Proudman Oceanographic Laboratory

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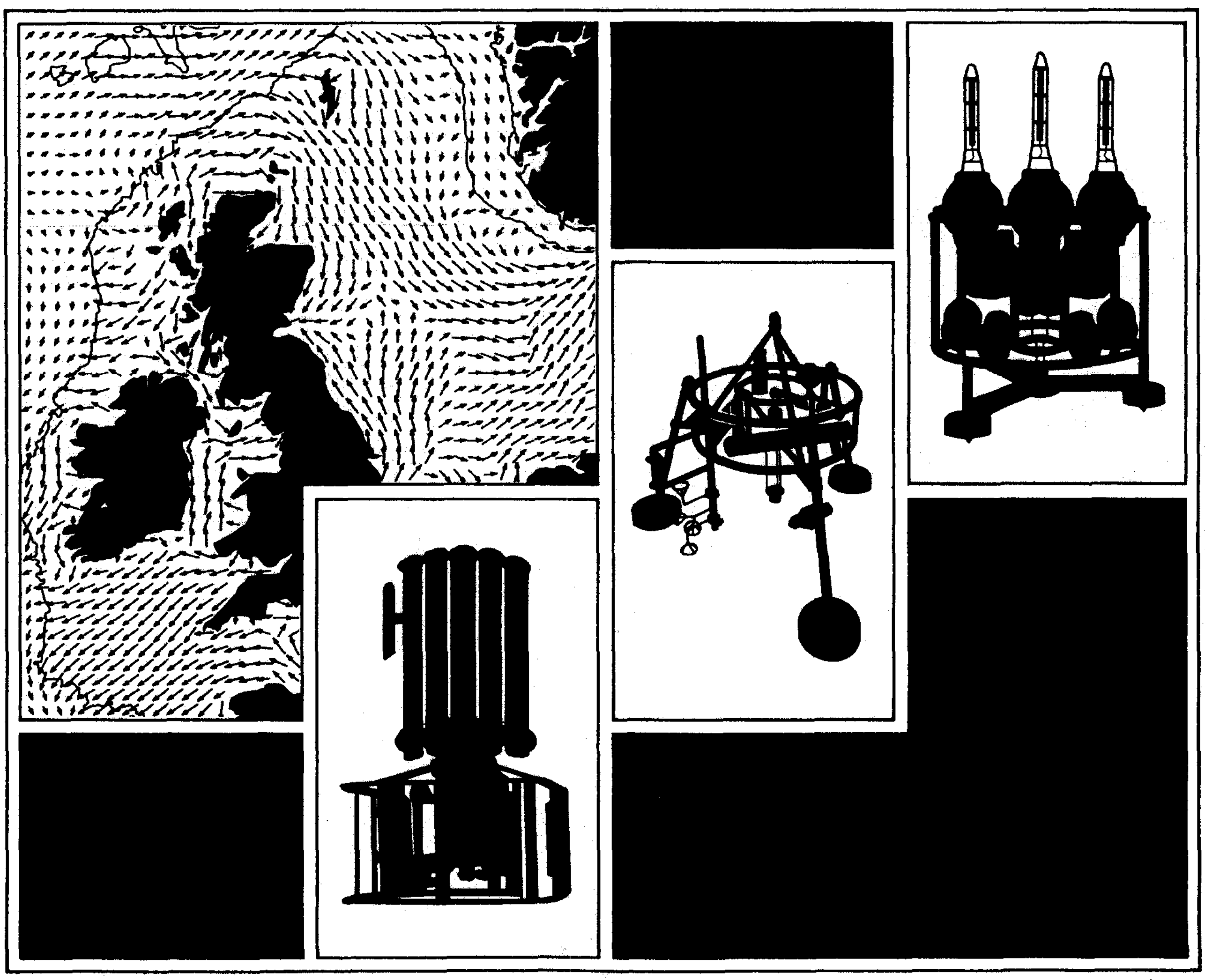
JD Richards SA Windle DL Blackman RA Flather and PL Woodworth

Report No 31 1993



Natural Environment Research Council

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REPORT NO. 31

Analysis of High Waters and Tides at Lawyer's Sluice in the Wash, Eastern England

August 1993

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ABSTRACT

An analysis has been completed of high water levels and tides at Lawyer's Sluice at the head of the Wash in eastern England. The Wash is a shallow tidal embayment surrounded by a large expanse of flat agricultural land which would be at risk if sea levels rose significantly. Data from a float tide gauge have provided an estimate of the trend in annual mean high water during the period 1953-1991. This value, 0.0 ± 0.9 mm/year, is somewhat lower than expected from geological information from the area. However, although the uncertainties are large, this at least suggests that sea levels have not risen at an anomalously high rate in this area in the recent past. Data from a pressure transducer water level recorder, together with those from the float gauge, have provided tidal and revised extreme level parameters, together with a check of the relationship of mean sea level to Ordnance Datum Newlyn at the site.

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Introduction

The Wash is a shallow, rectangular, tidal embayment on the east coast of England (Figure 1). Several rivers, including the Great Ouse, Nene, Welland and Witham, converge upon and flow into it, providing drainage for some of the most important agricultural land in the country. A large expanse of this land is only a few metres above present sea level (Figure 2), and a number of studies have indicated the potential threat to it should sea level rise significantly (Barkham, MacGuire and Jones, 1992; Shennan, 1992). Although investigations have been made of the recent rates of change of mean sea level (MSL) around the UK by means of tide gauge data (e.g. Woodworth, 1987), none of these have included data from this important region. Even today, the nearest 'A Class' gauges (Woodworth, 1992) are at Immingham and Cromer, both some distance from the Wash (Figure 1).

There are three main reasons why there have been no 'A Class' records from this area. Firstly, the 'A Class' network was based in its early stages on existing gauges operated by different authorities. Subsequently, the criteria for installation of new gauges were based on the complementarity with storm surge numerical forecast modelling. In the case of the Wash, there were no ports with suitable gauges to be included in the network, and a new additional gauge there would not have supplied considerably more east coast UK surge information than available from other sites. Secondly, the Wash is a low population area, and there would have been little local pressure for enhanced recording other than that already provided by the regional drainage boards. Thirdly, the gentle topography of the surrounding land and of the Wash bathymetry, together with the large tidal range, results in gauges at the coast 'bottoming out' at low tide, making them unsuitable for scientific MSL studies. In addition, there are few piers or other structures extending into deep water upon which gauges could be installed. Those gauges which do exist have provided data of generally poorer quality than 'A Class' standards, and are suitable for mean high water (MHW) or high water level extreme level investigations only.

Lawyer's Sluice Float Gauge: MHW Trends

This study has employed data from a site called Lawyer's Sluice in the western corner of the Wash between the Nene and Welland estuaries (Figure 1). It is, so far as we are aware, the only source of long term high water information in the area. Lawyer's is a gravity sluice, draining the land at low tide, and was constructed in 1950 as part of one of the most recent of a long series of reclamations (Kestner, 1962; Robinson, 1987). Since 1953, the same simple Kent float gauge fixed to the sluice wall has been well maintained by the South Holland Internal Drainage Board (SHIDB), although by now it is in need of major refurbishment or replacement. The datum of its weekly charts has been adjusted with respect to a benchmark on the concrete emplacement of the sluice by means of periodic checks with a tide pole. In turn, the height of the benchmark is known in terms of the national levelling system, Ordnance Datum Newlyn (ODN). The SHIDB engineers estimate the accuracy of the chart recording to be no better than 2 inches (50 mm). This is very crude by comparison to the 'A Class' network, although of course the gauge was installed for operational drainage board purposes rather than scientific research. While high water levels may be identified adequately, timings are approximate only and the charts are not suitable for more sophisticated tidal analysis. High water data from the gauge for 1953-1978 were employed by Graff (1981) and Coles and Tawn (1990) in studies of UK extreme sea levels.

From each of the weekly charts for 1953-1991, the high water levels were measured and entered into computer files at the Proudman Oceanographic Laboratory (POL). The reasons for any anomalies on the charts and for any gaps in recording were also noted. Figure 3 (upper panel) shows the time series of annual MHW, selecting only years which were at least 80 percent complete in order to avoid distortion by the seasonal cycle in MHW. The series is immediately reassuring in that it shows clear evidence for the expected 18.61 year nodal variation in MHW, indicating that the dataset is not completely dominated by measurement errors. A linear regression fit to the series in terms of a linear trend and an 18.61 year cycle results in the fit parameters:

linear trend	0.0 ± 0.9 mm/year
nodal cycle amplitude	61 ± 20 mm
nodal cycle minima at	1968.3 and 1986.9 ± 1.0 years

The total regression curve, and its linear trend component, are also shown on the upper panel of Figure 3, while the residuals from the fit are shown in the lower panel.

The 18.61 year 'nodal cycle' in MHW (and mean low water, mean tidal range, and individual lunar tidal constituents) is well understood (Pugh, 1987). In the deep ocean, mean high waters might be expected to vary by up to ± 3.7 percent of the amplitude of M2, the main twice-daily lunar tidal constituent, but around the UK shallow water effects result in a smaller percentage (Amin, 1987). In addition, the cycle should be at minimum at years 1969.2 and 1987.8. From Pugh and Vassie (1976) and from this study (see below), the amplitude of M2 at Lawyer's Sluice is known to be approximately 2.5 m, while Woodworth, Shaw and Blackman (1991) suggest a nodal modulation of order 2.5 percent in this area, or 63 mm for the anticipated amplitude in MHW. The nodal fit parameters determined above, therefore, are consistent with expectations. (Pugh and Vassie (1976) provide an overview of the present day tidal regime around the Wash, while Hinton (1992) discusses the development of the regime through the Holocene).

The residuals from the fit can stem from measurement errors and from interannual variations in storm surge activity and steric effects including river runoff. Their standard deviation is 54 mm, which is similar to the measurement error suggested by the SHIDB engineers, and which must be the dominant factor. However, in order to determine if the residual values contain an identifiable storm surge component, one of POL's numerical tide-surge models was run for the period 1955-1984 to simulate the MHW variations anticipated from variations in storm surge activity. The corresponding standard deviation for this factor was estimated to be 14 mm (Appendix 1), considerably less than observed in the data residuals. Consequently, we conclude that storm surges do not contribute to the data residuals to a great extent. While steric effects may also play a (less quantifiable) role, it indeed seems reasonable that most of the 54 mm is measurement error.

The linear trend observed in the data is essentially zero, while its relatively large standard error, compared to those usually obtained from MSL data (e.g. Woodworth, 1987), is as anticipated from a gauge with a 40 year record and several centimetre accuracy. The zero trend may be compared to those determined from geological sea level data from the Wash area, and to tide gauge and geological data from elsewhere. Shennan and Woodworth (1992) demonstrated that, on average, tide gauge MSL trends from the twentieth century from stations around the British Isles and North Sea are 1 mm/year larger than anticipated from extrapolation of Holocene geological data, although there are departures from this general rule. No data from the Wash were used in that study, although Shennan (1987) shows that geological information exists in reasonable quantities. From Shennan (1987), we take 0.8 mm/year for the submergence rate of the land in Fenland, which includes the Wash area, to which may be added the 1 mm/year of Shennan and Woodworth (1992), to give a 'predicted MSL trend' of 1.8 mm/year. Our value of approximately zero for the trend in MHW is, therefore, lower than expected, although the uncertainties are large. However, it is interesting that previously measured eastern England tide gauge MSL trends (Immingham and Lowestoft) are also lower than expected from geological information by approximately 0.5 mm/year (Shennan and Woodworth, 1992).

There are a number of factors to consider which may have affected our MHW trend estimate. For example, we can estimate with some confidence that the meteorological (surge) influence on the trend will have been small (Appendix 1). However, there are more problematical factors. One concern is that the reclamation embankment upon which Lawyer's Sluice is situated may have compacted over the years, although that would have resulted in a larger, not smaller, than expected trend. (An additional metre was added to the embankment following the major storm of January 1978). Another is that the nearby off-shore ditch, from which the embankment was constructed, will have been gradually filling in, thereby modifying the local circulation. Trends in MHW need not be the same as trends in MSL (Woodworth, Shaw and Blackman, 1991), especially if there have been large changes to the coast, as there have been in the Wash (Bird and May, 1976; Pye, 1993). The building of the embankment, together with the associated subsequent continued growth of the salt marsh seaward, may itself have caused a progressive modification in the local tidal regime.

What use, therefore, is our approximate value for the trend in MHW? This question has to be considered in the context of the importance of the area in any discussion of the potential impacts of sea level change in the UK (Shennan, 1992). So far as we know, the Lawyer's Sluice record is the longest, and the most complete and continuous (same instrument throughout) in the area, although it can by no means be considered a 'scientific quality' gauge. At least, we have demonstrated that sea levels have almost certainly not risen at an anomalously high rate in this area in the past half century.

Extreme Level Recalculations for Lawyer's Sluice

The extreme level calculations for Lawyer's Sluice by Graff (1981) employed a dataset of annual maxima for 1953-1978. In the 'r largest' terminology of Smith (1986) and Tawn (1988), r equals 1. However, the extreme levels estimated from that dataset were influenced significantly by a very high level (5.91 m above ODN) observed during a storm on 11 January 1978. Applying the Generalised Extreme Value (GEV) method to the dataset (assuming independence of annual maxima) gives:

Return Period (years)	Estimated Level (m above ODN)	Estimated Standard Error (m)
10	5.30	0.16
100	6.19	0.70
1000	7.44	2.00
5000	8.59	3.64

However, if one applies the GEV method to a study of the complete dataset now available to 1991, employs the five highest levels in each year (r = 5, rather than simply the annual maxima), and reassesses the January 1978 level downwards to 5.79 m above ODN after a reinspection of the tidal charts, one obtains:

Return Period (years)	Estimated Level (m above ODN)	Estimated Standard Error (m)
10	5.16	0.07
100	5.59	0.17
1000	5.98	0.31
5000	6.25	0.43

We believe these extreme level estimates to be more reliable, while the 11 January 1978 level (which resulted in widespread flooding and several fatalities) can be seen to have been exceptional. The example of this longer record, together with the ability to employ 'r largest' levels from each year, emphasises the potential of individual storms to distort the results of conventional extreme level analyses which employ only short records of annual maxima.

These estimates can be improved even further by adopting the 'spatial approach' of Coles and Tawn (1990) in which data from more than one site are considered. Using the earlier Graff dataset only, Coles and Tawn obtained the following significantly more precise estimates:

Return Period (years)	Estimated Level (m above ODN)	Estimated Standard Error (m)
10	5.14	0.04
100	5.66	0.08
1000	6.18	0.15

These final values were not computed by us but were kindly provided by Dr.J.Tawn; they are not quoted in Coles and Tawn (1990).

Lawyer's Sluice Pressure Gauge: Tidal Analysis

At low tide, a stream called Lawyer's Creek flows from the sluice into the Wash. On the opposite side of the stream from the float gauge, the National Rivers Authority (NRA) has operated a pressure transducer water level recorder for several years, although with a number of gaps in recording. Data from this gauge are transmitted to the regional NRA office by telephone every fifteen minutes and high water levels trigger flood warnings. The data are archived for subsequent analysis.

The instrument is an 'absolute' rather than a 'differential' transducer, so total pressure fluctuations are recorded, including those due to atmospheric pressure changes. The datum of the measurements is, in principle, adjusted to ODN by means of occasional simultaneous observations of the tide pole, although this must be only an approximate procedure with an absolute transducer. This gauge also bottoms out at low tide but its (nominally) precise timing makes its data suitable for the extraction of tidal constants, unlike those of the float gauge. Good tidal constants are necessary for tidal predictions and in the production of surge (total observed level minus predicted tidal level) statistics.

A pressure transducer dataset was made available to us by the NRA spanning the period March 1991 to June 1992, with a gap in May 1991. We had been warned that the quality of the data declined significantly from the start of the record, and we discovered this to indeed be the case. A detailed analysis showed there to be, in effect, several subsets of data, each with its own calibration and datum offset, between March and November 1991. Data from after November were unusable.

In order to apply our own calibration to the transducer information, the data were separated into the subsets and high water turning points identified. These were then compared to the high water values recorded on the float gauge charts, and a two parameter calibration (a relative scaling factor and an offset) determined by linear regression, taking the pressure transducer value as the dependent variable and the float gauge value as the independent value. (Recall that we did not make a complete digitisation of the float gauge charts but simply recorded high water levels). This assumes a linear calibration for the transducer, but experience has shown that to be adequate in most applications. Because the spring-neap cycle in high waters at Lawyer's Sluice spans several metres, it was possible to acquire reasonably accurate linear calibration parameters for each data subset.

With the pressure transducer calibrated, it was possible to extract tidal parameters for each data subset. The ability to extract tidal information by harmonic analysis from records which bottom out was demonstrated by Evans and Pugh (1982) in a study of data from locations in the Bristol Channel, where M2 is approximately 4 m in amplitude. They found that reasonably accurate constants for the major constituents, and even good estimates of effective MSL, could be obtained as long as the bottoming out occurred at or below MSL. The quality of the extracted parameters degraded rapidly as the bottom out level moved above MSL.

In the present case, bottoming out occurs about one foot above MSL (the precise level varies owing to periodic silting) and the analysis is consequently more difficult. The same set of 27 independent and 8 related constituents employed by Evans and Pugh (1982) was used here initially, but the ambiguity between the M2 constituent and the shallow water tides (M4 etc.) and the constant term (Z0) rendered the analysis unstable. Consequently, we decided upon a compromise solution of fixing the amplitudes and phases of the main shallow water tides (M4 and MS4) to those estimated from previous analyses of data from the Wash (Pugh and Vassie, 1976). In addition, all other shallow water tides were removed from the initial set of 35 constituents. This simplification removed the inherent ambiguity and provided values for the larger constituents consistent with existing tidal charts. However, the parameters derived for the minor constituents were still found to be unstable, both between different data subsets and with respect to slightly different program selections which were required to remove 'bottom out' data. This is to be expected from known limitations of the method (Evans and Pugh, 1982).

For the larger constituents, Table 1 gives the parameters obtained for the periods 'A' (days 70-120 1991), 'B' (days 152-212) and 'C' (days 213-244). While data also existed for September to November, they were of clearly poorer quality, producing large residuals in the tidal analyses and containing large apparent (and unphysical) long period tidal components. This is compatible with the gradual deterioration in quality of the transducer data through 1991 emphasised by the NRA. The values for M2 and S2 in Table 1 are consistent with tidal charts for the Wash area of the North Sea (e.g. Pugh and Vassie, 1976, Figure 9). While the amplitudes of N2, O1 and K1 are also reasonable, their phase lags are approximately 10, 15 and 25 degrees lower than anticipated respectively. Again, this is similar to the findings of Evans and Pugh (1982).

The constant tidal constituent (Z0) in these analyses provides an estimate of the effective MSL at the site, even if a real MSL does not exist owing to the bottoming out. Table 1 shows Z0 to be approximately 0.25 m above ODN. This is compatible with the known meridional dependence of east coast UK MSL relative to ODN (Thompson, 1980, Figure 7), although the accuracy of our estimate can be no better than ± 20 cm. However, the confirmation is useful for general surveying purposes, and in view of the need for the geological sea level measurements in the area, undertaken by colleagues at Durham University, to be related to modern sea level with adequate accuracy.

Conclusions

The data from the two tide gauges at Lawyer's Sluice have provided an approximate measure of the trend in mean high waters over the past four decades (essentially zero), together with estimates of tidal parameters and extreme levels, and a check on the relationship of MSL to ODN at the site. These findings were obtained from a location which 'bottoms out' at low tide, and with equipment that was installed for operational flood warning purposes, rather than scientific research. Therefore, they must be considered less reliable than if they had been derived from 'A Class' gauges, for example.

Nevertheless, our results are of interest for two main reasons. Firstly, they are the only ones of their type, which we know of, from this area which is of such importance with regard to potential future sea level change. Secondly, they provide an example of the application of information which may exist outside of the established scientific databases, and which may be of use to research if one searches for it.

We understand that there are plans by the SHIDB and NRA to upgrade the instrumentation at Lawyer's Sluice, while it is possible that an 'A Class' gauge may eventually be installed in the Wash (G.Alcock, private communication). It is clearly important that this area be equipped with adequate sea level monitoring.

Acknowledgements

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Appendix 1

A Thirty Year Run of a Numerical Tide-Surge Model

The Proudman Oceanographic Laboratory (POL) has a long history of numerical modelling of the tides and surges around our coasts (e.g. Flather, 1981; Heaps, 1983). However, in the last few years two particularly important developments have taken place.

Firstly, the increase in computer resources has enabled tide-surge models to be run for considerably longer periods than before. Simulated sea level time series spanning several decades can now be obtained for any point at the coast or on the North West European continental shelf. These time series typically take the form of hourly values of the sum of tide and surge, which is a large fraction of the total sea level variability. Depth mean currents are also computed. Although the models do not include steric effects, nor can they reproduce the contributions of eustatic sea level change or land movements, they are a significant advance on previous capabilities. Secondly, there has been a corresponding improvement in the quality of the meteorological datasets employed to drive the storm surge component of the models.

For the present analysis, improved meteorological datasets provided by the Norwegian Meteorological Institute were input to POL's medium resolution (35 km) tide-surge model for the period 1955-1984. Subsequently, time series at each model grid point were analysed to provide values of annual MHW and annual MSL which could be compared to tide gauge information.

With the medium resolution, the Wash is represented by a single grid point with a modelled tide approximately 10 percent lower in amplitude than at Lawyer's Sluice. However, the storm surge component might reasonably be assumed to be coherent over a large area, and to be similar throughout the Wash. Figure 4 shows values of annual MHW for the 'Wash' model grid point obtained in a similar way to the real Lawyer's Sluice MHW values of Figure 3. The lower average MHW (relative to MSL or ODN) can be seen, while the 'nodal fit' results in parameters:

linear trend	-0.1 ± 0.3 mm/year
nodal cycle amplitude	64 ± 6 mm
nodal cycle minima at	1951.1 and 1969.7 ± 0.3 years

The essentially zero trend indicates that the meteorological (surge) influence on the observed trend in MHW at Lawyer's Sluice will be small over this period, while the nodal cycle parameters can be seen to be well reproduced by the model. The residuals displayed in the lower panel of Figure 4 are relatively small with a standard deviation of 14 mm. This indicates that the surge component of the MHW variability at Lawyer's Sluice will be considerably less than the observed residual variability with standard deviation 54 mm reported above.

Modelled MSL cannot be compared to measurements at Lawyer's Sluice because the gauge 'bottoms out' at low tide. However, such comparisons can be made at neighbouring stations. (MSL data are generally more accessible than MHW information). Immingham and Lowestoft are the nearest 'A Class' sites either side of the Wash with several decades of MSL data. Figure 5 (top and middle) shows that modelled MSL is similar at the two stations, with the agreement with data slightly better for Lowestoft. Figure 5 (bottom) gives an example of a record for the eastern North Sea (Esbjerg in Denmark), where there is considerably greater storm surge variability, and where greater similarity between model and data might be expected, and is observed.

The model dataset described above is being employed at POL in a number of studies of regional sea level changes. It is intended that similar datasets, with improved spatial resolution and extending further back in time, will be produced in future.

Figure Captions

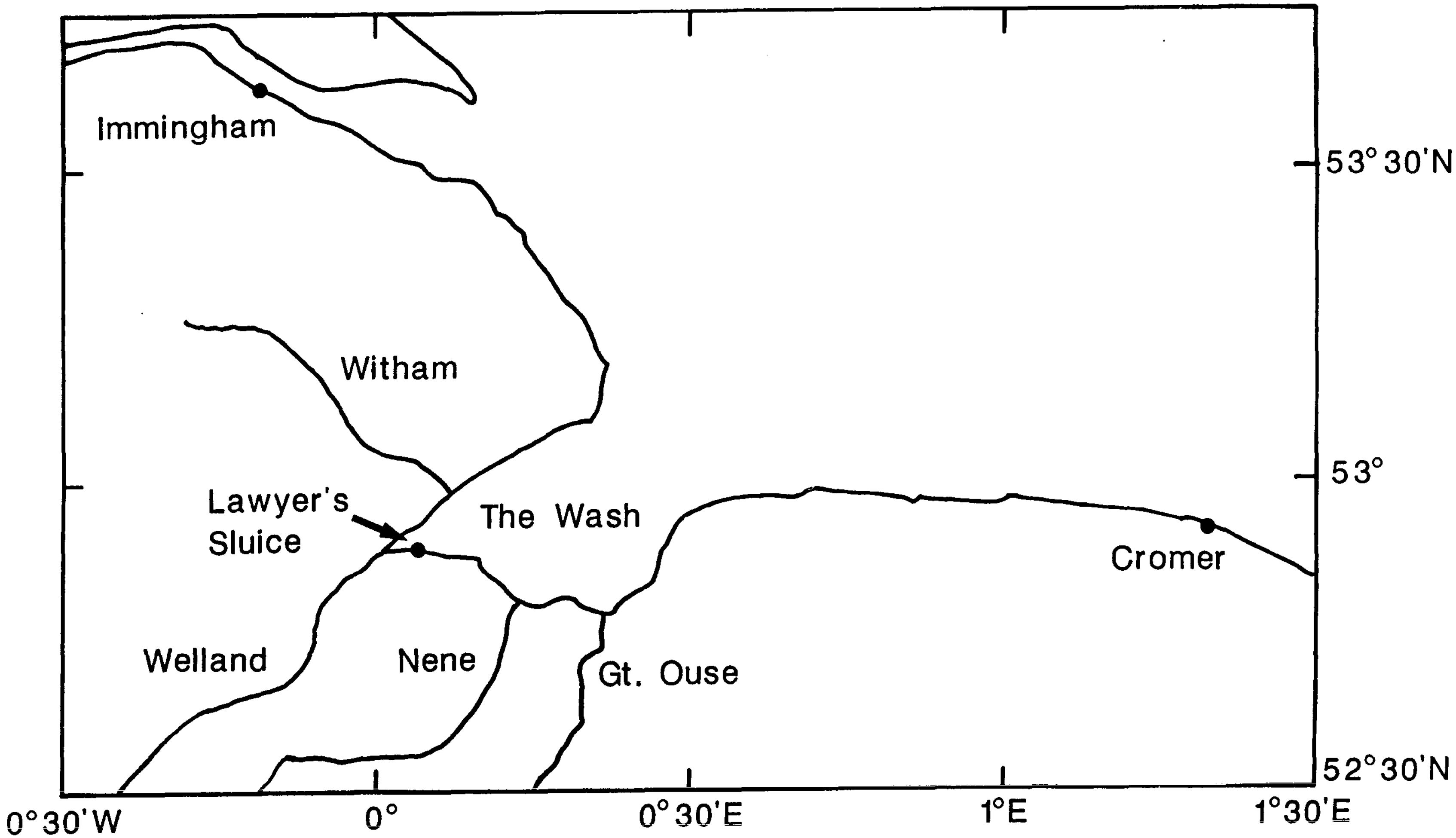
1. Map showing locations mentioned in the text.

2. Present flood risk areas in England and Wales from Barkham, MacGuire and Jones (1992). The shaded areas are essentially those which lie below 5 m ODN; see Pugh (1990) for the corresponding map. The names of regional water authorities are shown.

3. Time series of Lawyer's Sluice annual MHW (large dots) with values relative to the left-hand vertical scale (mm). Only years with at least 80 percent complete data have been selected. The series has superimposed the result of a linear plus nodal regression fit (small dots) and its linear part alone as described in the text. Fit values are shown connected together for consecutive years of data. The lower panel shows the corresponding fit residual series (crosses) with values relative to the right-hand vertical scale (mm).

4. Time series of annual MHW and fit residuals derived from numerical tide-surge model output for the Wash. Notation as for Figure 3.

5. Values of mean sea level (MSL) for Immingham, Lowestoft and Esbjerg (dots) compared to the tide-surge component of MSL at each site derived from a numerical model (stars).



Immingham
53° 30'N
Witham
53°
Lawyer's
Sluice
The Wash
Cromer
Welland
Nene
Gt. Ouse
52° 30'N
0° 30'W
0°
0° 30'E
1°E
1°30'E

Figure 1

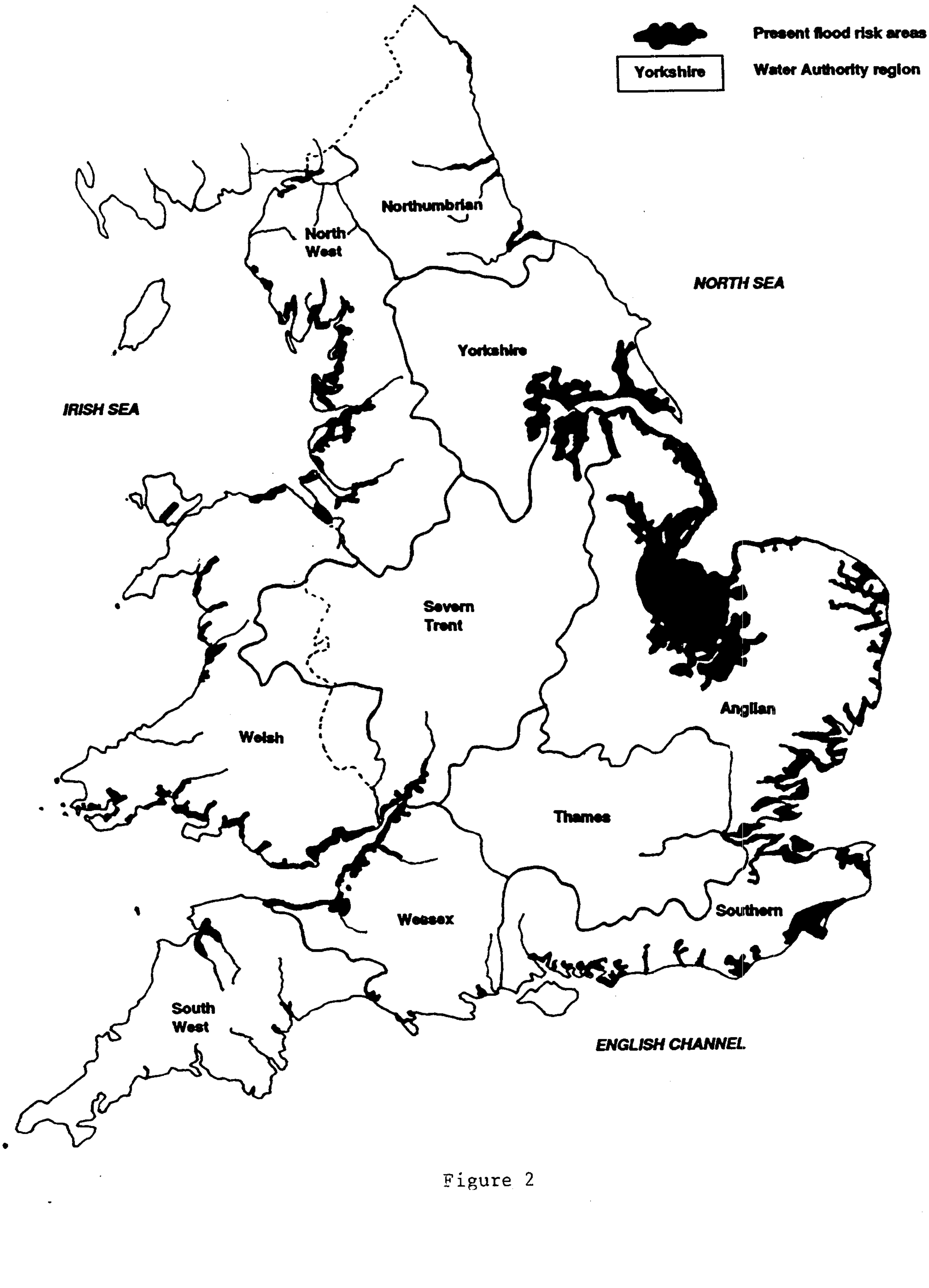
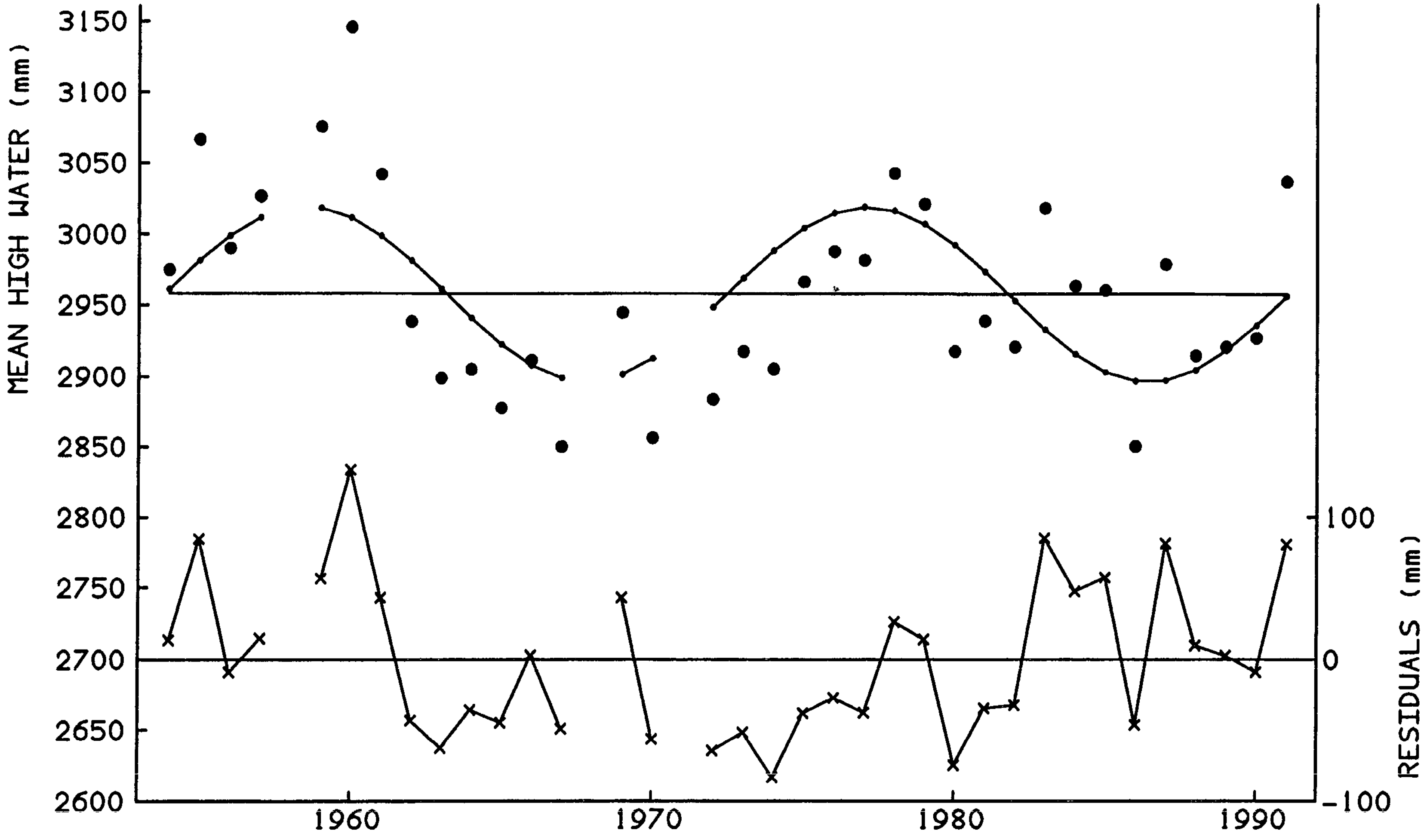

Present flood risk areas
Yorkshire
Water Authority region
Northumbrian
North West
NORTH SEA
Yorkshire
IRISH SEA
Severn Trent
Anglian
Welsh
Thames
Southern
Wessex
South West
ENGLISH CHANNEL

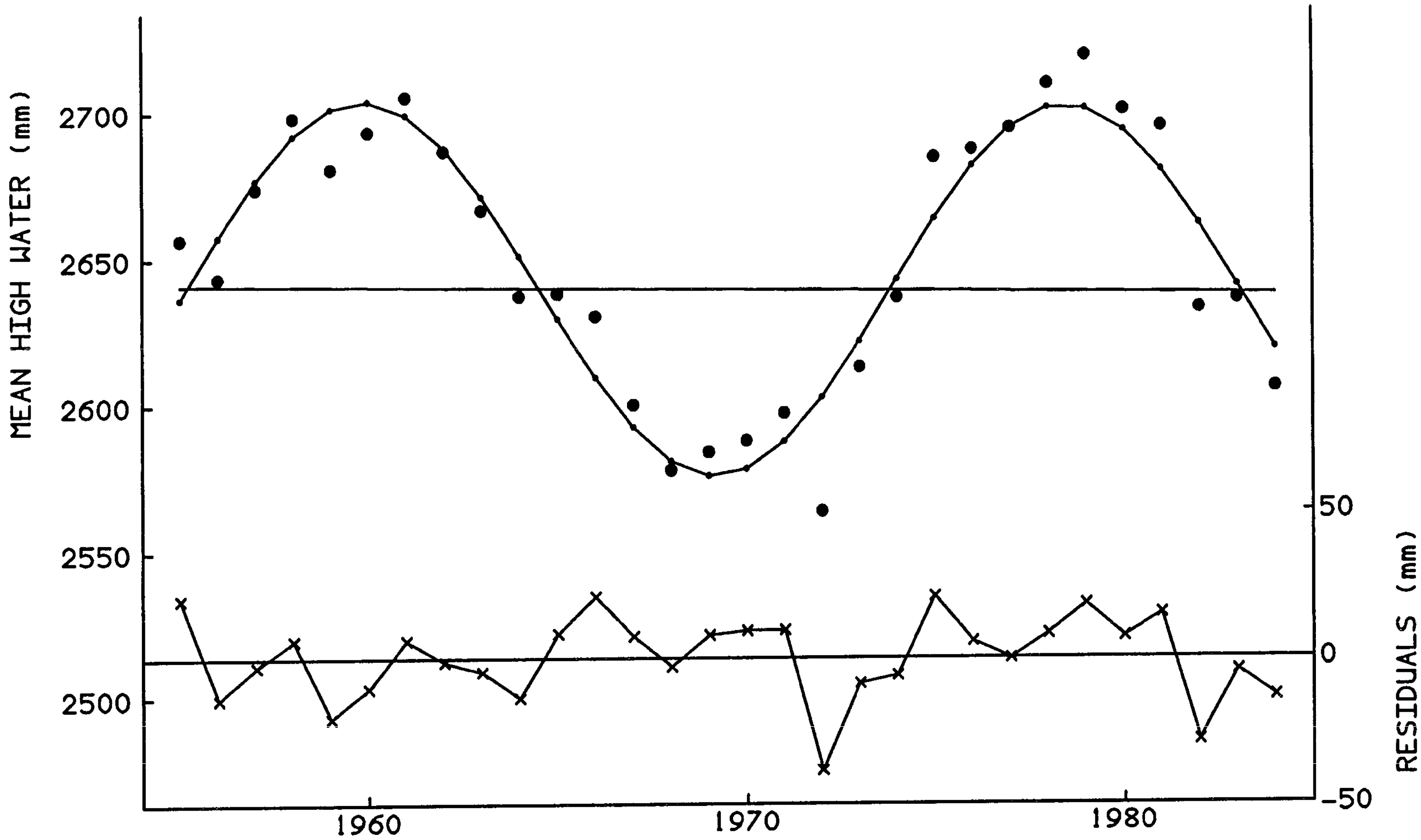
Figure 2

Figure 3



Lawyer's Outfall Sluice Tide Gauge Data

Figure 4



The Wash Model Data

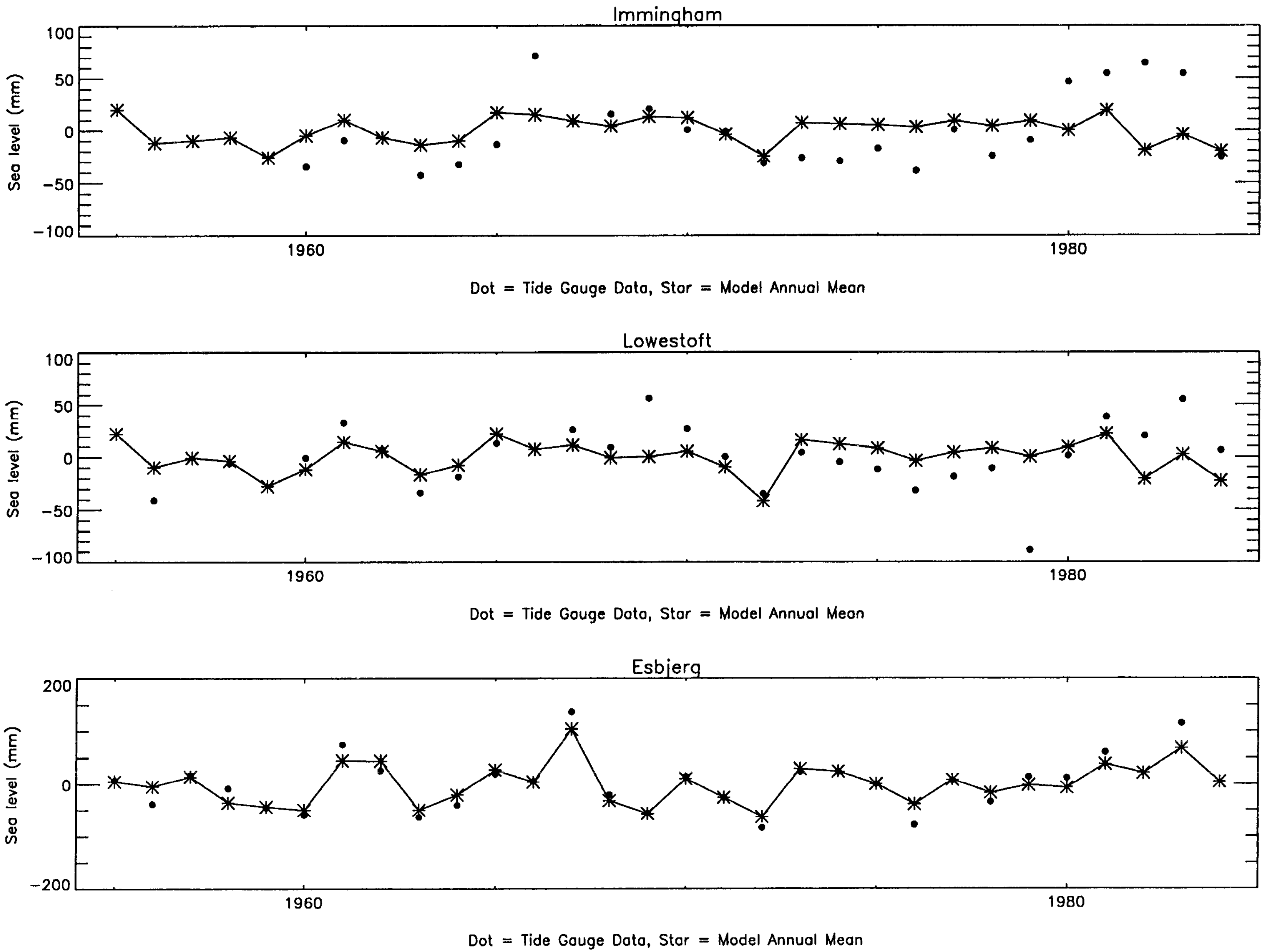

Immingham
Sea level (mm)
100
50
0
−50
−100
1960
1980
Dot = Tide Gauge Data, Star = Model Annual Mean
Lowestoft
Sea level (mm)
100
50
0
−50
−100
1960
1980
Dot = Tide Gauge Data, Star = Model Annual Mean
Esbjerg
Sea level (mm)
200
0
−200
1960
1980
Dot = Tide Gauge Data, Star = Model Annual Mean

Figure 5

Table 1

	Amplitude (m)	Greenwich Phase Lag (Degrees)
Period A:		
M2	2.306	179
S2	0.799	224
N2	0.561	145
O1	0.274	110
K1	0.248	273
Z0 (ODN)	0.326	
Period B:		
M2	2.524	178
S2	0.845	244
N2	0.546	151
O1	0.297	104
K1	0.262	272
Z0 (ODN)	0.181	
Period C:		
M2	2.510	182
S2	0.962	235
N2	0.477	155
O1	0.261	112
K1	0.280	270
Z0 (ODN)	0.329	