SEDIMENTATION PROCESSES IN TIDAL CHANNELS AND TIDAL BASINS CAUSED BY ARTIFICIAL CONSTRUCTIONS

by

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1. INTRODUCTION

Tidal basins and tidal rivers especially in areas of agricultural and industrial interest are more and more regulated and improved for different reasons such as draining, disposal of waste water, shipping and storm flood protection. This is - up to now - mainly done by dams, dikes, training walls, channel dredging, storm surge control barriers, etc..

In general, the tidal motion (tidal range and tidal velocities) in the whole system is affected by these man-made changes in the cross-sectional area of the tidal river. The hydrographical effects caused by such artificial constructions in tidal rivers have been outlined in the papers of H.G. WITTMER and al.(12). However, the morphological consequences of such measures are largely unknown.

The analysis of a real system, such as the EIDER-Estuary at the German Bay, which was affected by both a reduction in its tidal prism by the construction of a tidal dam in 1936, and by a reduction of its cross-sectional area by a storm surge control barrier in 1972, must therefore be highly appreciated.

In general, the most important changes of a tidal regime are caused by two different types of artificial influences:

- horizontal reductions of the tidal volume (for instance by damming-off a tidal river)
- vertical reductions of the cross-section(s) at any particular part of the tidal regime (for instance by storm surge control barriers or training walls)

In both cases the existing equilibrium conditions are disturbed and the relationships between the horizontal and vertical components of the tidal motion are distorted more or less according to the distance from the structure. As a consequence, the resulting pattern of flow and sediment transport is changed into a net flood-oriented flow. This leads to a very heavy siltation in the tidal system and consequently to a shrinking of the cross-sections.

An exact prediction of the sedimentation rates to be expected in tidal basins as a consequence of artificial constructions is not possible so far. However, the application of some simple equilibrium conditions, as have been used for the hindcasting of the sedimentation rates in the Eider-Estuary, seems to prove that an approximate evaluation of the morphological changes in a tidal system is nevertheless possible.

2. EQUILIBRIUM CRITERIA

Stability investigations of tidal basin inlets show the most important relationship between the cross-sectional area (F) and the associated mean tidal prism (V). Estuaries and tidal rivers follow - within certain boundary conditions - nearly the same relationship.

All the existing equilibrium criteria are based on the fundamental concept of correlating characteristical horizontal and vertical parameters of the system. In the following, two discharge oriented approaches shall be discussed in this paper.

W. HENSEN (2) defined a stability parameter (c_f) as an average flood current velocity under natural flow conditions as follows:

$$c_f = \frac{V}{D_f \cdot F_{fm}} \qquad (1)$$

with: V = mean tidal prism
D_f = duration of flood
F_{fm} = mean cross-sectional area (about half-tide)
c_f = average flood current velocity

Due to HENSEN, the equilibrium condition of a tidal system is given if the calculated c_f-value remains a constant, i.e.

$$c_f = c_{eq} = \text{const.} \qquad (2)$$

Although no fundamental research about this regime constant has been carried out, the average flood and ebb current velocities in tidal basins and tidal rivers with fine sand and silt seem to be of the order of $c_f \sim 0{,}67\,\text{m/s}$ (2).

A more detailed and especially vertically differentiated relationship was elaborated by E. RENGER (10).

When the continuity equation for non-steady flow is applied to any cross-section (s_i, z_i) of a tidal basin within the mean tidal range (ζ) the mean current velocity ($\bar{u}$)can be derived with a good accuracy as follows:

$$\bar{u} = \frac{A}{F} \cdot \bar{v} \quad \text{or} \quad \frac{u}{v} = \frac{A}{F} = \varphi\,(\zeta) \tag{3}$$

with: A = horizontal cross-section
F = vertical cross-section
$\bar{v}$ = mean velocity of tidal rise and fall

within the mean tidal range $\zeta = z'/H$

The equilibrium conditions of a tidal system were found to depend on a certain general vertical distribution $\varphi^{\mu}(\zeta)$ and on a reference value φ_R (H).

The morphological characteristic $\varphi^{\mu}(\zeta^{\mu})$is significant for the type of the tidal regime, whereas the reference value (φ_R(H)) obviously seems to depend on the mean tidal range (H).

3. GENERAL REMARKS ON THE REGIME CHANGING CONCEPT

As has been pointed out before, the two most important effects on a tidal regime are changes in the horizontal and vertical cross-sections. In both cases the existing hydrodynamical equilibrium is disturbed by the artificial constructions. The morphological reactions of the system (in most cases heavy sedimentation) show at first an increasing tendency but tend to reach a new state of equilibrium with time.

The mean flow characteristics of the system u(z') and c_f are directly related to the morphological changes of the tidal basin. This can be shown by the two formulas mentioned before:

$$\text{from (1)} \quad c_f \sim \left[\frac{V}{F_{fm}}\right] = \left[\frac{\int_0^H A\,dz'}{F_{fm}}\right] \tag{4}$$

$$\text{from (2)} \quad u(z') \sim \left[\frac{A\ (z')}{F\ (z')}\right] \tag{5}$$

where F_{fm} and F(z') are the terms in which morphological changes are represented.

As a first step and for a rather good estimate of the expected changing of the regime, only the morphological terms of both formulas need to be analized. The most important assumption for this analysis is, however, that the equilibrium criterias mentioned before can be applied furthermore to the remaining tidal influenced part of the system. In other words, the hydrodynamical components of the equilibrium approaches ($c_f = c_{eq}$, D_f, u(z') and v(z')) are of an universal importance and remain of the same numerical order as given in the former state.

4. STAGES OF MORPHOLOGICAL REACTIONS

With respect to the general remarks on the regime changing concept of tidal basins due to artificial constructions four typical stages of morphological reactions can be distinguished (Table 1):

Stage of time	Criteria		Stability
I. $t_1 = t_{eq}$ (exist) existing condition	$c_{f1}/c_{eq} \simeq 1$	$u_1/u_{eq} \simeq 1$	stable (assumed)
II. t_2, just influenced by artificial construction	$c_{f2}/c_{eq} \gtrless 1$	$u_2/u_{eq} \lessgtr 1$	non stable
III. t t_3 period of change	$c_f(t)/c_{eq} \rightarrow 1$	$u(t)/u_{eq} \rightarrow 1$	different degrees of unstability towards stability
IV. $t_3 = t_{eq}$(exp.) expected new equilibrium	$c_f/c_{eq} = 1$	$u/u_{eq} = 1$	stability

TABLE 1: Stages of morphological reactions

In stage II the two alternative signs indicate either reduction (symbol $<$) or enlargement (symbol $>$) of the tidal system.

The different morphological time stages for a schematic reduction of a tidal basin - for instance by the construction of a tidal dam - are shown for the two equilibrium approaches of HENSEN and RENGER (in figure 1 and 2, respectively). The figures show a schematical tidal basin and the parameters of state used in the approaches. The morphological changes to be expected are indicated for the different stages. The equations for the calculation of the corresponding cross-sections F are listed in Table 2 for the two different approaches.

Stage I: Existing condition

The existing condition is assumed to be in a dynamical equilibrium, i.e. no net sediment transport between ebb and flood current exists. The equilibrium state is represented by the c_f - and u - values, which vary within the mean tidal range ($0 \leq z' \leq H$). The equilibrium condition is shown

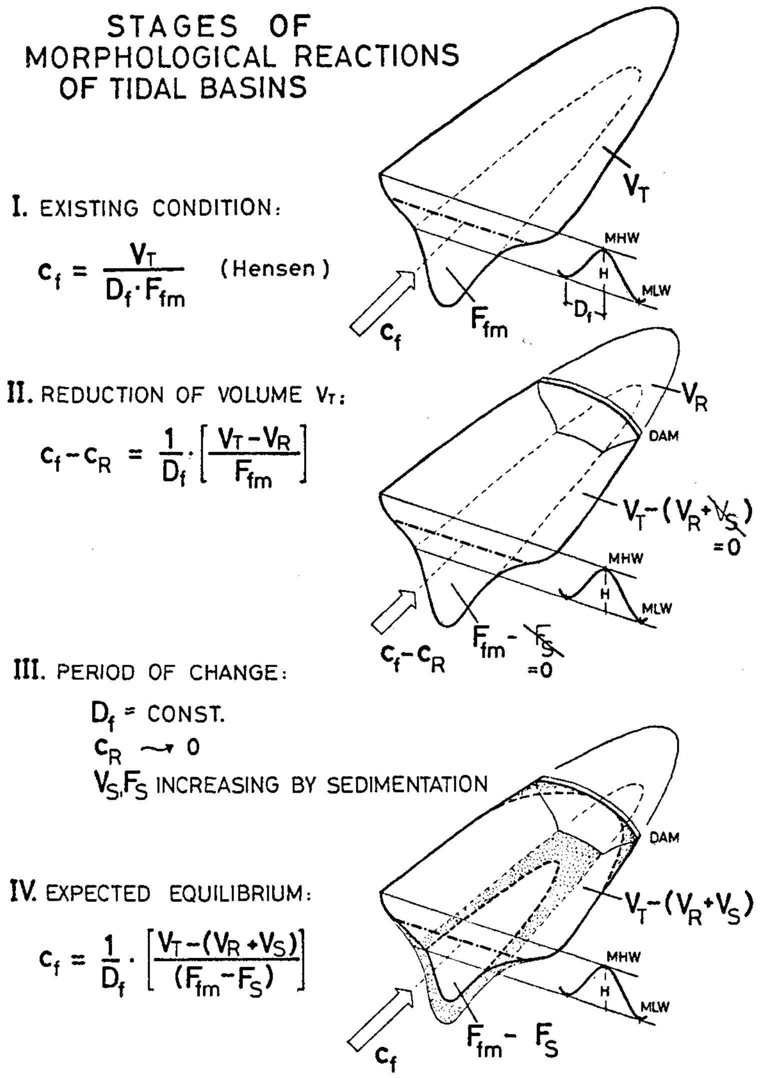

STAGES OF MORPHOLOGICAL REACTIONS OF TIDAL BASINS
I. EXISTING CONDITION:
$c_f = \frac{V_T}{D_f \cdot F_{fm}}$ (Hensen)
II. REDUCTION OF VOLUME V_T:
$c_f - c_R = \frac{1}{D_f} \cdot \left[\frac{V_T - V_R}{F_{fm}}\right]$
III. PERIOD OF CHANGE:
D_f = CONST.
$c_R \rightarrow 0$
V_S, F_S INCREASING BY SEDIMENTATION
IV. EXPECTED EQUILIBRIUM:
$c_f = \frac{1}{D_f} \cdot \left[\frac{V_T - (V_R + V_S)}{(F_{fm} - F_S)}\right]$
V_T
MHW
H
MLW
D_f
F_{fm}
c_f
V_R
DAM
$V_T - (V_R + \cancel{V_S})$
=0
$c_f - c_R$
$F_{fm} - \cancel{F_S}$
=0
$V_T - (V_R + V_S)$
$F_{fm} - F_S$

Figure 1

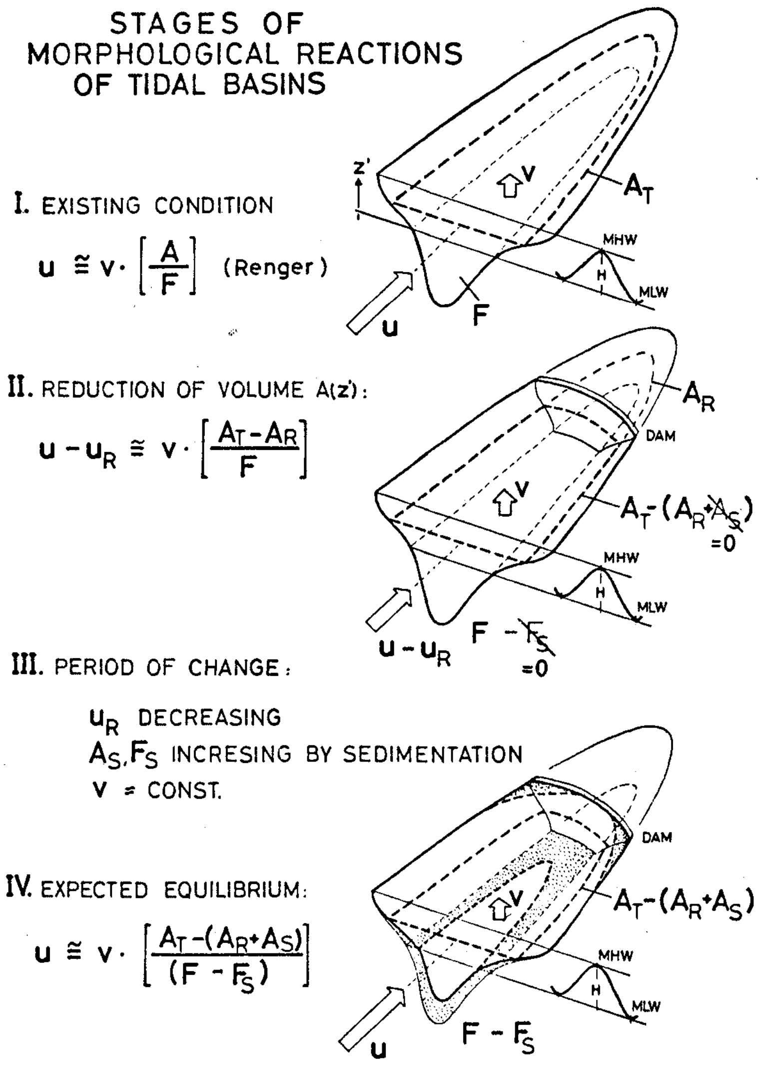

STAGES OF
MORPHOLOGICAL REACTIONS
OF TIDAL BASINS
I. EXISTING CONDITION
$u \cong v \cdot \left[\frac{A}{F}\right]$ (Renger)
z'
V
A_T
MHW
H
MLW
F
u
II. REDUCTION OF VOLUME A(z'):
$u - u_R \cong v \cdot \left[\frac{A_T - A_R}{F}\right]$
A_R
DAM
V
$A_T - (A_R + \cancel{A_S})$
=0
MHW
H
MLW
$u - u_R$
$F - \cancel{F_S}$
=0
III. PERIOD OF CHANGE:
u_R DECREASING
A_S, F_S INCRESING BY SEDIMENTATION
V = CONST.
IV. EXPECTED EQUILIBRIUM:
$u \cong v \cdot \left[\frac{A_T - (A_R + A_S)}{(F - F_S)}\right]$
DAM
V
$A_T - (A_R + A_S)$
MHW
H
MLW
u
$F - F_S$

Figure 2

in figure 1 and 2 for the two approaches.

Stage II: Directly after reduction of the tidal volume

The initial change of the significant parameter is caused by the man-made construction (tidal dam, see figure 1). Due to the location of the dam and the corresponding reduction of the tidal volume (V_R and $A_R(z')$, fig. 1 and 2), the velocity-pattern within the remaining part of the tidal basin will also change ($c_f - c_R$, $u - u_R$) as a natural hydrodynamical reaction.

Stage III: Period of time dependent morphological changes

As a consequence of the reduction in tidal volume, the existing sediment transport is changed into a resulting flood-oriented sediment transport. The latter will cause a continuous reduction in the cross-sections (F) of the remaining part of the tidal basin. The shrinking of the tidal basin will in turn affect the tidal motion in it (see fig. 1 and 2 - stage III). This process of morphological and hydrological changes will continue until a new state of equilibrium is reached.

Stage IV: Expected new equilibrium

The expected new state of equilibrium at the end of the time dependent morphological and hydrological changes in the tidal basin can only be predicted by means of a rough approximation. This is due to the fact that in both methods only the vertical and horizontal morphological parameters are considered to be variable, whereas all other variables are kept constant. The calculated cross-sections (F_{calc}) must therefore be considered as an upper limit of the expected ones, i.e. (see figure 1, stage IV and table 2):

$$F_{exp} < F_{calc} = F_{fm} - F_S \tag{6}$$

In the following, the approximated forecasting equations are applied to the case of the Eider-River at the German Bight where a considerable part of the tidal volume was dammed-off by the construction of a tidal dam in 1936 and a storm-surge barrier was built at its ocean entrance in 1972.

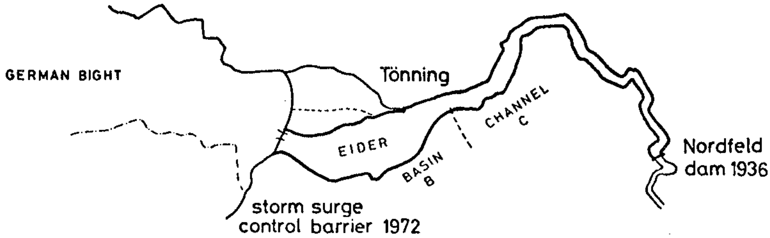
5. APPLICATION OF THE FORECASTING METHODS TO THE EIDER RIVER

General remarks: The tidal river of the Eider which flows into the inner German Bay had been dammed-off by a tidal dam at Nordfeld in 1936 (see figure 3).

Due to the construction of the dam, the initial tidal volume of the estuary was reduced by approximately 12 Mio m^3. As a result of this reduction in tidal volume, a heavy accumulation of silt and sediment was observed downstream of the tidal dam in the following 30 years. By means of

Stage of Reactions	Approaches for the calculation of the cross-sections (F) Method of W. HENSEN (1937)	Method of E. RENGER (1978)
I. Existing equilibrium condition	$F_{f_m} \sim \frac{V_T}{c_f}$	$F \sim \frac{A_T}{u}$ (all variables vary with (z') within the mean tidal range)
II. Stage directly after the reduction of the tidal volume	$F_{f_m} \sim \left\lvert \frac{V_T - V_R}{c_f - c_R} \right\rvert = \frac{\text{calc. } V}{(c_f - c_R)}$	$F \sim \left\lvert \frac{A_T - A_R}{u - u_R} \right\rvert = \frac{\text{calc. } A}{(u - u_R)}$
III. Period of time dependent morphological changes	$F_{f_m}(t) = F_{f_m}(I) - F_s(t)$ $F_{f_m}(t) \sim \frac{(V_T - V_R) - V_s}{(c_f - c_R)} = \frac{\text{calc.} V - V_s}{(c_f - c_R)}$ with: $D_f(t) \approx$ const. $c_R \rightsquigarrow 0$ $V_s \rightsquigarrow$ increasing from zero $F_s \rightsquigarrow$ increasing from zero	$F(t) = F(I) - F_s(t)$ $F(t) \sim \frac{(A_T - A_R) - A_s}{(u - u_R)} = \frac{\text{calc. } A - A_s}{(u - u_R)}$ with: $v(t) \approx$ const $u_R \rightsquigarrow 0$ $A_s \rightsquigarrow$ increasing from zero $F_s \rightsquigarrow$ increasing from zero
IV. Expected new equilibrium	exp $F_{f_m} <$ calc.$F_{f_m} \sim \frac{\text{calc.} V - V_s}{c_f(eq)} < \frac{\text{calc.} V}{c_f(eq)}$	exp.F. $<$ calc.$F \sim \frac{\text{calc } A - A_s}{u(eq)} < \frac{\text{calc.} A}{u(eq)}$

Table 2:



Volume below...	mNN	MEASURED IN 1936	1967	HINDCASTING OF THE influence of 1936	FORECASTING OF THE influence of 1972
... MHW	+1.64	100.56	49.65	52...43 (-12)	30...18 (-12)
MTR	3.28m	54.82	35.67	40...36 (-11)	27...16 (-11)
... MLW	-1.64	45.74	13.98	7 ... 9 (-1)	3 ... 2 (-1)
				E(B+C) E(B)+C	(C)

Figure 3

soundings carried out at certain intervals, a total sedimentation of about 50 Mio m^3 has been determined downstream of the dam covering an area of about 25 km^2 over a length of 30 km. A detailed description of the time-dependent morphological changes in the Eider basin can be found in reference (4) .

In the following, an attempt is made to hindcast the observed morphological changes in the Eider river by means of the two methods discussed before. In particular, the shrinking of the tidal volume below MHW and MLW is investigated and compared with the prototype measurements (7,8,9).

Hindcasting of the cross-sections: As has been outlined before, the new cross-sections to be expected after the construction of the tidal dam and the restoration of a new morpho-dynamical equilibrium (see figure 1, stage IV) can be determined by means of the following equation:

$$\text{calc } F_{fm} = \frac{\text{calc.}V}{D_f . c_f(eq)} = \frac{V_t - V_R}{D_f . c_f(eq)} \qquad (7)$$

For reasons already discussed before, the calculated F_{fm}-values according to equation (7) are somewhat higher than the actual values (exp F_{fm}) to be expected for each cross-section, i.e. calc. F_{fm} > exp.F_{fm}. The former can therefore be considered as an upper limit of the expected new cross-sections.

In Table 3, the results of the calculations for two different cross-sections of the Eider-River (profiles 78 and 115, see figure 3) are presented for four different years. The first calculation was carried out for year 1935, when the tidal dam was not yet built (Figure 1, stage I). The second calculation (1936) corresponds to stage II (fig.1), i.e. summarises the situation after the construction of the dam, whereas the calculations for the years 1967 and 1976 show the situation in the Eider river during the morphological changes (stage III and IV, respectively).

All parameters used for calculating the new cross-sections F_{fm} had to be taken from the tidal system at stages I (existing condition) and II (situation directly after the completion of the tidal dam). These values are printed in bold in Table 3.

CALCULATION OF THE EXPECTED CROSS-SECTIONS OF THE EIDER

year	Vol ($10^6 m^3$)		D_f (min)		F_{fm} (m^2)		c_f (m/s)	
PROFILE	78	115	78	115	78	115	78	115
1935	17.9	26.2	**352**	**362**	1.600	1.790	**0.52**	**0.67**
DAM								DAM
1936	**5.9**	**14.2**	310	320	1.600	1.790	0.20	0.41
1967	5.3	12.8	315	320	500	820	0.53	0.81
1976	5.1	12.3	320	322	324	640	0.82	0.98
				CALCULATED:	530	970 m^2		

Table 3

As can be seen from the figures in Table 3, there is a reduction of 12 Mio m^3 in tidal volume due to the construction of the tidal dam. The remaining tidal volumes of 14,2 Mio m^3 (profile 115) and 5,9 Mio m^3(profile 78) decrease, however, with time due to the heavy accumulation of silt and sand in the upper part of the estuary.

An even more pronounced effect could be observed for both profiles in the decrease in cross-sectional area (Table 3). The measurements obtained for 1976 might already be slightly affected by the influence of the new tidal control barrier which was built in 1972 at the ocean entrance of the Eider river. The values obtained for 1967 show, however, a fairly good agreement with the calculated F_{fm}-values according to equation (7).

Hindcasting of tidal volumes: During the last 6 years, systematic evaluations of about 25 existing tidal basins of the inner German Bay, were carried out by the Franzius-Institute, University of Hannover/Germany, which led to some general stability criteria for these tidal basins with a mean tidal range of about 3,0 m. It could be shown that the tidal volume V of a basin depends clearly on its drainage area E. The empirically determined relationship for the volumetric capacity of the tidal basin at MLW as well as for the mean tidal volume V_{Tm} are as follows (8,10):

$$\text{Mean tidal volume:} \quad V_{Tm} = 1{,}65 \cdot E^{1{,}036} \tag{8}$$

$$\text{Capacity at MLW :} \quad V_{MLW} = 4{,}39 \cdot E^{1{,}643} \tag{9}$$

where volumes V are in ($10^6 . m^3$) and drainage areas E in (km^2).

The two equations were applied to the Eider basin between the dam at Nordfeld (built in 1936) and the storm surge barrier (built in 1972) at its ocean entrance (see figure 3).

Because of the complex form of the Eider basin, two different approaches were used in the attempt to hindcast the observed sedimentation rates. For this, the Eider basin was subdivided into a basin (B) and a channel part (C), as shown in figure 3.

In the first approach, the sum of the areas B and C was used as significant drainage area, i.e. E = B + C, whereas in the second approach only the drainage area of the basin part (B) was used as variable and the remaining volume of the channel part (C) of about 12 Mio m^3 was added to the tidal volumes calculated by means of equations (8) and (9).

The results are shown in the table of figure 3. The calculations were carried out for 2 different tidal levels (MHW and MLW) and for the mean tidal range (MTR). As can be seen from the results, the hindcasted volumes (in Mio m^3) are in a rather good agreement with the values obtained by systematic soundings in 1967 (see table in figure 3).

6. FORECASTING OF THE INFLUENCE OF THE STORM SURGE CONTROL BARRIER, BUILT IN 1972

As has been pointed out in the introductory remarks, a change in the morphology of a tidal basin can also be caused by a local narrowing down of the existing cross-section of the basin, as for example by a storm surge control barrier. An artificial construction of this kind acts like a singular discontinuity within the horizontal distribution of the cross-sections along the river axis.

The effect of such discontinuities on the morphological reaction of a tidal system has been recently investigated by several authors (6,8,11). In general, an abrupt narrowing down of an existing cross-section of a tidal basin by means of an artificial construction leads to a distortion of the tidal wave with a partial reflection of the latter. The horizontal and vertical velocity components u(t) and v(t) of the tidal motion are changed which results in a distorted flow pattern on both sides of the construction. As a result, the transport capacity of the tidal flow is changed with a higher concentration of silt and sediment in the upper layers. This leads to an increase in the transport range of the sediments, especially under flood conditions.

The net effect of the narrowing down of the cross-section will be an accumulation of sediment and silt on both sides of the construction, the amount of which depending upon the degree of contraction.

At the new storm surge control barrier at the mouth of the Eider river (figure 3), heavy sedimentation was observed upstream and seaward of the construction since its completion in 1972.

By applying the tidal basin concept to the Eider basin restricted by the control barrier, an attempt can be made to forecast the sedimentation rates to be expected within the remaining basin. Using the two different approaches as mentioned before, an upper and lower limit for the reduced tidal volume to be expected could be determined. The results are shown in the table of figure 3. As can be seen from the calculated values, some additional 22 to 25 Mio m^3 of silt and sedimentation must be expected under MHW within the Eider basin (compared with 1967) until a new state of morphological equilibrium is reached (7). The evaluated soundings along the Eider river since 1972 seem to support this prediction (see figure 4).

7. CONCLUSIONS

The knowledge of morphological changes to be expected in tidal rivers and basins as a result of man-made constructions such as dykes, dams and tidal control barriers is of high interest for future decisions in tidal regions of agricultural and economical value. It was the aim of this paper to present two empirical approaches by means of which a prediction of the morphological reaction of a tidal system and an estimate of expected sedimentation rates is possible.

By using prototype measurements from the Eider River, it could be shown that the observed sedimentation rates were in fairly good agreement with obtained theoretical values from the two empirical approaches. Although further systematic research is needed in this respect, it seems that the two methods discussed in this paper promise to be a

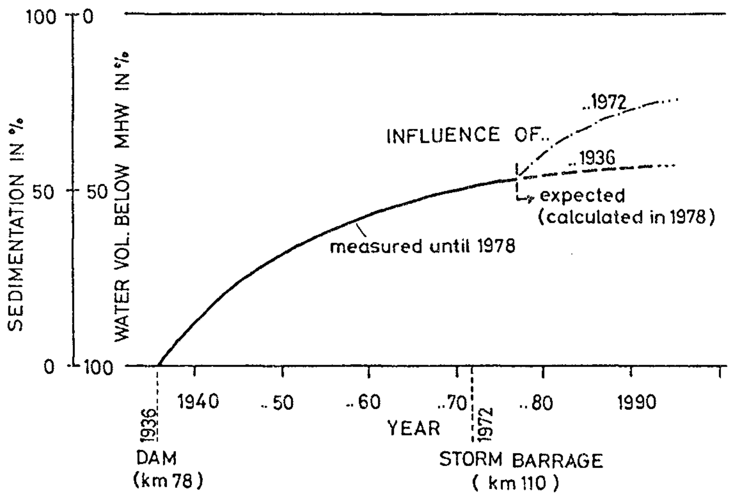


FIGURE 4

good tool in the prediction of sedimentation rates to be expected in tidal basins and tidal rivers due to artificial constructions in the tidal regime.

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