Wave Energy Distribution in an Estuary

by

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Abstract

A field investigation program on waves in the Weser Estuary, German Bight of the North Sea,was started to learn about the complex wave climate in this region. The comparison of results in the various locations shows that most of the wave energy is transferred from deep water across the reef region to the wadden area. The comparison of spectra in the different sites and the parametrization of these multi-peak-spectra gives another feasibility to describe estuarine waves.

Introduction

Waves coming from deep water and entering an estuary generate a very complex wave climate.
In addition to the influence of wind and shoaling water (refraction, diffraction etc.) nonlinear wave-to-wave-interactions occur.
Therefore it is very difficult to find a reasonable prediction method as a basis for the design of all structures and for shipping purposes in the region in question. A field investigation which for economical reasons has to be restricted to a few locations in a strongly divided area of an estuary normally can only give a limited view. But with a sophisticated choice of the sites the comparison of the results can give valuable references of the behaviour of waves in this area.

In 1976 a field investigation program on waves was started in the Weser Estuary (German Bight of the North Sea) (Fig. 1).

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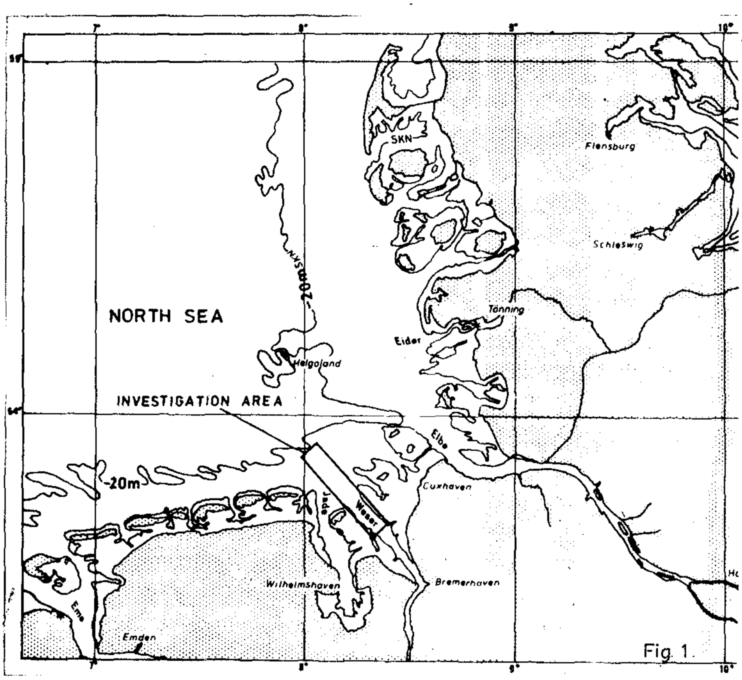


Fig. 1.

The measurements were carried out by the German Federal Waterways Administration which is part of the Federal Ministry of Transportation. They were supported by the German Coastal Engineering Board (KFKI).

Fig. 2 gives a better view of the investigation area with the single sites. The location ST lies at a water depth of about 20 m below MLW and is to registrate the waves coming from the open sea. RSW lies on the edge of the deep shipping channel "Neue Weser".

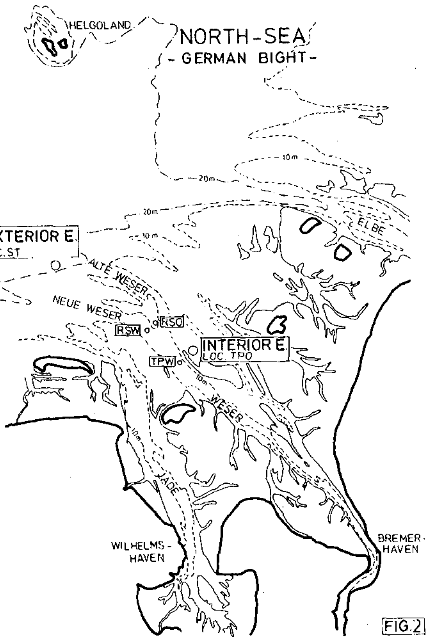


FIG.2

The water depth is 10 m below MLW. RSO lies behind the bar "Roter Grund", where the water depth is 7 - 8 m below MLW.
Finally the location TPW on the edge of the shipping channel is to record the change in wave height and period in the interior estuary in front of the wadden area. On most of these locations waverider buoys were installed, the radio-signals of which were received and recorded on a light-house in the near-by wadden area.

Though a lot of records with nearly all winddirections and - velocities could be gathered the following analysis was only worked out for a series of records with strong winds from WNW during a minor storm surge. Previous measurements had shown that already slight changes in wind-direction in this area very promptly exercise an influence on wave parameters.
Three of the main ideas of this program were:

a) to find a reasonable site for a permanent measuring station, which could lead to predictions for the whole estuary,

b) to find out wether long waves could penetrate the estuary causing a possible danger for deep-drawing ships

c) to express multi-peak-spectra by parameters, which can be correlated with different influence factors.

Loss of Wave Height or Energy on the Reef

Fig. 3 shows the significant wave height H_s (H1/3) versus the wind-velocity as an example for the location RSW. The distinctions between ebb - or flood - currents were not regarded in this case.
The results of a lot of measurements as far as this correlation is concerned made it possible to complete the plot of the variations of

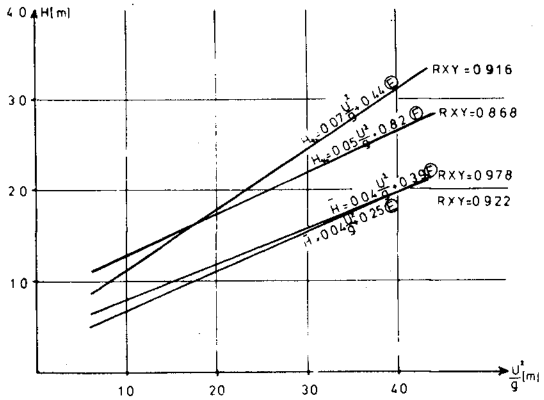
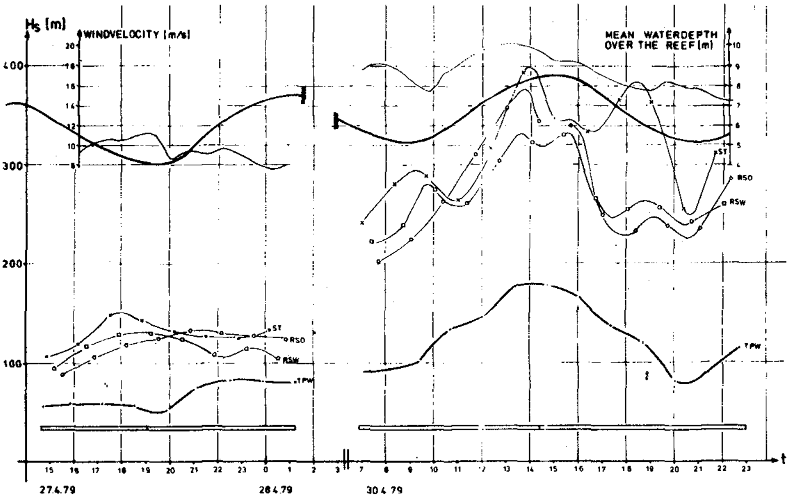


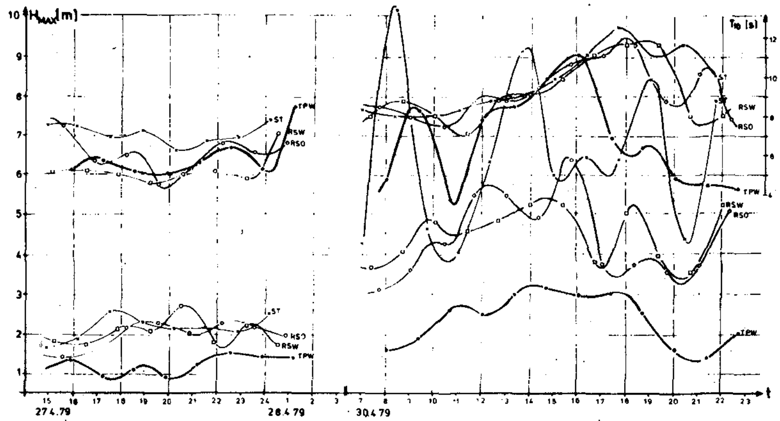
Fig. 3 H_s versus $\frac{u^2}{g}$ (m) - Loc. RSW; WIND SW - NNW

wave heights and periods on all locations though the technical equipment allowed a 20 - minutes - record every 80 minutes only. Fig. 4 shows the variations of wave parameters of 4 locations on April 27th and 30th, 1979. While in the left part only minor wind-velocities occur they rise up to 20 m/s on April 30th. In accordance with this and the mean waterdepth over the reef between RSO and ST the significant and maximum wave height H_s and H_{max} and the peak-period T_{fo} react.
The first task was to find interdependencies between the wave parameters of the different regions of the estuary. In this study the significant wave height H_s was looked at in detail. The waves coming from the open sea and entering the estuary at location ST are hardly affected by the sea bottom if they aren't too high under severe storm conditions.



VARIATIONS OF WAVE HEIGHT H_S, WIND AND TIDE

FIG.: 4



VARIATIONS OF WAVE HEIGHT H_{MAX} AND PEAK PERIOD FIG. 4

First influences are to be expected in the reef region and were to be recorded at the locations RSW and RSO. We expected to find a considerable loss of wave-energy and therefore wave - height in the reef region.

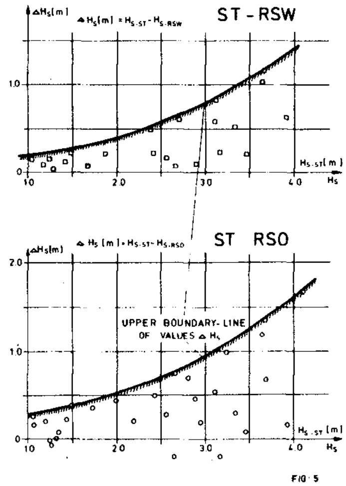


Fig. 5: ΔH_s versus H_s

Fig. 5 shows the difference of the significant wave height ΔH_s between ST and RSW respectively ST and RSO as a function of H_s at ST. With no reference to the water depth on the reef this is an accumulation of single points,which can be delimited by curves. These boundary lines weren't transgressed after the evaluation of a lot of additional records with the same wind-direction either. Though the slope of the curve ST - RSO is a little bit steeper the difference between RSW and RSO is smaller than expected.
Regarding the further course of waves into the inner estuary we found out a fairly good dependency between RSW resp. TPW.

Fig. 6 shows that the damping of wave height resp. the loss of wave energy between RSW and TPW decreases with increasing H_s at RSW.

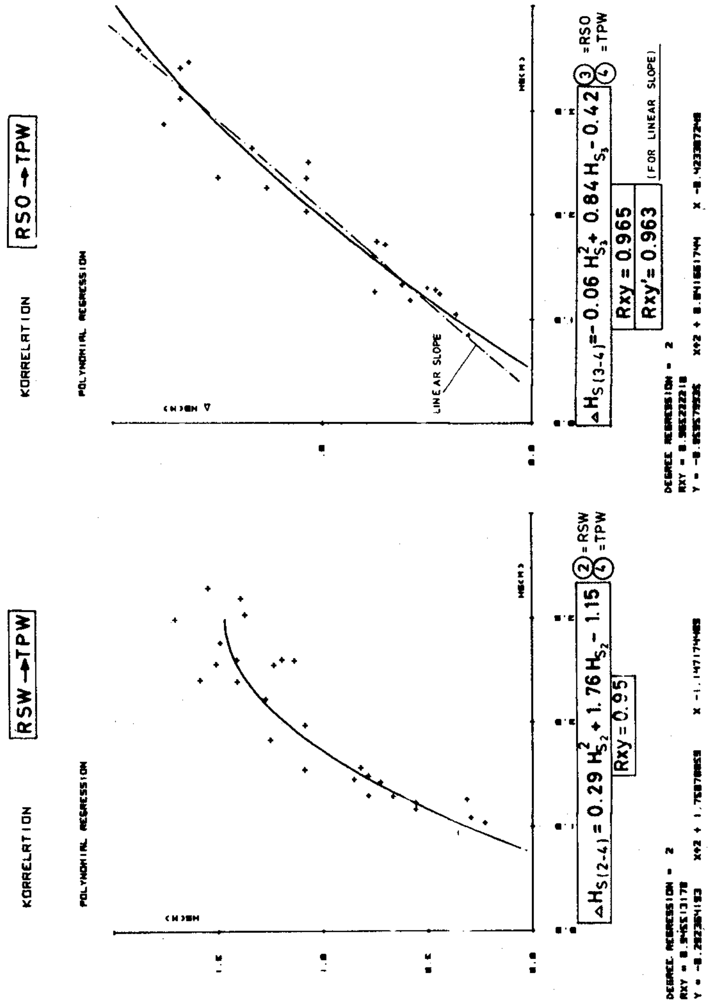


Fig. 6: Damping of wave height RSW - TPW and RSO - TPW

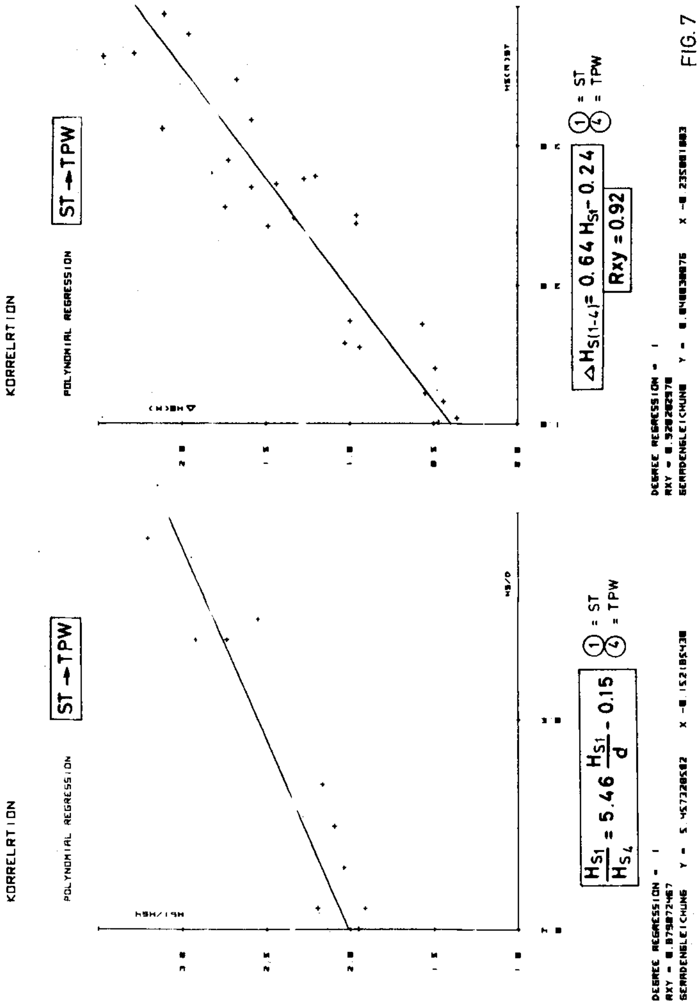

KORRELATION
POLYNOMIAL REGRESSION
ST → TPW
$\Delta H_{S(1-4)} = 0.64\, H_{St} - 0.24$
Rxy = 0.92
① = ST
④ = TPW
$\frac{H_{S1}}{H_{S4}} = 5.46\, \frac{H_{S1}}{d} - 0.15$
DEGREE REGRESSION = 1

FIG. 7

That seems to be an indication for the direct connection between both locations in the deep channel, which becomes better with increasing wave height. That is not so evident with RSO and TPW where the slope is nearly linear.
A certain correlation with the inclusion of the waterdepth over the reef resp. the water level in this area was only to be found between ST and TPW directly.* The scattering of values may be due to the oscillating tide currents, the influence of which is to be recognized at TPW predominantly. Tidal currents in this region can have a velocity up to 2.o m/s. The following table gives a view of some of the results of the measurements:

Table of significant wave height H_s and water depth d over the reef

1 ST	2 RSW	3 RSO	4 TPW	Depth d
2.42	2.20	1.92	0.90	5.75
2.81	2.31	2.12	0.95	5.20
2.89	2.80	2.43	1.12	5.30
2.65	2.57	2.84	1.37	6.40
3.17	2.92	3.38	1.54	7.40
3.94	3.31	3.77	1.80	8.30
3.80	3.20	3.41	1.79	8.50
3.47	3.27	3.39	1.76	8.60
3.35	2.80	3.00	1.51	8.10
3.66	2.49	2.29	1.32	6.80
3.64	2.62	2.47	1.12	5.90
2.56	2.40	2.27	0.78	5.30
3.12	2.55	2.59	0.96	5.30

H_s and d in (m)

<u>Results of the correlation:</u>

$$\frac{Hs1}{Hs2} = 1.07 \frac{Hs}{d} + 0.66 \quad (Rxy = 0.59)$$

$$\frac{Hs1}{Hs3} = 2.17 \frac{Hs}{d} + 0.17 \quad (Rxy = 0.69)$$

$$\frac{Hs1}{Hs4} = 5.45 \frac{Hs1}{d} - 0.15 \quad (Rxy = 0.88)$$

*Fig. 7

The three equations at the bottom of the table show once more that there is a poor correlation between ST, RSW and RSO - in other words: water depth over the reef or the reef itself doesn't play an important part for the decrease of height or energy.
To summarize the results of the investigations concerning loss of energy resp. damping of wave height Fig. 8 shows the mean proportional

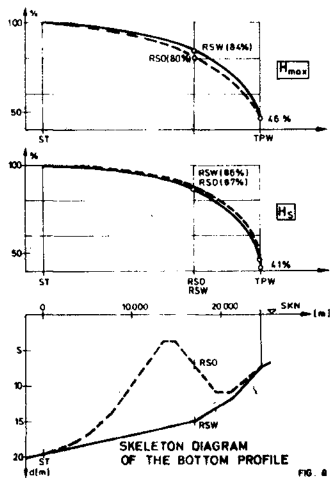


Fig. 8: Mean proportional decrease of wave height H_s and H_{max}

decrease of wave height H_s and H_{max}. It is shown that waves having travelled across the reef or via the deep channel still have 86 -87% of the original height. Only when having arrived at TPW there was another decrease of 38 - 45 %. (The lower part of the graph shows a skeleton diagram of the bottom profiles in the different routes.) This means that the maximum part of wave energy isn't lost in the reef region, as one could have expected especially for higher waves. More than 40 % are lost on the way between the reef region and the wadden area. That is an important conclusion for planning and design of all structures.

Discussion of Spectra

Normally the records were evaluated statistically and with the Fast-Fourier-Transformation of COOLEY and TUKEY a power spectrum was calculated. The comparison of a series of plotted energy spectra in Fig. 9, 10 and 11 gives an indication of the alteration of waves more obviously:

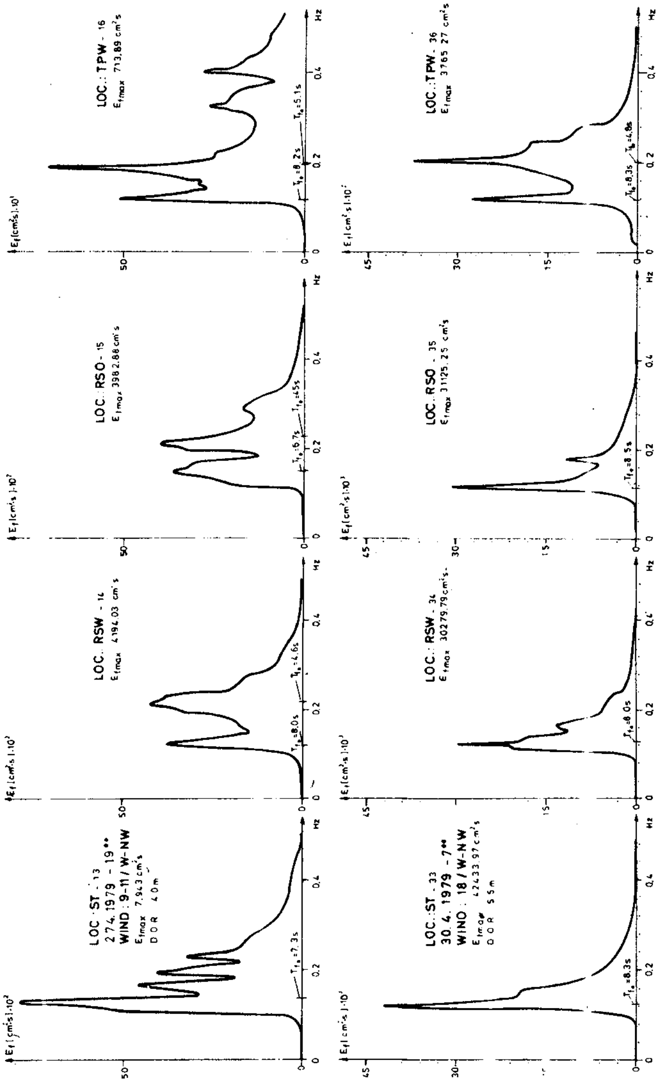


Fig. 9: Energy spectra in the Weser Estuary

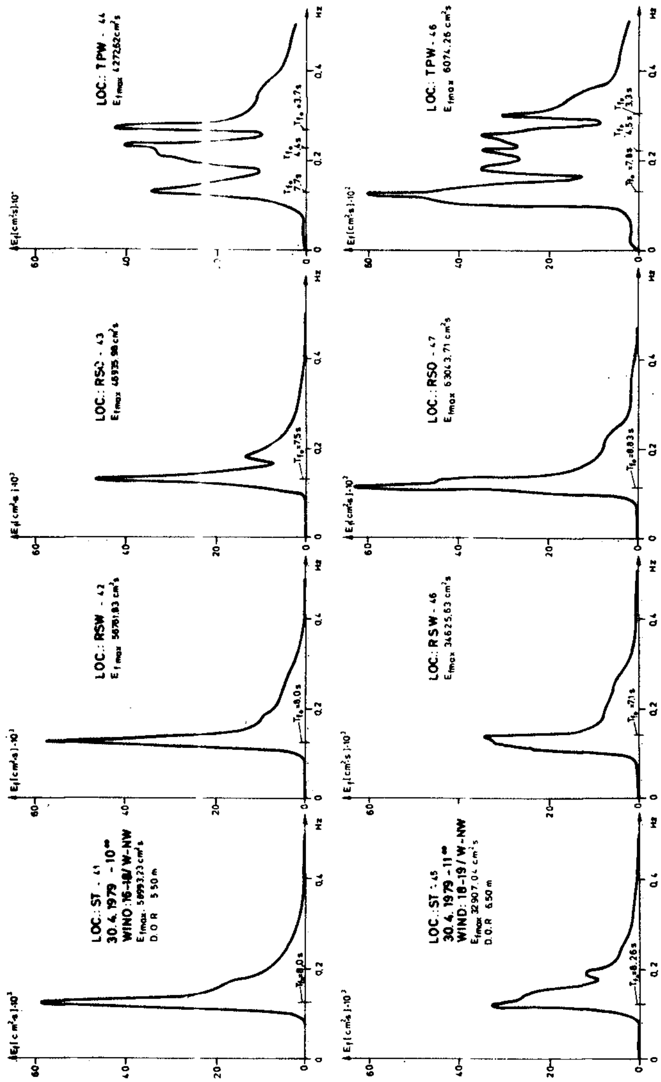


Fig. 10: Energy spectra in the Weser Estuary

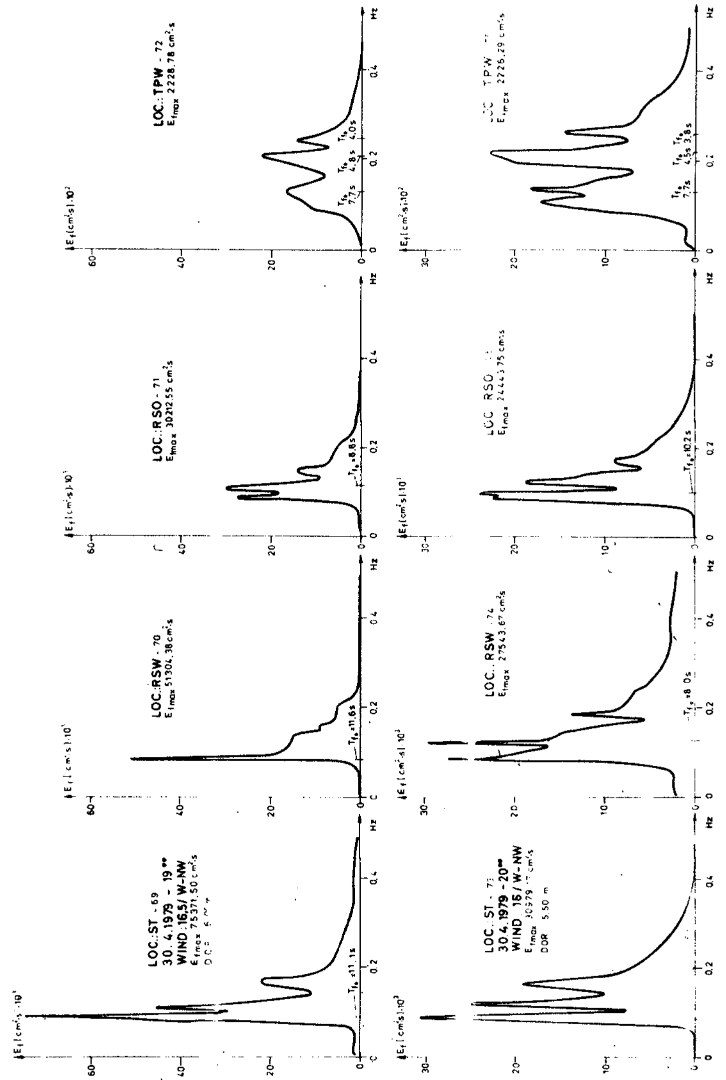


Fig. 11: Energy spectra in the Weser Estuary

Fig. 9: On loc. ST the spectrum shows energy shares of higher frequencies with a peak at 7.3 s. With low wind-velocities a max. height of 2.5 m arises. Waves with longer periods penetrate the estuary and are to be found with a small increase of the peak-period T_{fo}. The spectral shape varies strongly and shows the presence of more than one wave system. The spectra of April 30th, 7.oo, show a normal shape at ST and energy shares of the locally arisen sea at RSW and RSO. At TPW the maximum of energy density lies in the region of higher frequencies, but the penetrating long-period-waves with T_{fo} = 8.3 s can be recognized clearly.

Fig. 10 shows two additional series of energy spectra with higher wind-velocities, still increasing. This time one can see a typical spectral shape at loc. TPW. This - as we called it - 3-peak-spectrum shows the complexity and variety of waves in an estuary.
This shape could be detected again and again at this location.
Among others it points out that waves with longer periods penetrate the estuary without remarkable alteration of period or length.
This is important knowledge for ships with only a small underkeel-clearance, which enter the narrow channels of an estuary.
The two additional systems at this location can be explained by locally arisen sea and reflexion or refraction.

Fig. 11 shows another two series of energy spectra with decreasing wind-velocity and the 3-peak-shape at loc. TPW again. There is a lot of additional information in this graph, which can be extracted either by further discussion or computer analysis.
Though the frequencies of the long-period-waves don't change very much while penetrating the estuary the energy contents within certain frequency ranges can shift.

Fig. 12 shows the proportional shares of the spectral energy $m_o = \int E(f)df$ for three frequency ranges. The situation is presented for a) minor wind-velocity (increasing), b) high wind velocity (still increasing) and c) high wind-velocity (decreasing). It can be recognized that with minor wind velocities the spectral energy is concentrated within the frequencies o,1 - o,25 $^1/s$ with a drecreasing tendency into the inner estuary. Increasing wind-velocities generate longer waves with an increasing share into the inner estuary. With decreasing high wind-velocities this development has a downward movement with a high percentage of waves with periods 4 - 10 s in the interior estuary.

Parametrization of Spectra in Estuaries

The above mentioned analysis or discussion is very largescale as far as the evaluation of energy-shares and the description of spectral shape is concerned. But there is of course a possibility to have that done by a computer. To express the alteration of energy spectra or to describe them in a simple way we have the possibility of parametrization.

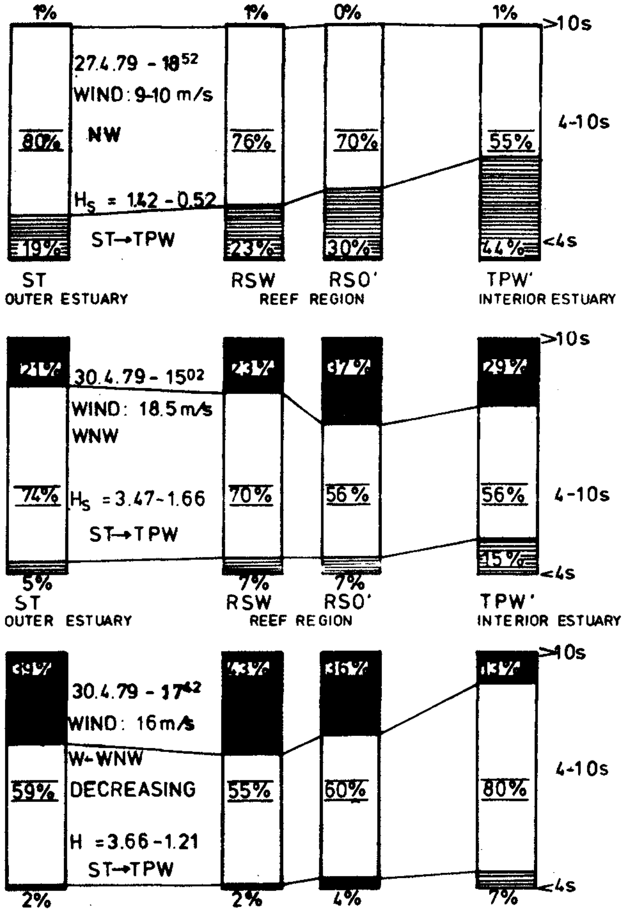


Fig. 12: Proportional energy shares for three frequency ranges.

Examples for that are given by the BRETSCHNEIDER-Spectrum, the PIERSON-MOSKOWITZ-Spectrum or the JONSWAP-Spectrum, which is expressed by the equation:

$$S_{(f)} = \alpha g^2 (2\pi)^{-4} \cdot f^{-5} \cdot \exp\left(-\frac{5}{4}\left(\frac{f}{f_o}\right)^{-4}\right) \gamma^{\exp \frac{-(f-f_o)^2}{2\sigma^2 f_o^2}}$$

Several attempts to express an estuary-spectrum in the JONSWAP-form were very unsuccessful because there was no possibility to register more than one peak. So we tried to divide a two-peak-spectrum into two parts, to approximate the measured (Hamming-smoothed) partial spectra to the JONSWAP-form and to superpose them again. One gets a 10-parameter-spectrum then:

$f_{K\,(p)}$ = SPECTRAL FUNKTION

$S_{(f)p}$ = PARAMETRIZED SPECTRUM

$S_{(f)H}$ = "HAMMING" - SMOOTHED SPECTRUM

$f_{K(p)}$ = $S_{(f)p} - S_{(f)H}$ → CONSTRAINT MINIMUM SEARCH

MIN. $\sum (f_{K(p)})^2$

↓

MIN. $\sum f_K(p+\Delta p)$

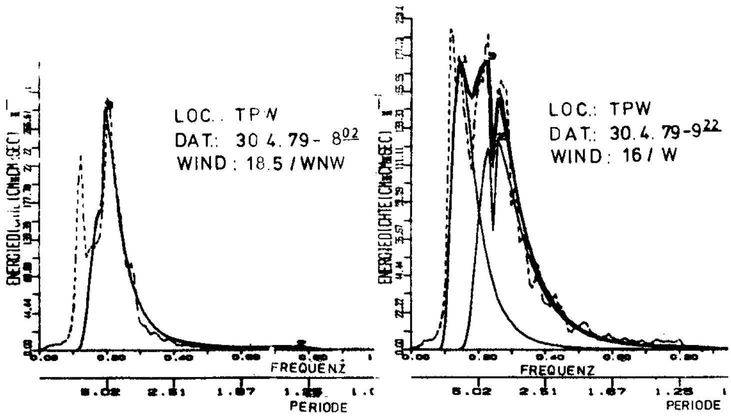
↓

TWO - PEAK - SPECTRUM

$$S_{(f)} = S_1(f_{01}; \alpha_1; \gamma_1; \sigma_{ab\,1}) + S_2(f_{02}; \alpha_2; \gamma_2; \sigma_{ab\,2})$$

Fig. 13 shows the results of a first attempt for three spectra.

1. APPROXIMATION - 10 PARAMETER-SPEKTRA



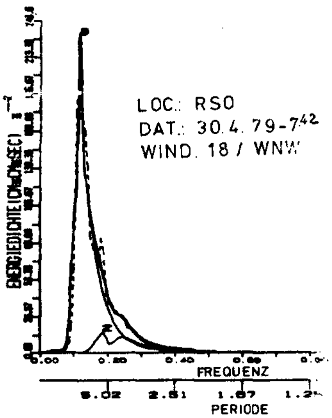
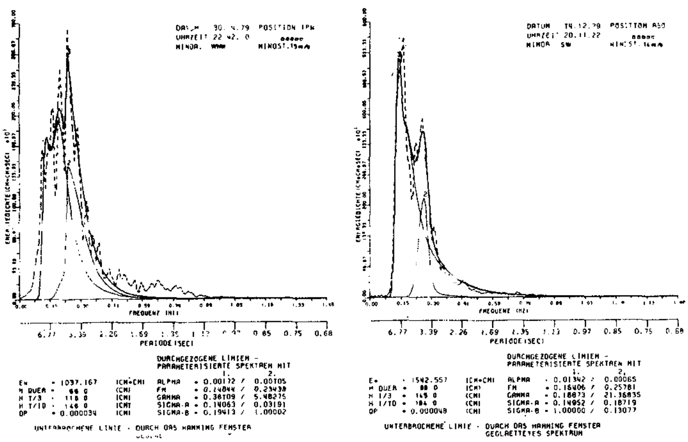


Fig. 13:
First Approximation-10-Parameter-Spectra

But this solution wasn't sufficient yet because of the shifting of the peak-frequencies f_{01} and f_{02} during the calculation resp. the approximation process.
Because of the inadequacies we defined the peak frequencies and gave them a fixed value after looking at the Hamming-smoothed spectrum. So we got a spectrum with 8 parameters which can describe a two-peak-spectrum in a sufficient way.

Fig. 14 shows 3 examples with a fairly good correspondence between measured and calculated spectra.



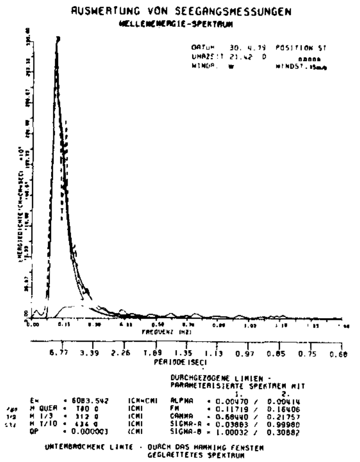


Fig. 14:
8-Parameter-Spectra in the Weser-Estuary
(the continuous line shows the superposed spectrum whereas the dotted line gives the measured (Hamming-smoothed) spectrum)

It is possible either to combine JONSWAP- and PM-Spectra in case of the parameter $\gamma < 1$ or to superpose more than two partial spectra if necessary.

Conclusions

The evaluation of a lot of wave records in the Weser Estuary gives a basis for a sufficient prediction system. With a permanent reference location it would be possible to predict wave heights and periods for the various regions of the estuary. The comparison of the height of waves in the exterior and interior estuary and the energy loss on the way prove that there is hardly any shelter by the submerged bars in the reef region so that the high waves can get to the wadden area. This fact has to be taken into account for nautical purposes too.
The wave-energy loss together with the tidal currents in this region cause a high amount of sand transport. Fig. 16 gives an idea of the morphological changes in the area of TPW and TPO. The erosion rate within one year per km^2 is 260.000 m^3 resp. 120.000 m^3 (Fig. 16).

The parametrization of estuary-wave-spectra has to be developed and tested for another series of more difficult cases. The description of a complicated multi-peak-spectrum by a couple of parameters and their correlation with the factors of influence is another step for the analysis of the complex wave climate in an estuary.

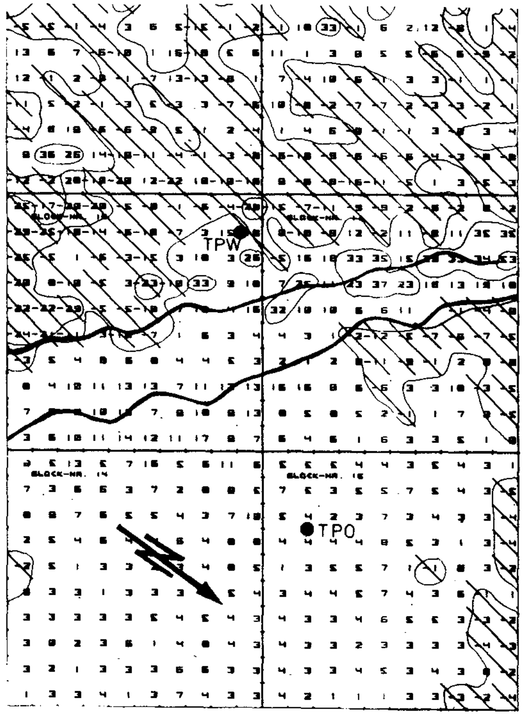


Fig. 16: Morphological changes in the Weser Estuary
+ = erosion, - = sedimentation

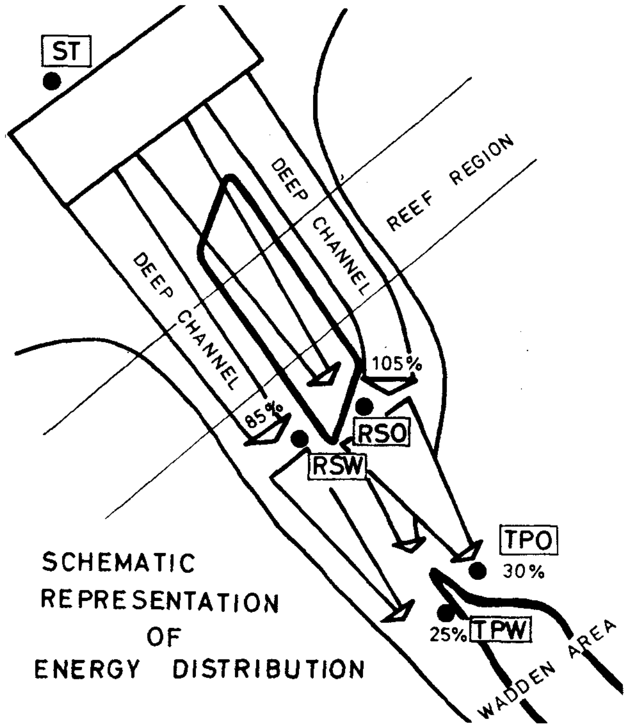


Fig. 15: Energy distribution in the Weser Estuary

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