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Tidal Thames Defence Levels

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Stage 1 Report on
Data Assembly and
Preliminary Analyses

June 1987

Thames Water

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Sir William Halcrow & Partners Ltd
Institute of Hydrology

HALCROW
Consulting Engineers

Sir William Halcrow & Partners Ltd
Burderop Park, Swindon,
Wiltshire SN4 0QD, England
Telephone (0793) 812479
International Telephone +44 793 812479
Telex 44844 Halwil G
Fax 0793 812089
International Fax +44 793 812089

And at
Vineyard House, 44 Brook Green,
London W6 7BY, England
Telephone 01-602 7282

Mr A P L Smith
Thames Water
Nugent House
Vastern Road
Reading
BERKSHIRE RG1 8DB

19 June 1987 Our ref WMG/TTM/11 Your ref

Dear Mr Smith

TIDAL THAMES DEFENCE LEVELS

We have pleasure in submitting 20 copies of our Stage 1 report on Data Assembly and Preliminary Analyses.

Please do not hesitate to contact me or Max Beran at IH if you have any queries.

Yours sincerely

E P Evans

E P Evans
DIRECTOR

Enc

EPE/sgb

SUMMARY

This report describes the progress made and conclusions drawn during Stage 1 of the Tidal Thames Defence Levels study and makes recommendations on the scope of work and methodology for the next stage of the project. The broad aims of the study are to establish the reliability of the tidal defences in the Thames and to define downstream boundary conditions for various named tributaries for use in future studies.

The River Crane was the only tributary included explicitly in the original scope of work but the following additional work has eeen requested during Stage 1.

- Flow-frequency analysis for the River Crane
  Similar studies for River Lea as required for River Crane
  Extension of ONDA model down to Southend and up to Molesey
  Crane and River Lea
  Joint probability distributions of levels and discharges on River
  Extension of the anlaysis up to 1 in 200 year return period.

A revision to the agreement and revised cost estimates to include these items has been submitted to Thames Water for approval.

Data collection has been a major component of Stage 1. Data acquired comprises tidal levels (including 47 years of diurnal tidal maxima), fluvial discharges (annual maxima, daily means and selected event data) topographical data for the computational hydraulic model, and general information.

A report on preliminary anlaysis of flows and levels at the mouth of the River Crane was submitted on 24 April 1987. The results were required urgently for use in the computational hydraulic model of the River Crane being developed by Thames Water. The 50 year return period flow was estimated to be 20.6 m^3/s for current conditions rising to 22.5 m^3/s for future 75% urbanisation conditions. The 50 year return period tide height was found to be 5.50 m based on historic data. At this probability level the Thames Barr, which has operating rules which aim to keep levels at Tower Pier below 4.85 m, could reduce the Crane mouth level to about 5.06 m. However this value is a very preliminary estimate based solely on pre-barrier conditions and will be revised during the ensuing stages of the study.

Preliminary analysis of the River Lea is nearing completion and results will be presented imminently under separate cover in a

similar form to the preliminary report for the River Crane. The River Lea channel network is much more complex than the River Crane and a much greater effort has been necessary in the preliminary stages to derive sensible conclusions. However this should be compensated by a lessening of the workload in the main River Lea anlaysis proposed for Stage 4 of the project. The complex network of channels and regulating structures and the numerous operating procedures make the accurate prediction of floods within specific channels impossible without the application of a river model.

Probability anlaysis of the primary data series is well under way but will overlap into Stage 2. Investigation of correlation between the primary data series indicates a weak tendency for interaction between surge and riverflow which will probably be modelled adequately by a seasonal or other decomposition of the data.

The analysis of trend in fluvial flows indicates that it can be safely excluded from the study. Trend analysis of annual maximum tide levels indicate a nearly uniform pattern of trend throughout the tideway which is compatible with values obtained by IOS for mean sea level (2 to 3 mm/annum).

Following a review of previous model studies and reports the ONDA model has been recommended to be adopted for the study as the most cost effective, reliable and versatile option available. On verbal approval from Thames Water the model has been extended to encompass the whole of the Tidal Thames from Molesey Lock to Southend, including the Thames Barrier. Additional topographic data was taken from the PLA hydrographic charts and data acquired from the Thames Water Barrier office and the surveys section.

The Thames barrier has changed the probability distributions of water levels in the tideway quite dramatically. A strategy for including this effect into the analysis by combining the bivariate probability distribution of fluvial flows and Southend levels with structure functions at specific locations has been defined. The structure function is a diagram showing lines of equal water level at a selected location in the tideway for different combinations of fluvial flows and downstream tide levels.

It is proposed that Stage 2 of the study will continue much in the same manner as envisaged in the original Consultancy Brief, although it will be necessary to take much more careful consideration of the dominating effect of the Thames Barrier.

TIDAL THAMES DEFENCE LEVELS

STAGE 1 REPORT

1. INTRODUCTION

INTRODUCTION

1.1 General

This interim report describes the progress of work carried out to date and conclusions drawn during Stage 1 of the Tidal Thames Defence Levels study. The objectives of the study are as described in the Consultancy Brief, which was confirmed in the letter of appointment by Thames Water on 27 February 1987 and forms the basis for the agreement with Thames Water. The work is being undertaken by Sir William Halcrow and Partners in association with the Institute of Hydrology. Since commencement of the study the scope has changed, with requests from Thames Water for further work to incorporate analysis of flood flows in the River Crane and also to carry out a similar investigation of flows and levels for the river Lee.

1.2 Scope

The main scope of Stage 1 were as follows:

(a) Assemble and assess river flow data at Teddington and at the tributaries, downstream, and levels at the downstream tidal boundary and intermediate tide gauges.

(b) Probability analyses of flows at Teddington and levels at downstream boundary including degree of dependency between the two series.

(c) Preliminary estimation of stage-frequency relationship at the river Crane mouth.

(d) Study ex-GLC computational hydraulic models and make recommendations on how they can be used in conjunction with the Teddington-Gallion ONDA model.

(e) Optional stage 1a to extend ONDA model to the downstream tidal boundary and include all structure operating rules.

1.3 Additional Work

During Stage 1 several items of additional work were requested by Thames Water. These were outlined in the proposed revision to the Consultancy Brief which was submitted for approval to Thames Water on 11 May 1987 together with revised cost estimates. The revision involved:

- additional analyses to include flow-frequency for the River Crane,
- a similar study for the River Lea as is to be carried out for the River Crane,

extension of the ONDA model down to Southend including the Thames barrier operating rules,
joint probability distribution of levels and discharges on both the River Crane and River Lea.
extend the analysis up to 1 in 200 years return period

Approval from Thames Water for these amendments to the scope of work is awaited, although verbal approval was given in the progress meeting of 14 May 1987 for both extension of the ONDA model and preliminary river Lee analysis to commence immediately.

1.4 Progress

Such items as fall under Stage 1 of the study are now complete:

The main bulk of data required for the study has been collected and input to the computer database prior to anlaysis. Outstanding data requested from Thames Water include river and tributary flows for calibration of the hydraulic model to be undertaken in Stage 2. Data acquisition is covered in Chapter 2.

Preliminary analysis of flows and levels at the mouth of the River Crane was the most urgent requirement during Stage 1 of the study, since the results were required for immediate use by Thames Water in the computational hydraulic model of the River Crane. The preliminary report for this component of the study was submitted on 24 April 1987 and a summary of results is presented in Section 3.1.

Preliminary analysis of flows and levels for the downstream reaches of the River Lea has also been carried out during Stage 1 of the study. The results are to be presented under separate cover and a brief description is presented in Section 3.2.

A review of the available computational models and relevant reports from previous studies has been carried out. A comparison of the ONDA model and the IOS model of the tidal Thames is presented in Section 4.1. The recommendation has been made to adopt the ONDA model as the most cost effective option for the study.

After receipt of verbal approval, given by Thames Water at the progress meeting of 14 May 1987, the ONDA model has been extended to include the complete reach from Molesey Locks down to Southend tide gauge including the Thames Barrier. This is described in Section 4.2.

The influence of the Thames Barrier on levels in the tideway is much more pronounced than originally anticipated. The procedure for including the effect of the barrier into the probability and hydraulic anlayses has been identified and is described in Section 4.3.

Probability analysis of the primary data series (flows at Kingston and levels at Southend) has begun, particularly with respect to trends in discharge and levels, distribution of tidal surges and correlation between the two primary variables. Progress to date is described in Section 3.3. This component will extend into Stage 2 of the study.

2. DATA COLLECTION

4 DATA COLLECTION

Data collection has been a major component of the Stage 1 work. Data required for the study comprises tidal levels, fluvial discharges, topographical data and general information:

(a) 47 years of the diurnal tidal maxima for tide gauges at Southend, Richmond, Tower Pier and Gallions (12 years only) have been collected from PLA and entered to the computer.

(b) 104 years of daily mean flows at Kingston/Teddington gauging station have been extracted from the data archive held at IH.

(c) Annual maxima and threshold exceedences for stations in (a) and (b) have been obtained, in the case of (a) from 1911.

(d) Annual maxima and POT flood discharge data for Marsh Farm and Cranford Park (R Crane) were extracted from microfilm data held at IH and brought up to date from charts at Thames Water's Waltham Cross office.

(e) Annual maxima and POT flood discharge data for Fieldes Weir, Low Hall and five tributaries (R Lea) have been taken from the IH data archive and Waltham Cross. Annual maxima have also been collected for tide gauges at Bow Locks and Brunswick Wharf on the River Lea.

(f) Tide Charts have been collected for tide gauges at Richmond, Chelsea, Tower Pier, Charlton, Silvertown, Gallions, Erith Deep Water, Tilbury, Coryton and Southend for several events with various combinations of surge tides, high fluvial flows and Barrier closures for use in calibration of the hydraulic model. Concurrent flow data have not yet been received from Thames Water. Information on gate movements, particularly at Teddington Lock, are not yet complete.

(g) Topographical data for extension of the hydraulic model have been taken from hydrographic charts obtained from PLA and cross sectional data have been input to the computer. Cross sectional data for the Molesey Lock to Teddington reach were taken from the River Thames Model database.

(h) Gate dimensions for Thames barrier and Teddington locks have also been obtained and entered to the model.

(i) General information collected includes statutory and interim defence levels, information on barrier operation, Storm Tide Warning Service (STWS) analysis of forecast errors etc.

3. HYDROLOGY

3 HYDROLOGY

3.1 Preliminary Study of Hydrology of the River Crane

The preliminary study of the River Crane (Paragraph 2.1.4 of the revised terms of reference) was required to provide TWA with a rapid assessment of design conditions for an ongoing project involving a computational hydraulic model of the River Crane. The objectives are to provide a stage frequency relationship for the Thames tideway at the Crane confluence and a flood frequency relationship for the Crane at Marsh Farm. At the time the work was carried out little was known of the possible impact on the river Thames stage frequency relationship of the Thames barrier operation, so the values presented represent very much an upper bound to that which is possible. The following represents a brief summary of the results prevented in the preliminary report, which was submitted in April 1987.

3.1.1 Flood Frequency Relationship

Annual Maximum and Peak over Threshold series were extracted for the full period of record (1939-date) at Marsh Farm gauging station. The effect of increasing urbanisation is very apparent in the increasing frequency of exceedences over the years. For example the 1947 flood was the largest up to that date but was exceeded in 1960 and on eight occasions since 1967. The effect of urbanisation on the mean flood conformed closely with the method of Flood Studies Supplementary Report No 5 (FSSR5) which predicts an increase of 60% over the period of record.

The data for the period from 1972 to 1986 was used to estimate the current mean annual flood. This was then scaled using the appropriate regional flood frequency relationship adjusted for the influence of urbanisation. This estimation strategy yielded a 50 year return period flood peak of 20.6m^3/s for current conditions rising to 22.5 m^3/s for future 75% urbanisation conditions.

3.1.2 Tidal Analysis

The short stage record (1976-date) kept for the Crane tide gates provided a certain amount of information on the relationship between the much longer Richmond level records (1911-date) and those at the Crane mouth. The difference between the two sites was typically 10 cm although quite large departures were on occasion observed. The tendency for a diminishing difference with increasing tide height was confirmed after analysing Richmond and Tower Pier high tidal levels. Sea levels in the Thames estuary are known to be rising relative to land levels and a figure of 3 mm/yr has been quoted as a working hypothesis in the preliminary Crane report.

This figure was applied to Richmond too although the annual maximum data themselves suggest lower trends for the upper estuary. A preliminary trend analysis of the tidal records led to a value for the 50 year return period tide height of 5.50 m.

Information received subsequently showed that the barrier should limit levels in the tideway to a maximum height of 4.85 m at London Bridge. Based on comparison of the fitted probability distributions this is approximately equivalent to 5.06 m at the mouth of the Crane. Subsequent analysis should reveal whether this equivalence which is based on pre-barrier data would hold for current conditions.

3.1.3 High Return Period Floods in the Tributaries

Subsequent Requests from Thames Water for estimates of high return period flood magnitudes and for an analysis of the Lea basin data has lead to the definition of a general analytical strategy for tributary streams to the tideway which tries to make maximum use of the relatively long flow records that are available in the London area. This can be specified as follows:

(i) fit the Gumbel distribution to the annual maximum series of sites with due regard to heterogeneity due to urbanisation;

(ii) use this fit to estimate floods up to a maximum return period of 2N years where N is the length of record used to fit the distribution;

(iii) extrapolate to higher return periods from this point using internal ratios derived from the regional flood frequency curve (with due regard to the influence of urbanisation on the shape of the growth curve).

This strategy was applied to the Crane data. The parameters of the Gumbel fit to the recent portion of the record is a = 2.4483, u = 9.157 m^3/s. It was considered prudent to restrict extrapolation with these parameter values to 20 year return period (16.42 m^3/s) beyond which the method of FSSR5 was applied. As explained in that report the method of extrapolation beyond 50 years was constructed in a consistent fashion but was not based on recorded data. The extrapolation was reviewed briefly taking advantage of the additional years of record now available. Data were assembled from 12 stations with 151 station years of record in the London area all with urban fractions between 50 and 81 per cent. The average growth factors for this data set were 2.13 and 2.37 at 100 and 200 year return periods. This accords quite closely with the values shown in Table 3.1 computed from FSSR5 of 2.19 and 2.44.

Table 3.1 R Crane at Marsh Farm-Flood Frequency (m^3/s)

AM return period - years						
2	5	10	25	50	100	200
10.1	12.8	14.7	16.9	18.5	20.7	23.2

3.2 Preliminary River Lea Analysis

3.2.1 Objectives

The objectives of this preliminary study were to ascertain the frequencies of floods and peak water levels in the Lower Lea and the frequency of peak water levels in the Thames near the Lea confluence. The lower Lea reaches in question are the tidal sections of this river system up to Lea Bridge on the Navigation channel and nearly up to the Flood Relief Channel river gauging station at Low Hall, and the sections immediately upstream of the tidal influence (see Figure 3.1).

Preliminary analysis of the River Lea is nearing completion and results will be presented imminently under seperate cover in a similar form to the preliminary report for the River Crane.

The River Lea channel network (Figure 3.1) is much more complex than the River Crane and a much greater effort has been necessary in the preliminary stages to derive sensible conclusions. The main problem stems from the facts that Low Hall gauge has a short record, for which deficiency Feildes Weir record had to be examined, and no records exist on the second branch of the Lea (the Navigation Channel) for which flood frequencies have had to be synthesised. However this will be compensated by a lessening of the work load in the main River Lea analysis proposed for Stage 4 of the project.

3.2.2 The Lower River Lea System

The Lea river system is very complex in its lower reaches downstream of Feildes Weir (See Figure 3.1). Until Feildes Weir the Lea has a predominantly rural and chalk catchment and generally natural channels, though significant offtakes exist upstream which supply various water undertakings. At Feildes Weir the Lea is regulated through two channels flanking its flood plain, the western channel supplying and later becoming the Lea Navigation Channel, and the eastern channel being the Lea Flood Relief Channel. Upstream of the Pymmes Brook confluence, relatively steady flows are maintained within the Navigation Channel so far as

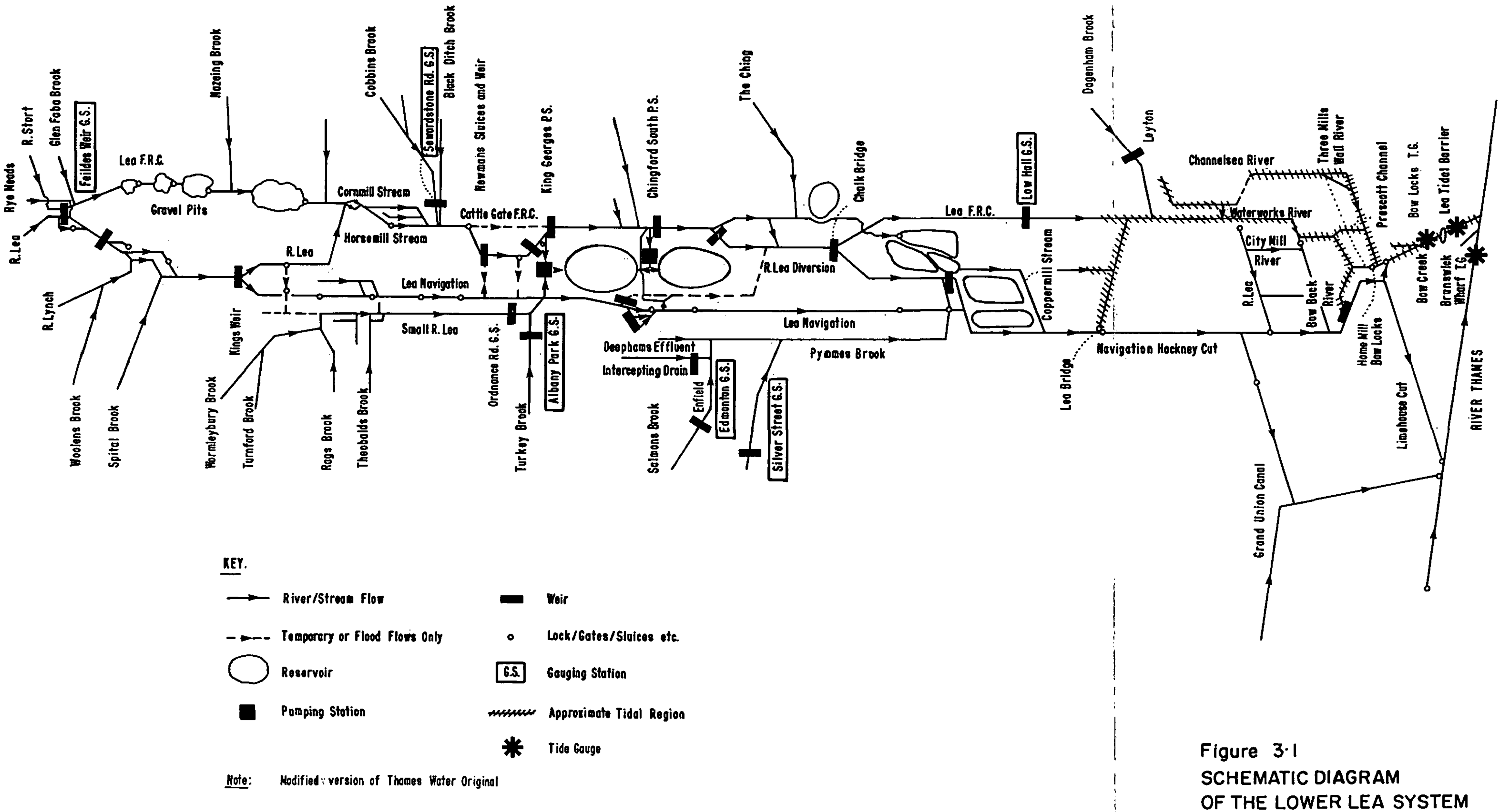


Figure 3·1
SCHEMATIC DIAGRAM
OF THE LOWER LEA SYSTEM

possible by diverting flood flows eastward through several channels to the Flood Relief Channel. A number of large raw water storage and service reservoirs exist within the flood plain between the two main channels, and are linked with the latter by a number of additional channels to affect supply and to accommodate spillage. The complex network of channels and regulating structures, and the numerous alternative operating procedures, make the accurate prediction of floods within specific channels impossible without the application of a river model.

As the Lea channels pass southwards from Feildes Weir, the catchments of incoming tributaries from east and west are progressively more urbanised, the lowest such as Dagenham Brook and The Moselle being almost entirely built-up. The degree of urbanisation in the Lower Lea tributaries has increased significantly in recent decades, and this influence would be expected to increase flood peaks unless balancing pond development has kept pace.

3.2.3 Data Availability

Water levels have been recorded at a number of stations along the tidal Thames from Teddington to Southend. The nearest Thames water level recording station to the mouth of the River Lea is at Brunswick Wharf (Figure 3.1), which is 0.5 km upstream of the confluence. This station ceased to operate in 1983 when the Thames Barrier was commissioned, but its effectively continuous record provides an annual series of water level peaks of 30 years. Upstream of the confluence with the Thames but within the tidal reach of the River Lea, the Bow Locks water level recording station offers a data set of 27 years of annual peak water levels since its start in 1934 until its data were affected by the commissioning of the Lea Barrier in 1972. This data series includes the exceptionally severe events of 1953 and 1949. The next nearest Thames long term water level recording stations upstream and downstream of the Lea confluence are at Tower Pier and N Woolwich (Gallions). Data for the latter stations extend back to 1912 and 1915 respectively. Trends are also detectable in the tidal water level records. However, the major influence on Lea confluence water level frequencies is now the Thames Barrier, the precise effects of which will only become apparent in the course of the full anlaysis in Part 2 of the study.

Floods on the main River Lea are measured at Feildes Weir and at Low Hall on the Flood Relief Channel. No river gauging station exists on the Navigation Channel, which, although floods are diverted from it to the Flood Relief Channel for much of its course, acts as the flood collecting channel for a number of flood-prone tributaries south of the Turkey Brook confluence, including among others the Salmon Brook, Pymmes Brook and Sadlers Mill stream. Direct estimates are therefore possible of flood frequencies on the Flood Relief Channel using the short Low Hall record supplemented by Feildes Weir longer record. However, flood frequencies on the lower Navigation Channel must be deduced from flood and catchment characteristics of gauged tributaries such as Salmon Brook, Pymmes Brook and Turkey Brook.

3.2.4 Tidal Water Level Data

Water level records relating to the Thames/Lea and tidal lower Lee have been collected from Thames Water for Brunswick Wharf, Bow Locks and the Lee Barrier. These data are in the form of microfilm. Annual maximum peaks and the dates of these peaks have been extracted from the microfilms. Further tidal Thames water level data for other stations upstream and downstream of the Thames/Lea confluence have been presented in the Preliminary Report on River Crane Flows and Levels, and some of these have been used in this study.

3.2.5 Flood Data for the Lower Lea and Tributaries

Flood peaks, generally in the form of annual maximum (AM) series and sometimes peak-over-threshold (POT) series, have been extracted from the records of usable river gauging station data for the Lower Lea and tributaries. In the course of extracting these data, certain data sets have been rejected as being of too poor quality.

The analysis of flood flows and tidal levels in the lower reaches of the river Lea is almost complete. Results and conclusions will be presented under separate cover.

3.3 Probability Analysis of Primary Data Series

The fitting of statistical distributions to tide and fluvial flow series and the study of their interaction is a prerequisite for the derivation of the distribution of maximum levels at intermediate points in the tideway. Conventionally for flood design purposes the statistics are expressed as return periods between annual maximum events. However in order to combine the statistical distribution with the hydraulic modelling it is necessary to use a time step appropriate to that over which events naturally interact. Thus it is necessary to relate annual maximum statistics to those at daily and semi-monthly time scales. The following sections illustrate the form of analysis that will be required during stage 2. Sufficient numerical information is given to permit an appreciation of some of the numerical problems that will have to be solved.

3.3.1 Statistical Analysis of Thames Discharge Data

The Thames at Teddington/Kingston provides over 100 years of data for annual maximum and daily analysis. Two series are available: gauged flows and naturalised flows (which include upstream abstractions etc). The latter series are required for statistical purposes such as trend analysis. However it is the gauged flows which are experienced within the estuary so these are used in structural relationships of estuary levels.

a) Relationship between daily and annual quantities:

Three internal statistical relationships are to be investigated concerning the probabilities of exceeding given discharges expressed in annual maximum, daily and semi-monthly terms.

b) The 1983 Surface Water Yearbook presents some evidence for a climatically induced trend in annual runoff totals. Fluctuations in the annual runoff are seen also by inspection of successive 20-year time slices from 1883 - 62, 81, 88, 76 and 85 m^3/s - which differ by amounts considerably in excess of their standard errors. The graphical presentation used in the Surface Water Yearbook, cumulative departure diagram, is not well equipped for detecting trend however, so a more formal analysis was used.

A linear regression of the logarithms of mean flows on time was considered. This indicated a small trend, equivalent to one quarter per cent per annum, in the annual runoff which was at the limit of significance. To investigate further more tests were carried out on the monthly runoff totals which indicate that only in the low-flow season is the trend significant. This may be due to a tendency towards drier summers (not reported elsewhere) or to data error, eg low flow rating changes or overestimation of the withdrawals for supply in earlier years.

Further insight into these suppositions was obtained by analysing the minimum and maximum daily values each month and over the whole year. As shown on Table 3.2 the trend in minima is most marked during the summer months. There appears to be no significant trend in the annual maxima and that in the summer months is probably a reflection of the low flow trend. More sophisticated tests are planned within the Maidenhead Flood Study to further discriminate the climatic influence but for present purposes it is felt that fluvial trend can be neglected.

Table 3.2 Kingston/Teddington trend in per cent per year in mean, minimum and maximum daily flows in each month

Month	Mean		Minimum		Maximum	
	Trend	t	Trend	t	Trend	t
Jan	0.56	1.38	0.52	1.22	0.55	1.43
Feb	0.73	1.75	0.79	2.13	0.84	1.92
Mar	0.57	1.48	0.70	1.99	0.51	1.18
Apr	0.76	2.19	0.80	2.59	0.89	2.20
May	0.93	2.62	0.96	3.01	1.17	2.71
Jun	1.00	2.70	0.98	3.37	1.21	2.53
Jul	0.83	2.66	0.95	3.11	0.70	1.91
Aug	0.99	2.97	0.94	3.12	1.51	3.36
Sep	1.17	3.28	0.93	3.19	1.91	3.88
Oct	0.85	1.91	1.31	3.87	0.96	1.66
Nov	0.46	0.89	0.54	1.31	0.73	1.16
Dec	0.62	1.37	0.54	1.18	1.02	2.32
Year	0.64	2.63	0.98	3.59	0.39	1.53

Note: t measures the statistical significance of the trend. The threshold for significance is 2.70 at 1% level.

3.3.2 Statistical Analysis of Tide Data

The Thames tideway is very well supplied with tide gauges as illustrated in Table 2.1 and Figure 2.1 of the Crane Preliminary report.

(a) Annual maxima data for tide stations for the pre-Barrier period have been presented in the Crane Preliminary report. Opportunity is being taken to correct some errors that have been revealed in the raw data given in Appendix A of the Crane Preliminary report.

(b) It is proposed to work with the distribution of maximum levels achieved during each neap-spring-neap tide cycle giving approximately two values each month.

(c) The annual maxima have been analysed for trend as described in Section 3.4 of the Crane preliminary report. The data corrections made thus far indicate a more nearly uniform pattern of trend behaviour throughout the tideway, but still compatible with values obtained by IOS for mean sea level.

(d) Knowledge of the surge distribution may be important in order to model the operation of the barrier, which is based upon a forecast of the surge added to the predicted high water level

(Section 4.3). Figure 3.2 shows a preliminary assessment of the magnitude of surges that have occurred at the time of high sea level. The histogram indicates a surge distribution which has a positive mean and with a long tail to the right.

3.3.3. Correlation Between the Primary Data Series

Figure 3.3 indicates that there is a weak tendency for interaction between surge and riverflow. This may be seen by contrasting the surge magnitudes corresponding to discharges in excess of 100 m^3/s - a preponderance of values between .2 and .5m - with that for lower flows where there is a preponderance of values between 0 and .4m. This level of correlation will probably be modelled adequately by a seasonal or other decomposition of the data.

3.3.4 Effect on Trend of Record Breaking Events

Section 3.4 of the Crane Preliminary report refers to Horner's analysis of record breaking events. It seems that the trend value so derived, 760 mm per century, played an important part in the original design calculations for the barrier. Because this value is considerably larger than in the results presented in the River Crane report (between 200 and 300 mm per century) and because of theoretical difficulties with approaches based on record-breaking events, the relationship between record breaking events and general trend has been investigated.

(a) Problems with the Approach

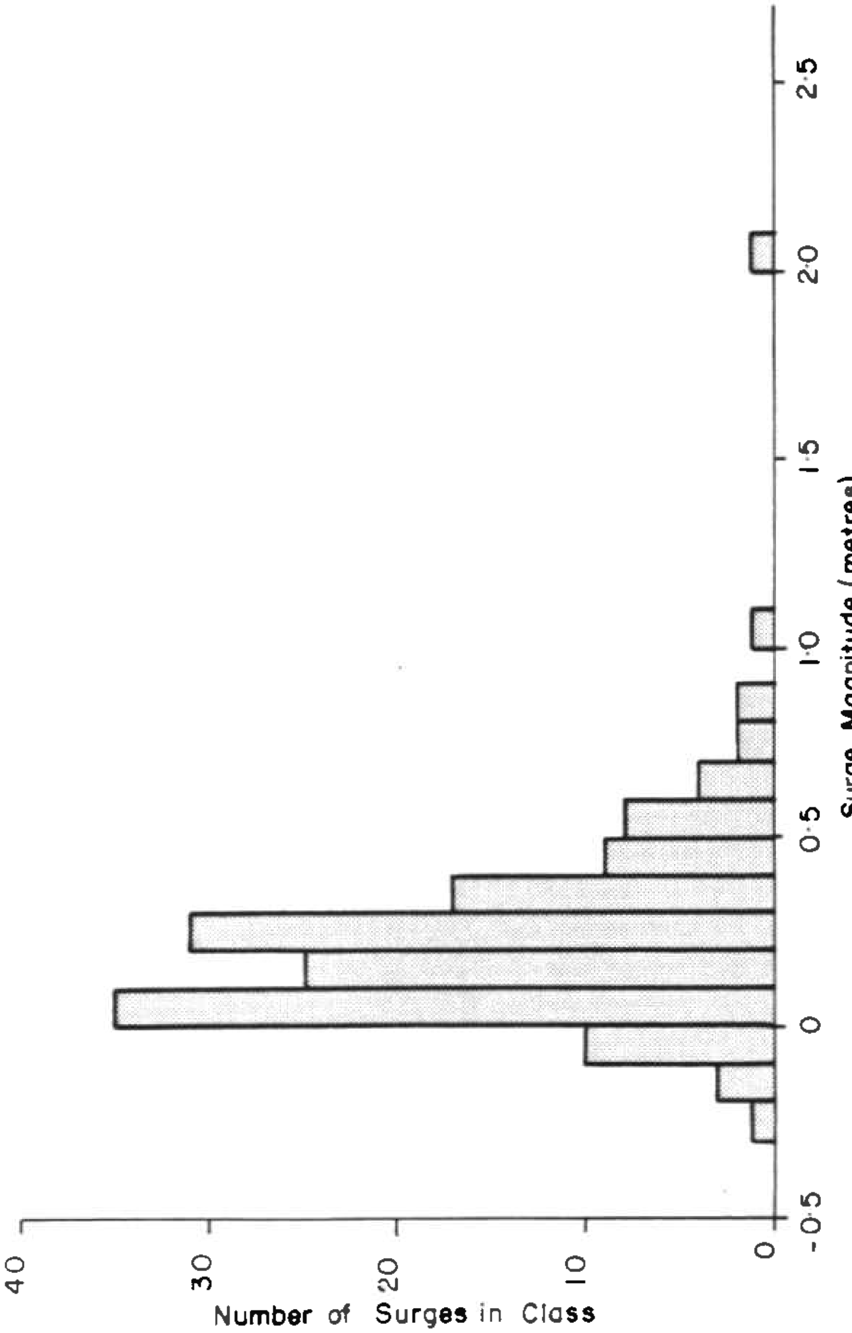
The theoretical difficulty can be seen very simply by considering an indefinitely long time series plot of a randomly varying but trend free series. In such a series records will inevitably be broken and hence an upward sloping line must always be obtained if such values alone are considered. Such a method clearly opens up some questions:

> Is a trend of 760 mm per century in the record breakers compatible with a 250 mm or indeed 0 mm per century? trend in annual maximum water levels
>
> How robust is such a procedure for estimating a trend?

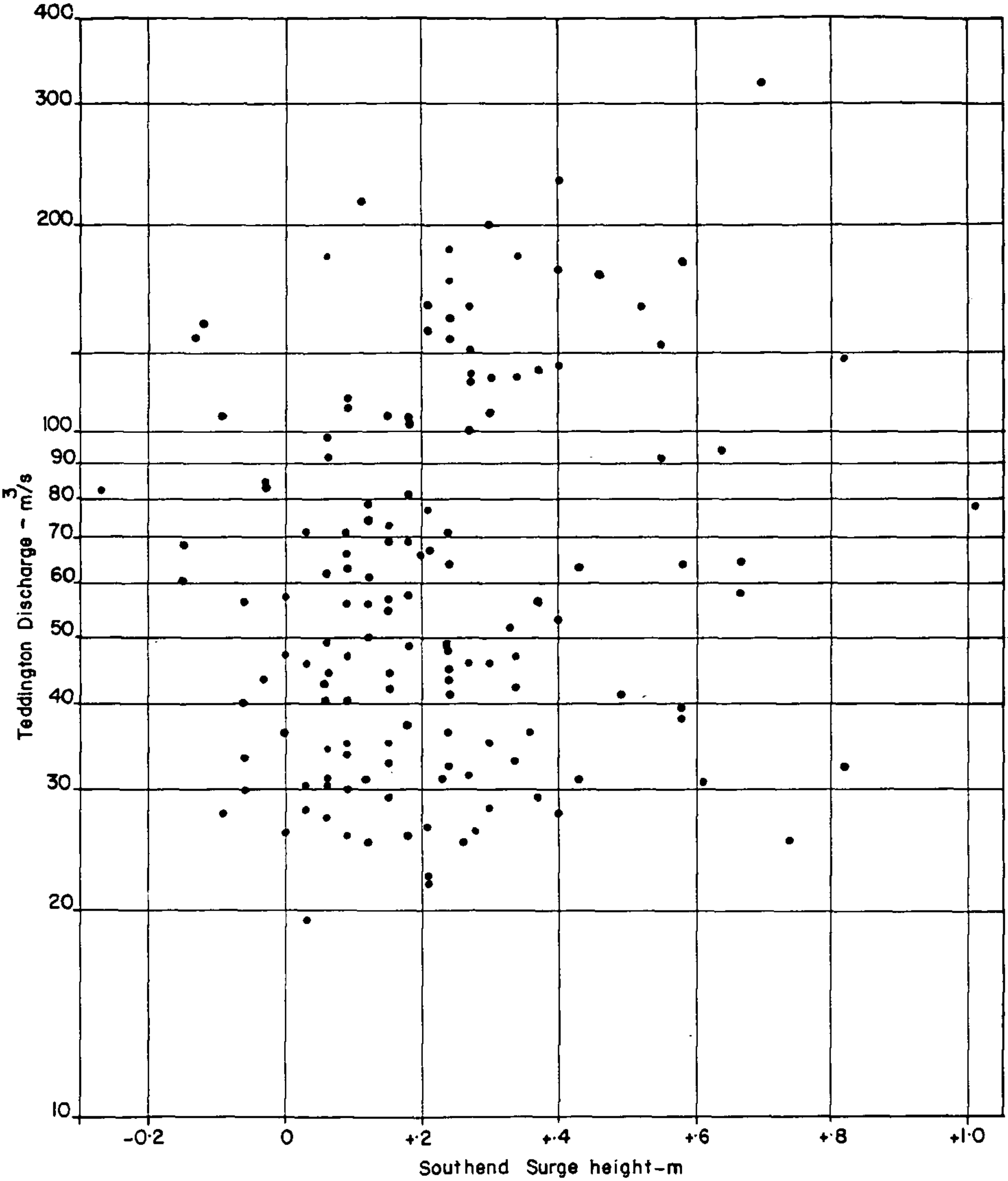
There is no simple analytical answer to these questions so a simulation approach was adopted. The rules of the simulation were:

> Random numbers are generated from a population with known distribution and trend;

Figure 3·2



HISTOGRAM OF SOUTHEND SURGE MAGNITUDES 1953–1966



CORRELATION BETWEEN SOUTHEND SURGE AND TEDDINGTON DISCHARGE

The series of record breakers was started at the first incidence of a value which exceeded the 0.8 quantilee (5 year return period);

Series with four or more record breakers only were accepted;

The trend was estimated as the coefficient of a linear regression on time of the record breaking events.

(b) Results of Simulation Experiments

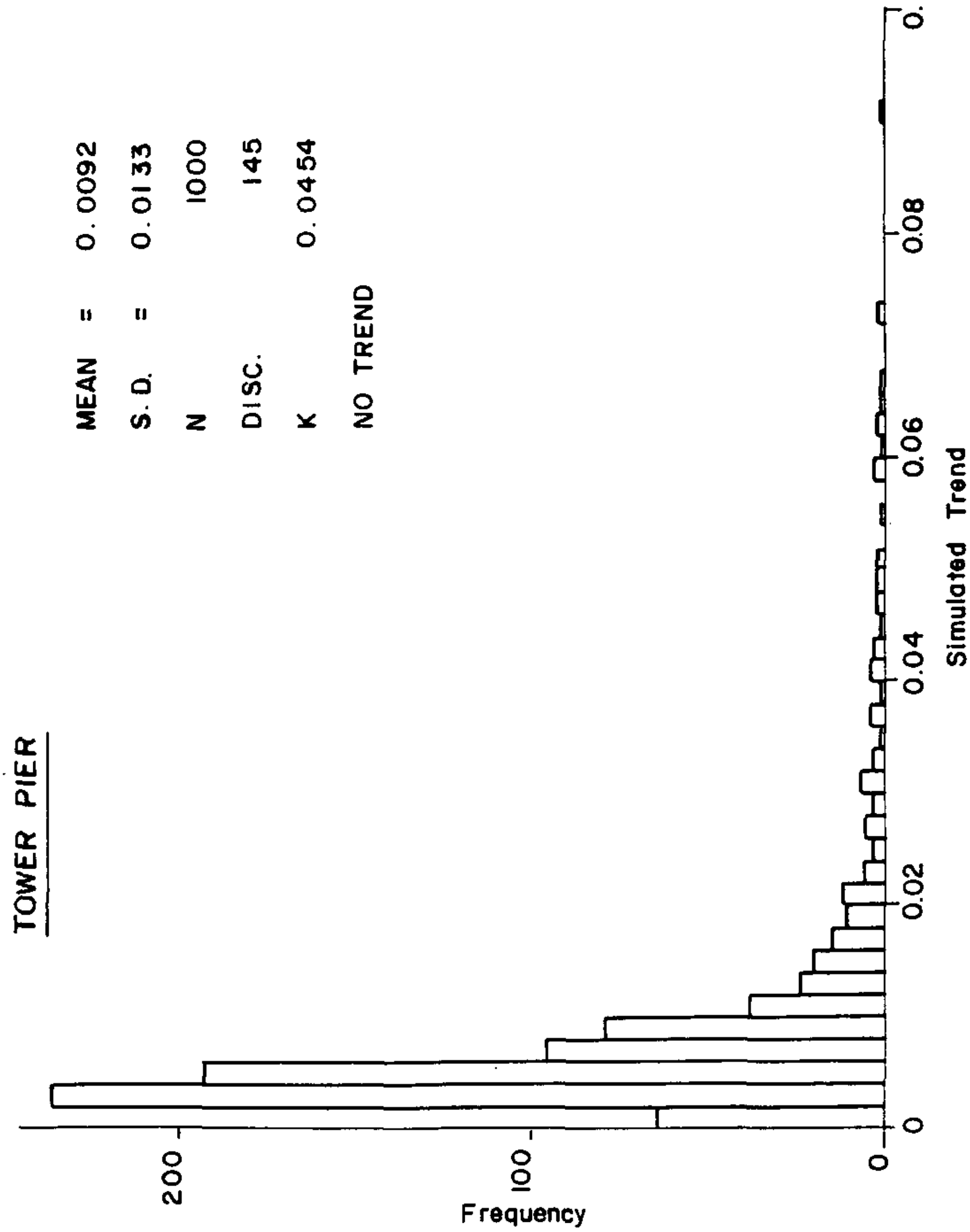
One thousand simulated trend-free 200 year records were generated for Tower Pier using the best fit parameters of the General Extreme Value distribution for that location. For each 200 year realisation it was possible to extract the record breaking events and then fit a linear trend to them. There were 145 cases where the third rule above led to its exclusion leaving 855 simulated trend values. Figure 3.4 shows these coefficients and indicates a wide range of values are possible from near zero to over 0.13 m per annum. The majority of the values fall in the interval from zero to 1.2 mm per annum with a mode close to 3.5 mm per annum. The mean trend of 9.2 mm per annum lies to the right because of the skewness in the distribution. High values of the trend will tend to occur in those series where the last record breaking event occurs well before the end of the record.

The imposed true trend in this simulation is of course zero yet the observed trend based upon record breaking events of 7.6 mm per annum lies well within the main region of the data. This answers part of the first question above; an observed trend in the record breaking of 7.6 mm per annum is entirely compatible with a truly trend-free population; more than one sample in three would have given even higher apparent trends.

Concerning the second question above the biased and highly variable results and the paradox of a reducing expectation of simulated trend with increasing population trend both lead to the conclusion that this method provides very poor estimates of trend.

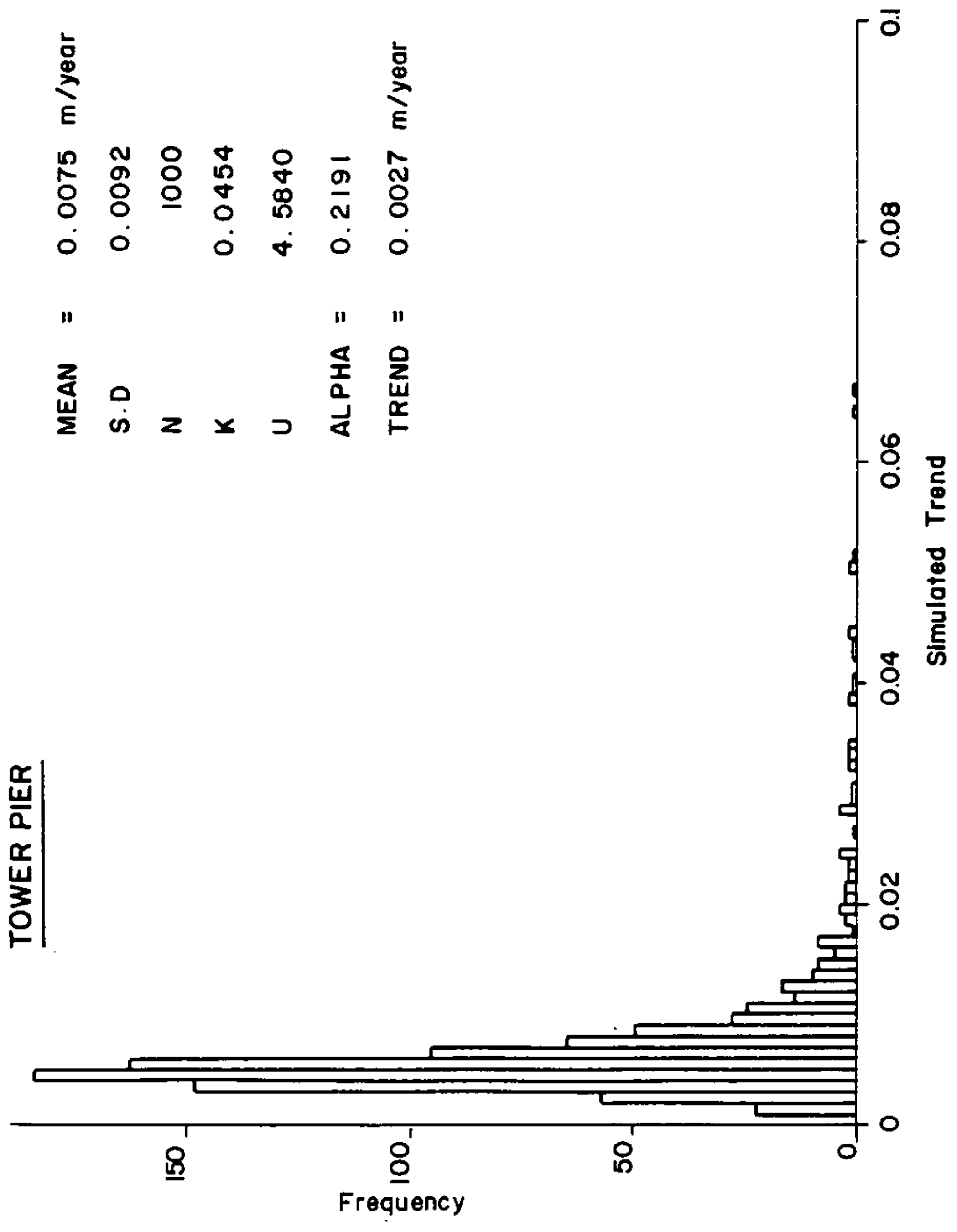
(d) Conclusions

The histogram of estimated trend values indicates a very wide spread of possible values which can with ease encompass values as high as 7.6 mm per annum from an entirely trend free population. The method is highly biased and rather dependent upon the particular set of ground rules used in the simulation.



HISTOGRAM OF SIMULATED TREND VALUES FOR TOWER PIER WITH ZERO POPULATION TREND

Figure 3·5



HISTOGRAM OF SIMULATED TREND VALUES FOR TOWER PIER
WITH POPULATION TREND 2·7 mm/year

The trend value obtained more directly from annual maxima or mean sea level is much to be preferred to an approach based upon record breakers.

3.3.5 Requirements for Further Analyses

Further work is necessary in order to establish the link between the flow duration curve and the annual maximum series.

The fluvial input to the tideway downstream of Teddington should not be neglected and a strategy for incorporating it into the distribution must be identified.

Further work is necessary to establish the statistical distributions for tide stations, especially to allow for the impact of the barrier operation. An optimal stratification is required to accommodate the weak dependence that can be observed between surge and tide.

4. COMPUTATIONAL HYDRAULIC MODEL

4 COMPUTATIONAL HYDRAULIC MODEL

This section contains a review of previous models of the tidal Thames. Recommendations have already been given to Thames Water opting for the application of the ONDA model. Following verbal agreement to proceed the ONDA model has been extended to include the complete tideway from Molesey Locks down to Southend. The Thames barrier has been included in the model and its mode of operation is described below together with the identified strategy for incorporating the effect of barrier operations into the probability analysis.

4.1 Review of Previous Models

The consultancy brief required a study of existing models to be carried out during Stage 1 of the study together with recommendations on the computational hydraulic model to be used. The options for the model were either the ONDA model which was used by Halcrow for investigating the operating rules for Richmond sluice, the IOS model which is currently used in operation of the Thames barrier, or a combination of both.

Several reports provided by Thames Water concerning hydraulic modelling studies for the tidal Thames have been reviewed during Stage 1. These reports tend to concentrate on the Thames Barrier, its operating rules and the effect it has on the river. Attention in previous studies has generally focussed on tidal rather than fluvial influences, since the former have a more dominant effect on water levels, particularly in the seaward reaches. Little is said of methods applied by GLC to set defence levels particularly for the upper tidal reaches.

Several hydraulic models have been derived for the tidal Thames of which three were physical scale models (two constructed by HRS and one at Wimpey Laboratories). Other scale models, such as the BHRA model, were built to study localised effects and covered only a short section of the tidal river. The results from physical model studies are of interest both as background information and for comparative purposes, but could not be used for the present study since these models, of course, have long been dismantled.

Of the various numerical models which have been derived, the HRS model was intended only to study sedimentation effects and is not relevant to this study. The two models which are of direct interest are the IOS numerical model, which originated in the early 1970's and is now used at the Thames barrier, and the more recent computational hydraulic model (ONDA) by Halcrow which was used for two recent studies concerning Teddington weir and the operation of Richmond sluice.

4.1.1 IOS Model

The IOS model was originally developed by Rossiter and Lennon in 1965 and received various refinements during the early 1970's. In 1974 the model was interfaced to a two dimensional model of the southern North Sea. Since then only minor refinements to the barrier equations and to the calibration have been made. This model is now used at the Thames barrier although not in real time mode. Operation of the barrier is based on the Meteorological Office's forecasts from their North Sea models (see Section 4.3.1). The IOS model uses an explicit finite difference scheme for which there are more strict limitations on time and distance steps than are required with implicit schemes. The time step adopted in the present model formulation is 3 minutes and the longitudinal distance step varies from 1 mile above Tower Pier increasing to 6 miles at Southend. The model covers the complete length of river from Kingston down to Southend in 44 steps and includes the lower Medway estuary. The Chezy friction formula is used and the friction coefficients are allowed to vary with stage. The convective term is omitted from the momentum equation in the finite difference scheme and an allowance for this is made by adjusting the friction coefficients. Staff at the Thames Barrier are confident that the model reproduces conditions satisfactorily in the vicinity of the barrier but are less sure of accuracy towards the upstream boundary. There is no quantitative analysis of accuracy available for the IOS model.

4.1.2 The ONDA Model

The ONDA model, is a very flexible analytical tool and incorporates an implicit finite difference scheme which has much less stringent stability constraints than for explicit schemes, the complete St Venant equations are used. It has a sparse matrix routine to speed matrix solution and is data steered. The Manning friction equation is used and a range of options enable a variety of complex hydraulic structures, bank overspills, boundary conditions etc to be included readily in a particular model formulation. The model is at present calibrated to reproduce a complete month of normal tides covering the complete neap-spring-neap tidal cycle coupled with low fluvial flows. The model encompasses the reach from Teddington Weir to Gallions tide recorder near Woolwich in 50 distance steps averaging about 1 km each and has used time steps of 10 minutes. Reproduction of observed conditions is very satisfactory. For the current application it will be necessary to recalibrate and check the model for high fluvial flows coupled with a high surge tide, since under these conditions the channel roughness could change due to changes in bed forms.

4.1.3 Choice of Model

As far as a choice between the two models is concerned, the ONDA model has been recommended since it is potentially more accurate, includes the latest developments for one dimensional computational hydraulic river models, and covers a wider range of options than could be achieved with the IOS models.

From a technical standpoint it is preferable because:

- it will permit tributaries to be joined to the main Thames in case interactions have to be studied,
- it is of known and satisfactory accuracy in its low flow calibration,
- IOS model is an unknown quantity in upper tidal reaches,
- ONDA incorporates the full dynamic flow equations which is important in tidal flow,
- it permits a longer time step,
- it easily permits different control rules and tributary barriers to be included.

Logistically it is preferable because:

- use of the IOS model at the Barrier would be impractical,
- transfer to Halcrow and the associated learning curve more time consuming than extending ONDA.

Minor modifications and extension required to the existing ONDA model are not considered to be significant disadvantages compared with the positive points. The small cost of extending ONDA down to Southend would also be offset against the time taken to transfer and familiarise with the IOS model. In short, adoption of the ONDA model would be the most cost effective option.

The third option which was available, operation of the two models in tandem, has been discounted both from a logistical standpoint and because of the difficulties which would be encountered at the boundary between the two models. The most obvious choice for the interface is the barrier site, but it is now seen that this could not be achieved since different boundary conditions prevail at different stages of the tide.

In conclusion, it has been recommended that the ONDA model is the most cost effective option, and should be extended and modified to include the whole reach from Southend up to the tidal limit above Kingston.

4.2 Extension of the Tidal Thames ONDA Model

Verbal approval was given at the progress meeting of 14th May 1987 to go ahead with optional stage 1a to extend the ONDA model and to include the Thames barrier in preparation for application in subsequent stages. This component is now complete and work is now continuing to recalibrate the model under Stage 2 of the study. Details of work which was required to extend the model are given below.

4.2.1 Topographical Data

Extension of the ONDA model required additional cross sectional data in the reach between Southend and Gallions tide recorder. Initially it was intended to use data from the IOS model at the Thames barrier; however, cross sectional data were not readily available although hydraulic properties of the river (Cross sectional areas and hydraulic depths) for a range of levels were obtained and used in preliminary runs of the model. More up to date data were then taken from the Port of London Authority hydrographic charts, which date from surveys made in 1983 and 1984. Cross sections were taken at spacings varying from 1.0 km at Gallion's reach to 2.5 km at the seaward limit. Locations of cross sections are shown in Figure 4.1.

Spring tides of insufficient severity to close the barrier quite often pass over Teddington weir, which was previously nominated as the upstream boundary of the model. As a result the upstream limit will now be moved to Molesey Locks. Cross sectional data for this reach has been taken from the data base for the river Thames model which is being developed concurrently in a separate study by the Consultant. The upper Thames modelling team has downloaded and transcribed this data which has now been included in the tidal Thames model.

4.2.2 Thames Barrier

The Consultants have recently developed a new routine for the ONDA model to include structures with multiple radial or vertical sluice gates. This routine enables the Thames barrier to be included in the model. The main gates for the Thames barrier are rising sector gates which differ from conventional radial gates in two respects: the gates rise from the bed rather than fall from an overhead position, and have a permanent gap beneath so that both overshot and undershot flow occurs simultaneously during closure. These conditions are now included in the ONDA model.

Figure 4.1
PLAN OF TIDAL THAMES
SHOWING LAYOUT OF MODEL

During Stage 2 of the study the extended ONDA model will be recalibrated using a variety of recorded events with various combinations of upstream flows and tidal boundary conditions. The model will then be applied to define the structure functions illustrated in Figure 5.1 at various locations thorughout the tideway.

5. OPERATION AND EFFECT OF THE THAMES BARRIER

5 OPERATION AND EFFECT OF THE THAMES BARRIER

5.1 Operation of Barrier

The Thames tide barrier was commissioned in late 1982 with the object of excluding high surge tides from the tideway through London. It has a dominating influence on the upper parts of the tidal level probability distribution. The barrier consists of four falling radial gates and six rising sector gates which can be closed in advance of a forecast high sea level. Its operation is at present determined primarily by high water at Southend and upland flows past Teddington/Kingston. The operating criteria are that the barrier should limit the maximum water level at London Bridge to 4.85 m. Its design criteria is that it should cope with the 10,000 year return period event (assessed for the year 2030).

As a matter of routine the barrier operations centre receives a surge forecast for Southend from the Storm Tide Warning Service (STWS), part of the Meteorological Office, 12 hours prior to each high tide. The STWS uses two methods: a mathematical model of the North Sea area and a regression equation using input data received from more northerly sites and meteorological observations. An average of the two is normally used as the basis of advice sent to users although judgement may be applied to weight in favour of one or the other forecasting procedures. The particular forecast level used in the barrier operation decision is that for the time of high tide itself, although hourly information is available from the North Sea model. The STWS also issues a seven hour and a three hour forecast, the latter based upon Lowestoft observed residual. However only the 12 hour forecast is usable in view of the requirement to close near to low tide and to serve notice to PLA and other interested authorities. The decision to close the barrier is based on the forecast tide peak, perhaps adjusted using the forecast errors at Southend prior to the current point in real time. The barrier gates are closed in pairs, each pair taking 10 minutes to close, and full closure of the barrier is usually spread over about one hour. Closure would normally be achieved within 2 to 3 hours after low tide, but under very severe conditions barrier staff would aim to complete the operation as soon after low tide as possible.

When the barrier is closed water continues to enter the tideway beneath the main rising sector gates through the permanent 20 cm gap. The discharge beneath the gates (on closure) is of the order 100 m^3/s for a difference in water levels of 3 metres across the barrier. Water also enters from the upland catchments, principally the Thames upstream of Teddington, the Lea and other tributaries within the London area.

The total upland catchment area is about 1000 km^2. The barrier operation procedure allows for this by adjusting the closure level at Southend according to the current discharge at Teddington/ Kingston. Thus, for example when the Teddington discharge is 10,000 MGD (525 m^3/s) the action level at Southend is 3.35 m, whereas when the discharge is only 2000 MGD (105 m^3/s) the action level at Southend increases to 3.80 m.

It has to be appreciated that the action level at Southend is itself a forecast quantity and hence entails an inevitable error. The degree of error has not been fully investigated but indications from STWS reports are that a 0.28 m rms error is to be expected. This is borne out by experience which also indicates that considerably larger underestimates are possible. Factors such as past experience, forecast error, height of low tide, and trend in upland discharge can vary the time and the rate of closure. Barrier operations staff attempt to take forecast errors into account by comparing forecast and recorded levels at low water at Southend prior to making the decision to close the barrier.

5.2 Effect of Barrier on Water Levels

The impact of the barrier can be viewed in two ways: (a) the impact on the course of events over a specific high tide cycle, and (b) the influence on the statistical distribution of levels upstream.

5.2.1 Effect During a High Tide Event

The Thames barrier has been closed in earnest on three occasions up to date: on 1 February 1983, 26 December 1985 and 27 March 1987. Information for the first two closures has been obtained from PLA and Thames Water. The barrier is currently operated to protect Central London from abnormal tides with a surge component. Normal spring tides (astronomic) without surges are allowed to pass through. Thames Water barrier staff have stated that for events for which the barrier is closed the resulting upstream water levels are certainly not higher than might be reached in conditions which would not require barrier closure under statutory requirements.

Examples of the effect of Thames barrier closure is demonstrated in Table 5.1.

Table 5.1 Effect of Barrier Closure

Location	Maximum Levels		
	27/12/85	1/2/83	26/12/85
Southend	3.1	3.7	3.3
Tower Pier	3.2	1.5	4.6
Richmond	3.7	2.0	4.9
Fluvial Flow (mean daily in m^3/s)	408	219	319
Closing time (hrs after low tide at barrier)	3.5	1.0	
Barrier state	closed		open

From the three events presented in Table 4.1 it seems clear that the highest levels experienced now that the barrier is operational do arise from non-closure conditions. For example, the monthly report for December 1986 of the London planning section of the Thames Water Rivers Division noted flooding along the upstream section of the tidal Thames under such non-closure conditions.

The impact of the barrier clearly diminishes as one considers points further upstream. For example the figures of Appendix C of the Crane Preliminary report indicates the larger influence of the fluvial contribution at Richmond compared with Hammersmith. However the relative contribution of fluvial and tidal components to level in the whole tideway is not certain at present.

5.2.2 Effect on Statistical Distributions

Figure 5.1 illustrates diagrammatically the general procedure for obtaining the probability distribution of a derived quantity, such as the stage at a point along the tideway, from primary variables such as sea level and upland flow. Two sets of relationships are required. The first relationship, termed the structure function and illustrated by the broken lines on Figure 5.1a, is the locus of

Figure 5·1

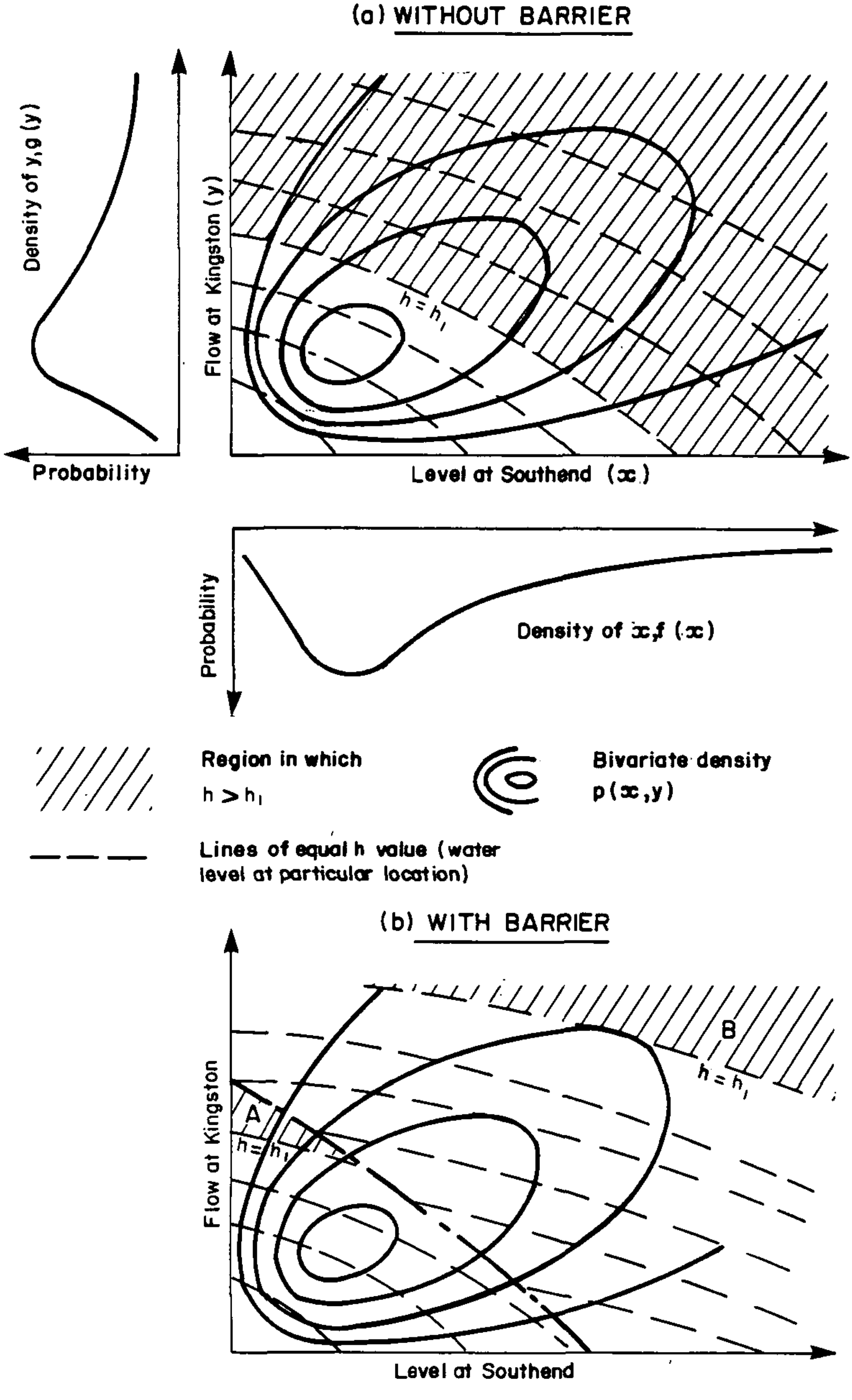


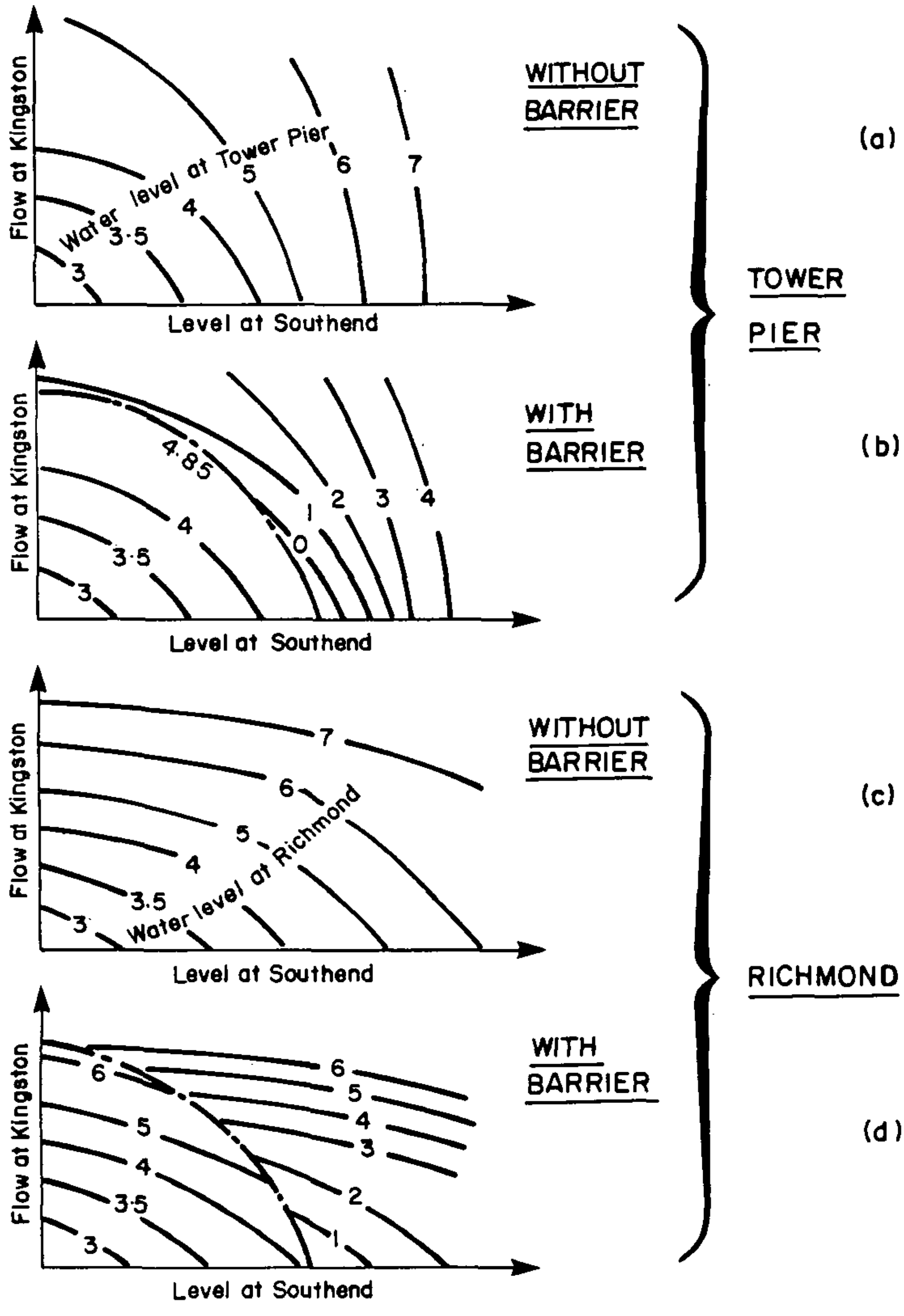
ILLUSTRATION OF METHOD OF COMBINING PROBABILITIES constant levels. The second set, the full lines on Figure 5.1a, shows the bivaraite distribution of sea level and upland flow and are lines of equal probability density. If the two variables are independent the bivariate probability density function is obtained as the product of the two "marginal" densities. The volume under the bivariate surface beyond some chosen level gives the probability of exceeding that level. Note that the bivariate surface is a constant for an estuary whereas the structure function varies from point to point.

This last point is illustrated in Figures 5.2a and 5.2c where the "without barrier" lines for Richmond are much more nearly parallel to the tide axis than those for Tower Pier where the tidal influence is more dominant. The barrier operation influences the structure function dramatically, as illustrated in Figures 5.2b and 5.2d. A literal interpretation of the operating rule would be to cut off the curve at 4.85 on Figure 5.2a as shown on Figure 5.2b. In application the structure function might be more complex to allow for uncertainty in the forecast leading to unnecessary or delayed closure. One way the forecast uncertainty could be incorporated would be to attach probabilities of barrier operation across the range of tide:flow combinations, as shown in Figure 5.3. The effect of variations in timing of closure would be to change the pattern of the structure function above the barrier closure line.

It is likely that the situation at Richmond is rather different than further downstream as the flatter structure curve leads to the barrier operations permitting higher levels for high flow events.

This is illustrated in Figure 5.2d. Application of the ONDA model will assist in the definition of the shape of the "barrier closed" curves. Difficulty will be experienced in assessing the effect of uncertainties in the forecast as illustrated in Figure 5.3, on the operation and hence on the choice of "barrier closed" or "barrier open" curves for particular cases.

The Thames barrier has changed the probability distributions of water levels in the tideway dramatically. The new distributions were shown above to depend on a complex interaction which is dominated by the Thames barrier operation. It is essential that barrier operations are simulated, and the three barrier closure events will therefore feature in the calibration procedure.



Barrier closure line

—5— Max. water level at specified location

NOTE Water levels shown are illustrative and do not relate to the actual situation.

ILLUSTRATION OF POSSIBLE EFFECTS OF THAMES BARRIER ON WATER LEVELS

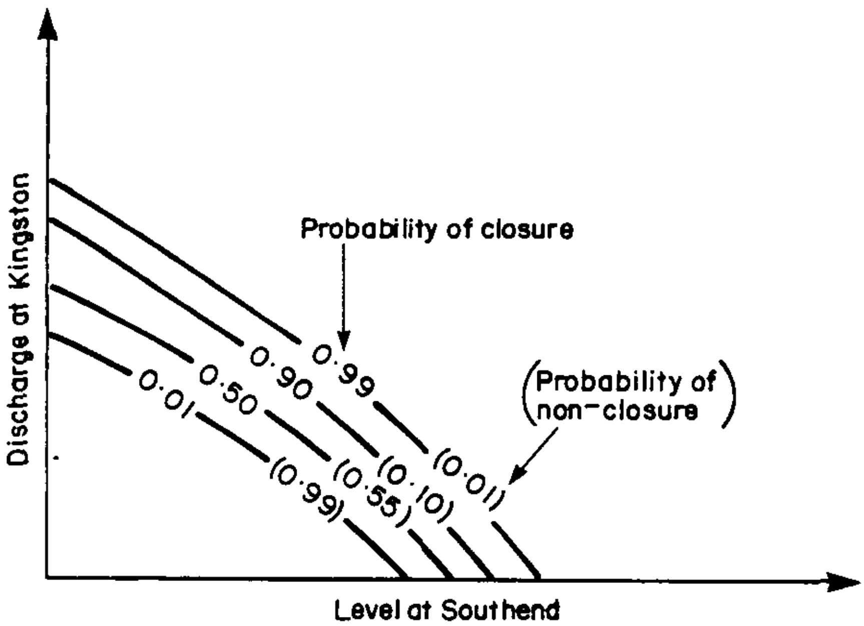


ILLUSTRATION OF PROBABILITY OF BARRIER CLOSURE

6. CONCLUSIONS AND RECOMMENDATIONS

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Completed Analyses

The purpose of the stageing of the study is to permit Thames Water to review its needs for further analysis in the light of what has been discovered to date. This report describes the data that have been collected or identified as available for both tide levels and tributary discharges, and presents preliminary statistical results for two tributaries, the Crane and Lee, regarding their discharge and level frequency relationships (sections 3.1 and 3.2)..

The basic procedure that would be followed in order to derive stage frequency relationships for intermediate points has also been identified. This consists of combining a hydraulic model of the estuary, in which intermediate levels can be predicted from tide and fluvial inputs, with a statistical description of the combined occurrence of those two main variables as illustrated in Chapter 5. Sample preliminary statistical descriptions of the primary variables are shown in section 3.3.

A review of hydraulic modeling requirements has been made and is summarised in Section 4. The ONDA model is to be used and the necessary modifications and extensions to the model are complete, although the model has not yet been recalibrated.

6.2 Recommendations for Stage 2 Analysis

In the terms of reference Stage 2 of the analysis would be devoted to the derivation of stage frequency distributions for intermediate points along the tideway in order to define defence levels up to 1,000 year return period.

At the outset it was supposed that the barrier's impact on this computation of intermediate stage frequency would be accommodated relatively simply by making the necessary adjustment to the tide frequency distribution to allow for post barrier conditions. This may not be the case. The barrier operation is a rather complex funtion of predicted (astronomic component) high tide at Southend, forecast surge residual 12 hours ahead for Southend, and Teddington/Kingston discharge. To this must be added rather inderterminate elements to allow for the incorporation of forecast errors plus the influence of operational constraints on barrier closure. Consequently the work to be carried out during Stage 2 will not deviate significantly from the original proposal and will include, the following:

Calibrate functional relationship to predict water levels at intermediate tide gauges from the primary boundary variables, by model simulation and anlaysis of stage records, allowing for the dominant effect of the Thames barrier. Determine influence of supposed secondary effects eg tributary inflow, hydrograph and tide and surge shapes.

Derive probability distributions of daily stage at intermediate tide gauges and convert to annual maxima. This will give the frequency of overtopping of defences of specified heights at tide gauges from Teddington to the Thames Barrier.

Calibrate a simple relationship between the primary variables and stage at intermediate points to reduce the number of hydraulic model runs. This may be based on a regression relationship or on a simplified hydraulic formulation. Use this to prepare longitudinal profiles through the tidal reach down to the Barrier.

Probability distributions of water levels at a given point in the tideway can be derived using methods illustrated by Figures 5.1 to 5.3. At present the exact form of these diagrams is not known, especially in the way the probability distribution overlays the structure function. Also, for the existing case (with Barrier closures) the form of the structure function above the Barrier closure line cannot be defined clearly without simulation results from runs of the hydraulic model. To clarify these points two interesting scenarios would be analysed using the hydraulic model as early as possible in the Stage 2 analysis:

(a) An extreme combination of a very high surge tide (say 1 in 1000 year) with a very high fluvial flow and barrier closure

(b) A very high fluvial flow coupled with the highest tide which is expected to be allowed to propogate upstream without barrier closure.

The results of these two runs, coupled with the analyses of water levels at intermediate tide gauges (particularly of Richmond and Tower Pier) would clarify the picture. One possibility is that the difference between water levels at low return period and those at high return period may be so small, now that the barrier is operational, that designs could be carried out using a "worst case" combination of tides and fluvial flows. This may very well reduce the work scheduled for subsequent analyses, if only with respect to Thames defence levels and not to boundary conditions and flows for tributaries. At present the indications are that this "worst case" would be of type (b) above. However the interactions are of such complexity that it is not possible at the present time to make an objectively based recommendation.