CHAPTER ONE HUNDRED EIGHTEEN

NORTH SEA TIDE AND STORM SURGE INVESTIGATION

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Abstract

An extensive investigation of tide and storm surge measurements in the coastal waters of the southeastern North Sea (German Bight) is now being concluded, giving new hints to tidal behaviour in a complex area, consisting of extended tidal flats, interrupted by islands, sand banks, estuaries and gullies. The analysis was promoted by the "German Coastal Engineering Board" (KFKI) and will be the basis of further investigations of the storm surge conditions in tidal estuaries.

Tidal records and high and low water values of 130 gauges in an area of 12.000 km^2 (5.000 sq.mi.) were used to evaluate

- cotidal lines in the German Bight
- mean tide curves
- regressions between different locations
- neap and spring tide conditions
- secular changes over the last 80 years
- storm surge development.

Tidal Character in the German Bight

The tidal motion in this area is induced by the amphidromic tide in the southeastern North Sea (fig. 1). It was believed that the tides in the triangle off the German coast proceed from the West to the East and then to the North, but it turned out that this is not the case: Coriolis and centri-

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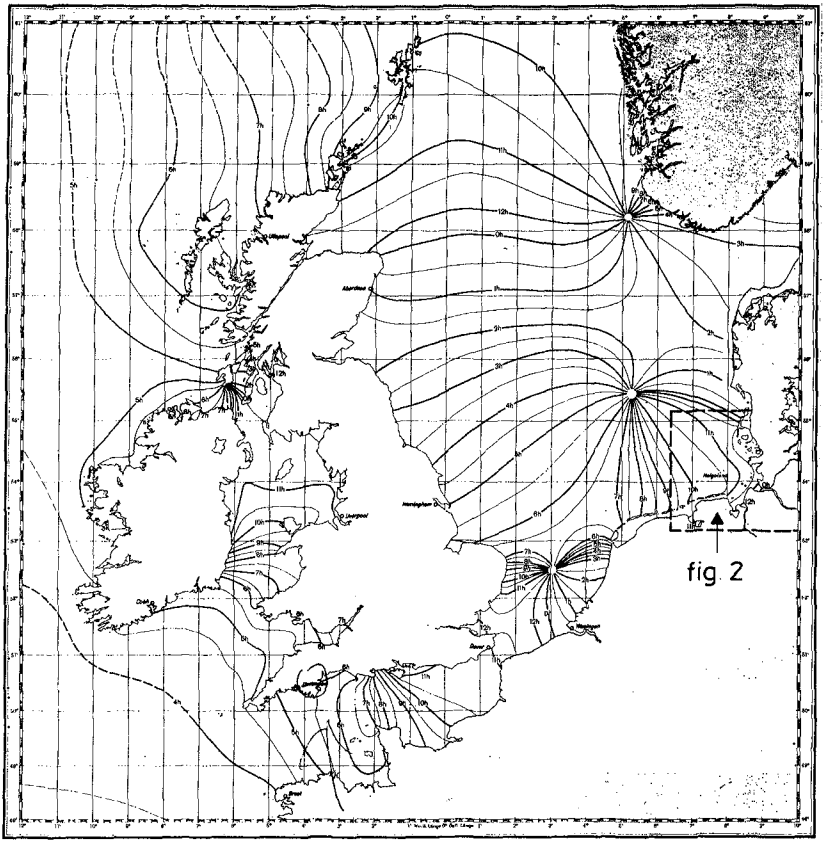

Figure 1. Cotidal Lines in the North Sea for Mean HW Conditions (Deutsches Hydrographisches Institut, 1982)

fugal forces lead to deformations of surface gradients resulting in a motion mainly from the West to the East, so it will be shown that the general conditions of fig. 1 are not realistic near the coastlines.

The area of investigation is given on fig. 2, including the long-term and seasonal tide gauges, indicated by black dots. They cover an area of 80 x 80 km^2 (50 x 50 sq.mi.), most of them in the three estuaries and on the tidal flats in a zone, 10 to 20 km wide. Fig. 3 to 8 show some of the results

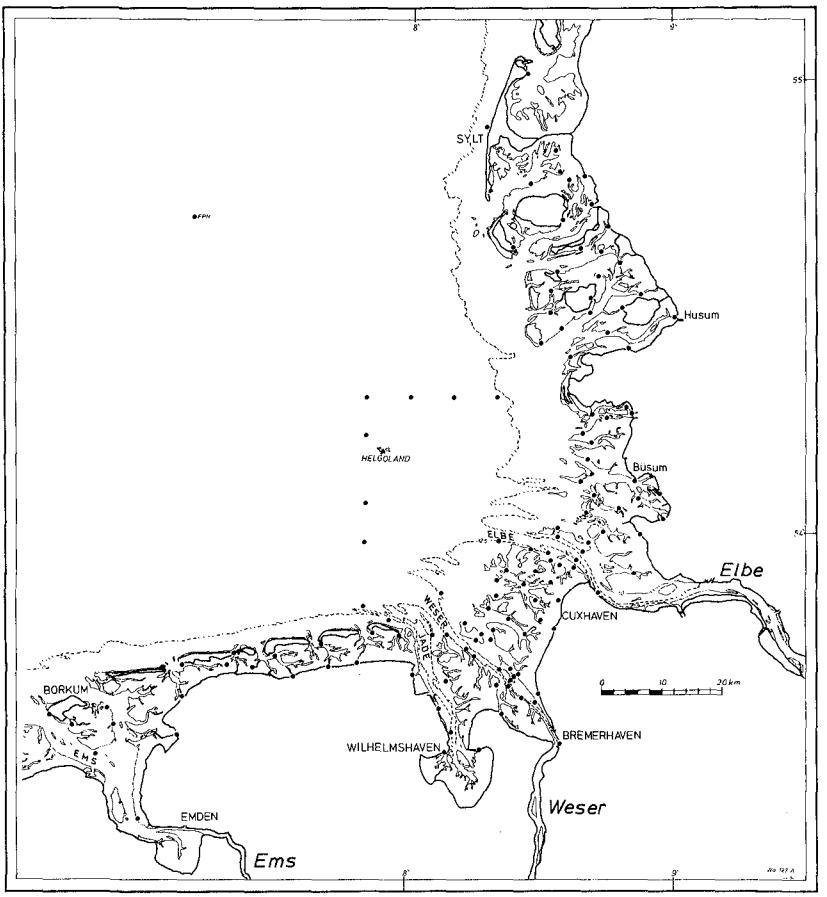

Figure 2. Long-term and Seasonal Tide Gauges in the South-eastern North Sea

that are to be published in the near future in detail (3).

Fig. 3 indicates the lines of mean HW occurence from 20 to 20 minutes, showing no full agreement with fig. 1: HW time is more or less propagating from the West to the East, signs of a rotation (due to an amphidromic point) cannot be realized. There is another very interesting result: The tide curves off the coast are usually asymmetric with values

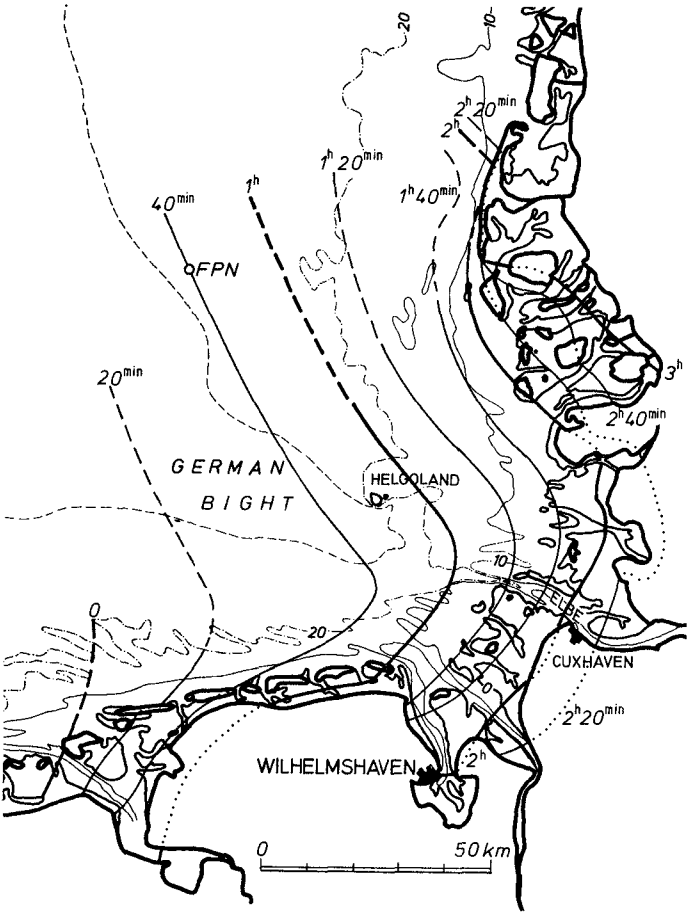

Figure 3. Cotidal Lines in the German Bight for Mean HW Conditions; Measurements 1975/79

T_F/T_E between 0.8 and 1.0 (fig. 4). It has to be taken into account that the curves in the North Sea - at least in water depths between 30 and 50 m - are not symmetric and that the asymmetry does not increase with the propagation to the coast, but decrease. An expected decrease is found in the estuaries; in some areas we even find longer ebbs than floods! Moreover, we are able to define the flats and

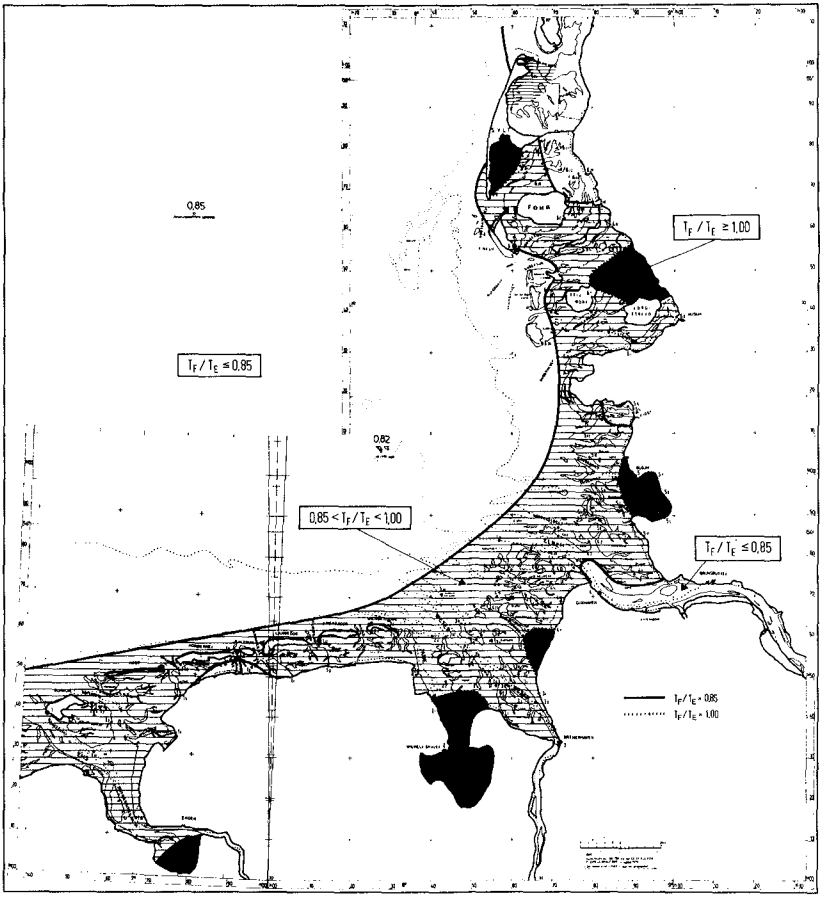

Figure 4. Flood Duration T_F over Ebb Duration T_E in the German Bight for Mean (Semi-diurnal) Tides

gullies as a system of neighbouring flood- and ebb-dominated areas (see fig. 5). The former are characterized by longer flood than ebb duration ($T_F > T_E$) and coastwards decreasing low water levels, combined with residual currents across the tidal flats towards the latter. The lines of mean HW levels, computed for 1975/79 and given in cm above gauge datum on fig. 6, rise with 10 cm/10 km from the Northwest to the

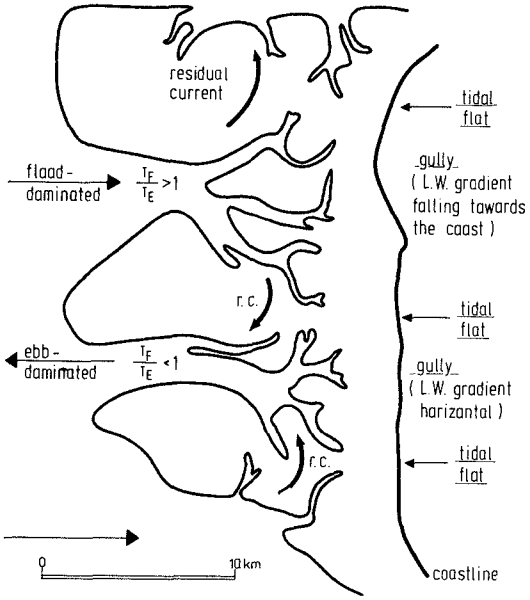

Figure 5. Array of Tidal Flats with Typical Pattern of T_F/T_E and Residual Currents

Southeast, becoming very complex in the eastern tidal flats and in the estuaries of Weser and Elbe. The highest mean HW levels are found in the bights west of the Weser and north of the Elbe estuaries. The mean tidal range on fig. 7 increases significantly from the deeper water zones towards the coastline (measurements from 1.3 m to 3.8 m with remarkable gradients in the northernmost wadden sea. Near-coast spring tidal range is about 60 cm higher.

The mean tide curves differ a lot. Fig. 8 gives some examples: Different heights and shapes, due to the topographical and current conditions. These curves of 130 tide gauges enabled us to calculate lines of constant water levels in the German Bight for all tide phases. As far as we know it is the first time that this could be done by such an amount of field data. And the result stated what had to be expected

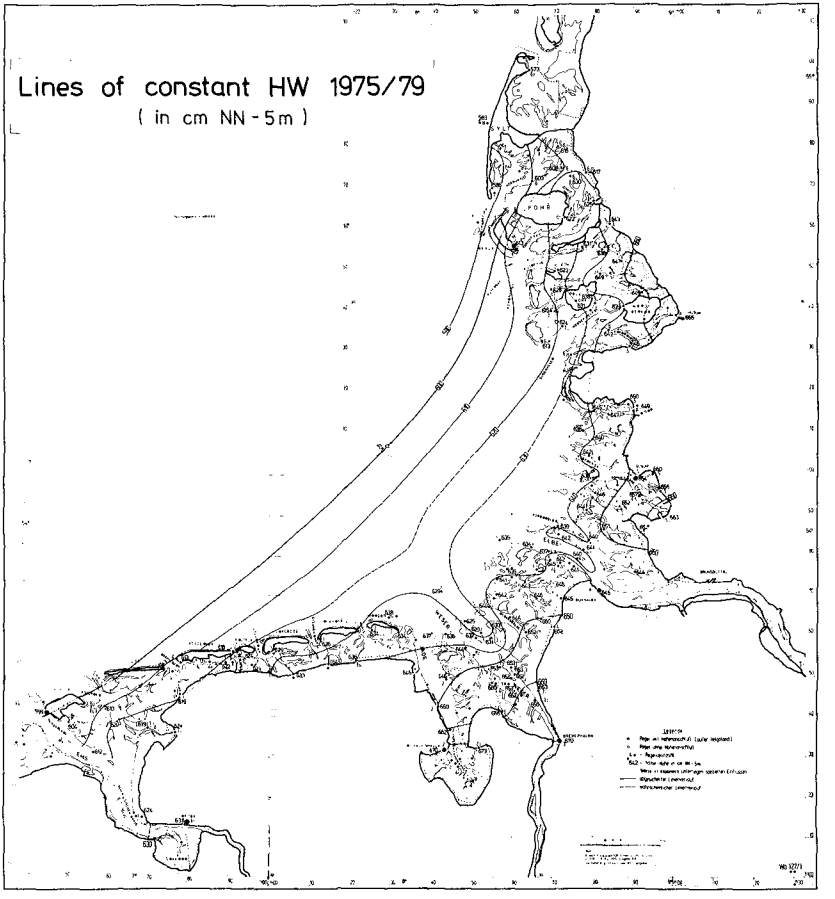

Figure 6. Mean HW Levels in the German Bight for 1975/79

by the cotidal lines on fig. 3: The amphidromic tide in the southeastern North Sea (fig. 1) does not rule the movements in the German Bight in a strong manner as was believed: We can assume a border of main influence (sketch on fig. 9). In the area between that border and the coastline, the tidal movement is stimulated from the West, and there should be only weak interactions across the assumed border. That

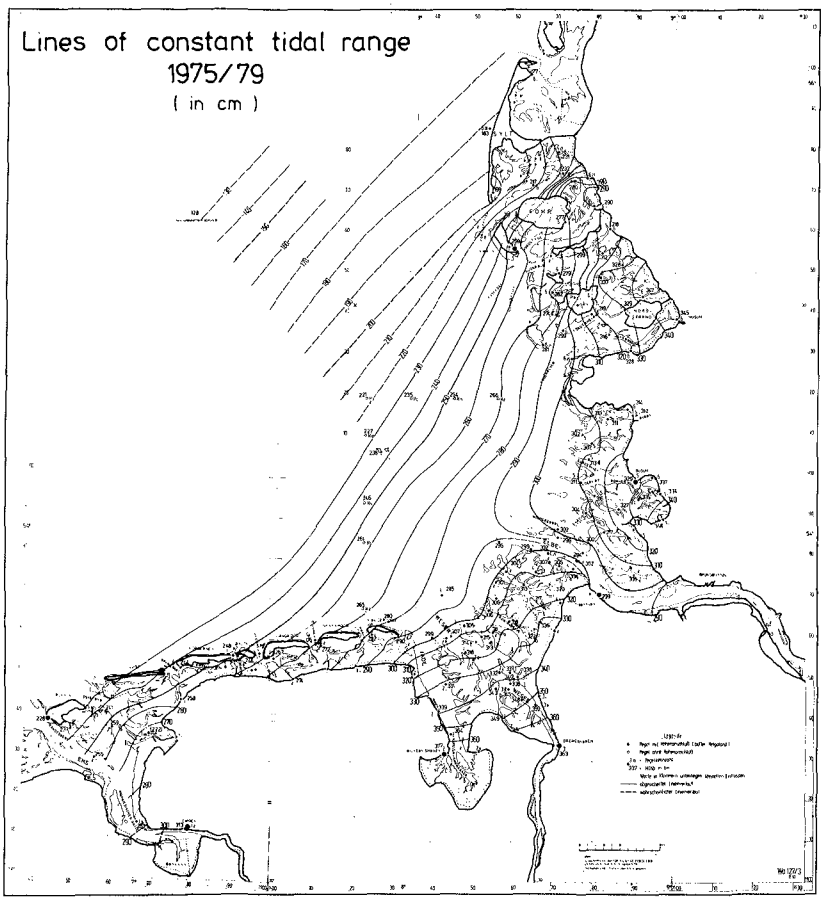

Figure 7. Mean Tidal Range in the German Bight for 1975/79, Given in cm

leads to a predominant west-east tidal motion (and south-west-northeast for the northern area), in agreement with current measurements and ice tracer observations. This is underlined by the effect that we can define a zone of about 6.000 km^2 (2.500 sq.mi.), where the water levels behave in an interesting way: During LW time at Borkum (BOR on fig. 9) the indicated zone is characterized by constant water levels

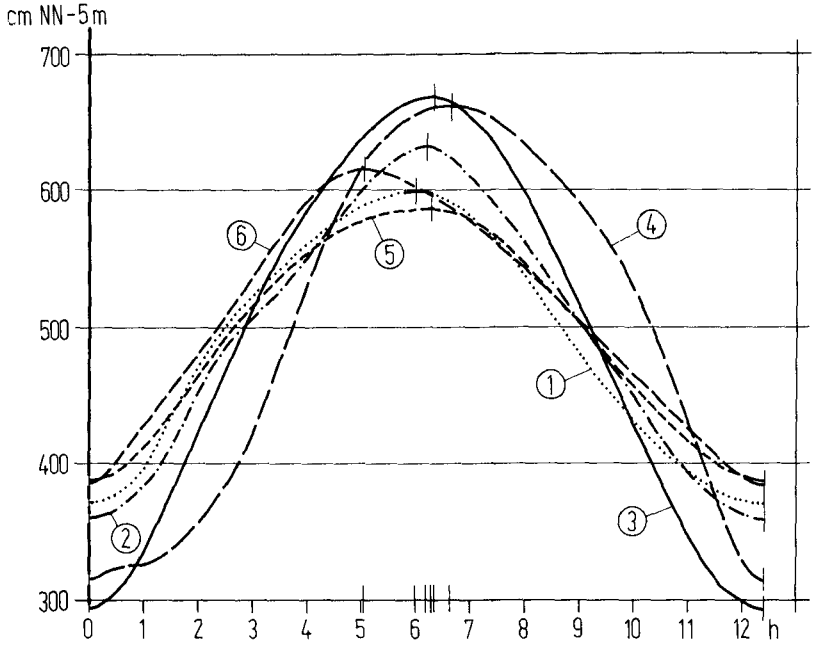

Figure 8. Examples for Different Mean Tide Curves in the German Bight (See Fig. 2):

1: Borkum: outside tidal flats

2: Bensersiel: straight coastline, protected by islands

3: Wilhelmshaven: bight effect

4: Steertloch: bight effect, south of Büsum

5: Hörnum: southern tip of Sylt, island effect

6: Osterley: east of Hörnum, island and tidal flat effects

(variances only within 10 cm), and they are the lowest in the whole German Bight at this tide phase. At HW time in Borkum the same area can be defined as of constant water level, being the highest at that phase. Conclusions are:

- Water is "pumped" into the inner bight during flood phases, building up a ridge with slopes to the North

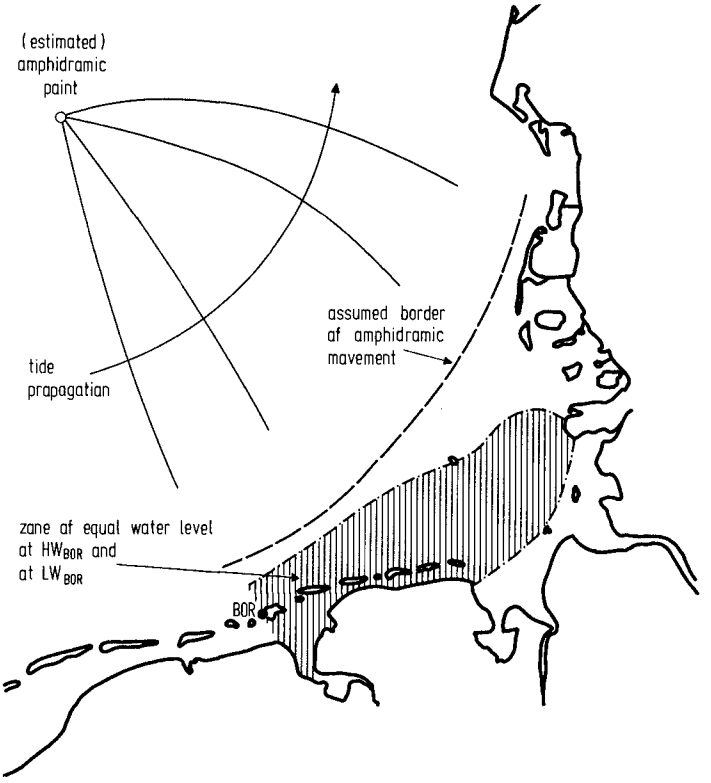

Figure 9. Mean Amphidromic Behaviour in the Southeastern North Sea and Zone of Special Conditions

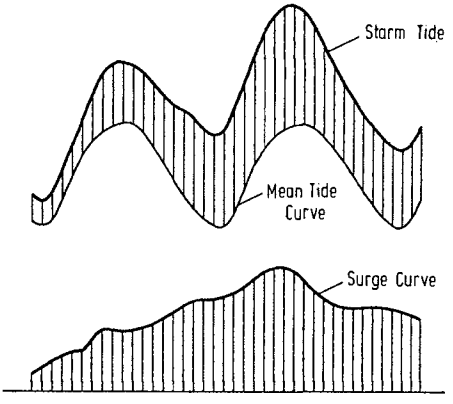

Figure 10. Definition Sketch, Mean Tide Curve and Storm Surge

and to the Southeast;

- water is moving out of the indicated zone, finally forming a trough;
- wind induced currents from westerly directions can easily fill up this trough; so storm surges usually start somewhere around LW_{BOR}, and constant wind conditions lead to higher surge values during LW than during HW (surge being defined as on fig. 10);
- no conservative tidal wave profil appears near the coast; consequently linear wave theory should not be applied to coastal tides.

In this context it is very interesting that computations of the Danish Hydraulic Institute in its numerical North Sea model show that the origin of the discussed trough lies west of the Dutch coast, i.e. in the sphere of the neighbouring (southern) amphidromic tide, migrating along the coast into the German Bight, thereby steadily deepening.

Recent HW and LW Changes

During the last decades tide and storm surge investigations along the German North Sea coast and in the estuaries have rapidly been intensified. But there are some gauges with records of more than 100 years as well, and two of them will have their bicentennial jubilee in 1986 (Cuxhaven and Hamburg). So much historic data is available. On the other hand the development of the last 15 years is to be of high interest: We can evaluate distinct changes in water levels since 1970 recognizable both in HW and LW. Three typical examples for the German Bight are given for the islands Borkum (BOR) and Helgoland (HEL) (fig. 11) and for Cuxhaven (CUX) at the seaward boundary of the Elbe estuary (fig. 12):

HW BOR: rising until 1970, the constant
HEL: rising until 1950 (?), then constant
CUX: rising until today, with an increase during the last decade.

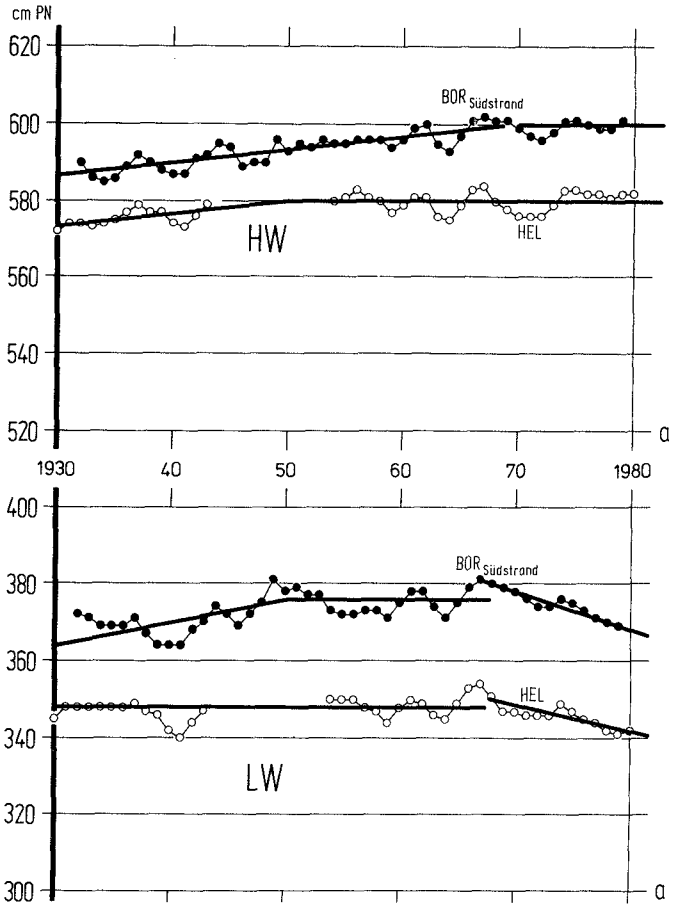

Figure 11. HW and LW Developments (3 Years Running Means) at Helgoland (HEL) and Borkum (BOR)

LW BOR: rising until 1950, constant until late 1960ies, the falling

HEL: constant until late 1960ies, then falling

CUX: rising until 1950, then slowly falling, with an increase in the late 1960ies.

The result is: at the islands 10 to 50 km in front of the coast HW has been constant since 1970, while at the coast (CUX is typical!) HW is rising remarkably. At the same time

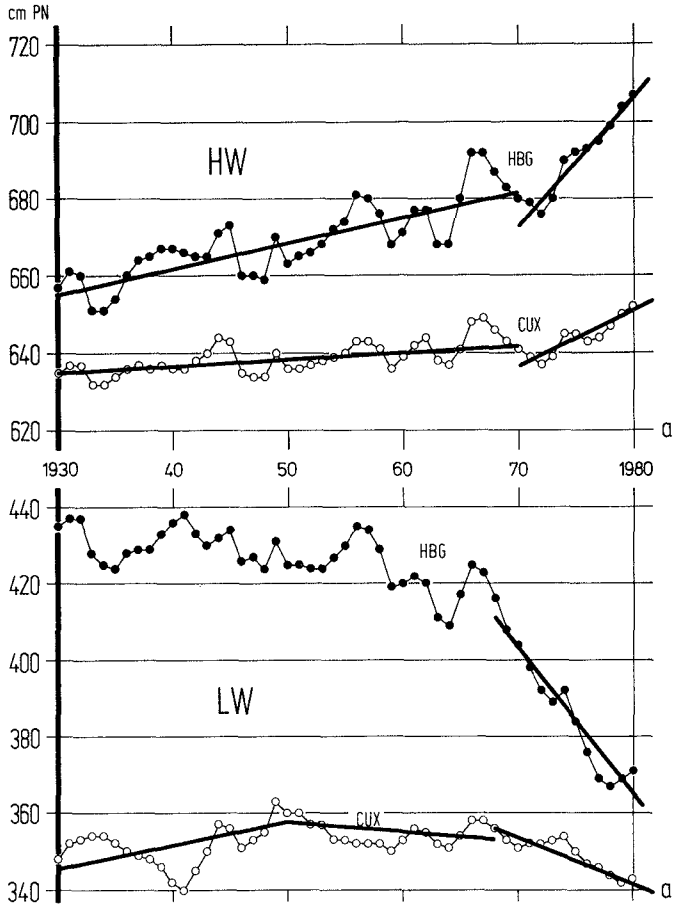

Figure 12. HW and LW Developments (3 Years Running Means) at the Elbe Estrance (Cuxhaven, CUX) and 100 km (60 mi.) upstream (Hamburg, HBG)

LW is falling at the islands and at the coast; so the tidal range increases rapidly.

In the tidal estuaries the HW and LW developments are gouverned by seaward and regime conditions. The seaward influence in the Elbe is shown in fig. 12. Hamburg (HBG) is situated 100 km upstream from Cuxhaven, and qualitatively

the developments are the same as in CUX. Especially the LW data also seems to show strong effects of deepening of fairway. The same is realized in other estuaries in Europe.

So this yields two conclusion: either all estuaries have been deepened since 1970 resulting in round about the same amount of LW-change, or something must have happened outside the estuaries. The latter idea was first published by the author in 1976 and emphasized later (2).

During the last years the number of indications about changes of tidal characteristics in the North Sea is rising:

- At the German coast we measure tidal ranges that have never occurred before;
- tidal current velocities in the outer parts of the estuaries (seaward of fairway improvements) increased;
- shapes of mean tide curves have changed destinctly.

The question is, whether the amphidromic tide in the southeastern North Sea is constant or not, and if not: why? This problem can not yet be solved, but we are trying to find a solution.

Storm Surge Tendencies

The coasts of the southeastern North Sea had to be protected against severe storm surges with high dikes and other defence constructions. The heights of these events steadily rose during the last 500 years due to secular water level increase of about 20 cm/100 years.

During the same period since 1960, when the mean tide conditions changed in front of the coast, the heights and frequencies of storm surges increased, as indicated by fig. 13 and 14: Ten years overlapping means have risen by 20 to 30 cm within a period of 30 years at stations 10 to 20 km off the coast (BOR, AW) and at the coast (CUX) as well (fig. 13), the main portion being during the last 20 years, accompanied by a distinct increase of the storm surge num-

ber (fig. 14): 10 events in three years until 1960 to 15 up to 20 since 1965. So this development is in phase with the rise of mean HW levels in this area (fig. 11, 12). The reasons are different, of course: Storm surge growth is the result of two developments: the number of storm has been increasing during the last decade, as has at the same time the frequency of the critical wind directions (e.g. 270° for the Ems, 280° to 290° for the Weser and Elbe).

All these tendencies, concerning mean tidal conditions at all gauges as well as storm surge heights and frequencies,

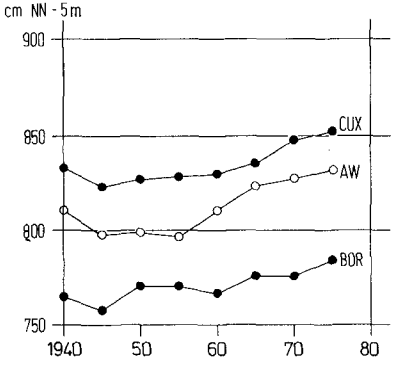

Figure 13. Mean Heights of Storm Surges Higher than 1.5 m above HW at the Entrances of Ems (BOR), Weser (AW) and Elbe (CUX) (10 Years Overlapping Means)

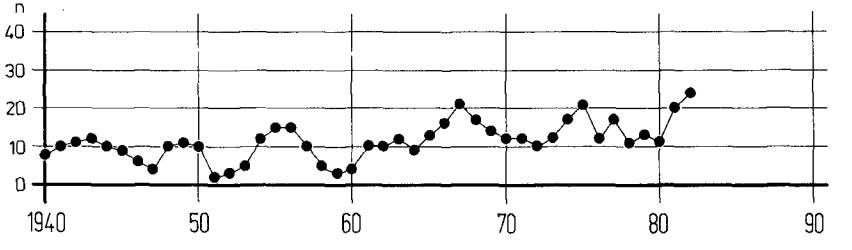

Figure 14. Number of Storm Surges in Cuxhaven Higher than 1.5 m above HW or Surge Heights above 2.0 m (Running Sums over 3 Years)

result in a rising danger for the coast of the south-eastern North Sea and especially for the estuaries including for instance Bremen and Hamburg (1).

Outlook

The detailed evaluation of field tide data of an area in front of the coast resulted in a number of new experiences and helps to improve explanations for certain proceedings. So we are enconraged to intensify the studies, starting in 1985, with

- more detailed investigations within the area of fig. 2,
- extension to the Dutch and Danish coasts and - if data is available - into the North Sea, both for the mean situation of 1975/79,
- a second evaluation of data of 1982/86 for the whole anlarged area,
- a comparison of the tide conditions in both periods to find hints about possible changes.

References

(1) Rohde H., 1984. New Aspects Concerning the Increase of Sea Level on the German North Sea Coast. Proc., 19th ICCE, Houston, Tx. 1984

(2) Siefert W., 1982. Bemerkenswerte Veränderungen der Wasserstände in den deutschen Tideflüssen. Die Küste, Vol. 37

(3) Siefert W., Lassen H., 1985. Gesamtdarstellung der Wasserstandsverhältnisse im Küstenvorfeld der Deutschen Bucht nach neuen Pegelauswertungen. In preparation for Die Küste. Vol. 42