Thames Water

Tidal Thames Defence Levels

Preliminary Report on River Crane Flows and Levels

April 1987

Thames Water

River Thames and Crane Tidal Defence Levels
Preliminary estimate for River Crane

1. INTRODUCTION

1.1 Terms of reference

Thames Water required a rapid assessment of the stage frequency relationship for the tidal Thames at the mouth of the River Crane in order to allow an initial scheme design to proceed. It is emphasised that further work will be done in subsequent stages of the investigation and there may in consequence be some revision to the values presented here especially in the light of joint probabilities of flood flows and high tides and surges.

During the study we were made aware of a second design scenario based upon a fluvial flood in the River Crane catchment coupled with average tidal conditions. In view of an apparent large difference between the design discharge and the maximum observed flood peak at Marsh Farm it was agreed that information on the frequency of high flows in the Crane should be incorporated in this report.

1.2 Summary of conclusions

There is evidence of an increasing trend through time in the annual maximum tide heights. This is most notable at seaward sites however for present purposes a value of 3.0 mm/yr has been adopted for the entire tideway. Comparison of Crane mouth and Richmond tide gauges indicates a 10 cm difference at low and normal tides diminishing to near zero with increasing return period. Section 3 shows the frequency analysis from which it is seen that the estimated 50 year return period tide hight at Crane mouth is 5.50m AOD. This includes a simple allowance for trend (Section 3.4) but does not allow for the effect of barrier operations (Section 3.5) which, at the time of writing, are incompletely known.

The review of Marsh Farm annual maxima described in Section 4 revealed a rising trend due, in this case, to increasing urbanization of the catchment. Table 4.4 shows the outcome of the frequency analysis from which the 50 year return period flood is assessed to be 20.6 m^3/sec under present conditions of development.

2. DATA

2.1 Tidal records

A preliminary review of sources of tidal data has revealed a considerable number of level records along the length of the Thames tideway. Approximate locations are shown on Figure 2.1, and Table 2.1 includes an unconfirmed summary of data availability. For purposes of this preliminary exercise the data that were used consisted of calendar year annual maxima from five sites; Southend, Tilbury, North Woolwich, Tower Pier and Richmond extracted by the Port of London Authority from chart records. The Richmond recorder is 500 m upstream of the Crane mouth and so was particularly relevant to the current study. Individual tidal maxima at Richmond for selected periods since 1980 were noted during a visit to the PLA office.

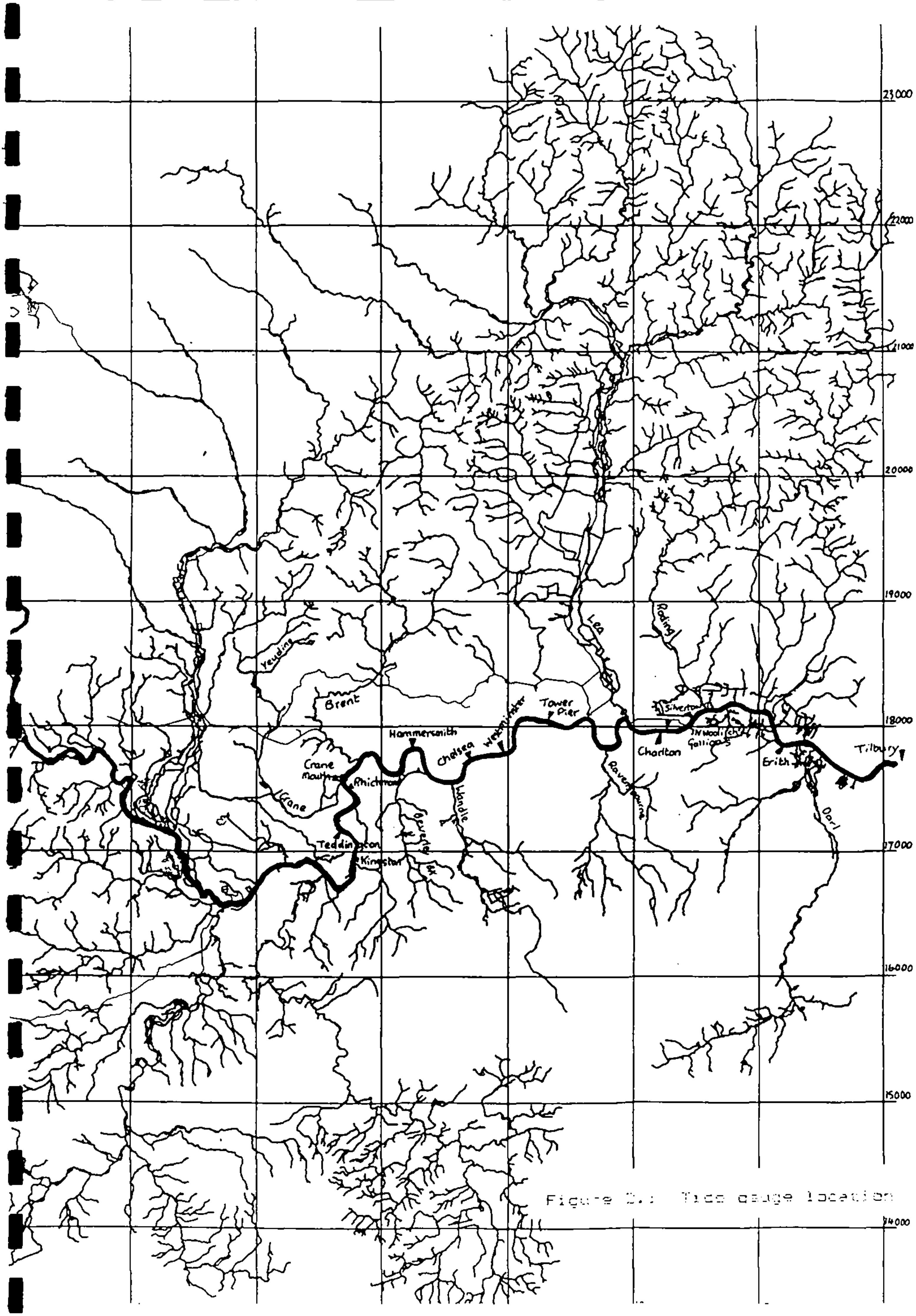


Figure D.1 Tide gauge location

Table 2.1 Primary sources of stage data for Tidal Thames

Station name	Period of record	Type of data	Medium
Richmond	1911-date*	continuous	charts
	1911-date	max and min	manuscript
	1911-date	ammual maxima	manuscript
Crane Mouth (us & ds)	1976-date	continuous	charts
Hammersmith	1954-?	continuous?)	charts(?)
Westminster	?-mid 70s	?	?
Tower Pier	1911-date*	continuous	charts
	1912-date	max and min	manuscript
	1912-date	annual maxima	manuscript
	1928-1983	hourly	digital
Lea barrier	?	continuous	chart
Gallions/	1915-date*	continuous	charts
North Woolwich	1915-date	max and min	manuscript
Royal Albert Dock	1915-date	annual maxima	manuscript
	1951-1974	hourly	digital
Tilbury	1911-date*	continuous	charts
	1911-date	max and min	manuscript
	1913-date	annual maxima	manuscript
	1929-1980	hourly	digital
Southend	1911-date*	continuous	chart
	1911-date	max and min	manuscript
	1911-date	annual maxima	manuscript
	1929-1983	hourly	digital
Sheerness	1874-1952	annual maxima	analysed
	1952-1985#	hourly	digital

* Availability unconfirmed and from multiple sources
\# Discontinuous or sporadic

The recorder at the Crane tide gates has operated since 1976 although charts were unavailable for the period prior to 1981. Five years is insufficient for statistical analysis but the downstream recorder charts were obtained from TWA and used in association with the Richmond tidal maxima to establish an adjustment to be applied to the Richmond long term record and so permit its use for the Crane.

2.2 Discharge data

Table 2.2 shows sources of discharge data for the River Crane. Most attention was paid to the Marsh Farm record which provided Peak over Threshold and Annual Maxima data spanning 46 years based upon the microfilm of the charts held at IH up to 1973, and brought up to date from the charts held at TWA Waltham Cross. From 1939 until May 1978 the available charts were of the direct discharge reading type which incorporates a built-in stage discharge relation. Subsequently a stage recorder was used.

TWA have adopted a WRB recommended formula rating for flow conversion after December 1977. This was based upon BS 3680 for broad crested weirs and appeared not to pay specific regard to Marsh Farm station geometry, the built-in rating, or the check meterings. The formula rating implies a 9 percent reduction in discharge at 0.4 m increasing to a 16 percent reduction at 1m head. Two check current meterings at between .4 and .5 m during 1978 do not indicate any tendency for the Lea rating to overestimate; indeed the measured discharges were 5% and 10% higher than that implied by the inbuilt rating. In view of this it was decided not to use the TWA rating but to use the implied rating built into the Lea recorder charts throughout the period of record.

The earlier (1929-1942) Bedfont station record was considered for use but discarded after inspection of its charts during the three year common period with Marsh Farm. Cranford Park was used only to check the threshold extraction of the Marsh Farm record during the common period.

Table 2.2 Discharge data for the River Crane

River	Station	Grid reference	Catchment area (km^2)	Available data
Crane	Marsh Farm	TQ154734	81.0	1939-date
Crane	Bedfont	TQ108754		1929-1942
Crane	Cranford Park	TQ103778	61.6	1974-date
Yeading W	Ruislip	TQ103859		
Yeading W	Yeading W	TQ084846	17.6	1974-date
Yeading E	Yeading E	TQ112845	9.6	1974-date
Yeading	Brookside Pk	TQ117812		1980-date

2.3 Catchment data

One inch and 1:50000 Ordnance Survey sheets spanning the period from 1920 to date were inspected in order to assess the rate of urbanization. Map sources include the Oxford University Geography Department and Bodleian Libraries (Figure 2.2).

The catchment boundary was obtained from TWA. Soil data were obtained from the Flood Studies Report WRAP map and the 1:250,000 Soil Survey of England and Wales Southern Sheet. Interpretation of the maps indicate that the Crane to Marsh Farm is 49% WRAP class 2 and 51% WRAP class 4.

3. TIDAL ANALYSIS

3.1 General

The preliminary analysis presented here focussed largely on the fitting of statistical distributions to annual maximum tide data, particularly that at Richmond "half-tide" weir. The requirement for an adjustment factor to relate Richmond levels to corresponding values at the Crane Mouth was investigated. Some consideration was given to the trend in the tide levels through time, but only little attention was given to the possible impact of the Thames barrier operation on future high levels.

3.2 Tide statistics

Appendix A is a copy of the annual maximum tide levels obtained from the PLA. Following the practice of the Proudman Oceanographic Laboratory (formerly IOS Bidston) the Generalised Extreme Value (GEV) distribution was fitted to all series (Graff, 1981). Parameters were fitted using the method of Probability Weighted Moments (Hosking et al, 1984). Appendix B presents the results graphically and Table 3.1 shows estuary levels corresponding to particular return periods.

Table 3.1 Quantiles for Thames tidal stations (m AOD)

Return period	Station: Southend	Tilbury	North Woolwich	Tower Pier	Richmond
2	3.53	3.94	4.36	4.60	4.89
5	3.78	4.19	4.61	4.84	5.09
10	3.96	4.37	4.77	4.99	5.20
25	4.21	4.60	4.98	5.16	5.32
50	4.40	4.78	5.13	5.29	5.39
100	4.60	4.96	5.28	5.41	5.46
1000	5.35	5.58	5.77	5.76	5.62

It is notable that at the highest return period there is a reversal of level between North Woolwich and Richmond. This same phenomenon is observed in some individual years of high tide and also is implicit in the tide diagrams prepared by GLC for Hammersmith and Richmond (Appendix C).

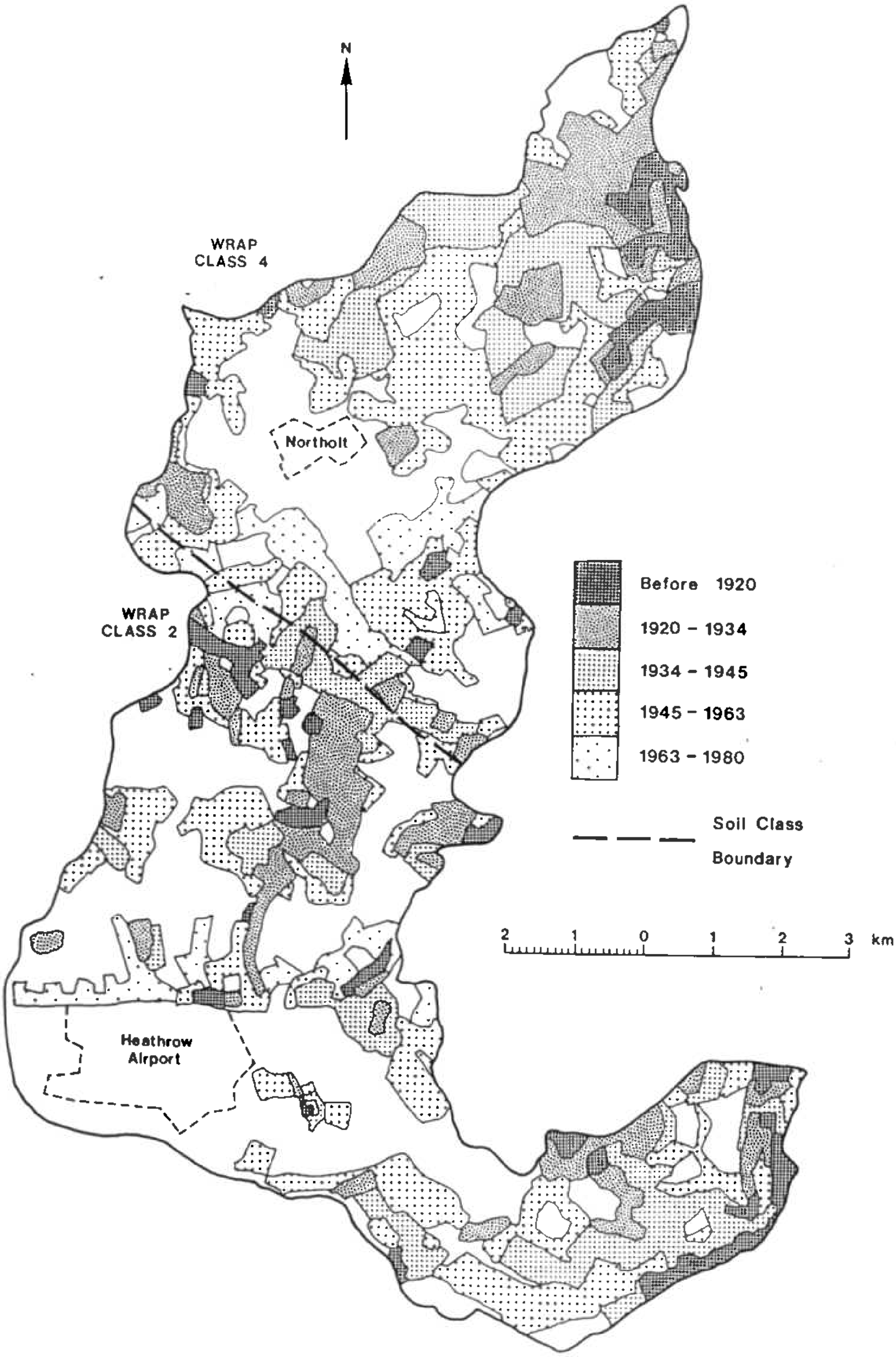


Figure 2.2 Urban development within Crane catchment

3.3 Adjustment to Crane confluence

Richmond is 500 m upstream of the point at which the River Crane emerges into the Thames. Water level charts for the recorder downstream of the Crane pointed doors were obtained from TWA in order to establish a relationship between the two sites. Richmond tidal maxima were noted for January 1981, parts of October, November and December 1982, December 1985 and all of January 1986. Also particular high and low tide events were picked off for 1982 and 1986.

The datum to which the Crane charts are set had not been adequately recorded and it was assumed that the point at which the float appears to "bottom" around slack tide was controlled by the invert of the inlet pipe which in turn was assumed to be set at 1.06 m AOD.

By this device it was found that the difference between the two sites was typically 10 cm although considerable departures from this average value were noted for individual dates. In the level range experienced there was no obvious trend either with Richmond Levels, Teddington discharge or Crane discharge. The highest Richmond level in the common period studied was 4.95 m on 26th December 1985 for which the difference was 3 cm. Such a level is a little higher than the two year return period event as shown on Table 3.1. The evidence taken from days of alleged annual Richmond maxima between 1981 and 1986 give somewhat ambiguous results but overall there is some evidence for a diminishing difference with increasing level.

It is concluded that for "average" and "low" high tide conditions, say less than 4 m at Richmond, the Crane level can be assumed to be 10 cm lower than Richmond levels. (However we recommend that the invert of the inlet pipe is resurveyed in order to check the datum assumption). For a design event within the return period range of Table 3.1 it is sufficient to interpolate linearly between Tower Pier and Richmond assuming that the distance to Crane mouth is 2 percent of the distance to Tower Pier. In practice therefore, and to the cm accuracy quoted on Table 3.1, Richmond values can be applied to Crane mouth without adjustment.

3.4 Trend in water levels

It has been firmly established that there has been an upward trend in the sea level relative to the land around the UK coast and this trend has been most marked in the Thames estuary (Alcock, 1984, Woodworth, 1987). Indeed it was this phenomenon that justified the construction of the Thames Barrier (Horner, 1977). Figure 3.1 shows the annual maxima plotted in time order and exhibits an apparent upward march in annual maximum water level which is most marked at Southend, Tilbury and Woolwich but rather less so at the upstream sites. A simple linear correlation and regression with time shown on Table 3.2 quantifies this same effect.

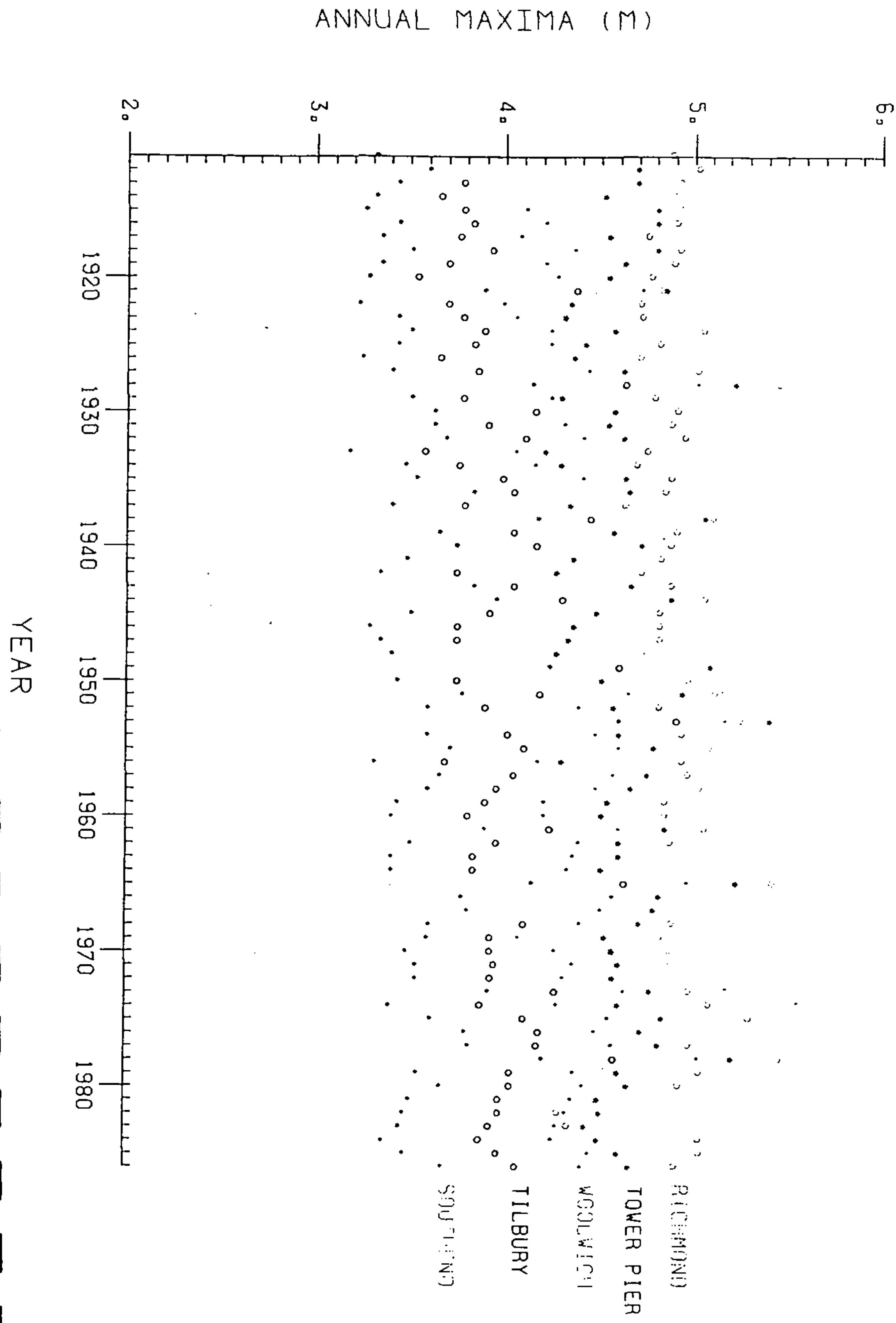


Figure 3.1 Annual maximum tide levels

Table 3.2 Correlation and rise in annual maximum level

	Station				
	Southend	Tilbury	North Woolwich	Tower Pier	Richmond
Correlation coefficient	0.23	0.29	0.26	0.14	0.08
Rate of rise mm/yr	2.86	3.47	2.82	1.58	0.73

Treated as isolated series the trends at the upper sites are not significantly different from zero but can be accepted as real effects in view of the internal consistency between sites and the national trend. The magnitude of the change is somewhat at odds with the 7.6 mm/yr quoted by Horner (1977) but may be in part explained by differences in the site and in the span of data.

Table 3.3 from Woodworth (1987) suggests that the upward trend in mean sea level may have diminished or even temporarily halted in recent years although he recommends that for practical studies this not be adopted but be considered a temporary respite.

Table 3.3 Trend in mean sea level at Sheerness according to Woodworth (1987)

Period	Trend (mm/yr)	
1916-62	3.65	
1936-82	1.01	
1916-82	2.27	
1987	-2.47	(based on quadratic fit)

To explore further the trend in the annual maxima the record was divided into three approximately equal periods and distributions were fitted separately to each. Table 3.4 shows the results for Richmond for the three periods.

Table 3.4 Fitted quantiles for Richmond (m AOD)

Period	Return period - years						
	2	5	10	25	50	100	1000
1911-35	4.86	5.07	5.20	5.36	5.46	5.55	5.82
1936-60	4.90	5.12	5.24	5.38	5.46	5.54	5.73
1961-85	4.94	5.28	5.44	5.60	5.68	5.75	5.89

These values display the expected trend at low return periods but the frequency curve for the most recent 25 years displays a rather different pattern at higher return periods. On closer inspection of the data and frequency curves such as Figure 3.2 it was apparent that this behaviour was due to an attempt to accommodate some very low annual maxima in 1981 to 1983. These values, quoted in Appendix A appear anomalous when compared with other tide stations and also cannot be reconciled with Crane mouth charts. Figure 3.3 shows differences between neighbouring sites plotted as a time series and indicates these and other unexpected features which call for closer scrutiny of the data.

In anticipation of these checks to be carried out after receipt of further tide data it is considered that for the preliminary design case it is advisable to adopt the average frequency curve for the total period augmented by 0.11 m to allow for the long-term trend applied over half the record length; ie a 50 year return period level of 5.50 m.

3.5 Effect of barrier closure

Horner (1977) describes the planned operating rule in terms of a threshold for closure equivalent to the 1965 event. This reached 4.15 m at Southend and 5.24 m at Richmond corresponding on Table 3.1 approximately to a 20 year return period event.

There has been little experience to date of the effect of the barrier operations on the statistical distribution of levels. A plot of Richmond versus Southend annual maxima revealed no tendency towards lower Richmond maxima for given Southend maxima during the most recent years; indeed the proposed threshold of 4.15 m at Southend has not been achieved since the barrier has become operational.

Given the relative proximity of the assumed operating threshold to the estimated 50 year event it is felt that for preliminary design purposes to a 50 year standard there need be no amendment to design conditions for the River Crane due to Thames barrier operations.

4. CRANE DISCHARGE ANALYSIS

4.1 General

This preliminary analysis focussed on the Marsh Farm record to provide an alternative view on the existing design calculations to that based on the "ex-GLC" rainfall runoff model. Consideration has been given to the influence of past, and to a lesser extent, future urbanization on the flood frequency regime. Marsh Farm does not measure the entire runoff of

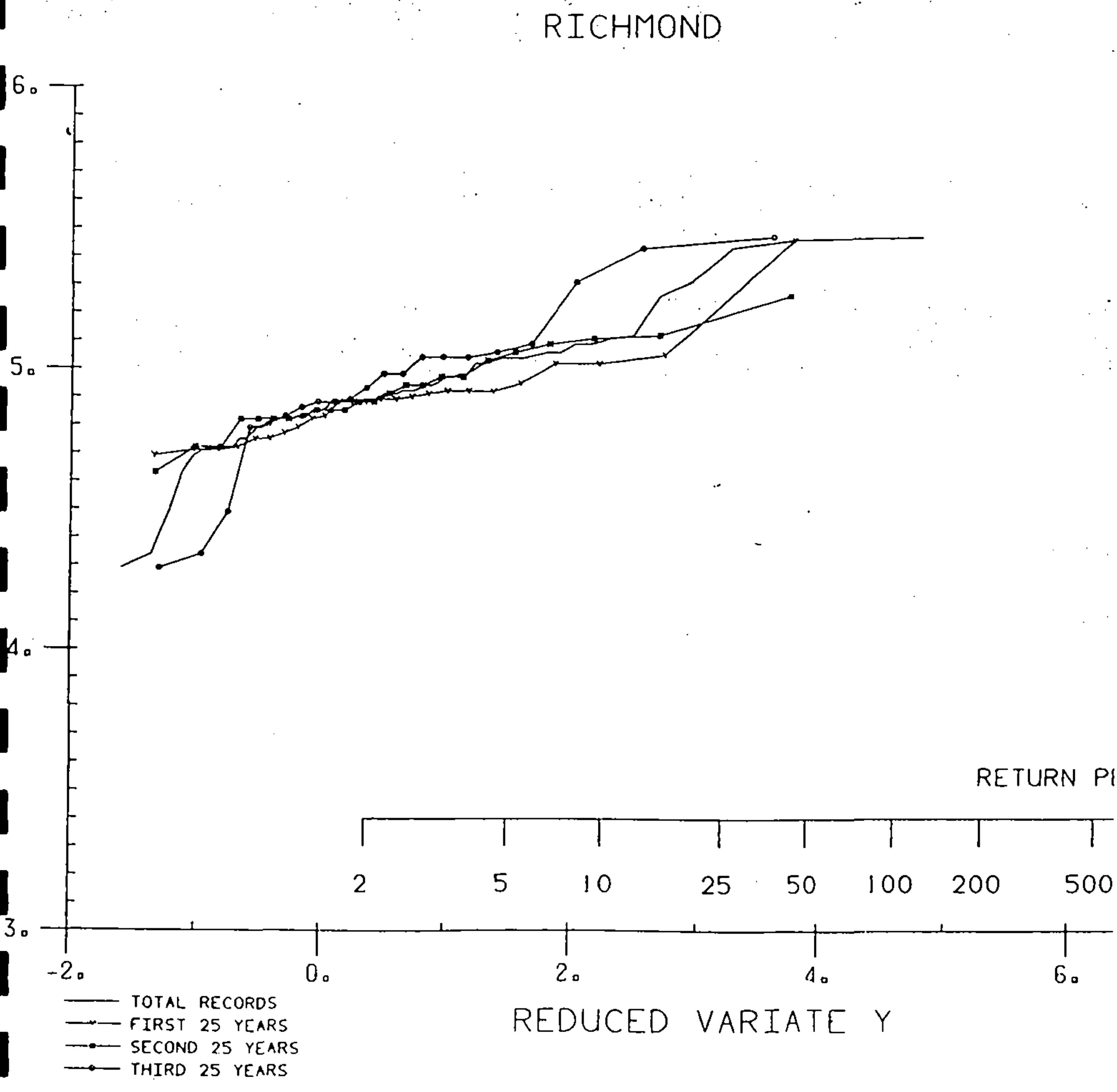
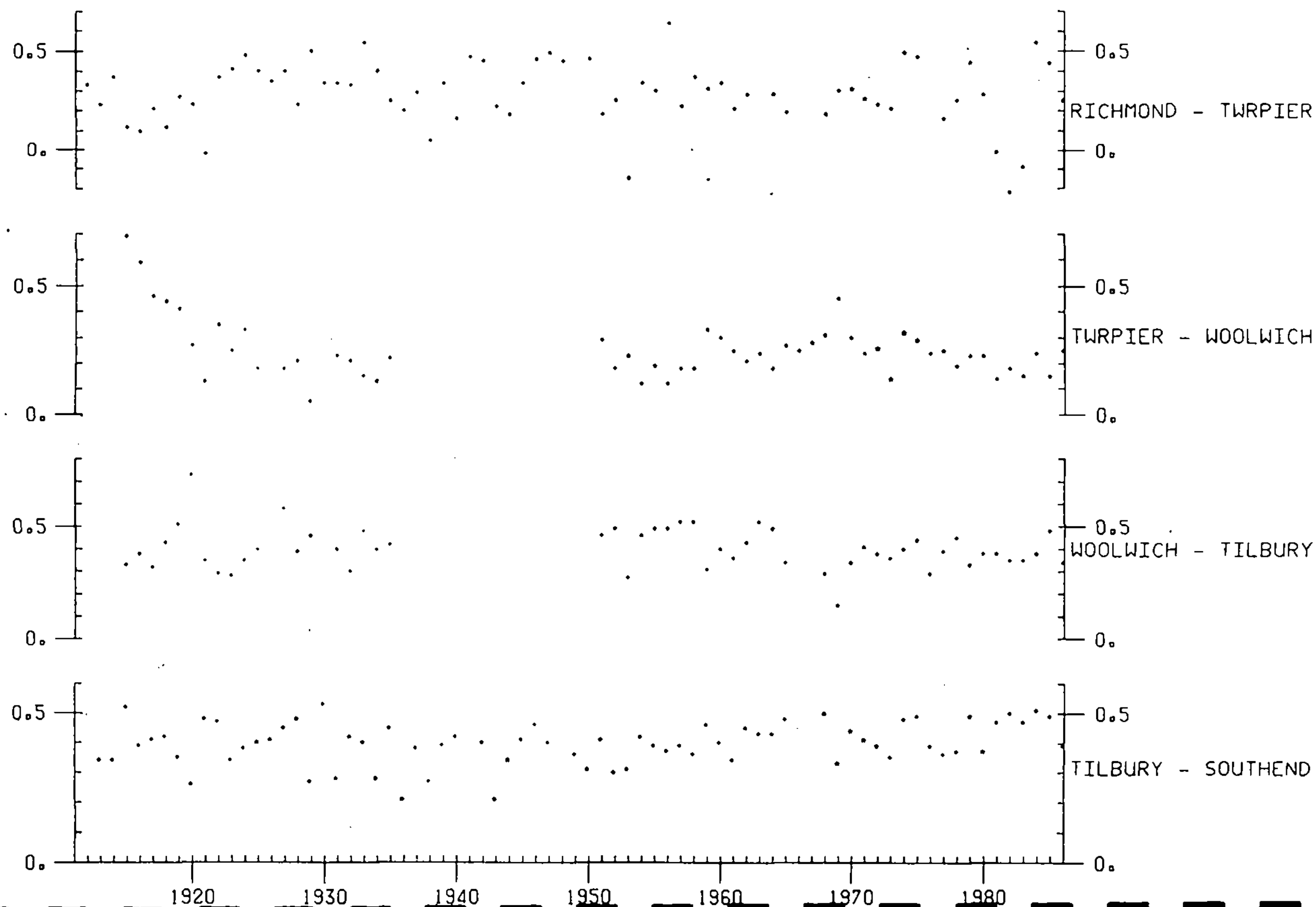


Figure 3.2 Tide level frequency curves for different periods

Figure 3.3 Differences between annual maxima at adjacent gauges



the Crane catchment as there is a diversion to the Duke of Northumberlands River via Mereway sluices. These are set automatically to divert approximately 1 m^3/s from the Crane and the discharge is monitored at Mogden gauging station.

4.2 Statistical analysis

Appendix D shows the annual maximum series for the full period of record and threshold exceedences from 1972. The influence of increasing urbanization is very apparent on the annual maximum data; for example the 1947 flood peak, which was the largest up to that date, was exceeded in 1960 and since 1967 by eight further annual maxima. In such circumstances it is not correct to analyse simultaneously the entire data set from the total period and the lead of Thames Water was followed in selecting for analysis the period after 1972.

Two separate analyses were carried out; the first used exceedences above 7.08 m^3/s (250 cusecs) and the second used annual maxima. Initially the analysis period was taken as 1972 to 1982 to conform to the TWA analysis period. Table 4.1 flood quantiles in m^3/s results compared with those obtained using the FSR POT method and the ex-GLC procedure which is based on a rainfall runoff model. It is notable that the current analysis gives considerably lower values. The reason for the disparity between the two POT based methods is not known but must be: (1) choice of threshold, (2) rating differences, or (3) application of the procedure. Note also that the return periods relate to the exceedance series type and should be increased by approximately .5 years to equate them to the annual maximum based values of later tables and graphs.

Table 4.1 Flood frequency analysis for Marsh Farm 1972-82

	POT return pelrod - years				
	2	5	10	25	50
ex-GLC	13.6	17.9	20.7	24.0	26.9
TWA POT	13.1	15.8	17.9	20.5	22.6
IH POT	11.6	13.9	15.7	18.0	19.8

Subsequently the more recent data were added in order to provide a 15 year record. Table 4.2 and Figure 4.1 show the results of both POT and annual maximum analysis (moments estimate). The two approaches yield very similar results although it must be remembered that the FSR does not recommend the data be treated in this way but rather to make use of the regional flood frequency curve if necessary with allowance for the effect of urbanisation on the shape of the curve. Comparing the values at POT return periods from Table 4.1 and 4.2 indicates that the addition of 4 extra years of data has resulted in a reduction of about 1 m^3/s in estimated flood magnitude.

Figure 4.1 Flood frequency relations for Marsh Farm

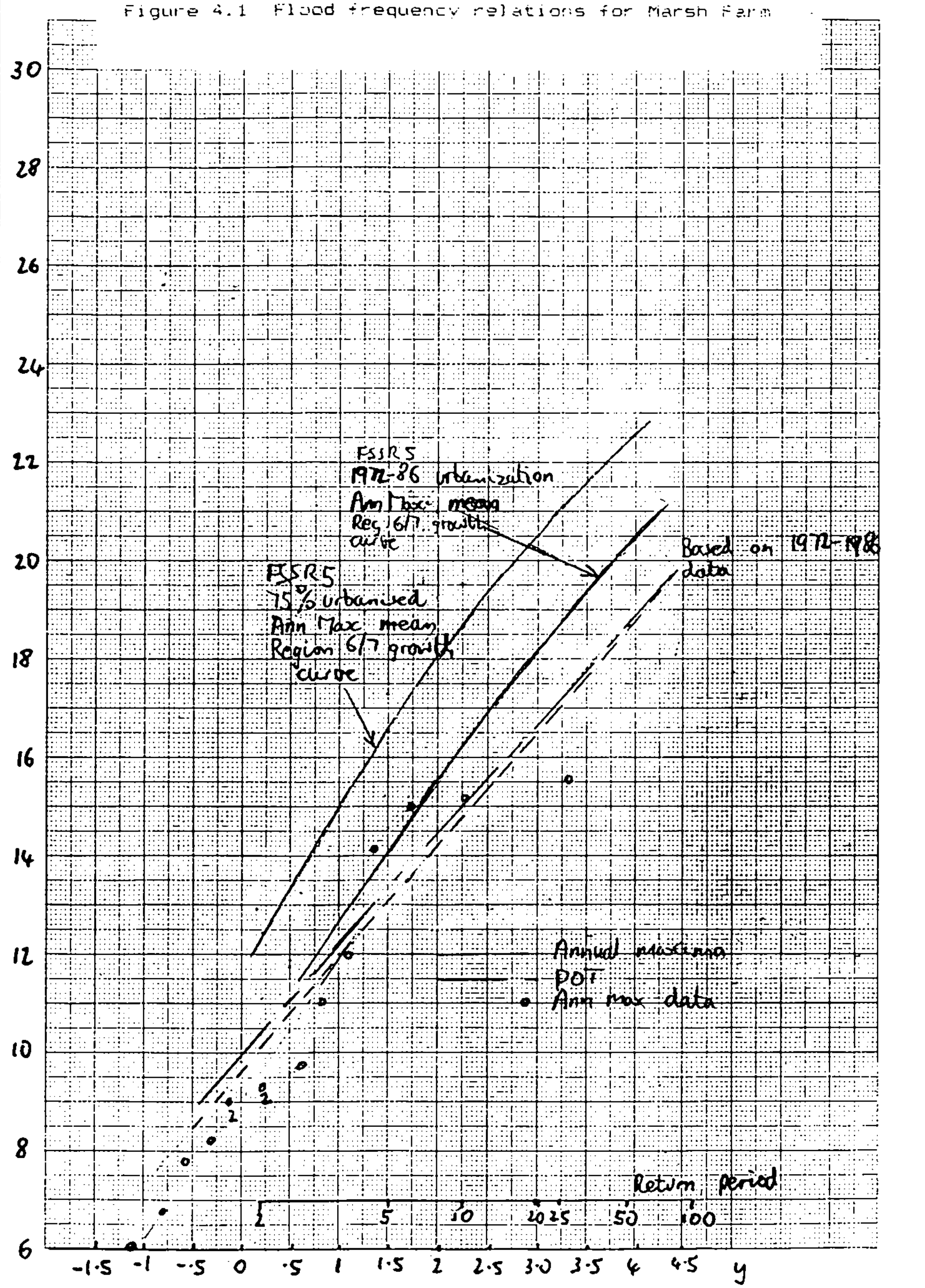


Table 4.2 Flood frequency analysis for Marsh Farm 1972-86

	AM return period - years				
	2	5	10	25	50
IH POT#	11.1	13.3	15.0	17.2	18.8
IH POT*	10.4	13.1	14.9	17.1	18.8
IH Ann Max	10.1	12.8	14.7	17.0	18.7

#POT return period for comparison with Table 4.1
*Annual maximum return period for comparison with IH Ann Max

4.3 Urbanization effect on mean annual flood

The annual maximum data from 1939 were blocked into ten year periods and for each decade the mean annual flood (M.A.F.) was calculated (as the arithmetic average of the annual maxima). Table 4.3 shows the steady increase over time in both flood magnitude and urban percentage.

Table 4.3 Effect of urbanization on Marsh Farm flood maxima

	Decade					
	1940	1950	1960	1970	1980	
M.A.F.	-	6.40	8.28	9.86	10.11	10.39
% urban	14.6	25.9	38.1	49.2	56.6	62.6
adjust	1.3	1.5	1.9	2.2	2.4	2.6

The method of FS Supplementary Report 5 was used to estimate the effect on the mean annual flood of the increase in urbanization. The adjustment factor of Table 4.3 is the predicted ratio from FSSR5 of the mean annual flood for a catchment with the given urban percentage to that for an undeveloped catchment. Over the period shown the agreement with observed values is good with both the measured and predicted increase in mean annual flood over 60 per cent.

4.4 Effect of urbanization on flood frequency

It is known that the effect of urbanization diminishes with increasing flood magnitude. This is reflected in the standard curves presented in FSSR5 for urban catchments. The net effect has been expressed in terms of an equivalent return period. For example the 50 year return period growth factor for a 50 percent urban catchment is equivalent to a 20 year return period flood from an undeveloped catchment. The corresponding value for a 75 percent urbanized catchment is a 15 year return period flood.

The FSSR5 technique combines these return period equivalences with the standard FSR regional growth curves in order to produce revised growth factors for urbanized catchments. Table 4.4 and Figure 4.1 show the estimated flood quantiles in m^3/s for Marsh Farm using as a base line the mean annual flood obtained from the 1972-1986 record. This indicates a somewhat more rapid increase with return period than that suggested by the

15 years of annual maxima although the gradient does decrease with increasing return period. The disparity in the slope arises from the adoption of the south-east region growth curve as the base for the urban adjustment.

Table 4.4 Urbanization effect of flood frequency

	AM return peirod - years				
	2	5	10	25	50
60% urb	10.4	14.1	16.3	18.8	20.6
75% urb	12.4	16.5	18.7	21.1	22.5

The question arises whether the data-base curve should be preferred to the regional curve. The recommended rule is that 25 years of record are required before one would over-ride the regional average curve. The total length of the Marsh Farm record exceeds this threshold although it is not possible to analyse it in its entirety due to heterogeneity. Inspection of the individual decade "slices" would support the use of the data based line, although given the uncertainties which surround the data and its treatment it is advisable to adopt the more conservative upper line which gives rise to a 50 year flood of 20.6 m^3/s under current conditions.

4.5 Future urbanization

A substantial proportion of the catchment thus far undeveloped is around the areas of Heathrow and Northolt airports (Figure 2.2) and this will clearly limit future development. If the urban fraction were to rise from its present value to 75 percent then the adjustment factor would increase the current mean annual flood from its current value to 12.3 m^3/s. Table 4.4 and Figure 4.1 show the revised estimates for this future level of urbanization with an estimated 50 year flood peak of 22.5 m^3/s.

4.6 Effect of Duke of Northumberland River

Water is diverted from the Crane into the Duke of Northumberland River via Mereway Sluice upstream of Marsh Farm gauging station. The structure consists of an automatically rising gate set to maintain diversions out of the Crane to approximately 1 m^3/s. Inspection of the charts at Mogden gauging station reveals periods when the flow exceeds this amount; typically a discharge of 2 m^3/s is experienced each year on at least one occasion. Such occurrences do not appear to coincide with flood maxima on the Crane and it is a possibility that they emanate from the treatment works or from manual operations on Mereway Sluice.

It is recommended that 1 m^3/s is added to all Marsh Farm flow statistics in order to represent catchment flow conditions upstream of the offtake. Of course to the extent that the reach to be improved is downstream of the diversion the unadjusted Marsh Farm data provides an appropriate representation of the flood frequency regime so detailed consideration of the diverted flows are not necessary for this study.

5. CONCLUSIONS AND RECOMMENDATIONS

The preliminary analyses described above encompass two main areas of study, Thames tidal maxima at the mouth of the Crane, and flood discharges within the Crane catchment. In further work it will be necessary to quality control the annual maximum tidal data paying particular regard to datum problems and internal consistency between adjacent recorders. The chart changing routine for the Crane should be improved so that the check gauge reading is written on the chart. The invert level of the inlet pipe should be resurveyed. Precise information is needed regarding the operating rules for the Thames Barrier.

With respect to the flood hydrology of the Crane catchment the source of differences between the POT analyses carried out by IH and TWA should be reconciled and the ex-GLC technique should be reviewed to check the source of bias. Local sources should be tapped to establish the reasons for apparent flood hydrographs in the Mogden record. Further current metering at Marsh Farm is necessary to confirm the rating curve for the station.

6. REFERENCES

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Appendix A Annual Maxima Tide Levels

Highest Recorded Tide in each year

FEET ABOVE NEWLYN DATUM

YEAR	DATE	SOUTHEND	TILBURY	WOOLWICH	LONDON BRIDGE	RICHMOND
1911	12 JAN	10.30	N/R	N/R	N/R	16.00
1912	7 JAN	11.80	N/R	N/R	15.40	16.47
1913	25 JAN	11.30	12.40	N/R	15.40	16.15
1914	15 MAR	10.30 SEPT	12.00	N/R	14.82	16.04
1915		10.70	12.40	13.50	15.75	16.15
1916		11.30	12.67	13.80	15.75	16.07
1917		11.00	12.32	13.40	14.90	15.57
1918		11.50	12.90	14.32	15.75	16.15
1919		11.00	12.15	13.80	15.15	16.04
1920		10.75	11.60	14.00	14.90	15.65
1921	1 NOV	12.75	14.35	15.48	15.90	16.86
1922	21 OCT	10.60 (8 JAN / 21 OCT)	13.15	13.10	14.23	15.44
1923	13 SEPT / 11 OCT	11.80	12.40	13.32	14.15	9 DEC 15.50
1924	28 DEC ~~[illegible]~~	11.50 ~~[illegible]~~	12.75 ~~[illegible]~~	13.90 ~~[illegible]~~	15.00 ~~13.85~~	16.57 ~~[illegible]~~
1925	30 JAN	11.30	12.60	13.90	14.50	15.82
1926	23 OCT	10.67	12.00	N/R	14.32	15.44
1927	26 DEC	11.20	12.65	14.67	15.17	16.48
1928	6 JAN	13.60	15.20	16.48	17.15	17.90 *
1929		11.50	12.40	13.90	14.07	15.70
1930	8 NOV	11.90	13.65	N/R	15.00	16.10
1931	28 DEC	11.90	12.82	14.15	14.90	16.00
1932	27 NOV	12.10	13.48	14.48	15.15	16.25
1933	13 APR	10.42	11.75	13.32	13.82	15.57
1934	18 JAN	11.42	12.33	13.65	14.07	15.40
1935	6 FEB	11.60	13.08	14.48	15.20	16.00
1936	1 DEC	12.60	13.30	—	15.25	15.90
1937	20 NOV	11.20	12.42	—	14.25	15.20
1938	12 FEB	13.70	14.60	—	16.60	16.75
1939	9 MAR	12.00	13.30	—	15.00	16.10 (18 OCT / 3 JAN) 16.00
1940	3 NOV	12.30	13.67	—	15.50	16.00
1941	21 OCT	11.45	N/R	—	14.30	15.83 * JUNE

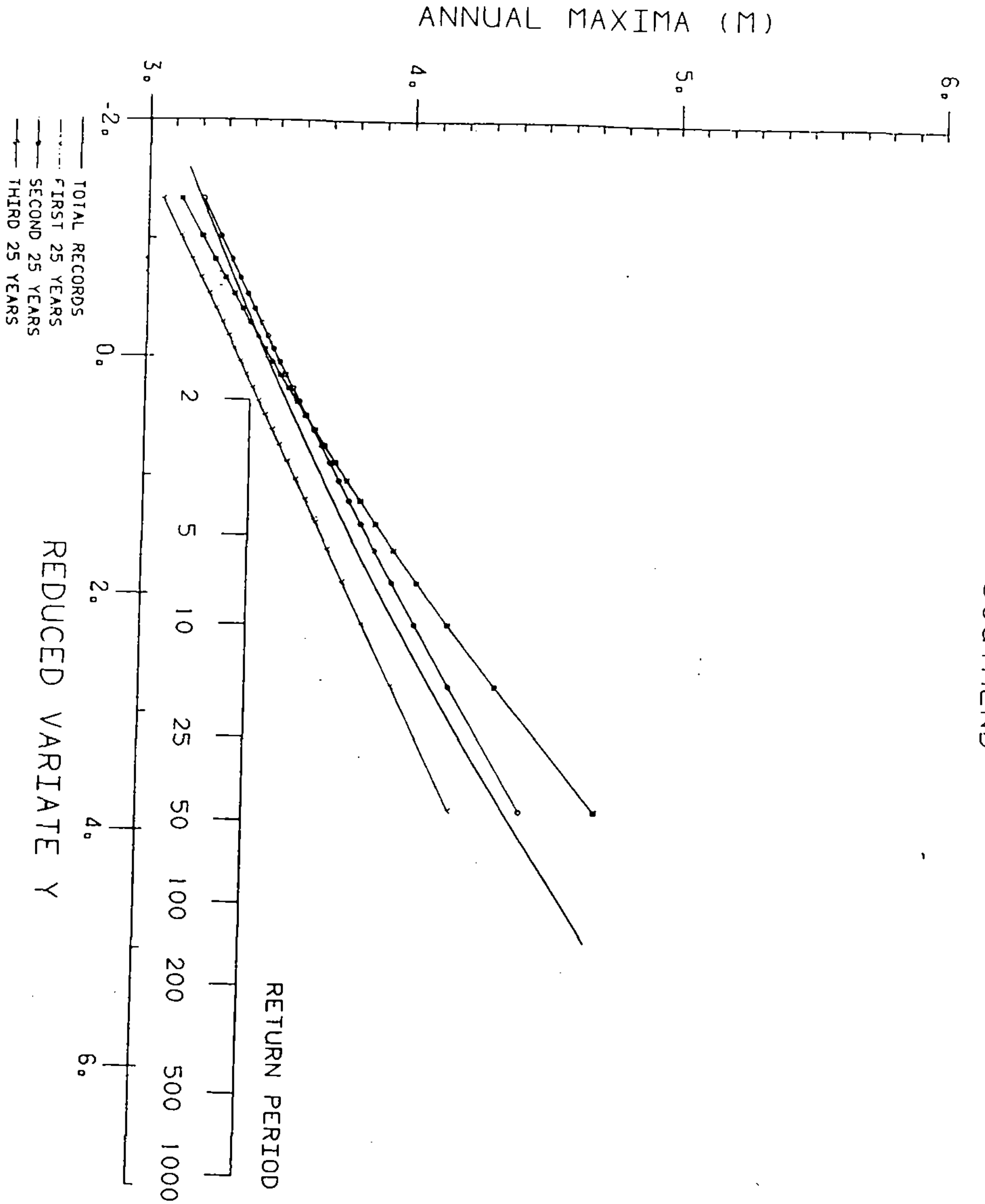
YEAR	DAT…
1942	2 AP…
1943	8 AP…
1944	26 JA…
1945	17 JA…
1946	5 AP…
1947	13 NO…
1948	4 OC…
1949	1 MA…
1950	6 FE…
1951	28 A…
1952	3 DE…
1953	31 JA…
1954	AP… / 4 MA…
1955	11 JA…
1956	6 OC…
1957	26 SE…
1958	14 OC…
1959	3 DE… / 31 DE…
1960	1 JA…
1961	21 MA…
1962	5 AP… / 8 FE…
1963	26 MA… / 3 NO…
1964	24 OC…
1965	10 DE…
1966	16 SE…
1967	5 OC…
1968	21 DE…
1969	29 SE…
1970	19 OC…
1971	1 FE…
1972	24 OC…
1973	14 DE…

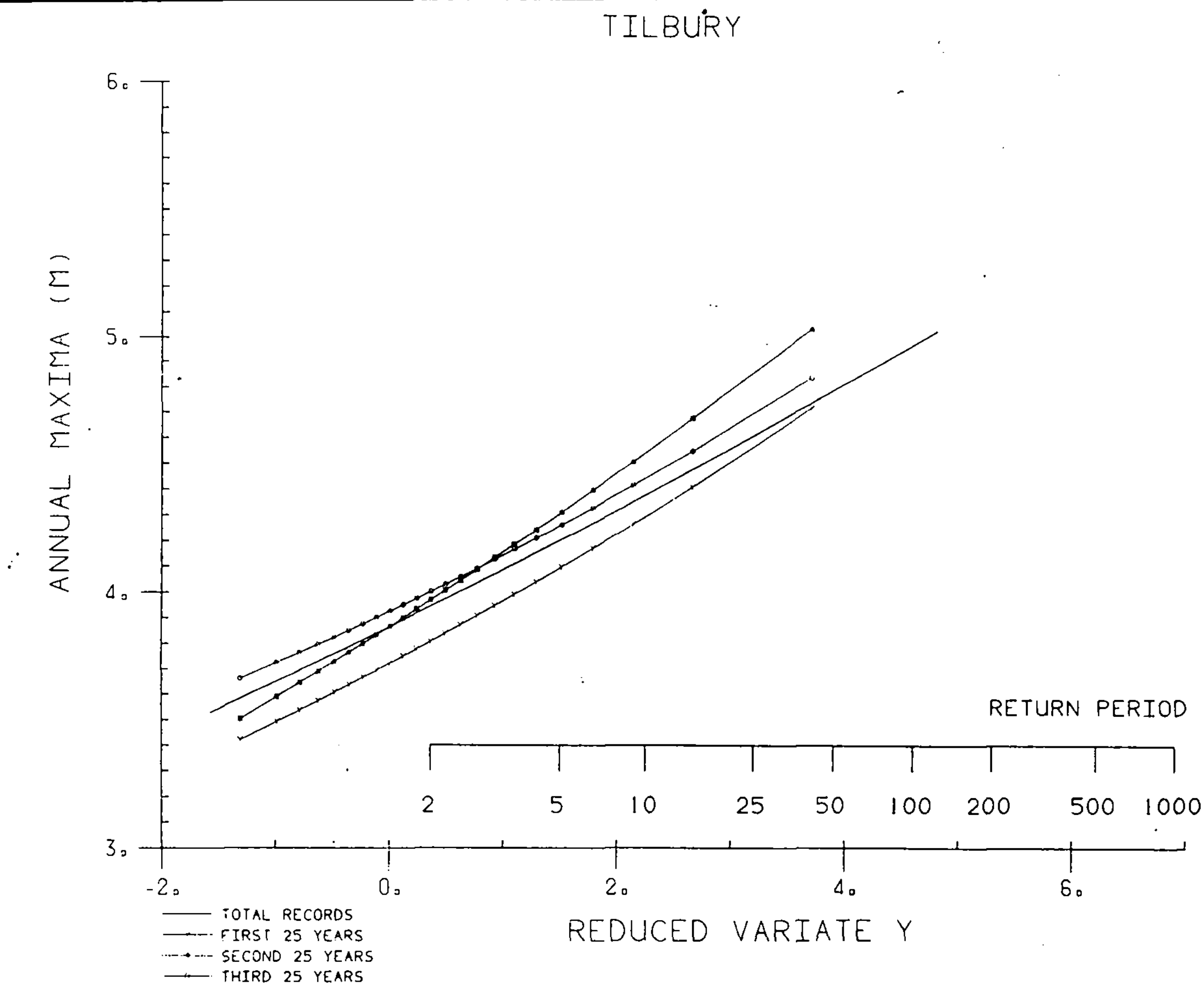
Richmond	Year	Date	Southend	Tilbury	Woolwich	London Bridge	Richmond
	1942	2 APR	11.00	12.30	–	14.00	15.50
15.00	1943	8 APR	12.60	13.30	–	15.30	16.00
16.47	1944	26 JAN	13.00	14.10	–	16.00	16.60
16.15	1945	17 JAN	11.50	12.85	–	14.70	15.80 20 DEC 15.75 17 JAN
16.04	1946	5 APR	10.80	12.30	–	14.30	15.80 6 MAR
16.15	1947	13 NOV	11.00 10.90	12.30	–	20 MAR 14.20 AM/PM	20 MAR 15.80
16.07	1948	4 OCT	11.80	N/R	–	14.0 8 AUG 13.95	15.50 8 AUG
15.57	1949	1 MAR	13.90	15.10	–	16.70	N/R
16.15	1950	6 FEB	11.30	12.30	–	14.80	16.30
16.04	1951	28 NOV	12.40	13.75	15.25	16.20	16.80
15.65	1952	3 DEC	11.80	12.80	14.40	15.00	15.80
15.86	1953	31 JAN	15.10	16.10	17.00	17.75	17.25
15.44	1954	APR 4 MAR	11.80	13.20	14.70	15.10 4 APR 12 NOV	12 NOV 16.20
9 DEC 15.50	1955	11 JAN	12.20	13.60	15.10	15.70	16.70
16.57 ~~15.20~~	1956	6 OCT	10.90	12.10	6 SEP 13.70	31 JAN 14.10 6 SEP 14.00	31 JAN 16.20
15.82	1957	26 SEPT	12.00	13.30	15.00	15.60	16.30
15.44	1958	14 OCT	11.80	13.00	14.70	15.30	16.50
16.48	1959	3 DEC 31 DEC	11.30	3 DEC 12.80	13.80	14.90	15.90
17.90 *	1960	1 JAN	11.20	12.50	13.80	14.80	15.90
15.70	1961	21 MAR	12.80	13.90	15.10	15.90	16.60
16.10	1962	5 APR 8 FEB	11.50	8 FEB 13.00	8 FEB 14.40	8 FEB 15.10	8 FEB 16.00
16.00	1963	26 MAR 3 NOV	11.20	26 MAR 12.60	14.30	26 MAR 15.10	N/R
16.25	1964	24 OCT	11.20	13 MAY 12.60	14.20 13 MAY	13 MAY 14.80	13 MAY 15.70
15.57	1965	10 DEC	13.60 4.15	15.20 4.62	16.30 4.97	17.20 5.24	17.83
15.40	1966	16 SEP	12.40 3.78	N/R	15.00 4.57	15.80 4.82	N/R
16.00	1967	5 OCT	12.50 3.81	N/R	14.80 4.51	15.70 4.79	N/R
15.90	1968	21 DEC	11.85 3.61	13.50 4.11	14.45 4.40	15.45 4.71	16.05
15.20	1969	29 SEPT	11.80 3.60	12.90 3.93	13.40 4.08	14.85 4.53 FEB 20	15.85 FEB 19-20
16.75 16.10 15 OCT 30 NOV	1970	19 OCT	11.45 3.49	{ 12.90 APR 3.93 { 12.50	{ 14.00 APR 4.27 { 13.70 4.18	{ 15.00 APR 4.57 { 14.40 4.39	{ 16.00 APR 6 { 15.45
16.00	1971	1 FEB	11.60 3.54	12.95 3.95	14.30 4.36	15.1 4.60	15.95
16.00	1972	24 OCT	11.60 3.54	12.90 3.93	14.15 4.31	15.0 4.57	15.75
15.83 8 JUNE	1973	14 DEC	12.85 3.92	14.00 4.27	15.20 4.63	15.65 4.77	16.35

Highest Recorded Tide in each year

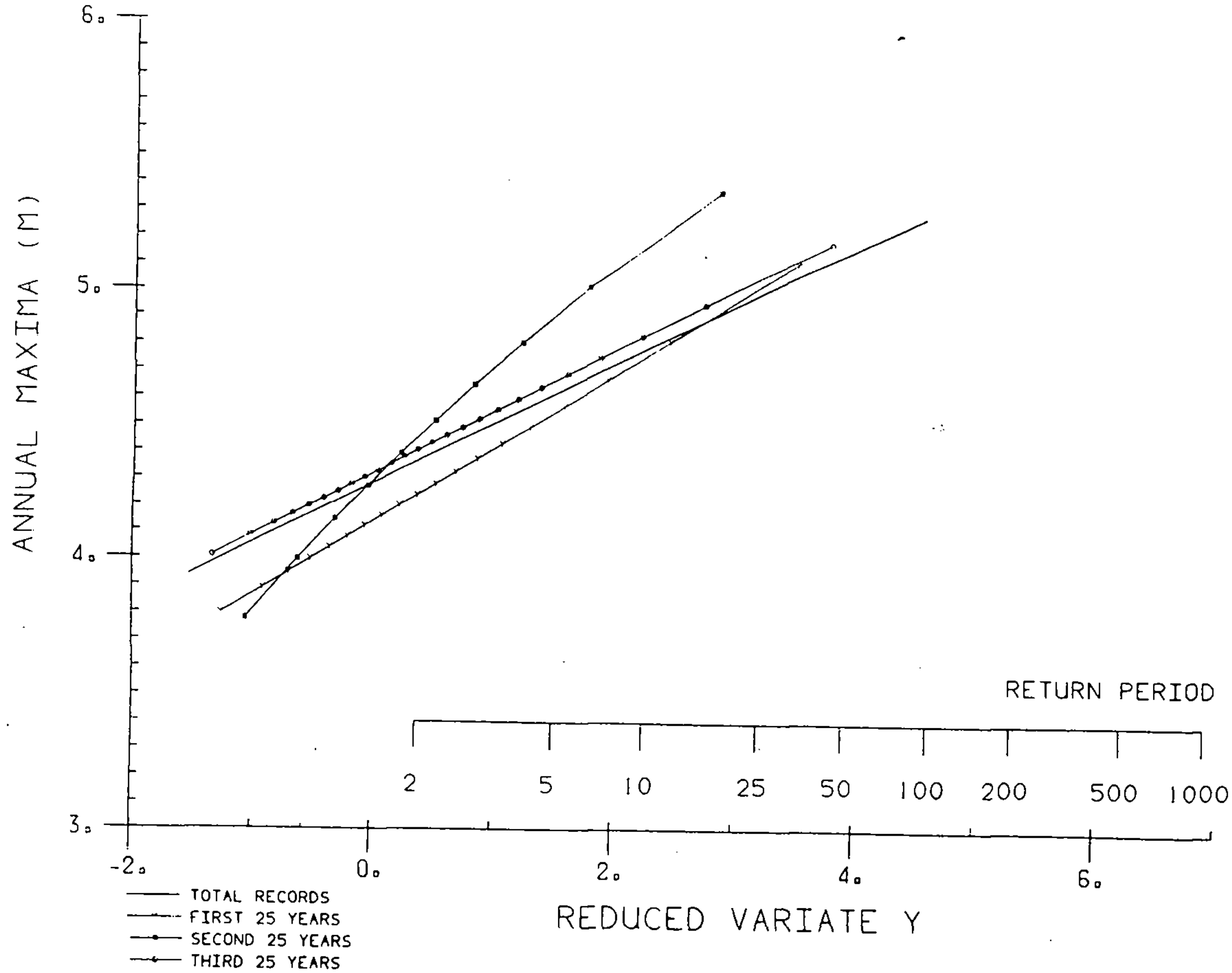
FEET ABOVE NEWLYN DATUM

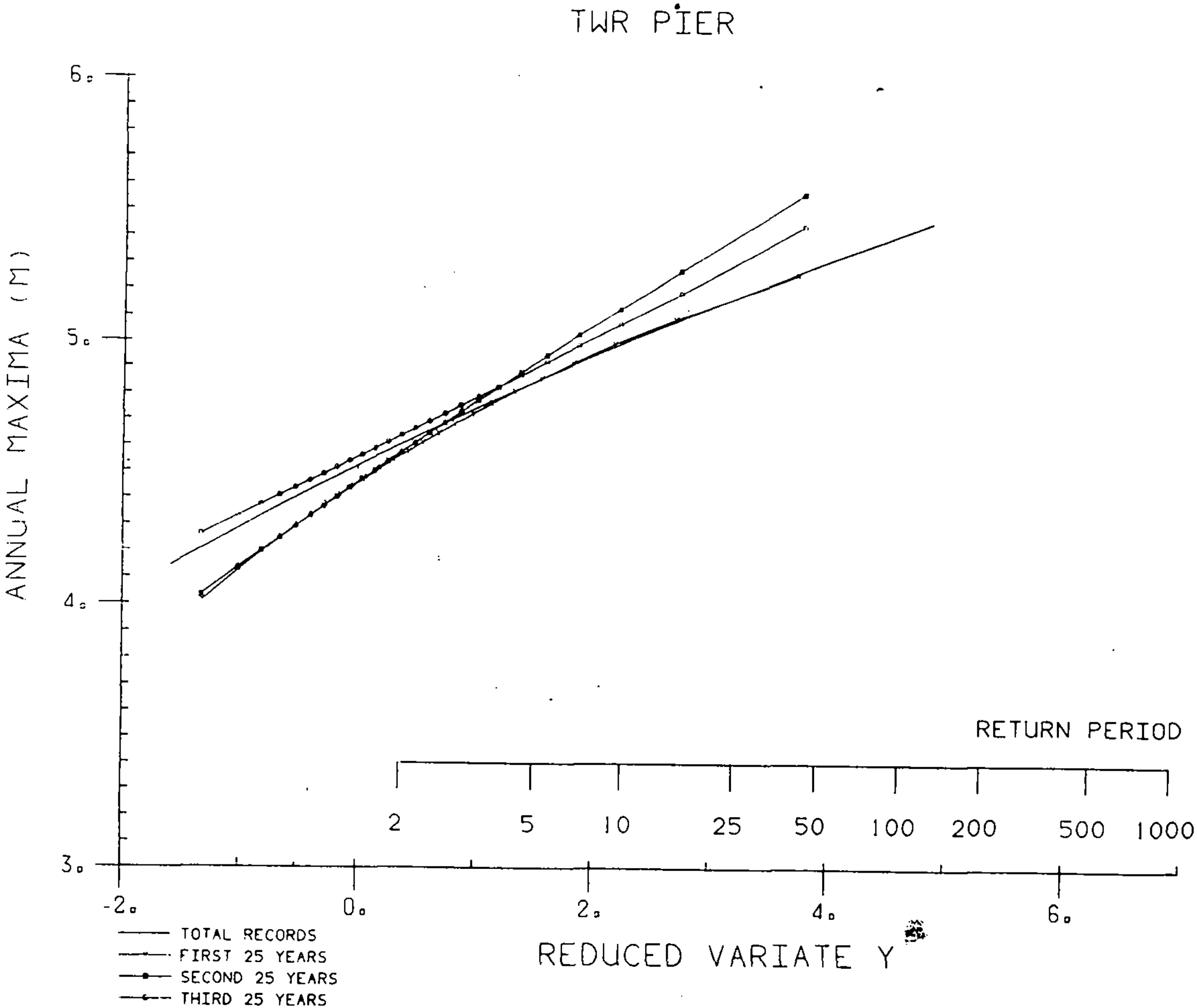
YEAR	DATE	2·40 SOUTHEND	3·12 TILBURY	3·35 WOOLWICH	LONDON 3·20 BRIDGE	·061 RICHMOND	2·16 WALTON	2·50 MARGATE	TEDDINGTON	
1974	18 SEPT	11·17	12·72	14 03	12 FEB 15·09	12 FEB 16·70				
1975	29 JAN	11·89	13·50	14·92	15·88	17·42				
1976	22 JAN	12·48	13·75	14·70	15·49					
1977	13 NOV	12·53	13·70	14·99	15·81	16·34				
1978	31 DEC	13·81 7·11	15·03 7·10	16·50 8·38	17·12 8·42	17·95 *				
1979	2 FEB	11·65 (6·45)	13·25 7·16	14·34 7·72	14·99 7·77	16·53 (ODN) 5·04				
1980	25 OCT	12·04 [illegible] 6·69	13·25 7·16	14·50 7·77	15·26 7·85	16·17 (ODN) 4·93	8·66 4·80	9·55 5·66	16·47 (ODN) 5·02	
1981	15 DEC	11·52 (6·41)	1306 (7·10)	14·30 (7·71)	14·76	1673 (5·10)	8·66 (4·89)	9·19 (5·39)		
1982	11 JAN	3·48 11/1 8/4	3·98 11/1 8/4	4·33 11/1	4·51 4·57 11/1	4·29 11/1	2·72 8/4	3·15 27/3		METRIC
1983	FEB 28	3·46	3·93	4·28	4·43	4·34 5/3	2·36	NB Poss 23/2		METRIC
1984	NOV. 22-23/24	3·37 22/1	3·88 23/1	4·26 23/1	4·50 24/1	5·04 24/1	2·59	2·68 23/1	5·16 24/1	
1985	APRIL 6/7	3·48	3·97 6/4 7/4	4·45 7/4	4·60 7/4	5·04 9/3	2·55 6/4	2·66 9/4		
1986		3·68 18/1	4·07 2/1	4·41 2/1	4·66 2/11	4·91 2/1	3·37 22/1	2·83 2/11		


SOUTHEND
ANNUAL MAXIMA (M)
3.
4.
5.
6.
REDUCED VARIATE Y
-2.
0.
2.
4.
6.
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
TOTAL RECORDS
FIRST 25 YEARS
SECOND 25 YEARS
THIRD 25 YEARS

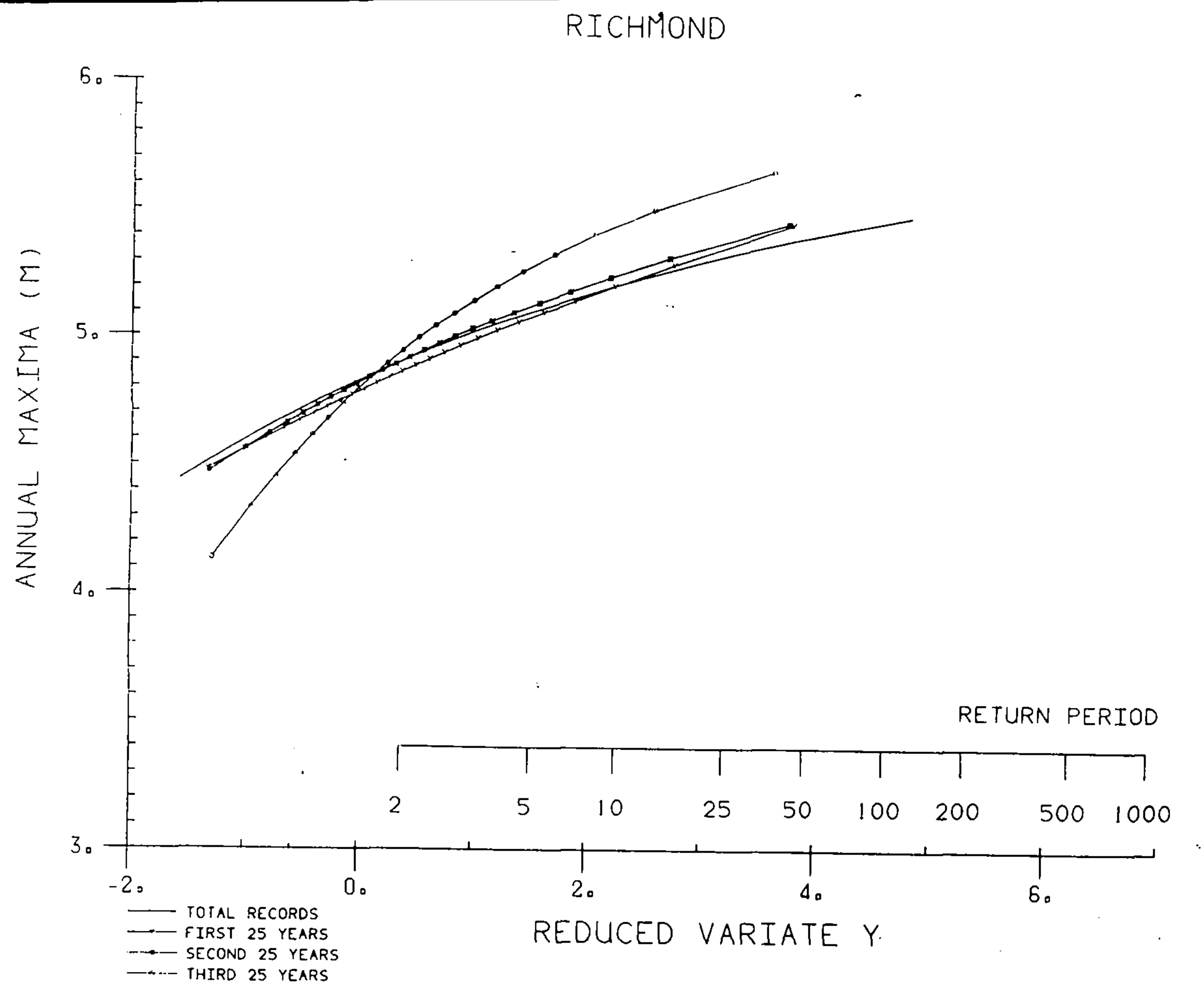

TILBURY
ANNUAL MAXIMA (M)
6.
5.
4.
3.
-2.
0.
2.
4.
6.
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
REDUCED VARIATE Y
TOTAL RECORDS
FIRST 25 YEARS
SECOND 25 YEARS
THIRD 25 YEARS

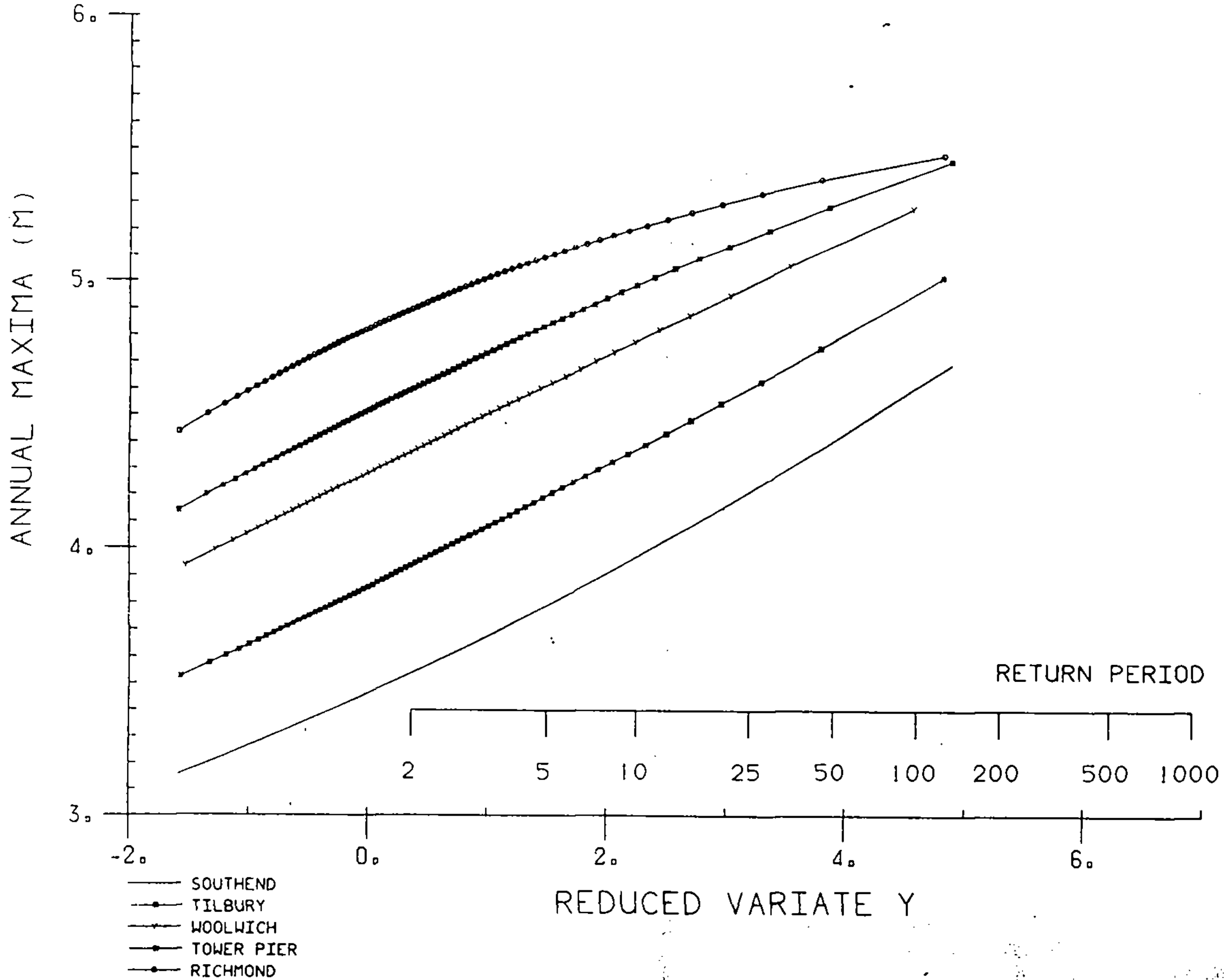
WOOLWICH

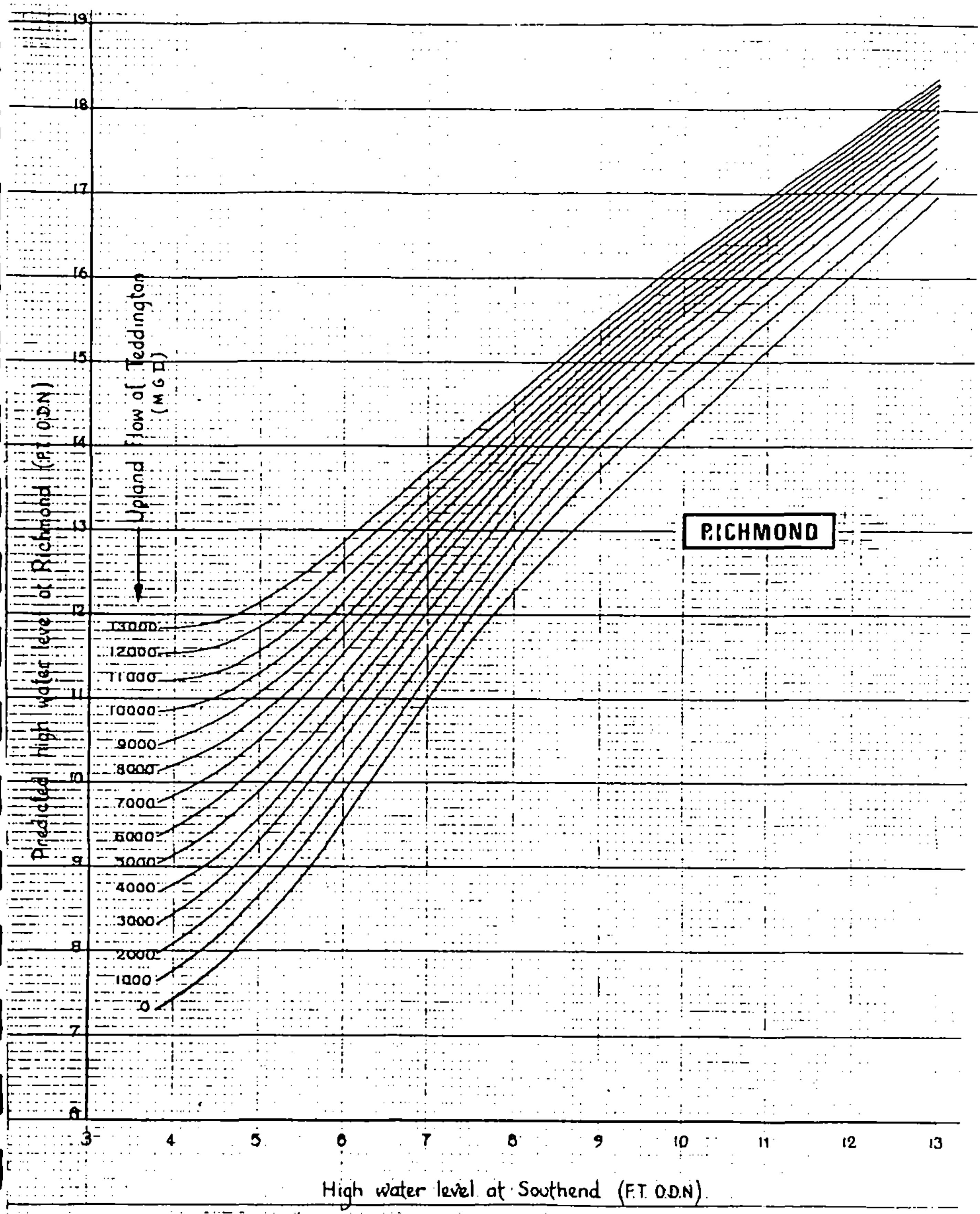

6.
5.
4.
3.
ANNUAL MAXIMA (M)
-2.
0.
2.
4.
6.
REDUCED VARIATE Y
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
TOTAL RECORDS
FIRST 25 YEARS
SECOND 25 YEARS
THIRD 25 YEARS



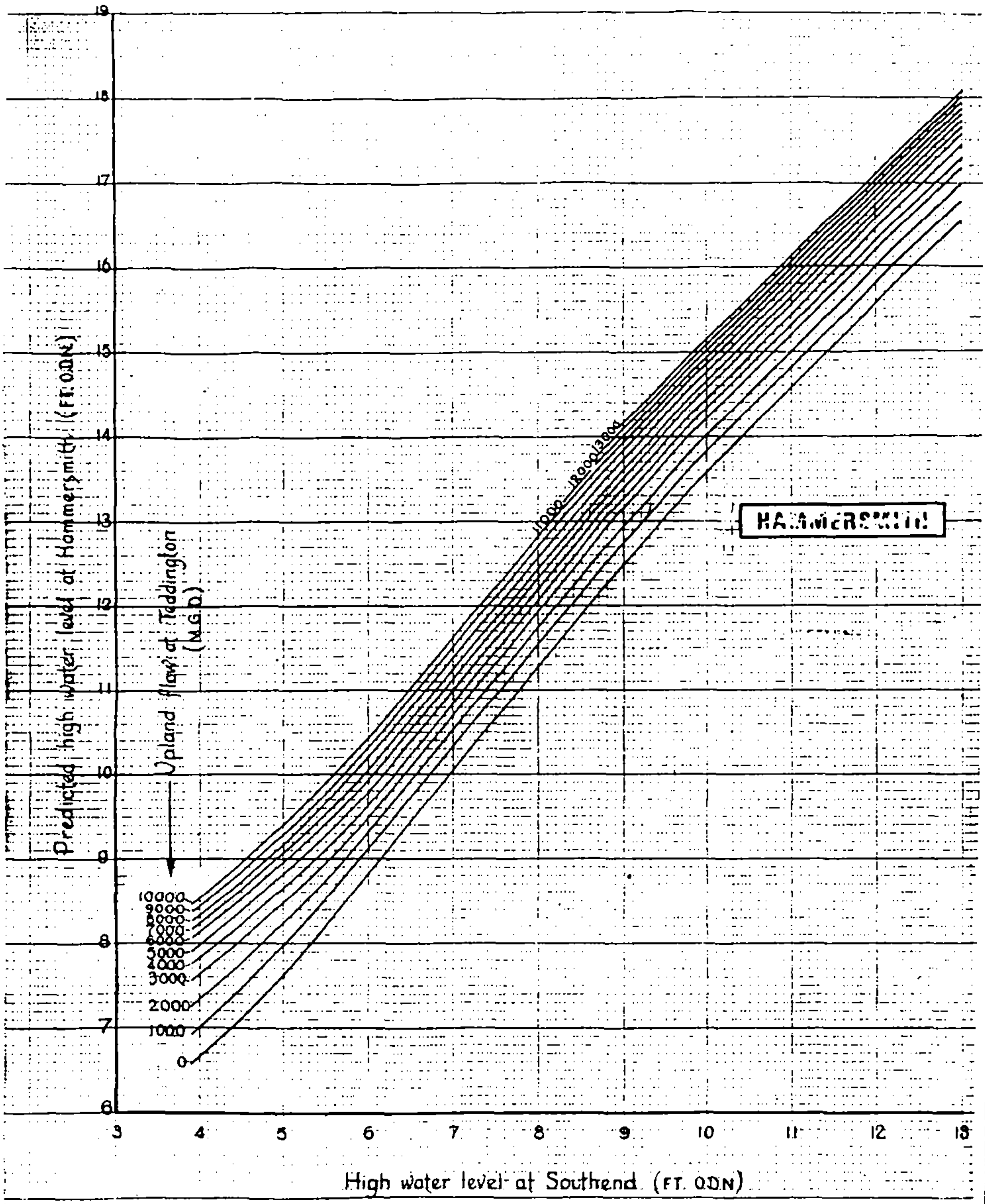
TWR PIER
ANNUAL MAXIMA (M)
6.
5.
4.
3.
-2.
0.
2.
4.
6.
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
REDUCED VARIATE Y
TOTAL RECORDS
FIRST 25 YEARS
SECOND 25 YEARS
THIRD 25 YEARS


RICHMOND
ANNUAL MAXIMA (M)
6.
5.
4.
3.
-2.
0.
2.
4.
6.
REDUCED VARIATE Y
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
TOTAL RECORDS
FIRST 25 YEARS
SECOND 25 YEARS
THIRD 25 YEARS


ANNUAL MAXIMA (M)
6.
5.
4.
3.
-2.
0.
2.
4.
6.
REDUCED VARIATE Y
RETURN PERIOD
2
5
10
25
50
100
200
500
1000
SOUTHEND
TILBURY
WOOLWICH
TOWER PIER
RICHMOND



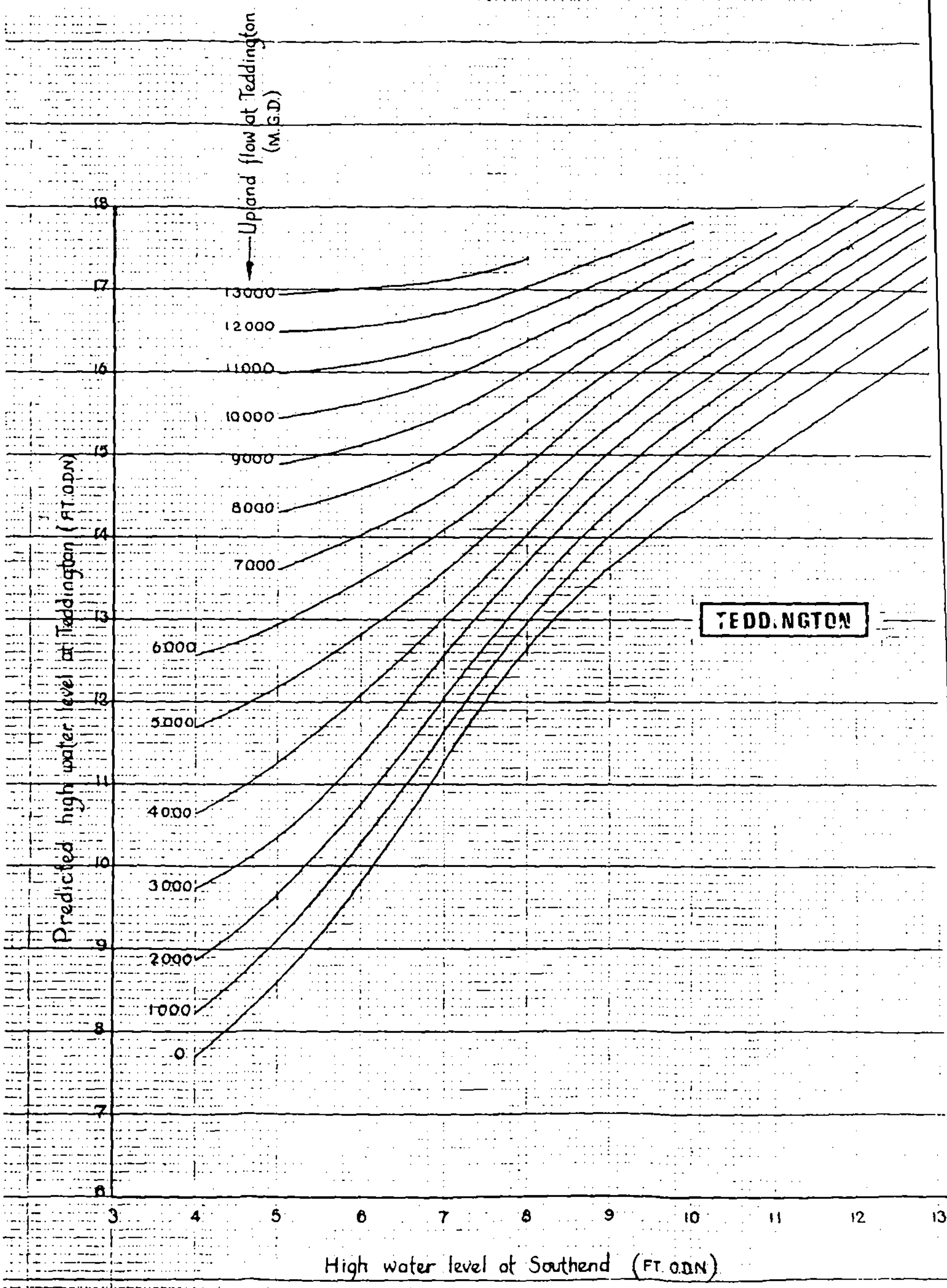
Appendix C Estuary levels as function of tide and upland discharge



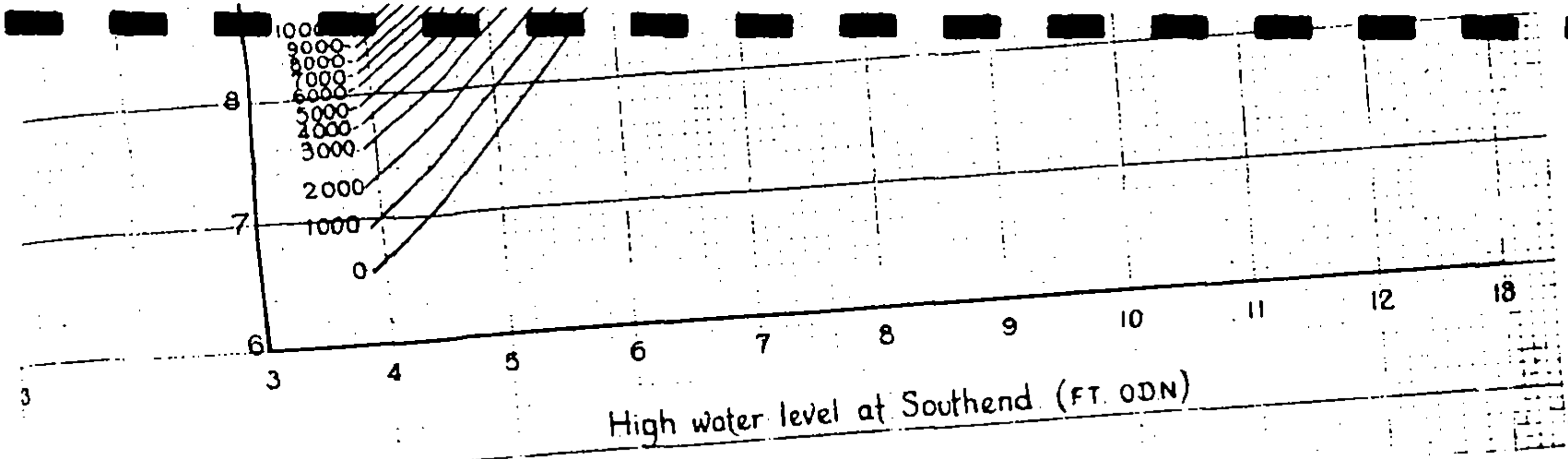
Notes

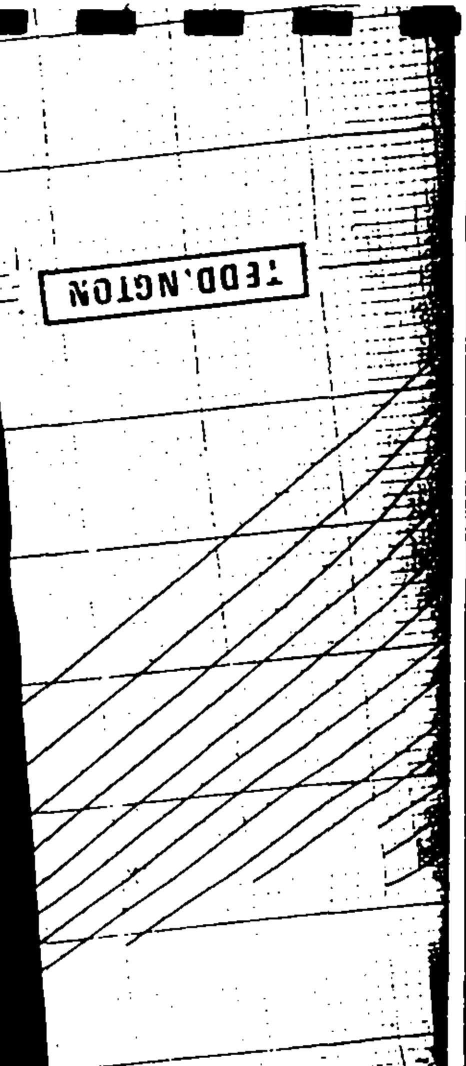
1 These graphs are based on an analysis of selected tides occurring between 1928 and 1970.

2 The curves give predictions for 1970. The trend in high water levels at the three places shown is about 1 ft per 100 years (rising relative to



Upland flow at Teddington (M.G.D.)
13000
12000
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
TEDD.NGTON
Predicted high water level at Teddington (FT. O.D.N)
18
17
16
15
14
13
12
11
10
9
8
7
6
3
4
5
6
7
8
9
10
11
12
13
High water level at Southend (FT. O.D.N)





Notes

1 These graphs are based on an analysis of selected tides occurring between 1928 and 1970.

2 The curves give predictions for 1970. The trend in high water levels at the three places shown is about 1 ft per 100 years (rising relative to high water level at Southend)

3 Accuracy for prediction can generally be expected to be :-
55% of predictions will be within ± 0·2 ft.
85% of predictions will be within ± 0·5 ft.
95% of predictions will be within ± 0·8 ft.
but predicted levels of very high tides may be less reliable.

	AMENDMENTS	Date	Initials
A	Redrawn and levels amended	10.3.72	[illegible]

DRAWING No.
HE/TF/T/121 A

Prepared by
Examined by

…TER LEVELS
…RSMITH

Appendix D

Annual maxima for Crane at Marsh Farm 1939-1986

Water year	ft^3/s	m	m^3/s
1939/40	285		8.07
1940/41	275		7.79
1941/42	250		7.08
1942/43	335		9.49
1943/44	115		3.26
1944/45	150		4.25
1945/46	150		4.25
1946/47	400		11.33
1947/48	130		3.68
1948/49	170		4.81
1949/50	210		5.95
1950/51	270		7.65
1951/52	270		7.65
1952/53	250		7.08
1953/54	240		6.80
1954/55	350		9.91
1955/56	360		10.19
1956/57	255		7.22
1957/58	325		9.20
1958/59	395		11.19
1959/60	185		5.24
1960/61	530		15.01
1961/62	335		9.49
1962/63	285		8.07
1963/64	360		10.19
1964/65	260		7.36
1965/66	335		9.49
1966/67	305		8.64
1967/68	460		13.03
1968/69	460		13.03
1969/70	110		3.12
1970/71	430		12.18
1971/72	275		7.79
1972/73	320		9.06
1973/74	390		11.04
1974/75	540		15.30
1975/76	240		6.80
1976/77	550		15.60
1977/78	500		14.16
1978/79		.546	6.09
1979/80		.968	15.01
1980/81		.735	9.77
1981/82		.720	9.34
1982/83		.662	8.21
1983/84		.712	9.06
1984/85		.720	9.34
1985/86		.830	12.03

POT data for Crane at Marsh Farm 1971/72-1985/6

Date	ft^3/s	m	m^3/s
5/3/72	275		7.79
6/12/72	320		9.06
20/6/73	260		7.36
21/9/73	280		7.93
4/9/74	350		9.91
27/9/74	390		11.04
14/11/74	400		11.33
21/11/74	540		15.29
18/1/75	300		8.49
29/1/75	320		9.06
8/3/75	335		9.49
19/4/75	260		7.36
16/5/75	450		12.74
14/9/75	285		8.07
27/9/75	330		9.34
30/11/76	350		9.91
13/1/77	275		7.79
11/2/77	270		7.65
20/2/77	275		7.79
10/8/77	550		15.57
7/12/77	290		8.21
11/1/78	380		10.76
3/5/78	250		7.08
7/5/78	500		16.16 14.16
10/12/79 78 w 79?		.720	9.34
28/12/79		.968	15.01
1/4/80		.702	8.92
14/6/80		.610	7.22
16/10/80		.735	9.77
25/5/81		.635	7.65
2/6/81		.700	8.78
6/8/81		.641	7.79
26/6/82		.720	9.34
22/10/82		.662	8.21
10/12/82		.621	7.36
24/3/84		.712	9.06
5/10/84		.720	9.34
22/11/84		.605	7.08
15/5/85		.664	8.21
26/12/85		.745	10.05
3/1/86		.830	12.03