CHAPTER SIXTY ONE

New aspects concerning the increase of sea level on the German North Sea coast

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ABSTRACT

The development of MThw on the German North Sea coast is probably related to the development of the climate. Other important contributing factors are discussed. For the last 20 years a relatively steep rise of MThw level is recognizable. An even steeper rise as a result of climate changes appears possible within the next 100 years. With regard to the great importance for coastal engineering, the necessity of attentive observation and international cooperation among different scientific disciplines is stressed.

1. INTRODUCTION

The development of the water level changes on a coast is of great importance for coastal engineering. In general the water level in the oceans and also on the coasts has risen more than 100 m since the maximum of the last ice age about 20,000 years ago, when huge masses of water were stored in large ice-covered areas. The steepest increase amounted to 2 m per century (2 cm/a) (5) (12) (18) (10). This rise was caused primarily by the melting of the ice and the subsequent increase of the water volume in the ocean. All other influences on the development of the water level changes on the coasts were negligible by comparison.

The steep rise of water level ceased about 6,000 years ago. With the flattening of the water level curve other influences on the development of water level on the coasts became evident. The development wasn't uniform. Oscillations can be found which can differ in locality as well as with time as described by many authors (12) (10) (13).

The development of the water level changes on a coast depends essentially on three superimposed effects:

1) The height of mean sea level in the ocean: Its development with time depends primarily on the general behavior of the temperature and hence on the ratio between the volume of mainland ice and the volume of sea water (development of the climate).

2) The wind conditions: They depend essentially on atmospheric pressure conditions (meteorological conditions in general) and can change with time.

3) The geographical and geological conditions of the specific coastal region. Changes of the morphology or the topography - natural as

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well as man-made - can produce a change in the development of water level. Tectonical changes of the sea-bottom and of the coast may also contribute to the water level changes.

These three factors are interdependent. A worldwide change of temperature can cause changes in the atmospheric circulation which affect the abundance and the paths of low-pressure systems. Changes of the wind-field and of the wind set up on the coast can be the consequence. A changing angle of attack of the sea against the coast can cause changes of the coastal configuration.

2. DEVELOPMENT OF WATER LEVEL FOR THE LAST 2,000 YEARS ON THE GERMAN NORTH SEA COAST

Figure 1 depicts schematically the probable development of MThw (Mean tidal high water, MHW) on the German North Sea coast for the last 2,000 years. If the levels of MThw and MTnw (Mean tidal low water, MLW) change in the same direction and the shape of the tidal curve re-

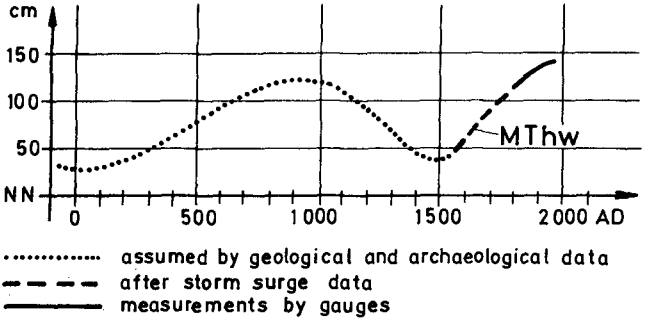


Figure1. Probable behavior of MThw on the German North Sea coast for the last 2,000 years (schematic)

mains constant, the development of MThw will be in accordance with the development of the "Mean Sea Level". But in most cases the shape of the tidal curves were affected by changes of the meteorological, topographical and morphological conditions. The influences of these factors are different on the levels of MThw and MTnw.

The curve of Figure 1 consists of three sections:

1) The period till the middle of the 16th century (dotted line): The data arise from geological and archaeological investigations. They are relatively uncertain in their magnitude and temporal classification. The topographical conditions of the coast are of great importance and are not exactly known for this period.

2) The period from the middle of the 16th century until the end of the 18th century (dashed line): There are already data of water levels on the German North Sea coast, namely of the height of severe and very severe storm surges. Figure 2 shows some sites on the German North Sea coast for which these data are known.

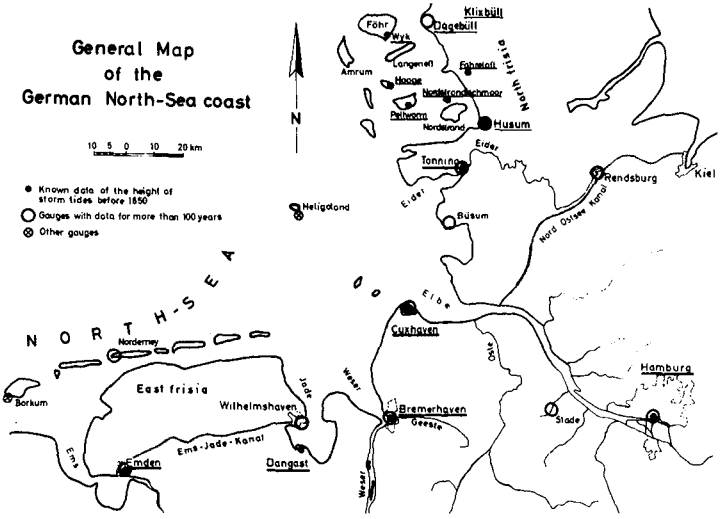


Figure 2: General map of the German North Sea coast with the sites of gauges and storm surge data

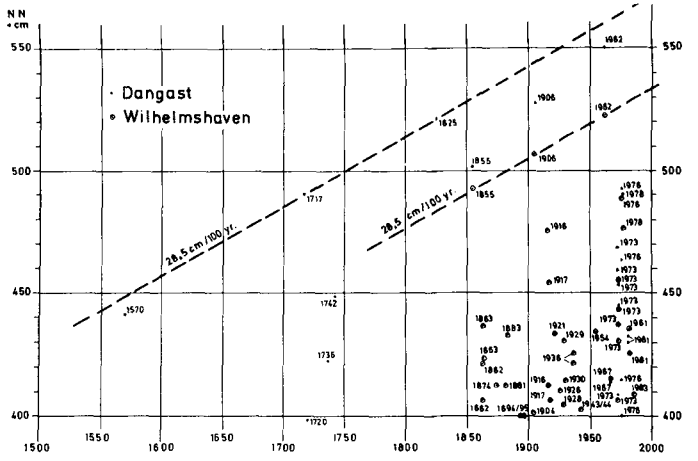


Figure 3: Maximum flood levels at Dangast and Wilhelmshaven since 1570 (15)

Figure 3 depicts the development of the maximum flood levels for one of these sites (Dangast/Wilhelmshaven) since 1570. One can recognize that the limiting line of the peaks of the highest storm surges rises 28.5 cm per century. A similar increase between 20 and 30 cm per century can be found at the other investigated sites (15) (16). Because the shape of the coast and the climatic conditions didn't change essentially in this

period, one may suppose that the level of the highest storm surges remains constant with respect to MThw and thus the increase of MThw also amounts to 20 - 30 cm per century i.e. an average of 25 cm per century.

3) The period from the end of the 18th century until present time (solid line): The shape of the coast and the climate have not changed fundamentally in this time. For this period records of some gauges are available (Figure 2). In the middle of the 19th century there were already as many gauges on the German North Sea coast as there are today (14). As long as gauges are not or only slightly affected by morphological changes of their environment, one can recognize an average increase of MThw of 25 cm per century. About 60 or 70 years ago the slope of the MThw curve began to decrease. The flat run of the curve is most pronounced on such gauges on which the man-made influences on the development of MThw are small (15) (16).

The graph in Figure 1 is in good agreement with the curve of temperature-development in Central England for the last 1000 years (7) (8) and a similar curve given by Benoist et al. (2) for the Antarctic. High water levels correspond to relatively high temperature, low water levels to a relatively low temperature. At the beginning of the second millenium A.D. the water level on the coast was relatively high. The height of the "Little Ice Age" was about 1600 A.D. and the water level was relatively low. This confirms assumptions that the development of water level change, shown in Figure 1, depends essentially on gradual changes of the climate (11). How much the water levels are influenced by other factors can only be determined from the careful analysis of gauge records. It was already said by (15) that the rise of MThw - see lower curve in Figure 4 - and correspondingly the rise of Mean Sea Level as well as the increase of the maximum flood levels - see upper curve in Figure 4 - depends essentially on changes of the climate. The frequency of the high

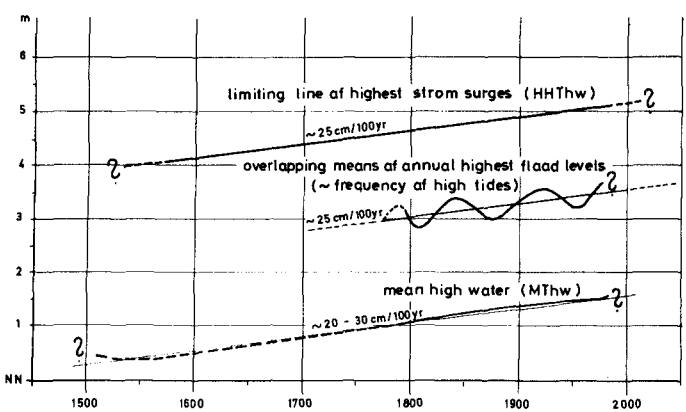


Figure 4: Development of water level on the German North Sea coast since the 16th century (15)

tides oscillates with long periods as the curve in the middle of Figure 4 shows. The oscillations depend on changes of the wind conditions and have meteorological causes (19).

3. ANALYSIS OF WATER LEVELS ON THE GERMAN NORTH SEA COAST FOR THE YEARS 1951 - 1980

For five gauges on the German North Sea coast - Borkum, Emden, Wilhelmshaven, Bremerhaven and Cuxhaven (Figure 2) - an exact analysis was made for the period from 1951 to 1980. Figure 5 shows as an example the frequency distribution of all Thw of the two years with the lowest MThw (1960) and the highest MThw (1967) at Cuxhaven. High water levels are produced by winds blowing towards the coast (from the directions north and west), low water levels by winds blowing away from the coast (from the directions south and east). In order to eliminate the influence of west winds on MThw, all Thw with a level of more than 50 cm above the arithmetical mean of all Thw for each year (MThw) were omitted. The hatched parts of the curves in Figure 5 show the omitted Thw. The number

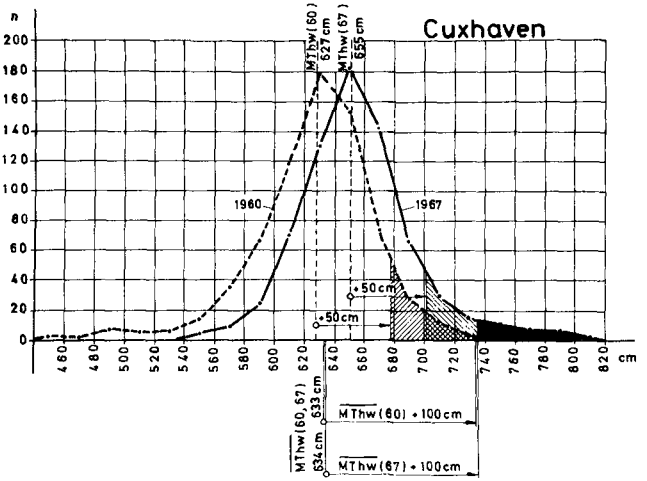


Figure 5: Frequency distribution of Thw at Cuxhaven for the years 1960 and 1967

of these high levels, caused by west winds, was much higher in 1967 than in 1960, a year with a relatively large number of low east wind tides. A new arithmetical mean was computed with the rest of the Thw for each year ($\overline{\text{MThw}}$). All Thw, influenced by onshore winds were disregarded in the computation of this new mean.

Figure 6 shows for Cuxhaven, as one example, that the differences between MThw and $\overline{\text{MThw}}$ are small. The figure also shows the 5 year overlapping means and their regression lines (A and B), determined by the method of the least squares. A clear increase of the $\overline{\text{MThw}}$ is recognizable which is only a litte less steep than the increase of MThw. The

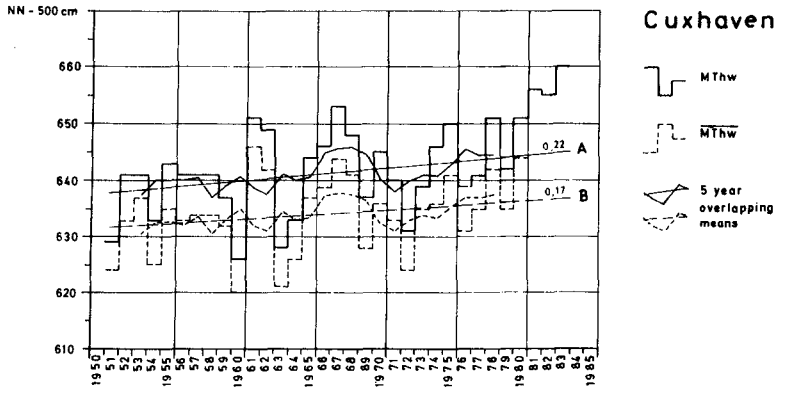


Figure 6: MThw and $\overline{\text{MThw}}$ at Cuxhaven 1951 - 1983

slopes of the regression lines of the 5 year overlapping means of MThw and $\overline{\text{MThw}}$ are collated for all 5 above mentioned gauges in the Columns 1 and 4 of Tabel 1.

	MThw	$>$ MThw + 1 m number	$>$ MThw + 1 m level	$\overline{\text{MThw}}$	$\geq \overline{\text{MThw}}$ + 1 m number	$\geq \overline{\text{MThw}}$ + 1 m level
	1	2	3	4	5	6
Borkum-Südstrand	0.23	0.12	0.37	0.20	0.18	0.27
Emden	0.23	0.18	0.42	0.20	0.17	0.59
Wilhelmshaven	0.22	0.09	0.50	0.19	0.17	0.32
Bremerhaven	0.22	0.14	0.51	0.18	0.22	0.30
Cuxhaven	0.22	0.17	0.55	0.17	0.26	0.29

Table 1: Slope "b" of the regression lines $y = a + bx$ of the 5 year overlapping means 1951 - 1980

Now all Thw with a higher level of 1 m or more above the regression lines of $\overline{\text{MThw}}$ (line B in Fig. 6) were selected. These Thw are visible in Figure 5 for the years 1960 and 1967 on the right hand side and are shaded black in the frequency distribution curve. The upper graph in Figure 7 shows the annual number of these high Thw, the 5 year overlapping means and their regression line for Cuxhaven. In comparison with the number of the Thw ≥ 1 m above $\overline{\text{MThw}}$ (line B in Fig. 6) the number of Thw > 1 m above the yearly MThw (line A in Fig. 6) is also given (dashed line in Fig. 7). The number of the last mentioned Thw is 330 for the whole period 1951 - 1980, the number of the Thw ≥ 1 m above $\overline{\text{MThw}}$ is 426. The

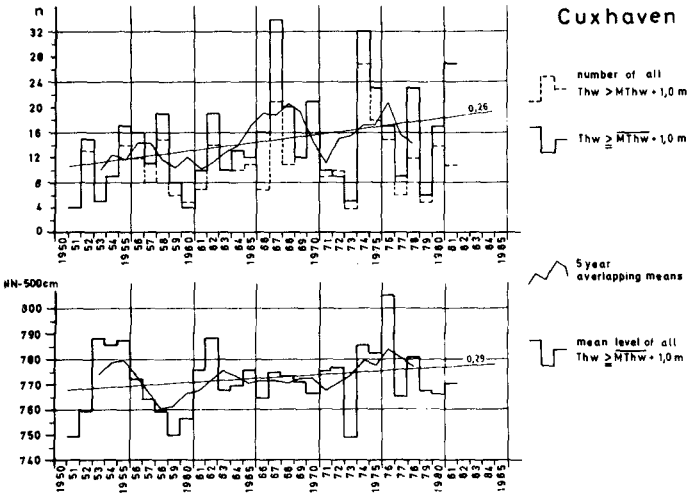


Figure 7: Thw $>$ MThw + 1 m and $\geqq$ $\overline{\text{MThw}}$ + 1 m at Cuxhaven 1951 - 1981 (number and mean level)

mean levels, which are computed from the Thw with a level of 1 m or more above $\overline{\text{MThw}}$, the 5 year overlapping means and their regression line are shown in the lower graph of Figure 7 for Cuxhaven.

The mean level of the high Thw increases as well as their number for the period 1951 - 1980. This applies also for the Thw $\geqq$1 m above line B in Figure 6 and for the Thw $>$1 m above line A in Figure 6 and has proved to be true for all 5 gauges as Table 1 shows (see Columns 2, 3, 5 and 6). The rise of the levels of the high Thw is remarkably steeper than the increase of MThw or $\overline{\text{MThw}}$, as the comparison of Column 3 with Column 1 and of Column 6 with Column 4 shows. This result doesn't change if the MThw are not computed for the hydrological year (November to October) but for the year September to August.

The comparison between the Columns 1 and 4 in Table 1 shows that the greatest part of the rise of MThw, observed on the German North Sea coast, is independent from the increase of the high Thw's which are influenced by west winds. The influence of the high tides on the rise of MThw is relatively small. Therefore it is permissible, as a first approximation, to look at the rise of the common yearly MThw for comparisons of the development of mean water level on the coast. This is important because the elimination of all tides influenced by stronger west winds has not been done for all gauges and for longer periods.

As Figure 7 shows, the number and the mean level of the high Thw is increasing. The last section of the middle curve in Figure 4 also shows this because a good correlation between the number of the high Thw in each year and the highest level of Thw in the same year exists. The factor of correlation lies between 0.61 and 0.73 for the five mentioned gauges. The middle curve in Figure 4 also gives an approximated scale

for the frequency of high tides. Periods with a high frequency of high tides always have been followed by periods with a lower frequency.

4. POSSIBLE FUTURE DEVELOPMENTS

As already mentioned above and as described in previous papers, the records of most gauges on the German North Sea coast show an average rise of 25 cm per century since the beginning of the observations. Since about 1920, the curves of the 19 year overlapping means of MThw on several gauges became less steep (15) (16). In such cases where the decrease of the slope was less strong, effects of man-made influences are probable (e.g. dredging in the estuaries or the construction of dams). It seemed to be possible that the less steep increase of the MThw-curve could turn over in a gradual decreasing curve. Because a correlation between the development of temperature and water level obviously exists, a maximum of the water level curve could come after a maximum of the temperature. Some observations of temperature pointed out such a development (7) (15) (16) (19). The decrease of the temperature and of the water level could be the beginning of a new "Little Ice Age" or even a new major ice age.

Recently a turning-point seems to be recognizable. The graphs of MThw of all gauges on the German North Sea coast rise steeper again during the last years. Figure 8 shows the curves of the 19 years overlapping means of MThw at Emden, Cuxhaven and Büsum. The figure which was published already in (15) (16) has been expanded for the years up to 1983. Moreover the time-scale has been shifted in such a way that the mean values refer to the last year of the period respectively (e.g. mean value of 1932/50 ≙ 1950). These three gauges show a very flat graph of

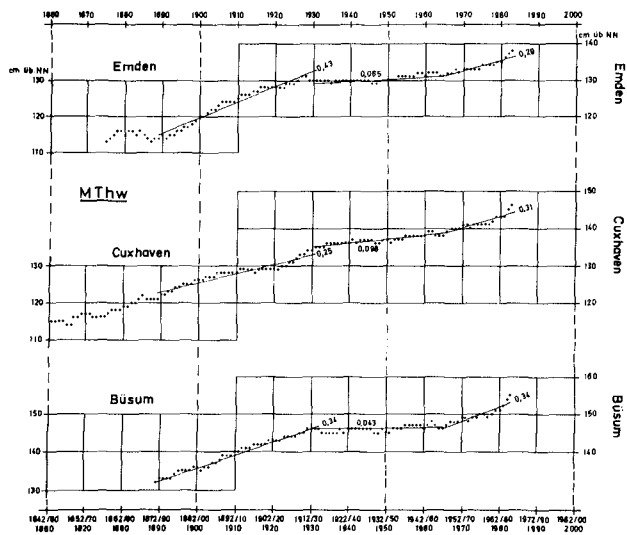


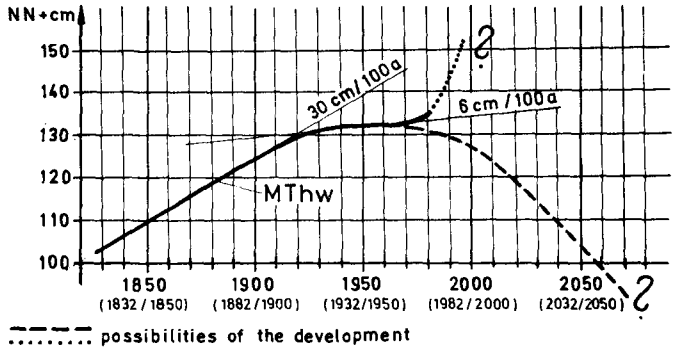
Figure 8: 19 year overlapping means of MThw at Emden, Cuxhaven and Büsum

MThw from 1920 to 1965. In the last years a steeper rise of the graphs is apparent. The slopes of the regression lines are quoted for the three periods 1871/89 - 1912/30, 1912/30 - 1947/65 and 1947/65 - 1965/83. Such a recent increase can also be observed on other gauges on the coast and in the estuaries (compare Columns 1 and 2 with Column 3 in Tabel 2).

		MThw till 1955	MThw 1873-1955	MThw 1956-1983	MTnw 1956-1983
		1	2	3	4
Emden	(1857)	0.25	0.23	0.54	-0.33
Wilhelmshaven	(1873)	0.23	0.23	0.37	-0.15
Cuxhaven	(1843)	0.25	0.24	0.51	-0.21
Büsum	(1871)	0.22	0.21	0.62	-0.25
Husum	(1870)	0.30	0.28	0.63	-0.09
Dagebüll	(1873)	0.28	0.28	0.65	-0.32

Table 2: Slope "b" of the regression lines y = a + bx of MThw in 3 different periods and of MTnw in the last period

Figure 9 gives a schematic curve of MThw generated by the graphs in Figure 8. The dashed line shows the development which seemed to be possible on the basis of the less steep graph of water level after 1920. On the basis of the new steeper rise one cannot exclude a development described by the dotted line. In the opinion of some climatologists an increase of the mean temperature of the atmosphere by 4° C during the next 50 or 100 years could be possible as a result of air pollution,



Figur 9: Schematic graph of MThw on the German North Sea coast since the middle of the 19th century and possible future developments

increase of carbon dioxide concentration etc. Such an increase of temperature would cause a change of the ice conditions in the polar regions. A rise of the sea level by some meters could be the consequence (1) (3) (4) (9).

There is no exact proof to date that the steeper rise of MThw, observed on the gauges on the German North Sea coast, is already the result of the beginning of a general increase of temperature. But such a development cannot be excluded. On the other hand a more or less decrease of MTnw has been observed on most gauges on the German North Sea coast (see Column 4 in Table 2), that means an increase of the mean tidal range (MThb). If the rise of MThw had climatic causes, a simultaneous rise of MTnw would be probable. Therefore it is possible that the increase of MThb - rise of MThw and a simultaneous decrease of MTnw - has oceanographic causes. Investigations of Siefert (20) provide some hints of generally changing tidal conditions in the North Sea. But such a change can also be the consequence of the rising sea level. Investigations about this problem by means of a numerical model have been started already.

5. CONCLUSIONS

The knowledge of the probable development of the water level on the German North Sea coast - in general on all flat coasts - is of greatest importance for coastal engineering. In Germany an increase of MThw of 25 cm per century has been taken as a basis for dimensioning of coastal protection constructions (e.g. dykes or storm surge barrages) (6). If instead one had to reckon with a rise of MThw of 2 m or more in the next 100 years and with at least the same increase of the storm surge levels, all coastal protection works would be ineffective. It is doubtful that an elevation of the dykes for such a water level rise would be possible everywhere. As one can conclude from the development of MThw at all locations on the German North Sea coast for the last 400 years in connection with the development of temperature in Central England (7) (8), an increase of 2 m or more would be thinkable in the case of an increase of the temperature of about 4° C. The increase of temperature is assumed to be 1° C since the culminating-point of the "Little Ice Age". In the same period MThw rose about 1 m (Fig. 1). Some scientists even speak of a possible rise of mean sea level of 5 or 6 m during the next 100 years (3) (4).

Therefore it is necessary to intensify investigations in order to predict the probable development of the global sea level as well as that of certain coastal sections for the next 100 years as exactly as possible. Three routes of research are deemed necessary:

1) One has to analyse all the factors responsible for the development of water level in the ocean and on the coasts as exactly as possible. This demands an extensive and close co-operation of the different scientific disciplines of climatology, meteorology, oceanology, glaciology, geodesy and coastal engineering. This co-operation has to be international. Coastal engineers should contact such projects as the International Climate Research Program and the Project No. 200 of the International Geological Correlation Program "Sea-Level Correlation and Applications". The results of these projects are of greatest practical importance for coastal engineering.

2) One has to analyse all records of gauges on the coasts or near the coasts as far back in time as possible. The aim must be to discover relationships between the development of water level and other factors, e.g. climate and wind set up. Such relationships can be of importance for the estimation of the water level behavior in the future. In the Federal Republic of Germany the records of many gauges are available. They go back up to 180 years. But only the youngest data are available for an analysis with automatic data processing (ADP). We started to convert, at least for the most important gauges, the older data - all daily Thw and Tnw level and time - to automatic data carriers. This requires careful examinations of the data. The older the data are, the more difficult become these examinations. Such investigations should also be done by all countries which possess gauge-records for long time periods.

3) One should try to erect new gauges at a greater distance away from the coast in order to receive water level records which are free from coastal influences. Also Ausubel (1) suggests an expansion of the present global tide gauge network. The new gauges have to have firm foundations: any vertical movement of the stations should be impossible. The water levels have to be recorded exactly for some decades. The German Coastal Engineering Board (KFKI), in which the federal authorities and the authorities of the German States work together, plans the construction of three such gauges in the North Sea (17). Figure 10 shows the sites of these gauges. They are situated at a distance of 25 to 35 km from the German North Sea coast in a water depth between 15 and 25 m below chart datum. The geo-

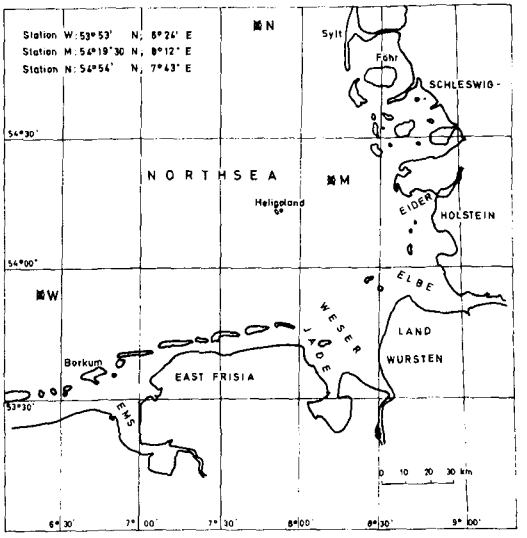


Figure 10: Sites of the three planned gauge-stations in front of the German North Sea coast

logical and morphological parameters are such that firm foundations are possible and movements are very unlikely. Gauge devices are planned which will stand on the sea-bottom and be fixed onto piles which are driven 10 or 20 m into the sea-bed. The devices work on the pressure transducer principle. The costs for the construction of the stations are not very high compared to the management and maintenance costs for several decades. The problem of an exact reference of the gauge-records to the altitude datum of the mainland is still unsolved. At first one can dispense with this reference. The gauge-stations are also of importance for other branches of research and practical tasks, e.g. for an exact surveying of the depths of the off-shore region and for storm surge research. The final design of the stations has not been completet. We hope to obtain the necessary financial support shortly so that the gauges may be operational by 1986 or 1987.

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