CHAPTER 257

SEA LEVEL TRENDS IN THE HUMBER ESTUARY : A CASE STUDY

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ABSTRACT

In 1990 Posford Duvivier were commissioned by the National Rivers Authority to collect, audit and place on a database 550 years of tide data from 15 locations on and in the vicinity of the Humber Estuary, UK. As part of this project 373 years of the data, from 10 locations (key stations), were analysed for trends in relative sea level. The areas covered in the trend analysis included: linear trend estimates on yearly average high tide levels from all the key stations; an examination of variations in trends with location and time; and an examination of the correlation between high water trends, mean tide level trends and low water trends. This paper discusses the trend analysis.

INTRODUCTION

The National Rivers Authority (Yorkshire, Severn Trent and Anglian Regions) are responsible for extensive tidal defences around the Humber Estuary in the UK. (see Figure 1). Knowledge of extreme water levels and trends in water level is necessary for the design of tidal defences. To enable these NRA regions to produce a consistent and sound strategy for the design of tidal defences in the Humber area, Posford Duvivier were commissioned by NRA Yorkshire Region to collect and analyse tide data from specified tidal stations. This data was to be placed onto a computer database and analysed for trends in water level and extreme water levels.

550 years of tide data from 15 locations (see Figure 2) on and in the vicinity of the Humber were collected, audited, reduced to a common level (mODN) and time (GMT) base and loaded onto the database. 373 years of this data, from 10 locations (key stations) were analysed for trends in relative sea level. These trends were used to establish a coherent trend for the Humber Estuary. This coherent trend was used to adjust high tide data within the database to a common base date, 1990. This adjusted data was then analysed to produce estimates of extreme water levels for use in the

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design of flood defences.

The areas covered in the trend analysis and discussed in this paper are

- Linear trend estimates on yearly average high tide levels from all the key stations
- The correlation between tide station trends
- The variation of trends with time
- The correlation between High Water trends, Mean Tide Level trends and Low Water trends

DATABASE

The layout of the tide data on the database is shown on Table 1. The database holds the date, time and height of both high and low water. Each high water and following low water is held as a pair. Each pair is given a sequence number unique to that tide. This enables a given tide or set of tides to be identified at each location up the estuary. For each tide an adjusted level (as at 1990) has been estimated based on the coherent estuary trend. This adjusted level is held within the database.

Software has been written to enable data that satisfies a set of user defined criteria to be retrieved from the database. This software also allows the user to carry out extreme value analysis and/or trend analysis on a station's full data set or on a specified set of retrieved data.

TREND ANALYSIS METHODOLOGY

Trend analysis was carried out on yearly averaged tide levels. A considerable amount of trend analysis has been carried out, during previous studies, using yearly average tide levels, and following an examination of trends using individual tide levels, monthly and yearly averages, it was considered appropriate that yearly averages be used in this study.

It was initially thought that river flow and surge tides might contaminate the trend estimates. However, at the key stations river flows did not significantly influence high tide level and any influence of these flows on trend estimates was reduced further by the use of yearly averages. Similarly the use of yearly averages effectively removes the effects of individual surge tides.

The use of yearly average tide levels also damps out "noise" in plots of levels against time. Noise may be due to diurnal tide differences, spring/neap tide cycles, monthly variations, random digitising errors, river flow, atmospheric pressure variations and surge tides.

An assessment of the effects of monthly variations in high tide levels at Immingham indicated that if at least ten months tide data was available for a year the average of this data would be a reasonably accurate estimate of the yearly average. Therefore, in auditing data at all stations, a valid yearly average was considered to exist if at least 10 months tide data existed for that year. Table 2 lists the number of valid yearly average high tide levels at each of the key stations.

Accurate assessment of tide level trends requires data uncontaminated by river flow and as long a data record as possible. Because a considerable amount of key station low water data is affected by river flow, (particularly that at Blacktoft and Goole the two stations with the longest data sets) and because high tide data at the key stations is not significantly affected by river flow, the analysis was concentrated on high tide levels. The correlation between trends in high water levels and trends in both low and mean tide levels was obtained from an analysis of Immingham data.

Trend estimates were based on a straight line fit to the tide data using the method of least squares. It was initially intended that the tide data be examined for both linear and curved trends. However, it was found that future water level estimates based on a quadratic fit to the raw data were very sensitive to errors in the curve parameters, and this method was therefore rejected.

ANALYSIS OF HIGH TIDE LEVELS

Plots of yearly average high tide level against time were examined for each station and are shown in figures 3(a) and 3(b). These plots were found to be consistent with each other and gave no indication that the trend in high tide level changes up the estuary. However, they show that a considerable variation in the trend estimate could occur depending on the data period examined. Therefore, when comparisons of trend estimates for two stations were being made, simultaneous data was used.

Blacktoft had more valid yearly average high tide level data than any other station, except Goole. Since the Blacktoft data was of a more reliable nature, it was decided to compare trends at each station with trends at Blacktoft. Trend estimates were made for each station and compared with the simultaneous trend at Blacktoft.

The results of this comparison are given in table 3. The actual value of the trend estimates are not important as they cover considerably differing data periods for different stations. For the same reason comparisons should only be made across table 3 not vertically. It can be seen that most of the station trend estimates are within one standard deviation of the Blacktoft estimate.

Within statistical error, therefore, table 3 shows no evidence of a change in trend in yearly average high tide levels as one moves up the Humber estuary. The coherent trend, in high tide level, for the estuary should therefore be based upon trend estimates for the station with the longest set of reliable data, which in the case of the Humber

Estuary was Blacktoft.

NODAL TIDE EFFECTS

General

Inspection of Figures 3(a) and 3(b) show that the yearly average high tide levels vary with time. The plot of levels for Blacktoft indicate this variation is cyclical with a period close to 20 years. In a study of yearly average water levels in the Thames, Rossiter (1969) refers to oscillations in annual average levels due to the "Nodal tide". The Nodal tide is due to the variation in the plane of orbit of the moon around the earth. This variation has a period 18.61 years. The nodal tide effect causes the tidal ranges to modulate, resulting in tides having a maximum and minimum once every 18.61 years.

Nodal Tides

In principle, the nodal tide would cause what is known as the M_2* tide component to vary by ± 3.7% over 18.61 years, with minima at 1913.4 (approx.) ± N x 18.61 years and maxima at 1922.7 (approx.) ± N x 18.61 years. The nodal tide could therefore cause the yearly average high water level at Immingham to vary by about 167mm.

However, the nodal oscillations of real tides appear to be less than the theorectical ± 3.7%. The occurrence of minima or maxima are also slightly (+0.5 year for Immingham) out of phase with the theory. Work by P. Woodworth (1991) of POL indicates that the nodal oscillation on high water level at Immingham would cause the yearly average high tide level to vary by 136mm with a minimum at 1951.1. It should be noted that a variation in average water level of 136mm in 9.3 (18.6/2) years gives a short term "trend" of 14.6mm/year.

The nodal tide causes a significant modulation in tidal range but only a small modulation on mean sea level. Woodworth (1987) cites estimates of the amplitude of nodal tidal oscillations on mean sea level of about 9-10mm.

Effect of Nodal Tide on Estuary Trend

It is therefore important, when estimating a coherent estuary trend, using high tide data,that the period of data used should be an integral number of 18.61 year periods, should be of sufficient length that the effect of the nodal tide is insignificant, or the data should be corrected for nodal tide effects.

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* The M_2 component is the lunar tide component, with period 12.42 hours, which dominates tides around the UK coast

It is not yet known how the effect of these nodal oscillations propagate up an estuary. It is thought that they may not vary much. At Immingham the amplitude of the nodal tide is about 3.0% of the M_2 tide. Assuming the nodal tide propagates up the Humber, as 3% of the M_2 component, this will result in a nodal oscillation of 121mm at Blacktoft.

Correcting the yearly average high tide levels at Blacktoft for this assumed nodal tide effect increases the linear trend estimate for the full data set from 3.57 to 3.71mm/year, see table 4. The use of this nodal tide correction causes a reduction in the standard deviation of the trend estimate from, 0.37 to 0.24mm/year. If an accurate estimate of the nodal tide amplitude were known for Blacktoft a more precise trend estimate could therefore be calculated. A plot of this Blacktoft data with nodal tide correction is given in Figure 4.

This increase in precision, though it may be significant in terms of reduction in the standard error of the trend, did not result in a significant change in the trend estimate. It was therefore decided that the estimation of a coherent estuary trend could be based on a trend estimate for the full Blacktoft data set without correction for nodal tide effects.

A coherent estuary trend of 3.57mm/year ± 0.37mm/year was thus adopted.

RELATIONSHIP BETWEEN TRENDS IN HIGH TIDE LEVEL, MEAN TIDE LEVEL AND LOW TIDE LEVEL

General

The coherent estuary trend of 3.57mm/year ±0.37mm/year can be used to adjust past annual maxima data to the 1990 base date. Assuming that these historic trends continue, extreme water level estimates at future dates can be made. These future extreme levels are the extreme estimates based on annual maxima adjusted to 1990, plus a future rise based on historic trends.

Estimates exist for future sea level rise as published by the Intergovernmental Panel on Climate Change (IPCC) (1990). At present there are large uncertainties on these future sea level rise estimates which take account of global warming. In the near future, given a lessening of the uncertainties on sea level rise estimates, one may wish to use these rise estimates in place of historic trends. The greenhouse effect estimates relate to mean sea level, not yearly average high tide level, however, they do not include for local land movements.

To enable use to be made of future sea level used rise estimates it is thus necessary both to know the relationship between trends in high tide levels and trends in mean sea level and to obtain an estimate of land movement for the Humber area.

It should be noted that mean tide level used in this study (HW+LW)/2) is not the same as mean sea level. However, over a period of time mean tide level is a constant amount above or below mean sea level. Therefore a trend in mean tide level is equivalent to a trend in mean sea level.

Relationship from other Studies

Other studies have stated that trends in high tide and mean sea level are not the same. For example, Pugh (1990) cites two studies which indicate that trends in high tide level are higher than trends in mean sea level. One of these studies by J.R. Rossiter (1969) found that at Tower Pier trends on high tide levels were considerably greater than trends on MTL, 7.74 ± 1.16mm/year against 4.33 ± .82mm/year. During the same study, however, Rossiter found that the trends on high and mean tide levels at Southend were not statistically different. Another study indicated that at Flushing, Holland, the high tide trend was 3.3mm/year, against 2.2mm/year for the mean sea level.

Rossiter's study quoted above covers a data period of 30 years. This data period is less than an integral number of nodal tide periods. His study took no account of the nodal variation in tide levels and may therefore be biased.

Relationship from Present Study

To attempt to correlate trends in high, mean and low tide levels in the Humber, Immingham tide data was examined. As discussed earlier, nodal tide effects result in an oscillation of approximately 136mm in high tide levels at Immingham, with a low at 1951.1. Table 5 gives trend estimates and the standard deviation of these trend estimates for yearly average high, mean and low tide level at Immingham, with and without correction for nodal tide effects. Figure 5 gives plots of these yearly average tide levels with and without nodal corrections.

Ignoring nodal tide effects indicate that high tide level is rising slower than both mean tide and low tide level. However, having corrected the high and low water levels for nodal tide effects the difference between the trends for the three levels is not statistically significant. Correcting for nodal tide effects also gives a significant reduction in the standard deviation of the high and low tide trend estimates.

This study indicates, therefore, that an increase in mean sea level will result in a similar increase in high water level.

Future Levels

Based upon the assumption that the difference between relative sea level rise and global mean sea level rise is, in the Humber, due predominantly to land sinkage, and using the 3.57mm/year rise as the best estimate of relative sea level trend in the Humber, and the IPCC, (1990) estimate of sea level rise of 1 to 2mm/year over the last 100 years, we estimate the rate of land sinkage in the Humber as 1.57 to 2.57mm/year. It is acknowledged that this is a simplistic approach and that the difference may be due to other factors, not yet fully understood.

At present, therefore, future trend estimates of relative sea level rise based on estimates of absolute sea level rise should consider this estimate of land sinkage as additional.

CONCLUSIONS

It was found during the study that

- spatial variation in high tide trends for stations within the estuary was found not to be statistically significant
- nodal tide effects must be considered when water level trend estimates are made based on high tide data. The longer the data set the smaller is the effect of nodal tide on trend estimates
- a coherent trend estimate of 3.57mm/year, ±0.37mm/year was found for the Humber estuary. This estimate is based on the Blacktoft data set (70 years)
- this study indicates that, for the Humber estuary, an increase in mean sea level will result in a similar increase in high water level
- in the Humber area, there is an additional 1.57-2.57mm/year increase in relative sea level over global sea level trends. This may be due to land sinkage.

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TABLE 1

Humber Estuary Tidal Defences Database Layout

Sequence Number	High Date	High Time	High Level	Low Date	Low Time	Low Level	Adj Level
70001	01 Jan 1970	11:20	1.85	01 Jan 1970	16:57	-1.37	1.94
70002	01 Jan 1970	23.20	2.27	02 Jan 1970	05:53	-1.28	2.36
70003	02 Jan 1970	12:08	1.93	02 Jan 1970	17:33	-0.80	2.02
70004	03 Jan 1970	00:31	2.27	03 Jan 1970	06:58	-1.43	2.36
70005	03 Jan 1970	13:29	1.90	03 Jan 1970	19:05	-0.79	1.99
70006	04 Jan 1970	01:41	2.09	04 Jan 1970	08:12	-1.53	2.18
70007	04 Jan 1970	14:29	2.16	04 Jan 1970	20:29	-1.48	2.25
70008	05 Jan 1970	03:00	2.29	05 Jan 1970	09:16	-1.88	2.38
70009	05 Jan 1970	15:34	2.45	05 Jan 1970	21:53	-1.80	2.54
70010	06 Jan 1970	03:47	2.54	06 Jan 1970	10:12	-2.21	2.63
70011	06 Jan 1970	16:40	2.71	06 Jan 1970	22:56	-2.32	2.80
70012	07 Jan 1970	04:53	2.78	07 Jan 1970	11:23	-2.61	2.87
70013	07 Jan 1970	17:24	2.89	07 Jan 1970	23:54	-2.81	2.98
70014	08 Jan 1970	05:46	3.03	08 Jan 1970	12:19	-2.66	3.12
70015	08 Jan 1970	18:17	3.20	09 Jan 1970	00:55	-3.11	3.29
70016	09 Jan 1970	06:53	2.78	09 Jan 1970	13:00	-3.38	2.87
70017	09 Jan 1970	19:04	3.14	10 Jan 1970	01:39	-3.48	3.23
70018	10 Jan 1970	07:40	3.33	10 Jan 1970	13:55	-2.75	3.42
70019	10 Jan 1970	19.48	3.80	11 Jan 1970	02:26	-3.26	3.89

Station	Number of Years
North Shields	20
Scarborough	35
Spurn Point	16
Immingham	29
Hull	11
Brough	36
South Ferriby	10
Blacktoft	66
Goole	69
Keadby	40

TABLE 2

Number of Valid Yearly Average High Tide Levels each Key Station

TABLE 3

Relationship between Station Trend and Blacktoft Trend *

Values at Station			**Concurrent Values at Blacktoft Station**		
	Trend	**Std.Dev. of Trend**	**Trend**	**Std.Dev.**	**No. of Years of Concurrent data**
Station	mm/yr	mm/yr	mm/yr	mm/yr	
Goole	2.9	0.4	3.5	0.4	65
Keedby	4.5	0.7	4.5	0.9	34
Brough	4.4	0.8	3.9	0.9	36
South Ferriby	11.7	4.9	9.0	3.1	10
Hull	-5.1	2.8	-7.1	2.0	11
Immingham	3.6	0.9	2.6	1.1	29
Spurn Point	0.8	2.5	1.6	2.43	16
Scarborough	3.3	0.6	4.5	0.8	35
North Shields	3.5	0.8	2.9	0.9	20
	Immingham**		North Shields		
	2.26	1.34	3.19	1.00	19

* Using yearly average high tide levels, concurrent data

** Comparison of Immingham and North Shields

TABLE 4

Blacktoft Trend Estimate

	Trend	Std.Dev. of Trend
	mm/yr	mm/yr
Without Nodal Tide Correction	3.57	0.37
With Nodal Tidal Correction	3.71	0.24

Data set examined 1923 - 1989

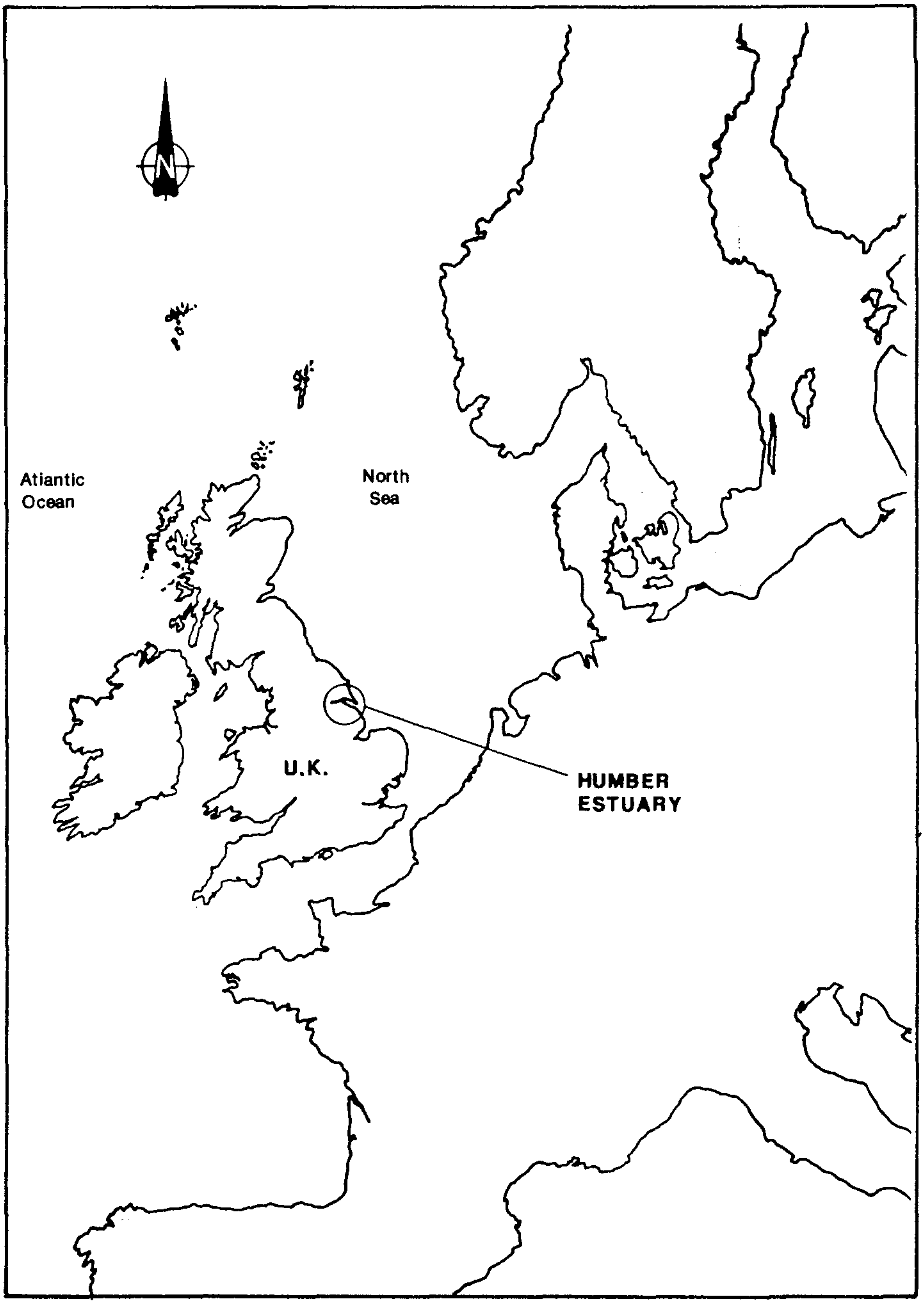
TABLE 5

Immingham: Relationship between Trends in High, Low and Mean Tide Level*

	With Correction for Nodal Tide		Without Correction for Nodal Tide	
	Trend	Std.Dev. of Trend	Trend	Std.Dev. of Trend
	mm/yr	mm/yr	mm/yr	mm/yr
High Tide	3.43	0.63	2.62	1.07
Mean Tide**	3.40	0.58	3.52	0.57
Low Tide	3.60	0.56	4.41	1.13

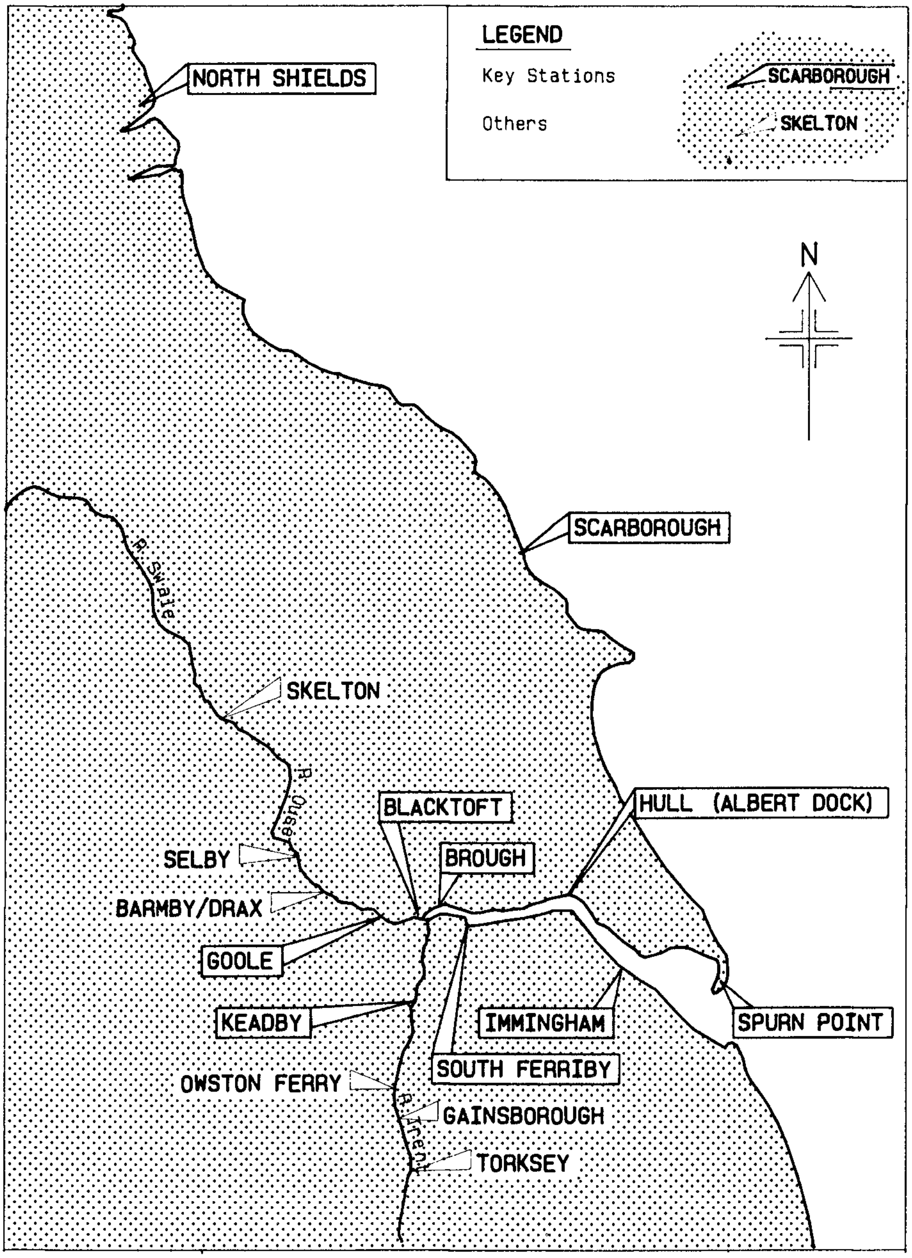
* levels used are yearly averages

** using a nodal tide amplitude of 10mm



LOCATION PLAN – HUMBER ESTUARY

FIG. 1



LOCATION OF STATIONS

FIG. 2

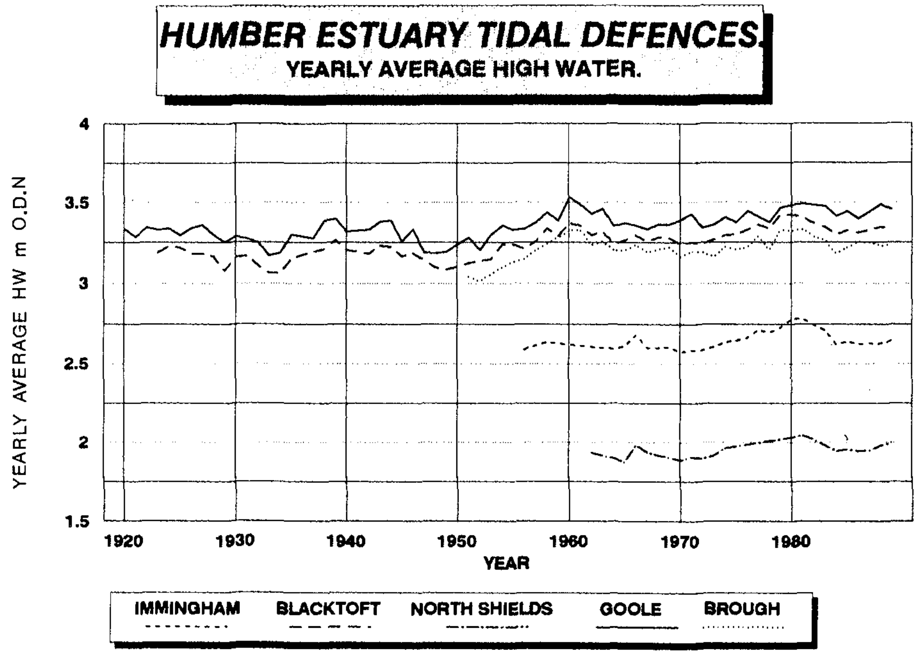

HUMBER ESTUARY TIDAL DEFENCES.
YEARLY AVERAGE HIGH WATER.
YEARLY AVERAGE HW m O.D.N
4
3.5
3
2.5
2
1.5
1920
1930
1940
1950
1960
1970
1980
YEAR
IMMINGHAM
BLACKTOFT
NORTH SHIELDS
GOOLE
BROUGH

FIG. 3a

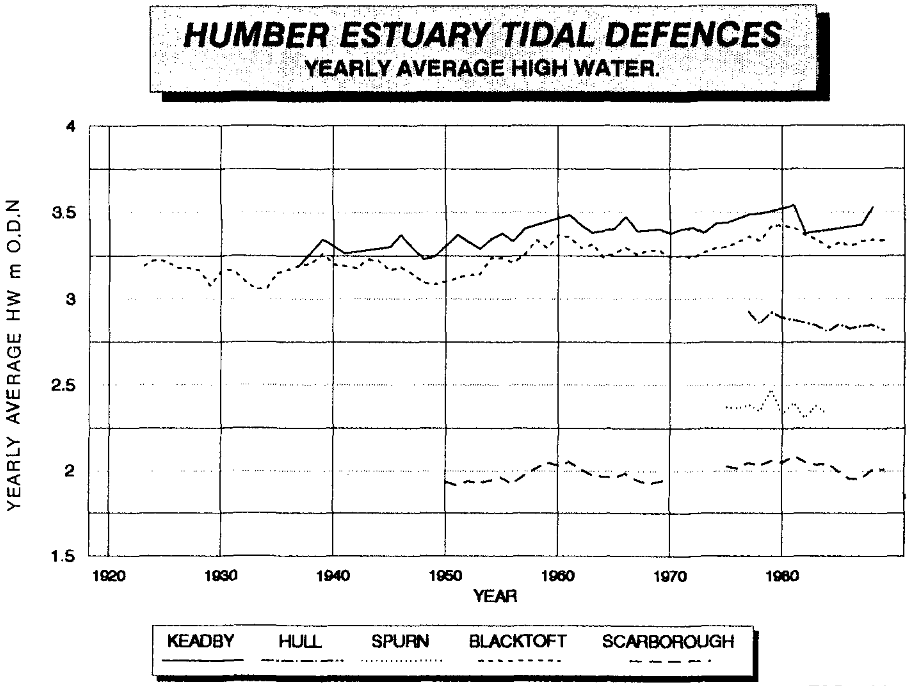

HUMBER ESTUARY TIDAL DEFENCES
YEARLY AVERAGE HIGH WATER.
YEARLY AVERAGE HW m O.D.N
4
3.5
3
2.5
2
1.5
1920
1930
1940
1950
1960
1970
1980
YEAR
KEADBY
HULL
SPURN
BLACKTOFT
SCARBOROUGH

FIG. 3b

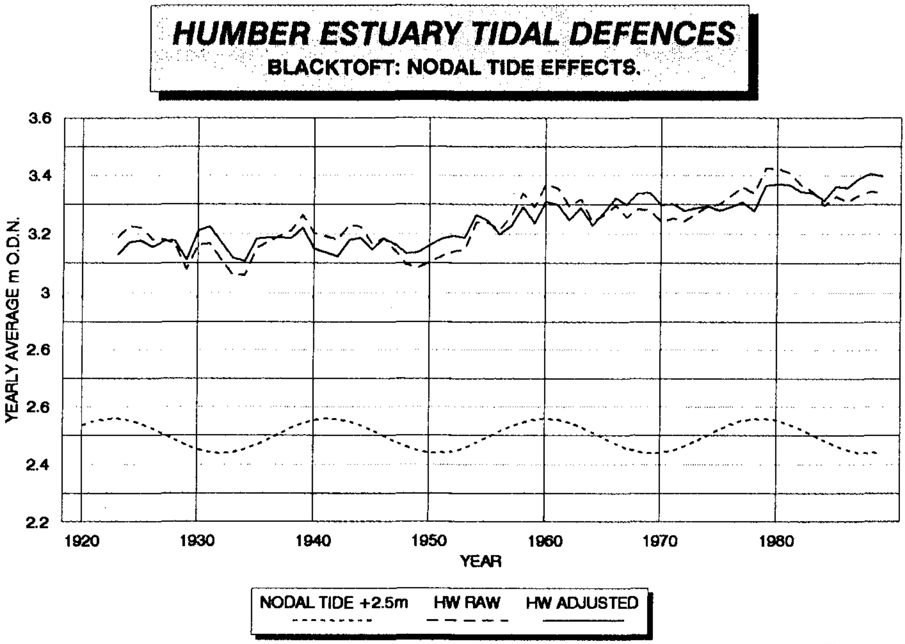

HUMBER ESTUARY TIDAL DEFENCES
BLACKTOFT: NODAL TIDE EFFECTS.
YEARLY AVERAGE m O.D.N.
3.6
3.4
3.2
3
2.6
2.6
2.4
2.2
1920
1930
1940
1950
1960
1970
1980
YEAR
NODAL TIDE +2.5m
HW RAW
HW ADJUSTED

FIG. 4

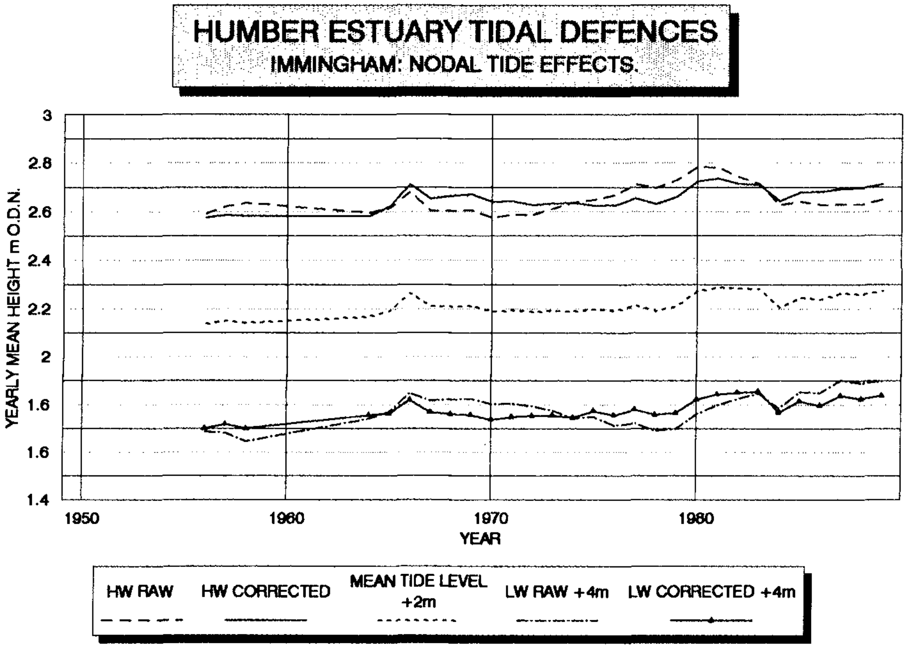

HUMBER ESTUARY TIDAL DEFENCES
IMMINGHAM: NODAL TIDE EFFECTS.
YEARLY MEAN HEIGHT m O.D.N.
3
2.8
2.6
2.4
2.2
2
1.6
1.6
1.4
1950
1960
1970
1980
YEAR
HW RAW
HW CORRECTED
MEAN TIDE LEVEL +2m
LW RAW +4m
LW CORRECTED +4m

FIG. 5