CHAPTER 234

Parametrization
for conceptual morphodynamic models
of Wadden Sea areas

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Abstract

    Climate changes could lead to remarkable changes of
boundary conditions with respect to the interactions
between hydrodynamics and morphology. This would impact
especially coastal areas with movable beds like the
Wadden Sea of the Southern North Sea. Therefore
applicable tools for a prediction of morphodynamical
development due to changing conditions are demanded. The
German-Dutch research project *"Morphological development
of the Wadden Sea region with special emphasis of the
impact of an increasing relative sea level rise - WADE"*
deals with the described problem by developing suitable
conceptual morphodynamic models. An essential part of
these models is parametrization. Empirical investigations
were carried out for different tidal basins of the German
Wadden Sea leading to parameters which describe and
quantify the interactions between hydrological impacts
and morphological responses. The gained results had been
applied to a case study based on an empirical model.

Introduction

    The German Wadden Sea consists of barrier islands,
tidal basins and salt marshes which is important with
respect to several ecological and economical aspects.
Viewing the ecology, it is a consistent system of highly
specialized flora and fauna. Beyond the actual
geographical extension it is a remarkable resting- and

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breeding-ground for migrating birds. Economically it represents a main component of the coastal defence system by which the islands and the low lying parts of the marshland are protected. The Wadden Sea is also used for fishery and recreational means.

The goal of the investigations is to answer the critical question how tidal basins (tidal flat areas) will be influenced by changing hydrological and morphological boundary conditions and whether they will be able to keep pace with an accelerated relative sea level rise.

Therefore, a converted version of the model by Van Dongeren & de Vriend (1994) has been applied to predict the longterm behaviour of tidal basins. This empirical conceptual morphodynamical model needs parametrizations of the hydrographical and the morphological boundary conditions and their physical interactions. The paper deals with these parametrizations (tidal basins in total and as hierarchically systems of subareas) by empirical functions which are based on statistical analyses.

Investigation area

The investigations have been carried out for two study areas along the German coast of the North Sea: The *"East Frisian Wadden Sea"* and the *"Bay of Dithmarschen"*.

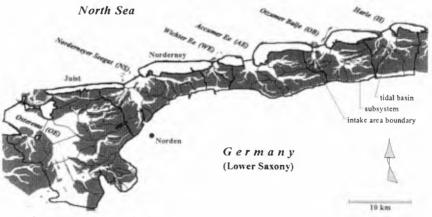The East Frisian Wadden Sea extends about 80 km from the west (*Osterems*) to the east (*Harle*) see Fig. 1.

Fig. 1 East Frisian Wadden Sea with islands, tidal inlets, basins and subsystem-areas (1990)

It covers an area of about 800 km² between the mainland and its barrier islands. The East Frisian Wadden Sea contains 6 tidal inlets with the connected tidal basins. Each basin (intertidal catchment area) is divided into several "hierarchical subsystems", limited by the area boundaries.

The Bay of Dithmarschen is located in front of *"Schleswig-Holstein"* It is an open single tidal basin (Fig. 2). In 1972 and 1978 parts of the bay had been reclaimed: by the enclosure in 1972 about 11.5 km² in the southern part and in 1978 about 21.5 km² in the nor- thern part. Before 1972 the area covers about 200 km²; it has been divided into "subsystems" - see Fig. 2.
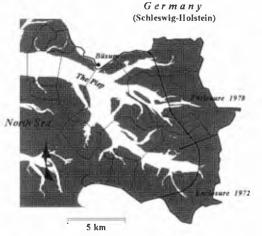

Fig. 2 Bay of Dithmarschen with hierarchical subsystems (1969)

Both investigation areas are characterized by semidiurnal tides propagating east- respectively north- wards along the coast. According to Hayes (1975) the areas can be classified as tide-dominated and high- mesotidal (the medium tidal range for the East Frisian- area is about 2.50 m; that for the Dithmarschen-bay is about 3.30 m). The significant mean wave hights (offshore) induced by the predominand wind out of the western sector are in the range of 1.0 m. Fresh water run off or discharges by sluices are negligible.

Data sets

The basis-data for the investigations of the East Frisian Wadden Sea are the three topography surveys from 1960, 1975 and 1990. The calculations for the Bay of Dithmarschen are based on 9 surveys carried out between 1942 and 1990. The density of data is very high and detailed.

The investigations have been executed by using a Geographic Information System (GIS, ArcInfo by ESRI[TM]) (Liebig, 1993). The topographical data of the study areas

were implemented by digitizing maps. All parameters have
been calculated with this database as geometrical
quantities.

Parametrization

     Within the scope of these investigations the para-
metrizations for the tidal basins and the subsystems were
restricted to areas, volumes and a characteristic height
describing the geometrical structure inside a tidal
basin. In a further step it is desirable to include a
parameter which describe the impact of the wave climate.

     The extension of the areas for parametrization have
been fixed by the intersecting lines between the actual
topography and horizontal reference levels. The reference
levels have been defined as horizontal planes. Exemplary
calculations showed, that the error between horizontal
and inclined planes are less than 1%. The reference
levels are the mean high water (MHW), mean low water
(MLW) and the German ordnance-datum (NN) which
approximately corresponds with the MSL for the German
Bight. The mean values have been calculated over the last
five years before the survey. Missing data have been
completed by using correlations between adjacent gauges.

     With respect to the hierarchy of the subsystem
structure the investigated functions were also checked
for small areas. In general the scattering increases with
decreasing size of the area. When subsystems are located
close to the coastline, than the characteristics (tide-
or wave-dominated) can be affected by tides or waves. The
characteristics of subsystems may be influenced by
anthropogenic changes of the boundaries, especially by
land reclamation means - see Bay of Dithmarschen.

     The spatial dimension (6 & 1 tidal inlets) allows
complementary investigations to verify different
relationships.

     The "basic parameters" (O'Brien, 1931) are:

A_b basin area
A_c cross sectional area
V_T mean tidal prism.

     Additional geometric parameters describing the
morphological structure of the Wadden Sea areas are
(Renger, 1976):

A_i intertidal area (MLW - MHW)

and (Dieckmann, 1985; Wieland et al., 1987):

l_i characteristic level of the intertidal area
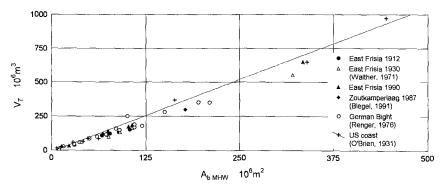V_i intertidal sediment volume.

The last three parameters have been proven as valid to balance the morphological dynamics or the changing sediment volumes inside a tidal basin.
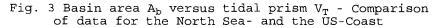
The validity of the functions for areas smaller than $A_{b\ MHW} = 10$ km² is questionable as a result of local influences. Moreover the nonlinear functions needs a threshold value to estimate physical suggestive results. Also in this context the threshold value should be greater than $A_{b\ MHW} = 10^7 m^2$ and $V_T = 10^7 m^3$ respectively.

General aspects and relations based on the parameter basin area A_b

Amongst the basin area A_b, the mean tidal prism V_T is the main parameter which influences the shape and structure of the tidal inlet or the morphology respectively. Figure 3 displays the comparison between those data sets for tidal basins along the North Sea coast and the US-coast.

Results of investigations based on historic data which go back to the seventeens century are published by Niemeyer (1993).

Fig. 3 Basin area A_b versus tidal prism V_T - Comparison of data for the North Sea- and the US-Coast

Consistent data based on GIS-proceeding have been elaborated for a period of about 30 years for the East Frisian Wadden Sea and 50 years for the Bay of Dithmarschen. Figure 4a shows the data for the East Frisian

Wadden Sea with linear regression functions. It shows a tendency of increasing tidal prisms with time. This is possibly a result of changing tide levels (Fig. 6).

The quality of the results gained by statistical investigations are clearly explained by the data set of 1975: The scatter plot of A_b versus V_T in logarithmic scale displays a good fitting of the linear function (Fig. 5). The comparision of observed versus predicted values showed a satisfactory accordance not only for the tidal basins, but also for the small subareas.
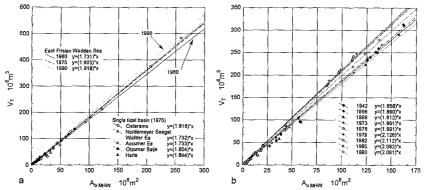

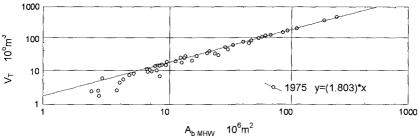Fig. 4 Basin area A_b versus tidal prism V_T - East Frisian Wadden Sea (a) and Bay of Dithmarschen (b)

Fig. 5 Basin area A_b versus mean tidal prism V_T - East Frisian Wadden Sea (logarithmic scale)

The comparability of tidal basins of the East Frisian Wadden Sea has been investigated. The result is a concentrated bunch of functions that have no orderly sequence in regard to the location along the coast (Fig. 4a).

However, the fitted regression functions of the coefficients show a slight increase along the coast from west to east (Fig. 6).

    Similar results are yielded by the investigations
for the Bay of Dithmarschen (Fig. 4b). The coefficients
are slightly higher than those of the East Frisian Wadden
Sea. The mean value comes to 1.855 for the period between
1942 and 1969. On account of the reclamation in 1972, it
would be expected that the function of 1973 would shift.
But the decreasing MHW (0.05 m) and MLW (0.03 m)
compensates this effect. The counterrotating effect
occured in 1976 as a result of the increasing tidal level
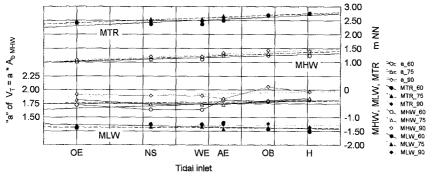and tidal prism.

Fig. 6 Coefficient "a" of $V_T = a*A_{b\ MHW}$, MHW, MLW and
    MTR for locations of the East Frisian Wadden Sea

    The data of the second reclamation in 1978 display
a consistent outcome. The mean value comes to 2.095 for
the period between 1982 and 1990. A weak tendency of a
decreasing tidal prism and basin area is noticeable. The
difference between the coefficients of 1973 (a = 1.862)
and 1990 (a = 2.091) corresponds with an increasing tidal
prism of about 12 %. The comparison between the East
Frisian Wadden Sea and the Bay of Dithmarschen yield a
greater tidal prism (3 to 9 %) relatively to the basin
area for the Bay of Dithmarschen.

    The second parameter which is used in modelling is
the intertidal area A_i. The intertidal area is defined as
the vertical projection of the topography within the
limits defined by the MHW and MLW (Renger, 1976). The
investigation of the relationships A_b versus A_i led to
nonlinear functions. In contrast to the previous
findings, the data do not show a continuous shifting
(Fig. 7a). Because of the slight differences of the
results for the distinguished time-periods, it is
reasonable to calculate a mean function for the whole
period; the result is:
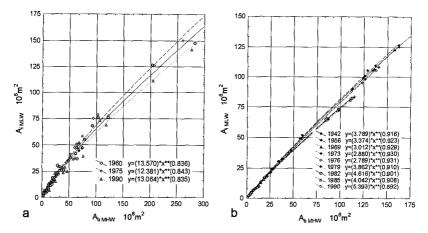
$$A_{i\ MLW} = 13.172\ A_{b\ MHW}^{0.837}.$$

Fig. 7 Basin area $A_{b\ MHW}$ versus intertidal area $A_{i\ MLW}$ - East Frisian Wadden Sea (a), Bay of Dithmarschen (b)
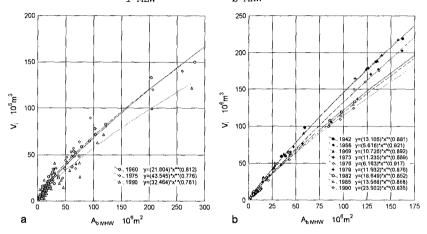
The data of the Bay of Dithmarschen display a similar image (the data are divided into two groups). There is no significant deviation due to the first reclamation in 1972. As a result of the second reclamation in 1978 there is a distinct shifting visible. The data from 1979 to 1990 tend to a backwards directed development due to a decreasing basin area A_b and an increasing intertidal area A_i. This led to the expectation that the mean function of the period 1942 to 1969 describes an equilibrium state (Fig. 7b):

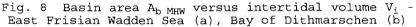$$A_{i\ MLW} = 3.372\ A_{b\ MHW}^{0.923}.$$

Furthermore the relation of the intertidal area versus the basin area indicates a greater share of the intertidal area for the Bay of Dithmarschen than for the East Frisian Wadden Sea. The amount of this difference depends on the size of the basin area; for $A_b = 100$ km² the difference of A_i is 25 %.

The intertidal volume V_i, describing the sediment volume, is defined as the volume between MHW and MLW according to Wieland et al. (1987). This is the range which is mainly influenced by the tidal prism. The investigation shows two groups of data. One includes the data of the years 1960 and 1975. The regression functions are nearly coincident. The other one is the function of 1990, which is substantially different (Fig. 8a). The intertidal volume V_i decreased significantly compared to 1960 and 1975 as a result of a raise of MHW and MLW in

combination with changes of the topography (erosion). The function which decribes the equilibrium state can be calculated with the data of 1960 and 1975. This leads to:

$$V_{i\ MLW} = 32.99\ A_{b\ MHW}^{0.790}\ .$$

Fig. 8   Basin area $A_{b\ MHW}$ versus intertidal volume V_i - East Frisian Wadden Sea (a), Bay of Dithmarschen (b)

The evaluation for the Bay of Dithmarschen shows three different relationships (Fig. 8b). The relations shown in the upper part enclose the years 1942, 1969 and 1973. The survey of 1973 had been carried out one year after the first enclosure. The middle part shows the functions of 1956 and 1976. The contradictory developments of both groups are mainly affected by changing water levels and are not the consequences of erosion or sedimentary effects. In the bottom-group of relationships, the scattering is very small; the tendency of decreasing intertidal volume results also in the growth of the MLW. The general tendency of decreasing tidal volumes relativ to the basin areas results in the enclosure of the high lying supratidal areas in front of the coast. Based on 1942 and 1969 the equilibrium function is:
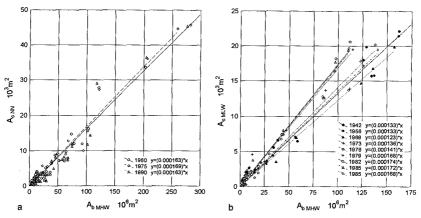
$$V_{i\ MLW} = 11.96\ A_{b\ MHW}^{0.886}\ .$$

For investigations based on the relationship between basin area A_b versus cross sectional area A_c it is important, that the lowest scattering was found by using A_c related to the reference level NN (area between NN and the contour line). A_c was determined at the location with the strongest constriction of the streamlines. The

analysis led to linear functions (Fig. 9a). Based on all three data sets together, the mean function of the East Frisian Wadden Sea has been found as:

$$A_{c\ NN} = 0.000165\ A_{b\ MHW}.$$

The data of the Bay of Dithmarschen display the distinguished "influenced" and "noninfluenced areas" as a result of the enclosure works (Fig. 9b). The equilibrium function was calculated with the data of the last survey before enclosure (1969):

$$A_{c\ NN} = 0.000123\ A_{b\ MHW}.$$

Fig. 9 Basin area $A_{b\ MHW}$ versus cross sectional area $A_{c\ NN}$ - East Frisian Wadden Sea (a), Bay of Dithmarschen (b)

In order to describe the development of the height of intertidal areas or the volumes respectively, the characteristic level l_i (Dieckmann, 1985) has been investigated. Herewith it is possible to verify the progress of erosion or sedimentation for stages of dynamic equilibrium. The parameter l_i is defined as the level where the intertidal area A_i is half exposed and half submerged. This led to a characteristic level between MHW and MLW. The scatter plot of l_i versus $A_{b\ MHW}$ shows an asymptotic behaviour with increasing $A_{b\ MHW}$ (Fig. 10 and 11). The graphs contain the empirical function which represent the lower and upper limit of l_i. Deviations of l_i indicate a nonequilibrium stage of the subsystem or the impact of local influences by the different boundary conditions that lead to variations between the subsystem and its total tidal basin.

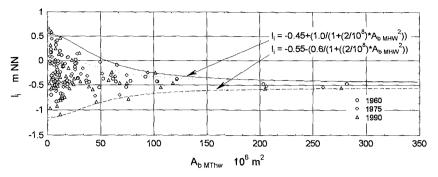Fig. 10 Basin area $A_{b\ MHW}$ versus intertidal level l_i of the East Frisian Wadden Sea
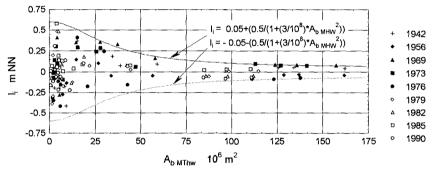

Fig. 11 Basin area $A_{b\ MHW}$ versus intertidal level l_i of the Bay of Dithmarschen

Relations based on the parameter mean tidal prism V_T

The mean tidal prism V_T has been defined as the volume between MHW and MLW. The analysis of the relationship between V_T and A_i led to the same behaviour as explained before (Fig. 12a and b). Remarkable is the overlapping bunches of functions for both investigation areas. This is possibly a result of the parameter V_T which implizitely includes the tidal range as one of the main boundary condition for the classification of tidal inlets (Hayes, 1975). The derivation of an equilibrium relationship are based on the years 1960 and 1975 for the East Frisian Wadden Sea and on 1942 and 1969 for the Bay of Dithmarschen. The relations are:

$$A_{i\ MLW} = 15.50\ V_T^{0.805} \quad \text{(East Frisian Wadden Sea)}$$

$$A_{i\ MLW} = 9.199\ V_T^{0.841} \quad \text{(Bay of Dithmarschen)}.$$
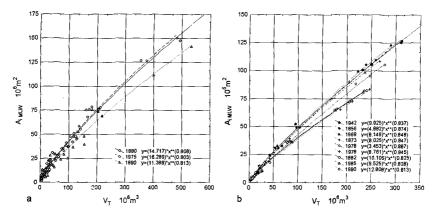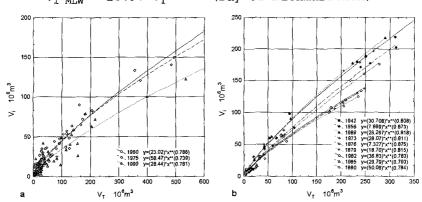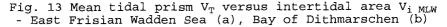
Fig. 12 Mean tidal prism V_T versus intertidal area A_i MLW
- East Frisian Wadden Sea (a), Bay of Ditmarschen (b)

Furthermore the relation tidal prism V_T versus intertidal volume V_i indicates the same grouping of influenced and noninfluenced surveys (Fig. 13a and b). The equilibrium functions are:

$$V_{i\ MLW} = 36.83\ V_T^{0.761} \quad \text{(East Frisian Wadden Sea)}$$

$$V_{i\ MLW} = 28.97\ V_T^{0.812} \quad \text{(Bay of Dithmarschen).}$$

Fig. 13 Mean tidal prism V_T versus intertidal area V_i MLW
- East Frisian Wadden Sea (a), Bay of Dithmarschen (b)

It appears that the overall aspect about the amount of the intertidal volume relativ to the size of basin area and tidal prism is greater for the Bay of Dithmarschen than for the tidal basin of the East Frisian Wadden Sea. The small differences during 1979 up to 1990

seems to tend to a new relationship as a result of
changing geometrical boundary conditions.
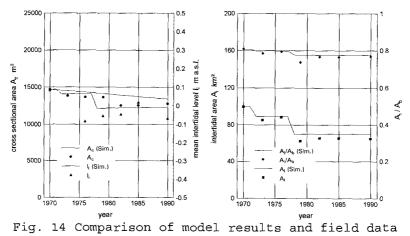
Example of application

The described functions (parameters) were applied in
a conceptual morphodynamic model for large scale
morphological changes of hierarchically structured
channel-basin-systems in tide-dominated coastal areas.
This model is based on Van Dongeren & de Vriend (1994).
The model reproduces erosion and sedimentation due to
changes of tidal parameters by moving sand volumes within
a hierarchically system composed of channels and
connected subareas (Goldenbogen, 1994). It has been
applied for the Bay of Dithmarschen by using some of the
above presented parametrizations (Schroeder, 1994):

$$A_{i \ MLW} = 3.372 \ A_{b \ MHW}^{0.923}$$

$$A_{c \ NN} = 0.000123 \ A_{b \ MHW}$$

$$l_i = 0.05 + 0.5 \ / \ (\ 1 + (\ 3 * 10^{-8} \ A_{b \ MHW} \ )^2 \ ).$$

The simulation cover a period of 20 years. Figure 14
shows the results at the location southern of Büsum (see
Fig. 2). Two superimposed effects have been calculated:
a rise of the relative sea level (0.005 m/a) and the
enclosures in 1972 and 1978.

Fig. 14 Comparison of model results and field data

On account of the small amount of the assumed
relative sea level rise this influence does not become
noticeable. The enclosures is reproduced by the model in
a realistic manner. With the exception of the cross

sectional area A_c, which has been simulated by a continued process, all the other parameters show a discontinually pattern as impact of the enclosure (immediately reduction of predominant highly situated areas in front of the coastline). A new equilibrium stage requires an increase of the intertidal area A_i over time, as it, for example, has been after the first enclosure of the Bay of Dithmarschen in 1972.

The model does not consider influences of changing wave climate or the geometric shape of the basin. This require further adaptations of the equilibrium functions.

Conclusions

The results of investigations for two different tide-dominated Wadden Sea areas of the Southern North Sea (open bay and bays sheltered by barrier islands) demonstrate, that a reliable parametrization of the interactions between hydrological impacts and morphologically responses is possible. This result is proven as well for tidal basins as for distinguished subareas of different size and location. However, the validity of functions for tidal areas smaller than $A_{b\ MHW}$ = 10 km^2 is questionable. The proven empirical functions had been applied to a conceptional morphodynamic model. The results showed that empirical morphodynamical modelling is a suitable tool to reproduce transitional morphological stages leading from a former to a new equilibrium fixed by changed boundary conditions. The method can lead to a profound forecasting of the development of Wadden Sea areas in medium time scales, needed for decisions on engineering and ecological purposes.

Acknowledgement

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