CHAPTER 80

A NEW EQUILIBRIUM ANALYSIS FOR NEARSHORE TIDAL BASINS

R. Dieckmann*1 and H. W. Partenscky*2

Abstract

A large tidal flat area of about 40 tidal basins with catchment areas of between 10 and 790 km^2 exists along the coast of the German Bight. Not all of these tidal basins are morphologically stable.

The main parameter necessary for determining the state of equilibrium is the volumetric capacity of the concave portions of the tidal basin. In order to examine the equilibrium state it is necessary to compare the volumetric capacity of the tidal basin determined from hydrographic charts (measured volume) with a theoretical volume given by newly developed stability criteria representing averaged conditions (volume balances). Significant deviations between the theoretical and the measured volumes indicate a state of non-equilibrium.

Using stability criteria it is possible to desribe the state of equilibrium of a tidal basin in a stepwise manner either from the bottom of the tidal basin to the datum plane MHW in order to obtain a cross-sectional stability profile, or from the shore to the seaward boundary of the basin in order to obtain a longitudinal stability profile.

The applicability of the new method for analyzing the equilibrium of a tidal basin will be demonstrated by the example of the Süderau tidal basin in the north of Germany.

1. Introduction

The North Sea is a shallow marginal sea of the Atlantic Ocean. In the south eastern part of the North Sea, known as the German Bight, the coast is formed over a length of 480 km by a tidal flat area of 7500 km^2 consisting of approximately 40 tidal basins with catchment areas of 10 to 790 km^2.

The tidal flats of the German Bight are regions of extensive alluvial activity which has never ceased over many centuries of history. In their composition and form the tidal flats are the result of the constructive and destructive actions of the North Sea. The severe storms surges of the 13th and 14th century, as well as during the 17th and 18th centuries, have caused considerable loss of land along this

*1 Dr.-Ing., Agriculture and Water Resources Office (ALW Husum), Herzog-Adolf-Str. 1, D-2250 Husum, FRG.

*2 Prof. Dr.-Ing. Dr.phys, Director of the FRANZIUS-INSTITUTE for Hydraulic Research and Coastal Engineering, University of Hannover, Nienburger Str. 4, D-3000 Hannover 1, FRG.

coast. Land reclamation measures and offshore dykes have only been able to offset a portion of these erosional losses. Therefore not all of the tidal basins in this area are morphologically stable.

In order to clarify the morphological behaviour of the nearshore zone and to be able to estimate the degree of further erosional losses, sub-regions of the tidal basins have been systematically investigated for about 10 years in relation to their equilibrium state. Further erosional losses must be prevented by appropriate construction works in order to safeguard this unique natural landscape. In addition, the tidal flats are of great importance in the coastal protection system since they considerably reduce the hydrodynamic loading on the coastal dykes.

The initial results of this long-term investigation programme were presented at the Coastal Engineering Conference in Copenhagen, 1984/1/ and in Cape Town, 1982/2/.

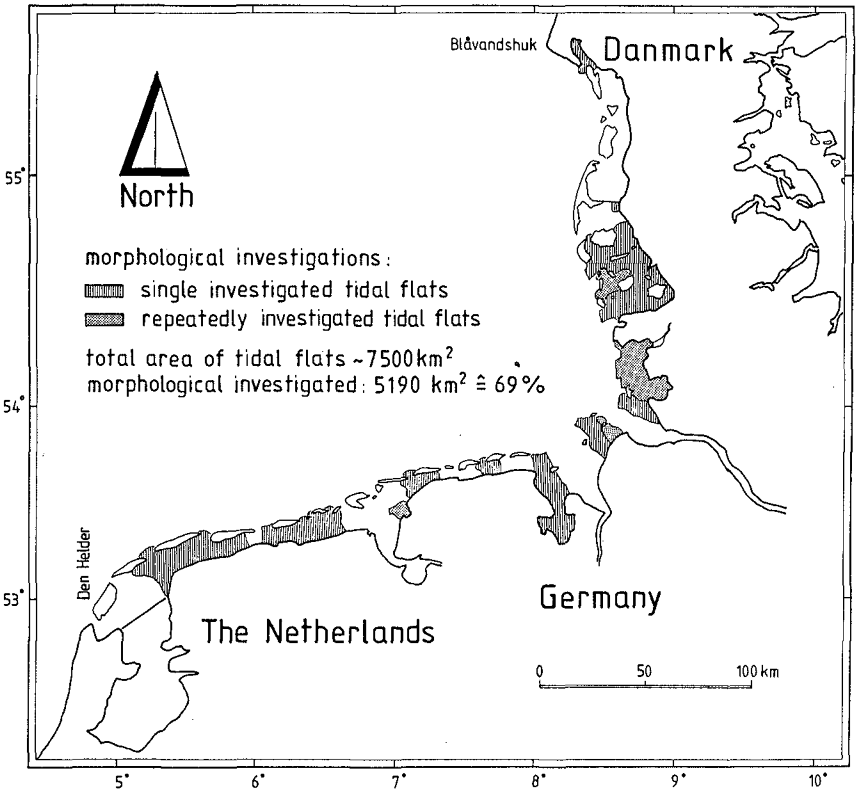


Fig. 1: Morphologically investigated areas along the coast of the German Bight.

2. Concept of the Investigations

2.1 Geomorphological and hydrological Boundary Conditions

The surface shape of a tidal flat area is very complicated. To describe it, the definition of basis units for data collection is necessary. Such basis units are the drainage basins of the tidal creeks and gullies (tidal basins).

Today, the investigated tidal basins of the German Bight represent approximately 69 % of the whole tidal flat area. In addition to this, some tidal basins have been repeatedly investigated. A total data volume from 6250 km^2 of tidal flats is available (see Fig. 1).

The main task of the morphological investigations is to generalize the morphology of the tidal basins by determining the so called constant-level area distribution (CLAD)/3/.

The constant-level area distribution for a tidal basin may be obtained by assigning the included area of a particular closed contour to the geodetic height corresponding to that contour. A distribution function is obtained from a graphical representation of the latter areas which is similar in form for all tidal basins having the same characteristics (see Fig. 2).

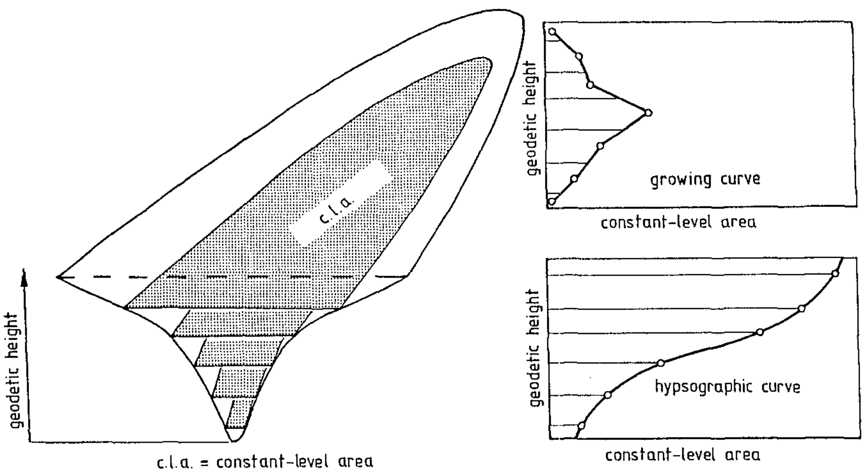


Fig. 2: Determination of the constant-level area distribution (CLAD) of a tidal basin (schematic) /3/.

In order to determine the CLAD, it is necessary to measure the constant-level areas from charts using a planimeter. In the case of larger investigation areas or those having a more complex morphology, the CLAD may be determined for a region as a whole by the summation of the individual contributions of a number of sub-areas.

By numerical integration of the CLAD, the volumetric summation curve (VSC) for a tidal basin may easily be determined (see Fig. 3).

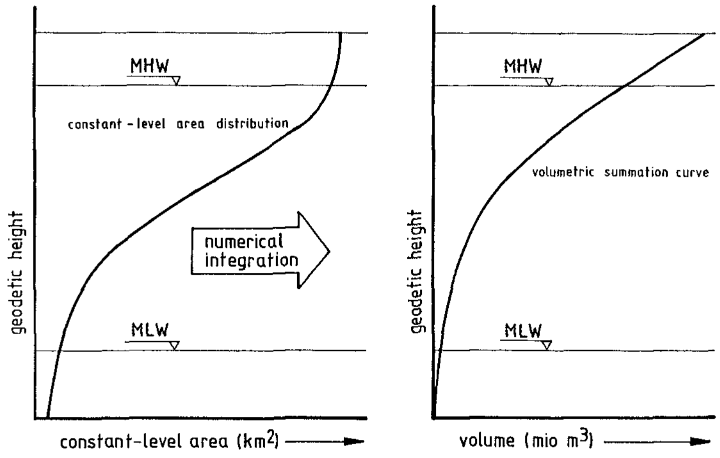


Fig. 3: Constant-level area distribution (CLAD) and volumetric summation curve (VSC) of a tidal basin /3/.

The VSC represents the total volumetric capacity of a hollow-shaped tidal basin with respect to different depths. Values of special importance are the volumetric capacity below the datum planes MLW and MHW /4/.

Applying to HAYES tidal classification /5/, it is possible to subdivide the shallows along the coast of the German Bight into the following 4 classes:

CLASS	TIDAL RANGE
Microtidal coast	< 1 m
Low mesotidal coast	1 - 2 m
High mesotidal coast	2 - 3 m
Low macrotidal coast	3 - 5 m

This classification is of great importance, especially from the geomorphological point of view. On the mesotidal coast, the flats of the German Bight are bordered by barrier islands. In passing from the low mesotidal to the high mesotidal coast the islands of the barrier island chain become smaller. Along the low macrotidal coast no barrier islands are present. This coast is open to the sea (see Fig. 4).

For the comparision of CLAD- or VSC-curves of different tidal basins, the tidal classification mentioned above has to be taken into account.

In Fig. 5, typical CLAD-curves of the 3 types of tidal basins are plotted as a function of the relative surface area (constant level area). When considering the intertidal area between MHW and MLW, the curves clearly show the decrease of this part of the tidal basins with decreasing tidal range. These differences in the morphological structure of several tidal basins can be shown clearly by comparing CLAD- and VSC-curves of the Meldorfer Bucht, which is situated in the low macrotidal range of the West Meep, which represents a tidal basin of the low mesotidal coast. Although both tidal basins have nearly the same surface area and volumetric capacity at MHW, the CLAD- and VSC-curves are totally different (see Fig. 6).

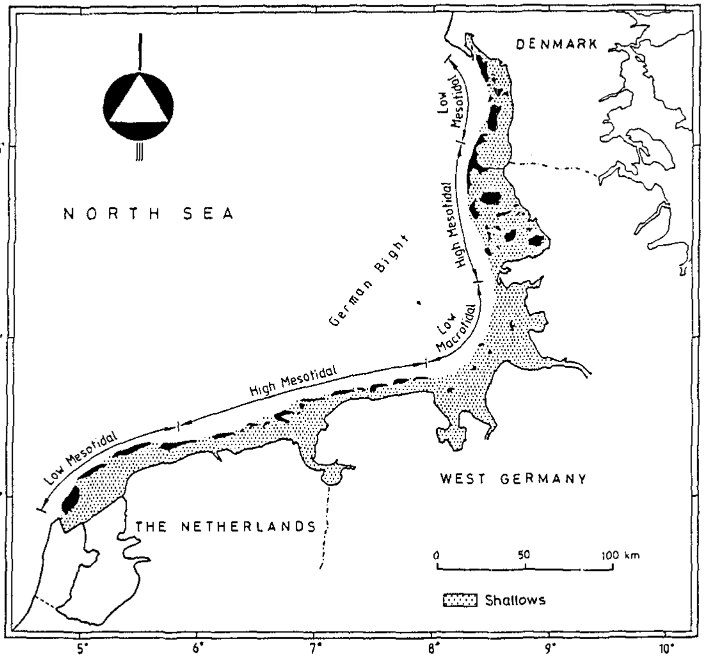


Fig. 4: Map of the German Bight showing the tidal flats /3/.

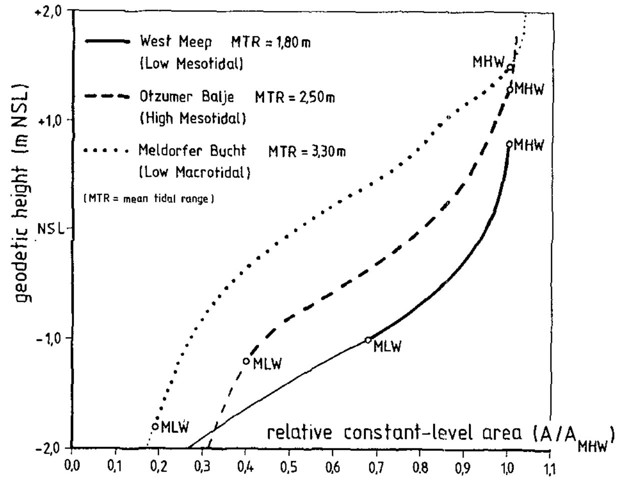
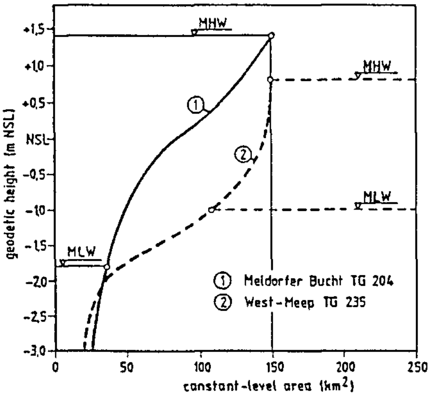
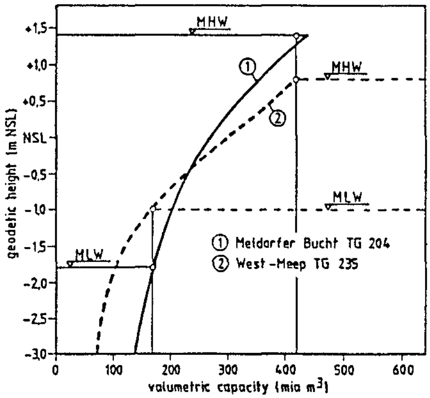


Fig. 5: Comparision of the types of CLAD plotted as a function of the relative surface area /3/.



a) Differences in the course of the CLAD - functions



b) Differences in the course of the VSC - functions

Fig. 6: General morphological structure of the Meldorfer Bucht and West Meep tidal basins /3/.

2.2 Regime Theory Basis for the Investigations

River drainage basins or tidal creeks (tidal basins) may be considered as open passive systems (regimes), the states of which may be described by parameters. An open system allows the transport of material and energy across the system boundaries (tidal basin boundaries). Passive systems only change their state when an external disturbance enters the system /6/. Theoretically, such systems are in a time-independent state of equilibrium, which in the case of a tidal basin must satisfy three essential physical conditions:

-- the continuity condition,
-- the relationship between the flow velocity, the depth, the slope and roughness of the channel and
-- the relationship between the flow velocities and the sediment transport.

If external influences disturb the regime of the tidal basin, this must alter to comply with the new boundary conditions and attain a new state of equilibrium within a particular time interval.

Since, however, tidal basins are subjected to many varying boundary conditions and disturbances which have apposing effect, a final state of equilibrium is never reached. Due to the feedback mechanisms between the disturbances and the reactions of the regimes, time delays occur. Self-correcting processes therefore fluctuate about a mean condition representing the modal value, i.e. a dynamic state of equilibrium develops /7/ which corresponds to the mean equilibrium state.

In the case of disturbances, the regime parameters behave in different ways. Only few but important system parameters react very sensitively to disturbances. It is well-known from regime theory, the size of the drainage area is the most important parameter of a channel system.

Accordingly, a strict mathematical relationship (Fig. 7) exists between the drainage area and the volumetric capacity of a tidal basin. The regime of a tidal basin reacts thereby by altering its drainage area by erosion or sedimentation depending upon whether the drainage area has increased or decreased until a new state of equilibrium has been established.

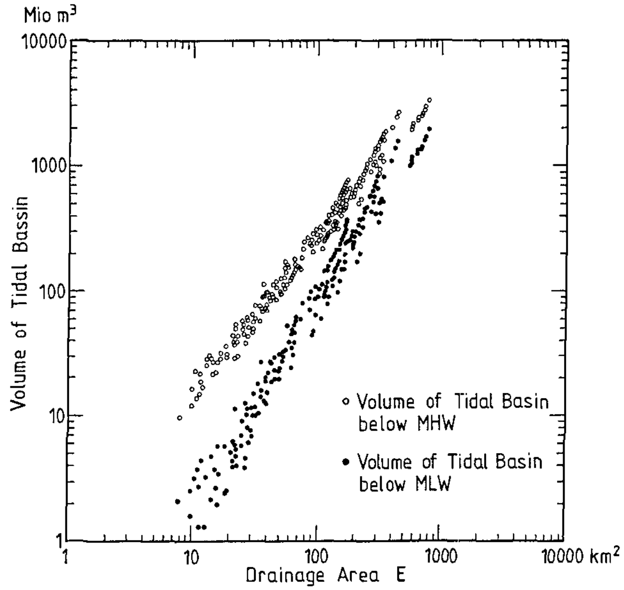


Fig. 7: Relationships between the volumetric capacity below MLW and MHW and the drainage area of tidal basins in the German Bight /3/.

2.3 Approach and Method

The main parameter necessary to determine the state of equilibrium is the volumetric capacity of the concave portions of the tidal basins. The stability criterion for a tidal basin of given dimensions is given by the following equation:

$$V = \alpha^{*} \cdot (d_z \cdot a_z)^{\beta^{*}} \qquad (1)$$

where

V = volumetric capacity of the tidal basin for the state of equilibrium,

α^*, β^* = regression coefficients, which are functions of tidal conditions and the tidal section under consideration,

d_z = maximum depth in the tidal basin with respect to the constant level elevation (z) and

a_z = size of the constant level area at the elevation (z).

In order to examine the equilibrium state of a tidal basin and to make predictions of the expected degrees of sedimentation and erosion for a region which may not be in a state of equilibrium, it is necessary to compare the theoretical volumetric summation curve with a measured curve based upon hydrographic charts.

In the event that significant deviations are revealed through a comparision of the theoretical and measured volumetric summation curves (volumetric balance) for the tidal basin under consideration, this implies that the area concerned is in a non-equilibrium state.

For the case of a volume deficiency, i.e. the measured volume is less than the theoretical volume, the tidal basin is in a state of erosion. In this case, erosion continues until the volume corresponding to the equilibrium state is attained. Conversely, a tidal basin with a volume excess reacts by undergoing gradual sedimentation until a state of equilibrium (theoretical volume) is reached /2/.

As a basis for determining the actual volumetric summation curve, accurate computations of the volumetric capacity are necessary for the channel system under investigation. For this purpose, accurate contour maps of the tidal basins are essential.

3. Stability Criteria for Tidal Basins

3.1 Determination of Regression Coefficients

In order to determine the theoretical volume which characterises the mean equilibrium state of a tidal basin, it is necessary to determine the regression relationship between the actual existing volume (see Section 2.1, Figs. 2 and 3) and the value given by the product ($d_z \cdot a_z$) from the relationship (1) for all 71 of the tidal basins and sub-regions investigated. The regression coefficients α^* and β^* for the individual tidal basins were determined by the least squares error method of GAUSS from altogether 450,000 data values by means of a special computer program.

In order to obtain a good approximation of the geomorphological boundary conditions, it is necessary to consider the following parameters:

- -- the seaward boundary of the tidal basin (see /3/),
- -- the differences in the structure of the tidal basin with respect to tidal conditions (Section 2.1),
- -- seperate evaluations of the channnel regions and the flat sections of the tidal basin.

The regression coefficients determined for the investigated tidal basins with varying tidal ranges were represented in relation to tidal range under consideration of the height domains channel region (section 1) and flat section (section 2), as shown in Figs. 8a, 8b. From these diagrams, the regression coefficients α and β were determined for an evaluation of the theoretical volume of a tidal basin in relation to the particular mean tidal range (MTR).

The results were as follows:

channel region $\alpha_1 = 0.383 - 0.0133\ \mathrm{MTR}$ (2)

$\beta_1 = 0.883 - 0.004\ \mathrm{MTR}$ (3)

flat section $\alpha_2 = 1.115 - 0.161$ MTR (4)

$\beta_2 = 0.989 - 0.026$ MTR (5)

It is noted that the quality of the approximation for the region 2 (flat section), as expressed by the correlation coefficients, is generally slightly worse. This is not related to errors in the method used but to the "particular morphological characteristics" of the investigated drainage areas which were particularly abundant in the cases considered and which could not be described in terms of the parameter "volumetric capacity".

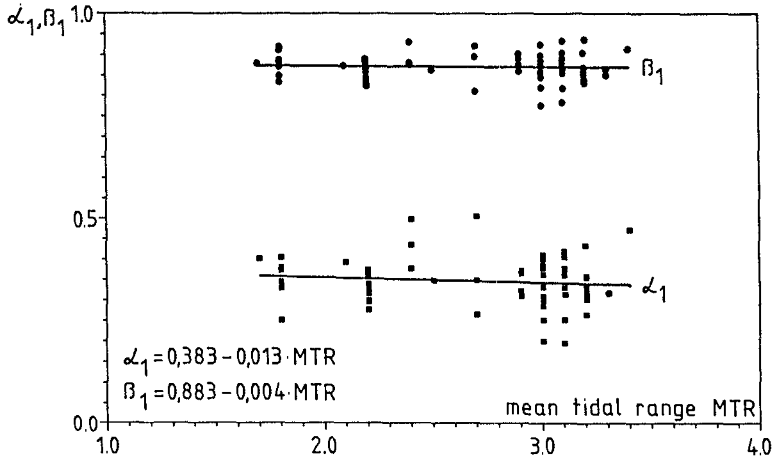


Fig. 8a: Regression coefficients α_1 and β_1.

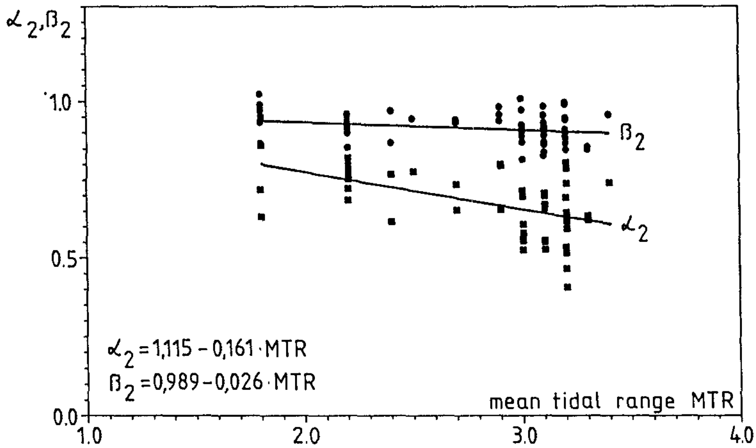


Fig. 8b: Regression coefficients α_2 and β_2.

3.2 Formulation of the stability criteria

The volumetric capacity (nominal volume), which represents mean conditions for the given tidal range, may be regarded as a criterium for the hydrological-morphological stability of a drainage area. This nominal volume may be represented on the basis of the previously described general formula for the region below MLW as follows:

$$V_{z_1} = \alpha_1 \cdot (d_z \cdot a_z)^{\beta_1} \quad \text{(Mio m}^3\text{)} \qquad (6)$$

For the tidal range region, the following holds:

$$V_{z_2} = \alpha_2 \cdot (d_z - d_{MLW})(a_z - a_{MLW})^{\beta_2} \quad \text{(Mio m}^3\text{)} \qquad (7)$$

where

d_{MLW} = depth below MLW (m),

a_{MLW} = constant level area of the reference plane MLW (km^2)

Here, the two sections 1 (channel bed to MLW = channel region) and 2 (MLW to MHW = flat section) must be considered. The coefficients α_i and β_i which should be substituted in the Equations (6) and (7) for the particular case in question may be obtained from Figs. 8a and 8b.

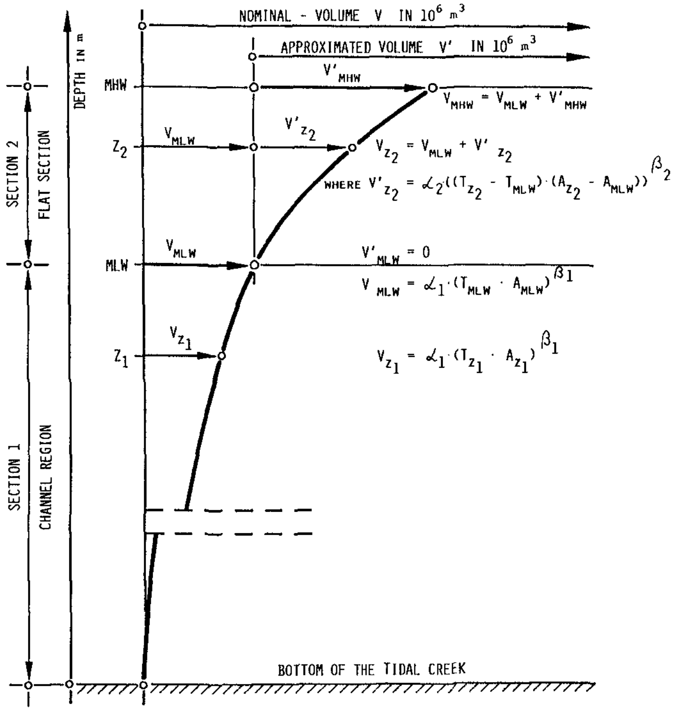


Fig. 9: Determination of the approximated nominal-volumes in the two investigation sections: channel region (section 1) and flat section (section 2) /3/.

Figure 9 shows by way of example the method of determining the approximated nominal volumes in both sections. In section 2 (flat section) a transformed coordinate system based upon the particular value of V_{MLW} is used. By this means, discontinuity in the approximated nominal volumes in the transition zone between sections 1 and 2 is avoided.

Special investigations have shown that the stability criteria not only apply to complete tidal basins, but also to parts thereof (see /8/).

Using the stability criteria, it is possible to describe the state of equilibrium of a tidal basin in a stepwise manner either from the bottom of the channel to the datum plane MHW in order to obtain a cross-sectional stability profile of the basin or from the shore to the seaward boundary of the basin in order to obtain a longitudinal stability profile.

To what extent the composition of bed material influences the stability criteria cannot be stated with any certainty at the present time. In view if this, the given relationship (Equation 6 and 7) can be applied with confidence only for tidal basins of the German Bight.

4. Examples of Application

4.1 General Information

The predictive capability of the stability criteria will be demonstrated by application to the Süderau, which is an approximately 200 km^2 tidal basin on the north coast of the German Bight (Fig. 10).

Along this part of the coast, erosional processes prevail as a result of the geomorphological development of the tidal region since the catastrophic storm surge of 1634. Today this erosion poses a danger to the stability of the tidal areas, the shore protection structures of the mainland, and the entire ecosystem.

Special problems exist in the region of the "Strand", which is a 200 m wide and about 10 m deep channel connecting the two channel systems Norderhever and Süderau (Fig. 10). Due to the tidal conditions in this region, a residual discharge of approximately 50 Mio. m^3 per tide passes through the Strand from the Norderhever into the Süderau. This residual discharge acts as a flushing mechanism in the Süderau. Owing to the large load-carrying capacity of this flushing discharge, the Süderau has been transformed into a very wide and deep tidal basin. At low tide, an additional tidal volume of $10 \cdot 10^6$ m^3 flows to the west from Norderhever into the neighbouring Rummelloch-West (see Fig. 10).

Owing to the historical development and the widening of the Süderau by the flushing discharge, it is to be expected that this tidal basin is in a hydrological-morphological state of non-equilibrium.

4.2 Stability Investigations of the Süderau

The stability criteria make it possible to make predictions of the stability behaviour of a tidal basin from the bed of the channel up to the reference plane MHW. For this purpose, extensive preliminary work was necessary, as given in detail in Section 2.3.

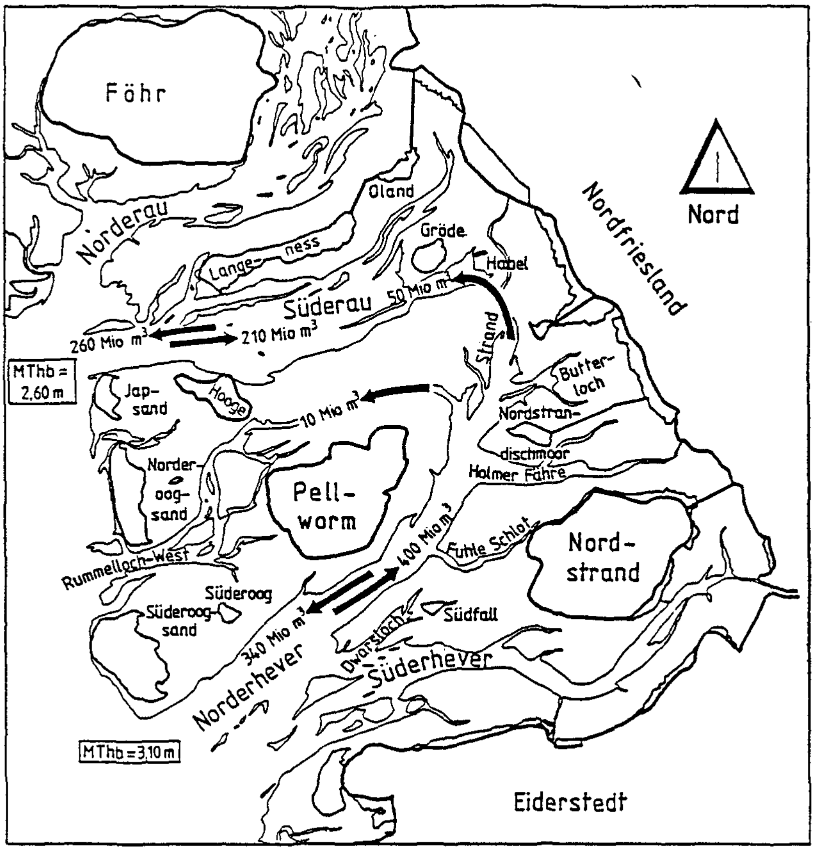


Fig. 10: Balance of tidal discharge in the region of the mudflat channel systems Norderhever-Strand-Süderau and Rummelloch-West.

The results of the evaluations and the subsequent necessary computer analysis are presented in the form of output listings which contain amongst other parameters the theoretical and measured volumes and the volume balances.

With this data, the stability profile of a tidal basin may be represented. The latter shows in the form of a volume balance summation curve the overall degrees of sedimentation or erosion to be expected until an equilibrium state is reached landwards of the profile considered. The stability profile (Fig. 11a) of the Süderau tidal basin indicates a clear volume excess, i.e. the measured volumes are greater than the theoretical ones. On the basis of this, sedimentation in the order of $39 \cdot 10^6$ m^3 is to be expected below MLW (channel region), whilst in the tidal range region (flat section), $(212 - 39) \cdot 10^6$ $m^3 = 173 \cdot 10^6$ m^3 is to be expected. The clear non-equilibrium state, particularly above MLW, is mostly due to the flushing capacity of the tidally-induced

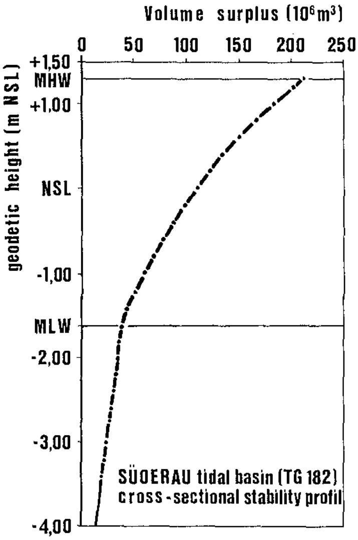


Fig. 11a: Stability profile of the Süderau tidal basin.

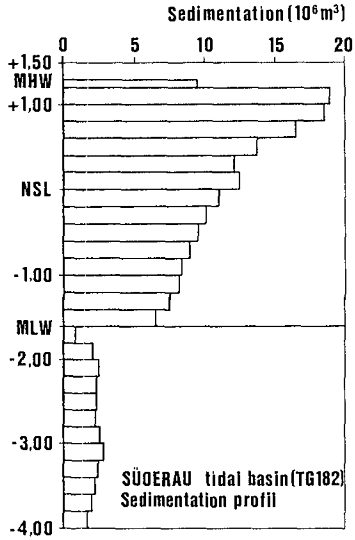


Fig. 11b: Sedimentation profile of the Süderau tidal basin.

flushing discharge from the Norderhever into the Süderau.

The sedimentation profile (Fig. 11b) shows the volume changes (sedimentation) to be expected per height interval. The sedimentation quantities per height interval are determined by simply taking differences from the stability profile summation curve. For sufficiently small height intervals, a functional curve for the sedimentation profile is obtained, which represents the derivative of the stability with respect to the geodetic height.

The stability criteria are also valid for parts of tidal basins. By means of appropriate incremental volume balances in a tidal basin from the coast towards the sea for different reference planes (e.g. MLW or MHW), longitudinal stability profiles are obtained. The latter provide a visual representation of the overall stability behaviour of the entire tidal basin. The longitudinal stability profiles of the Süderau for the reference planes MLW and MHW show that the tidal basin is not only in a state of non-equilibrium at its seaward boundary but also over the entire region, except for several unimportant cases of erosion in the immediate vicinity of the coast (see Fig. 12).

The amount of sedimentation to be expected in the Süderau may be visualized as a cube with a side length of approximately 6 km. It is not expected, however, that the amount of sedimentation predicted on the basis of the volume balances in the present state will actually occur. This will be the case as long as the tidally-induced flushing discharge from the Norderhever (see Fig. 10) continues to be effective. This flushing discharge has produced an artificial state of non-equilibrium which may only be removed when the flushing discharge is

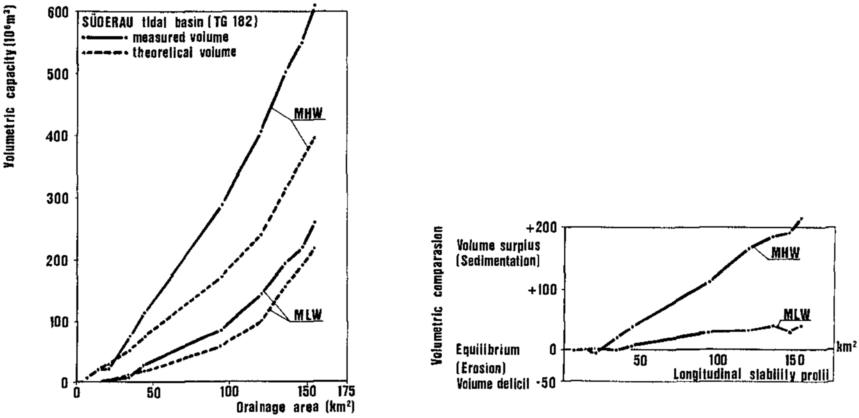


Fig. 12: Longitudinal stability profiles of the Süderau tidal basin.

prevented, as for example by means of an offshore dyke between the mainland and the Island of Pellworm (see Fig. 10). This dyke is being designed at present, and is expected to be constructed sometime after 1990.

5. Conclusion

The investigations described here show that it was possible to obtain a considerable improvement in the stability criteria so far known for tidal basins in the German Bight. This was done by taking into account the differences in the structure of the tidal basins with respect to varying tidal conditions and the separate evaluation of the creek and the flat section of the tidal basin.

The stability analysis for the Süderau tidal basin, that was undertaken as being representative of others, reveals not only the efficacy of the newly developed criteria and of the associated evaluation procedure, but also the possibility of applying it to tidal basins that have special boundary conditions as a result of particular hydrological and morphological developments.

6. References

/1/ RENGER, E.; PARTENSCKY, H.W.: Stability Criteria for Tidal Basins. Proc. 14th Intern. Conf. on Coastal Engineering, Vol II, pp. 1605-1618, Copenhagen (1974).

/2/ DIECKMANN, R.; PARTENSCKY, H.W.; SCHWARZE, H.: Morphological Reactions of Tidal Systems due to Nearshore Construction Works. Proc. 18th Intern. Conf. on Coastal Engineering, Vol. III, pp. 2495-2503, Cape Town (1982).

/3/ DIECKMANN, R.: Geomorphologie, Stabilitäts- und Langzeitverhalten von Watteinzugsgebieten der Deutschen Bucht. Thesis. Mitteilungen des FRANZIUS-INSTITUTS für Wasserbau und Küsteningenieurwewesen der Universität Hannover, Heft 60, (1985).

/4/ DIECKMANN, R.; PARTENSCKY, H.W.: Quantitative Geomorphology of Tidal Flat Areas. Proc. Iceland Coastal and River Symposium, pp. 53-62, Reykjavik, Iceland (1985).

/5/ HAYES, M.O.: Barrier Island Morphology as a Function of Tidal and Wave Regime. In LEATHERMAN, S.P. (Ed.): Barrier Islands, pp. 1-27, Academic Press. Inc. New York (1979).

/6/ HOWARD, A.D.: Geomorphological Systems - Equilibrium and Dynamics. American Journal of Science, Vol. 263 (1965).

/7/ LANGBEIN, W.B.; LEOPOLD, L.B.: Quasi-Equilibrium States in Channel Morphology. American Journal of Science, Vol. 262, (1964).

/8/ PARTENSCKY, H.W.: Neue Erkenntnisse über das Stabilitätsverhalten und den Sedimenttransport in Watt-Priel-Systemen. Mitteilungen des Franzius-Instituts für Wasserbau und Küsteningenieurwesen der Universität Hannover, Heft 50 (1980).

/9/ PARTENSCKY, H.W.; DIECKMANN, R.; OSTERTHUN, M.: A German Multipurpose Offshore Diking Project and its Effects on the Morphology and Ecology of the Adjacent Tidal Flats. Proceedings Coastal Zone 85, ASCE, New York (1985).