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Institute of Hydrology

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Natural Environment Research Council

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River Roding fluvial/tidal flood defence project

Phase I: Feasibility study

Report to the National Rivers Authority, Thames Region

January 1992

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Executive summary

1. As part of review of flood defences in the Thames estuary, the National Rivers Authority required an assessment of the probability of water levels up to a return period of 1000 years along the River Roding, from Redbridge to its mouth. Water levels are controlled by the interaction of Thames tidal levels and flows from the catchment upstream.

2. The Institute of Hydrology was contracted to undertake a feasibility study to ensure that adequate information was available to undertake the study frequency analysis of the water levels based on the joint probability modelling of coincident high Thames estuary levels and fluvial flows.

3. The Barking barrier spans the Roding at its mouth and when closed precludes all water from the Thames and thus removes the tidal influence. The barrier is closed and when the Thames barrier is closed or a high tide warning is given.

4. The generally slow response of the Roding catchment to rainfall suggests that daily mean flow data (1950-1991) from Redbridge provide an adequate time series for the analysis. Effluent discharged to the study reach from Beckton STW can be significant, but data were not available for whole period 1950-1990, thus they need to be generated synthetically.

5. Records of water level at various locations in the Thames estuary are available for the period 1950-1985. These can be used to derive a series of water levels at the mouth of the Roding. Data for 1986-1991 were required.

6. A hydraulic model had been constructed to provide structure functions relating water levels along the study reach to given fluvial flow and water levels at the mouth. Structure functions need to be produced for fluvial flow up to 64 m^3s^{-1} and for water levels at the mouth up to 5.0 m for conditions when the Barking barrier is open.

7. Further structure functions need to be produced for fluvial flow up to 64 m^3s^{-1} and for effluent discharge from Beckton STW up to 25 m^3s^{-1} for when barrier is closed.

8. For each node along the study reach a statistical distribution can be fitted to the annual maximum water levels to estimate return periods up to around 80 years.

9. For nodes upstream of the tidal limit the annual maximum floods for return periods up to 1000 years at Redbridge will be converted to stage.

10. The relationships between stage frequency at Redbridge and nodes along the study reach, up to the 80 year return period, can be derived. These relationships, and estimates of stage at Redbridge for higher return periods, can be used to extrapolate stage frequency curves for other nodes up to the 1000 year return period level.

11. It is estimated that Phase II of the study will cost not more than £16,000 plus VAT, including all staff time, computing and production of reports.

1. Background

As part of its review of the level of service provided by flood defences in the Thames estuary, the National Rivers Authority required an assessment of the probability of water levels exceeding critical values along the lower reaches of the River Roding.

Two major factors influence water levels in the lower Roding:

(1) water levels in the Thames at the mouth of the Roding; and
(2) fluvial flows from the Roding catchment;

Thames water levels are themselves controlled by the height of the tide and flows from the Thames catchment and are influenced by whether or not the Thames barrier is closed.

The lower Roding can be protected from high water in the Thames by closure of the Barking barrier, which spans the Roding at its mouth. Fluvial flows may be increased by effluent discharge.

A hydraulic model of the lower Roding had been developed to predict water level given any combination of Thames water level and Roding river flow.

The Institute of Hydrology was contracted to undertake a frequency analysis of the water levels up to the 1000 year return period, based on the joint probability modelling of coincident high Thames estuary levels and fluvial flows.

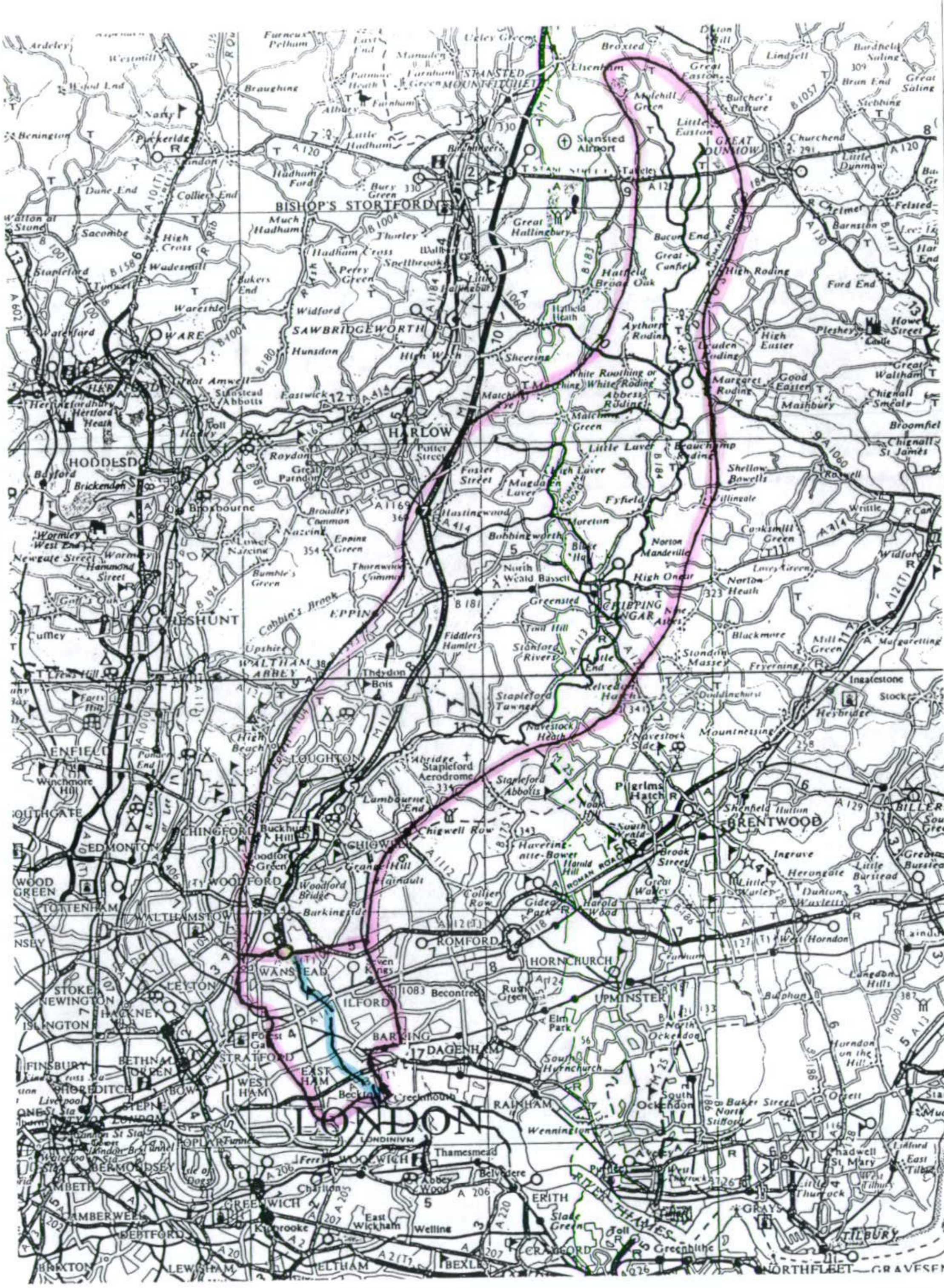
The study was divided into two phases:

Phase I: feasibility study to ensure that adequate information was available to undertake the study

Phase II: full stage frequency analysis

2. Introduction

The River Roding rises in north-west Essex and flows southward to join the River Thames at Barking, a length of some 50 km (Figure 2.1). The catchment is low lying and underlain by boulder clay on London clay with glacial gravels in the lower part of the catchment. The catchment is narrow with few major tributaries. The middle and upper reaches of the catchment are rural but the lower reaches are heavily urbanised.



catchment boundary
study reach
Redbridge flow measurement station

Figure 2.1 Location map

The section of river under study is the 10 km reach between Redbridge and the confluence of the Roding and the Thames. The lower part of this reach, called the Barking Creek, is tidal, the bed is composed of silt and water levels are influenced mainly by Thames tides. Normal high tide level in the Thames is 5.5 m AODN and the land adjacent to the Creek is, in places, as low as 1.5 m AODN. The Creek banks are protected by earth embankments and by the Barking barrier, which spans the river atits mouth. When closed the barrier precludes water from the Thames entering the Barking Creek. The middle section of the reach is slightly meandering, and its bed is composed of silt and gravel. Water levels are determined by the interaction of tides and fluvial flows. The riparian land is low lying and protected by embankments. Further upstream towards Redbridge, the channel bed is dominated by gravel, the river meandering and there are large variations in channel width. Water levels are controlled by fluvial flows with little tidal influence.

It is clear that stage frequency at the upstream end of the reach will be controlled by the frequency of fluvial events, whereas at the downstream end the stage frequency will follow that of the tidal Thames. Levels at intermediate sections will be controlled by both tidal levels and fluvial flows to degrees according to their location.

No significant tributaries join the Roding along the study reach, but flows may be augmented significantly by effluent discharges from a sewage treatment works.

Water levels in the Thames estuary are controlled by three components: the astronomical tide which varies according to a regular, predictable cycle; storm surges caused by adverse weather conditions in the North Sea; and fluvial flows from the Thames catchment.

3. Requirements for the study

Since water levels in the lower Roding are determined by the interaction of Thames estuary levels and fluvial flows, calculation of a stage-frequency relationship requires an analysis of the joint probability of coincident estuary levels and fluvial flows and the resulting water level. This analysis requires:

(a) a time series of the flows in the River Roding;

(b) a concurrent time series of levels in the Thames at its confluence with the Roding;

(c) a hydraulic model to provide water levels along the study reach given (a) and (b); and

(d) a statistical model to analyse frequency of resulting levels.

Each of these elements is discussed in detail below.

4. Fluvial flows from the Roding

Fluvial flows on the River Roding are measured at the Redbridge (TQ 415884), some 10 km upstream of its confluence with the Thames, where the catchment area is 303.3 km^2. This measurement station defines the upstream limit of the study reach. The station was established in November 1949 with construction of a broad crested weir beneath the road bridge. This was superseded in 1962 by an *Essex* profile (modified flat-v Crump) weir slightly upstream of the previous weir. Calibration of the weir above 35 m^3s^{-1} is based on model tests. All flows have remained within bank during the period of record.

The highest flow on record is 62.4 m^3s^{-1} which occurred on 22 November 1974, however, the peak flow during the 1947 flood (before the station opened) was estimated as 80 m^3s^{-1}. Figure 4.1 shows the annual maximum instantaneous peak flows (1950-1990) at Redbridge plotted against return period, T, using the Gringorten plotting formula:

$$F = (m-0.44)/(n+0.12) \tag{4.1}$$

where F is the non-exceedence probability ($F = 1-1/T$), n is the number of years of record and m is the rank of the ith maxima. Also shown on Figure 4.1 are curves representing the generalised extreme value (GEV) distribution fitted to the data by the method of probability weighted moments (PWM) and the results of applying the *Flood Studies Report* (NERC, 1975) regional growth factors to the at-site estimate of the mean annual flood. The *Flood Studies Report* recommends that floods of return period up to twice the record length only (in this case $2n = 82$) are estimated from the annual maximum data. Above this point the regional flood frequency curve should be employed. To effect this in practice the two curves need to be merged. This would produce a 1000 year flood estimate of around 136 m^3s^{-1}. For some distance below Redbridge (to where tidal influences become significant) fluvial flows will control water level. To derive stage frequency relationships up to the 1000 year level, in this reach, the hydraulic model will need to be run with input fluvial flows up to 136 m^3s^{-1}.

Daily mean flow data were available from the Surface Water Archive for the period 1950-1991. Clearly, flow varies during the day so that the daily mean flow series does not exhibit all the characteristics of the flow hydrograph. Nevertheless, provided that the flow does not vary significantly, a daily mean flow is adequate for the study. Indeed if the flow can be assumed to be constant over a tidal cycle, the analysis of the interaction of fluvial flows and tides is greatly simplified. This is assumption is considered further below.

Table 4.1 shows the physical characteristics of the catchment. The Roding is in one of the driest parts of the UK with mean annual rainfall only 635 mm and more extreme rainfall, M52D (the 5 year rainfall of 2 day duration) and RSMD (an index of flood-producing rainfall) are also amongst the lowest in the country.

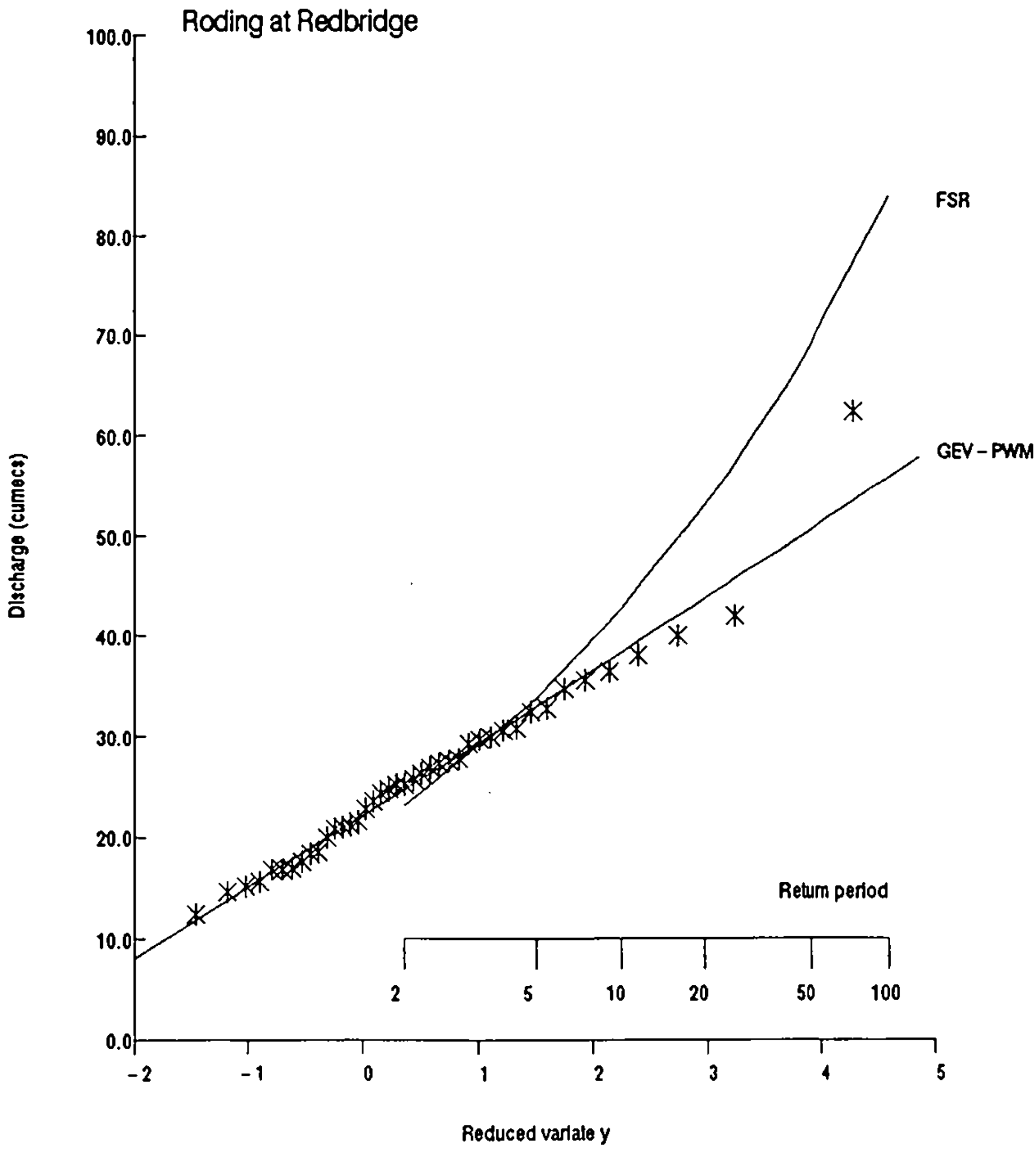


Figure 4.1 Flood frequency curves for the River Roding at Redbridge

The lower reaches of the catchments are underlain by soils which have a low, class 4, winter rain acceptance potential (WRAP), thus they tend to generate high runoff. The middle and upper reaches of the catchment contain more permeable class 3 soils. The baseflow index provides a indication of the proportion of runoff that derives from stored sources based on an arbitrary separation of the daily flow hydrograph. Catchments draining impervious catchments typically have baseflow indices in the range 0.15 to 0.35 whereas a chalk stream may have a BFI of 0.9 as a consequence of the high groundwater component in river discharge. The value of 0.4 for the Roding suggests that a high proportion of rainfall feeds the quick response component of the hydrograph.

As indicated above the urban 10% of the catchment is concentrated near to the gauging station. Hydrologists who have analysed data from the Roding suggest that, on some hydrographs, runoff from

Table 4.1 Physical characteristics for the Roding catchment

Morphological	
Drainage area (km^2)	303.0
Main stream length (km)	62.6
Main stream slope, S1085 (m km^{-1})	1.22
Stream density (junctions km^{-2})	1.17
Climatological	
Mean annual rainfall, SAAR (mm)	635.
5 year rainfall of 2 day duration (mm)	42.7
Index of flood-producing rainfall, RSMD (mm)	15.9
Land type	
Urban area (%)	10.
Lakes (%)	0.
Soil WRAP class 3 (%)	80.
class 4 (5)	20.
Hydrological	
Mean flow (m^3s^{-1})	1.86
10% flow (m^3s^{-1})	4.46
Base flow index	0.40

the urban part of catchment can be distinguished from main rural portion. Flow hydrographs typically exhibit a steady rise to a plateau with the main peak following with a lag of around 24 hours. The rising limb may be steep, of the order of 10 hours (eg. Figure 4.2), but is normally less severe, rising more evenly to a peak after around 48 hours (Figure 4.3). This indicates that a flow of slightly less than the peak is sustained over a least one tidal cycle.

Individual hydrographs show the response to a particular rainfall profile. The effect of rainfall profile shape may be eliminated by deriving a unit hydrograph for the catchment. In his review of the *Flood Studies Report* unit hydrograph rainfall-runoff analysis, Boorman (1985) included 13 flood events from the River Roding for analysis of percentage runoff. However, unit hydrograph parameters were available only for six of these due primarily to a lack of short duration rainfall data, although

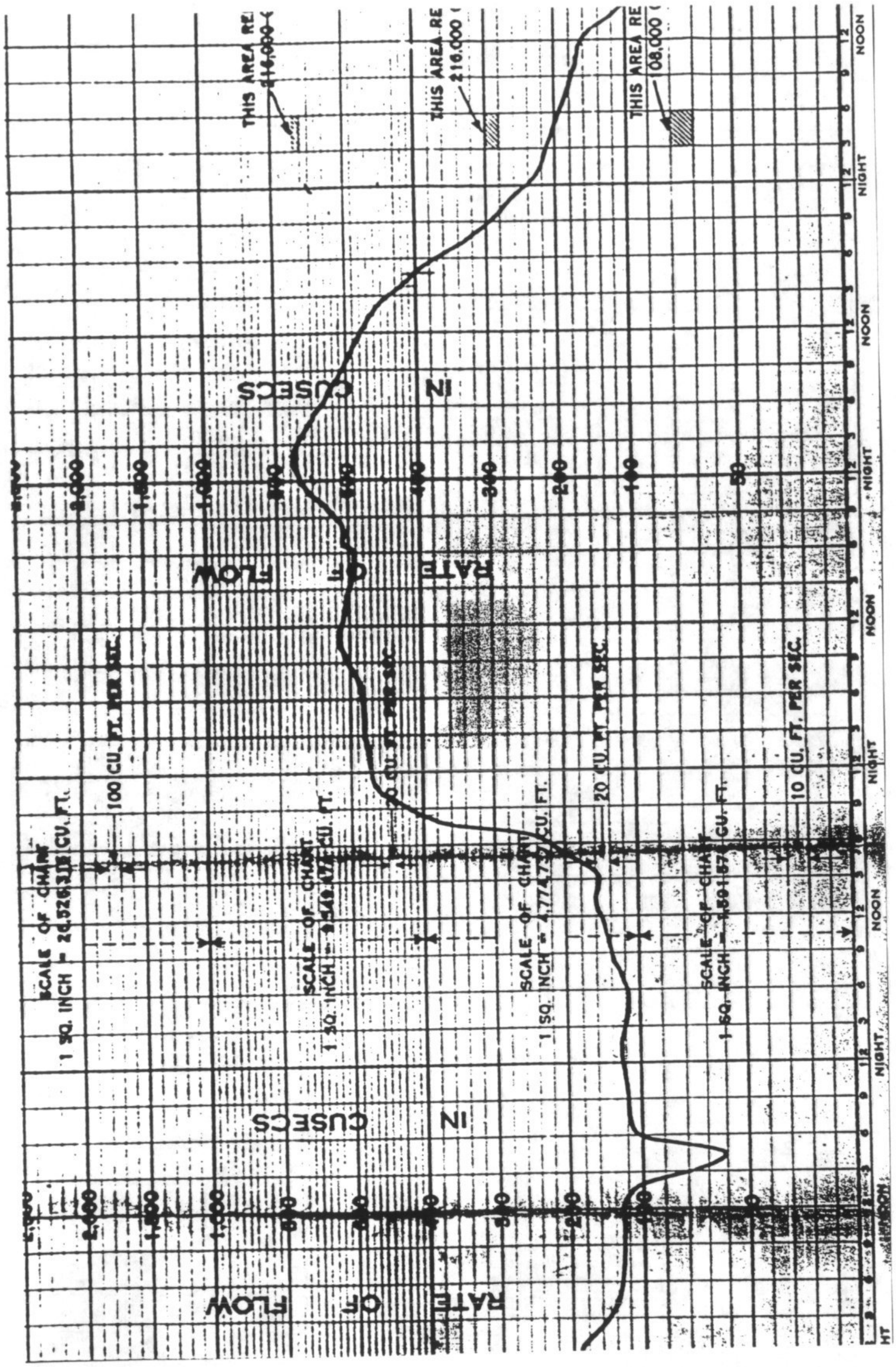


Figure 4.2 *Flow hydrograph for the Roding at Redbridge 26/3/54*

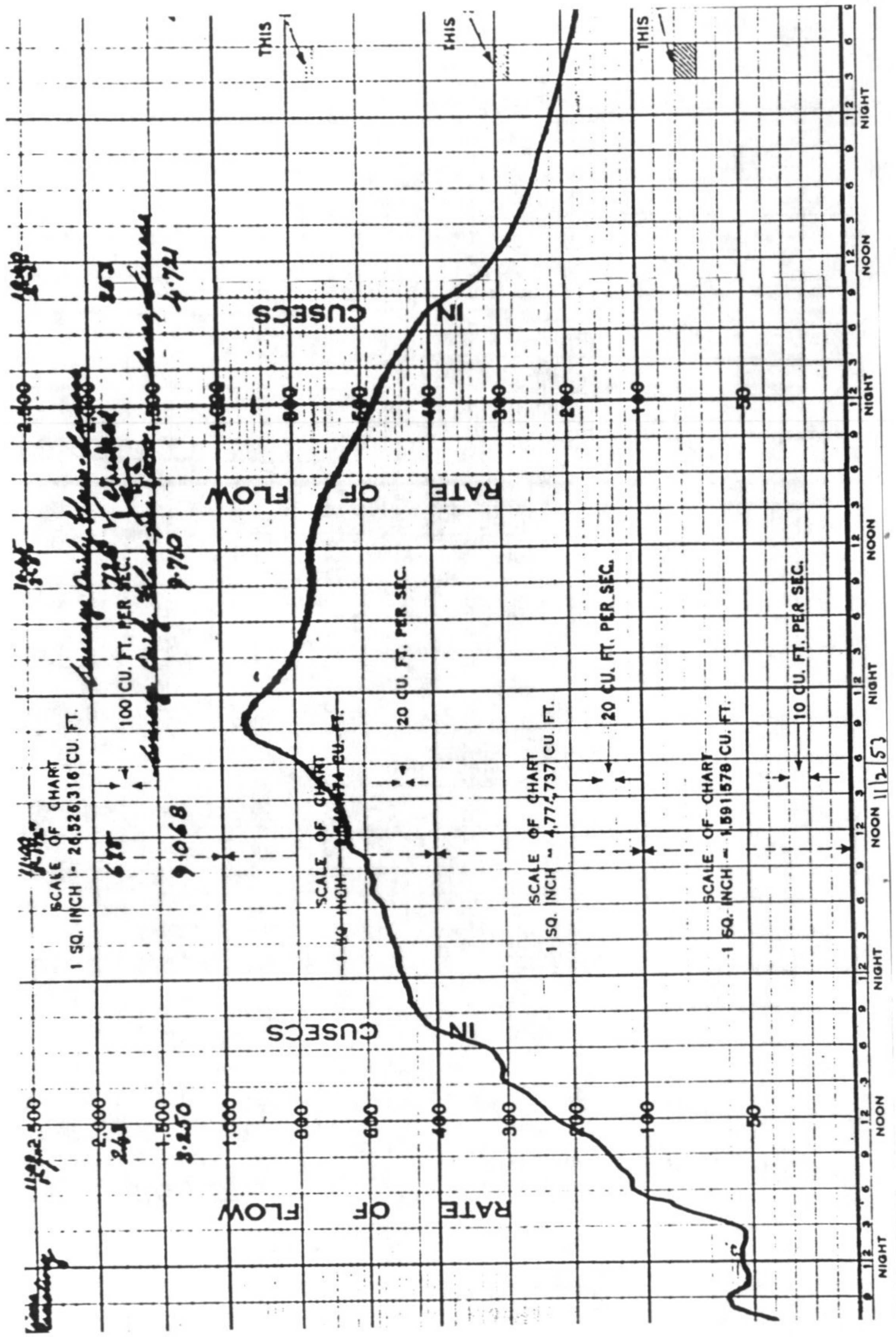


Figure 4.3 *Flow hydrograph for the Roding at Redbridge 9-14/2/53*

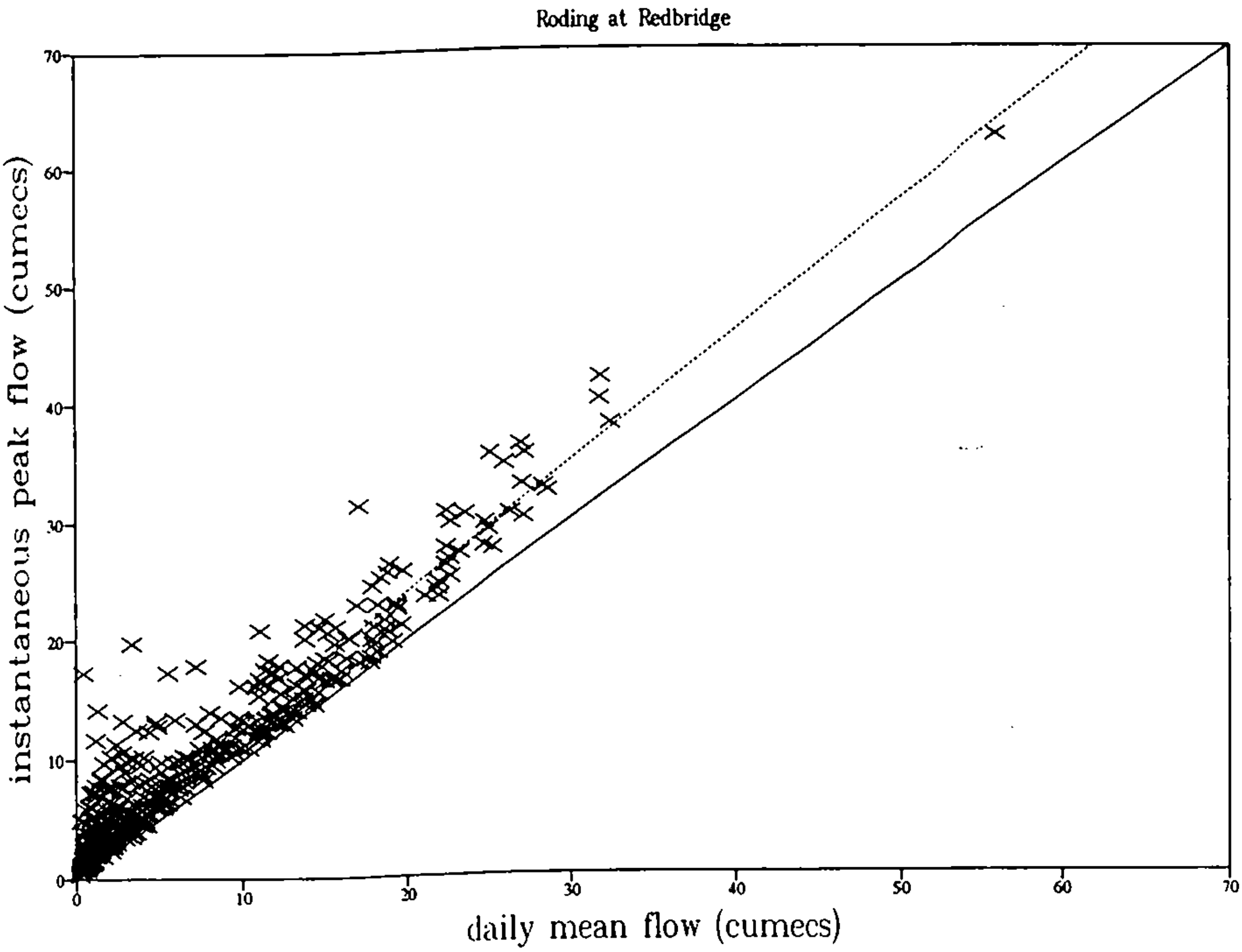


Figure 4.4 ***Highest instantaneous flows at Redbridge against mean flow for the day of the peak (m^3s^{-1}).***

some were rejected because the unit hydrograph was double-peaked. Time-to-peak of the one hour unit hydrograph ranged from 26.5 to 39.0 hours with an average of 33 hours. These results support the assumption that the Roding exhibits a relatively slow response to rainfall and that daily mean flows provide an adequate description of the flow hydrograph.

An alternative method of assessing the variability of flow in the catchment is to consider the ratio of mean to peak flow. Figure 4.4 shows a graph of the highest instantaneous flow in each month of the record (1950-1990) plotted against the mean flow for the day of the peak. It is noteworthy that even for the highest daily mean flow, 56.1 m^3s^{-1}, the peak was only 62.4 m^3s^{-1}, ie. 11% higher. The solid line in Figure 4.4 represents a one-to-one relationship, whereas the dotted line resulted from a least squares regression:

$$Qmax = 1.99 + 1.10\ Qmean \qquad (r^2 = 0.92) \tag{4.2}$$

The line slope of greater than unity shows a tendency for a greater difference between the peak flow (Qmax) and the mean (Qmean) for that day. The relationship is influenced by a large number of small events where the peak is only slightly greater than the mean flow, but provides an adequate model.

Below Redbridge no major tributaries enter, but there is some lateral inflow from a higher urbanised riparian area. Runoff from this area will most likely be very rapid, reaching the Thames before the main flood peak arrives from Redbridge. Hence it is unlikely that the peak flow will be increased.

It is concluded that, ideally, flows of shorter duration than one day should be used since many hydrographs show a rapid variation in flow on the rising limb which could coincide with a surge tide. However, a flow slightly less than the peak is normally sustained for longer than a tidal cycle and the peak flow itself tends only to be a few percent higher than the plateau. The daily mean flows, adjusted to estimate the peak using equation (4.2), provide an adequate time series for the analysis.

In addition to lateral inflows below the gauging station, flows may be augmented from effluent discharges. This is considered next.

5. Discharges from Beckton Sewage Treatment Works

Beckton STW is sited on the right bank of the Roding at its confluence with the Thames. It has a design peak output capacity of 31.25 m^3s^{-1}. At low tide this is discharge directly into the Thames via the Beckton outfall. However, when the Barking barrier is closed, effluent from Beckton is discharged into the Roding via the auxiliary outfall, about 150m upstream of the barrier. The discharge is not diverted at low water when the Barking barrier closes, but is delayed until the Thames reaches a level at which effluent stops flowing from the treatment works and above which reverse flow would occur. As soon as the Thames level falls back below this critical level, discharging directly to the Thames is resumed. These actions minimise water levels behind the barrier. Unfortunately there are no records to quantify this critical Thames level at which water would start flowinf into the works although bed of the outlet culvert is thought to be at 4.0 mAODN). However, according to the operators at Beckton, the Barking barrier had always been closed on past occurrences. The Thames and Barking barrier close when the level at London bridge will reach 4.87 mAODN (see section 7 below), this is equivalent to a level at the mouth of the Roding of between 4.4 and 4.7, depending on the combination of tide level and Thames flows. Thus the minimum level that effluent discharge from Beckton is diverted to the Roding is 4.4 m. This datum is used below.

Flow into Beckton STW comes from the main interceptor sewers in London north of the Thames. When flows to Beckton STW are very high, the Abbey Mills pumping station diverts some of the flow (up to 20 m^3s^{-1}) bound for Beckton into the Channelsea river, a tidal embayment in the River Lea system. A new overflow was being considered at Beckton to permit this extra flow to be discharged directly into the Thames.

The sewer 'catchment' draining to Beckton STW is around 300 km^2 (about the same as the Roding but all urban) extending from Hamersmith and Brent to Barking and its response time is considered to be around 6-7 hours. Effluent takes about 14 hours to be treated before it is discharged.

Daily mean discharge data from Beckton were available for all of 1987, most of 1989 and some of 1990. Figure 5.1 shows the 1987 discharges together with flows at Redbridge for the corresponding days. It can be seen that average discharge from Beckton is around 12 m^3s^{-1} and increases coincide with increases in flow at Redbridge as a result of storms crossing north London. However, it is also evident that there is a poor correlation between absolute values: high discharges from Beckton occurred during June, whereas flows at Redbridge were generally low. In contrast the high flows experienced at Redbridge in October and November were associated with only moderate increases in discharge from Beckton. Figure 5.2 shows discharge from Beckton for each day in 1987 plotted against flows at Redbridge. There is not a strong relationship between the two data sets, apart from the apparent decrease in variability of effluent discharge with increase in river flow, which may be a consequence of fewer data at high flows. The response of the sewer catchment is clearly much quicker than the river catchment, thus discharge from Beckton on one day might be related to flows at Redbridge on the following day. However, similar graphs to Figure 5.2, produced at lags of one and two days, showed a similar wide scatter of data points. Figure 5.3 shows histograms of discharge from Beckton for 1987 and for 1989. The two distributions have similar shapes and both exhibit slight positive skewness, but it is clear that discharges in 1987 were significantly higher. No changes to operating capcities or procedures were introduced between 1987 and 1989, thus it is assumed that the difference is due to meteorological conditions.

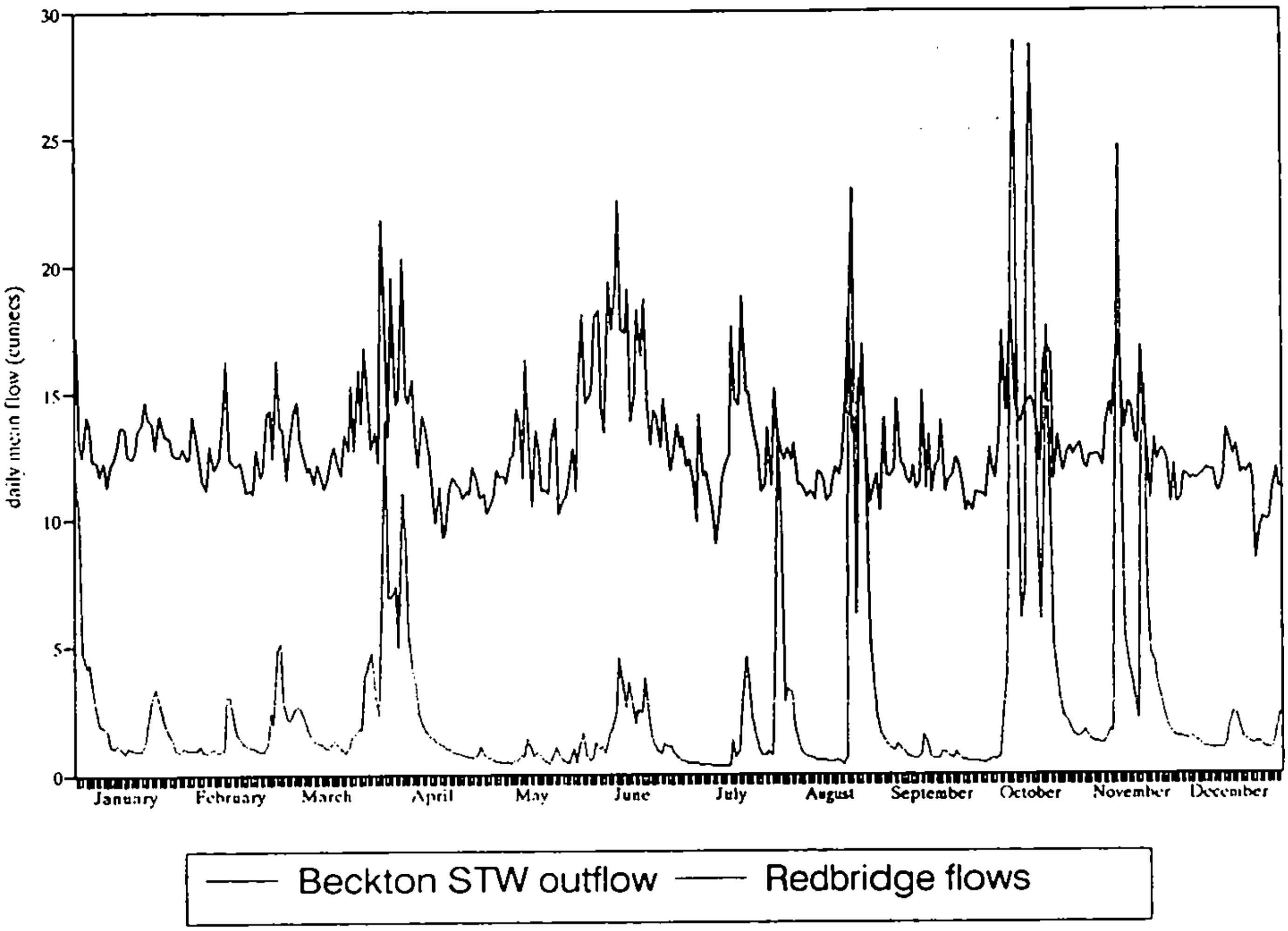


Figure 5.1 *Daily mean discharges from Beckton STW for 1987 together with daily mean flows at Redbridge for the corresponding days (m^3s^{-1}).*

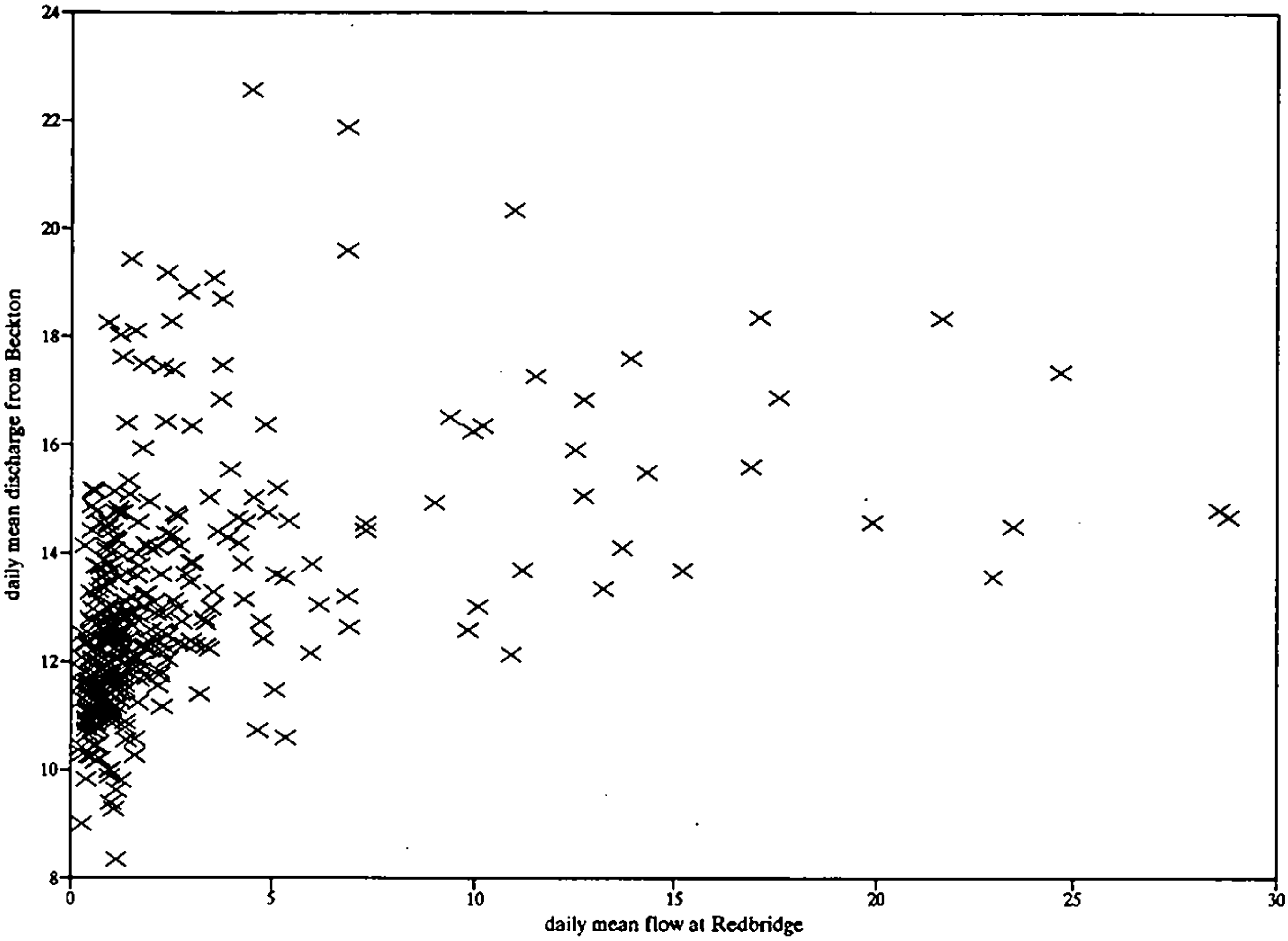


Figure 5.2 ***Daily mean discharges from Beckton STW for 1987 against daily mean flows at Redbridge for the corresponding days (m^3s^{-1}).***

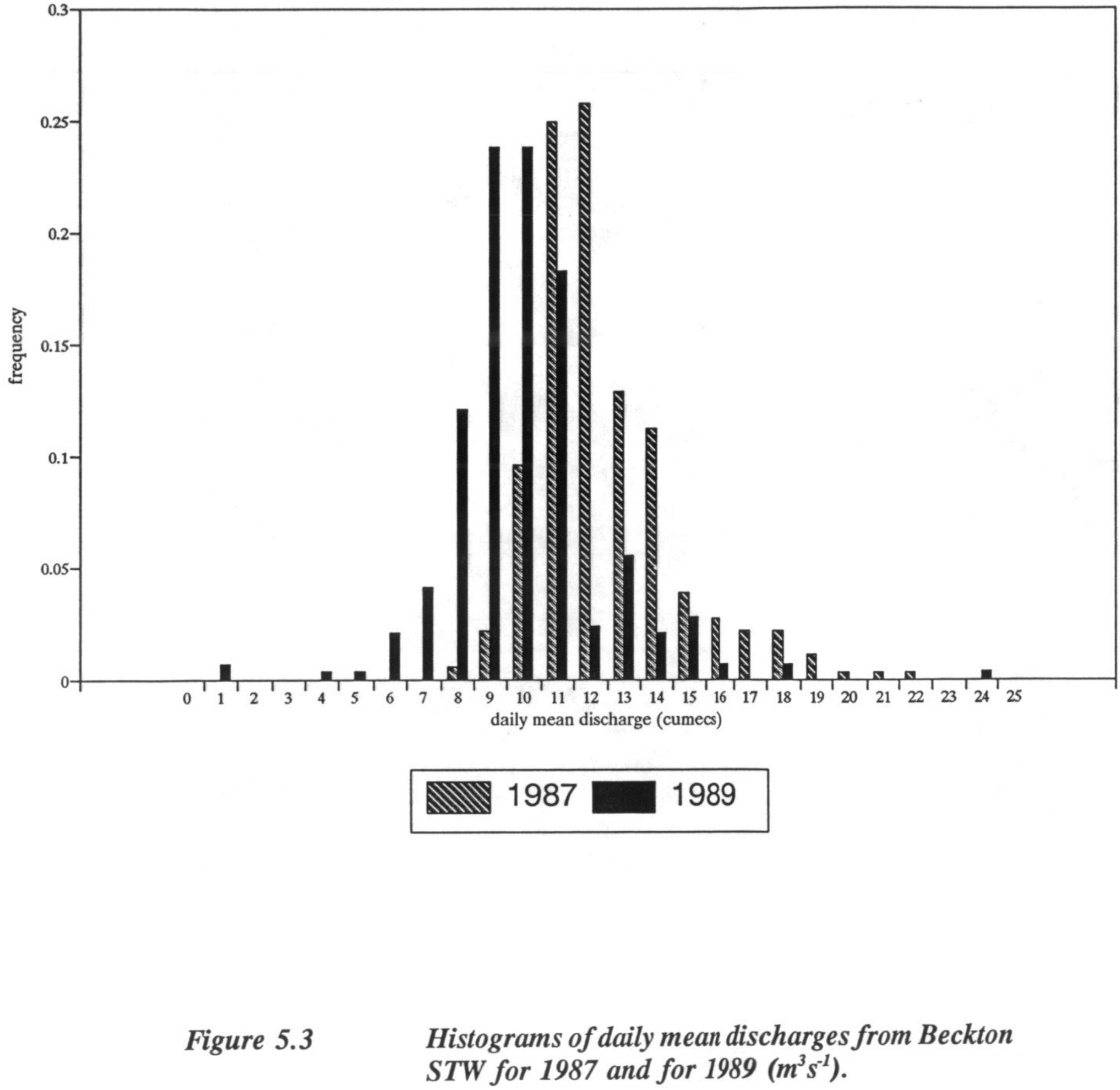


Figure 5.3 *Histograms of daily mean discharges from Beckton STW for 1987 and for 1989 (m^3s^{-1}).*

Indeed 1987 was considerably wetter than 1989, for example the total rainfall over the Roding catchment in 1987 was 727 mm (Institute of Hydrology, 1988), compared with 554 mm for 1989 (Institute of Hydrology, 1990). Insufficient data were available to compare these with 1990.

It was concluded that, since records of discharge from Beckton were not available for the same period as flows at Redbridge, they would need to be generated synthetically by sampling randomly from a frequency distribution for each day. The distribution would be derived by combining data for 1987 and 1989.

6. Water levels at the mouth of the Roding

A number of gauges have recorded tide level in the Thames estuary from 1950 to the present. The closest gauge to the River Roding mouth is Gallions, approx. 1.5 km upstream from the mouth and 4 km downstream of the Thames Barrier. Adjacent tide gauges are (u/s) Silvertown, just downstream of the Thames Barrier, and (d/s) Erith, approximately 8.5 km downstream of the River Roding mouth. Figure 6.1 shows the location of the Thames tide gauges. For the following tide gauges, water level maxima (one for each high water, two per day) were available in computer file (short missing periods are ignored):

Table 6.1 Available tide maxima data in the Thames estuary

Gauge name	Period of record
Southend	1 1 1939 - 31 12 1985
Gallions	1 1 1975 - 31 12 1985
Tower pier	1 1 1939 - 31 12 1985
Richmond	1 1 1939 - 31 12 1985

In addition, the daily mean flow at Teddington is given in the same file, as well as an indication of whether the Thames Barrier was open or closed during each tidal cycle. The file was compiled manually from tide gauge charts. Half hourly tide levels, from which maximum water levels can be extracted, were available on magnetic tape as given in Table 6.2.

In these data files no indication is given of Barrier closure dates. These data were compiled from computerised records of the automatic gauges.

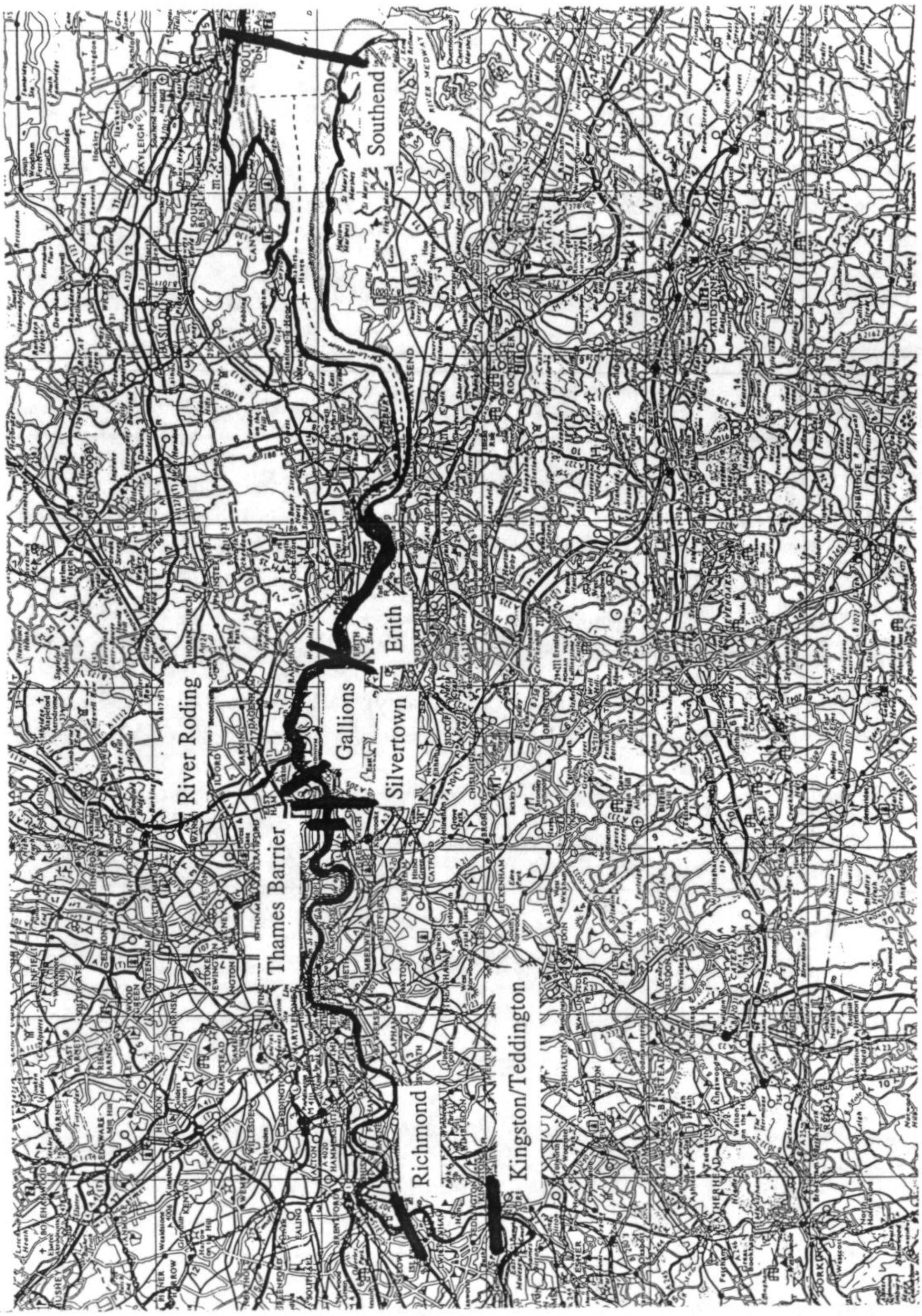


Figure 6.1 ***Schematic diagram showing tide gauges in the Thames estuary***

Table 6.2 Available half hourly tide data in the Thames estuary

Gauge name	Period of record
Erith	1 4 1988 - 30 4 1991
Westminster	1 10 1987 - 30 4 1990
Silvertown	1 9 1987 - 30 4 1991

No direct measurements have been made of water levels at the mouth of the River Roding. However, the unknown level at the River Roding mouth, can be derived from Molesey flow (synonymous with Kingston/Teddington flow) and Southend level data, using the appropriate structure function given in Tidal Thames Defence Levels report (Thames Water, 1988), each one of which gives the tide level at one point along the Thames as a function of the flow at Molesey and the Southend tide peak. Two structure functions are given for each site, one for a situation with the Thames Barrier open and one with the Barrier closed. Furthermore, the relationship between the maximum water level at any two points on the Thames may be found by comparing their respective structure functions.

Of the available structure functions the following may be relevant to the present study:

Richmond
Tower Bridge (very near Tower Pier)
Gallions
River Roding
Erith

No structure function is available for Silvertown or Westminster. The following derivation of tide levels at the River Roding is feasible, given the available level data and structure functions:

Period	**Method**
1 1 1939 - 31 12 1985	directly, using structure function for River Roding. Data used: Southend levels, Teddington flows, barrier operation flag (from 1 11 1982).
1 4 1988 - 30 4 1991	indirectly, using structure functions for River Roding and Erith tide gauge. Data used: Erith level data. Data missing: barrier operation flag.

No data are available at present to estimate the levels at the mouth of the River Roding during the period 1 1 1986 to 31 3 1988. Whereas this represents only 2 years out of 52, they may be important for the study because of the actual operation of the Thames barrier. Data are therefore required for Southend for 1986-1988 and, ideally, for 1989-1991 as well.

The study aims to estimate return periods of levels at the present situation, with the Thames Barrier in place. It will therefore be necessary to derive from the historic records of levels and flows in the Thames when the Barrier would have been operated in the past, and adjust calculated levels at the Roding mouth accordingly using the appropriate structure function.

The maximum level reached at Southend over the period 1950-1985 was 4.6 m (with a Thames flow of 72 m^3s^{-1}); this is equivalent to around 5.3-5.4 m at the Roding mouth.

7. Operation of the Barking barrier

The Barking barrier is sited at the mouth of the Barking creek. It was designed on tidal surge levels with a 1000 year return period in the year 2030 AD and came into operation in 1982. The barrier comprises of three vertical drop gates. The central gate is parked high to allow the passage of shipping, whereas the two side gates are parked just above normal high water level.

The Barking barrier is closed when the Thames barrier due to be closed. The Thames barrier is closed if the controller believes that, without closure, the water level at London Bridge will reach 4.87 mAODN. The assessment is made on forecast levels at Southend produced by the Storm Tide Warning Service (STWS) and flows at Teddington as given in Table 7.1.

Table 7.1 Rules for closing Thames and Barking barriers

	Southend level (mAODN)	
Thames flow mgd (m_3s^{-1}	Action level	Closure level
1000 52.6	3.55	3.85
2000 105.2	3.50	3.80
3000 157.8	3.50	3.80
4000 210.4	3.45	3.75
5000 263.0	3.40	3.70
6000 315.6	3.35	3.65
7000 368.2	3.30	3.60
8000 420.8	3.25	3.55
9000 473.4	3.15	3.45
10000 526.0	3.05	3.35
11000 578.6	2.95	3.25
12000 631.2	2.85	3.15

A list of actual closures of the Thames barrier was examined. The barrier had been closed routinely at low water for testing and on 10 occasions for flood protection purposes. Only during one closure would the level at London Bridge have exceeded 4.87 m. On the other occasions the actual level would not have reach 4.87 m.

Once the decision to close the Thames barrier has been made staff at the Barking barrier are alerted. The main gate of the barrier weighs 300 tonnes and takes 45 minutes to close ie 35 minutes for the central gate to fall from the 'parked' position to the water level and a further 10 minutes to reach the river bed. When closed the barrier precludes all water. Thus, ideally, the barrier is closed at low water to allow maximum storage for fluvial flows from upstream and effluent discharge. This will be six hours before high water. The Thames Barrier closes four hours before high water, thus if the STWS steps down its warning within two hours of the Barking barrier closing, the Thames barrier may not close (although this has not happen in practice). In contrast, the Barking barrier will always be closed if the Thames barrier is closed.

The Barking barrier can only be opened when water levels on either side are equal. Normally this would be on the next low tide after closure (ie 12 hours later), since surges do not last for two tidal cycles, but the exact timing will depend on the level of water which has built upstream behind the barrier.

It has been found unnecessary to close the barrier during normal tides but only if a high water level is enhanced by a surge.

The barrier operation rules have important consequences for the stage frequency relationship. At the downstream end of the study reach water levels are controlled by levels in the tidal Thames up to a level where the Barking barrier will close (about 4.4 - 4.7 m depending on the combination of tidal level and Thames flow) and water levels in the lower Roding will be controlled by fluvial flows ponding behind the barrier. Flows will be augmented by discharges from Beckton STW when the level exceeds 4.4 m. The hydraulic model will need to be run continually for an entire tidal cycle with constant inflow to see if, following a barrier closure, significantly high water levels result.

It is clear that closure of the barriers relies on the judgement of the operations manager. To determine whether, given perfect forcasts of water levels, the barrier would have been closed during historical events, had it been built, Table 7.1 can be used. However, in practice the barriers are closed more often. To investigate the implications of this a sensitivity analysis should be undertaken. This will involve deriving level/frequency curves for the Roding study reach assuming that the barriers close at a lower level eg. when the level at London Bridge reaches 4.7 m (rather than 4.87 m). Alternatively, some a lower level could be related to the average level that water would have reached during actual closures had the barriers stayed open.

8. The hydraulic model

A study was initiated in 1988 to investigate the hydraulic performance of lower Roding from Redbridge to its confluence with the Thames in order to determine flood defence levels, to examine the effectiveness of the Barking barrier operation and to investigate potential improvements in flow control. The model used was ONDA which was developed by Sir William Halcrow and Partners and the study was undertaken by the NRA Thames Region Hydraulic modelling group. ONDA is a one dimensional model which uses the St Venant flow equations to relate stage and discharge at nodes about 200 m apart along the study reach.

Output from the model must make it possible to estimate the peak level resulting from any combination of fluvial flow and tidal level. If it can be assumed that fluvial flows are constant over a tidal cycle, the relative timing of tidal cycle and flood hydrograph can be ignored.

Derivation of water levels for frequency analysis up to the 1000 year level will require a different specification for model runs depending on the sections of the study reach:

1. In the reach above any tidal influence, and above the influence of discharges from Beckton STW when the Barking barrier has been closed at the previous low water, fluvial flows over the range 10 to 136 m^3s^{-1} (the 1000 year flood discharge) need to be routed through the model.

For the above, estimates of flood magnitude for each return period derived at Redbridge can then be converted directly to stage.

2. In the reach below the influence of discharges from Beckton STW, and when the Barking barrier has been closed, fluvial flows from Redbridge and effluent discharges from Beckton need to be examined. Structure functions will need to be determined which relate water level to:

   (a) fluvial flows from Redbridge over the range 1 to 64 m^3s^{-1} (the highest daily mean flow adjusted by Equation 4.2);
   and

   (b) discharges from Beckton STW works over the range 0 to 25 m^3s^{-1} (the highest recorded daily mean discharge), these need to added for a time period for which the Thames water level exceeds 4.4 m.

The length of time that water levels at the mouth of the Roding exceed 4.4 m needs to be established. For occasions where the level exceeds 4.4 m significantly it can probably be assumed that the duration does not vary greatly with the peak level reached. However, if there is a consistent variation in the duration of levels above 4.4 m, a third dimension to the structure function will be required:

(c) tidal levels over the range 4.0 to 5.5 m (from slightly below the level at which the barrier will be closed up to a level slightly above the maximum recorded between 1950 and 1985).

A further assumption made is that low water in the Thames (when the Barking is closed) is always sufficiently low that its precise level does not influence the initial storage available behind the barrier. To confirm this the properties of the Roding/Thames confluence will need to be examined using the hydraulic model and historical low water levels.

3. In the reach where tidal influence is significant, and when the Barking barrier is open, historical sequences of fluvial flows and tidal levels will need to be examined. Hence structure functions will need to be determined which relate water level to:

   (a) fluvial flows over the range 1 up to 64 m^3s^{-1} (the highest daily mean flow adjusted by Equation 4.2); and

   (b) tidal levels over the range 0 to 5.0 m (slightly above the level at the barrier will be closed).

It is assumed that all model runs will be undertaken by NRA and structure functions provided.

9. The statistical model

A water level/frequency relationship for Redbridge up to 1000 years can be derived directly by converting the results of flood frequency analysis (see section 4) to estimates to water level using the stage/discharge rating curve for Redbridge.

(a) For sections of the study reach below Redbridge but above significant influence from tides:

flows of return periods up to 1000 years, defined by the analysis at Redbridge, can be input to the hydraulic model to derive the equivalent water levels.

(b) For the sections influenced by tides:

water levels, derived by applying the daily series of recorded river flow, effluent discharge and tidal level to the appropriate structure functions, will be analysed. An appropriate extreme value distribution will be fitted to the data to estimate levels of specified return period.

For (b), since only around 40 years of data are available (1950-1991), it will only be possible to estimate water levels up to around the 80 year return period. To overcome this, the relationships between stage frequency above and below the tidal limit up to the 80 year return period will be examined. Using these relationships and estimates of stage above the tidal limit for higher return periods, stage frequency curves for nodes below the tidal limit will be extrapolated to the 1000 year return period level.

10. Recommended procedures to be adopted in main study

The following steps will be undertaken during the main study:

1. To generate of a series of levels for each high tide over the period 1950-1991 at the mouth of the Roding. This will be derived from data for tide gauges in the Thames estuary.

2. To produce a list of days when the Barking barrier was closed, or would have been closed (had it been build) for the period 1950-1991. It will be assumed that the Barking barrier will always have closed if the Thames barrier was (or would have been) closed, hence any effect on Thames levels effected by closure of the Thames barrier can be ignored.

3. To compile a series of daily mean flows on the Roding at Redbridge for the period 1950-1991. These data are available from the Surface Water Archive.

4. To generate a synthetic series of daily mean discharges into the Roding from Beckton STW. These data will generated by random sampling from a distribution fitted to the available data. The discharge will be assumed to be zero if the level of the Thames is less than 4.4 m AODN and positive if the Thames is equal to or above that level.

5. For each day of period 1950-1991 the status of the Barking barrier will be checked. If the Braking barrier is closed, water levels in the study reach will be derived by applying the flow at Redbridge and (for the section below Beckton) the discharge from Beckton to the appropriate structure function.

6. If the Barking barrier is open, water levels in the study reach will be derived by applying the flow at Redbridge and levels at the mouth of the Roding to the appropriate structure function.

7. For each node along the study reach the annual maximum water levels will be collated and a statistical distribution fitted. Return periods up to around 80 years will be estimated.

8. For nodes upstream of the tidal limit the annual maximum floods for return periods up to 1000 years at Redbridge will be converted to stage.

9. The relationships between stage frequency at Redbridge and nodes on other reaches up to the 80 year return period will be examined. Using these relationships and estimates of stage at Redbridge for higher return periods, stage frequency curves for other nodes will be extrapolated to the 1000 year return period level.

11. Costs and schedule

Phase II of the study is estimated at, not more than £16,000 plus VAT. This includes all staff time, travel and subsistence, computing and production of draft and final reports.

Additional expenditure for digitising Southend tide level charts may be required.

It is assumed that NRA will undertake all hydraulic modelling and will provide all necessary structure functions.

12. Further information required

Peak tide levels for Southend are required for the period 1986-1991. If these are not available in digital form, levels will need to be extracted from the charts.

It is recommended that Thames Water Utilities record the level of the Thames (at the Roding mouth) when future diversions of effluent are made to the Roding. This critical level governs the time over which effluent is discharges behind the barrier and may be crucial to determining flood defence levels.

13. Conclusions

Water levels in the lower River Roding are determined by a complex set of controls namely:

(1) fluvial flows from the catchment upstream of Redbridge;
(2) effluent discharges from Beckton STW;
(3) water levels in the River Thames at the mouth of the Roding; and
(4) whether or not the Barking barrier is closed.

Water levels at the upstream end of the reach are controlled by the fluvial flows, whereas at the downstream end the stage frequency will follow that of the tidal

Thames, if the Barking barrier is open. Levels at intermediate sections will be controlled by both tidal levels and fluvial flows to degrees according to their location. If the Barking barrier is closed water levels along the entire reach will be controlled by fluvial flows and effluent discharges.

The generally slow response of the Roding catchment to rainfall suggests that daily mean flow data (1950-1991) from Redbridge provide an adequate time series for the analysis. Effluent discharged to the study reach from Beckton STW can be significant, but data were not available for whole period 1950-1991, thus they need to be generated synthetically.

Records of water level at various locations in the Thames estuary are available for the period 1950-1985. These can be used to derive a series of water levels at the mouth of the Roding. Data for 1986-1991 were required to extend the analysis to the present.

A hydraulic model had been constructed to provide structure functions relating water levels along the study reach to given fluvial flow and water levels at the mouth. Structure functions need to be produced for

(1) fluvial flows up to 64 m^3s^{-1} and for water levels at the mouth up to 5.0 m for conditions when the barrier is open; and

(2) fluvial flows up to 64 m^3s^{-1} and effluent discharges up to 25 m^3s^{-1} for conditions when the barrier is closed.

For each node along the study reach a statistical distribution can be fitted to the annual maximum water levels to estimate return periods up to around 80 years.

For nodes upstream of the tidal limit the annual maximum floods for return periods up to 1000 years at Redbridge will be converted to stage.

The relationships between stage frequency at Redbridge and nodes along the study reach, up to the 80 year return period, can be derived. These relationships, and estimates of stage at Redbridge for higher return periods, can be used to extrapolate stage frequency curves for other nodes up to the 1000 year return period level.

It is estimated that Phase II of the study will cost not more than £16,000. This includes all staff time, computing, production of draft and final reports and travel and subsistence.

14. References

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