CHAPTER 126

REPRODUCTION OF PHYSICAL PROCESSES IN COASTAL AREAS

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Summary

Physical processes in the ocean, adjacent and marginal seas are mainly of special interest for oceanography and related sciences, whilst the knowledge and the understanding of these processes in coastal areas, estuaries and tidal rivers is also of significant practical importance for coastal engineers. Just measurements and observations are not sufficient to obtain a comprehensive insight into these processes and to explain and to understand the spatial and temporal states and their variations. Hydrodynamical-numerical investigations are delivering a considerable assistance.

Within this paper my remarks will be restricted to some examples of the numerical reproduction of physical processes in shallow - water areas:

1) Dynamics depending on tides and wind;
2) Horizontal dispersion of suspended matter.

In concluding this paper I shall mention a special coastal model with a permanent refined grid-net, which is a part of the well - known North Sea model.

Using the vertically integrated hydrodynamic equations

$$u_t + \frac{ru\sqrt{u^2+v^2}}{h+\zeta} - fv + uu_x + vu_y + g\zeta_x = 0$$

$$v_t + \frac{rv\sqrt{u^2+v^2}}{h+\zeta} + fu + vv_y + uv_x + g\zeta_y = 0$$

$$\zeta_t + ((h+\zeta)u)_x + ((h+\zeta)v)_y = 0$$

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where x,y space-coordinates
t time-coordinate
$h+\zeta$ actual waterdepth
f Coriolis parameter
g acceleration of gravity
r constant friction coeffdcient
u,v components of the mean velocity

transformed into difference equations, hydrodynamical models have been applied in previous years to describe physical processes in the ocean as well as in coastal regions. For the numerical treatment of hydrodynamical equations the natural conditions, such as depth distribution, boundary values and - as far as these are effective - meteorological data and density distribution have been considered. In many cases the quantitative reproduction of tides and storm-surges has been successful and good agreement between measured and computed values was obtained. Regarding the metbod I will not go into the details, see special publications by Hansen. The results of numerical investigations can suggest, in which areas or at whieh places measurements are necessary or of special interest. One must however verify the results of tbese numerical studies against observations, because there is no other possibility of testing them. Analytical solutions exist only in simple cases.

The motion in shallow areas, tidal estuaries and mud flats is very complicated. The tidal curves are particularly non-harmonic. The depth distribution and the nonlinear interaction at the bottom and at the surface are of great influence on motion processes. Sands, flats and coastal areas fall dry for a limited time during a tidal period depending on its height.

When considering the actual water-depth in the equation of continuity and the quadratic friction term, which depends directly on the velocity and the water-depth, the differential equations become nonlinear. These nonlinear terms in the vertically integrated equation of continuity can be included in the numerical treatment. This seems to be very significant in order to reproduce motion processes in shallow-water areas, in which these terms are very essential, considering that tbe tidal range and the depth can be of the same order.

These nonlinearities are responsible for the non-harmonic behaviour of the tidal curves. A particular advantage of the numerieal approach is that a reasonable simulation of the bottom topography and coastal boundaries may be included in the model. It is only a question of grid-distance and expense of time on computers, if the bottom topography and the coast shall be approximated with high accuracy.

In order to prove the application of hydrodynamical-numerical models on extreme shallow-water areas, we have the problem that motion processes including the overflow of flats and drying banks should be reproduced. It is necessary to distinguish all possible cases. From time to time it may occur that there will be no water at some grid-points. One has to check the neighbourhood of each grid-point from time-step to time-step with regard to the actual water-depth, the depth-distribution and the physical possibility of transports and directions of transports. These and the former mentioned distinctions of several cases are formulated as a system of numerous questions for the computer. It is now necessary to prove the accuracy. Therefore, this numerical method was applied to some models, which permitted a comparison between analytical and numerical results. If the agreement of both of these results in the stationary state is sufficient, it may be assumed that the numerical treatment of the differential equations from the beginning of the computations until the stationary state approximates also the unknown nonstationary results.

A closed rectangular basin with a dimension of 36 km x 48 km was covered with a net-work of equal distances. In several models with constant depth of 0.5 m, 0.4 m and so on until 0.1 m a homogeneous constant wind-velocity of 5 m/sec, 10 m/sec and 20 m/sec in x-direction was applied. In the stationary state the transport disappears, and it follows that the vertically integrated velocities become zero.

Fig. 1 shows the slope of the sea-surface under the action of a homogeneous constant wind and a comparison between the analytical solution and the hydrodynamical-numerical treatment. The straight line L_0 is the distance without water along the bottom. The agreement in this point of the comparison is remarkable and important for further investigations.

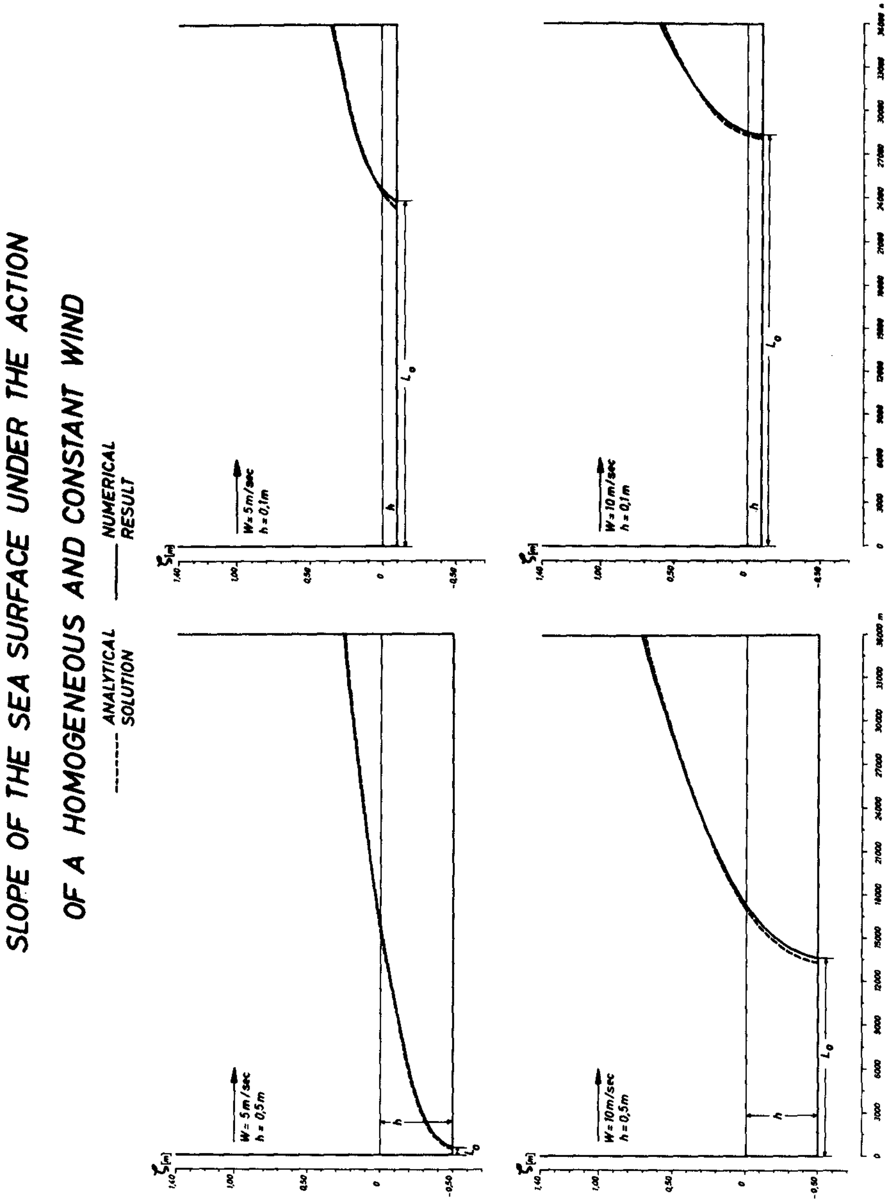

SLOPE OF THE SEA SURFACE UNDER THE ACTION
OF A HOMOGENEOUS AND CONSTANT WIND
ANALYTICAL SOLUTION
NUMERICAL RESULT
W = 5 m/sec
h = 0,1 m
W = 10 m/sec
h = 0,1 m
W = 5 m/sec
h = 0,5 m
W = 10 m/sec
h = 0,5 m
L_0
h

Fig. 1

After this theoretical example we can go to the next step and prove this method in a complicated natural model.

Fig. 2 shows a plan view of the outer Elbe with bottom topography and computational grid. A part of the "Neuwerker Watt" including the Isle of Scharhörn near the estuary of the Elbe River was covered with a rectangular net-work with a mesh-distance of 670 m. The water-levels determined by seven gauges around this area for the tidal periods from the 29th September until the 3rd October in 1967 were used as boundary condition. The figure also shows the water-level gauges and the boundary points. The depth-distribution of this region is very complicated and varies from NN - 16 m near the boundary to NN + 3.5 m in the inner part of this area. The observed water-level in the interior points A, B and C is known but not given in the computation.

In fig. 3 a comparison between computed and observed time variation of water-level in these three interior points is represented. The differences are less than ± 8 cm. The agreement during the period of extreme shallow-water is a remarkable result of this computation.

With respect to river tides hydraulic engineers applied the continuity equation to compute average velocities in cross-sections of the river from gauge records and measurements of fresh-water inflow from the upper river. The geometry of the river must be known. This method of cubature was applied to the Elbe River by Klein and others. This method represents the only possibility for the verification of numerically determined mean velocities. One example of the comparison for the interior points A, B, C and D is shown in fig. 4. The agreement seems to be sufficient, if you consider the rather complicated horizontal and vertical distribution of velocities.

It is necessary for further investigations to consider even this vertical distribution in connection with the problem of reproducing horizontal and vertical dispersion of suspended matter. In this connection I should like to mention a special publication by Sündermann (1971).

The reproduction of the water-levels and the vertically integrated velocities and the proof of the model's similitude with nature is an important supposition for hydrodynamical-numerical investigations

PLAN VIEW OF THE OUTER ELBE, SHOWING BOTTOM TOPOGRAPHY AND COMPUTATIONAL GRID.

COMPUTED AND OBSERVED TIME VARIATION OF WATER LEVEL AT THE THREE INTERIOR POINTS A, B AND C.

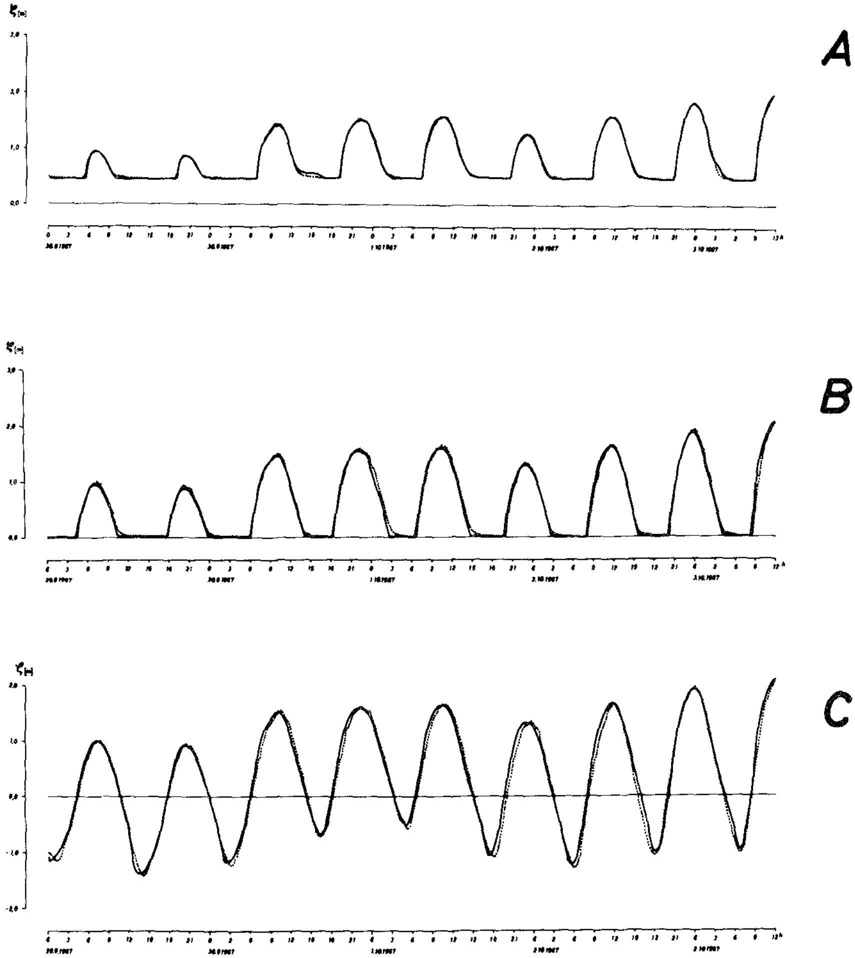


Fig. 3

COMPARISON OF MEAN CROSS SECTIONAL VELOCITIES

----- COMPUTED BY THE METHOD OF CUBATURE
—— HYDRODYNAMICAL - NUMERICAL COMPUTATION

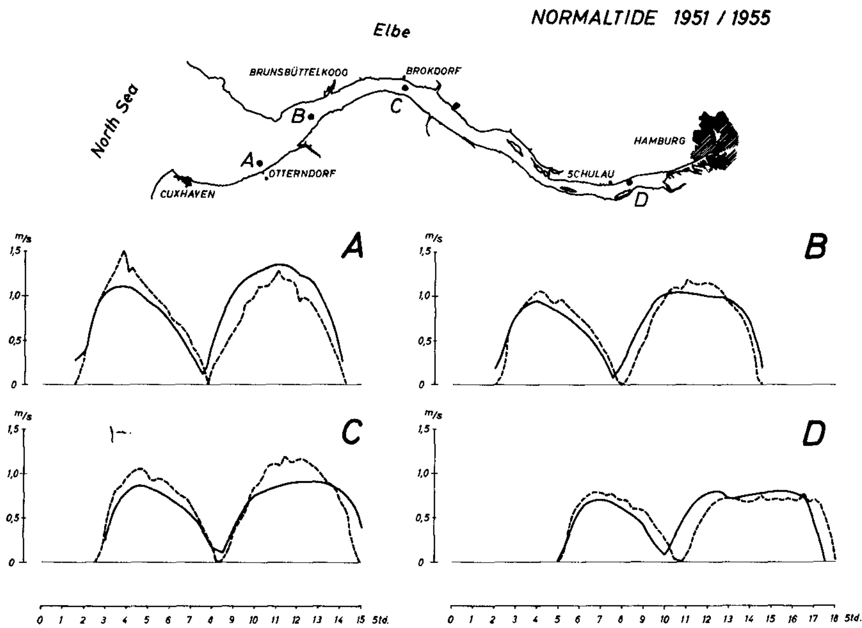


Fig. 4

of horizontal dispersion of suspended material. If this supposition is fulfilled, one can try to include the equation of mass-transport for example in the form

$$S + uS_x + vS_y = AS_{xx} + BS_{yy}$$

where S is the quantity of suspended material as a product of volume and concentration

A is the coefficient of horizontal eddy diffusivity in x-direction and

B the same in y-direction.

The physical process of horizontal dispersion is a turbulent process of transport depending on bottom topography and the motion of water in the vertical and horizontal direction. In the case of diffusing momentum the horizontal coefficient of diffusivity can be understood as an interior horizontal friction. If the density is equal to one, the dimension of these coefficients A and B is m^2/sec. Investigations by Elder and Bowden have shown that the following formula is applicable:

$$A = 5.9 \ r \ (h+\zeta) \ u$$
$$B = 5.9 \ r \ (h+\zeta) \ v$$

r is a non-dimensional constant friction parameter, equal to $3.0 \cdot 10^{-3}$ and $h+\zeta$ the actual waterdepth.

Before the equation of transport is applied to a hydrodynamical-numerical model, it is necessary to mention the substantial assumption used in the numerical treatment, in order to correctly interpret the results obtained. The material - in this connection marked - bas uniform quality and is an admixture of water in such a concentration as not to essentially change the density. The material remains in suspension during the dynamical process. Erosion and sedimentation have not been considered. It is assumed that the material is dispersed equally from the bottom to the surface. The investigated concentrations reproduce a mean distribution of the material at the grid - points, which are representative for a fixed area in the grid-net. A twodimensional model corresponding to the Elbe River in its given morphological structurs was used. In addition to the condition at the open boundary near Cuxhaven, observed waterlevel and - as a function of time - the time-dependent concentration of suspended material is given according to measurements of Nöthlich. He specifies the average quantity of seston during these measurements

with 28.6 mg/l dry weight at high-water-time

and 56.4 mg/l dry weight at low-water-time

at one point within the Elbe Estuary. It was assumed that this distribution is valid for the whole cross-section at the mouth of the river.

The computation began at low-water-time, and the tide, averaged over the years 1951/55, was used. Because simultaneous measurements are unavailable, it was only possible to compare the numerical results with measurements from the year 1967. It is well-known that the dispersion of suspended matter in a tidal river varies with the season and depends on meteorological circumstances and the salinity stratification of the estuary. As a first approximation it has been assumed that the main components of the transport of suspended matter during the time of measurements are the same as over the averaged tidal cycle. The essential numerical results are presented in fig. 5. It shows the distribution of seston conditioned by the dynamical processes in the Elbe River between Otterndorf and Stadersand. In the upper part the distribution during the time of maximum, and in the lower part the distribution during the time of minimum, of seston concentration in Cuxhaven is shown. At high-water as well as at low-water-time in Cuxhaven a zone of high seston concentration about 200 mg/l exists near Brunshüttel. During high-water-time this zone is broader than at low-water-time, whilst there is no difference in the length of the zone. This turbidity zone is a typical phenomenon in the Elbe River and is a result of an interaction between several components. Based on the qualitative reproduction of this turbidity zone by means of hydrodynamical-numerical methods it can be concluded that the main reason for the situation of this zone is determined by the hydrodynamics of the river. In this section the residual currents are very small.

A comparison between computed and measured mean concentration of seston in five sections of the Elbe River is shown in fig. 6. It must be noted that measurements were made at several places and at different tidal phases. The maximum and the minimum of seston at the

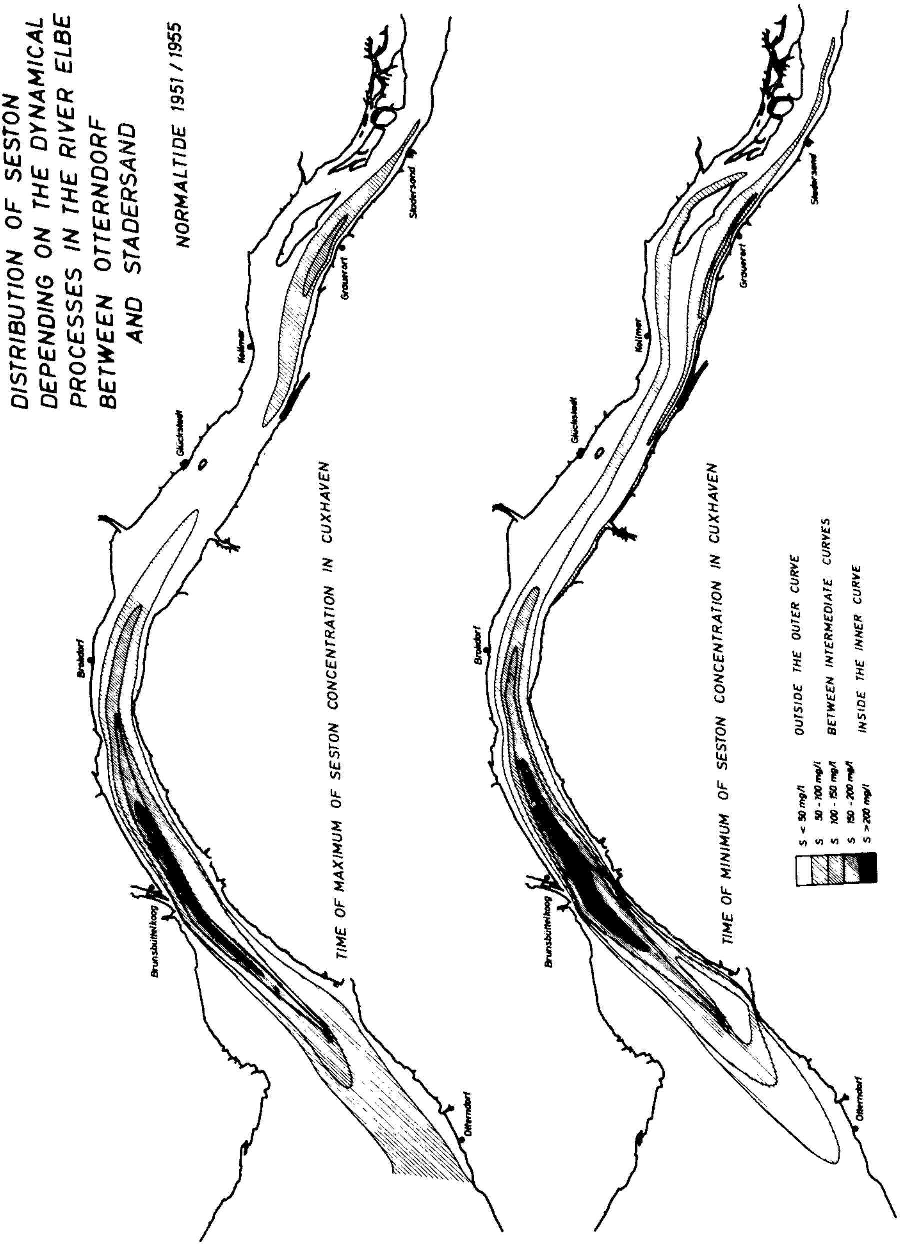

DISTRIBUTION OF SESTON DEPENDING ON THE DYNAMICAL PROCESSES IN THE RIVER ELBE BETWEEN OTTERNDORF AND STADERSAND
NORMALTIDE 1951 / 1955
TIME OF MAXIMUM OF SESTON CONCENTRATION IN CUXHAVEN
TIME OF MINIMUM OF SESTON CONCENTRATION IN CUXHAVEN
Stadersand
Grauerort
Kollmar
Glückstadt
Brokdorf
Brunsbüttelkoog
Otterndorf
S < 50 mg/l
S 50 - 100 mg/l
S 100 - 150 mg/l
S 150 - 200 mg/l
S > 200 mg/l
OUTSIDE THE OUTER CURVE
BETWEEN INTERMEDIATE CURVES
INSIDE THE INNER CURVE

Fig. 5

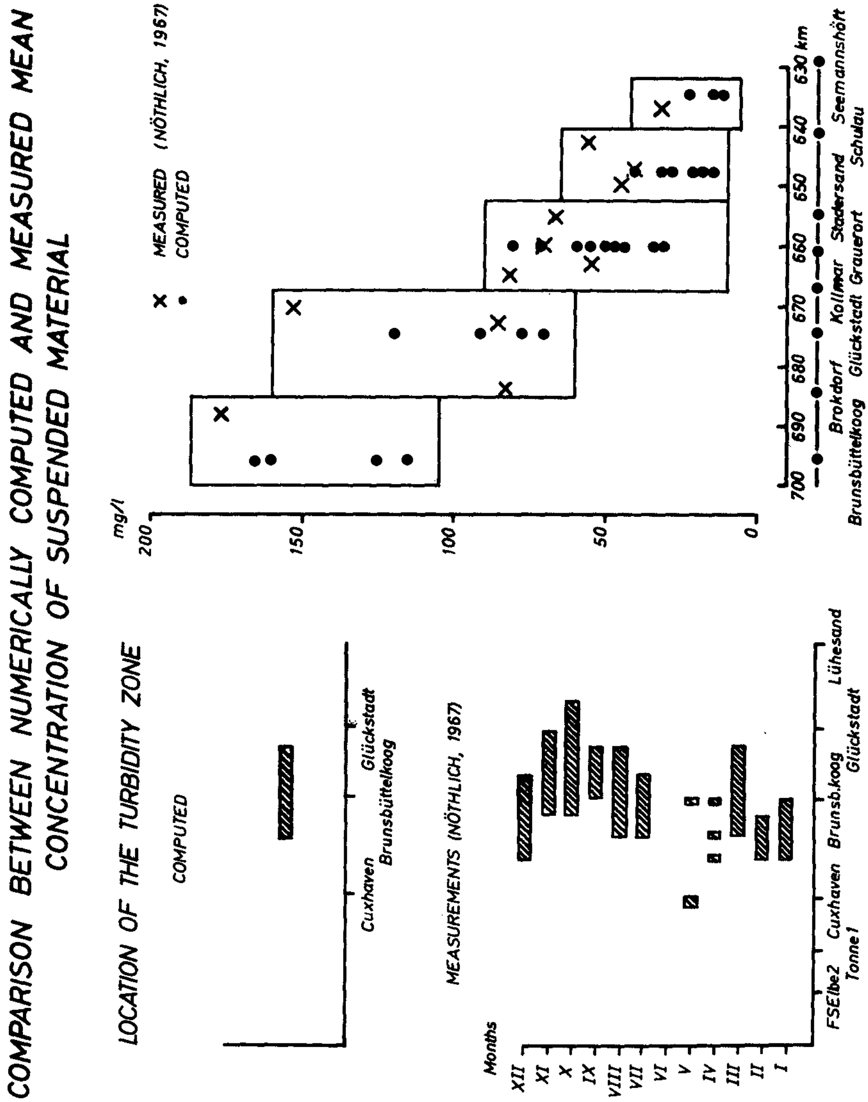

COMPARISON BETWEEN NUMERICALLY COMPUTED AND MEASURED MEAN CONCENTRATION OF SUSPENDED MATERIAL
LOCATION OF THE TURBIDITY ZONE
COMPUTED
Cuxhaven
Brunsbüttelkoog
Glückstadt
MEASUREMENTS (NÖTHLICH, 1967)
Months
XII
XI
X
IX
VIII
VII
VI
V
IV
III
II
I
FSElbe2 Tonne1
Cuxhaven
Brunsb.koog
Glückstadt
Lühesand
MEASURED (NÖTHLICH, 1967)
COMPUTED
mg/l
200
150
100
50
0
700
690
680
670
660
650
640
630 km
Brunsbüttelkoog
Brokdorf
Glückstadt
Kollmar
Grauerort
Stadersand
Schulau
Seemannshöft

Fig. 6

grid-points, which are situated near the points of observations, could be specified.

Taking into consideration the above-mentioned restrictions, one can see a general agreement between measured and computed values. On the left hand side of this figure the agreement between computed and measured location of the turbidity zone is shown.

These results suggest various possibilities of anplication with regard to the numerical methods, and they constribute to the development of a model, which is suitable for inclusion of other, for example hydrobiological, components. On the other hand it is possible to use models of this kind for prohlems of pollution. As a first approximation the location of the turbidity zone in the Elbe River can be explained as a consequence of the very small residual currents, which one can define as a mean velocity over one tidal period. It also means a very long hindrance of waste-water transport in this area. If the question arises of how to change this condition, then one has to consider many interacting components. It is thus important in certain coastal engineering projects not only to change the velocities and their directions, but also include into the consideration a variation of the residual currents.

The next figure 7 shows the distribution of residual currents during one M_2 tide in the North Sea. It may be mentioned that the M_2 tide introduced at the Dover Straits and on the northern entrance of the North Sea as a pure harmonic function of time, produced residual currents in the interior of the North Sea and accordingly, a circulation with an unperiodical watertransport. The largest transports in the eastern and the northern direction occur in the southern and eastern parts of the North Sea. This numerical result corresponds to observations. For the inner and deeper parts the above statement is sufficient. For coastal regions more information is required, hence, this figure should serve as an example only. In coastal areas one needs more detailed information about water-level and velocities, and other physical processes. The model shown before in figure 7 is thus not sufficient for considering the special physical processes, which occur in coastal regions and shallow water.

DISTRIBUTION OF RESIDUAL CURRENTS DURING ONE M_2-TIDE IN THE NORTH SEA

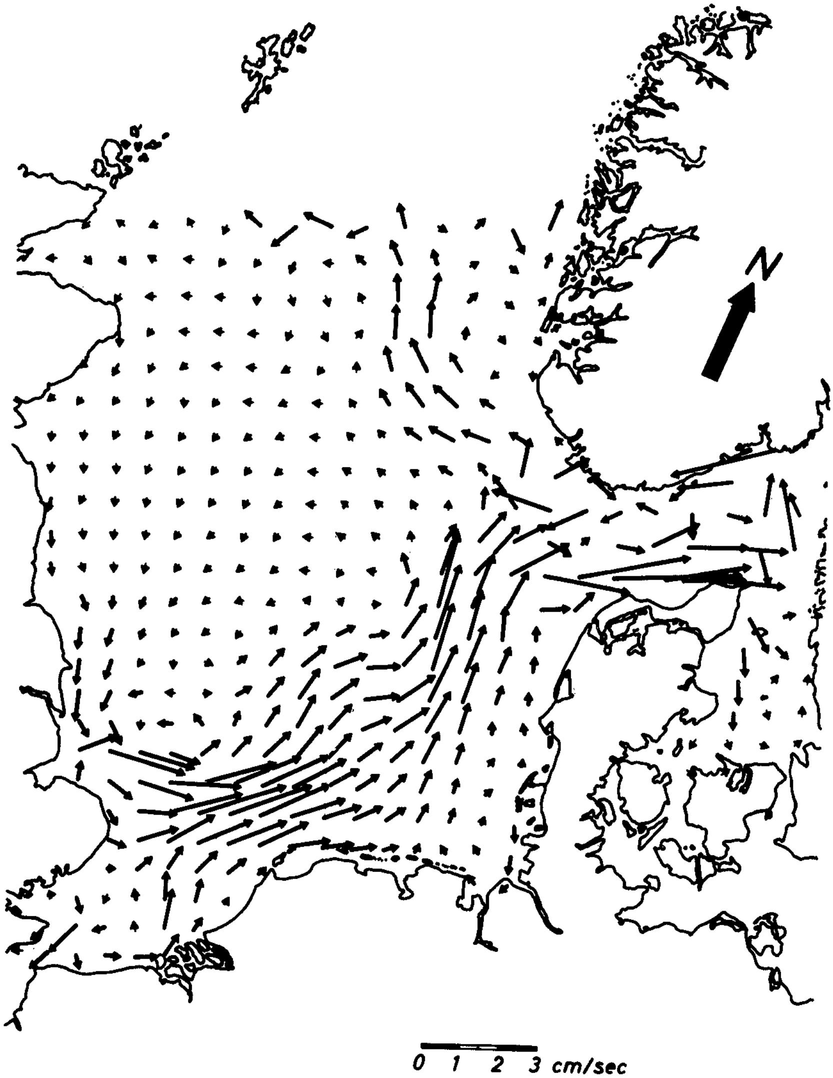
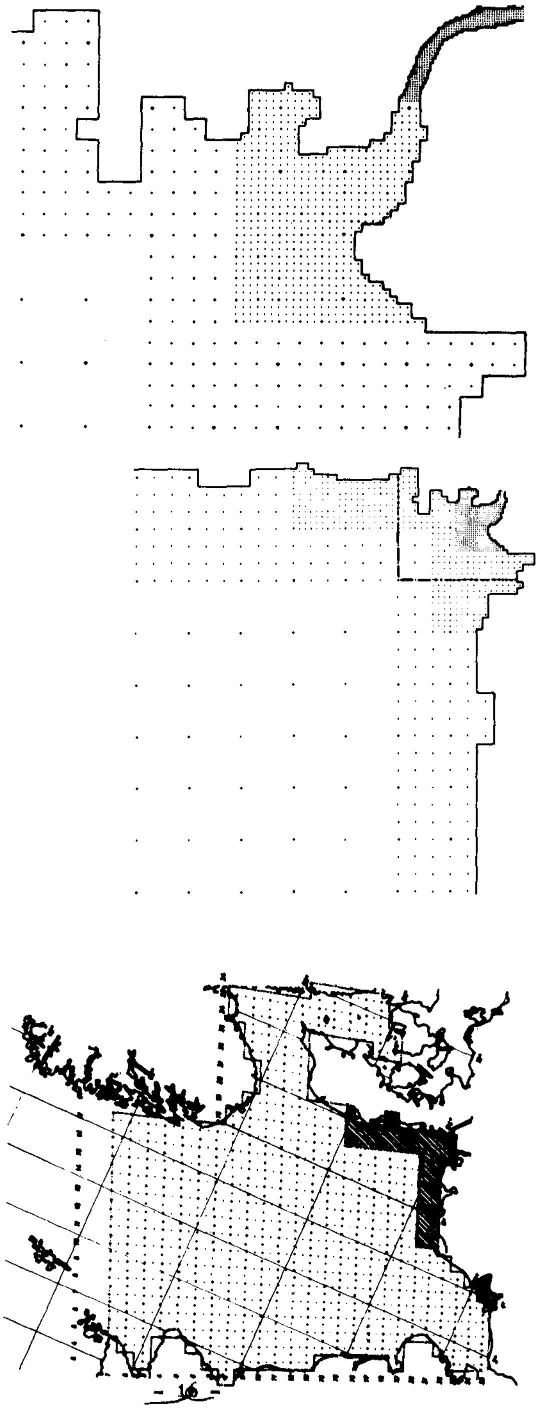


Fig. 7

In these areas it is necessary to refine the gridnet which is normally used in the open sea. A closer meshed network is advantageous for a good approximation of the bottom topography and coastal configuration. The numerical treatment is limited by the capacity of computers which are available, and the condition of numerical stability must be taken into account.

Figure 8 shows a model with a permanent refined network. A special technique makes it possible to refine the net in any choosen area. This figure gives an example of a section of a refined gridnet in the Elbe Estuary. This one third (1/3) refinement can be continued until the desired distance of the mesh-size is reached and the approximation of islands, sands, depth distribution and coastal configuration has the necessary accuracy. As a first result of these investigations figure 9 shows a refined representation of the distribution of residual currents over one tidal period in the Elbe Estuary.

This coastal area model of the German Bight and the Elbe Estuary shall be an example and a suggestion for coastal engineers. By using such models it is possible to study the influences of coastal buildings upon the variations of waterlevels, mean velocities and residual currents.



GRIDNET OF THE NORTH SEA AND REFINED GRIDNET IN THE GERMAN BIGHT

Fig. 8

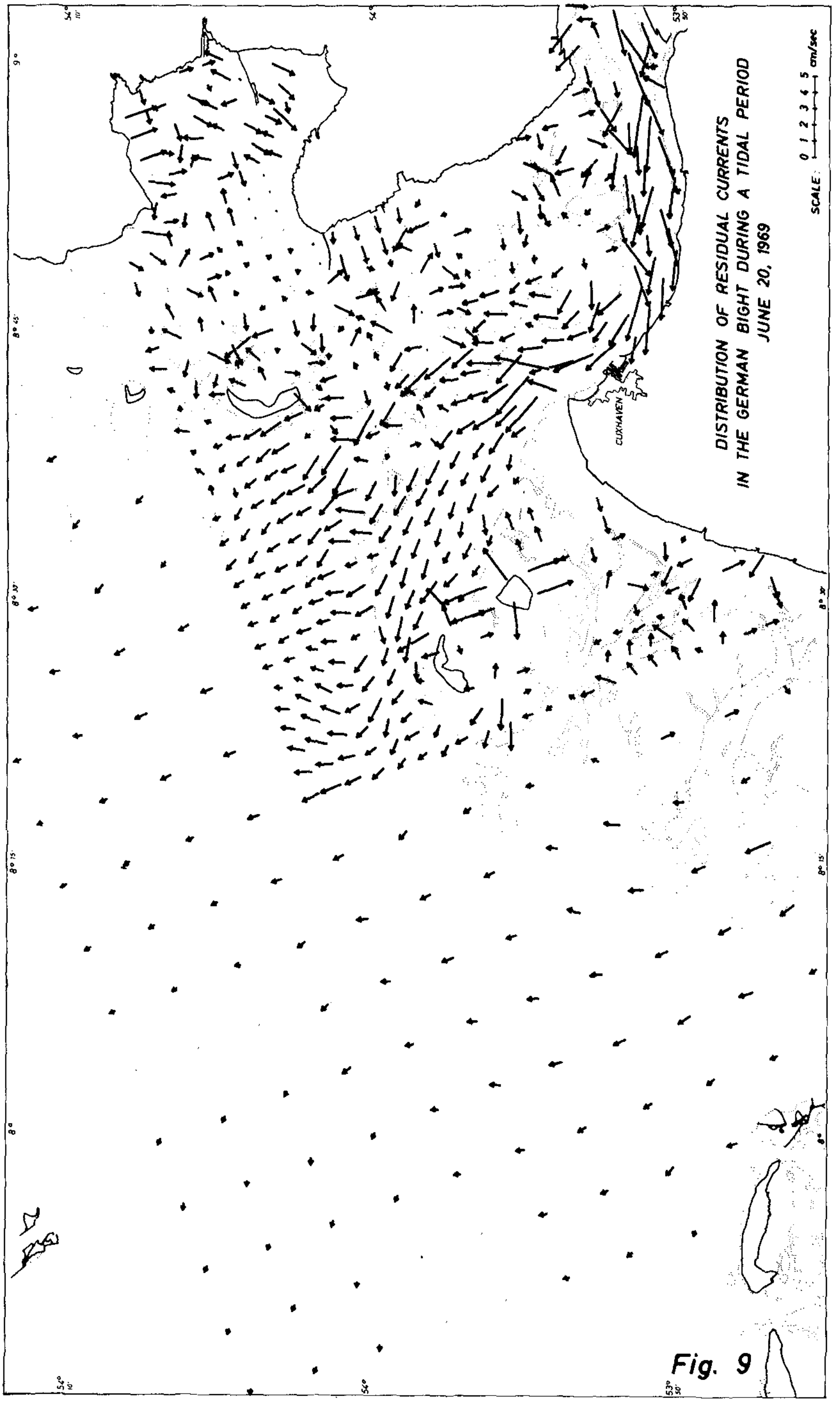

DISTRIBUTION OF RESIDUAL CURRENTS
IN THE GERMAN BIGHT DURING A TIDAL PERIOD
JUNE 20, 1969
CUXHAVEN
SCALE: 0 1 2 3 4 5 cm/sec

Fig. 9

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