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Institute of Oceanographic Sciences
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January 1985.

INSTITUTE OF OCEANOGRAPHIC SCIENCES

NATURAL ENVIRONMENT RESEARCH COUNCIL

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This report forms part of a project on extreme still water levels funded by the Ministry of Agriculture, Fisheries, and Food.

CONTENTS

1. Introduction

This report concerns the estimation of extreme still water levels at Immingham, Lowestoft, Harwich, Walton-on-the-Naze and Sheerness; see Figure 1 for locations. Still water level (swl) is defined here as the observed water level at a location when waves have been averaged out. It contains contributions due to astronomical tides, meteorologically induced surges and mean sea level. A contribution to the surge level may be a steady mean wave set-up due to any wave activity during the period of observation. This may be an important factor in the swl reached at any sea-defence site as the set-up at the shorelines on beaches is about one-fifth of the significant wave height offshore (James 1983).

Long periods (Table 1) of carefully edited sea level data have been processed and analysed to yield data and statistics of the astronomical tide, meteorologically induced surge, and mean sea level components at each port, as well as of the total observed still water level. Both the Generalised Extreme Value (GEV) and Joint or Combined Probability (JP) methods have been used to compute probabilities of exceedance of extreme levels and hence return frequencies or periods. Estimates of both extreme high and low sea levels have been computed using the JP method.

Empirical factors, based on the statistics of extreme sea level, tide and surge have been computed. These have good stability over the region and can be used to compute approximate extreme levels at locations where only short-period measurements are available.

2. Data reduction

Hourly values of sea level measured relative to the local tide gauge benchmark were digitised from analogue charts from stilling well gauges at the 5 ports. Most of the records were fairly complete except for short periods when the tide gauges malfunctioned.

At Immingham, from 1969 to 1981, charts were used from the Munro gauge situated on the inshore side of the western jetty (Ordnance Survey (OS) Grid reference TA 1988 1671). In addition to the chart recorder located at Immingham, a distant reading recorder was set up at the Storm Tide Warning Service (STWS) at Bracknell; hence two sets of tide gauge records existed. Between 1964 and 1968 there was no indication of which set of records were used for data reduction or whether both sets were used. Notable gaps were of 8 days in January 1971 (float tube blockage), 21 days December 1972 (charts missing), 7 days June 1974 (float jammed), and 19 days July - August 1978 (clock problems).

At Lowestoft, from 1970 to 1978, charts were used from the Munro gauge situated on the north side of the harbour (OS Grid reference TM 5479 9274). From

1979 onwards, punched paper tape data was used from an OTT digital gauge installed on the stilling well - any minor gaps were filled with data from the Munro gauge. A notable gap was of 6 days in April 1977 (chart omitted, timing problems).

At Harwich, from 1967 to 1976, charts were used from the Legé gauge situated at OS Grid reference TM 2582 3275. Data reduction was discontinued in 1976 due to deterioration in data quality following installation of a Munro transmitter attached to the Legé gauge. Notable gaps were of 7 days in March 1967 (reason unknown), 15 days March 1970 (pen not inking), 7 days April 1970 (pen not inking), 8 days July - August 1970 (pen not inking), 16 days February 1972 (power cut), 54 days November - December 1973 (power cuts), 63 days January - March 1974 (reason not known), 36 days April - June 1974 (possible datum shift), 8 days July - August 1974 (bad record), 8 days November 1974 (float problems), 34 days November - December 1974 (no charts received), and 7 days April 1976 (chart missing).

At Walton, from 1967 to 1978, charts were used from the Lea gauge installed on Walton Pier (OS Grid reference TM 2560 2150). The Pier was severely damaged by a storm on 31 December 1978 and the gauge out of action thereafter. Notable gaps were of 62 days August - October 1968 (difference of opinion on continuity checks of heights) and 67 days January - March 1978 (counterweight wire parted after a storm damaged the Pier).

At Sheerness, from 1965 to 1975, charts were used from the Munro gauge situated at Garrison Point (OS Grid reference TQ 9074 75447). A notable gap was of 35 days in November - December 1965 (charts lost at source).

The records of hourly sea level were rigorously checked and carefully edited using the Tidal Elevation Reduction Package (TERP) suite of computer programs. Previously processed records were brought up to modern standards using this method (Graff and Karunaratne 1980). The method consisted fundamentally of plotting the surge residuals (i.e. observation minus predicted tide) as a function of time and of examining the plotted values by eye for irregularities. Errors, due principally to datum shifts or irregular timing, were then corrected by referring to the original tide gauge charts. Dubious surges were checked using weather records and other tide gauge records. A summary of the data periods used is given in Table 1.

At any time (t), the observed sea level (ζ) can be considered as the sum of a tidal component (x), a surge component (y), and a mean level (Z_o) :

$$\zeta(t) = x(t) + y(t) + Z_o \qquad (2.1)$$

The edited sea level records were analysed to yield data and statistics of these three components.

3. Astronomical tide levels

The tidal component of the observed record is the coherent part of the sea level that responds directly or indirectly to astronomical forcing. The harmonic method of analysis models the astronomical tide as a finite number, N, of harmonic constituents with an amplitude H and angular speed, σ,

$$x(t) = \sum_{n=1}^{N} f_n(t)\, H_n \cos(\sigma_n t + V_n + u_n - G_n). \qquad (3.1)$$

V is the initial phase at an arbitrary time origin t = 0 and G is the constituent's phase lag with respect to the equilibrium tide, and Greenwich epoch. f and u are slow modulating theoretical functions mostly with the period 18.6y of regression of the lunar nodes.

The periods of data records analysed are given in Table 1; these were chosen to cover maxima and minima of the nodal cycle and hence yield average values for f and u. However, for Immingham, the observed data period virtually covered a nodal cycle and so the actual observed nodal variation could be analysed. The modulation of the principal constituents was found to be smaller in the real tide than in the theoretical tide, because the relationship between a principal constituent and its nodal term was different in shallow water from that assumed in the equilibrium theory, due to tide-tide interactions generated by bottom friction effects (Amin 1985). Therefore, additional constituents were incorporated in the tidal prediction model for Immingham to allow for the observed modulations.

The tidal constants (H and G) of the principal tidal constituents and some shallow water constituents are given in Table 2, together with the mean sea level of the analysed data period. The full set of constants were used to generate an hourly time series of the tide component over the period of 19 years given in Table 1 for each port. The probability density function (p.d.f.) for the tides was generated numerically from the tidal time series in class intervals of 0.1m, and is shown for each port in Figures 2a - e.

For each port the distribution was bimodal with the two peaks or modes occurring near Mean High Water Neaps (MHWN) and Mean Low Water Neaps (MLWN). The asymmetry of the modes (i.e. their difference in height) is associated with non-linear harmonics of M_2 and S_2. The asymmetry was particularly noticeable at Lowestoft where M_4 was close to quadrature with M_2.

The tails of each distribution did not extend to infinity but terminated at approximately Highest and Lowest Astronomical Tide (HAT, LAT). More precise HAT and LAT levels were extracted from predicted High and Low Waters for the years when the predicted hourly levels reached their extreme values. HAT, LAT and other tidal statistics are given in Table 3 relative to mean sea level at the port.

4. Surge levels

Hourly values of the meteorologically-induced surge levels at the 5 ports were computed as the difference (the surge residual) between the observed and predicted levels - the mean sea level used was the mean of all the hourly observed values. The probability density function for the surges was generated numerically from the time series using a class interval of 0.10m, and is shown for each port in Figures 3a - e. The p.d.f's had a Normal or Gaussian appearance but there was a positive skewness and longer tails than the Gaussian distribution has. Table 4 gives the statistics of the surge distributions for each port in the form of the standard deviation, the coefficients of skewness and kurtosis, and the maximum and minimum surge levels reached during the observation period. The coefficients were defined as follows :

$$\text{k th moment} = \mu_k = \frac{1}{N} \sum_{i=1}^{N} (y_i)^k \qquad (4.1a)$$

$$\text{Standard deviation} = \sigma = (\mu_2)^{\frac{1}{2}}$$

where y_i = ith surge level, N = total number of observations of surge levels.

$$\text{coefficient of skewness} = \mu_3^{\,2} / \mu_2^{\,3} \qquad (4.1b)$$

$$\text{coefficient of kurtosis} = \mu_4 / \mu_2^{\,2},$$

and Sheppard's corrections for grouping were used (Kendall and Stuart 1963).

The standard deviation of the surges was fairly constant down the coast but increased at Sheerness. Skewness is a measure of symmetry and has a value of zero for a symmetrical Gaussian distribution. The positive values obtained indicated that the longer tail of the surge distribution lay towards the positive surge values, i.e. that extreme positive surges were more probable than extreme negative surges. This is apparently due to an inverse response by the sea to an asymmetry in the frequency of extreme atmospheric pressures : extreme low pressures are more probable than extreme high pressures (Pugh and Faull 1983). The values of skewness were reflected in the maximum and minimum surge levels, which showed extremes on the positive rather than negative side for all ports except Sheerness, where the extreme values were virtually identical; the skewness was much smaller and close to zero, indicating a more symmetrical surge distribution.

Kurtosis is a measure of the flattening of a distribution relative to a Gaussian distribution, which has a standard kurtosis value of 3. All the surge distributions had similar values greater than 3 and they were therefore leptokurtic - i.e. more sharply peaked than a Gaussian distribution with greater height and longer tails.

The frequency of surges on a monthly basis was computed, using a class interval of 0.10m, and monthly surge probability distributions are given for each port in Figures 4a - e. As an example of their use, there was a 1% probability that the observed level at Immingham was exceeded by 0.7m in December during the observation period.

Analyses of the amplitude and duration of extreme observed surges at the 5 ports are given in Table 5. The extremes are defined in terms of the standard deviations (σ) of the hourly surge residuals about a zero mean. Absolute comparisons of surge frequencies cannot be made because of the variable observed data periods, but a rough qualitative rule suggests that extreme positive or negative surges greater than 7σ or 6σ respectively occurred on average once a year. During the major storm surge of 1976 January 3, the duration of surge level above 4σ at Immingham, Lowestoft, Harwich and Walton was 7, 22, 20 and 21 hours respectively (Sheerness data was not available). The maximum hourly surge observed was 1.68, 2.05, 2.24 and 2.21m respectively ($>8\sigma$, $>9\sigma$, $>11\sigma$, $>10\sigma$). During the major storm surge of 1978 January 11-12, the duration of the surge level above 4σ at Immingham and Lowestoft was 15 hours at both ports respectively with a maximum surge level of 1.36m ($>7\sigma$) and 1.59m($>7\sigma$) (data from the other ports was unavailable).

Extreme surge levels were estimated using two methods: by extrapolating a logarithmic curve fitted by least squares to the cumulative distribution of the surge levels, and by a "peaks over threshold" (POT) technique. A simple POT model (NERC 1975) was used in which the number of exceedances per year of surge levels (y) greater than a threshold level (yo) was treated as a Poisson variate whose parameter (λ) was estimated by

$$\hat{\lambda} = M/N \tag{4.2}$$

where M is the number of exceedances in N years of record. The magnitudes of the exceedances were treated as an exponential distribution whose parameter (β) was estimated by

$$\hat{\beta} = \bar{y} - yo = \sum_{i=1}^{M} \frac{y_i}{M} - yo \tag{4.3}$$

where $\bar{y}$ is the mean of the exceedance surge levels. Then the surge level with return period of R years was estimated from

$$y(R) = yo + \hat{\beta} \ln \hat{\lambda} + \hat{\beta} \ln R . \qquad (4.4)$$

The standard error (S.E.) of the return period surge level was computed from

$$(S.E.)^2 = \frac{\hat{\beta}^2}{\lambda N} \left[1+(\ln \lambda R)^2\right] . \qquad (4.5)$$

The POT method was applied to surge events rather than to hourly values by considering the maximum hourly surge level in each 24 hour period. A threshold level of 3σ was used, which is the Storm Tide Warning Service (STWS) threshold level for a surge event (Lt. Cdr. J. Townsend - personal communication). This threshold gave frequencies of positive and negative surge events of 18 - 20 y^{-1} and 9 - 11 y^{-1} (Sheerness 17 y^{-1}) respectively, compared with average frequencies recorded by STWS of 17 and 14.5 per surge season (September to April).

The estimated return period positive and negative surge levels obtained using the two methods are given in Tables 6a - b respectively, together with the mean, which was considered to be the best estimate. The standard errors given are those from the POT method.

5. Mean sea levels

Figure 5 shows the monthly mean sea levels (msl) at the 5 ports as supplied to the Permanent Service for Mean Sea Level (PSMSL) (J. Scoffield, personal communication, 1984, and PSMSL 1976 (with updates)). The monthly means for all ports except Sheerness were computed by the IOS Tidal Computations and Statistics Group as the mean of thedaily mean sea levels, which were themselves computed by applying the Doodson Xo filter to the hourly values of the observed still water level. No monthly mean was computed for any month with less than 15 days of good data. Data for Sheerness was computed and supplied by the Hydrographic Department of the Ministry of Defence.

There is good correlation of annual and interannual variations of mean sea level over the region, see for examples, the msl peaks at the end of 1970, 1972, and 1974. Variations in msl throughout a year (the "seasonal cycle") arise from meteorological changes (from wind stress action in shallow water and from sea level air pressure variations) and oceanic changes (from sea water density variations and the reversal or modulation of ocean currents). In British waters, meteorological and density (sometimes called "steric") changes are the main contributions to the msl seasonal cycle and are of approximately equal importance. Meteorological factors provide a peak of msl in winter while steric changes have their maximum contribution to msl in late summer. At present knowledge, the steric component of the cycle is regular from year to year and it is the meteorological forcings which dominate the interannual variability in msl in British waters.

Over long time scales (i.e. decades), sea level records from most tide gauges show a "secular trend" (a long-term change) which can be ascribed to a combination of oceanographic, climatic and/or geological effects. The gauge measures the difference between long term changes in the actual sea levels (arising from slow oceanic or climatic changes), and apparent changes in sea level due to vertical changes in the land it is situated upon (due for example to geological effects such as post-glacial uplift or sinking). Any long-term trend could be due to

a) a global warming (or cooling) of the atmosphere causing an increase (decrease) in water volume, through thermal expansion (contraction) of the water column and possible melting (freezing) of the polar ice-caps.

b) an increase (decrease) in long term local mean atmospheric pressure causing a decrease (increase) in msl through the inverse barometer effect.

c) a vertical re-adjustment of the Earth's crust to long-term loading effects (e.g. post-glacial uplift or sinking) causing an increase or decrease in msl. (There is also a loading effect on the sea bed from any increase in water volume, but this is a secondary effect).

Estimates of the secular trend in msl at the 5 ports are given in Table 7 and have been obtained using models (1 and 3 of Thompson 1980) employing multiple regression least squares fits to monthly mean sea levels (J. Scoffield, personal communication, 1984). Both models included semi-annual and annual terms and model 3 also included meteorological terms to model the effect of atmospheric pressure. The model 3 estimates are therefore the more reliable because the random input due to changes in mean annual atmospheric pressure have been removed. Cartwright (1983) has analysed 66 years of Newlyn msl data and has accounted for about one-third of the rise (1.34 mm y^{-1}) in terms of a local downward trend in atmospheric pressure. The estimates given in Table 7 also show a reduction in the rate of rise of mean sea level when atmospheric effects are removed, in two cases (Immingham and Lowestoft) changing a positive value (msl rise) into a negative value (msl fall).

However, these estimates should be treated with great caution in any projection of msl trends for design purposes because of the short data spans used. Barnett's work (1984) suggests that the global rise in msl has been linear up to the present time, but projected estimates (Hoffman et al 1983) give a non-linear accelerating rise in msl, with a rise of 1.44 to 2.17m "most likely" by AD 2100.

6. Total still water levels

The frequency distribution of observed total levels for each port was not substantially different from the tidal distribution (Figures 2a - e), but the inclusion of surges spread the tails of the total distribution beyond the levels of HAT and LAT. The cumulative distribution of observed levels was computed and is shown in Figures 6a - e as a Flood-Exposure Index. This gives the probability of exceedance of a particular level; e.g. at Immingham, there was a 0.4 probability that any hourly observed level was below -0.8m and a corresponding probability of 0.6 that any level was above -0.8m.

7. Extreme still water levels

Two methods have been used to estimate extreme still water levels : the Generalised Extreme Value (GEV) method and the Joint or Combined Probability (JP) method.

The GEV method involves fitting the cumulative frequency distribution of the annual observed sea level maxima by a distribution and extrapolating to low probabilities and hence long return period values. The technique used was based on the Jenkinson method used by Lennon (1963) and Suthons (1963) (see also Graff (1981)). The series of n annual maxima, $h = h_1, h_2 \ldots\ldots h_n$ were ranked in ascending order of magnitude and the cumulative frequency of the mth value was found from

$$P = (2m - 1) / 2n \tag{7.1}$$

The cumulative frequency distribution was fitted by one of a family of extreme value distributions, described by the two- parameter General Extreme Value (GEV) distribution (Jenkinson 1955)

$$h = a(1 - e^{-ky}), \tag{7.2}$$

where a and k are conditional parameters of the distribution calculated from the mean annual maximum and the standard deviations of the annual and biennial maxima, and y is the reduced variate

$$y = -\ln (-\ln P). \tag{7.3}$$

The curves are classified as Fisher-Tippett types 1, 2, 3 (Fisher-Tippett 1982) depending on the curvature, and hence the value of k, since

$$dy / dh = (1 / ak)\exp ky. \tag{7.4}$$

Hence k=0, F-T type 1, h has neither an upper nor lower asymptotic limit,

$k < 0$, F-T type 2, h has a lower asymptotic limit,

$k > 0$, F-T type 3, h has a higher asymptotic limit.

Frequency distribution curves of height, h, against reduced variate, y, or return period were drawn (see Figures 7a - e), and the value of h for different return periods (rp) read off, the curve being extrapolated if necessary, since, for annual maxima,

$$(rp)^{-1} = 1 - P = 1 - \exp(-e^{-y}), \tag{7.5}$$

noting that the probability, P, is the observed probability of annual maximum $< h$. The statistical theory of the method assumes that the annual maxima data are stochastically stationary, i.e. random and uncorrelated. The method can still be applied provided that the annual maxima are reduced to a standard epoch and the trend removed - this was necessary for Immingham and Sheerness (see below).

The GEV method produces estimates of extreme levels which are unstable and depend critically on the length of data analysed and on the inclusion or exclusion of particular values (Graff 1983, Alcock 1984). For example, a reanalysis of Avonmouth annual maxima by Blackman (1985), using 6 extra annual maxima either unavailable to Graff or rejected by him, increased the previous estimate of the 100y return period level by 0.35m and the 250y level by 0.44m. This lack of stability makes extrapolation to probabilities less than 0.01y (return period > 100y for annual events) very undesirable using this method. Theoretically, only estimates for return periods less than four times the data length should be used. Estimates of the extreme levels are given in Table 9a, corresponding to specific return periods.

The Joint Probability method is based on the separation of hourly values of swl into tide, surge and msl components. Separate probability distributions for tide and surge were computed (see Sections 2 and 3) and the probabilities of obtaining tide and surge levels combined together to obtain the probability of a particular swl, and hence return period levels.

If P_T and P_S are the probability density functions for tide and surge, then the probability of occurrence of a particular swl (h) was computed as

$$P(h) = \int_{-\infty}^{\infty} P_T(h-y) . P_S(y)dy, \tag{7.6}$$

e.g.

$$P(h=4m) = P_T(T=4m) \times P_S(S=0) + \ldots + P_T(T=0) \times P_S(S=4m). \tag{7.7}$$

From P(h), the probability of exceeding a particular level (H) was computed from the cumulative distribution function

$$Q(H) = \int_{H}^{\infty} P(h)dh \qquad (7.8)$$

and the probability of exposure of a level from

$$R(H) = \int_{-\infty}^{H} P(h)dh. \qquad (7.9)$$

The JP method therefore produced extreme statistics in terms of these probabilities of exceeding high levels and of falling below low levels. These were converted into return periods by taking into account the sampling interval (1 hour) i.e.

$$rp = \left[Q(H) \times 8766\right]^{-1} \quad \text{or} \quad \left[R(H) \times 8766\right]^{-1}, \qquad (7.10)$$

where rp is the return period in years and 8766 is the number of hourly samples in 1 year. Pugh and Vassie (1980) have investigated the problem of converting probabilities of instantaneous values into yearly return periods when the samples are not independent, as with hourly swl observations (due to correlation of the surge residuals). They found that the necessary theoretical adjustment to the equation(7.10) was so small compared with the uncertainty associated with statistical sampling that, in practice, it is unnecessary.

The JP method assumes the independence of tide and surge and this was investigated by studying the variance of the surge distribution as a function of tidal level. It is well known from empirical and model studies (Keers 1968, Prandle and Wolf 1978a, 1978b, Wolf 1978) that tide - surge interaction increases down the east coast from Lerwick to Immingham, becomes small at Lowestoft, and increases between Lowestoft and Southend. The interaction between tide and surge is influenced by the effects of various non-linear terms (quadratic friction, shallow water, convective). Wolf (1978) found that while the influence of quadratic friction was greatest - primarily in damping a surge (especially at high water), the influence of the shallow water terms was significant in producing surge amplification on the rising tide by changing the phase speeds of the surge and tide waves.

Extreme levels at the 5 ports were computed using separate surge p.d.f.s for different parts of the tidal range; surge data being usually grouped into 7, 5, 3 and 1 tidal divisions about the zero level (8 divisions were used at Sheerness instead of 7 because of the asymmetry of the tidal p.d.f.). Some of the exceedance probability curves are shown in Figures 7a - e, with the probabilities expressed as return periods in years.

The best estimates using the JP method were chosen from the appropriate computations taking surge-tide interaction into account. These are given in Tables 8a - b as return periods in years for exceedance or exposure of specific levels. Tables 9a - e give levels corresponding to specific return periods up to 250 years. All estimates were computed with respect to the mean sea level of the analysis period but are also given in Tables 9a - e relative to Ordnance Datum Newlyn (ODN).

For all ports, the estimates from the JP method have been taken as the best overall estimates because of the inherent instability of the GEV method.

At Immingham, 62 annual maxima from 1920-81 were used in the GEV method. The series had a trend of 6.22 mm y^{-1} with a significant correlation of 0.48, and therefore the data were detrended using 1980 as the reference year. The value of the parameter K was 0.11 and therefore the best fit distribution was a Fisher-Tippett type 3. With the JP method, three tidal bands were considered the most appropriate to model the tide-surge interaction. Using the estimates from the JP method gave estimated return periods of 41 and 38 years for the 1969 and 1983 observed levels of 4.75m ODN and 4.74m ODN respectively. The 1953 visually estimated observed level of 4.51m ODN would have a return period of 8 years.

At Lowestoft, 28 annual maxima from 1954-81 were used in the GEV method. The series had a trend of 2.42 mm y^{-1} but no significant correlation (-0.06) so no trend was removed from the data. The value of the parameter K was -0.17 and therefore the best fit distribution was a Fisher-Tippett type 2, which has no high asymptotic limit. We also recomputed the estimates using the estimated observed level of 3.35m ODN in 1953, and this very significantly altered the fit of the Fisher-Tippett curve and hence the return period estimates (e.g. an increase of 0.46m on the 100 year level) - these are also given in Table 9b. This illustrates the sensitivity of the GEV method to the addition, or omission, of individual annual maxima. With the JP method, values from the computations using 1 tidal band, i.e. no tide-surge interaction, were considered to be the overall best estimates. Using these estimates gave estimated return periods of 40 and 54 years for the 1976 and 1983 observed levels of 2.74m ODN and 2.78 respectively. The 1953 level of 3.35m ODN would have a return period of 14674 years; the surge component of 2.41m would have a return period of 66 years, using the estimates from Table 6a. If the visually estimated observed level is reliable then the 1953 surge must be considered an extremely (!) exceptional event, presumably due to the simultaneous occurrence of an extreme surge with a very high tide. (The predicted tide level was 0.94m ODN, only 0.02m below MHWS).

At Harwich, 51 annual maxima from 1926-76 were used in the GEV method. The series had a trend of 60.2 mm y^{-1} but no significant correlation (0.28) so no trend was removed from the data. The value of the parameter K was -0.05 and therefore the best fit distribution was a Fisher-Tippett type 2, which has no high asymptotic limit. With the JP method, values from the computations using 5 tidal bands were considered to best model the tide-surge interaction and give the overall best estimates. Using these estimates gave estimated return periods of 4 and 3 years for the 1969 and 1976 observed levels of 2.96m ODN and 2.90m ODN respectively. If reliable, the 1953 visually estimated observed level, 3.99m ODN, would have a return period of 40618 years; the surge component of 2.32m would have a return period of 26 years, and the predicted tide level of 1.67m ODN was 0.1m below MHWS.

At Walton, only 11 annual maxima from 1968-79 were available for use in the GEV method. The series had a trend of 4.64 mm y^{-1} but no significant correlation (0.09) so no trend was removed from the data. The value of the parameter K was 0.05 and therefore the best fit distribution was a Fisher-Tippett type 3. With the JP method, values from the computations using 5 tidal bands were considered to best model the tide-surge interaction and give the overall best estimates. Using these estimates gave estimated return periods of 3, 12, and 2 years for the 1969, 1973, and 1976 observed levels of 3.08m ODN, 3.23m ODN and 3.04m ODN respectively.

At Sheerness, 133 annual maxima from 1819-1978 were used in the GEV method. The series had a trend of 2.49 mm y^{-1} with a significant correlation of 0.40, and therefore the data were detrended using 1980 as the reference year. The value of the parameter K was -0.04 and therefore the best fit distribution was a Fisher-Tippett type 2 which has no high asymptotic limit. With the JP method, values from the computations using 8 tidal bands were considered to best model the tide-surge interaction and give the overall best estimates. Using these estimates gave estimated return periods of 2 and 1 years for the 1973 and 1983 observed levels of 3.83m ODN and 3.73m ODN. The 1953 observed level, 4.70m ODN, would have a return period of 7766 years; the surge component of 2.16m would have a return period of 8 years, and the predicted tide level was 0.2m below MHWS.

8. Interpolation of extreme still water level estimates

Once extreme levels have been estimated at specific sites, values may need to be obtained for intermediate points where long period data sets are unavailable.

Lennon (1963) suggested a method based on relating the given extreme swl level L_R, with return period R years, to Mean High Water Spring level (MHWS)* and Mean Low Water Spring level (MLWS)*. His similarity measure is given by

* measured relative to mean sea level.

$$F_R = \frac{L_R - MHWS}{MHWS - MLWS} \qquad (8.1)$$

If the value of this measure is approximately constant for a given return period level along a stretch of coast, then the extreme level can be found at points where MHWS and MLWS are known. However, this measure is unstable near tidal amphidromes and in regions of extensive shallow water, as the values in Table 10 indicate.

A more stable parameter is the factor

$$\beta_R^+ = \frac{L_R^+}{M_2+S_2+S_R^+} \qquad (8.2)$$

where L_R^+ and S_R^+ are the high swl and positive surge with return period R years, and M_2 and S_2 are the amplitudes of the two major semi-diurnal constituents; their sum is a useful indication of the spring tidal amplitude. This is given in Table 10 for R = 50 and 100 years for the 5 ports, together with the factor (ψ_R) between the minimum and maximum total swl, and the factor (τ) between Highest Astronomical Tide (HAT) or Lowest Astronomical Tide (LAT) and the spring tidal amplitude, i.e.

$$\psi_R = \frac{L_R^-}{L_R^+} \qquad (8.3)$$

$$\tau^+ = \frac{HAT}{M_2+S_2}, \qquad \tau^- = \frac{LAT}{M_2+S_2} \qquad (8.4)$$

where R is return period in years and +(-) refers to high (low) levels.

The height of the R-year high still water level above msl at intermediate points along the East Anglian coast may be estimated by taking the sum of the spring tidal amplitude and R-year surge level there and multiplying by the factor for the nearest reference port given in Table 10. The procedure can be extended to provide estimates of the R-year low still water level by multiplying the result obtained by the factor ψ_R from Table 10. Values of M_2 and S_2 need to be available from empirical or model analyses (Flather 1976). Values of the R-year surge level can be obtained either by using the value at the nearest reference port given in Table 6, or from distribution of surge levels over the North Sea based on empirical analyses and model simulations, see Figure 9 for example (R. Flather 1986).

9. Summary and conclusions

a) Tide gauge records have been processed to yield long periods of carefully edited hourly still water levels. This has been a very time consuming task, made more difficult by some poor data and the less than meticulous documentation of gauge performance, errors, datum changes etc. at some ports. The present development and installation of new instrumentation with automatic regular datum checks and data telemetry to IOS Bidston, and the present improved documentation and data reduction is intended to make future data processing and analysis more straightforward.

b) The tidal analysis of the still water levels has given information on the tidal characteristics in terms of tidal constants, the tidal p.d.f., and associated statistics. The Highest and Lowest Astronomical Tides have been rigorously determined. The analysis of the Immingham data has enabled the actual nodal modulation of the major constituents to be determined, and better modelled in tidal predictions. Further work is required to account for the shape of the tidal distributions in more detail, the modulation of tidal constituents and hence improved modelling of the tides.

c) The surge characteristics at each port have been presented in the form of the surge p.d.f., the frequency distribution of all surges on a monthly basis, and the observed amplitude and duration of extreme surges. The surge distributions showed similar statistical properties, except at Sheerness where the standard deviation increased and the distribution was more symmetrical. It is intended that the monthly surges be analysed according to tidal level.

Extreme surge levels were estimated by extrapolating the cumulative distribution of the levels and by a POT technique. The results were in reasonable agreement, but further work is needed in applying the POT technique to surge levels, especially in modelling the seasonal variability.

d) Monthly mean sea levels at the 5 ports show good correlation and have been analysed to give secular trends, in particular from a regression model which removed the input due to changes in mean atmospheric pressure. However only short data spans have been available for use and the regression model should be extended to cover more historical data. More work should also be done in analysing the secular trend at individual ports in terms of oceanographic, climatic and/or geological effects, using long msl and atmospheric pressure records.

e) The frequency distribution of observed swl at each port has been presented as a Flood-Exposure Index, which gives the probability of any level being above or below a specified value.

f) Extreme still water levels have been estimated using the Generalised Extreme Value (GEV) method and the Joint or Combined Probability (JP) method. The estimates obtained using the GEV method depended critically on the data length and on the inclusion or exclusion of particular values - the inclusion of the 1953 annual maxima at Lowestoft increased the 100 year return level by 0.46m. Some data lengths were so short that only levels for short return period could be reliably computed, e.g. Walton's 11 annual maxima only justified extrapolation to a 44-year return period.

The JP method required the modelling of tide-surge interaction, as revealed by an analysis of the variance as a function of tidal level. This was done by grouping the surge data according to different tidal levels.

The best estimates of extreme levels were taken from the JP method because of the inherent instability of the GEV method. However, these estimates produced very long return periods for the 1953 storm surge levels at Lowestoft and Harwich. These observed levels were visual estimates (because of gauge malfunctions) and therefore may be unreliable and exaggerated because of local wave action. However, the JP method may not be adequate to deal with those storm levels where the surge component is much larger than the tide component (at Lowestoft the 1953 estimated storm surge level was 2.5 times the tide level; at Harwich it was 1.4 times the tide level). The maximum of the observed surge population at Lowestoft and Harwich was smaller (by 0.36m and 0.08m respectively) than the estimated surge component of the 1953 storm surge event, and therefore the surge population may not have adequately represented the true population. It may be necessary to include as many historic storm surge data in the method as is feasible using observations or models. Obviously, the stability of the JP method needs further investigation, as does the implied stationarity of the surge - generating process (Lamb 1982, Pugh and Faull 1983).

g) A parameter for interpolating extreme swl estimates between reference ports has been evaluated which has more regional stability than Lennon's similarity measure. It requires a knowledge of the amplitudes of M_2 and S_2 and the return period surge level at the site and the return period total level at the reference port. Of these, the surge level would be the most difficult to obtain and an estimate from a modelled distribution of surge levels may have to be used if the site is far from a reference port.

h) Finally, although the probabilities of occurrence and exceedance of levels have been converted into return frequencies or periods, attention is drawn to

Table 11. Although the return period is the average time between occurrences or exceedances of an event, there is a finite risk that one such event will occur during a period less than the return period. This risk (ri) is related to the return period (rp) and design life of the structure (L) by

$$ri = 1 - (1 - 1/rp)^L \quad (8.1)$$

and is tabulated in Table 11. If L = rp, then ri = 0.63, i.e. there is a 63% probability that the return period event will occur during the life time of the structure; the risk can be reduced by choosing a return period greater than the effective or planned lifetime of the structure.

10. Acknowledgements

We acknowledge the considerable efforts of our colleagues Sheila Shaw, Rose Maher and Joyce Richards in processing the tide gauge data. We thank Joyce Scoffield, Ian Vassie and Phil Woodworth for useful discussions. Joyce Richards drew the figures and Linda Parry had the onerous task of typing the manuscript. This report forms part of a project on extreme still water levels funded by the Ministry of Agriculture, Fisheries and Food - we thank them for their support.

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12. List of Figures

13. List of Tables

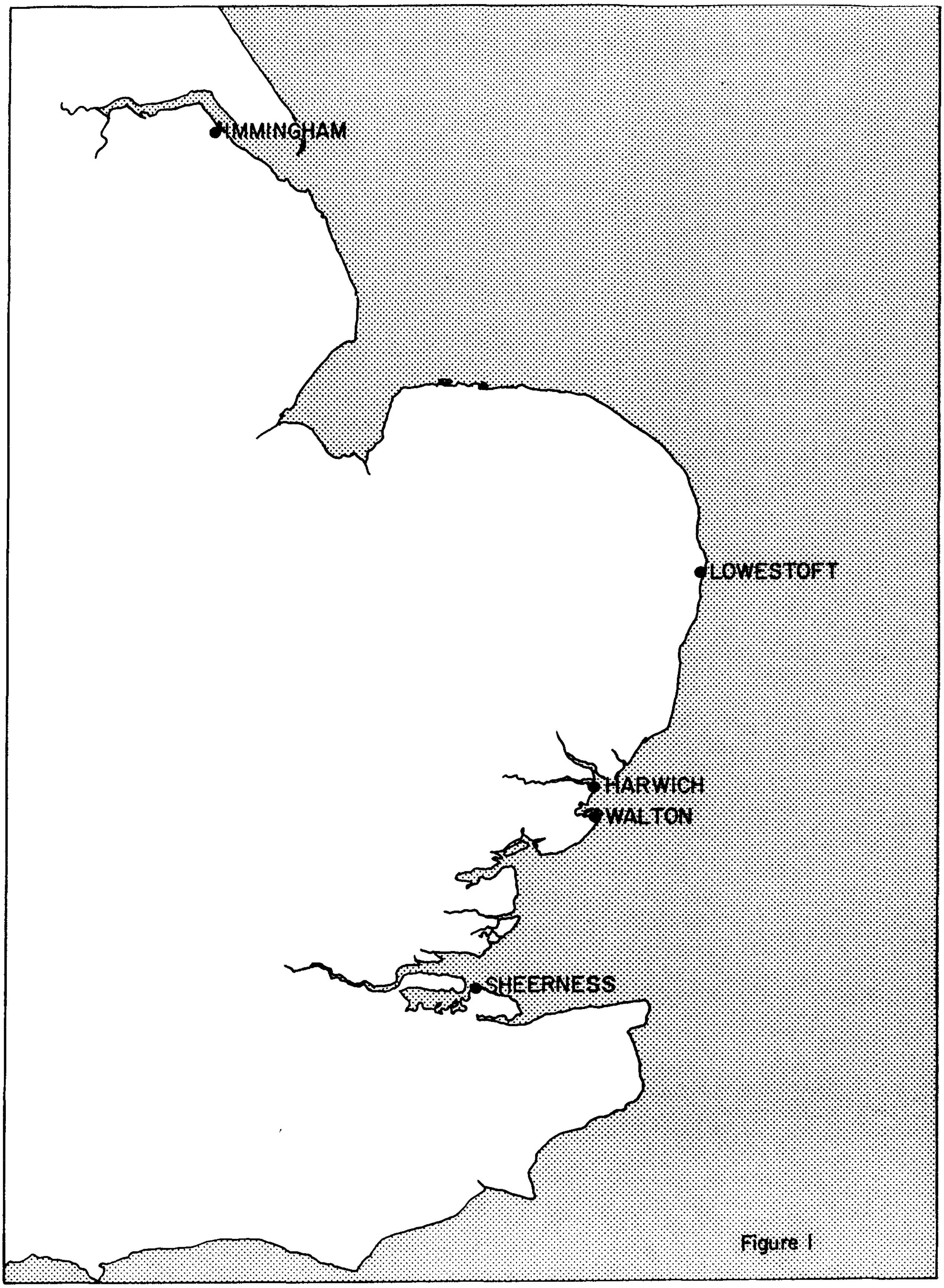


Figure I

IMMINGHAM

SURGE DISTRIBUTION (18 YEARS: 1964 - 1981)

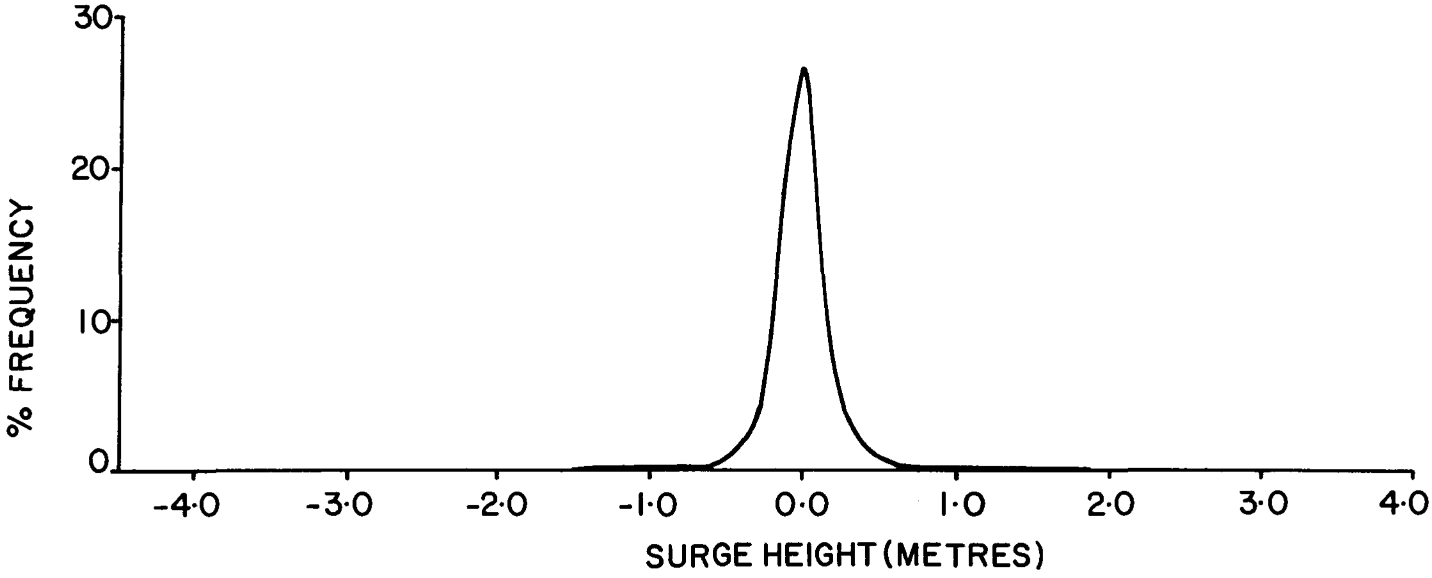


Figure 3a

TIDAL DISTRIBUTION (19 YEARS: 1964 - 1982)

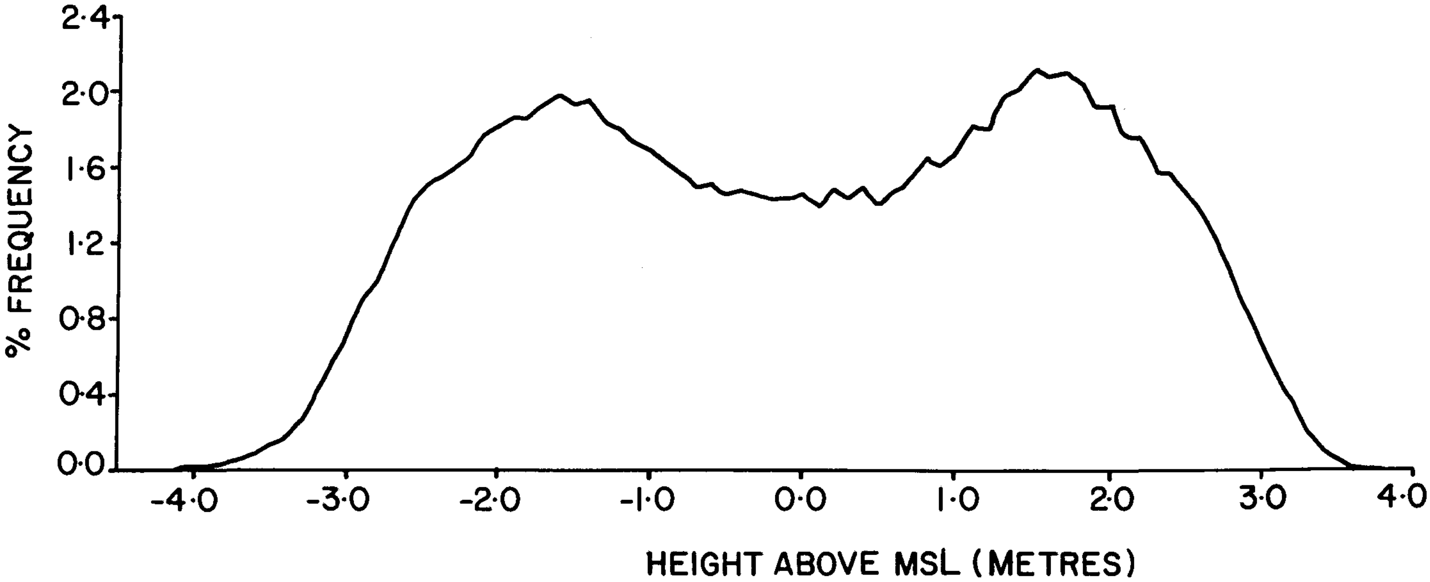


Figure 2a

LOWESTOFT

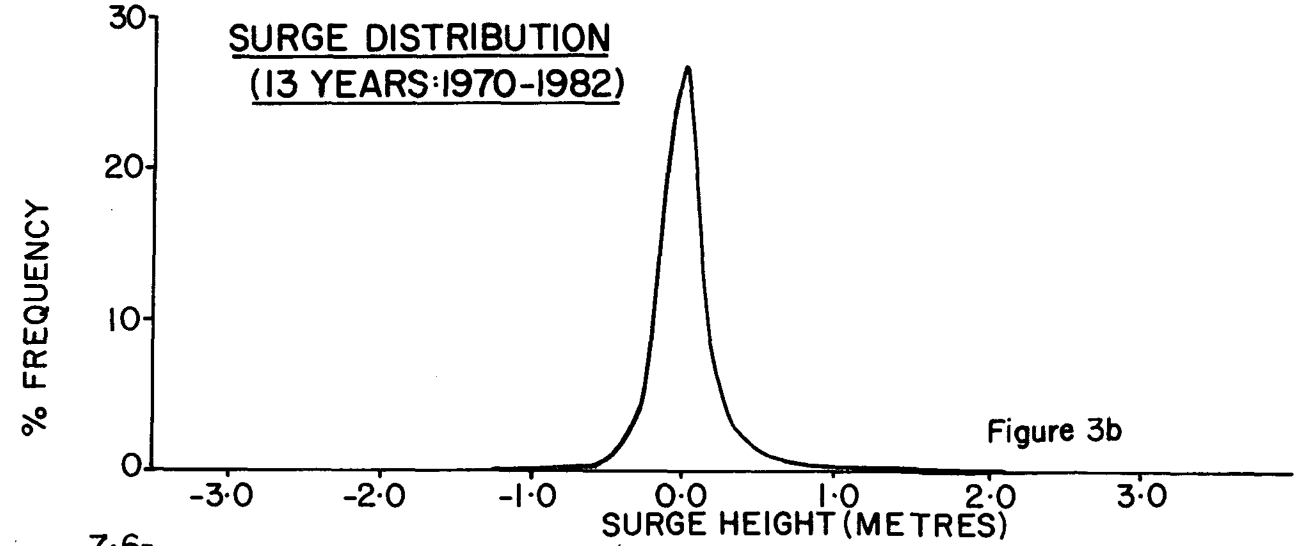


Figure 3b

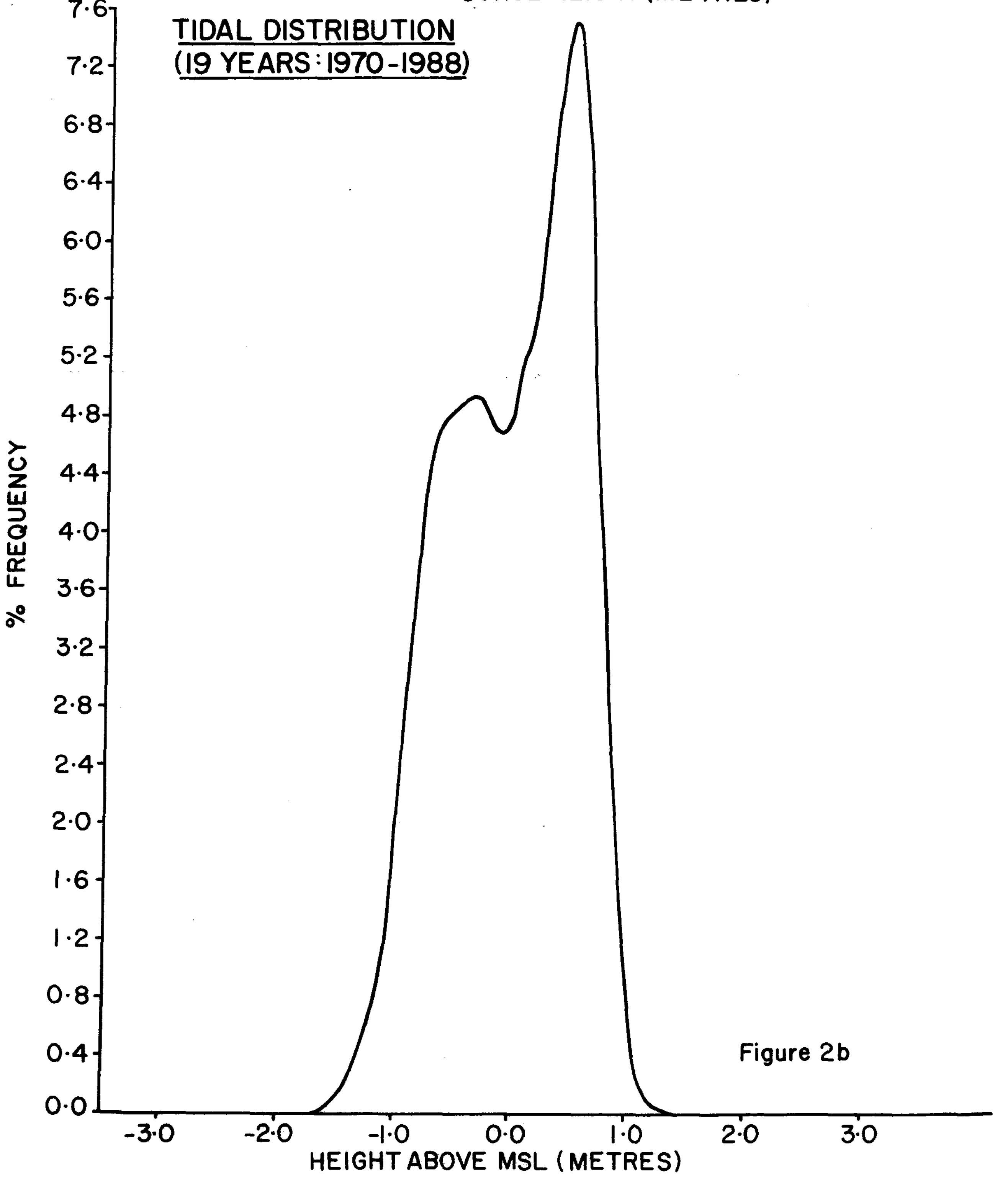


Figure 2b

HARWICH

SURGE DISTRIBUTION (10 YEARS: 1967-1976)

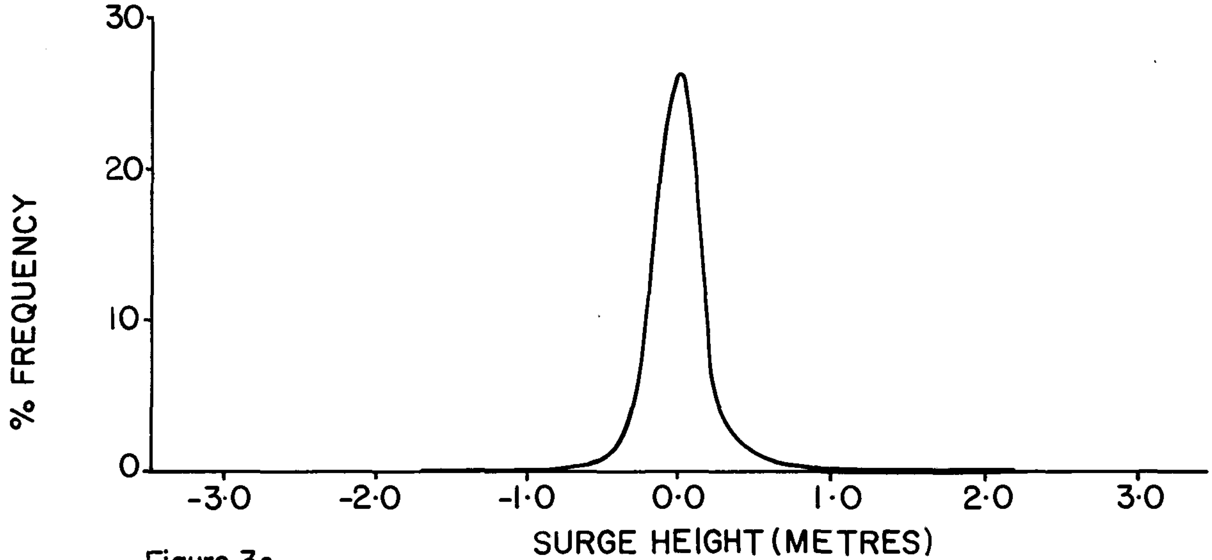


Figure 3c

TIDAL DISTRIBUTION (19 YEARS: 1967-1985)

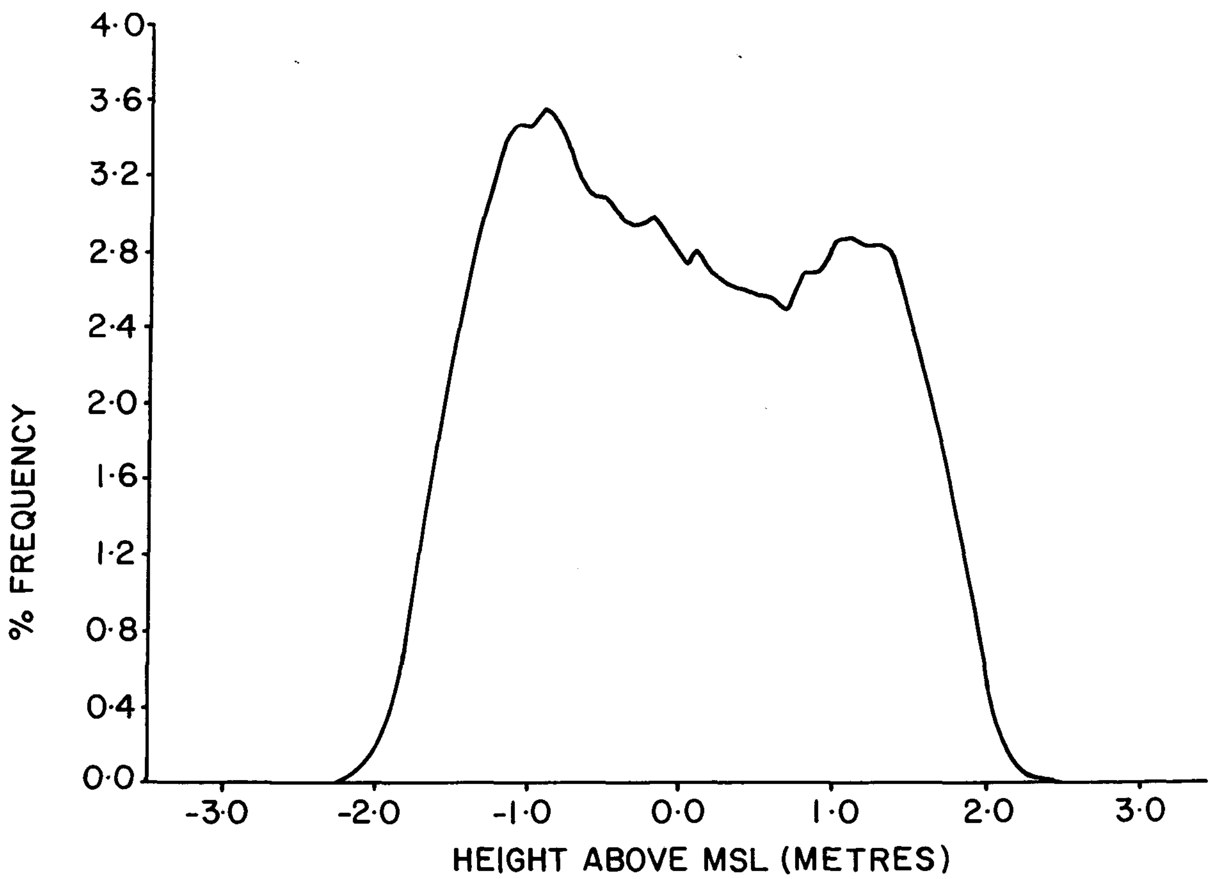
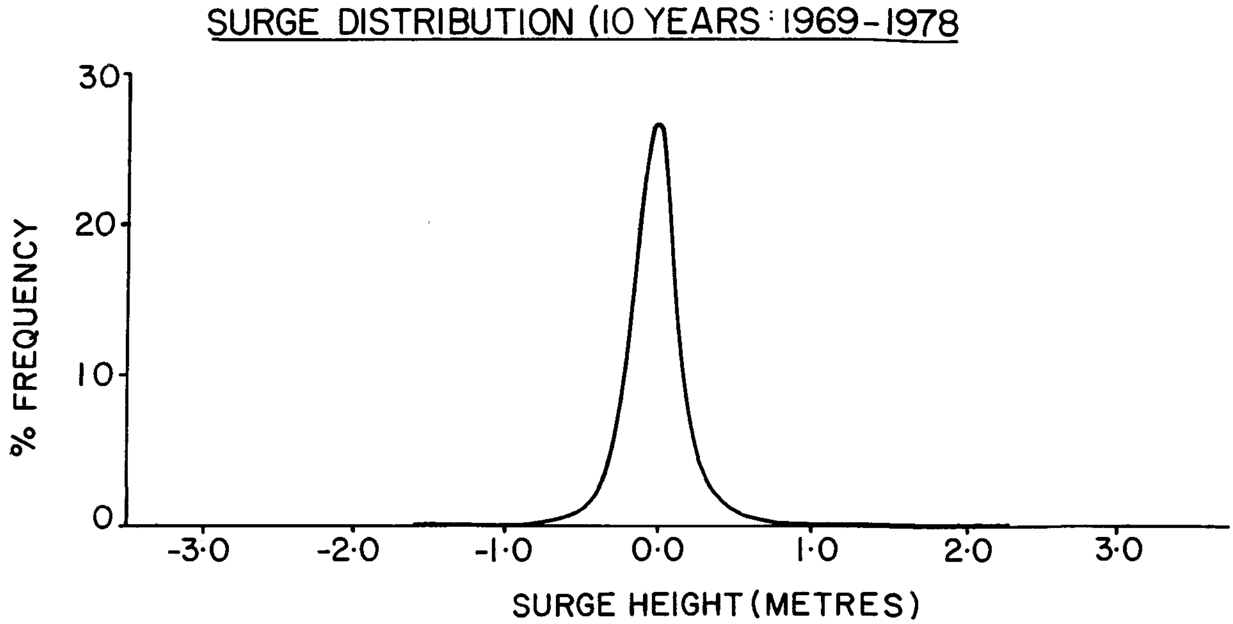


Figure 2c

WALTON-ON-THE NAZE



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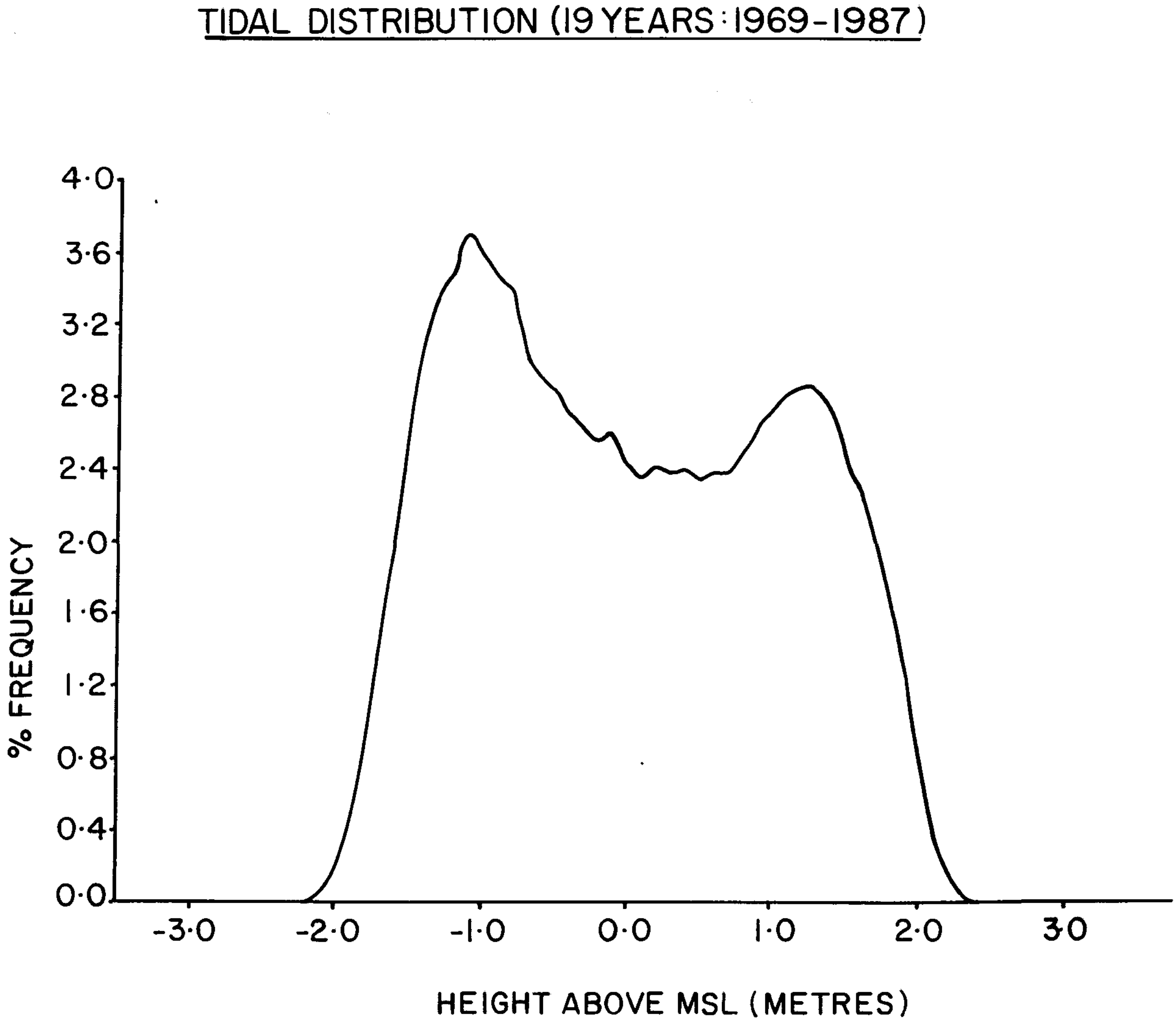


Figure 2d

SHEERNESS

SURGE DISTRIBUTION (11 YEARS: 1965-1975)

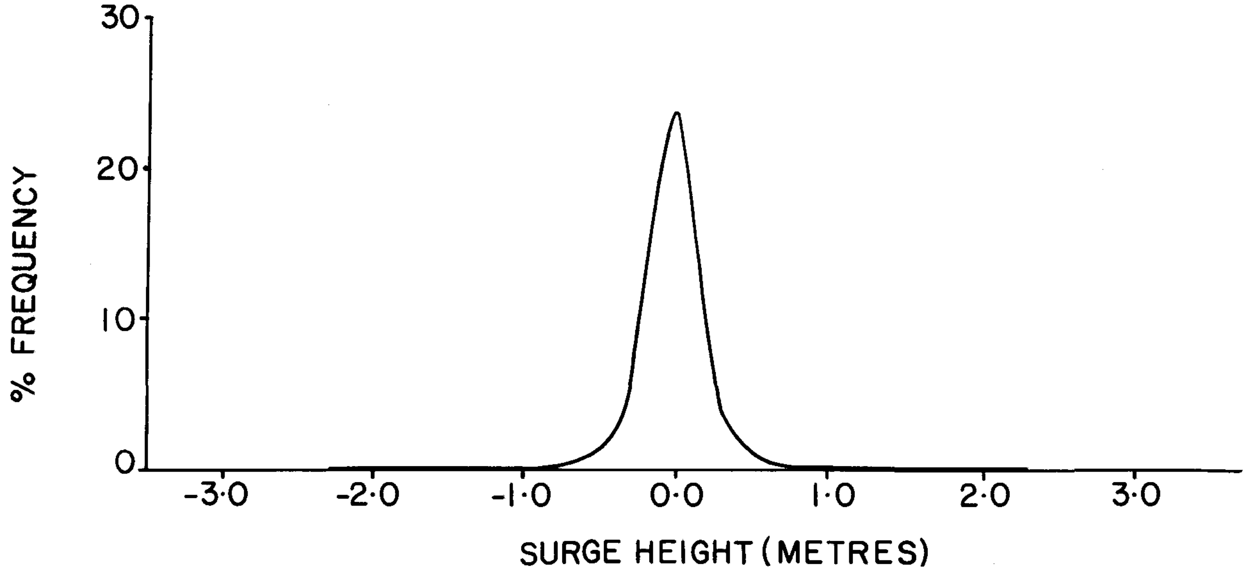


Figure 3e

TIDAL DISTRIBUTION (19 YEARS: 1965-1983

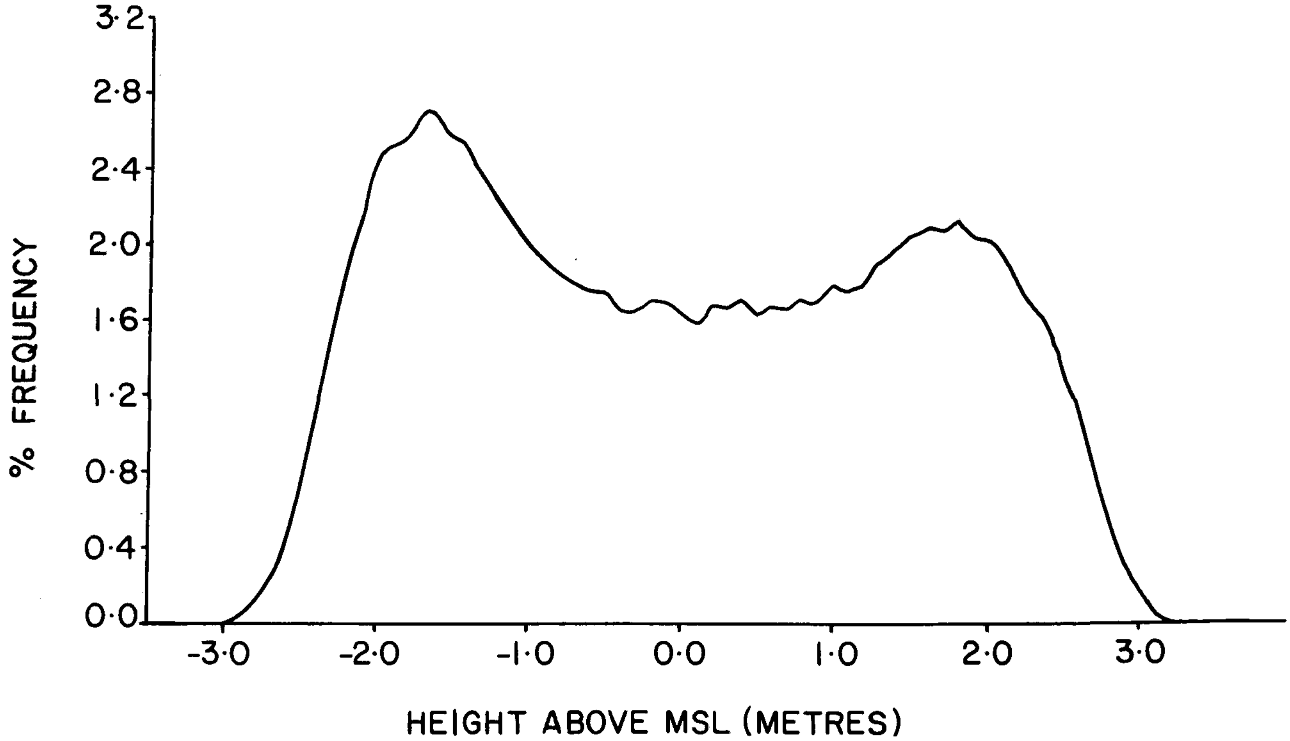


Figure 2e

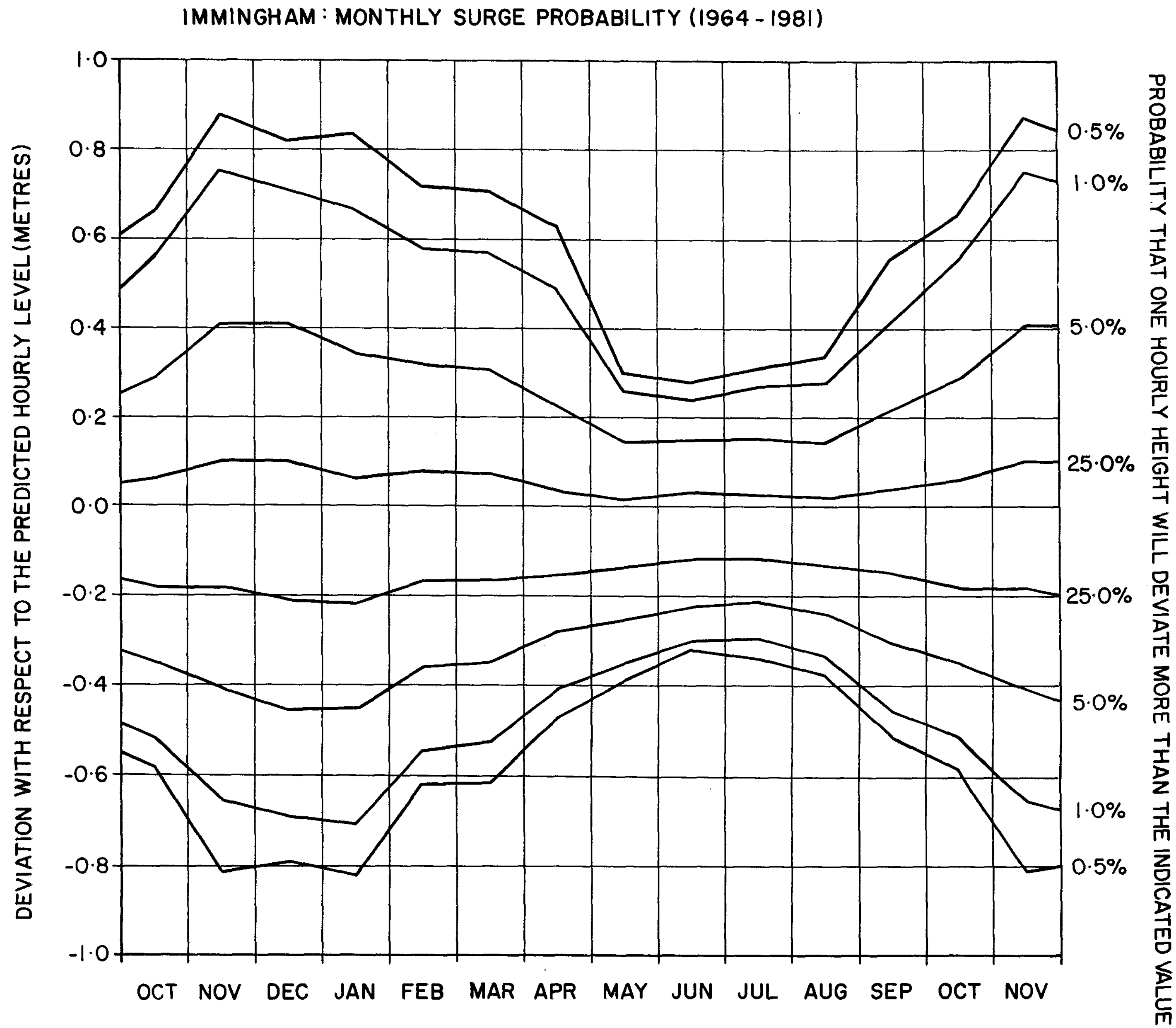

IMMINGHAM : MONTHLY SURGE PROBABILITY (1964 - 1981)
DEVIATION WITH RESPECT TO THE PREDICTED HOURLY LEVEL (METRES)
1·0
0·8
0·6
0·4
0·2
0·0
-0·2
-0·4
-0·6
-0·8
-1·0
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
0·5%
1·0%
5·0%
25·0%
25·0%
5·0%
1·0%
0·5%
PROBABILITY THAT ONE HOURLY HEIGHT WILL DEVIATE MORE THAN THE INDICATED VALUE

Figure 4a

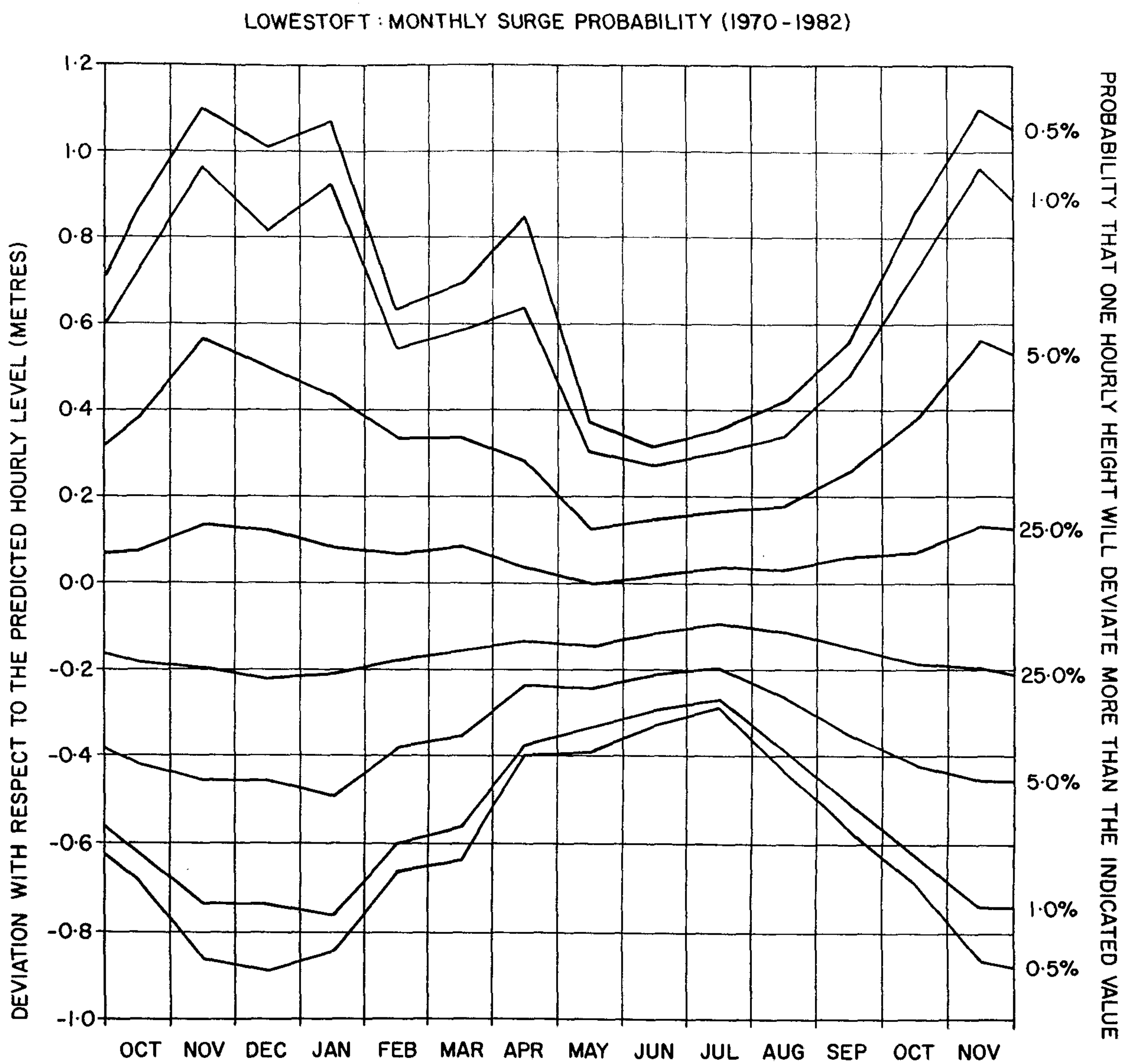
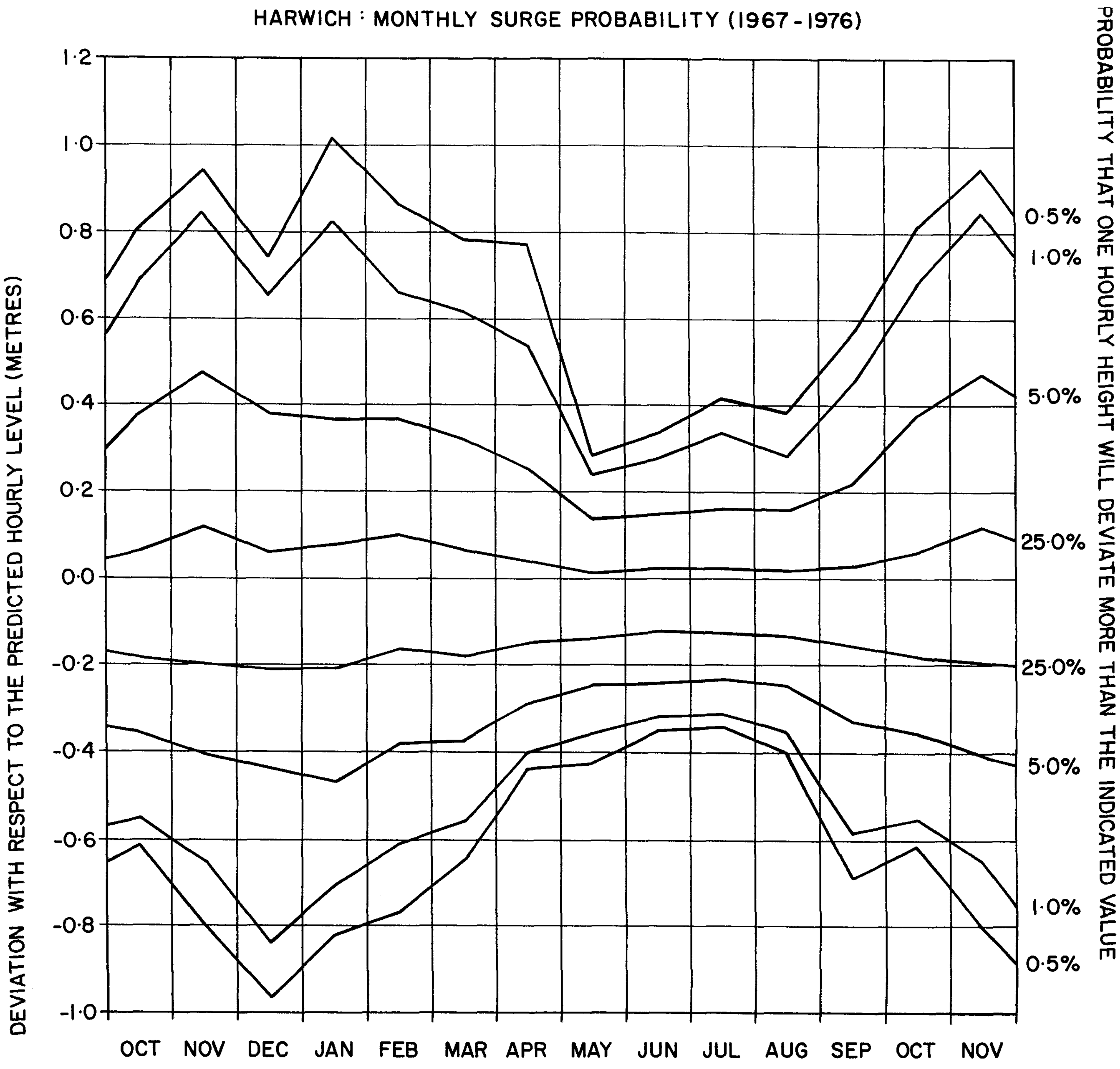
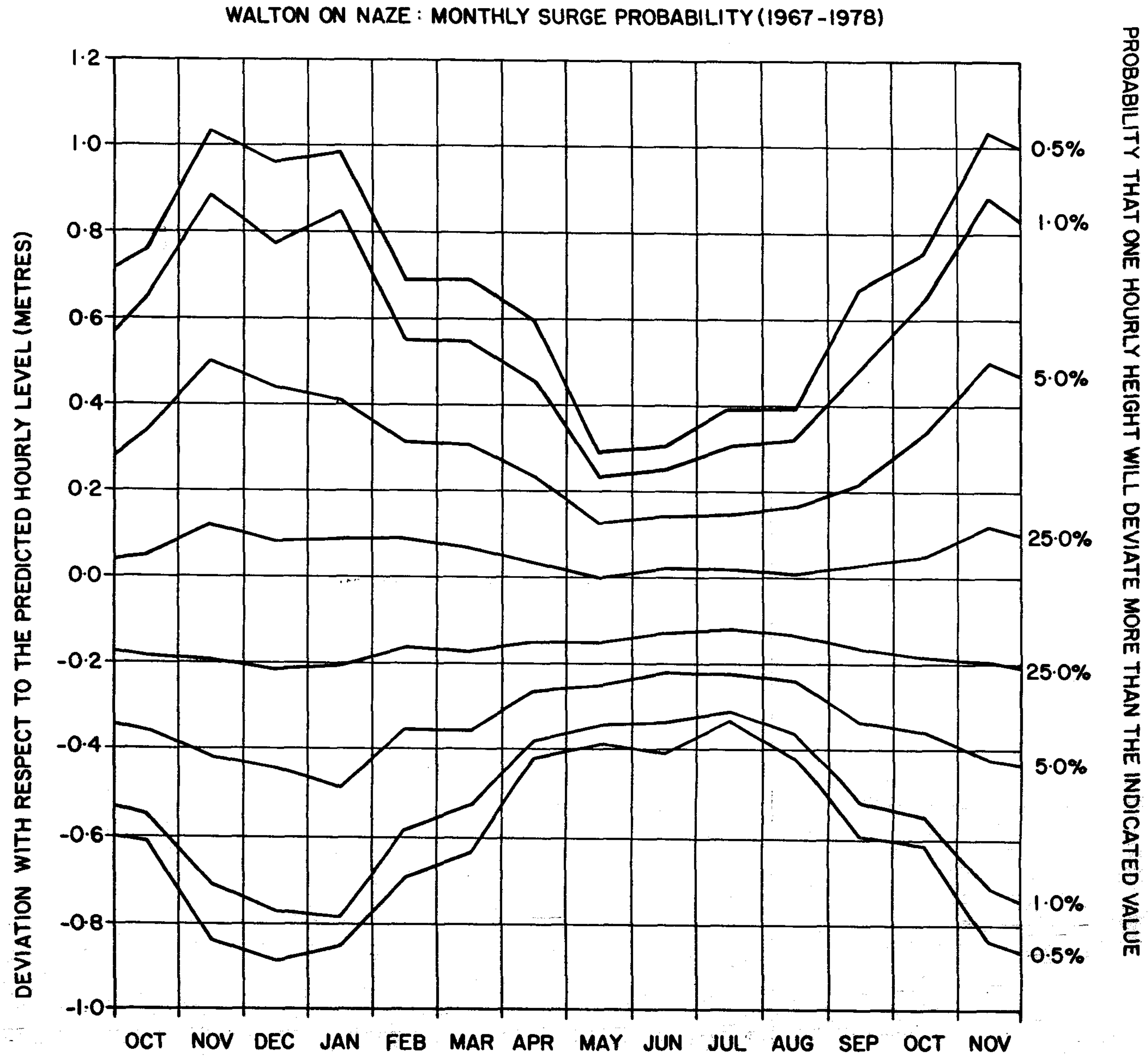

LOWESTOFT : MONTHLY SURGE PROBABILITY (1970 - 1982)
DEVIATION WITH RESPECT TO THE PREDICTED HOURLY LEVEL (METRES)
PROBABILITY THAT ONE HOURLY HEIGHT WILL DEVIATE MORE THAN THE INDICATED VALUE
1·2
1·0
0·8
0·6
0·4
0·2
0·0
-0·2
-0·4
-0·6
-0·8
-1·0
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV
0·5%
1·0%
5·0%
25·0%
25·0%
5·0%
1·0%
0·5%

Figure 4b



HARWICH : MONTHLY SURGE PROBABILITY (1967-1976)
DEVIATION WITH RESPECT TO THE PREDICTED HOURLY LEVEL (METRES)
PROBABILITY THAT ONE HOURLY HEIGHT WILL DEVIATE MORE THAN THE INDICATED VALUE
1·2
1·0
0·8
0·6
0·4
0·2
0·0
-0·2
-0·4
-0·6
-0·8
-1·0
OCT
NOV
DEC
JAN
FEB
MAR
APR
MAY
JUN
JUL
AUG
SEP
OCT
NOV
0·5%
1·0%
5·0%
25·0%
25·0%
5·0%
1·0%
0·5%

Figure 4c



WALTON ON NAZE : MONTHLY SURGE PROBABILITY (1967-1978)
DEVIATION WITH RESPECT TO THE PREDICTED HOURLY LEVEL (METRES)
PROBABILITY THAT ONE HOURLY HEIGHT WILL DEVIATE MORE THAN THE INDICATED VALUE
1·2
1·0
0·8
0·6
0·4
0·2
0·0
-0·2
-0·4
-0·6
-0·8
-1·0
0·5%
1·0%
5·0%
25·0%
25·0%
5·0%
1·0%
0·5%
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV

Figure 4d

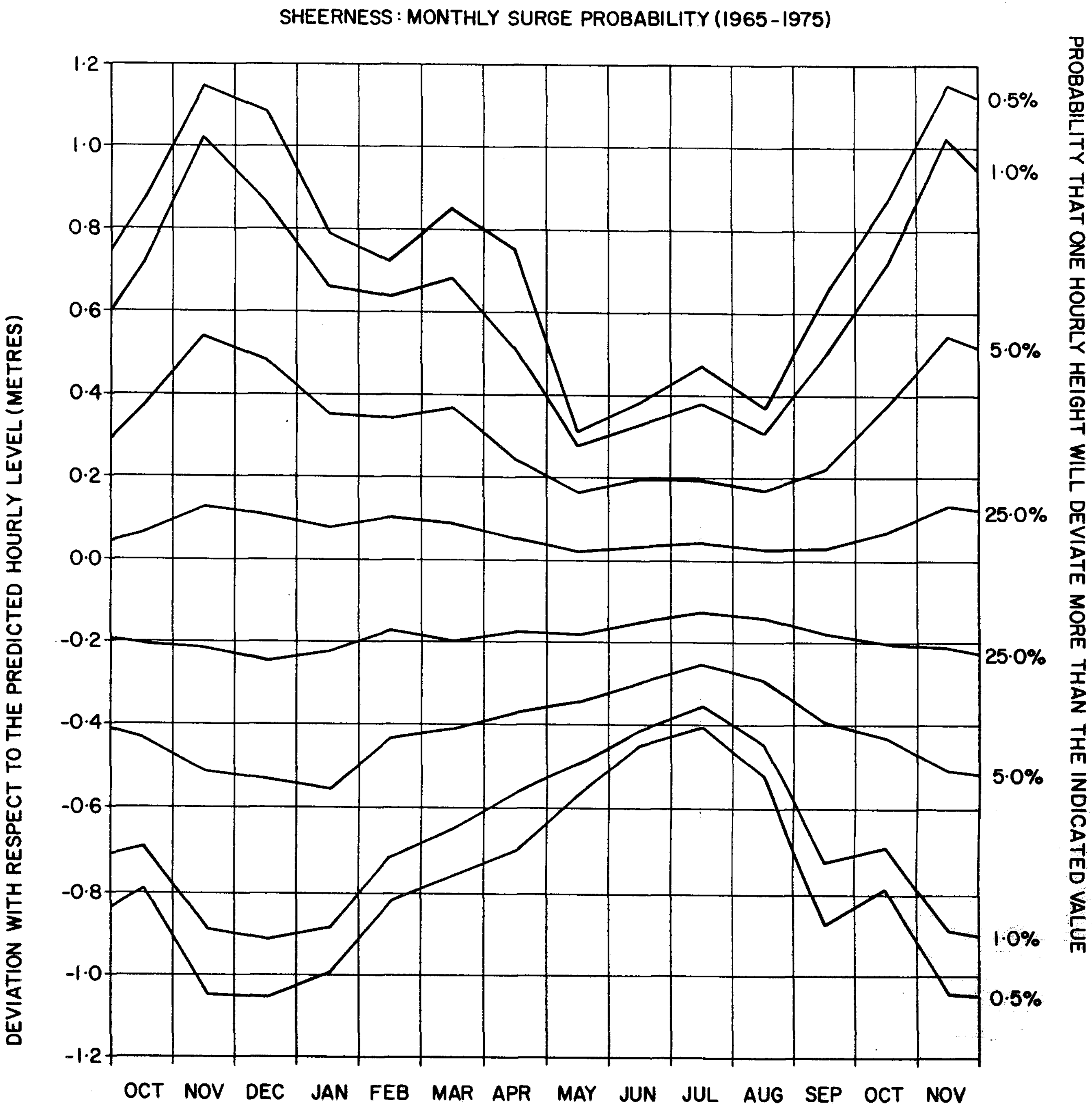

SHEERNESS: MONTHLY SURGE PROBABILITY (1965-1975)
DEVIATION WITH RESPECT TO THE PREDICTED HOURLY LEVEL (METRES)
PROBABILITY THAT ONE HOURLY HEIGHT WILL DEVIATE MORE THAN THE INDICATED VALUE
1·2
1·0
0·8
0·6
0·4
0·2
0·0
-0·2
-0·4
-0·6
-0·8
-1·0
-1·2
0·5%
1·0%
5·0%
25·0%
25·0%
5·0%
1·0%
0·5%
OCT NOV DEC JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV

Figure 4e

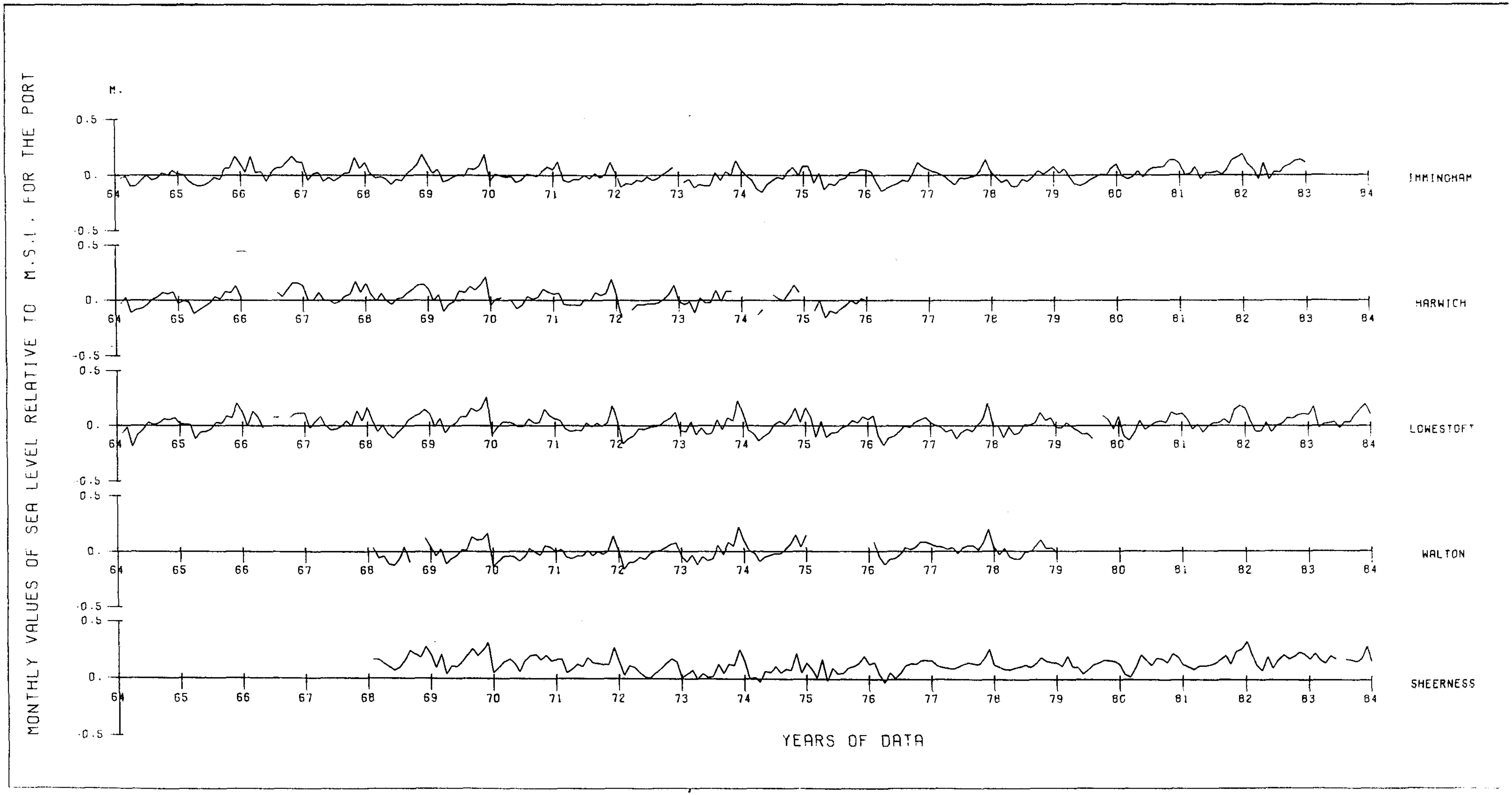


Figure 5 : MONTHLY MEAN SEA LEVELS

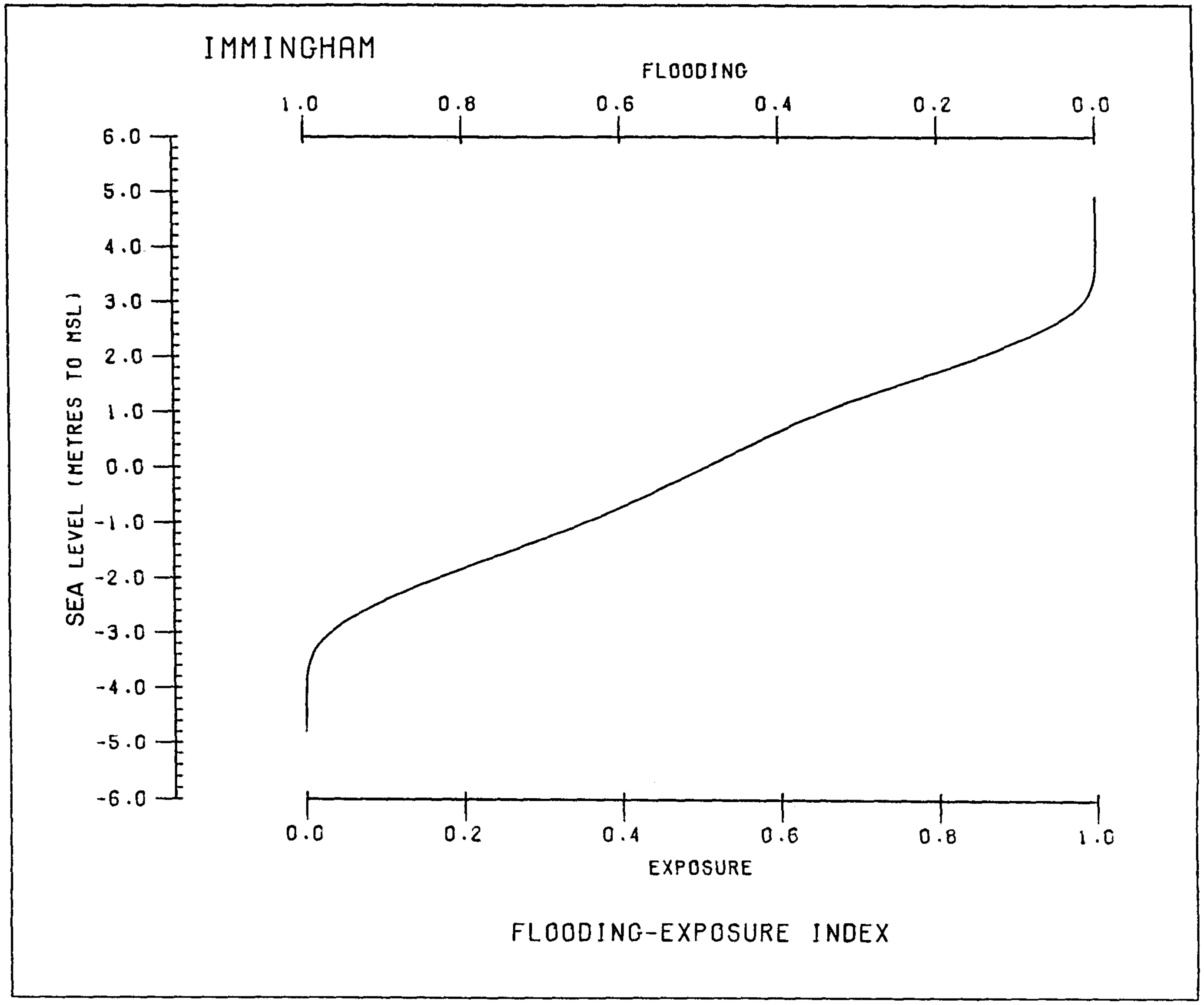

IMMINGHAM
FLOODING
1.0
0.8
0.6
0.4
0.2
0.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
SEA LEVEL (METRES TO MSL)
0.0
0.2
0.4
0.6
0.8
1.0
EXPOSURE
FLOODING-EXPOSURE INDEX

Figure 6a

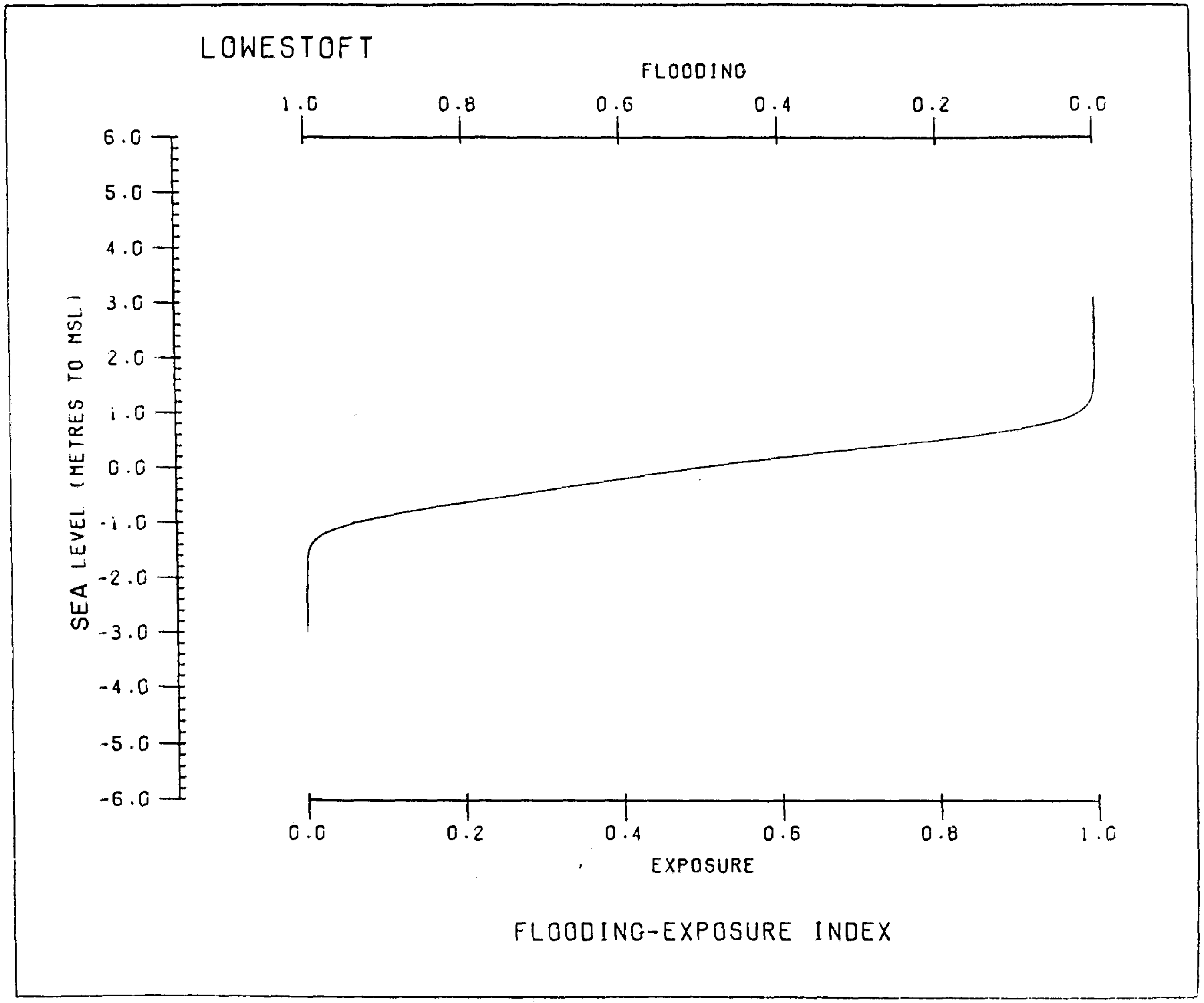

LOWESTOFT
FLOODING
1.0
0.8
0.6
0.4
0.2
0.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
SEA LEVEL (METRES TO MSL)
0.0
0.2
0.4
0.6
0.8
1.0
EXPOSURE
FLOODING-EXPOSURE INDEX

Figure 6b

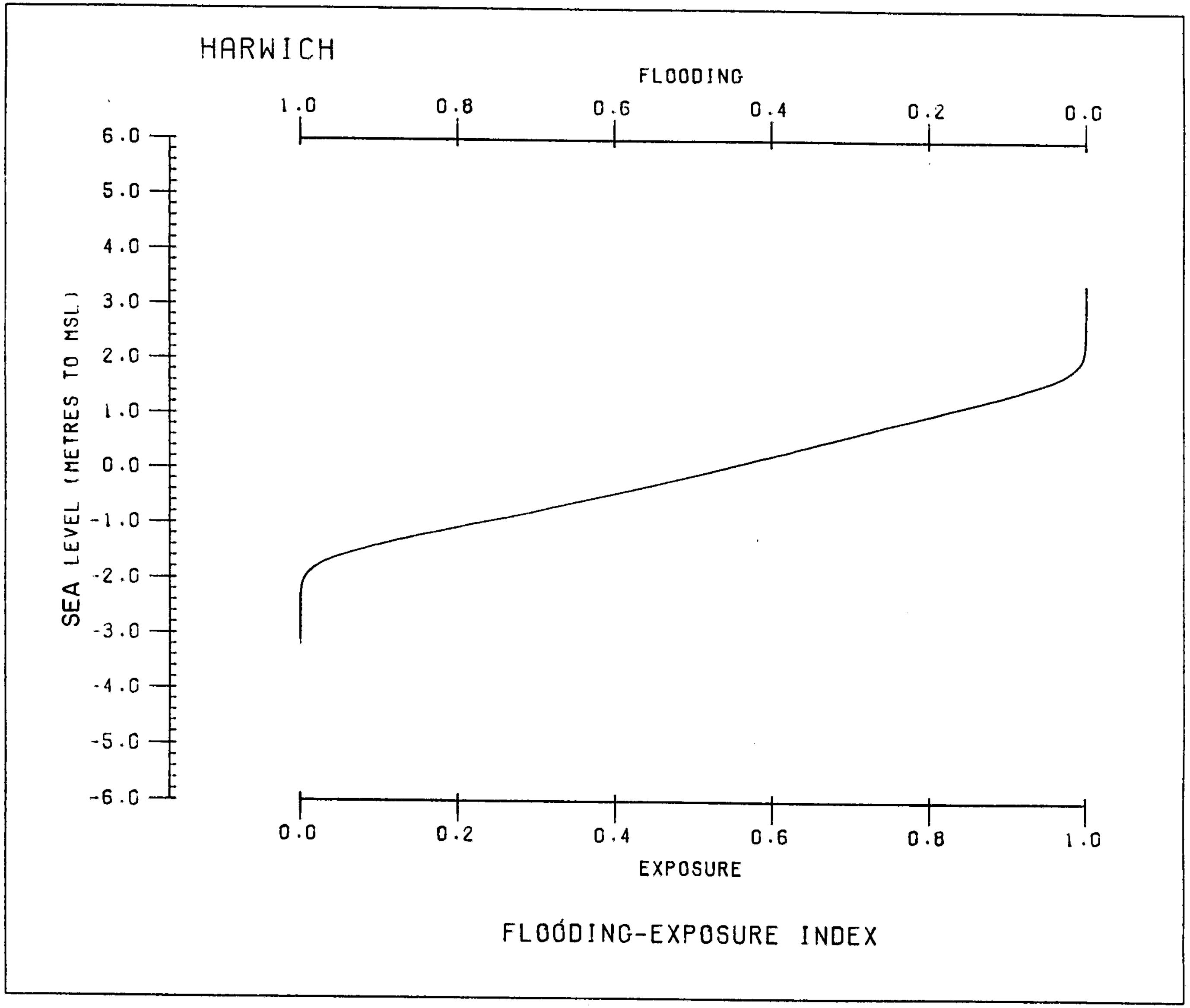

HARWICH
FLOODING
1.0
0.8
0.6
0.4
0.2
0.0
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
SEA LEVEL (METRES TO MSL)
0.0
0.2
0.4
0.6
0.8
1.0
EXPOSURE
FLOODING-EXPOSURE INDEX

Figure 6c

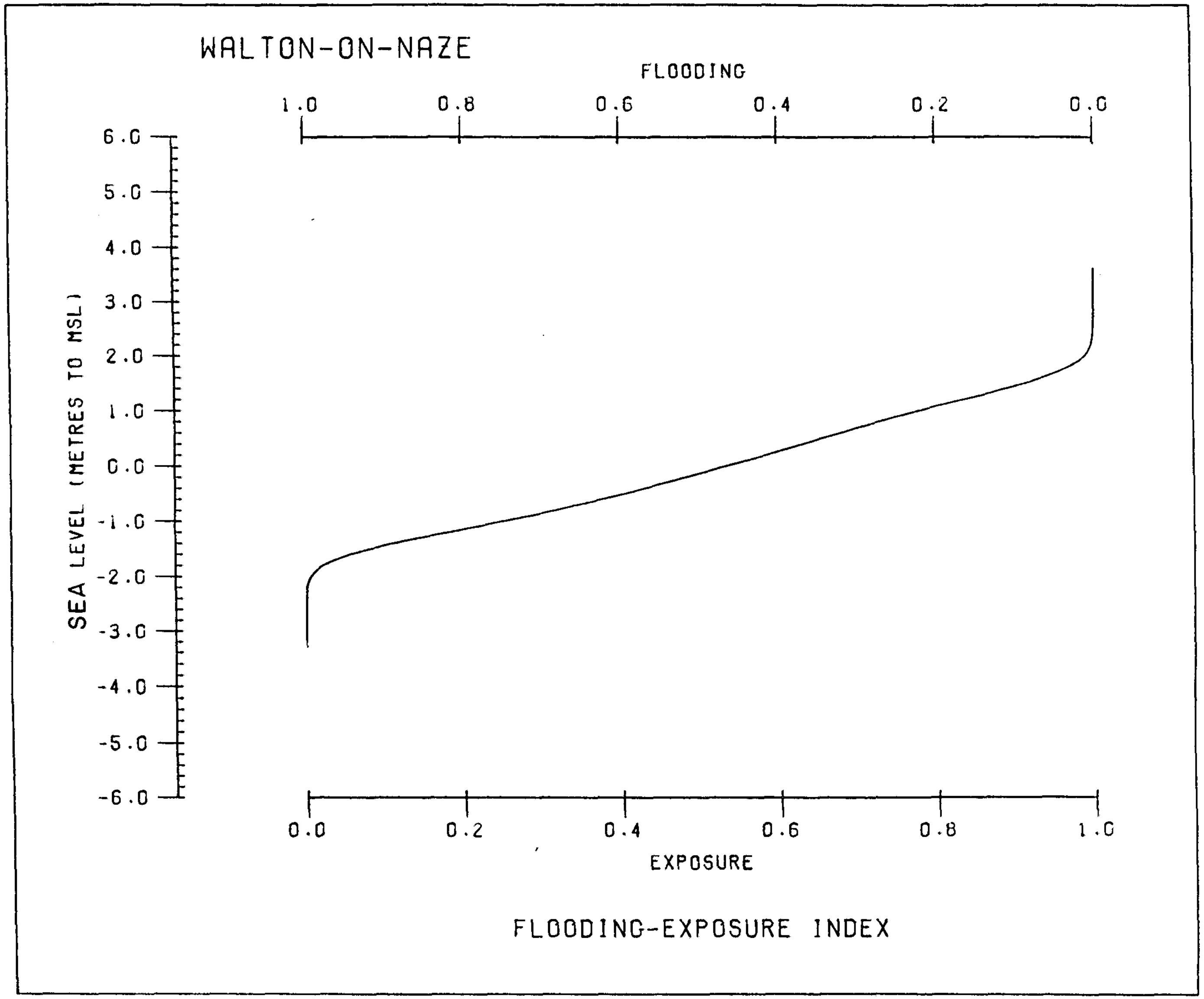
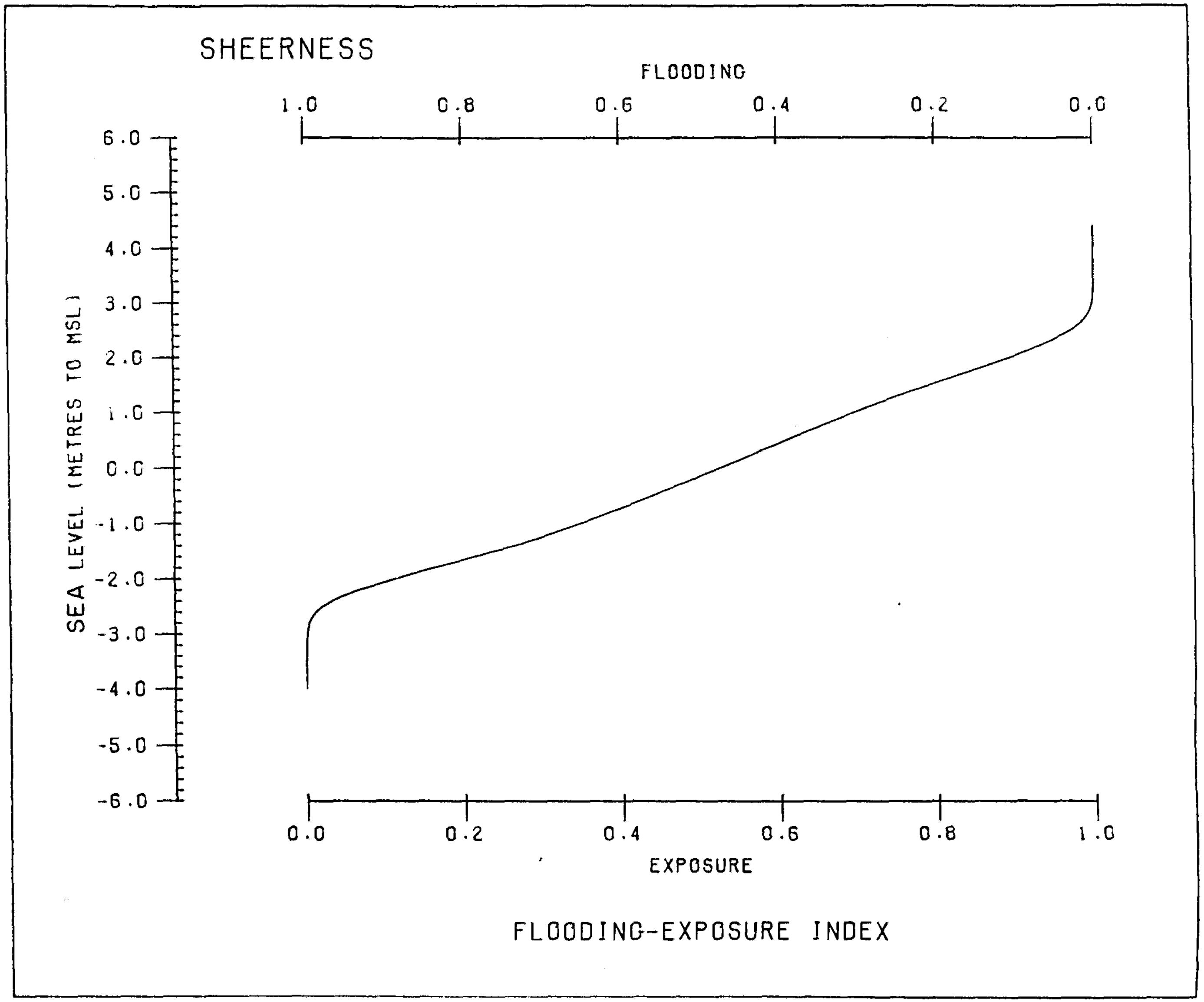

WALTON-ON-NAZE
FLOODING
1.0
0.8
0.6
0.4
0.2
0.0
SEA LEVEL (METRES TO MSL)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0.0
0.2
0.4
0.6
0.8
1.0
EXPOSURE
FLOODING-EXPOSURE INDEX

Figure 6d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FLOODING
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0.6
0.4
0.2
0.0
SEA LEVEL (METRES TO MSL)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
-4.0
-5.0
-6.0
0.0
0.2
0.4
0.6
0.8
1.0
EXPOSURE
FLOODING-EXPOSURE INDEX

Figure 6e

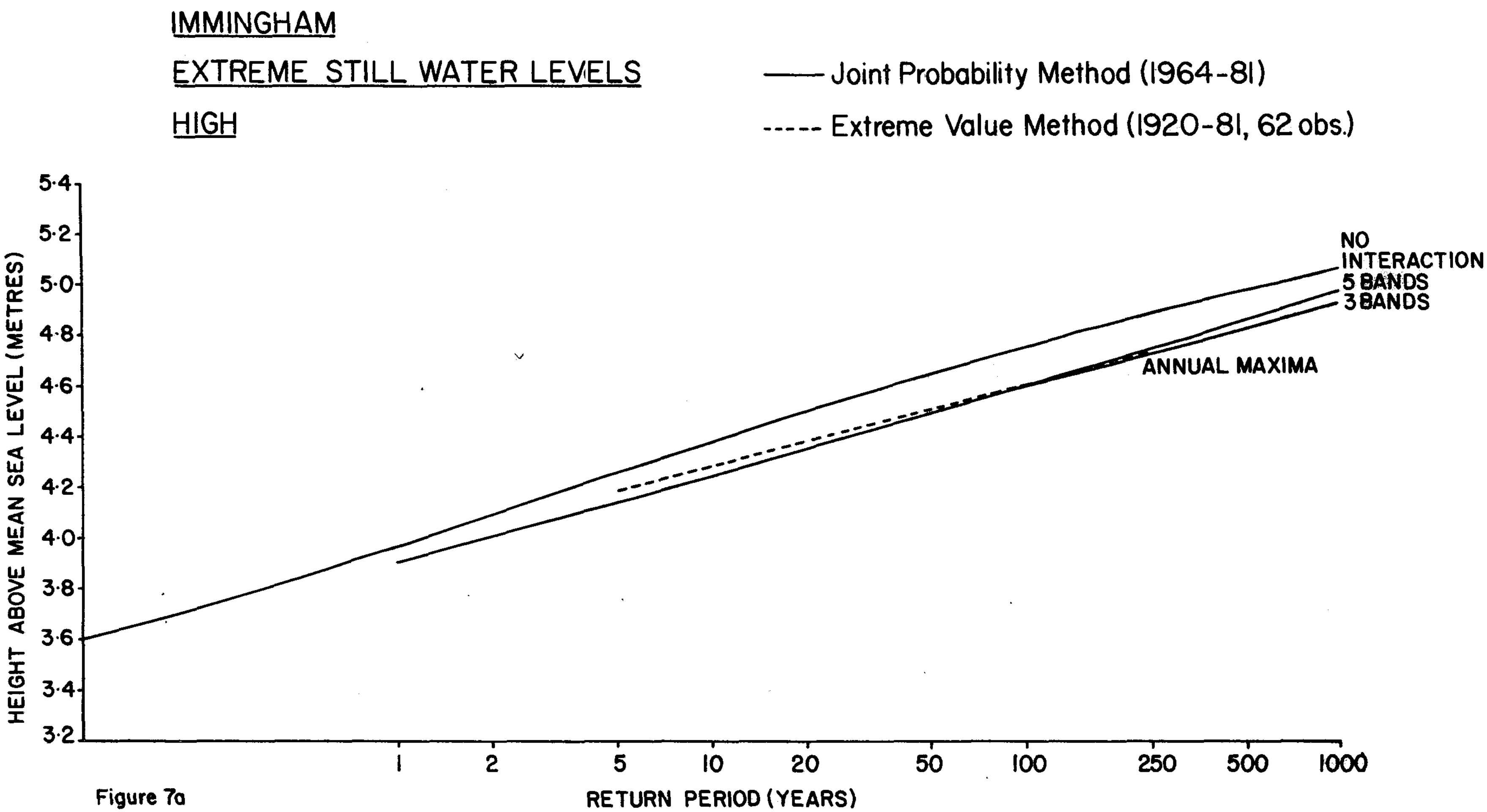

IMMINGHAM
EXTREME STILL WATER LEVELS
HIGH
Joint Probability Method (1964-81)
Extreme Value Method (1920-81, 62 obs.)
HEIGHT ABOVE MEAN SEA LEVEL (METRES)
5·4
5·2
5·0
4·8
4·6
4·4
4·2
4·0
3·8
3·6
3·4
3·2
NO INTERACTION
5 BANDS
3 BANDS
ANNUAL MAXIMA
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 7a

IMMINGHAM

EXTREME STILL WATER LEVELS

LOW

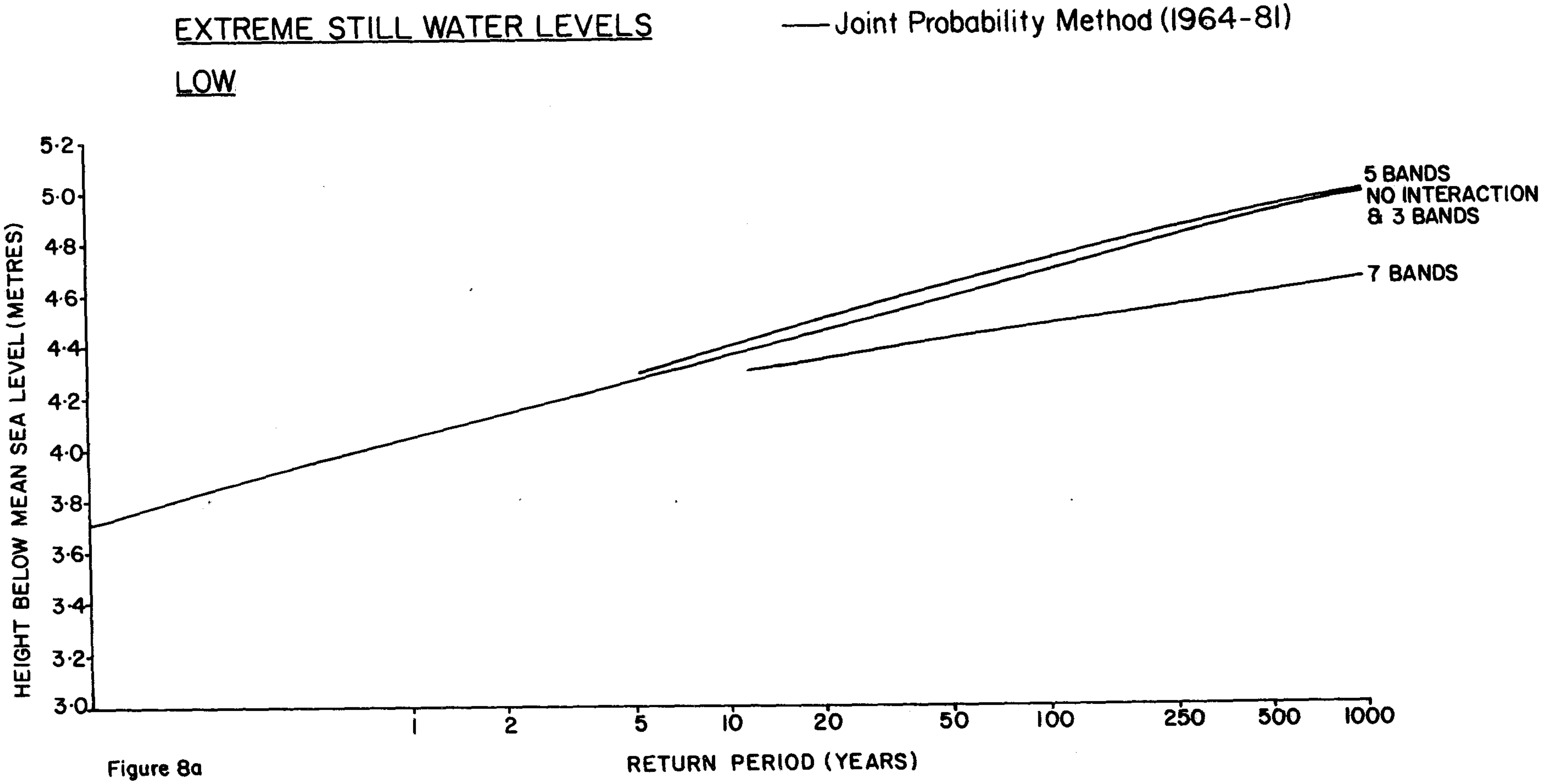


Figure 8a

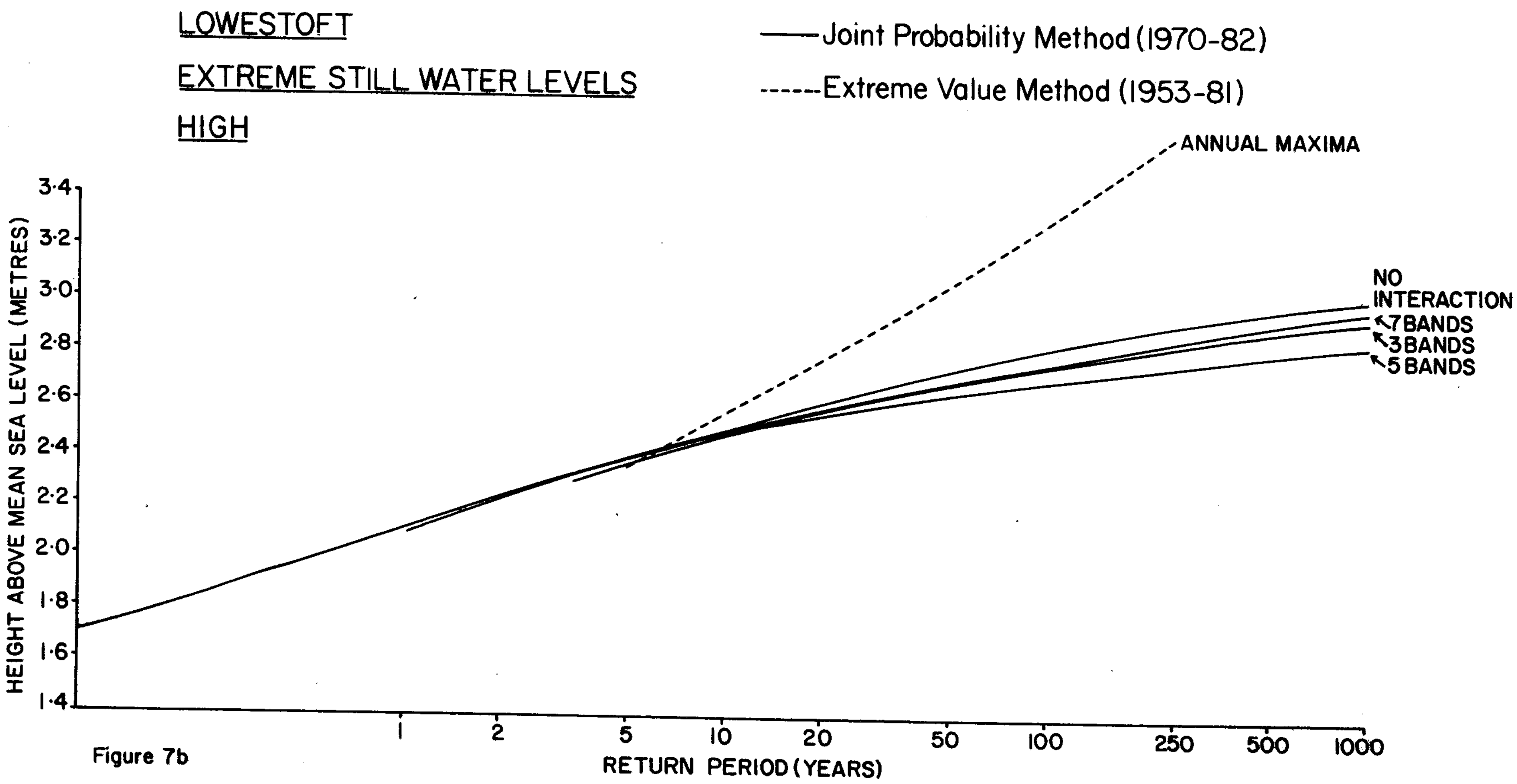
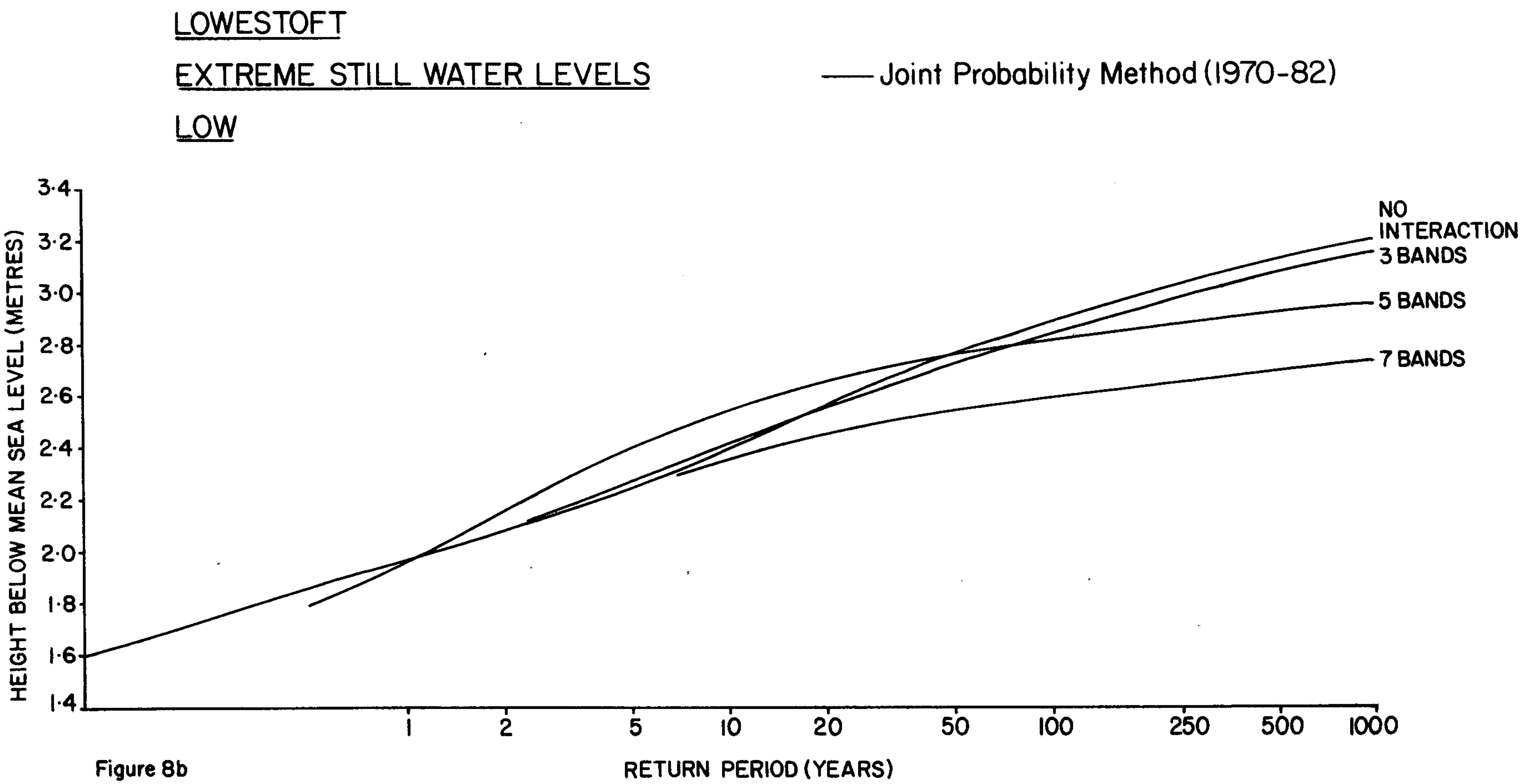

LOWESTOFT
EXTREME STILL WATER LEVELS
HIGH
Joint Probability Method (1970-82)
Extreme Value Method (1953-81)
ANNUAL MAXIMA
NO INTERACTION
7 BANDS
3 BANDS
5 BANDS
HEIGHT ABOVE MEAN SEA LEVEL (METRES)
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
1·8
1·6
1·4
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 7b


LOWESTOFT
EXTREME STILL WATER LEVELS
LOW
—— Joint Probability Method (1970-82)
HEIGHT BELOW MEAN SEA LEVEL (METRES)
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
1·8
1·6
1·4
NO INTERACTION
3 BANDS
5 BANDS
7 BANDS
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)
Figure 8b

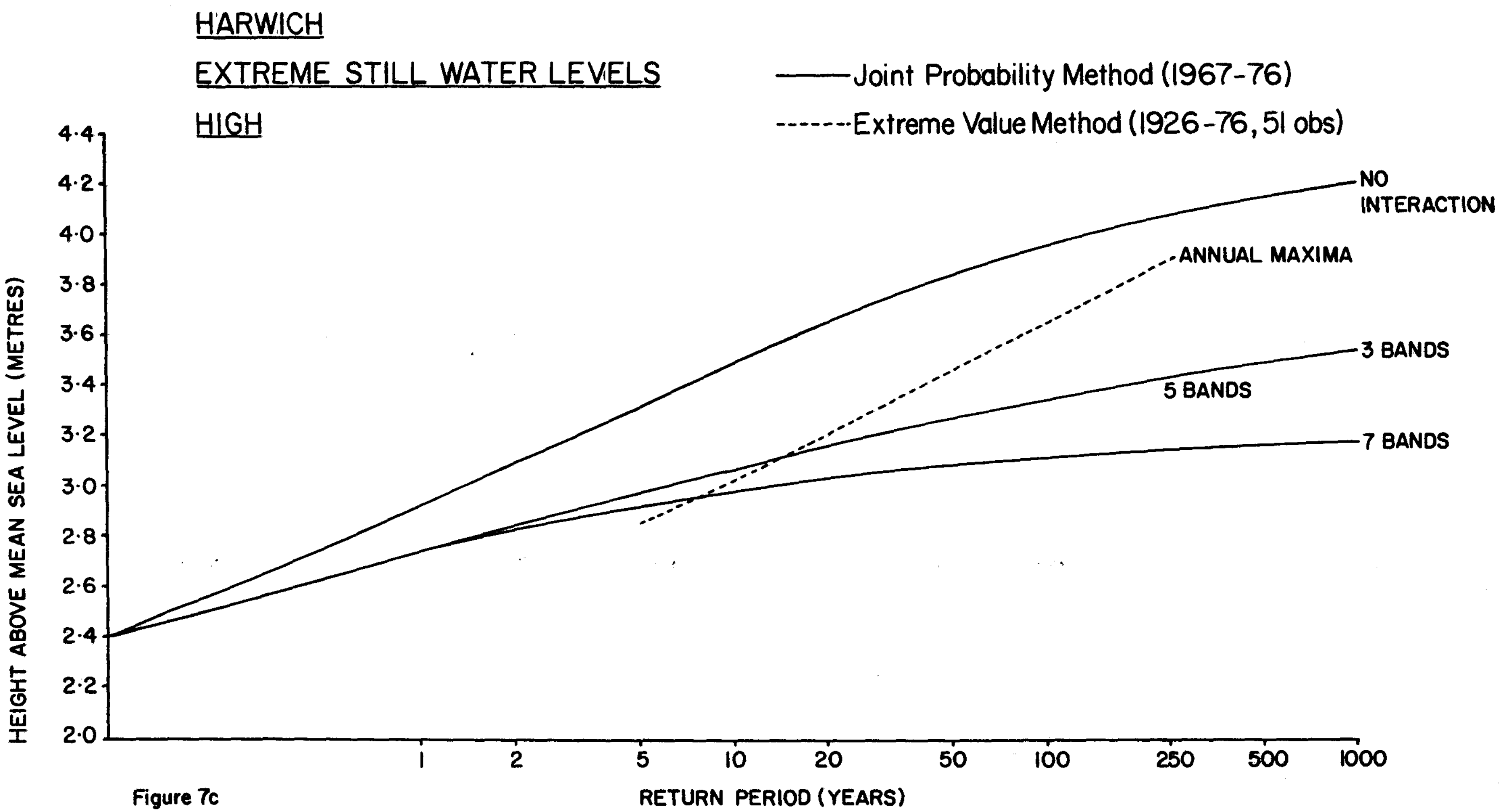

HARWICH
EXTREME STILL WATER LEVELS
HIGH
Joint Probability Method (1967-76)
Extreme Value Method (1926-76, 51 obs)
HEIGHT ABOVE MEAN SEA LEVEL (METRES)
4·4
4·2
4·0
3·8
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
NO INTERACTION
ANNUAL MAXIMA
3 BANDS
5 BANDS
7 BANDS
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 7c

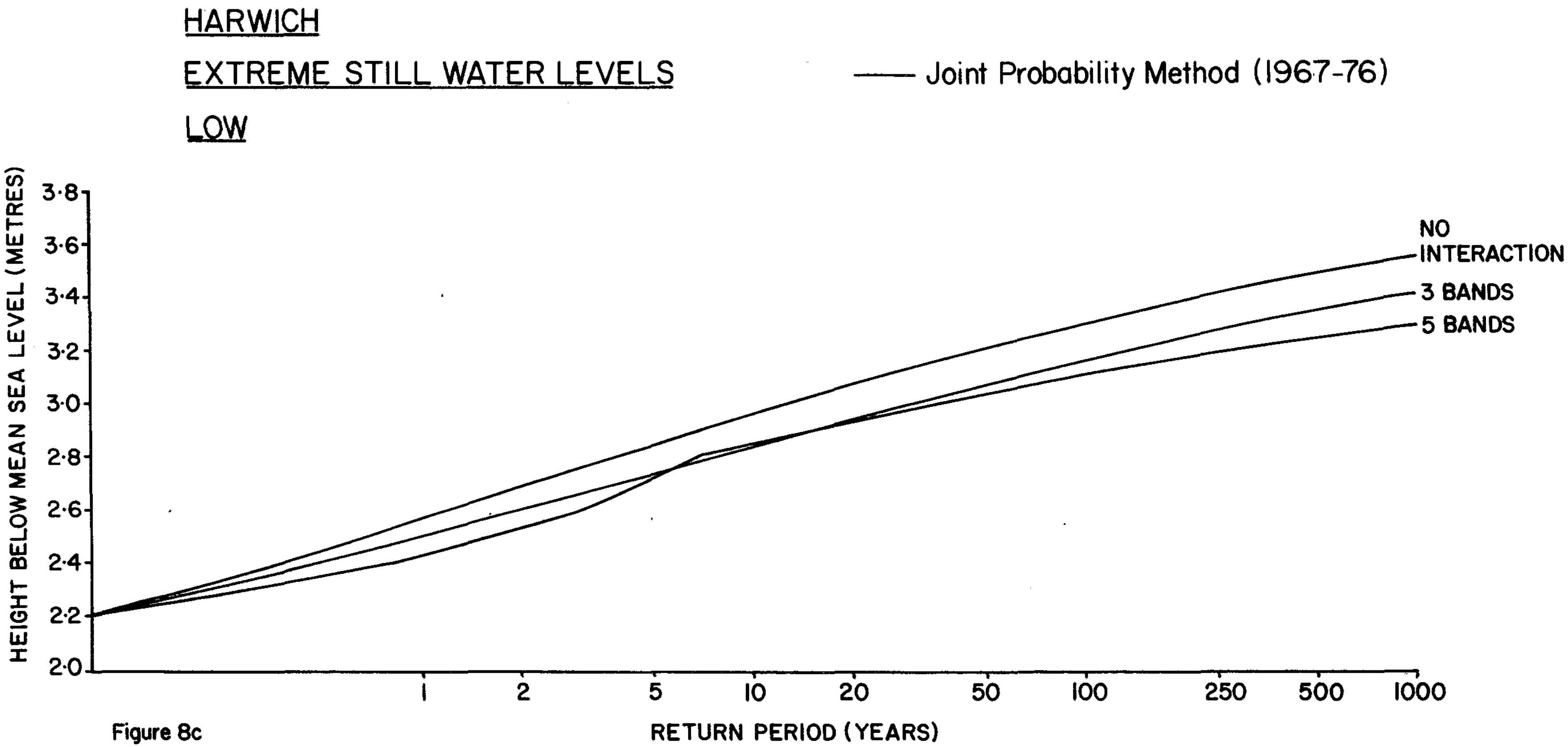

HARWICH
EXTREME STILL WATER LEVELS
LOW
Joint Probability Method (1967-76)
HEIGHT BELOW MEAN SEA LEVEL (METRES)
3·8
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
NO INTERACTION
3 BANDS
5 BANDS
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 8c

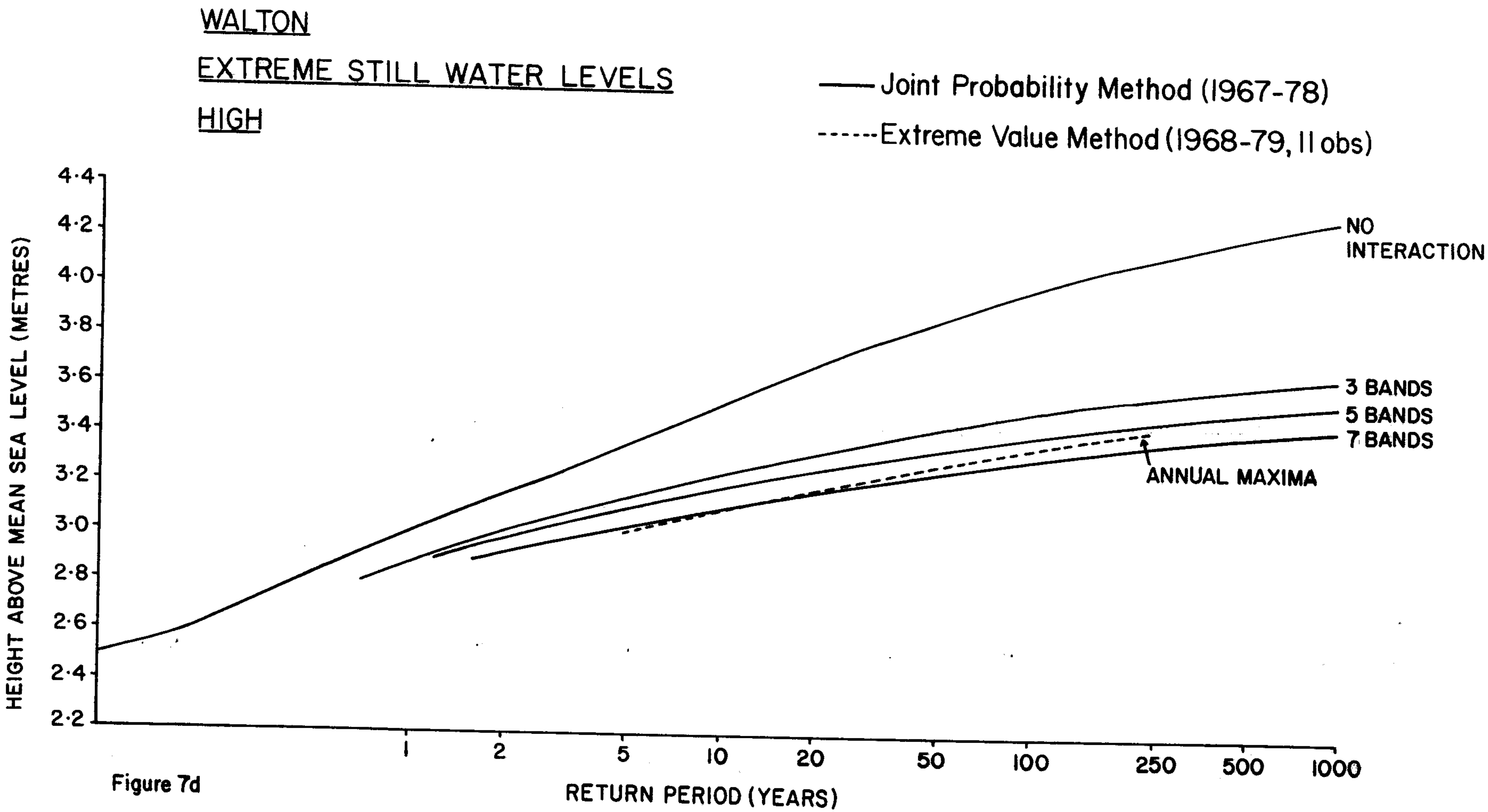
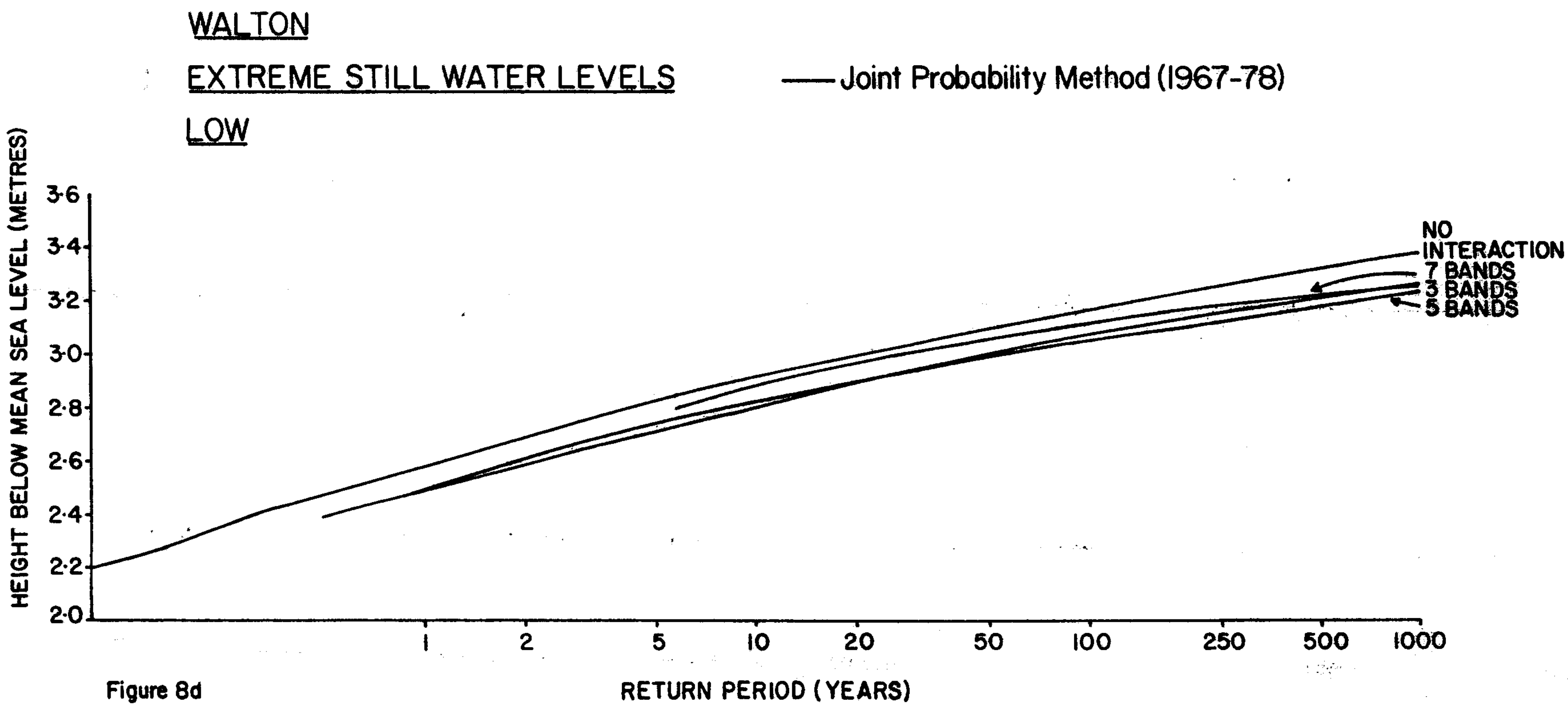

WALTON
EXTREME STILL WATER LEVELS
HIGH
Joint Probability Method (1967-78)
Extreme Value Method (1968-79, 11 obs)
HEIGHT ABOVE MEAN SEA LEVEL (METRES)
4·4
4·2
4·0
3·8
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
NO INTERACTION
3 BANDS
5 BANDS
7 BANDS
ANNUAL MAXIMA
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 7d



WALTON
EXTREME STILL WATER LEVELS
LOW
—— Joint Probability Method (1967-78)
HEIGHT BELOW MEAN SEA LEVEL (METRES)
3·6
3·4
3·2
3·0
2·8
2·6
2·4
2·2
2·0
NO INTERACTION
7 BANDS
3 BANDS
5 BANDS
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 8d

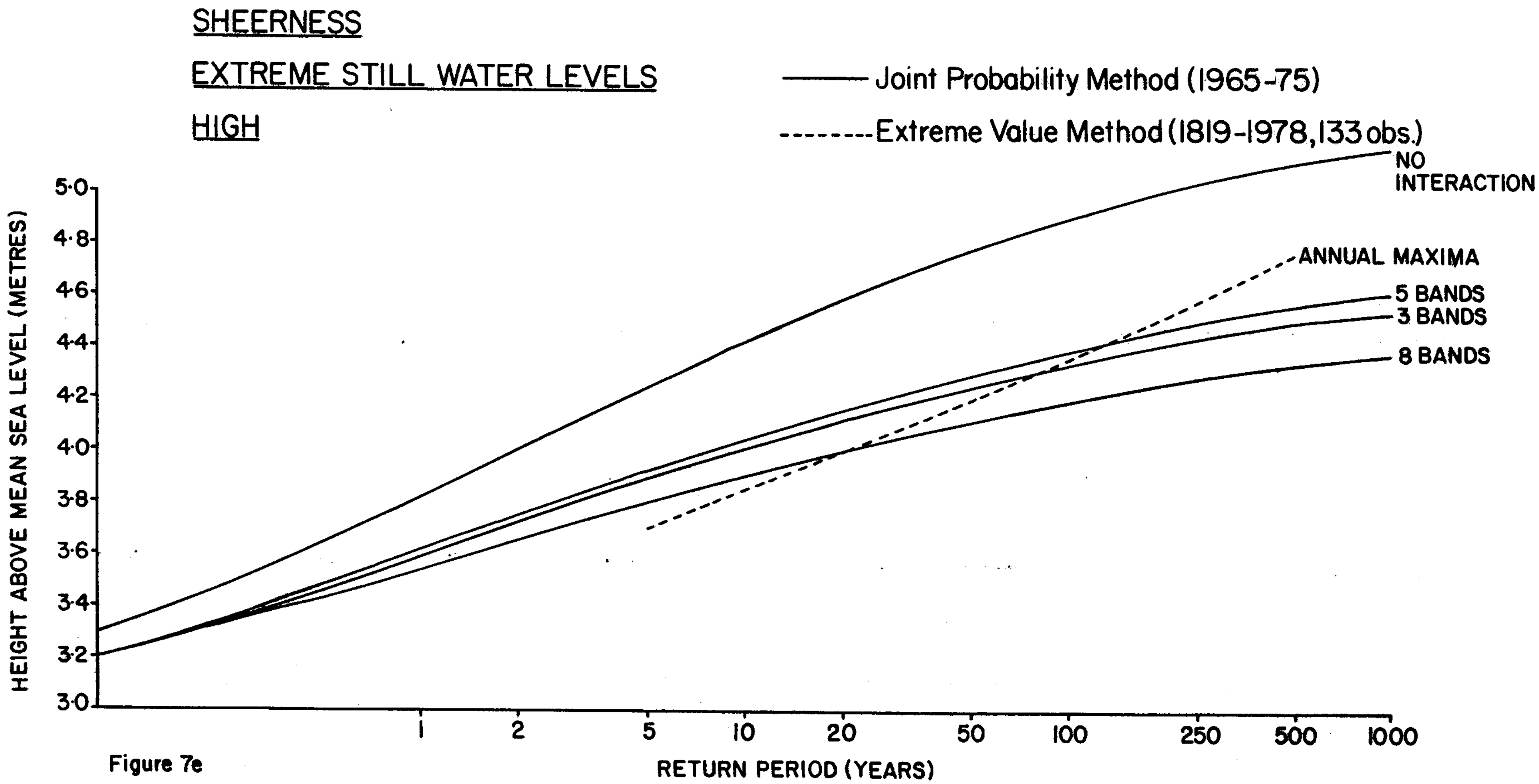

SHEERNESS
EXTREME STILL WATER LEVELS
HIGH
Joint Probability Method (1965-75)
Extreme Value Method (1819-1978, 133 obs.)
NO INTERACTION
ANNUAL MAXIMA
5 BANDS
3 BANDS
8 BANDS
HEIGHT ABOVE MEAN SEA LEVEL (METRES)
5·0
4·8
4·6
4·4
4·2
4·0
3·8
3·6
3·4
3·2
3·0
1
2
5
10
20
50
100
250
500
1000
RETURN PERIOD (YEARS)

Figure 7e

SHEERNESS

EXTREME STILL WATER LEVELS

LOW

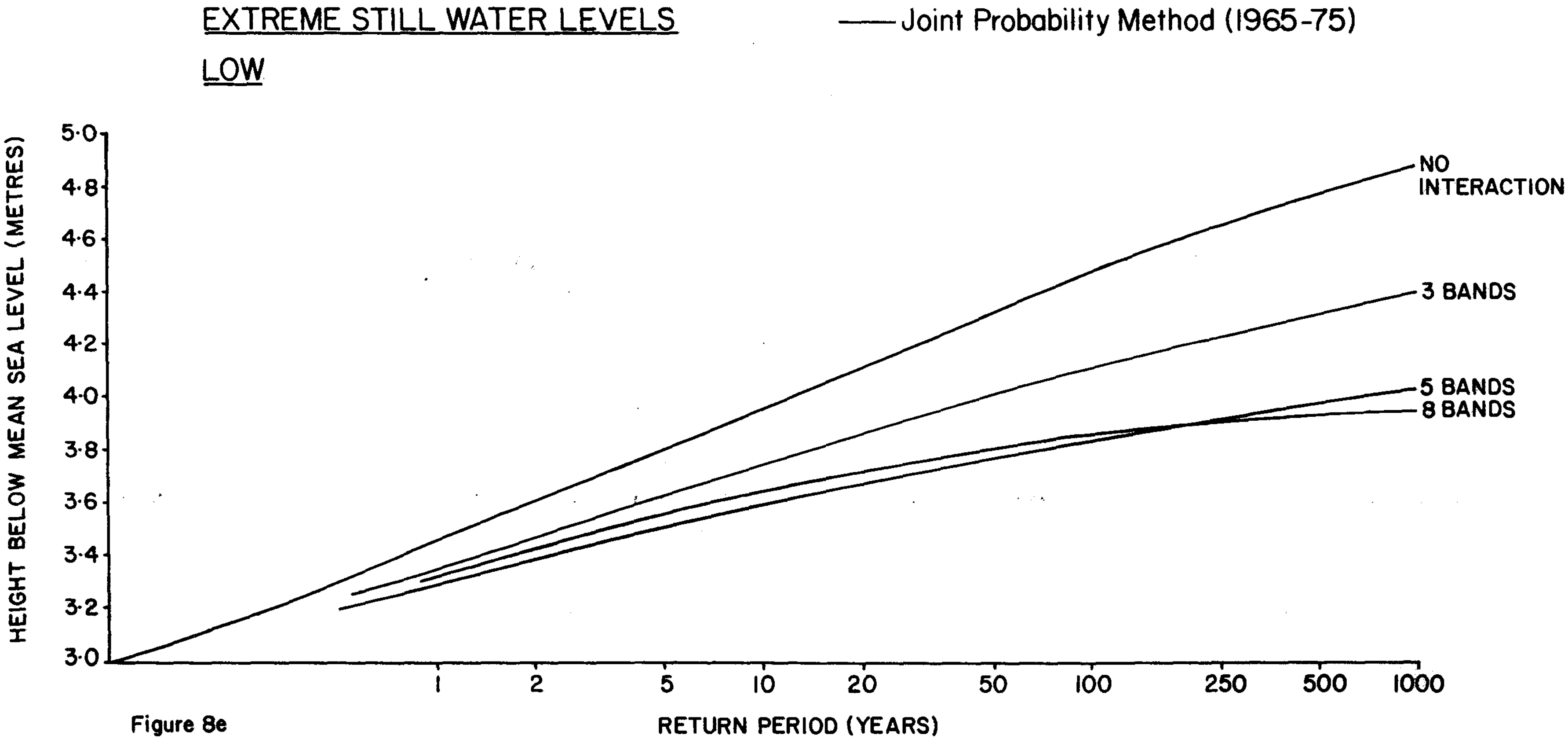
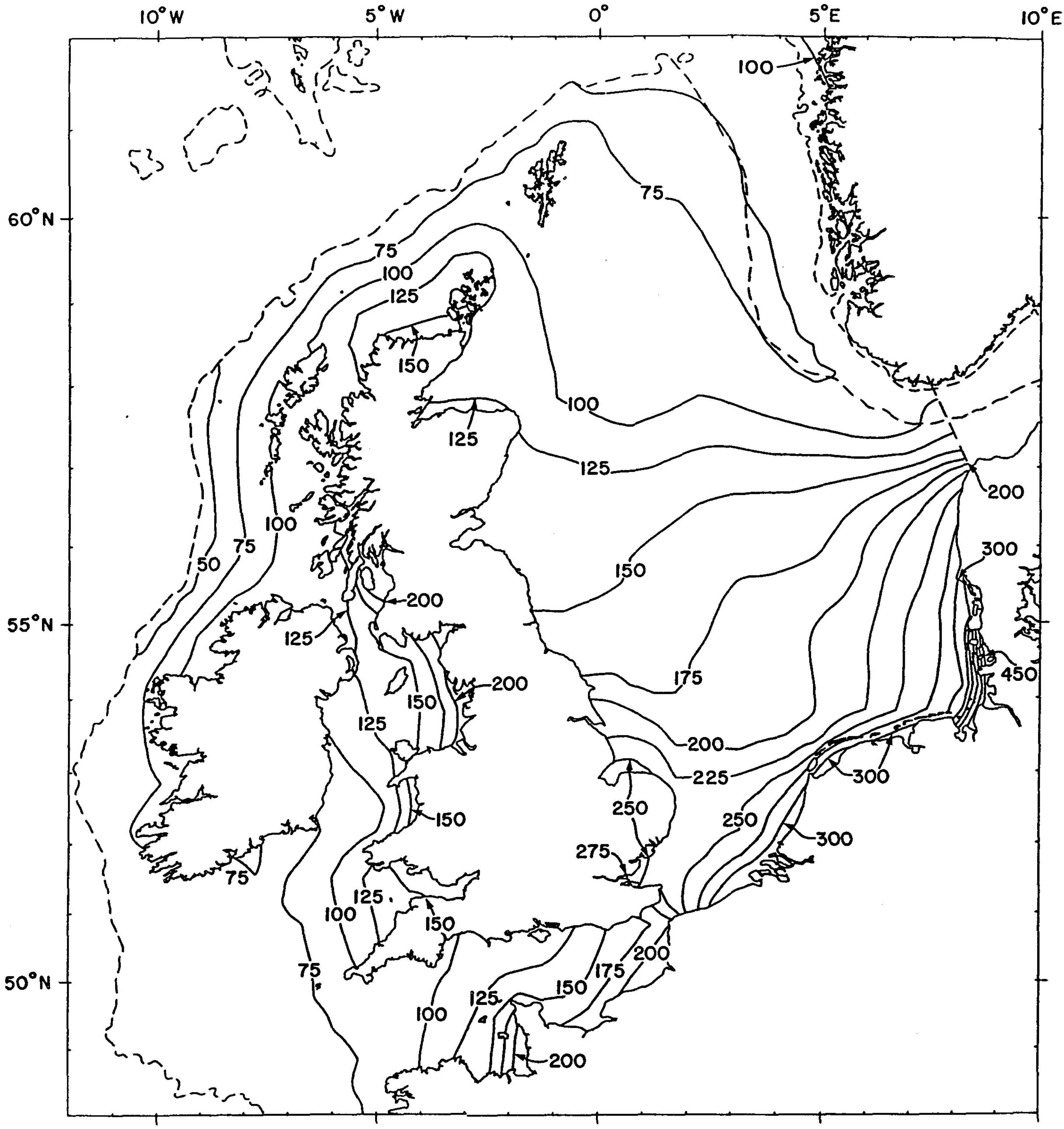


Figure 8e



10°W
5°W
0°
5°E
10°E
60°N
55°N
50°N
100
75
100
125
150
125
100
125
150
200
300
450
200
225
250
275
300
250
300
175
150
125
200
150
125
200
100
75
50
75
100
125
150
100
125
150
75
200
175
150
125
100
200

Figure 9.

	Observed data	Tidally-analysed data	Predicted tidal data
Immingham	1964-81	1964-81	1964-82
Lowestoft	1970-82	1971-80	1970-88
Harwich	1967-76	1968-76	1967-85
Walton	1967-78	1969-77	1967-85
Sheerness	1965-75	1968-75	1965-83

TABLE 1 - Data periods

		Immingham		Lowestoft		Harwich		Walton		Sheerness	
		H	G	H	G	H	G	H	G	H	G
Mean sea level (to ODN)		273		35		68		18		104	
Solar annual	Sa	69	225.1	58	217.6	72	202.8	67	202.7	49	201.7
Solar semi-annual	Ssa	14	130.3	27	129.1	17	117.0	15	111.6	12	70.4
Lunar monthly	Mm	11	170.7	22	174.2	4	288.5	3	261.4	5	23.0
Lunar semi-fortnightly	Msf	9	65.7	2	210.1	14	82.5	19	75.9	23	90.4
Lunar fortnightly	Mf	17	183.5	25	183.8	14	178.7	13	180.1	13	192.7
Lunar diurnal	O_1	174	113.7	137	159.5	133	176.3	128	176.8	132	188.6
Solar diurnal	P_1	50	268.2	42	318.9	39	339.9	38	341.9	41	355.5
Luni-solar diurnal	K_1	153	281.6	118	332.3	107	356.1	104	356.4	113	13.5
Lunar elliptic	N_2	428	141.0	136	230.3	229	302.5	240	305.8	345	329.8
Lunar semi-diurnal	M_2	2282	162.6	704	258.8	1329	327.7	1405	331.1	2020	354.3
Solar semi-diurnal	S_2	753	212.5	214	298.1	375	21.1	398	24.3	584	50.8
Luni-solar semi-diurnal	K_2	217	210.7	62	298.2	108	20.4	117	23.9	171	50.7
Shallow water	M_4	24	181.5	47	331.4	94	346.2	86	317.3	102	13.5
Shallow water	MS_4	33	244.7	39	24.8	63	55.2	47	26.2	38	81.1
Shallow water	S_4	10	327.5	4	115.6	4	169.5	1	117.6	5	22.1
Shallow water	M_6	12	140.5	39	116.7	66	290.3	46	290.6	54	34.9
Shallow water	$2MS_6$	22	184.3	40	162.9	66	340.0	46	339.3	54	86.4

TABLE 2 - Tidal constants (millimetres and degrees) to mean sea level

	Immingham	Lowestoft	Harwich	Walton	Sheerness
HAT	3.75	1.28	2.32	2.39	3.23
MHWS	3.04	0.92	1.70	1.80	2.60
MHWN	1.53	0.49	0.95	1.01	1.44
MLWN	-1.53	-0.49	-0.95	-1.01	-1.44
MLWS	-3.04	-0.92	-1.70	-1.80	-2.60
LAT	-4.04	-1.63	-2.25	-2.24	-3.05

Note :

HAT = Highest Astronomical Tide
LAT = Lowest Astronomical Tide
M = Mean
H = High
L = Low
W = Water
S = Springs
N = Neaps

TABLE 3 - Tidal statistics (metres) relative to mean sea level

	Maximum	Minimum	Standard deviation	Skewness	Kurtosis
Immingham (1964-81)	1.829	-1.357	0.192	0.2828	7.5206
Lowestoft (1970-82)	2.046	-1.891	0.213	0.5832	8.3511
Harwich (1967-76)	2.243	-1.562	0.202	0.5904	9.4861
Walton (1967-78)	2.209	-1.452	0.205	0.5838	9.0193
Sheerness (1965-75)	2.255	-2.280	0.229	0.1255	8.9835

TABLE 4 - Statistics of surge distributions based on hourly values

	duration (hours)	events less than -7σ	-6σ	-5σ	-4σ	events greater than 4σ	5σ	6σ	7σ	8σ
Immingham	1-4	17	17	22	39	119	54	25	23	
(1964-81)	5-12	1	1	6	26	47	15	4		
$\sigma = 0.192$	12+					2				
Lowestoft	1-4	9	9	10	28	57	30	14	12	9
(1970-82)	5-12	4	4	5	10	32	13	9	3	4
$\sigma = 0.213$	12+				1	13	3			
Harwich	1-4	10	10	17	37	56	29	11	9	10
(1967-76)	5-12			3	9	21	10	5	2	1
$\sigma = 0.202$	12+					5				
Walton	1-4	11	13	18	37	74	37	20	14	11
(1967-78)	5-12	1	1	3	13	26	10	7	2	1
$\sigma = 0.205$	12+				1	5	1			
Sheerness	1-4	11	13	23	49	63	38	18	12	12
(1965-75)	5-12					15	7	1	1	
$\sigma = 0.229$	12+					2				

TABLE 5 - Amplitude and duration of observed surges

Return period (years)		Immingham	Lowestoft	Harwich	Walton	Sheerness
S^+_{250}	l.s.	2.33	2.68	3.05	2.89	3.12
	POT	2.41	2.70	2.71	2.86	2.98
	mean (S.E.)	2.37 (0.10)	2.69 (0.13)	2.88 (0.16)	2.88 (0.15)	3.05 (0.17)
S^+_{100}	l.s.	2.18	2.51	2.82	2.68	2.89
	POT	2.21	2.48	2.49	2.62	2.73
	mean (S.E.)	2.20 (0.09)	2.50 (0.12)	2.66 (0.15)	2.65 (0.14)	2.81 (0.15)
S^+_{50}	l.s.	2.07	2.38	2.65	2.53	2.72
	POT	2.07	2.31	2.31	2.43	2.55
	mean (S.E.)	2.07 (0.08)	2.35 (0.11)	2.48 (0.13)	2.48 (0.13)	2.64 (0.14)
S^+_{25}	l.s.	1.95	2.24	2.47	2.37	2.56
	POT	1.92	2.14	2.14	2.25	2.36
	mean (S.E.)	1.94 (0.07)	2.19 (0.10)	2.31 (0.12)	2.31 (0.11)	2.46 (0.12)

TABLE 6a - Estimated positive surge levels (metres)

Notes :

l.s. = "least squares fit" method

POT = "peaks over threshold" method

S.E. = standard error from POT method

Return period (years)		Immingham	Lowestoft	Harwich	Walton	Sheerness
S^-_{250}	l.s.	-1.71	-2.46	-2.28	-1.99	-3.04
	POT	-1.98	-2.04	-2.31	-2.37	-2.79
	mean (S.E.)	-1.85 (0.11)	-2.25 (0.14)	-2.30 (0.17)	-2.18 (0.16)	-2.92 (0.17)
S^-_{100}	l.s.	-1.61	-2.28	-2.13	-1.87	-2.81
	POT	-1.82	-1.87	-2.12	-2.17	-2.56
	mean (S.E.)	-1.72 (0.09)	-2.08 (0.12)	-2.13 (0.15)	-2.02 (0.14)	-2.69 (0.15)
S^-_{50}	l.s.	-1.53	-2.15	-2.01	-1.77	-2.63
	POT	-1.69	-1.74	-1.97	-2.01	-2.39
	mean (S.E.)	-1.61 (0.08)	-1.95 (0.11)	-1.99 (0.14)	-1.89 (0.13)	-2.51 (0.13)
S^-_{25}	l.s.	-1.45	-2.01	-1.89	-1.67	-2.46
	POT	-1.57	-1.61	-1.82	-1.86	-2.21
	mean (S.E.)	-1.51 (0.08)	-1.81 (0.10)	-1.86 (0.12)	-1.77 (0.09)	-2.34 (0.12)

TABLE 6b - Estimated negative surge level (metres)

Notes :

l.s. = "least squares fit" method

POT = "peaks over threshold" method

S.E. = standard error from POT method

	Data Span (years) 1) Model 1 2) Model 3	Trend in mean sea level ($mm\ y^{-1}$) $\pm$ standard error	
		Model 1	Model 3
Immingham	1) 1960-81 (22) 2) 1962-80 (19)	1.50 $\pm$ 0.50	-0.03 $\pm$ 0.73
Lowestfot	1) 1960-82 (23) 2) 1962-80 (19)	0.56 $\pm$ 0.56	-0.84 $\pm$ 0.82
Harwich	1) 1954-75 (22) 2) 1962-75 (14)	2.11 $\pm$ 0.55	0.00 $\pm$ 1.23
Walton	1) 1968-78 (10) 2) 1968-78 (10)	3.03 $\pm$ 1.50	1.27 $\pm$ 1.48
Sheerness	1) 1832-1982 (74) 2) 1968-82 (15)	3.00 $\pm$ 0.10	1.54 $\pm$ 0.93

TABLE 7 - Secular trends in mean sea level

Note :

Model 1 - includes seasonal terms but no meteorological terms

Model 3 - includes both seasonal and meteorological terms

Level (m) above msl	Immingham	Lowestoft	Harwich	Walton	Sheerness
2.1		1.0			
2.2		1.7			
2.3		3.1			
2.4		5.5			
2.5		10.2			
2.6		19.4			
2.7		39.4			
2.8		87.5	1.4		
2.9		224	3.0	1.2	
3.0		685	6.8	2.3	
3.1		2544	16.4	4.7	
3.2			35.6	10.4	
3.3			74.9	27.8	
3.4			235	91.9	
3.5				387	
3.6				2912	1.5
3.7					2.8
3.8					5.2
3.9	1.0				10.1
4.0	1.9				20.1
4.1	3.7				42.2
4.2	7.2				103
4.3	14.0				321
4.4	27.2				1764
4.5	52.8				
4.6	102				
4.7	200				
4.8	413				
4.9	880				
5.0	2170				

TABLE 8a - Return periods (years) for exceedance of specified levels, from Joint Probability method

Level (m) below msl	Immingham	Lowestoft	Harwich	Walton	Sheerness
2.0		1.2			
2.1		2.2			
2.2		3.8			
2.3		6.1			
2.4		9.5			
2.5		14.3	1.6	1.0	
2.6		21.9	2.9	1.8	
2.7		34.9	4.5	3.4	
2.8		58.9	7.1	7.0	
2.9		107	14.7	19.0	
3.0		206	36.2	57.1	
3.1		421	103	171	
3.2		936	324	708	
3.3		2508	2037		
3.4					1.7
3.5					3.3
3.6					6.6
3.7					14.7
3.8					42.4
3.9					225
4.0					987
4.1	1.5				
4.2	3.2				
4.3	6.5				
4.4	13.0				
4.5	25.9				
4.6	52.1				
4.7	110				
4.8	261				
4.9	768				
5.0	3231				

TABLE 8b - Return periods (years) for exposure of specified levels, from Joint Probability method

Method (data period, data length)		Return Period (years)				
		10	25	50	100	250
Joint Probability (1964-81, 18 years)	High (to msl)	4.27	4.39	4.50	4.60	4.73
	Low	-4.36	-4.49	-4.58	-4.68	-4.77
	High (to ODN)	4.55	4.68	4.78	4.88	5.00
	Low	-4.09	-4.22	-4.31	-4.41	-4.50
Extreme Value (1920-81, 62 maxima)	High (to ODN)	4.57	4.70	4.79	4.88	4.99

TABLE 9a - Immingham : Extreme levels for specific return periods

Method (data period, data length)		Return Period (years)				
		10	25	50	100	250
Joint Probability (1970-82, 13 years)	High (to msl)	2.50	2.64	2.73	2.82	2.91
	Low	-2.41	-2.63	-2.77	-2.89	-3.03
	High (to ODN)	2.54	2.68	2.77	2.86	2.95
	Low	-2.37	-2.59	-2.73	-2.85	-2.99
Extreme Value (1953-81, 29 maxima)	High (to ODN)	2.59	2.87	3.09	3.33	(3.68)
(1954-81, 28 maxima)	High (to ODN)	2.46	2.63	2.75	2.87	(3.01)

TABLE 9b - Lowestoft : Extreme levels for specific return periods

Note : (Bracketed) values are for return periods more than 4 x data length (see text)

Method (data period, data length)		Return Period (years)				
		10	25	50	100	250
Joint Probability (1967-76, 10 years)	High (to msl)	3.05	3.16	3.25	3.33	3.42
	Low	-2.85	-2.95	-3.04	-3.10	-3.18
	High (to ODN)	3.12	3.23	3.32	3.40	3.49
	Low	-2.78	-2.88	-2.97	-3.03	-3.11
Extreme Value (1926-76, 51 maxima)	High (to ODN)	3.10	3.34	3.53	3.72	(3.98)

TABLE 9c - Harwich : Extreme levels for specific return periods

Note : (Bracketed) value is for a return period more than 4 x data length (see text)

Method (data period, data length)		Return Period (years)				
		10	25	50	100	250
Joint Probability (1967-78, 12 years)	High (to msl)	3.19	3.28	3.35	3.41	3.47
	Low	-2.83	-2.93	-3.00	-3.05	-3.13
	High (to ODN)	3.21	3.30	3.37	3.43	3.49
	Low	-2.81	-2.91	-2.98	-3.03	-3.11
Extreme Value (1968-79, 11 maxima)	High (to ODN)	3.12	3.22	(3.30)	(3.37)	(3.46)

TABLE 9d - Walton : Extreme levels for specific return periods

Note : (Bracketed) value is for a return period more than 4 x data length (see text)

Method (data period, data length)		Return Period (years)				
		10	25	50	100	250
Joint Probability (1965-75, 11 years)	High (to msl)	3.90	4.01	4.12	4.20	4.28
	Low	-3.65	-3.75	-3.81	-3.86	-3.90
	High (to ODN)	4.01	4.12	4.23	4.31	4.39
	Low	-3.54	-3.64	-3.70	-3.75	-3.79
Extreme Value (1819-1978, 133 maxima)	High (to ODN)	3.96	4.15	4.31	4.46	4.68

TABLE 9e - Sheerness : Extreme levels for specific return periods

Factor	Immingham	Lowestoft	Harwich	Walton	Sheerness
F_{50}	0.74	1.48	0.96	0.93	0.79
F_{100}	0.76	1.53	0.98	0.95	0.81
τ^+	1.24	1.39	1.36	1.33	1.25
τ^-	-1.33	-1.78	-1.31	-1.24	-1.18
ψ_{50}	-1.02	-1.01	-0.94	-0.90	-0.92
ψ_{100}	-1.02	-1.02	-0.93	-0.89	-0.92
β^+_{50}	0.88	0.84	0.78	0.78	0.79
β^+_{100}	0.88	0.83	0.74	0.77	0.78

TABLE 10 - Similarity factors

Notes: F_R (Lennon's measure) $= \dfrac{L_R - MHWS}{MHWS - MLWS}$

$\tau^+ = \dfrac{HAT}{M_2+S_2}$ $\qquad \tau^- = \dfrac{LAT}{M_2+S_2}$

$$\psi_R = \frac{L_R^-}{L_R^+}$$

$$\beta_R = \frac{L_R^+}{M_2+S_2+S_R^+}$$

Design life, L (years)	Design return period, rp (years)			
	50	100	250	500
50	0.636	0.395	0.182	0.095
100	0.867	0.634	0.330	0.181
250	0.994	0.919	0.633	0.394
500	0.999	0.993	0.865	0.632

TABLE 11 - Risk of event occurring as a function of design life and design return period.