low and moderate return periods, Figure 3.6 shows return period flow for Day's, Bray/Windsor and Teddington. As return period increases the flow at Bray/Windsor appears to decrease relative to Teddington whilst that at Day's Weir increases. This comparison suggests that the EV1 fit to Bray/Windsor data underestimates higher. return period discharges.

3.6 COMBINED ESTIMATE OF FLOOD FREQUENCY

Table 3.5 shows the five separate estimates of flood frequency for Maidenhead as developed in Sections 3.2 to 3.4. after adjustment for the difference in catchment from Bray/Windsor.

Table 3.5 Flood frequency data from five estimates (m^3/s)

	Flood estimate based on				
	Teddington data		Bray/Windsor data		
	Section 3.2	Section 3.3	Section 3.4		
Q(T)	Recorded data (1)	Historical addition (2)	Total period (3)	Regional estimates Region 6/7 (4)	"Thames River" (5)
Q(2)	217	219	243	215	215
Q(5)	293	302	326	260	260
Q(10)	344	359	379	289	289
Q(25)	409	433	446	382	341
Q(50)	456	491	495	468	380
Q(100)	504	549	543	570	419
Q(200)	551	608	590	689	457

Figure 3.7 shows the same information in graphical form. The estimates are not strictly independent, columns 1, 2, 4 and 5 depending to some extent on the Teddington flood record. The regional approach is clearly deficient at low return period where the locally derived result is considered to be most accurate. A central line has been struck through the alternative estimates as shown in Figure 3.8. The recommended single line makes use of an average between the Bray/Windsor line (3) and the Teddington line with historical data (2) to 25 year return period above which the line derived from the Teddington record including historical information is used. Table 3.6 gives corresponding ordinates. Figure 3.8 shows the recommended curve in relation to the envelope from the Stage One Final Report (paragraph 6.27.7) . The recommended line is contained everywhere within these bounds although somewhat closer to the upper limit at intermediate return periods. This is due in part to the small difference between peak and daily mean data but more to the weight given to low gradient estimators derived from POT approaches to flow and stage data. However, overall the agreement is considered to be very satisfactory.

Table 3.6 Recommended flood frequency curve and 90% confidence limits (see Appendix A)

T (years)	2	5	10	25	50	100	200
Q (m^3 s)	231	314	369	440	491	549	608
lower 5%	210	284	334	396	438	487	532
upper 5%	252	344	404	484	544	608	684

4. The 1947 flood

The Thames Conservancy report of 1947 reviewed the history of flooding in the Thames valley with particular reference to the flood of March 1947 which reached a peak flow of 714 m^3/s at Teddington on 20 March. The 1947 flood, unlike the floods of 1894, 1915 and 1929, was not preceded by a long period of heavy rainfall but was due to a combination of snowmelt, frost and rain. Throughout February 1947 a severe frost had created an impervious catchment surface. On the 10, 12 and 15 March heavy rain of 50.3mm fell on the frozen and snow covered ground which combined with the thaw beginning on 16 March resulted in flooding. The 1947 flood hydrographs for Bray/Windsor and Teddington are shown in Figure 4.1. The Teddington hydrograph is based on daily mean flows whilst the Bray/Windsor hydrograph uses stage readings from the Bray tackle sheets and the stage/discharge relationships from Section 2.2. The return period of the peak of the 1947 flood varies from 50 to 140 years. The value from the recommended mean line is 56 years which is in close accord with values obtained by previous investigations in the Thames basin.

5. Duration of inundation

5.1 GENERAL

The duration over which a given flood level is exceeded can be important in terms of flood damage. Chapter 6 of the Stage One Final Report therefore considers the expected durations of various flood levels at Maidenhead. The level duration records from the lock keepers log were used to determine a relationship between flood duration above a bench level and the peak level attained by the flood. The regression equations used to describe the relationship were combined with the flood frequency relationship to determine the duration of floodwater above any chosen level for five different return periods.

The approach used in this report differs from that in the Stage One Final Report since Windsor flows were used to determine durations rather than the level duration listings. One problem identified was that a duration of one day above a given level in the level duration listing does not mean that the level was exceeded for a whole day but only that the level was exceeded at some time during the day. Use of the Windsor hydrographs would therefore be expected to indicate a shorter duration above a flow than that suggested by the Bray tailwater level duration listing since the hydrograph records the exact duration above a given flow.

5.2 ANALYSIS OF FLOOD HYDROGRAPHS

The Windsor 15 minute hydrographs were used to determine the duration above flow thresholds for events above typical low flood level. Data were available for 15 such events between December 1979 and April 1987. These data were supplemented with three larger events from earlier years: March 1947, December 1960 and November 1974. The duration that a given percentage of flow was exceeded was plotted against peak flow. This shows that as percentage of peak flow decreases the mean duration increases and the scatter about the mean increases.

5.3 CALCULATION OF DURATION

The relationship between the duration, flow and peak flow was examined for the 18 events. The following equation was obtained which relates the mean duration to the 'distance' between the threshold and the peak:

$$D = 0.282\ (Qp\text{-}Q)^{0.726}$$

where D = duration (days)
Qp = peak flow (m^3/s)
Q = flow (m^3/s)

Factorial standard error = 1.40 $r^2 = 62.2$

This relationship gives the results shown in Table 5.1.

5.4 RECOMMENDATIONS FOR APPLICATION

Two points should be emphasised. The first is that these durations are mean values. The flood frequency curve gives the magnitude of the peak flow for a return period, not the shape of the hydrograph. The non-uniformity of rainfall and catchment conditions in time and space results in a wide variety of hydrograph shapes and, therefore, durations, for events having a peak flow of a given return period. The factorial standard error quoted above measures

Table 5.1 Duration in days for which discharge threshold exceeded

Return period (years)	Peak discharge (m^3/s)	Threshold discharge (m^3/s)							
		250	300	350	400	450	500	550	600
2	232	-	-	-	-	-	-	-	-
5	314	5.8	1.9	-	-	-	-	-	-
10	369	9.2	6.2	2.4	-	-	-	-	-
25	440	12.9	10.3	7.5	4.1	-	-	-	-
50	491	15.3	12.9	10.3	7.5	4.2	-	-	-
60	506	16.0	13.6	11.1	8.4	5.3	1.0	-	-
100	549	17.9	15.7	133	10.8	8.0	4.8	-	-
200	608	20.4	18.3	16.1	13.7	11.2	8.5	5.4	1.3

this variability that can occur about the mean. Its consequence may be exemplified by the following: as the table indicates a 60 year return period flood can be expected to remain above the 500 m^3/s threshold for one day - however, different conditions which may arise in causing this flood can give a wide variety of durations; the duration which exceeds 95% of all possible is 1.7 days, 70% longer than the mean.

The second point is that these results relate to single peaked hydrographs. It is conceivable that the hydrograph, once it has dropped below the threshold may, within a very short time, rise above it again. Such a condition becomes increasingly unlikely as the return period and the threshold increase.

6. Time trend

6.1 GENERAL

The Stage One Final Report presented prima facie evidence for trend in the Thames data sets. Attention there focused on the apparent dearth of major flood events in the period from 1961 to 1973, the downturn in the incidence of threshold exceeding levels at a number of head and tailwater level recording stations since the 1947 flood, and the possibility of cyclicities in the rainfall pattern. It has to be said that the very evident visual impression of reduced flood incidence as seen in the water levels is not repeated in the corresponding time series of maximum daily flows (page 6-24 of Stage One Final Report). This section concentrates on the Teddington flow record and catchment average rainfall to investigate the evidence for trend commencing with mean values in section 6.2 and progressing to extremes in section 6.3.

6.2 TREND IN THE ANNUAL SERIES

6.2.1 Annual runoff

A long time series of random trend-free data exhibits fluctuations through normal statistical variations. A judgement on the reality of a superimposed trend has to be judged in the light of this expected irregularity. Although the Teddington record is among the longest in Britain it is not without faults: the gauging arrangements have not always been ideal and the gauged record requires adjustment in order to return it to a "natural" inflow. The 1983 Surface Water Yearbook (NERC, 1985) details the gauging history and the changes which have occurred within the catchment over its first 100 years of operation. If the 100 year record is divided into 20 year "slices" the following statistics are found:

Table 6.1 Statistics of mean runoff

Period (1)	Annual m^3/s (2)	January m^3/s (3)	July m^3/s (4)
1883-1902	62.55	112.58	26.80
1903-1922	80.70	145.13	38.86
1923-1942	88.10	166.25	35.73
1943-1962	76.00	137.46	29.54
1963-1982	85.16	133.40	42.47
Standard error	5.2	14.6	3.1
Trend significance	2.22	1.50	2.26

Table 6.1 indicates that considerable swings in average values have occurred in the past and that these are not restricted to particular parts of the year. The range of values in all three columns indicate larger fluctuations than expected from a normal sample with differences exceeding four times the standard error of estimating the mean.

More sophisticated autocorrelation and spectral anlyses reveal the fact that there is a year-on-year correlation of 0.22 which is presumably due to the large geological storage within the catchment. The consequential slight "reddening" of the spectrum leads to fewer and longer runs and larger fluctuations than from an entirely random "white noise" type of series. This carry-over memory needs to be born in mind when judging the significance of fluctuations.

The most direct test for trend is the correlation of the annual runoff with time. The values of Student's t for the correlations are shown on Table 6.1 having removed the effect of serial correlation. The January value is insignificant, and the July and whole year values border on 5% significance. Inspection of the seasonal pattern shows an increasing significance through the year rising to a maximum in September then depleting to a winter minimum. Such a pattern would be consistent with some causative factor which primarily influences low flows.

6.2.2 Annual and seasonal rainfall

Areally averaged catchment rainfall data are available from 1890 and similar analyses have been applied to annual and monthly rainfall totals both in a raw and in transformed form.

Table 6.2 Statistics of annual and seasonal rainfall

Period (1)	Annual mm/day (2)	January mm/day (3)	July mm/day (4)
1891-1910	1.85	2.59	1.85
1911-1930	2.10	2.32	2.37
1931-1950	1.95	2.32	1.96
1951-1970	2.06	2.16	1.97
Standard error	0.08	0.22	0.21
Trend significance	0.79	1.46	-1.42

The general pattern of high and low 20 year periods in the runoff reappears in the rainfall data although the degree of inter-period annual fluctuation falls within two standard errors of estimating the mean; seasonal fluctuations are larger. There is no discernible between-year correlation in the rainfall data and there is no apparent trend in the annual or seasonal totals, the significance levels - again expressed in terms of the Student's t statistic - falling far below the acceptance range.

Rainfall is not necessarily a good indicator of runoff so a runoff oriented index of rainfall was also subjected to trend analysis. To achieve this the catchment rainfall was fed into the Thames Water hydrological model (Greenfield, 1984; Moore et al, 1986) and the output - being Teddington estimated discharge - was then subjected to the same tests.

This demonstrates very adequately that the moderate up and down turns in the rainfall translate into somewhat larger ones viewed in terms of runoff. The trend analyses agrees with the raw rainfall trend above with little or no tendency for higher values in the low flow season.

Table 6.3 Statistics of mean runoff computed from Thames Water model

Period (1)	Annual m^3/s (2)	January m^3/s (3)	July m^3/s (4)
1891-1910	67.18	116.41	32.49
1911-1930	87.85	174.02	39.45
1931-1950	74.97	139.19	34.01
1951-1970	80.66	155.68	35.80
Standard error	4.9	13.6	2.1
Trend significance	1.19	0.83	0.65

6.3 TREND IN THE EXTREMES

6.3.1 Discharge extremes

Similar analyses to those above can be performed on maximum daily flows.

Table 6.4 Statistics of annual and seasonal maximum discharge

Period (1)	Annual m^3/s (2)	January m^3/s (3)	July m^3/s (4)
1883-1902	316.3	191.64	43.86
1903-1922	325.4	236.45	59.59
1923-1942	370.9	298.20	51.35
1943-1962	355.2	250.79	46.58
1963-1982	340.4	229.60	66.37
Standard error	28.9	23.2	6.3
Trend significance	1.53	1.43	1.91

Comparing Tables 6.1 and 6.4 shows agreement in the wettest and driest decades and a more subdued level of fluctuation in the annual maxima than in the annual means. However the fluctuations between 20 year periods in individual monthly maxima remains high in relation to the standard error of estimating the mean.

From the monthly observed runoff values it had become apparent that the trend coefficients approached closer to significance during the months of low flow than at other times of the year. Table 6.5 has been prepared from monthly and all-year minima and maxima and indicates clearly the control of flow magnitude on the trend. Values above 2 are significant at the 5% level.

Table 6.5 Monthly trend significance (expressed as Student's t statistic)

Month	Minimum	Maximum
January	1.22	1.43
February	2.13	1.92
March	1.99	1.18
April	2.59	2.20
May	3.01	2.71
June	3.37	2.53
July	3.11	1.91
August	3.12	3.36
September	3.19	3.88
October	3.87	1.66
November	1.31	1.16
December	1.18	2.32
All year	3.59	1.53

6.3.2 Rainfall extremes

Mean rainfall displayed lower period to period fluctuations than runoff and as Table 6.6 demonstrates extreme rainfalls exhibit yet smaller fluctuations with all

Table 6.6 Statistics of annual and seasonal daily rainfall maxima

Period (1)	Annual maximum mm (2)	January mm (3)	July mm (4)
1891-1910	25.48	1219	13.7
1911-1930	27.06	14.39	16.48
1931-1950	23.69	12.72	14.72
1951-1970	28.11	12.48	16.23
Standard error	1.52	1.24	1.78
Trend significance	1.63	0.34	0.14

seasonal and annual maximum rainfalls lying within a two standard error band.

No monthly time trends were visible in the one-day rainfall maxima and more complex spectral analyses revealed no regular periodic behaviour. The same picture is revealed by annual and seasonal maxima after transformation through the Thames Water rainfall runoff model; the period to period fluctuation is contained within two standard errors.

6.4 CONCLUSION ON TIME TREND

A variety of analyses have been performed on mean and extreme flow, and on catchment rainfall. The overall conclusion is that there is no proven trend although there is an indication that low flows are increasing. This may be due either to catchment changes or to some feature of the naturalisation process; the latter appears more likely as the effect is visible only during low flow months when the importance of the naturalisation process is much enhanced.

Fluctuations do appear in the mean runoff which are partly mirrored in the rainfall data when time slices are separately analysed. These fluctuations appear to be statistically significant but there is no evidence that they are part of any irreversible trend, indeed all surplus and deficit periods of the past have been reversed. Spectral analyses showed no significant cyclicities at any periodicity. High flows and rainfalls display a much less marked fluctuation with period to period differences falling within their expected band of variation.

Hence if a downturn in flood levels does exist it must be due to improvements in the efficiency of the channel and control structures, there is no evidence of non-random behaviour in the flood flow series. This conclusion can also be read to imply that any apparent downturn in the frequency of floods is within the variation expected and a resumption of a previous pattern can be expected.

7. Flow duration curve

7.1 INTRODUCTION

The flow duration curve relates to work on sediment load in the proposed flood relief channel. The curve is nominally for a point upstream of Boulters Lock, Maidenhead but it is convenient to use Bray/Windsor as representative sites for the study point since the residual area between the off-take point and Bray is very small.

7.2 OUTLINE OF METHOD

The flow duration relationship is based upon daily mean discharges. Regional information, especially the Teddington/Kingston record played a key role. The Teddington flow duration curve using naturalised daily mean flows from 1883 to 1985 required two types of adjustment to derive the flow duration relationship for Maidenhead:

(a) Scale adjustment - the Teddington flow exceeded for a given percentage of time was multiplied by a factor to account for the lower discharge at Maidenhead.

(b) Shape adjustment - to account for the difference in the shape of the flow duration curve between Maidenhead and Teddington.

7.3 SCALE ADJUSTMENT

The scale factor should relate to the ratio of the average runoff at Teddington and Maidenhead. The following information was used for assessment of the scale adjustment:

(a) catchment area

(b) monthly runoff totals for some months during the period of record for Windsor

(c) monthly mean flows for Thames tributaries between Maidenhead and Teddington

The area ratio of the Windsor and Teddington catchments (see Table 2.1) is 0.695. This differs from the area ratio of the Stage One Final Report. Use of the area ratio might be justified by the similarity in rainfall totals. However, there is a difference in potential evaporation between the areas above and below Maidenhead. The lower potential evaporation above Maidenhead (Figure 7.1) implies that for the same rainfall the Maidenhead catchment will have a higher runoff in relation to its area than the Teddington catchment. The area ratio should therefore be considered as a lower bound for the scale adjustment.

Monthly runoff totals (in cumec-days) were available from the ultrasonic gauge at Royal Windsor Park for 20 months between January 1980 and September 1985. These were plotted against the monthly totals for the same months at Kingston (Figure 7.2) and a simple log linear regression gave the relationship:

$$W = 0.678\ K^{1.014}$$

where W = monthly runoff at Royal Windsor (cumec-days)
K = monthly runoff at Kingston (cumec-days)

The long term (1883-1985) average flow for Teddington is 78.2 m^3/s giving a monthly flow (for a 31 day month) of 2425 cumec- days. From the above equation when K=2425, W=1834 ie flow at Windsor is 75.6% of the flow at Kingston. Other discharges within the observed range yield similar ratios.

For each year between 1980 and 1985 the mean flow at Kingston was compared with the sum of the mean flows for three rivers downstream of Maidenhead: the Wey, Mole and Colne. The gauged flow of these three rivers combined is 13.2% of the flow at Kingston compared with their area ratio of 14.6% ie mean runoff 90.7% of the area ratio. Assuming these three rivers are representative it implies that the area downstream of Maidenhead contributes less flow per unit area to Teddington than the area upstream of Maidenhead. This accords with the impression gained from the distribution of potential evaporation (Figure 7.1) . The area below Maidenhead is 30.5% of the catchment area of Teddington and applying the specific runoff ratio of 90.7% would provide 27.7% of the Teddington flow. This implies that the catchment area to Maidenhead contributes 72.3% of the Teddington flow.

From a consideration of the three alternative ratios:

(a) an area ratio of 0.695
(b) a monthly total flow ratio of 0.756
(c) a flow ratio of 0.723 implied from downstream annual means, it was decided to scale the Teddington flow by a factor of 0.73 for the study site.

7.4 SHAPE ADJUSTMENT AND RESULTS

To determine a shape adjustment the shapes of flow duration curves and values of Base Flow Index (Low Flow Studies, 1980) were considered at gauging stations along the Thames and Thames tributaries. Figure 7.3 shows the curves for Day's Weir, Bray and Teddington. The impact of the relatively impermeable catchments north and east of Oxford is very apparent in the Day's Weir curve. The Base Flow Index (BFI) is a measure of the proportion of baseflow under the flow hydrograph and is controlled primarily by the catchment geology. Also its value is not much perturbed by data error. A permeable catchment will have a large proportion of baseflow giving a high BFI value and a flat flow duration curve. Below Maidenhead BFI values from many tributary inflow areas are relatively low (0.4 to 0.5) which results in steeper flow duration curves. Upstream of Maidenhead the proportion of chalk is larger giving very high BFI values. The net effect is that Maidenhead would be expected to have a flatter flow duration curve than at Teddington.

Mean monthly flows at Bray were plotted against those for Teddington for the period October 1959 to September 1965 (Figure 7.4) . This suggests that at low flows the Bray:Teddington flow ratio is higher than suggested by the scale factor of 0.73 and vice versa at high flows implying a less steep flow duration relationship than at Teddington. On consideration of the equivalent relationship with Windsor and of the gauging difficulties it was felt that the trend would not be as marked as Figure 7.4 suggests but nevertheless would be present in some measure.

The Bray BFI (0.70) and flow duration curve support the idea that the Teddington flow duration curve is too steep to represent the conditions at Maidenhead, but was thought to exaggerate the effect. The shape of the flow duration curve at Maidenhead was therefore taken as the average of those at Teddington and Bray. The flow duration curve is shown in Figure 7.5 and tabulated values in Table 7.1.

Table 7.1 Flow duration curve - Thames at Maidenhead

Percentage of time flow exceeded	Flow (m^3/s)
0.05	347.8
0.10	318.0
0.20	285.0
0.50	246.0
1.00	223.6
2.00	197.0
5.00	160.6
10.00	126.5
20.00	86.3
30.00	64.8
40.00	50.5
50.00	39.9
60.00	31.6
70.00	25.7
80.00	20.7
90.00	16.6
95.00	14.1
98.00	12.1
99.00	11.0
99.50	9.8
99.80	9.1
99.90	8.5

7.5 EXTENSION OF THE FLOW DURATION CURVE TO 500 M^3/S

The highest flow shown on the flow duration curve derived from daily mean discharges was 350 m^3/s. The flow duration relationship required extension to consider the design flow suggested in the Stage One Final Report of 500 m^3/s. This higher discharge was considered in terms of the durations over "bench levels" below flood peaks (Section 5.2) rather than daily mean flows. Duration over a bench level increases with the magnitude of the peak as does the range of durations about the mean (see Section 5.2).

From the current analysis a flood peak of 500 m^3/s corresponds to close to 50 year return period. The average size of those floods which exceed 500 m^3/s is close to 550 m^3/s hence the required bench level is 0.91 of the average peak. Inspection of recent flood hydrographs reveals a range of durations corresponding to this ratio between 1 and 4.5 days. During the 1947 flood a bench level of 91% of the peak discharge was exceeded for six days.

If six days, the 1947 flood-based figure, is adopted as the mean duration of floods exceeding 500 m^3/s then the implied duration of exceedance would be 12 days per century, ie 0.033%. For a more rigorous approach it is necessary to integrate over all possible exceeding discharges and if this is done the expression for the expected duration becomes:

$$E(D)=2N\{1-10.\exp(10).EI(10)\}$$

where N is the mean duration over a 50% bench level

EI is the exponential integral, $\int_x^\infty e^{-t}/t.dt$

EI is tabulated in Abramowitz and Stegun (1964) and evaluating this expression for the above case gives 11 days per century (0.030%), a very similar outcome to the simple assumption outlined earlier. However, these calculations assume that all flood hydrograph shapes would be as broad as the 1947 event and a mean value of 0.02% is considered more probable.

8. Summary and Conclusions

Annual maxima data for Bray/Windsor and Teddington (including historical data) gave two flood frequency relationships which were scaled to apply to the Maidenhead site. An average of the two curves provides the recommended flood frequency relationship for the Maidenhead study site up to a return period of 25 years. Beyond 25 years the flood frequency relationship derived from the Teddington record including historical information is used. The recommended flood frequency curve for Maidenhead gives a return period of 56 years for the 1947 flood discharge of 500 m^3/s.

The Thames flow record is characterised by periods of apparent departure from a mean rate of occurrence. All such apparent downturns in the past have been temporary and the record can be regarded as stationary.

From analysis of Royal Windsor flood hydrographs an equation was derived showing the mean duration for which a bench level of discharge is exceeded to be a function of the peak flood discharge, and the bench level discharge. For example, on average a discharge of 250 m^3/s would be exceeded for about 16 consecutive days during a flood whose peak was 500 m^3/s.

A flow duration curve was determined for the Maidenhead site after adjusting the Teddington flow duration curve by a scale factor and a shape factor. A flow of 500 m^3/s would be exceeded 0.02 % of the time.

9. References

Abramowitz, M. and Stegun, I. (1964) Handbook of mathematical functions. *Dover Publications*, New York.

Greenfield, B.J. (1984) The Thames Water catchment model. Internal Report, Water Resource Planning and Control, T and D, Thames Water

Griffiths, P.P. (1969) The two extremes (floods and droughts) *Thames Conservancy Report.*

Institute of Hydrology (1980) Low Flow Study Report.

Lewin, Fryer and Partners (1986) Maidenhead Flood Study, Investigation of alternative methods of flood alleviation. Final Report.

Moore, R.J., Jones, D.A., Black, K.B. and Parks, Y. (1986) Real-time drought management system for the Thames Basin. Institute of Hydrology.

NERC (1975) Flood Studies Report. London

NERC (1979) Design flood estimation in catchments subject to urbanisation. Flood Studies Supplementary Report 5.

NERC (1985) Flow gauging on the River Thames - the first 100 years. *Hydrological Data UK, 1983 Yearbook.*

Stock, R.V.W. (1947) Report on the flooding of urban and agricultural districts in the Thames valley with special reference to the high flood of March, 1947. *Thames Conservancy.*

Symons, G.J. (1894) The floods of November, 1894. *Symons's Monthly Met. Mag. 367 : 161 - 170.*

Symons, G.J. and Chatterton, G. (1895) The November floods of 1894 in the Thames Valley. *Quart. Journ. Royal Met. Soc. 21 : 189 - 209.*

Thames Conservancy (1914) Report of the engineer to the conservators of the River Thames on floods in the Thames Valley.

Appendix A

CONFIDENCE INTERVAL DETERMINATION

A1. Introduction

Three sources of information were analysed in order to determine the flood frequency relationship to be used for the Maidenhead study area.

(a) Annual maxima from Bray/Windsor

(b) Annual maxima from Teddington/Kingston using supplementary historical data and suitably scaled to Maidenhead

(c) Bray/Windsor mean annual flood and Thames River regional flood frequency curve

The recommended flood frequency curve is a composite of the curves obtained from the first two approaches.

It is possible to assign confidence limits to each of the curves as if they were separately obtained. Accepting any of these limits would be tantamount to ignoring the beneficial effect of having used three approaches in arriving at the chosen relationship and so would exaggerate the magnitude of the uncertainty.

A2. Strategy for forming composite confidence intervals

A judgement is required about the effect of the support from the three approaches summarised above. Three alternative strategies were considered:

(a) Assume that the three approaches are entirely independent - this has the effect of reducing the basic error by $\sqrt{3}$ i.e. 1.732

(b) Assume that the three approaches are equivalent to two entirely independent approaches - this has the effect of reducing the basic error by $\sqrt{2}$ i.e. 1.414

(c) Assume that the effect of the supporting information is equivalent to determining the value of k, the shape parameter.

In each case the baseline error was taken to be that applying to the second approach above, which was employed over the entire useful return period range.

A.3 Derivation of baseline error

There are two primary components to the error determination:

(a) Variance of flood quantiles for Teddington/Kingston

(b) Variance of the multiplication factor between Maidenhead and Teddington.

Considering Teddington/Kingston flood frequency the method of maximum likelihood was used to estimate the parameters of the best-fit distribution. The derivation of the variance-covariance matrix of the GEV parameters is obtained from:

$$V = E \begin{Bmatrix} d^2L/du^2 & d^2L/du.da & d^2L/du.dk \\ d^2L/du.da & d^2L/da^2 & d^2L/da.dk \\ d^2L/du.dk & d^2L/da.dk & d^2L/dk^2 \end{Bmatrix}^{-1}$$

which is the reciprocal of the matrix of second derivatives of the log-likelihood surface evaluated at the estimated u, a and k values.

Expressions can be obtained readily for the derivatives in the simple case of a continuous sample of annual maximum data. However, the situation is much more complicated in the present case where historical information is incorporated in a doubly censored form. To overcome the lack of closed form expressions for the elements of the matrix finite difference estimates of the derivatives were obtained on a net of 5 x 5 x 5 = 125 values surrounding the expected u, a and k values. Comparisons with known solutions enabled a method to be developed for selecting suitable finite difference increments.

The variance-covariance matrix was found to be:

$$\mathrm{cov}(u,a,k) = \begin{Bmatrix} 112.739 & 31.398 & 0.182 \\ 31.398 & 56.462 & 0.094 \\ 0.182 & 0.094 & 0.003 \end{Bmatrix}$$

The variance of a quantile estimate Q(T) uses the GEV formula:

$$Q(T) = u+a(1-\exp(-ky))/k$$

where $y = -\ln(-\ln(1-1/T)$ ie Gumbel's reduced variate, from which:

$$\mathrm{var}(Q(T)) = \sum (\partial Q/\partial \theta_i)(\partial \theta/\partial \theta_j)\mathrm{cov}(\theta_i,\theta_j)$$

where $\theta_1=u,\ \theta_2=a,\ \theta_3=k$

$\partial Q/\partial u=1$

$\partial Q/\partial a=(1-e^{-ky})/k$

$\partial Q/\partial k=(-a/k^2)(i-e^{-ky}(1+ky))$

Recalling also that:

$$\mathrm{s.e.e}(Q(T)) = \sqrt{\mathrm{Var}(Q(T))}$$

and the upper and lower 5% points on the sampling distribution of Q(T) are given by:

$$Q(T) +/- 1.645 \times \text{s.e.e}(Q(T))$$

the following table is obtained:

T (years)	10	25	50	100	250	500
Q(T) m^3/s	502	606	686	766	877	963
s.e.e	24	36	49	65	93	118
lower 5%	541	665	766	875	1030	1157
upper 5%	463	547	605	659	724	768

A.4 Adjustment to Maidenhead

The factor $r = 0.73 \times 0.98$ has been adopted to convert Teddington flows to Maidenhead flows. This factor is a further source of error which needs to be incorporated. After consideration of the alternative measures and the variation between events it was considered that the standard error of the factor is 0.025. The combination of errors makes use of the following formula:

$$\text{var}(r \times Q(T)) = r^2 \times \text{var}(Q(T)) + Q(T)^2 \times \text{var}(r)$$

from which a revised confidence interval table can be drawn up:

T (years)	10	25	50	100	250	500
Q(T) m^3/s	359	434	491	549	627	689
s.e.e	21	30	39	51	70	88
lower 5%	324	384	426	465	512	544
upper 5%	394	483	555	632	743	834

A.5 Effect of composite estimate

The baseline values in the above table do not allow for the support given by the other two methods and the consequent reduction in standard error. The table below shows the reduction in standard error after making the three assumptions discussed in Section 2.

T (years)	10	25	50	100	250	500
Q(T) m^3/s	359	434	491	549	627	689
baseline	21	30	39	51	70	88
fixed k	21	27	32	36	43	48
av. of 2	15	21	28	36	50	62
av. of 3	12	17	23	29	41	51

The assumption of a fixed shape parameter appears more generous at high return periods and it was felt that in no circumstance would the reduction be allowed to drop below the value obtained by considering the composite curve to be made up of two independent estimators. The finally recommended confidence intervals are thus made up from the "fixed k" values below 100 year return period and the "average of 2" values beyond.

T (years)	2	5	10	25	50	60	100	200
Q(T) m^3/s	231	314	369	440	491	506	549	608
s.e.e	13	18	21	27	32	33	36	46
lower 5%	210	284	334	396	438	452	487	532
upper 5%	252	344	404	484	544	560	608	684

Figure 2.1 Location of gauging stations

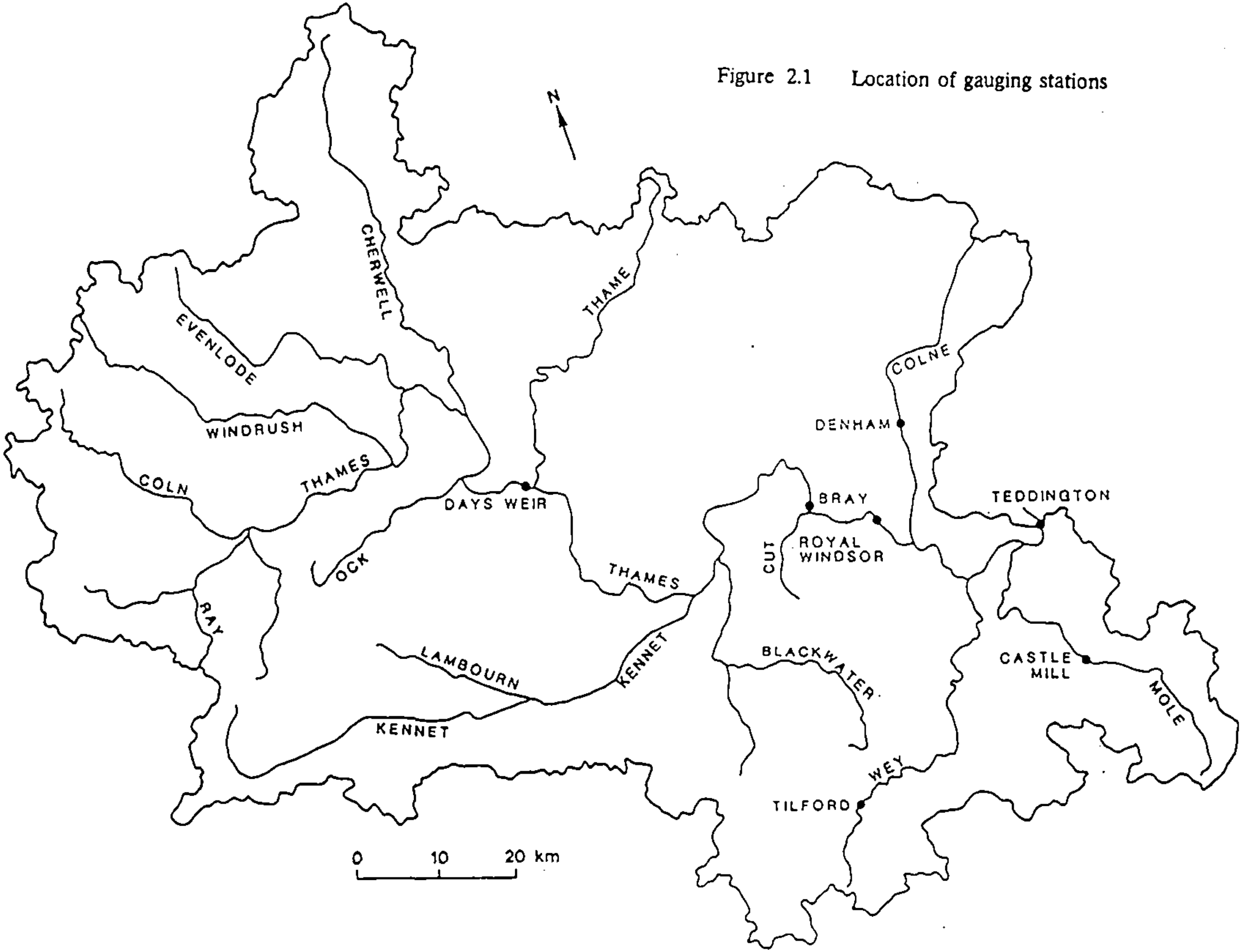
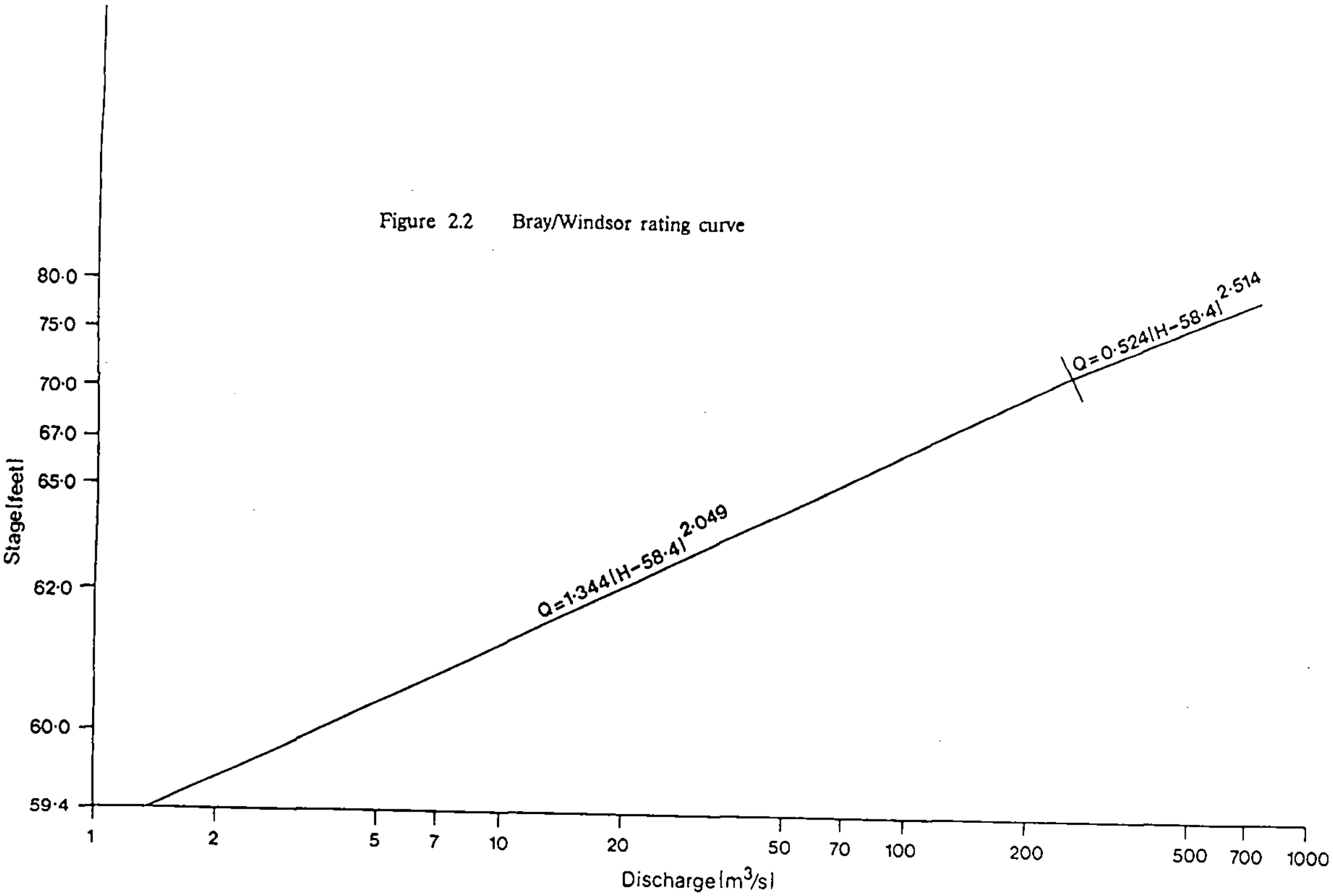


Figure 2.2 Bray/Windsor rating curve



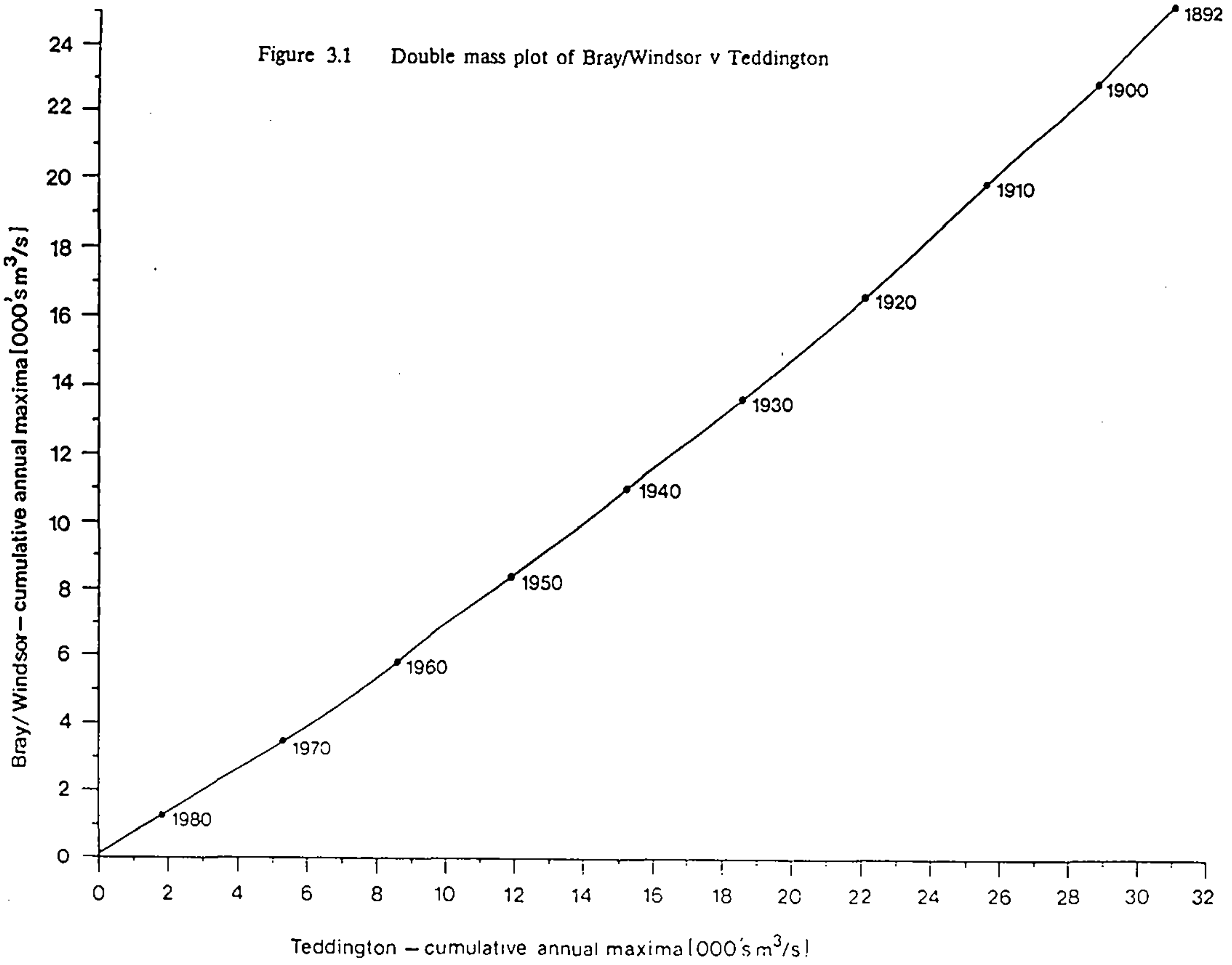


Figure 3.1 Double mass plot of Bray/Windsor v Teddington

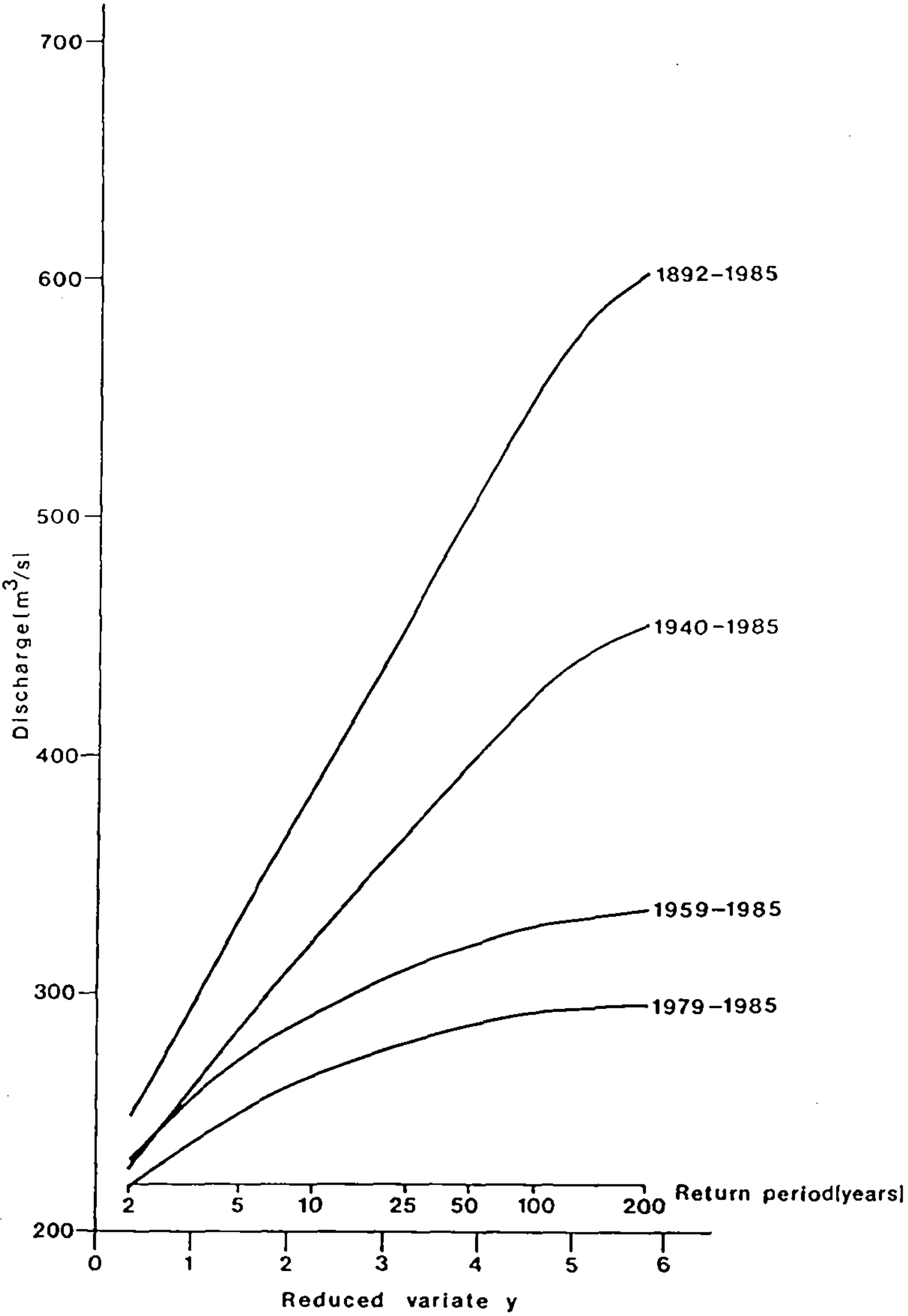


Figure 3.2 GEV flood frequency curves for Bray/Windsor

Figure 3.3 Flood frequency curve at Teddington

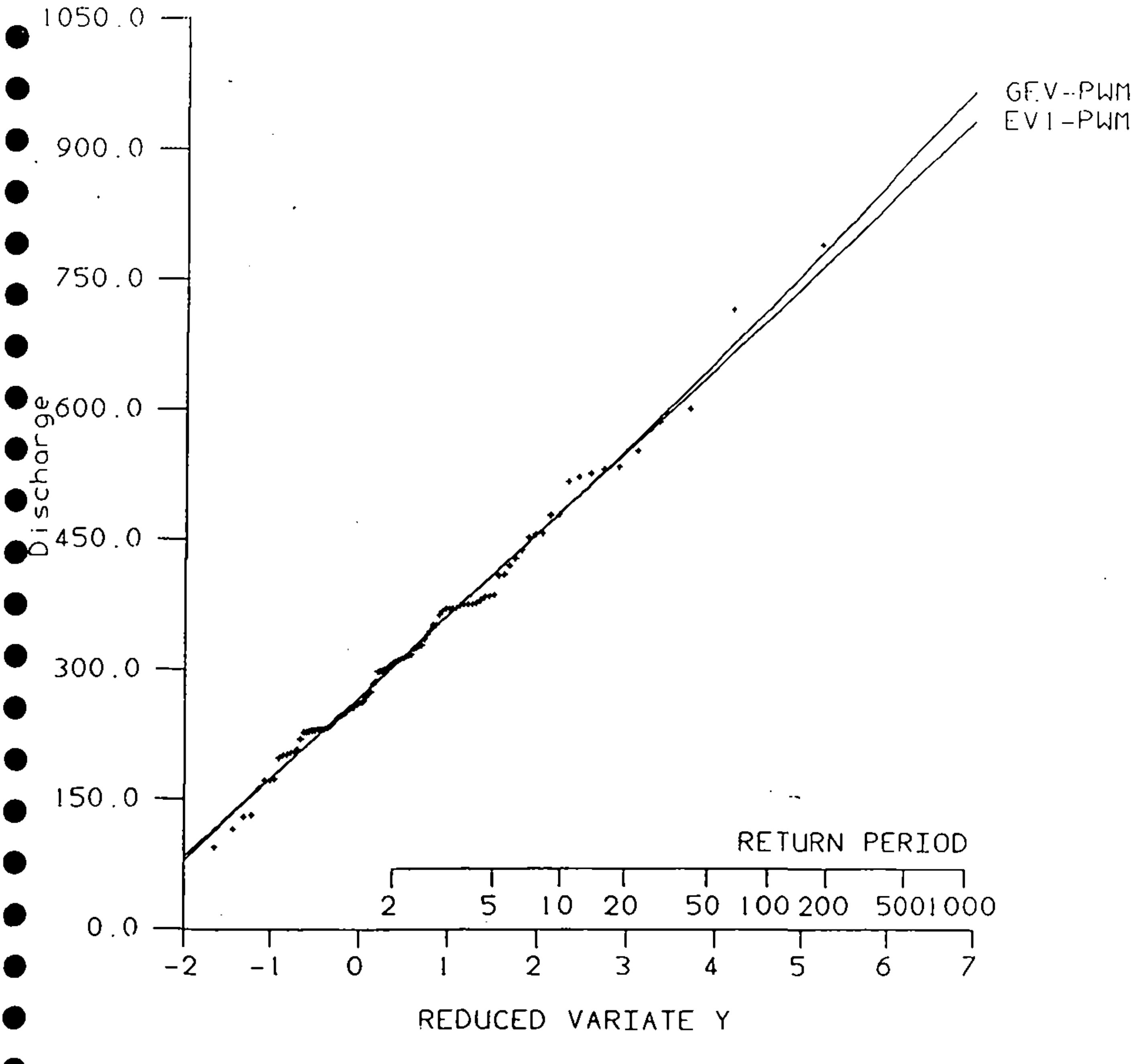


Figure 3.4 Flood frequency curve at Teddington - with and without historical data

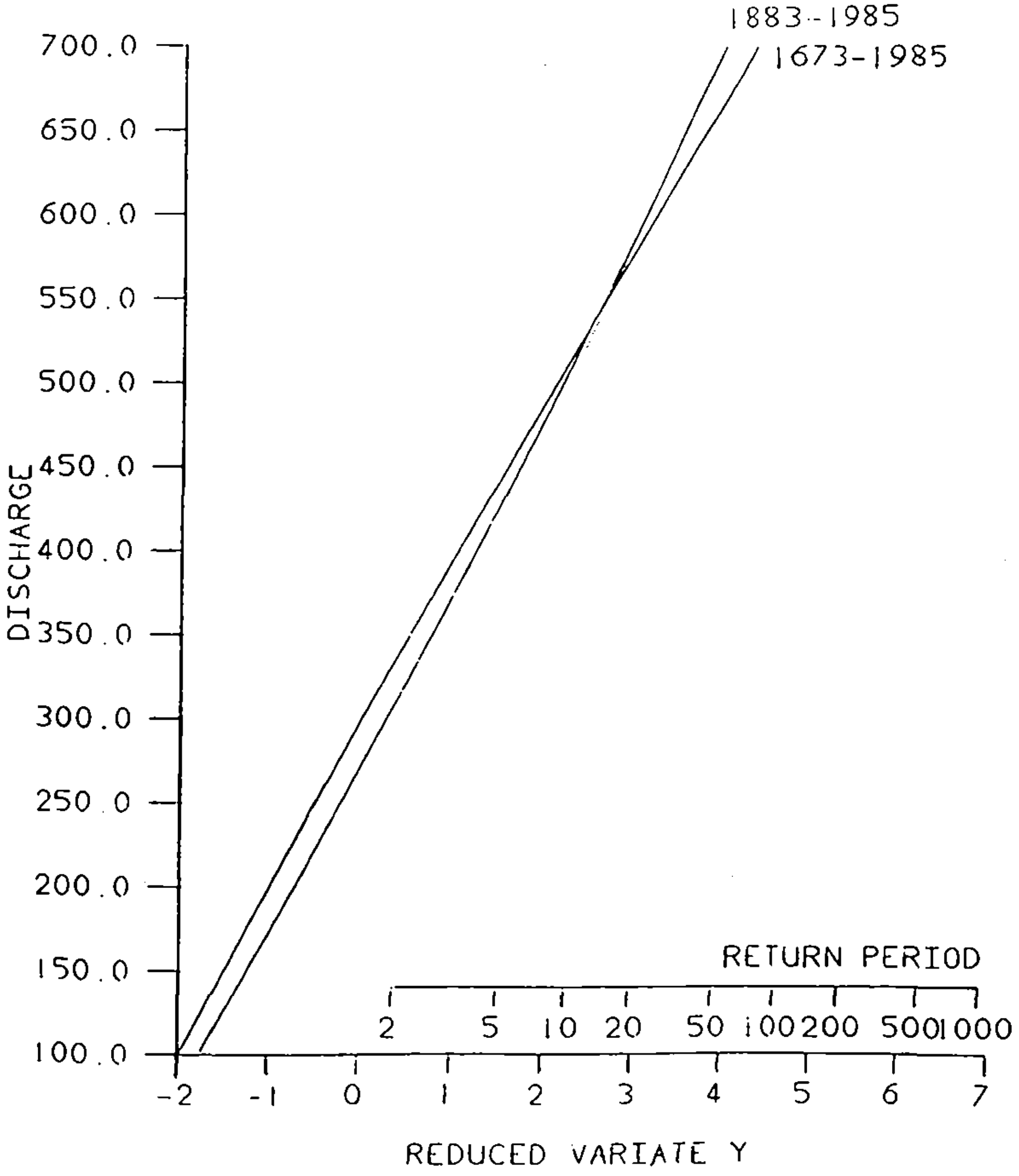
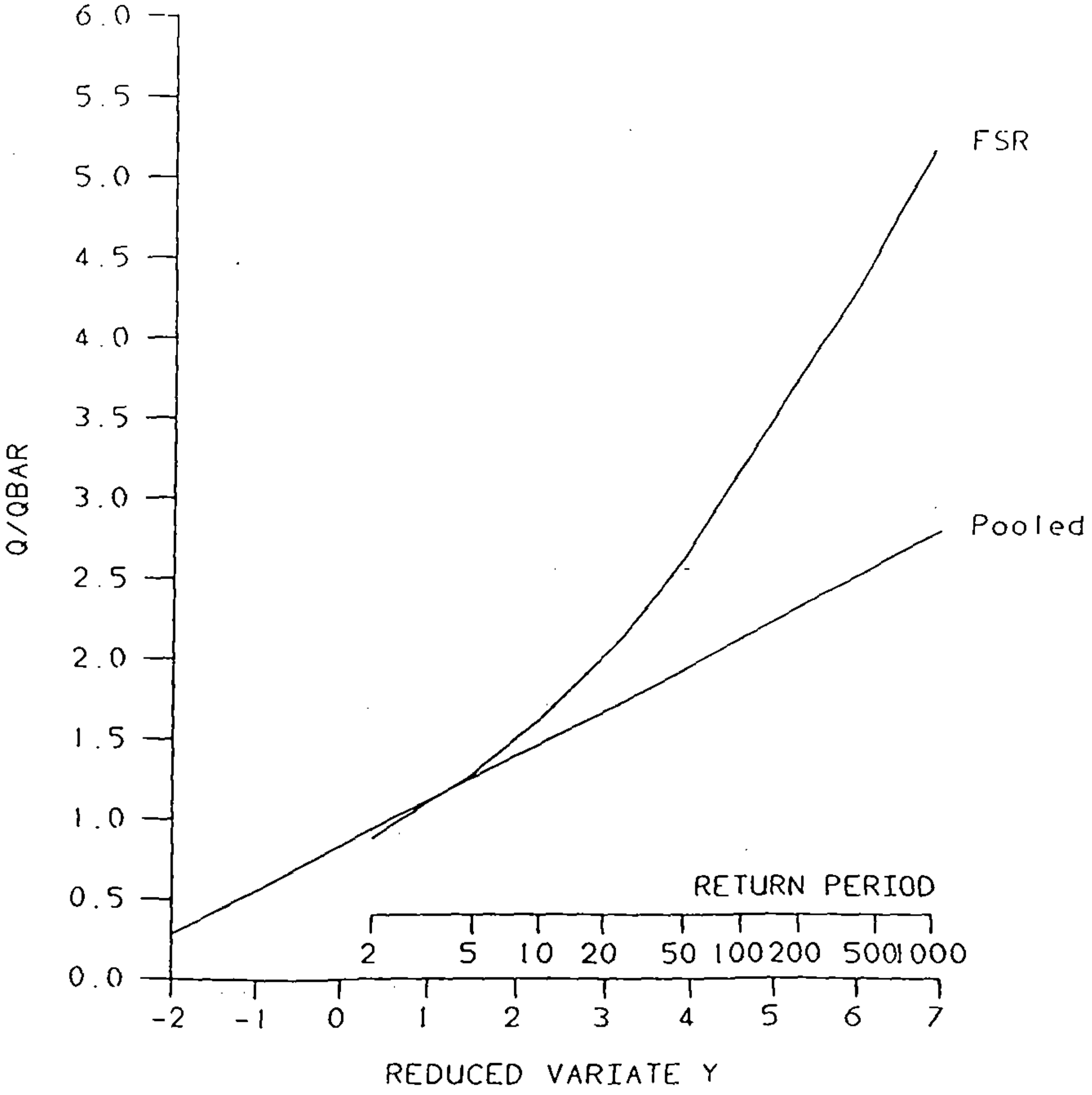


Figure 3.5 Regional analysis



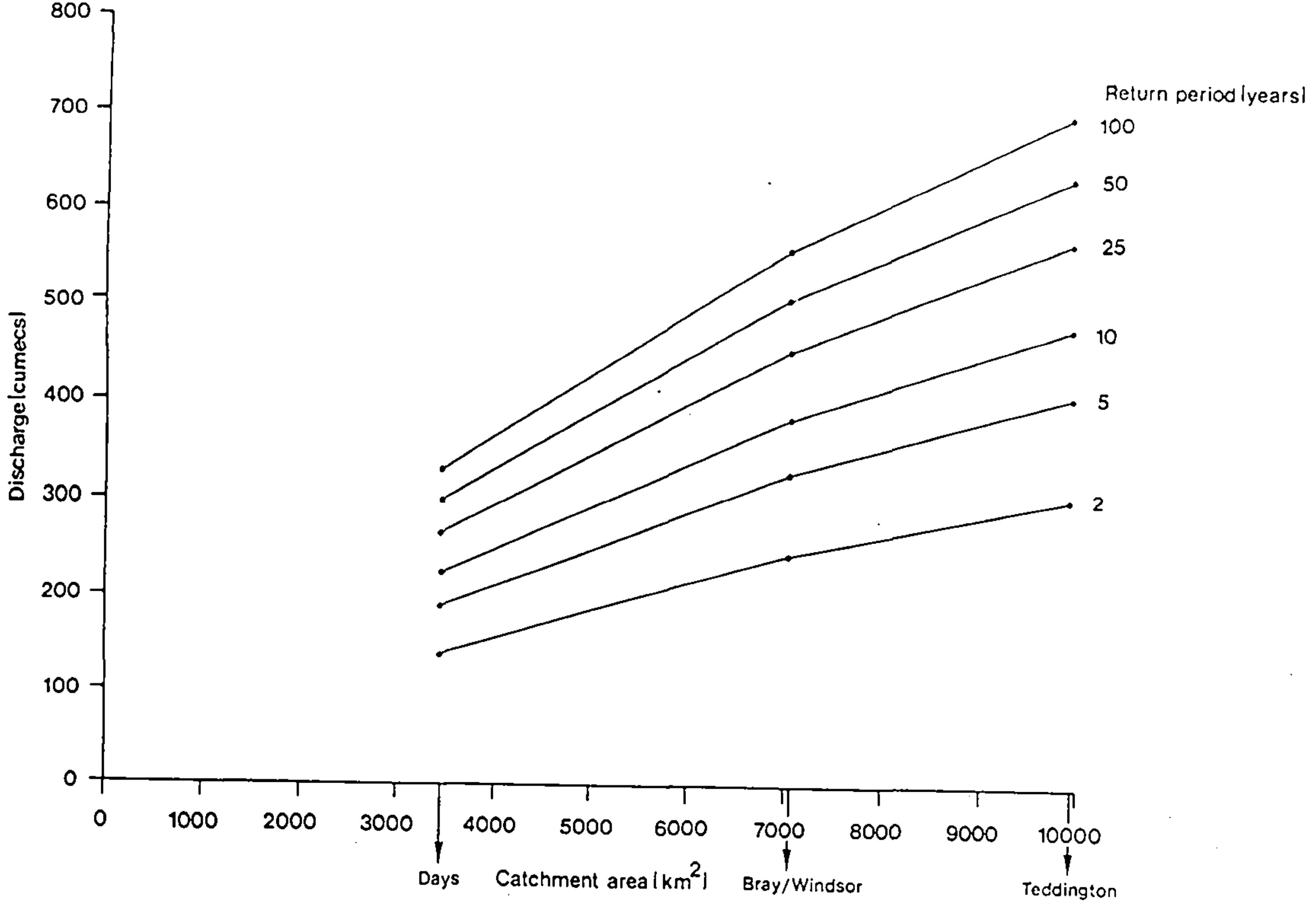


Figure 3.6 Return period flow along the Thames

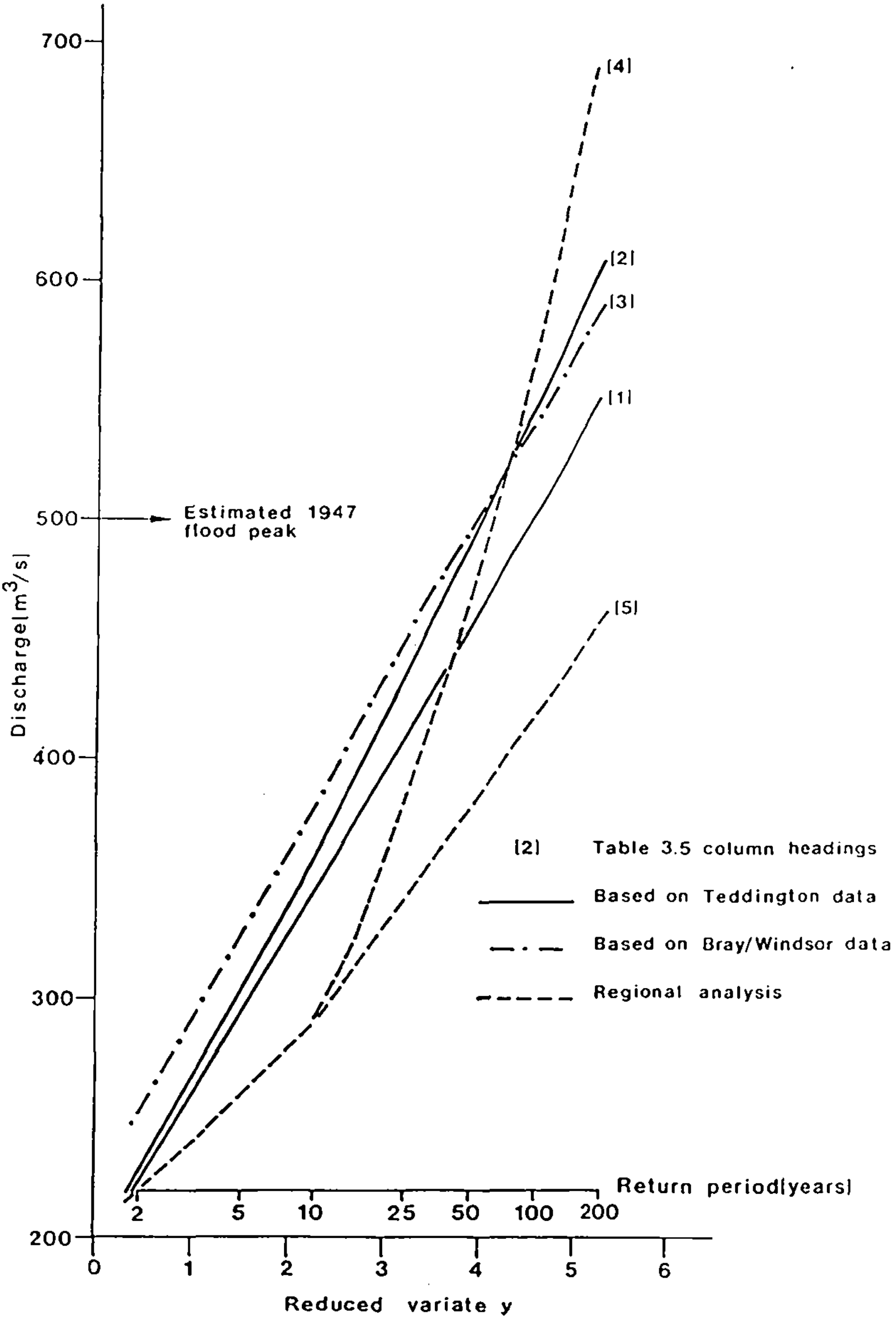


Figure 3.7 Flood frequency data from five estimates for Maidenhead

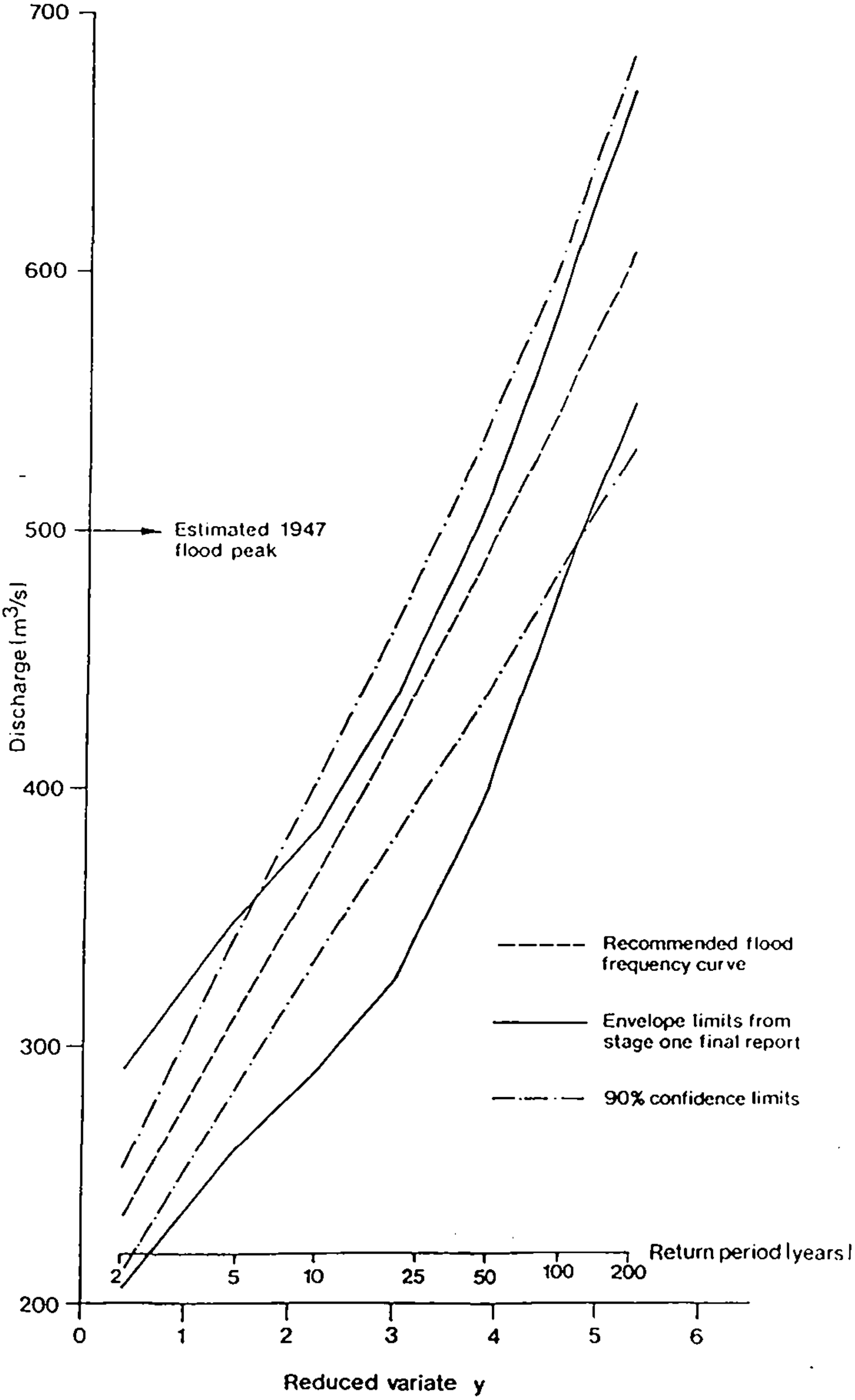


Figure 3.8 Recommended flood frequency curve at Maidenhead

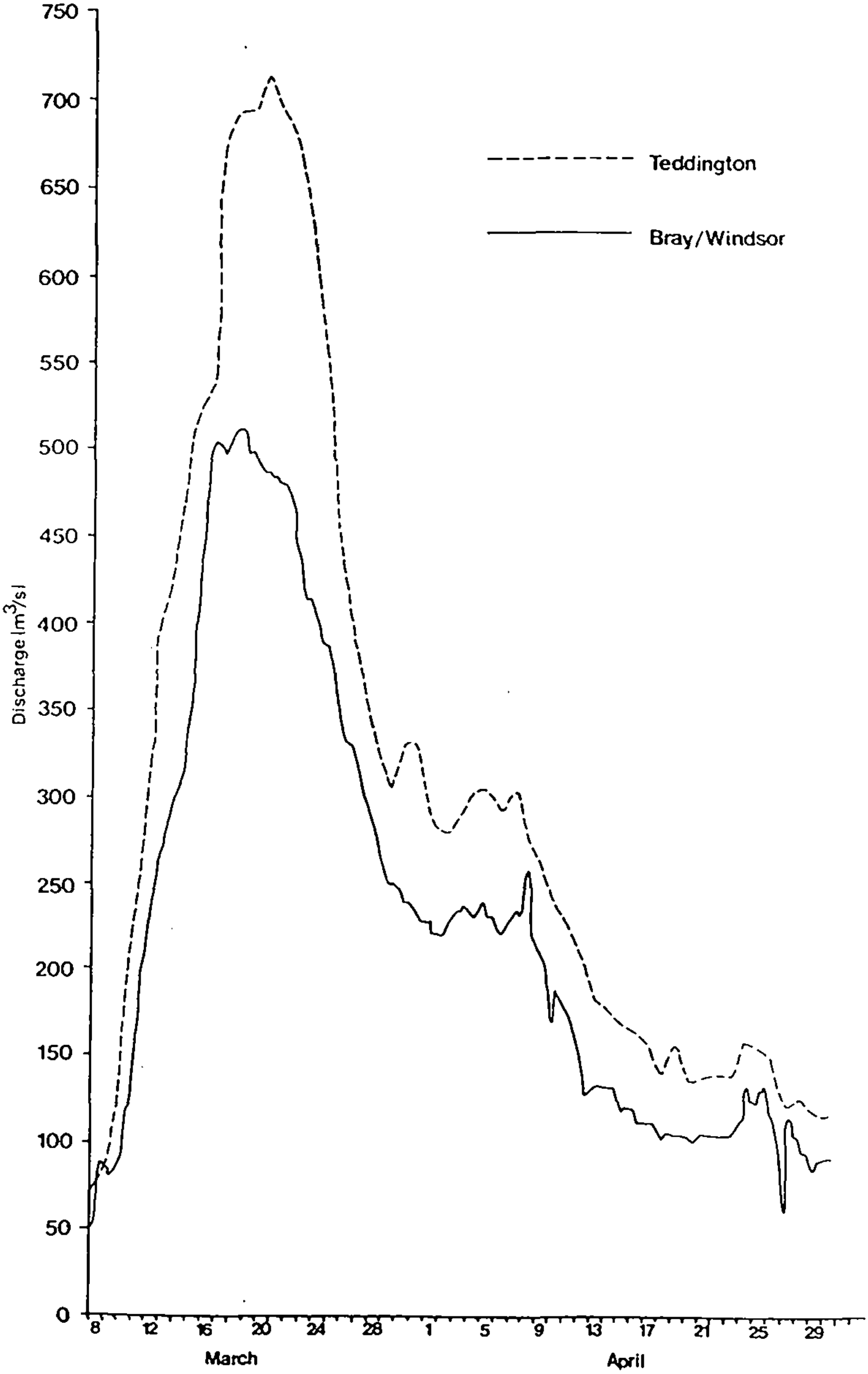
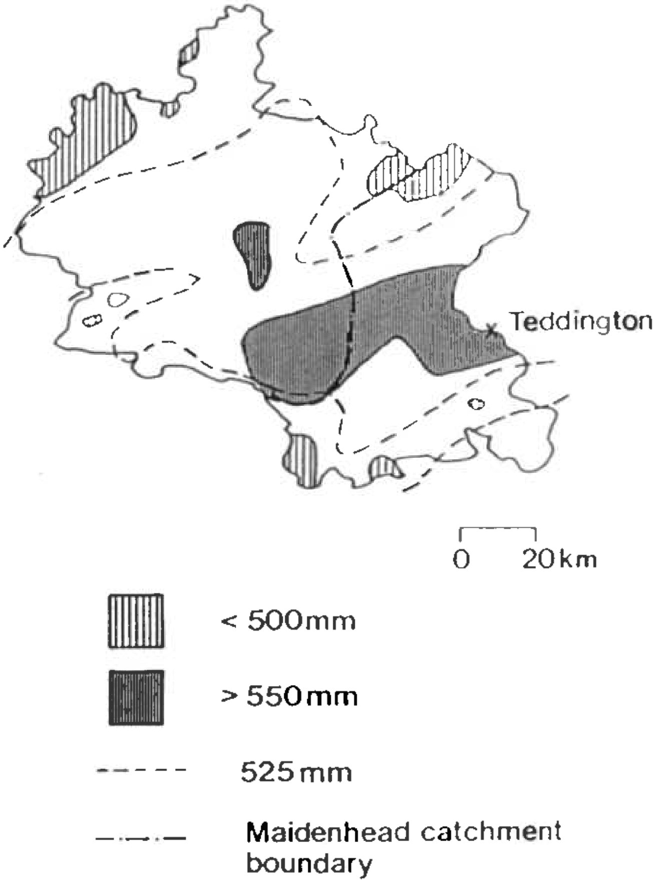


Figure 4.1 1947 flood hydrographs for Bray/Windsor and Teddington

Figure 7.1 Potential evaporation of the Thames catchment above Teddington



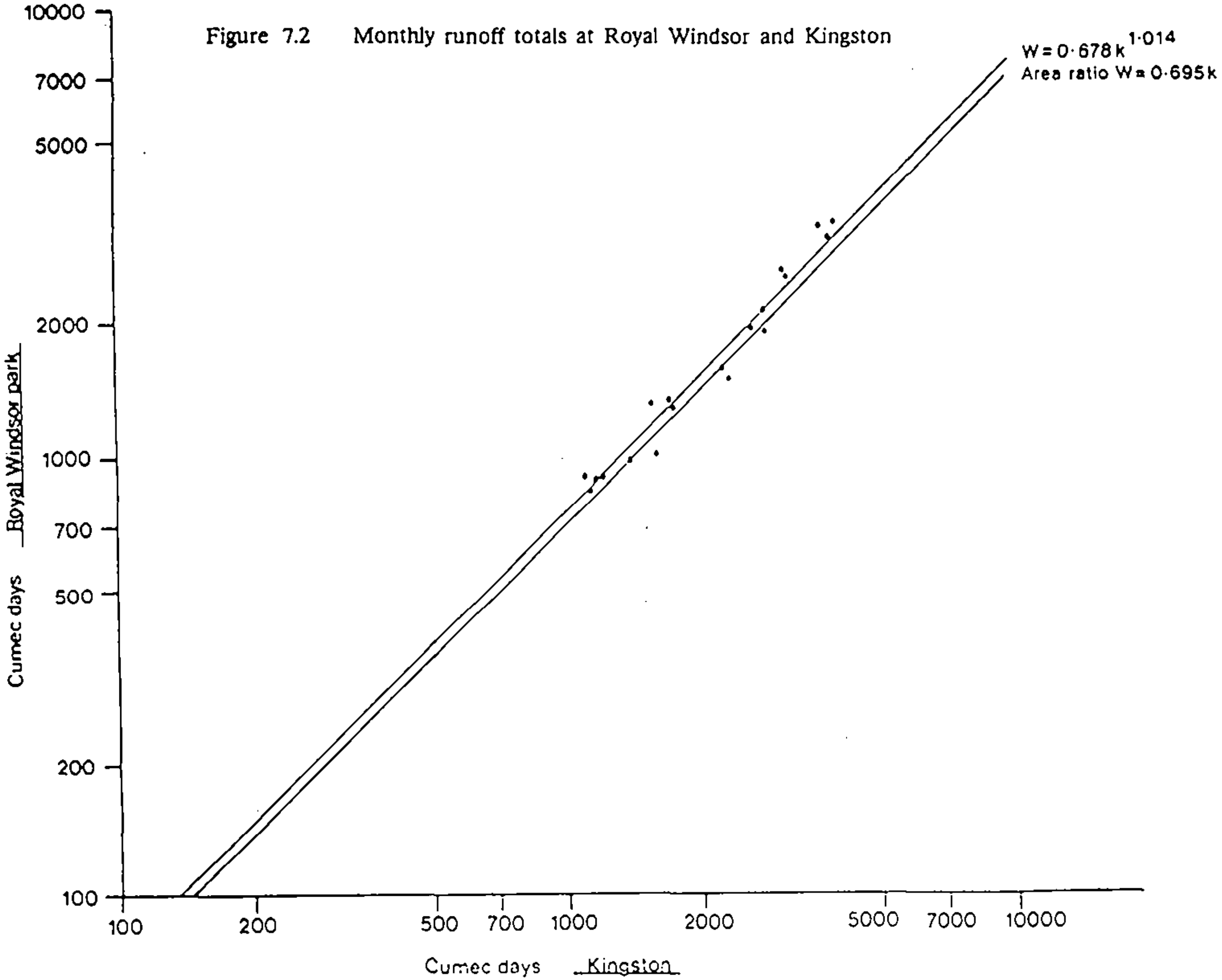
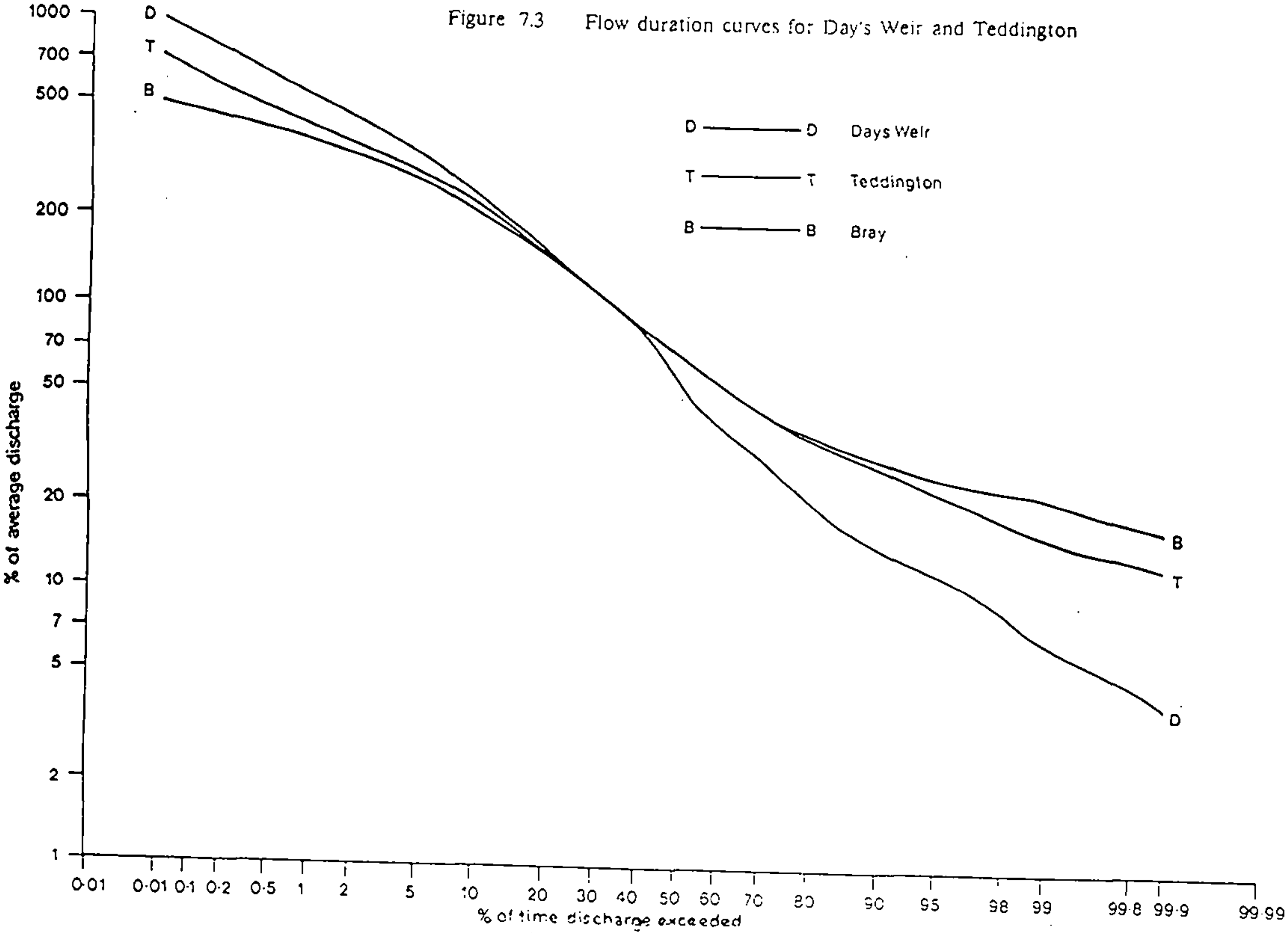


Figure 7.2 Monthly runoff totals at Royal Windsor and Kingston

Figure 7.3 Flow duration curves for Day's Weir and Teddington



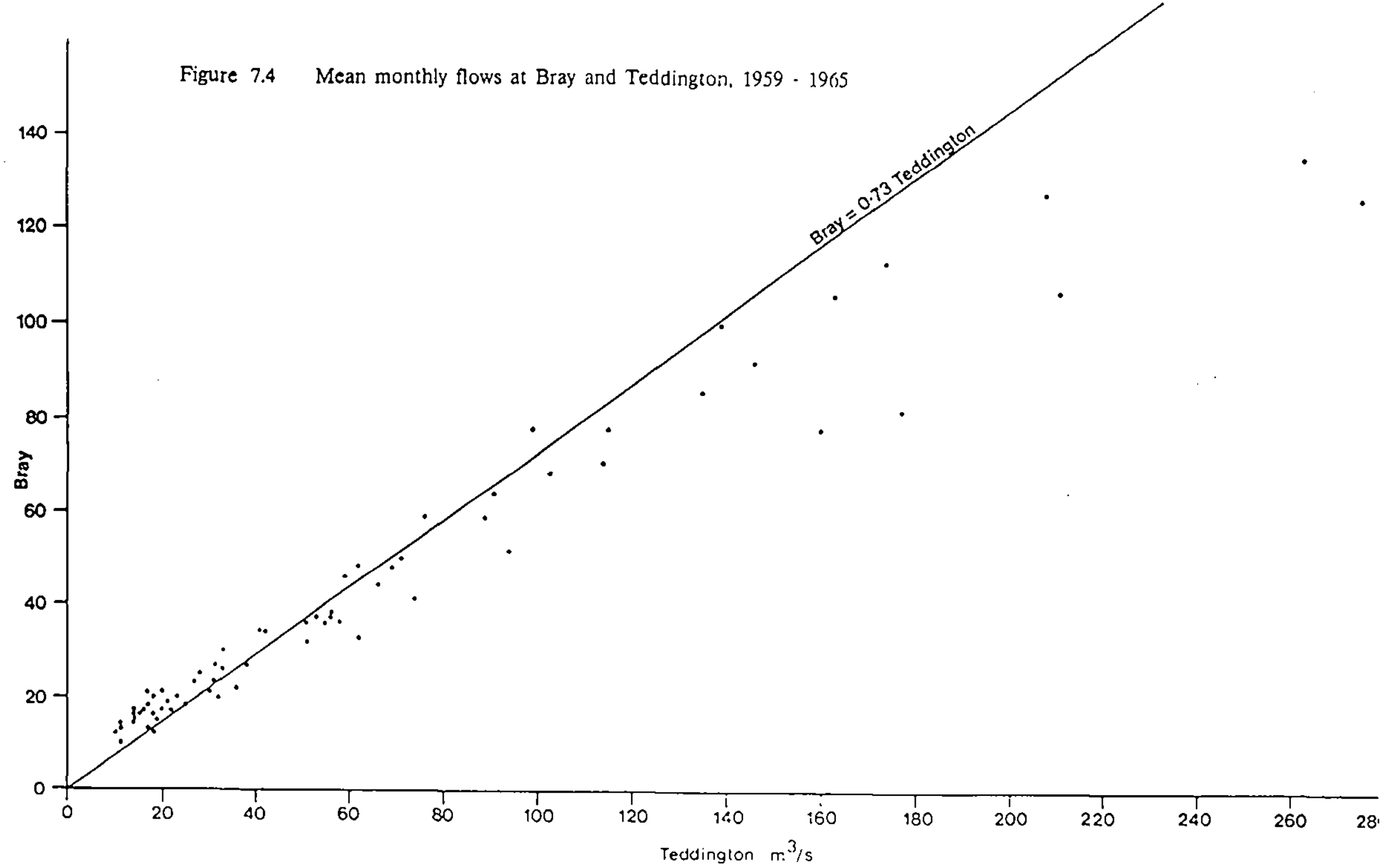
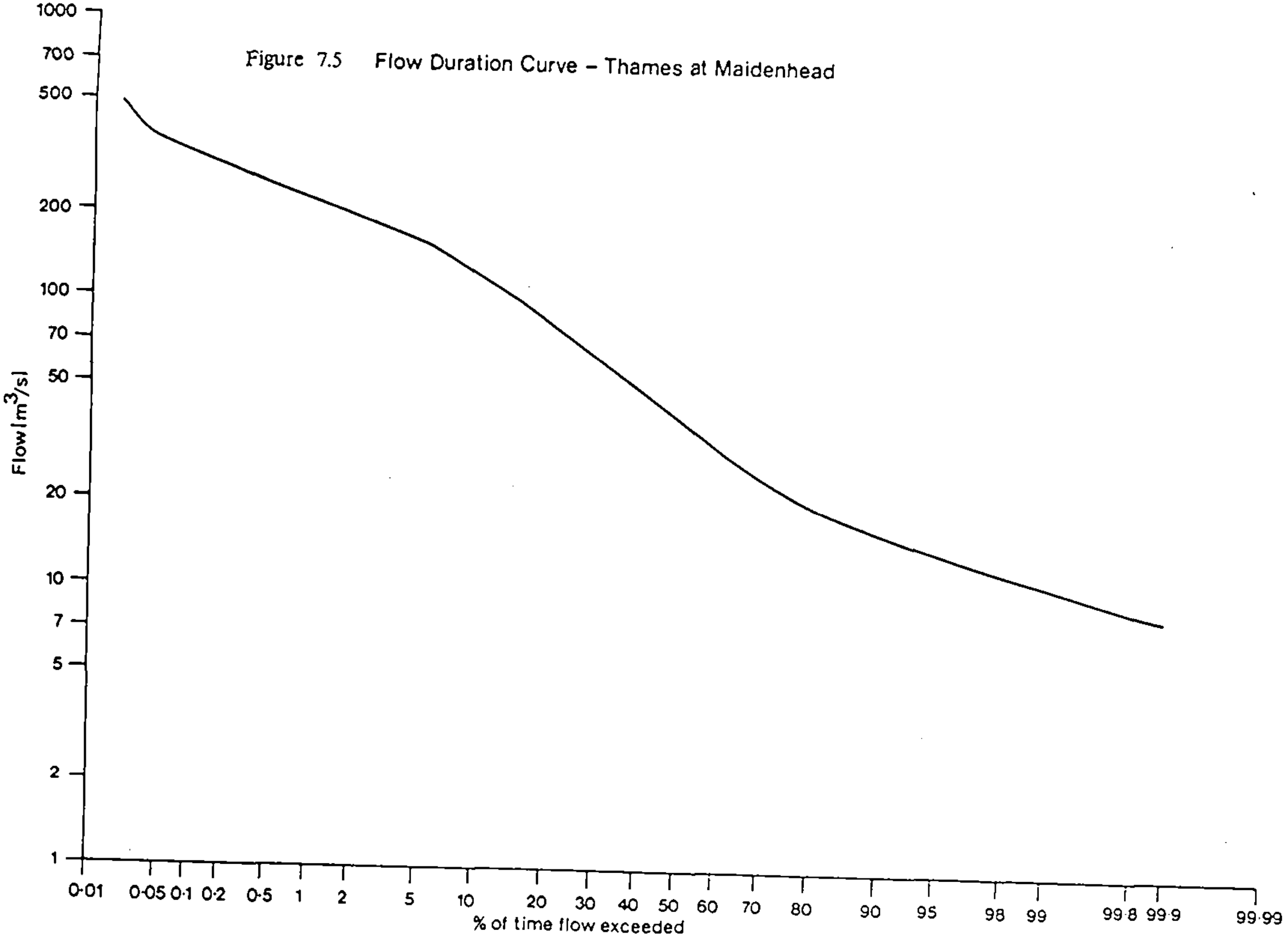


Figure 7.4 Mean monthly flows at Bray and Teddington, 1959 - 1965

Figure 7.5 Flow Duration Curve – Thames at Maidenhead



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