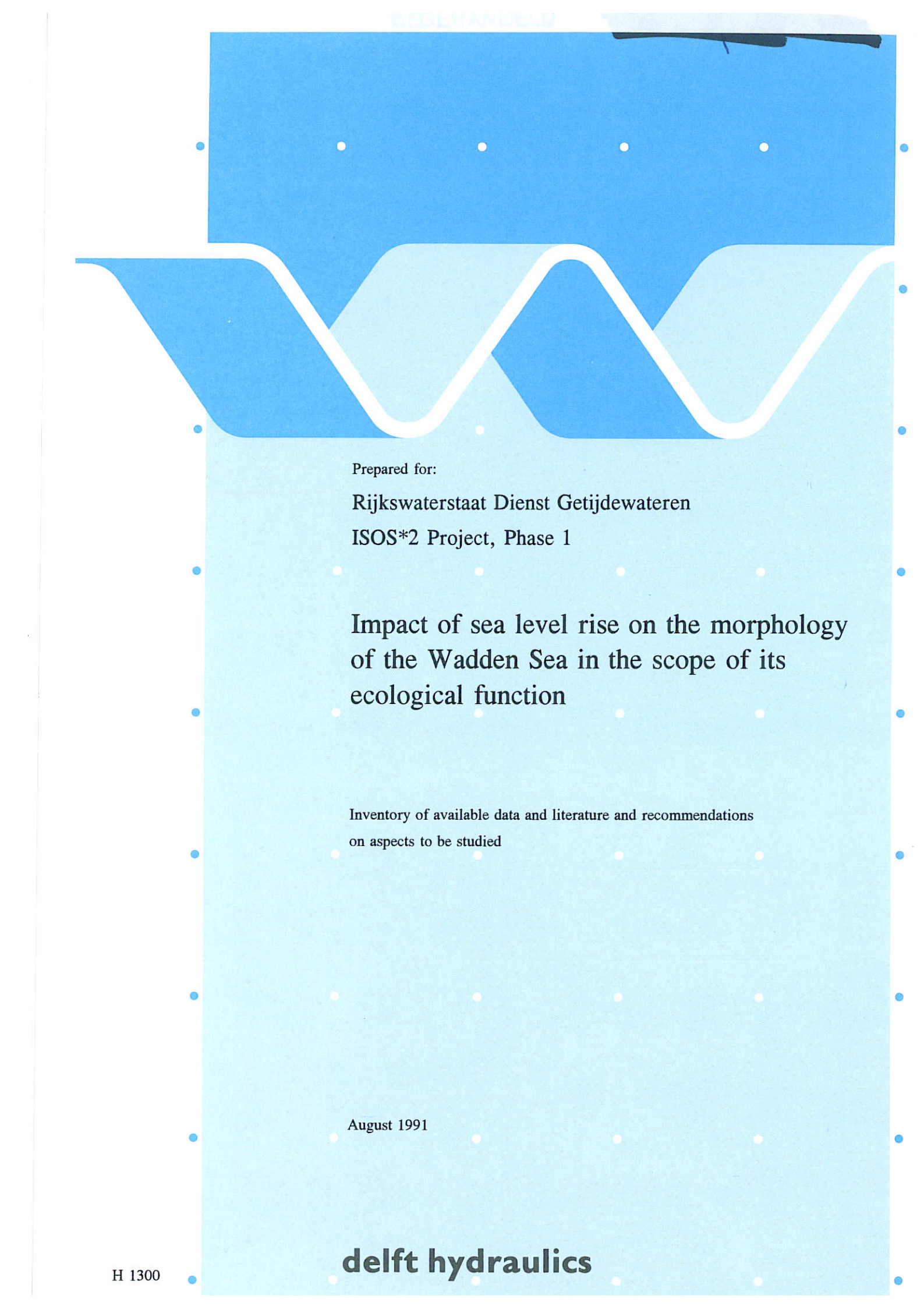




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Rijkswaterstaat Dienst Getijdewateren

ISOS*2 Project, Phase 1

Impact of sea level rise on the morphology of the Wadden Sea in the scope of its ecological function

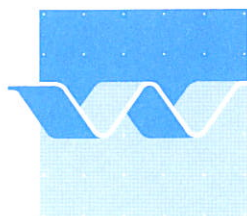
Inventory of available data and literature and recommendations
on aspects to be studied

August 1991

Impact of sea level rise on the morphology of the Wadden Sea in the scope of its ecological function

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W.D. Eysink



delft hydraulics

CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS

	page
1. <u>Introduction</u>	1
1.1 Purpose of the study.....	1
1.2 Terms of reference.....	3
1.3 Conclusions and recommendations.....	4
2. <u>Morphological relations and data from literature</u>	6
2.1 General.....	6
2.2 Morphological relations from literature.....	7
2.2.1 Tidal channels and inlets; cross-sectional stability.....	7
2.2.2 Channel width and depth.....	11
2.2.3 Size and shape of outer deltas.....	13
2.2.4 Volume of channel systems in tidal basin and estuaries.....	14
2.2.5 Tidal flats.....	16
2.2.6 Sedimentology.....	18
2.2.7 Other quantities.....	18
2.3 Field data of the Dutch Wadden Sea.....	19
3. <u>Recommended approach of phase 2</u>	20
3.1 Applicability of various morphological relations.....	20
3.2 Missing links for a conceptual morphological model.....	21
3.3 Recommendations for further investigation.....	22

REFERENCES

FIGURES

LIST OF FIGURES

1. Sand volume outer deltas in USA in relation to the mean tidal prism of the inlet according to Walton and Adams [59]
2. Morphological relationships outer delta according to Vincent and Carson [61]
3. Reduction of tidal prism of a basin due to tidal flats
4. Relative area of the intertidal zones in the Dutch Wadden Sea and the Delta area
5. Total number of discharge measurements in each tidal basin of the Dutch Wadden Sea
6. Long term water level records of stations in the Dutch Wadden Sea
7. Tentative time schedule of phase 2

LIST OF SYMBOLS

A_b	: storage area of basin at MHW if level not specified
A_c	: flow area of a tidal channel below a specified level (MSL if not specified)
A_{ch}	: channel area = $A_{b,MLW}$
A_f	: tidal flat area in basin = $A_b - A_{ch}$
A_{od}	: area of outer delta
a	: empirical coefficient
$\bar{a}$	: parameter
α	: parameter
C	: roughness coefficient of Chézy
c_A	: empirical coefficient
c_r	: empirical coefficient
$d_{max,MSL}$	: maximum depth below MSL
$\bar{d}_{MSL}$	: width-averaged depth below MSL
Δh	: (average mean) tidal range in basin
EV	: ebb volume
index ch	: characteristic
FV	: flood volume
g	: gravitational acceleration
L	: length
MHW	: mean high water level
MLW	: mean low water level
MSL	: mean sea level
MWL	: mean water level
M_{tot}	: total annual littoral drift
NAP	: Normaal Amsterdam Peil
n	: empirical coefficient
P	: tidal prism ($\approx TV/2$)
Q	: discharge rate (general)
$\hat{Q}$	: sinusoidal maximum discharge rate
Q_{bs}	: bed shaping river discharge rate
Q_{max}	: maximum discharge rate
Q_r	: river discharge
ρ	: density of water
T	: tidal period
TV	: tidal volume (FV + EV)

LIST OF SYMBOLS (continued)

τ_s	: stability shear stress
u	: flow velocity
u_*	: shear stress velocity
u_{*s}	: stability shear stress velocity
V_{MLW}	: channel volume below MLW
V_{od}	: sand volume stored in outer delta
V_z	: channel volume below level z
W	: channel width at MSL

1. Introduction

1.1 Purpose of the study

The Dutch Wadden Sea consists of a number of tidal basins and barrier islands separated by inlets. The morphology of the Wadden Sea area is determined by numerous factors and mechanisms, such as:

- tidal range and flow,
- seasonal wind and waves,
- geometry of the basins,
- pre-existing morphological and sedimentary structures due to geological processes,
- sediment transport mechanisms with related erosion, sedimentation and hydraulic sorting of sediment types,
- inland discharge and related salinity variation in time and space resulting in density currents and flocculation of particles, and
- biogenic input on coagulation of particles and on critical shear stress with respect to initial motion.

Also the Wadden Sea is an area with ecological functions which are of great national and international importance. In this respect the following functions can be recognized:

- spawning grounds and nursery area for fish, shell fish and shrimps,
- feeding grounds and resting place for many kinds of birds, among others large quantities of migratory birds,
- habitat of seals, and
- natural salt marsh and dune vegetation.

The above functions are mutually related through the food chain and dependant on the characteristics of the habitat such as the water quality, availability of nutrients, disturbance by man and the morphology of the area.

An accelerated increase of relative sea-level rise may create severe problems for coastal protection and will induce changes in the morphological development and in the related multivarious but vulnerable ecosystem of the Wadden Sea area. These alterations will also effect the functional uses of the area like fishery and natural potentials.

The acceleration of relative sea-level rise due to global climatic changes is a realistic expectation and will become an enormous challenge for coastal

defence management. Its effects will not only require the redesign and strengthening of existing coastal structures, but will probably also demand whole new concepts. Therefore the future morphological development will be of crucial importance for coastal defence management as well for barrier islands as for Wadden Sea coasts.

Due to these facts the main objective of the ISOS*2 project will be the development of methods which allow a reliable forecast of the future morphological response of the Wadden Sea area under both natural and human influences. Special emphasis is given to the effects of an acceleration in relative sea-level rise.

A reproduction of the morphological development of the Wadden Sea area by use of high resolution numerical modelling techniques with consideration of the above mentioned boundary conditions, is with presently available knowledge and tools not possible in a reliable way. Nevertheless, a distinct need exists to predict the impact of changing hydrodynamical conditions in the Wadden Sea due to both impacts of nature and human interventions with a fair degree of accuracy, as there are for example:

- relative sea-level rise,
- change of tidal amplitude,
- closure works,
- systematic sand borrowing and dumping of dredged sediments, and
- bottom subsidence due to extraction of natural resources.

Therefore, a more simple model is looked for which can be used to predict this impact with a sufficient degree of confidence. A promising option is the development of a conceptual model which is based on a number of empirical morphological relationships. Such relationships are valid on a high integration level and are not sensitive for instabilities and extrapolation errors like numerical models. A disadvantage is that the conceptual model will present less detailed results.

Main objective of the project is therefore the development and improvement of conceptual morphodynamic model as a tool for prognostization of the resulting morphological response on an accelerating sea-level rise in a long-term time scale (100 years).

This model should be able to present predictions on morphological changes as a result of increased sea level rise which are sufficiently detailed and reliable for predictions on the related ecological impact.

The developed knowledge and models will allow policy-makers, engineers and scientists to predict and control natural and human interferences on the Wadden Sea and adjacent coast. Furthermore, also other disciplines planning and working in the Wadden Sea area will benefit from their results.

1.2 Terms of reference

At the request of the Public Works Department of the Dutch Government DELFT HYDRAULICS made a proposal (Ref. HK8335/H1300/FH/Im dd 13th February, 1991) for:

- The development of conceptual models of the tidal basins of the Dutch Wadden Sea with the assistance of the Public Works Department and a study on the impact of sea level rise on the morphology of that sea. The study will be done in close cooperation with the Public Works Department.
- Guidance of the inventorization and brainstorming for the sedimentological study.
- Participation in the project group ISOS*2.

The investigations will be performed in the years 1991-1992 and are divided into three phases.

The first phase is the initiation of the study which comprises:

- Making an inventory of all relevant existing field data such as sounding maps, tide data, flow data, sediment data, wave data, activities of man, etc.

A comprehensive data inventory for the evaluated research areas and suitable data processing will provide both phenomenological analysis and verification of the initial version of the quasi-equilibrium model.

Phenomenological analysis will not only yield a deeper insight into morphodynamical processes of the Wadden Sea area but is preliminarily used to deliver results for improvements of the conceptual model.

- Set-up of a central base.
- Literature survey on existing morphological relationships.
- Selection of empirical morphological relationships to be studied in more detail to arrive at a consistent set of generally valid relationships.
- Reporting of the findings of phase 1.

The second phase of the study consists of the processing of the most suitable existing data. The selection of those data sets will be done in close cooperation with the client. After the data processing, various correlations will be made aiming at the assessment of suitable morphological relationships which will be generally valid for (dynamic) equilibrium conditions. Based on a selection of suitable relationships a conceptual equilibrium model will be made which will be verified based on, for example, data of the tidal basin of the Zoutkamperlaag.

Wishes from an ecological point of view will be incorporated if possible. The findings of this part of the study will be reported in a separate phase 2 report. Depending on the results of phase 2, the client will make a decision whether or not to start with phase 3 of the ISOS*2 project.

In phase 3 of the study an attempt will be made to make a transition model which can be used to describe the way of adaptation with time from the original equilibrium situation to another after the original equilibrium is disturbed in one way or another. Also this phase will be reported separately.

The above reflects the broad lines of the proposal. The Public Works Department commissioned the phases 1 and 2 of the study to DELFT HYDRAULICS in their letter BXFO/914230 of 18th February, 1991 (Order no. DG-255).

This report deals with phase 1 of the study which has been executed by W.D. Eysink of DELFT HYDRAULICS and O. van Kleef of the University of Utrecht. The study has been guided by F.M.J. Hoozemans of DELFT HYDRAULICS and Dr. J.P.M. Mulder and T. Louters representing the client. The report has been drawn up by W.D. Eysink.

1.3 Conclusions and recommendations

The Dutch Wadden Sea is a wetland area of great ecological importance as spawning ground and nursery area for fish, shell fish and shrimps, feeding and resting grounds for large amounts of migratory birds, habitat for seals and with its rich vegetation of the salt marshes and dunes.

An increased sea level rise (e.g. caused by mankind) may have large scale effects on the morphology of the tidal flat areas of the Wadden Sea. This

may disturb the delicate balance between the different ecological functions of the area. At present no numerical model can provide reliable predictions on this matter in a complicated system as that of the Wadden Sea.

Data from literature indicate that the development and application of empirical morphological relationships for the Dutch Wadden Sea may provide a promising alternative to arrive at fair predictions of the possible (morphological) consequences of sea level rise. Recommendations for further investigations are presented in Section 3.3.

2. Morphological relations and data from literature

2.1 General

The hydraulic conditions in tidal basins are important as dominant energy sources causing sediment transports, erosion and sedimentation, and sorting of sediment to size, mineral density and rollability. Together these phenomena form the basis of a complex geomorphodynamic system in which also flocculation of silt and clay particles and coagulation of those particles by shell fish and diatoms play an important role.

Today it is not possible yet to simulate the above complex processes sufficiently accurate in a numerical model. However, in spite of the complex and dynamic character of these areas, some system can be recognized in nature if we look in a broad way neglecting details such as migration of channels and shoals. It appears that we can express certain characteristic quantities in empirical relationships which are useful tools for engineers.

Literature concerning the stability of tidal inlets in relation to the tidal prism and other hydraulic parameters is available.

Also similar relations for stable profiles along tidal channels are presented as well as relations for the total volume of channels in a basin with tidal flats.

Only a few relations for outer deltas (in the USA) are presented in literature.

Very little is known about relations for tidal flats, such as ratio of flat area over basin area and height of the tidal flats in relation to characteristic tide levels and local wave energy.

In the present study an attempt will be made to find general relationships between hydraulic parameters and dimensions of tidal channels (size, volume, width and depth), outer deltas (sand volume and shape), tidal flats (relative area and height) and sediment characteristics (type of soil, D_{50} , sorting rate). An important item of the study will be to find significant interrelations between the above relationships which would allow for the set-up of a conceptual model for quasi-equilibrium stages and a transition model describing the way of adaptation of a system in which the equilibrium is disturbed in one way or another.

The study will be executed based on existing field data of the Wadden Sea and data from literature in general.

2.2 Morphological relations from literature

General discussions on hydro-morphological relations from literature already have been presented by Gerritsen [1], Steijn [2] and Van Kleef [3]. The major findings of these reports are summarized and discussed in this section.

2.2.1 Tidal channels and inlets; cross-sectional stability

Tidal inlets

It appears from literature that people are aware of some relation between size and tidal volume of a tidal inlet since at least the beginning of this century [4, 5, 6]. This resulted in a general relationship like:

$$A_{c,MSL} = c_A P^n + a \quad (1)$$

where:

- $A_{c,MSL}$ = flow area below MSL in the throat of the inlet,
- P = representative tidal prism of the basin,
- n = empirical coefficient,
- c_A, a = empirical coefficients depending on the definition of P , the value of n and the selected reference level (in this case MSL).

This relation has been confirmed many times ever since, where the empirical coefficients n , a and/or c_A appear to be dependent on local conditions such as (e.g. [7-14]):

- type of tide (semi-diurnal, diurnal or mixed),
- wave climate (calm, moderate, rough),
- size of inlet (small, general range, large),
- presence of jetties, and possibly,
- type of bed material, upland sediment transport rate, littoral drift and/or salinity effects on flow profiles.

To some extent the data will be effected by inaccuracies in particularly the tidal prism. In several cases the tidal prism has been calculated based on the tidal range and the size of the basin behind the inlet. Especially for large basins this may introduce significant inaccuracies.

The tidal prism in equation (1) must be considered as a characteristic hydraulic parameter representing the integrated hydraulic energy which is present in the never lasting tidal flow passing the inlet. Other authors used related parameters such as:

- Flood volume FV,
- Ebb volume EV,
- Tidal volume TV = FV + EV,
- Maximum discharge rate $Q_{\max}$ related to P, FV or EV,
- Maximum discharge rate $\hat{Q}$ related to a sinusoidal tide,
- Maximum flow velocity $u_{\max}$ or $\hat{u}$ related to $Q_{\max}$ and $\hat{Q}$ respectively,
- Average tidal velocity $\bar{u}$ related to P, FV, EV or TV,
- Stability shear stress velocity u_{*s} or shear stress τ_s related to $Q_{\max}$.

This was done to arrive at a better fit and a trial to find the best physical parameter related as closely as possible with sediment transport. The need for distinction between ebb and flood arose from studies on inlets of estuaries with upland discharge and of tidal channels with ebb or flood dominance.

The use of the stability shear stress τ_s is introduced by Bruun and Gerritsen [15] and used by the latter et al in studies on the stability of Dutch inlets and tidal channels in the western Wadden Sea [1,16-19]. Through τ_s the effect of waves can be taken into account by applying the concept of Bijker [20]. A promising option is the application of the dimensionless parameter with τ_s :

$$A_c = c_\tau \{Q_{\max} / (C \sqrt{\tau_s / \rho g})\}^n + a \quad (2)$$

where:

- A_c = flow area of tidal channel below MSL or, even better, below the water level at which $Q_{\max}$ occurs,
- c_τ, a = empirical coefficients,
- n = empirical exponent,
- C = roughness coefficient of Chézy,
- ρ = density of water,
- g = gravitational acceleration.

In this way also the effect of the bed roughness and the hydraulic radius of the channel profile is taken into account through the Chézy coefficient which could be a relevant parameter [1, 14, 21, 22, 23].

Estuaries and tidal channels

O'Brien already concluded that the inlets of estuaries follow the same relationship for tidal inlets of lagoons [12]. Based on data from literature Eysink concluded that such a relationship is also valid along a tidal channel in the Wadden Sea [24] and along the estuary of the Western Scheldt with a low river discharge [25]. It even appeared to be true up to the tidal limit in the river for the Nakdong estuary in Korea with a distinct seasonal upland discharge, if the dry season tidal prism is corrected for the river regime [26]:

$$A_{c,MSL} = 80.10^{-6} EV_{ch} \quad (3)$$

with

$$EV_{ch} = P + Q_{bs} T/2 \quad (4)$$

where:

- $A_{c,MSL}$ = local flow profile below the mean water level related to the back-water curve corresponding with Q_{bs} ,
- EV_{ch} = characteristic ebb volume at the considered cross-section,
- P = local tidal prism in the dry season,
- Q_{bs} = bed shaping river discharge, i.e. the constant discharge rate which yields the same annual sediment transport as the actual river regime.

The general validity of relation (1) also along tidal channels was confirmed by other investigators [16-19, 22, 27, 28, 29].

Mason [30] compared a regime concept for stable alluvial channels with relation (1) for tidal inlets and concluded there was a close similarity if P was replaced by $\hat{Q}$ in relation (1). Also Van der Kreeke and Haring [31] tried to incorporate the effect of river discharge Q_r into the relationship for the cross section of a tidal channel through the definition of the tidal volumes for a sinusoidal tide:

$$TV = \hat{Q}T \left[\frac{Q_r}{\hat{Q}} + \frac{2}{\pi} \left\{ 1 - \left(\frac{Q_r}{\hat{Q}} \right)^2 \right\}^{0.5} \right] \quad (5)$$

or

$$FV = Q_T \frac{1}{\pi} \{1 - (\frac{Q_r}{Q})^2\}^{0.5} \quad (6)$$

or

$$EV = Q_T \left[\frac{Q_r}{Q} + \frac{1}{\pi} \{1 - (\frac{Q_r}{Q})^2\}^{0.5} \right] \quad (7)$$

They did not find a proper relationship, possibly because of an inadequate definition of Q_r .

Some authors tried to find simplified models to predict ebb or flood dominance in an inlet or channel [32, 33, 34]. These models relate the geometry of the basin to the tidal flow history curves and sediment transport.

It is believed this type of approach is too theoretical and complicated based on a strongly schematized flow model implying limited accuracy. The approach merely presents a simplified mean to judge whether an inlet has a flood or ebb dominance in terms of sediment transport based on the shape of the basin. It does not give a direct relation describing an equilibrium condition, and therefore, will not be very useful for the present study.

Some additional aspects

Shigemura [9] succeeded to improve the correlation of his empirical relations by introducing the additional parameter $r_{as} = A_c/A_{b,MWL}$. Since P is directly related to the storage area $A_{b,MWL}$ (or A_b), he actually improved the correlation by selecting the cross sectional areas of the different inlets to their relative size. The factor r_{as} , very likely, has nothing to do with the cause of the scatter in the data of Shigemura.

Escoffier [35] developed a simple analytical relation between the maximum flow velocity in the inlet of a lagoon as a function of the size of the lagoon, the tidal range at sea, the flow profile of the inlet and the length and roughness of the inlet channel. By comparing the solution of this equation with the characteristic flow velocity for a stable inlet he finds a stable and unstable solution for the inlet profile. Based on the same concept Van der Kreeke [36, 37, 38] developed a theory to consider the stability of the inlets of a lagoon with two inlets.

Both theories are suitable for the design of a stable inlet to a lagoon. The authors compare an analytical solution of a simplified flow model with a characteristic flow velocity for a a stable inlet. Trough the latter they in

fact apply relation (1) in a different shape to judge if that criterion for stability is met. So, both theories are examples of the application of relation (1) and do not provide new information for the present study.

Bruun [39] related the stability of a tidal inlet to the ratio tidal prism P over littoral drift M_{tot} towards the inlet. For values of $P/M_{tot} < 20$ the inlet is unstable and for $P/M_{tot} > 150$ they are stable.

The above stability criteria or different ones from other authors will not be of much interest for the present study. They are only relevant for the design of a new stable inlet or to explain the stability or instability of an existing inlet. The present inlets of the Wadden Sea are all stable with respect to their existence and will remain so in the next centuries as long man do not interfere at a large scale.

2.2.2 Channel width and depth

In literature far less attention is paid to the quantities channel width and depth than to its cross sectional area. Most of the literature presenting information on those quantities is related to tidal inlets.

Mehta presents two diagrams relating the mean depth below MSL in inlets with the width at MSL for inlets with and without jetties ranging in size from model inlets (from Mayor and Mora [40]) to large inlets in nature [41].

Shigemura [8] made an attempt to relate the width of the tidal inlets with the tidal prism P and the average tidal velocity $\bar{u}$.

Fitzgerald et al [42, 43] established a relationship between the basin area A_b and the width of the inlet W :

$$W = 43 A_b - 547 \quad (\text{m}) \quad \text{with } A_b \text{ in km}^2 \quad (8)$$

Dieckman et al [29] presented graphs indicating relationships between the maximum depth in an inlet and the tidal prism and between the maximum and average depth in tidal inlets in the German Bight.

Hume and Herdendorf [44] give diagrams for the maximum depth and mean depth related to the width of inlets of New Zealand.

Sha [45] presents a diagram relating the maximum depths of the inlets of the Dutch Wadden Sea with the tidal prism and Eysink [46] gives a relation between the mean depth of those inlets and the tidal prism:

$$\bar{d}_{MSL} = 0.35 [P \cdot 10^{-6}]^{0.65} \quad (9)$$

Data on width and depth of tidal inlets of the East Frisian Wadden Sea can be derived from [45] and articles of Walter [47] and Luck [48].

From the data it is obvious that the relations on channel width and depth show far more scatter than those on the flow area. In a way this seems logical; if a channel is confined in width or depth (e.g. by hard bed layers or bank protection works) nature will respond by making the cross-sectional area by widening or deepening the channel in the direction where this is possible.

Data on channel width and depth along tidal channels and estuaries are not available yet.

Boon and Byrne [34] deduced a relation between channel depth and width from observations of Mehta (in [49]):

$$d_{MSL} = 0.042 W^{0.92} \quad (10)$$

where:

d_{MSL} = depth in the channel cross section,
 W = width of the channel at MSL.

It is considered useful to develop similar or better relationships based on data of the Dutch Wadden Sea as a basis for the set up of an empirical equilibrium model. Channel width and depth should be related to hydraulic parameters rather than geometrical parameters, and to bottom conditions such as existence of non-erodable layers or protection works. Such relations will be important to allow for realistic predictions on future morphological developments in case of human interference in a system or in case of changes in sea-level rise for example.

2.2.3 Size and shape of outer deltas

In literature many classifications of coasts and outer deltas are presented [2] which relate characteristic features to hydraulic parameters such as tidal range, characteristic flow velocities, wave conditions, dimension and shape of tidal basin, etc. [15, 39, 50-57]. These classifications only provide qualitative relationships with little or no quantitative information.

Only a few researchers focussed on empirical relationships concerning the amount of sand stored in an ebb-tidal or outer delta or other related parameters. This amount of sand is related to the balance between the strong and relatively concentrated ebb flow bringing sand out into the sea, the relatively weak converging flood flow bringing part of it back into the basin and the wave action dispersing the sand along the coast.

Dean and Walton [58] determined the volume of sand protruding above a fictive equilibrium profile interpolated between the unaffected beach profiles on both sides of the outer delta for 23 inlets. Walton and Adams [59] extended this data set to 44 inlets and related the sand volumes to the tidal prism and wave climate of the various inlets. The latter was characterized by the parameter H^2T^2 in which H is the average wave height and T the average wave period. They found a rather distinct trend, though there is a considerable scatter for the relation for the mildly exposed coasts and even more in case of the moderately exposed coasts (see Fig. 1). Causes might be physical but to a large extent also due to inaccuracies in the cubation procedure of the sand volume. The general trend that the sand volume reduces with increasing wave activity seems realistic. The same relationships but in metric units are presented in [60].

Vincent and Carson [61] carried out some research on other quantities of outer deltas. They related the maximum depth of the main ebb channel in the outer delta (in the inlet), the minimum depth of this channel at the bar on the sea side, the length of this channel from the throat of the inlet to the point with the minimum depth and the horizontal area of the outer delta to the cross sectional area of the inlet (see Fig. 2). The results showed distinct trends (see Fig. 2). Also other correlations they presented are interesting.

Hume and Herdendorf [44] made similar correlations for tidal inlets in New Zealand and also investigated the influence of littoral drift on some of the quantities.

Also Sha [45] did some work in this direction for inlets of the Dutch Wadden Sea which could be of interest for the present study.

It is worthwhile to study the existence of such relationships for outer deltas of the Dutch Wadden Sea. At present no or hardly any information in this respect is available yet.

2.2.4 Volume of channel systems in tidal basins and estuaries

In a study on the morphological impact of the construction of a dam (1963) and a storm surge barrier (1972) in the Eider, Renger and Partensky developed a method to estimate the total amount of sediment needed for a full adaptation of the basin to a new equilibrium [62].

Originally they worked only with a relation for a channel cross section like equation (1). Lateron they developed an expression relating the channel volume V_{MLW} below MLW to the size of the basin A_b (in km^2):

$$V_{MLW} = 8 * 10^{-3} A_b^2 \quad (\text{in } 10^6 \text{ m}^3) \quad (11)$$

and an expression relating the channel area enclosed by the MLW-contour A_{ch} ($= A_{b,MLW}$) to the size of the basin A_b (in km^2)

$$A_{ch} = 2.5 * 10^{-2} A_b^{2/3} \quad (\text{in } km^2) \quad (12)$$

Further they determined a set of empirical expressions describing the volume distribution of the basin below MHW:

$$V_z = V_{MLW} * \bar{a}^z \quad \text{or} \quad z = \bar{a} \log (V_z / V_{MLW}) \quad (13)$$

with

$$\bar{a} = 5 * A_b^{-0.272} \quad (14)$$

where z = level in m relative to MLW level.

Equation (13) is an approximation of the storage curve of the basins which has been made dimensionless in the sense of volume through V_z/V_{MLW} but not in the sense of the vertical measure z . Hence, basically it only can be valid for one tidal range.

It is not clear how the parameter "a" has been defined and is determined from field data. Substitution of relations (11) and (14) in equation (13) results in:

$$V_z = 8 * 10^{-3} A_b^2 [5 A_b^{-0.272}]^z \quad (\text{in } 10^6 \text{ m}^3) \quad (15)$$

This equation becomes odd for large values of A_b . If A_b becomes 371.3 km², $\bar{a}$ becomes unity and V_z is constant for each z which is physically impossible.

Lateron Renger [63] introduced dimensionless scaling parameters:

$$\phi^* = \left(\frac{A_b}{A_c}\right) / \left(\frac{A_b}{A_c}\right)_{\max} \quad \text{for horizontal measures} \quad (16)$$

and

$$\zeta = z/\Delta h \quad \text{for vertical measures } (\Delta h = \text{tidal range}) \quad (17)$$

for comparison of different tidal basins.

Though a lot of attention was paid to the analysis of the storage curves of various basins, it apparently never actually has been used for predictions. In 1980 Renger and Partensky [28] used the mean flood velocity as a stability parameter for cross sectional profiles and presented the relations:

$$P = 1.65 A_b^{1.036} \quad (A_b \text{ in km}^2, P \text{ in } 10^6 \text{ m}^3) \quad (18)$$

and

$$V_{MLW} = 4.39 * 10^{-2} A_b^{1.643} \quad (A_b \text{ in km}^2, V_{MLW} \text{ in } 10^6 \text{ m}^3) \quad (19)$$

The latter distinctly differs from relation (11) which they presented earlier.

Substitution of (18) in (19) yields

$$V_{MLW} = 0.027 P^{1.586} \quad (20)$$

which corresponds well with a previous relation of Renger [27]:

$$V_{MLW} = 0.022 P^{1.566} \quad (21)$$

This corresponds quite well with the findings of Eysink [46] who found:

$$V_{NAP} = 65 * 10^{-6} P^{1.5} \text{ (Wadden Sea, } V_{NAP} \text{ and } P \text{ in m}^3 \text{)} \quad (22)$$

and

$$V_{NAP} = (73 \text{ to } 80) * 10^{-6} P^{1.5} \text{ (Grevelingen, Eastern and Western Scheldt)} \quad (23)$$

where V_{NAP} = channel volume below NAP ($\approx$ MSL)

The relations (20) through (23) are remarkably similar though relations (20) and (21) are valid for a lower reference level than the relations (22) and (23). *It is recommended to study also this type of relations in more detail based on a properly selected and more detailed data set of the Dutch Wadden Sea. They provide a good basis to judge the overall stability of a basin or to predict the response to changes in the basin in terms of volume changes.*

2.2.5 Tidal flats

The relative area of tidal flats in a basin, that is the area with a bed level between MHW (or MHWS) and MLW (or MLWS), is an important parameter which affects the tidal prism of the basin. This can be simply demonstrated by the following equation (see also Fig. 3):

$$P = (1 - \alpha A_f/A_b) A_b \overline{\Delta h} \quad (24)$$

where:

A_f = intertidal area in basin,

$\overline{\Delta h}$ = average mean tidal range in the basin,

α = average bed level relative to Δh above MLW in the intertidal zone which generally will be within the range of 0.3 to 0.5.

This demonstrates that it is dangerous to apply a direct relation between P and A_b like Renger and Partenscky did [28]:

$$P = 1.65 A_b^{1.036} \quad (18)$$

From equation (24) it follows that P also depends on α , A_f/A_b and Δh . Equation (18) only holds for one tidal range and then only if α and A_f/A_b are uniquely related to A_b .

For large basins the tidal prism deviates from the actual tidal volumes if the length of the basin becomes significant relative to the length of the tidal wave. Then the phase differences in HW and LW over the area becomes noticeable which reduces the actual tidal volume below the theoretical tidal prism.

According to general classifications of coastal features [50, 53] the presence of tidal flats depends on the tidal range. This parameter, however, certainly is not the only one and very likely not the proper one.

For the Dutch Wadden Sea with a meso-tidal range, the relative tidal flat area A_f/A_b appears to be distinctly dependent on the size of the basin [46] (Fig. 4). The same was found by Renger and Partenscky [62] for the German Bight with a comparable relation:

$$A_{ch} = 2.5 * 10^{-2} A_b^{2/3} \quad (25)$$

or

$$A_f/A_b = 1 - 2.5 * 10^{-2} A_b^{1/2} \quad (26)$$

Also for the Delta area in the South-West of the Netherlands with a meso to macro tidal range, a similar relation was found but with relatively modest tidal flat areas (Fig. 4).

The dependence of the size of the basin as well as the difference between the different areas is believed to be caused by wave action, in particular locally generated waves. The size of the basin represents a fetch length.

Large basins, especially long basins oriented in the direction of the dominant wind, allow for more wave action around HW which very likely prevents the growths of extensive areas of tidal flats.

A lot of additional research in this field will be required before the mechanism of the generation of tidal flats is fully understood. In the present study a lot of attention will be paid to this item as it is a very relevant one for the study of the effects of increased sea-level rise as explained later on.

2.2.6 Sedimentology

Eysink presents his findings on the sedimentology and sediment transports in the Wadden Sea based on an extensive literature survey up till then in [24].

In [25] Salomons et al present some general information on the bottom composition and sediment transports in the Western Scheldt with some references which may be useful for the present study.

It is believed that a lot of information on the bed composition in the Eastern Scheldt and Grevelingen must be available in various reports of Rijkswaterstaat and in literature. This will be checked in a later stage of the study.

2.2.7 Other quantities

In some literature information is presented on the widths of the tidal inlets, the lengths of the barrier islands and the size of the tidal basins inclusive historical data without any correlation [47, 48, 64].

In other literature the length of the barrier islands is correlated with the tidal range [52, 65, 66, 67].

*It may be worthwhile to look into those aspects, though it is doubtful that this will result in reliable and useful relationships. The morphological scale of these units is too big and related to too long periods of significant changes in comparison with the period of interest for ISOS*2. Besides, it will introduce too many uncertainties due to interference of man by defending most of the barrier islands and closing small inlets between two island thus making one big island out of two or three small ones.*

2.3 Field data of the Dutch Wadden Sea

Van Kleef [68] made an extensive inventory of field data and reports of Rijkswaterstaat of the Dutch Wadden Sea.

The field data consists of:

1. A great number of discharge measurements scattered all over the Dutch Wadden Sea and spread over many years starting from 1948. The total number of discharge measurements in each basin is presented in Fig. 5.
2. A number of the above measurements have been combined with sediment transport measurements which is indicated in [68].
3. Regular soundings (approx. 5 years interval) of the bathymetry of the Wadden Sea over the period starting in 1950 for the eastern part and in 1930 for the western part.
4. Regular soundings of a number of standard profiles in the Wadden Sea.
5. Short term tide observations in a great number of locations in the Wadden Sea on top of the standard stations spread over many years.
6. Longterm tide records of a great number of standard tide stations in the area (see Fig. 6).
7. Wave data collected by Rijkswaterstaat at various stations in the North Sea, the Wadden Sea, and in the Delta area.
8. Ripple measurements in the basins of Marsdiep and Vlie.
9. Median sediment diameters in the Wadden Sea with reference to other sources of information on sediment data.
10. Historical maps of the Wadden Sea.
11. Extensive lists of reports of Rijkswaterstaat (and others) on studies of the Wadden Sea.

The above data base provides good possibilities for the present study.

3. Recommended approach of phase 2

3.1 Applicability of various morphological relations

In Section 2.2 various morphological relations presented in literature have been selected and discussed. A number of them can be and already have been applied in coastal engineering to design stable tidal inlets for navigation or to predict the (large scale) morphological impact of particular works in an estuarine area.

For example, the construction of a dam or barrage will cause changes in the characteristic tidal volumes on both sides of the structure. Basically, this has consequences for the size of the channels on both sides unless no sediment is available to cause any adaptation to the new equilibrium.

The reduction of the channels may negatively affect navigation and ecology but ultimately also result in a raise of the backwater curves of the river draining through the estuary. The latter requires raising of the river dikes to warrant safety against inundations (e.g. Haringvliet/Rhine-Meuse and Nakdong estuary).

The reduction of the channel size only can occur if sediment is supplied from elsewhere. Initially this will be supplied by the adjacent tidal flats and the outer delta, but ultimately it all has to be supplied from outside the tidal basin, i.e. from the coastal zone of the sea and the foreshore and possibly by the river. The latter only is possible if the river sediments are not fully trapped in the reservoir upland of the barrage (e.g. IJsselmeer, Haringvliet).

It can be concluded that a closure of a tidal basin or part of it (e.g. Grevelingen, Lauwerszee) somehow will affect the coastal zone of the sea adjacent to the tidal inlet as well.

Natural accretion, man-made land reclamation, sand mining or bottom subsidence in a tidal basin will have similar effects on the channel system, the outer delta and the coastal zone near the tidal inlets [46]. The effects can be determined through the relationships for the channel volume and the sand volume stored in the outer delta. This provides ultimate changes in terms of sand volumes. If the time histories of these changes are known, this provides source or sink terms at a tidal inlet which are valuable boundary conditions for studies on the longterm behaviour of the sea coast [69]. In [26,

46] a method is presented to determine the required time histories in an approximate way.

Examples of what can be achieved with a few morphological relations, simple models or calculations on tidal flow, some basic rules on sediment transport and, if available, some historic data on morphological developments are shown in [26] and [70].

More accurate and detailed predictions on the morphological impact of particular works should be possible if a number of the known relations can be developed further and proper interrelations between different relations can be established. Basically, this also holds for the impact of increased sea-level rise.

3.2 Missing links for a conceptual morphological model

Most of the presently relations available from literature are valid for parts of the morphological system which are below MSL. This holds for the relationships for the channel profile, the channel volume of a tidal basin and generally for the sand volume stored in the outer delta.

Only little is known about the tidal flat area, or more specifically the area between MSL and MHW. The size and shape of this intertidal zone is important for the tidal volume passing the channel(s). Also little is known about the interactions between the different relationships and how the system reacts on gradual changes like sea level rise or bottom subsidence. The importance of this may be illustrated by the following hypotheses [21, 46, 71]:

1. If the response of the tidal flats to the above changes is fast and the levels of the flats will follow the relative changes in MSL or MHW (almost) instantaneously, then the tidal prism of the basin does not change in time, but the volume of the tidal channels does. As a consequence the increase in the channel volume will be compensated by a nett sand influx from outside the basin.
2. If the tidal flats can not follow the relative sea level rise, the tidal prism of the basin will gradually increase. Consequently, the tidal channels in the basin will widen to match the increased tidal prism and sand will be transported to the expanding outer delta and the sea.

What really will happen can only be predicted if a proper relationship can be determined between the shape of the storage curve of the basin (or of the tidal flats in more detail) and the hydraulic parameters and the size of the tidal basin. Also a good understanding of the interrelation between the tidal flats, the channels and the relevant hydraulic and sedimentologic parameters will be required. It is anticipated such interrelations must be found based on basic considerations on the transport and conservation of mass of the sediments.

Ample attention will be required in the present study to cover these aspects, e.g. through historical information on tide levels and levels of tidal flats.

Though empirical relationships for the outer delta are known, none of them is based on data of dutch tidal inlets. To ensure that the empirical coefficients are right, similar or better relationships have to be assessed based on data of dutch tidal inlets.

Empirical relationships for dutch tidal channels have been determined before and form a good basis for this study. Further confirmation of their validity based on more data is still possible and even may lead to further refinement and improvement of them. This can be done with a modest effort as most of the basic data will be needed for the study of other aspects anyway.

3.3 Recommendations for further investigation

It is recommended to perform the present study along the following lines:

First step of phase 2

Start phase 2 of the study with the selection of a reliable set of more or less simultaneous data of all tidal basins of the Dutch Wadden Sea consisting of:

- sounding maps of the entire basin and its outer delta of a period of a few years not preceded by important changes by man,
- discharge measurements in the tidal inlet and in other cross sections (if available) of the same period,
- characteristic tide levels of a number of stations in the basin of that period,
- wave climate data of the adjacent North Sea and in the tidal basin (if available).

From the above data set a great number of relevant parameters can be derived such as:

- size of the basin, channel area and tidal flat area,
- characteristics tidal levels and ranges,
- storage curves of the basins and parts of it, i.e. the horizontal (wet) area as a function of the level relative to NAP,
- flow areas (below MSL, MLW and MLWS) and profiles of selected channel cross sections in the basin, the inlet and at the outer delta where a tidal prism has been measured or can be reliably derived from a measured one,
- mean and maximum channel depths below MSL and channel width at MSL (or MLW),
- channel volumes (below MSL, MLW and MLWS) of the entire tidal basin and parts of it behind selected cross sections,
- sand volumes stored in the outer deltas according to the definition of Walton and Adams [59],
- tidal volumes passing the selected cross section,
- maximum discharge rates and related water levels,
- maximum and mean tidal flow velocities,
- maximum and mean tidal shear stress velocities,
- weighted wave heights and periods at selected, cross sections to determine the relevant wave effect on the shear stress velocity (Bijker factor),
- hydraulic radius of selected cross sections,
- stability shear stress as defined by Bruun and Gerritsen [15, 1].

This list can be extended with other parameters if considered useful.

The above list may look abundant and suggests a lot of effort to be done to get all those data. In reality a great number of data easily follows from other ones. For example, the storage curve and the characteristic tide levels of a basin also give the size of the basin, the channel area and the tidal flat area. Besides, they allow for the estimation of the tidal prism. The discharge history at a particular cross-section allows for the derivation of the local tidal volumes (ebb, flood, total), the maximum discharge rates (ebb, flood) and the related tide levels. Together with the cross-section data this can be extended to the maximum and tide average flow velocities, the stability shear stress velocity, etc.

Once all the basic data have been collected or derived, it is easy to select any of them for correlation. This is part of the work of the second step of phase 2.

Second step of phase 2

The above data can be stored in a central data base which will facilitate making different correlations between geometrical and hydraulic parameters. The efforts will be focussed on but not necessarily limited to:

- **Channel dimensions** like flow area, width (at MSL and MLW), mean and maximum depth, channel volume (below MSL and MLW).
- **Basin characteristics** like size, relative area of channels and tidal flats, shape of storage curves and natural accretion rate.
- **Tidal flat dimensions** like relative size, shape, mean and maximum levels (relative to MSL and MHW) of individual flats.
- **Outer delta dimensions** like sand volume, overall size and characteristic dimensions of channels on the outer delta.
- **Mutual interrelations** between characteristics quantities.

Thus proper relations can be achieved which will be valid for the Dutch Wadden Sea or possibly will have a more general validity.

Third step of phase 2

If the above exercise yields promising results, it is worthwhile to repeat it with data of different periods. This will further support the validity of the relationships derived so far and it also provides information on the historical developments/behaviour of a number of quantities. This may especially be of interest for the behaviour of the tidal flats (area and characteristic heights) over the past 50 years in relation to changes in MSL and/or MHW.

Fourth step of phase 2

A selection of suitable relationships will be used to build a conceptual equilibrium model which will be verified based on, for example, data of the tidal basin of the Zoutkamperlaag.

A tentative time schedule of the activities of phase 2 is presented in Figure 7.

Finally, in phase 3 of the study an attempt will be made to make a transition model which can be used to describe the adaptation history of a disturbed situation to a new equilibrium.

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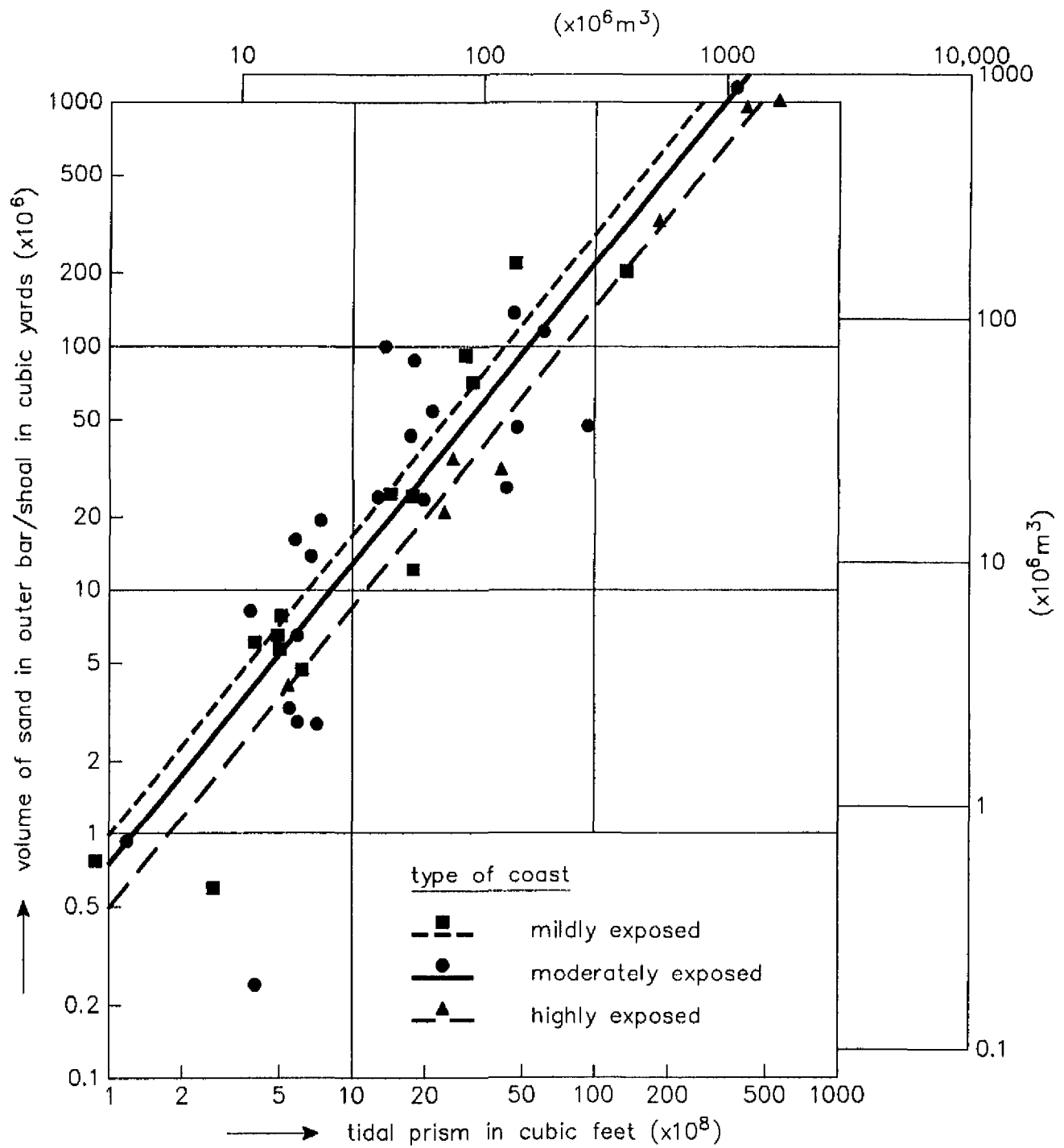
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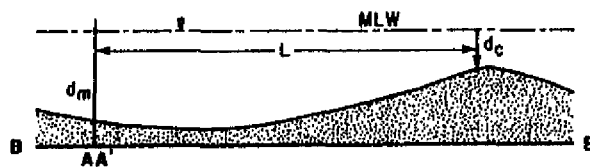
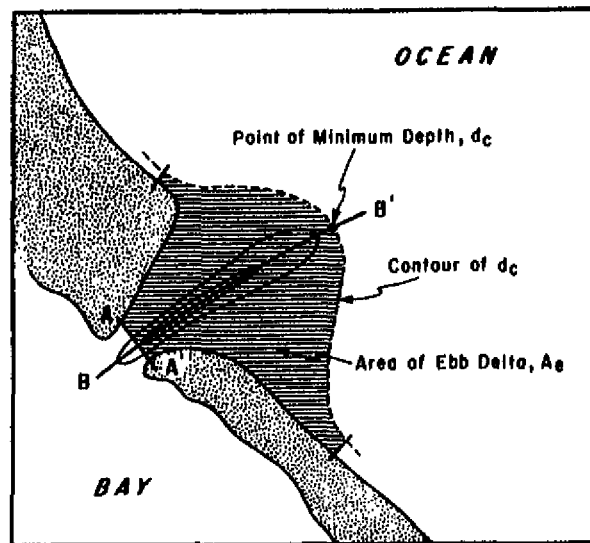
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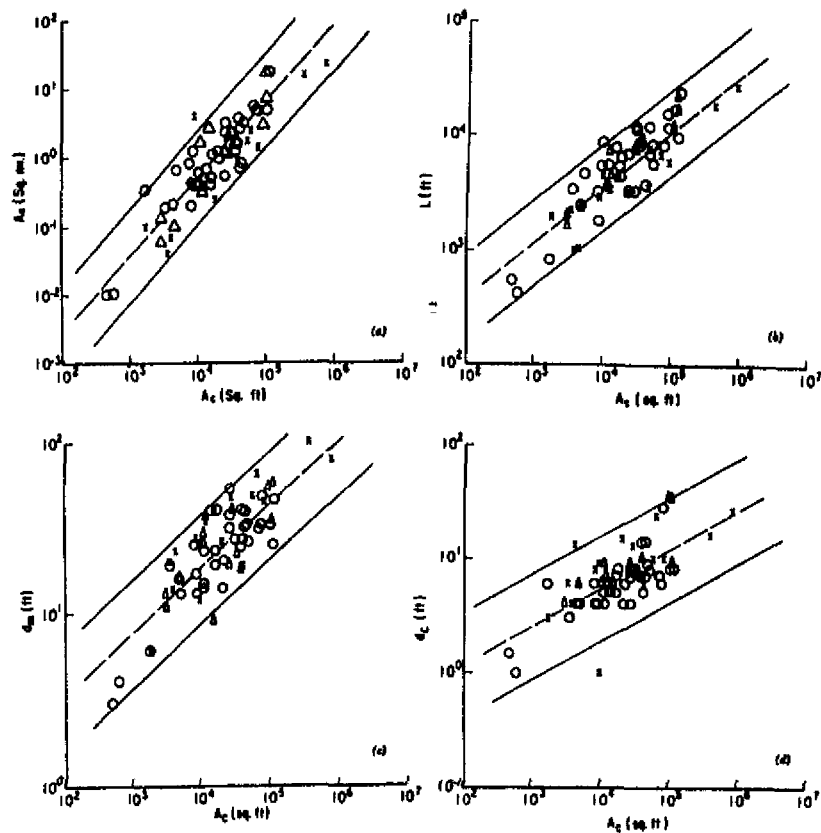
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SAND VOLUME OUTER DELTAS IN USA IN RELATION
TO THE MEAN TIDAL VOLUME OF THE INLET
ACCORDING TO WALTON AND ADAMS [59]



definition of parameters d_a , d_c , d_m , W , L , A_E



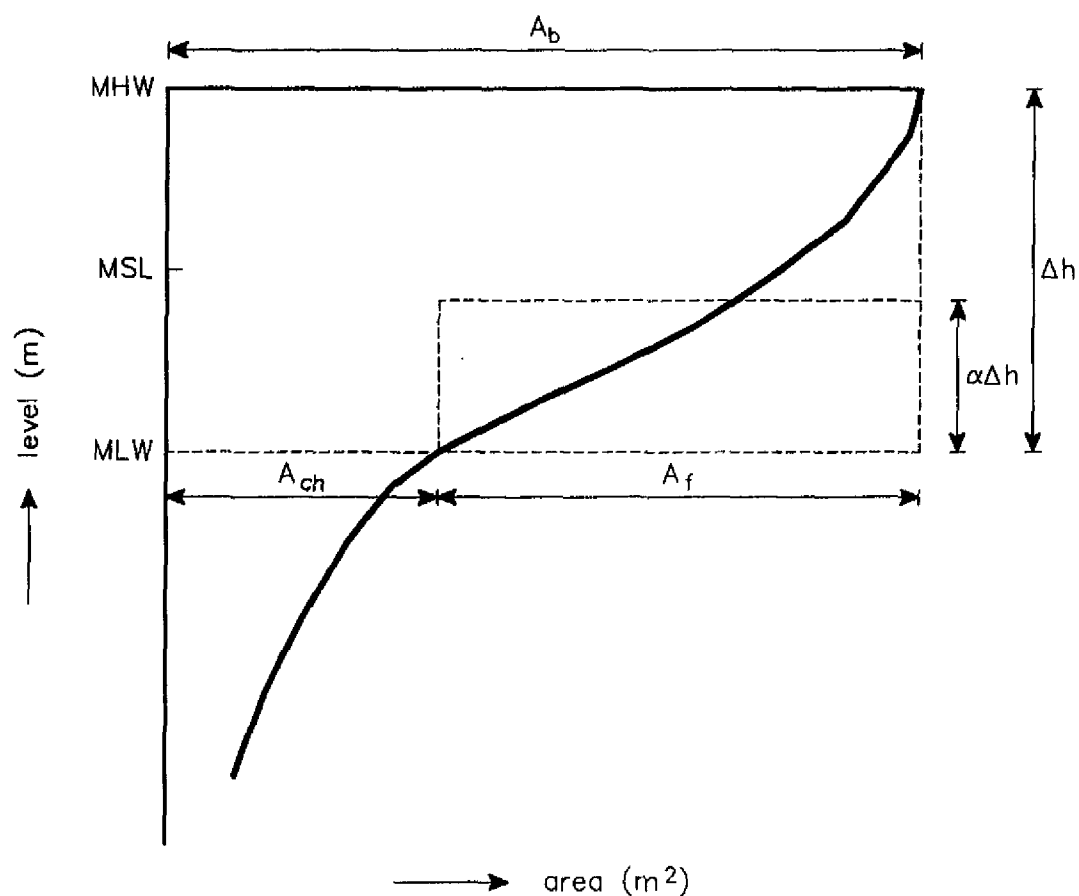
MORPHOLOGICAL RELATIONSHIPS OUTER DELTA
ACCORDING TO VINCENT AND CARSON [61]

EXAMPLES

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FIG. 2



$$P \approx A_b \Delta h - A_f \alpha \Delta h = (1 - \alpha A_f / A_b) A_b \Delta h$$

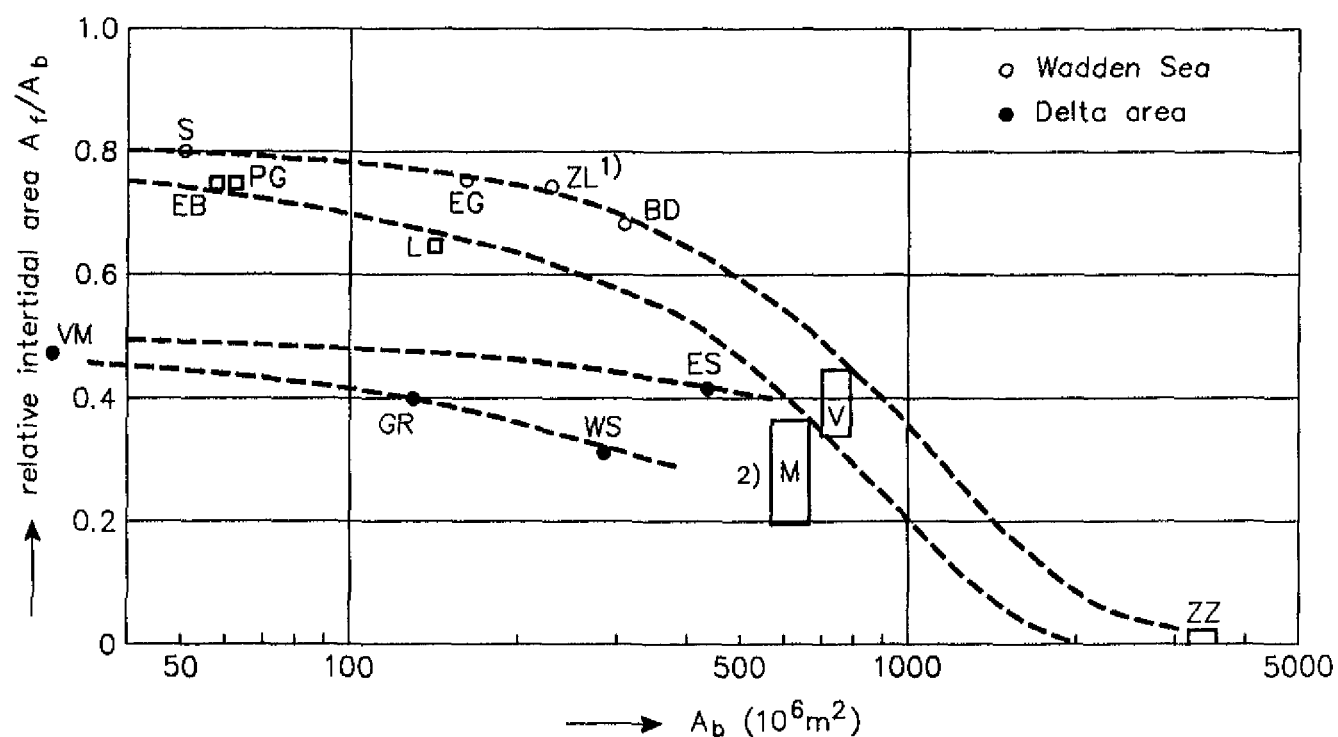
$\alpha \Delta h$: average height of tidal flats above MLW

REDUCTION OF TIDAL PRISM OF
A BASIN DUE TO TIDAL FLATS

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FIG. 3



1) before closure of the Lauwerszee

2) after closure of the Zuiderzee (IJsselmeer); no equilibrium yet ?

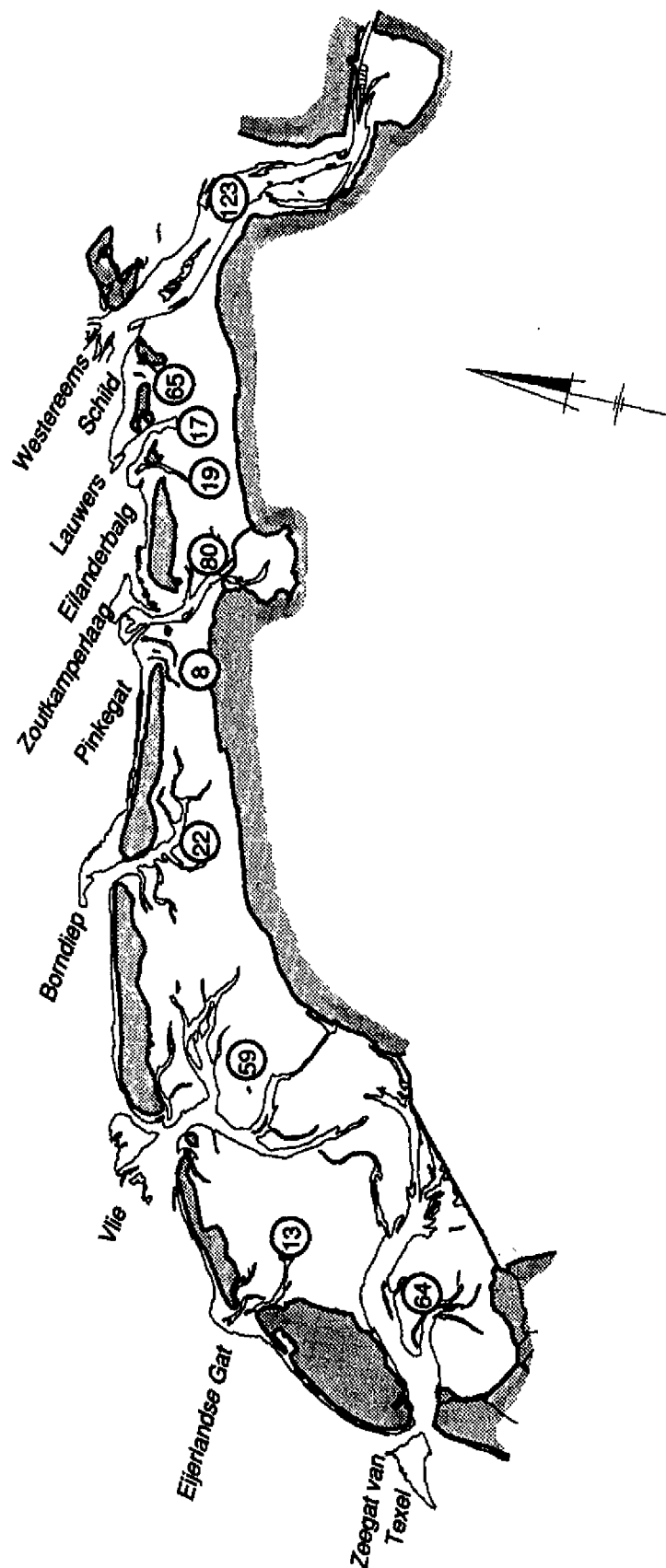
Wadden Sea

M = Marsdiep/Zeegat van Texel
 EG = Eijerlandse Gat
 V = Vlie
 BD = Borndiep
 PG = Pinkegat
 ZL = Zoutkamperlaag
 EB = Eilanderbalg
 L = Lauwers
 S = Schild

Delta area

WS = Western Scheldt
 VM = Veerse Meer
 ES = Eastern Scheldt
 GR = Grevelingen

RELATIVE AREA OF THE INTERTIDAL ZONES IN
 THE DUTCH WADDEN SEA AND DELTA AREA



TOTAL NUMBER OF DISCHARGE MEASUREMENTS IN
EACH TIDAL BASIN OF THE DUTCH WADDEN SEA

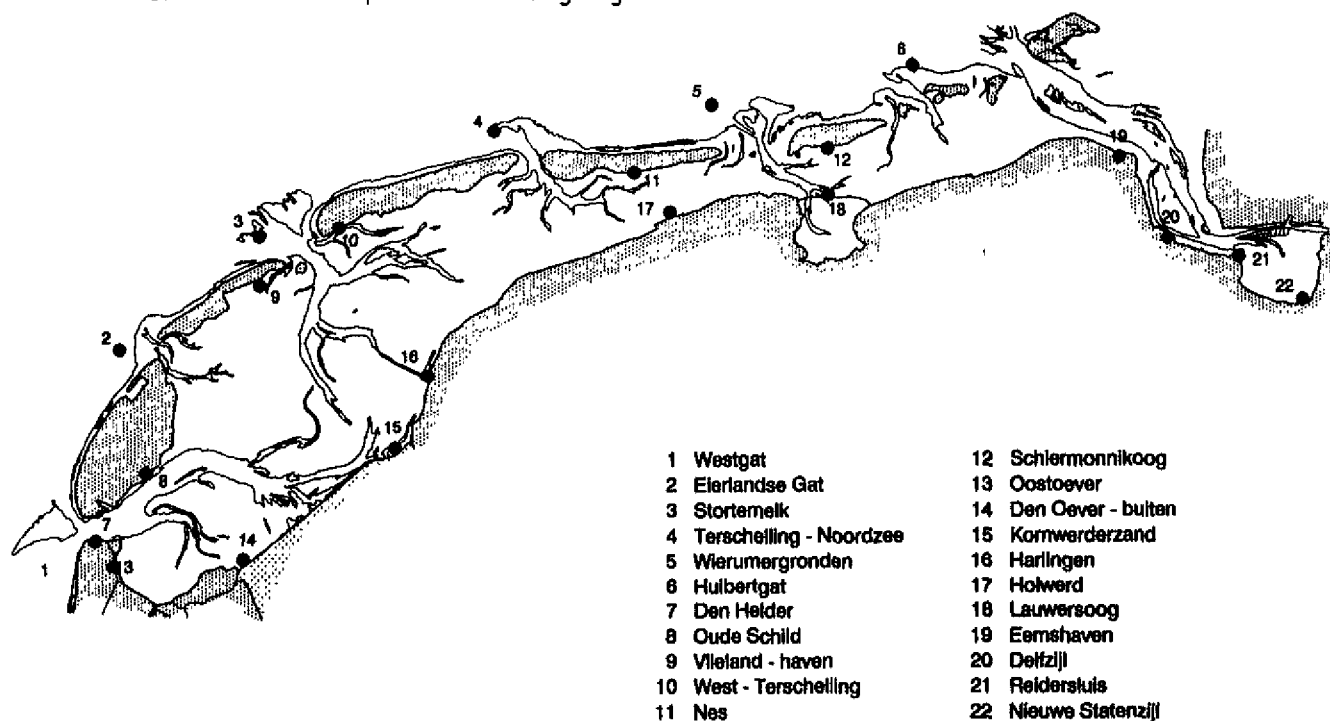
UIT [3]

DELFT HYDRAULICS

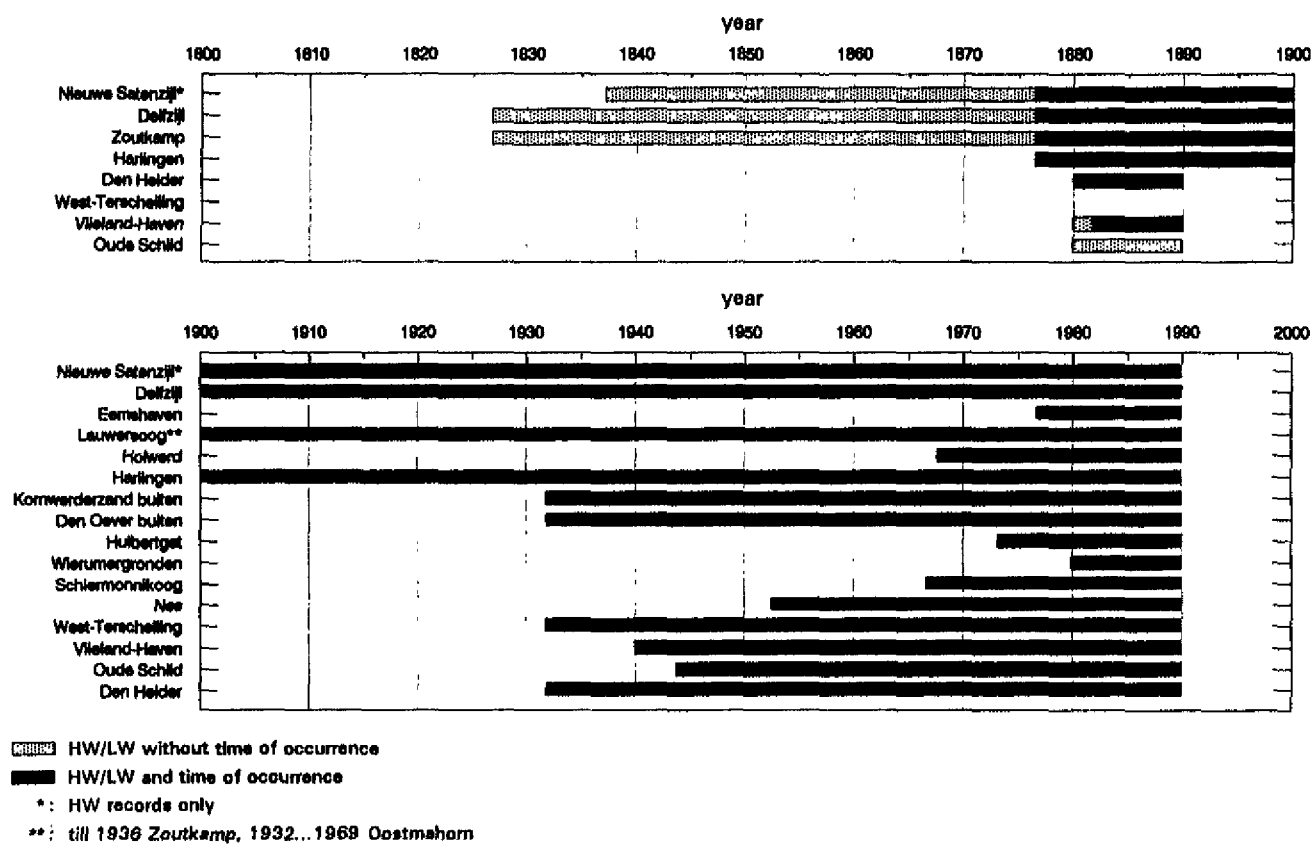
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FIG. 5

location of most important tide gauges in the Wadden Sea



waterlevel records available in DTBEST of RWS



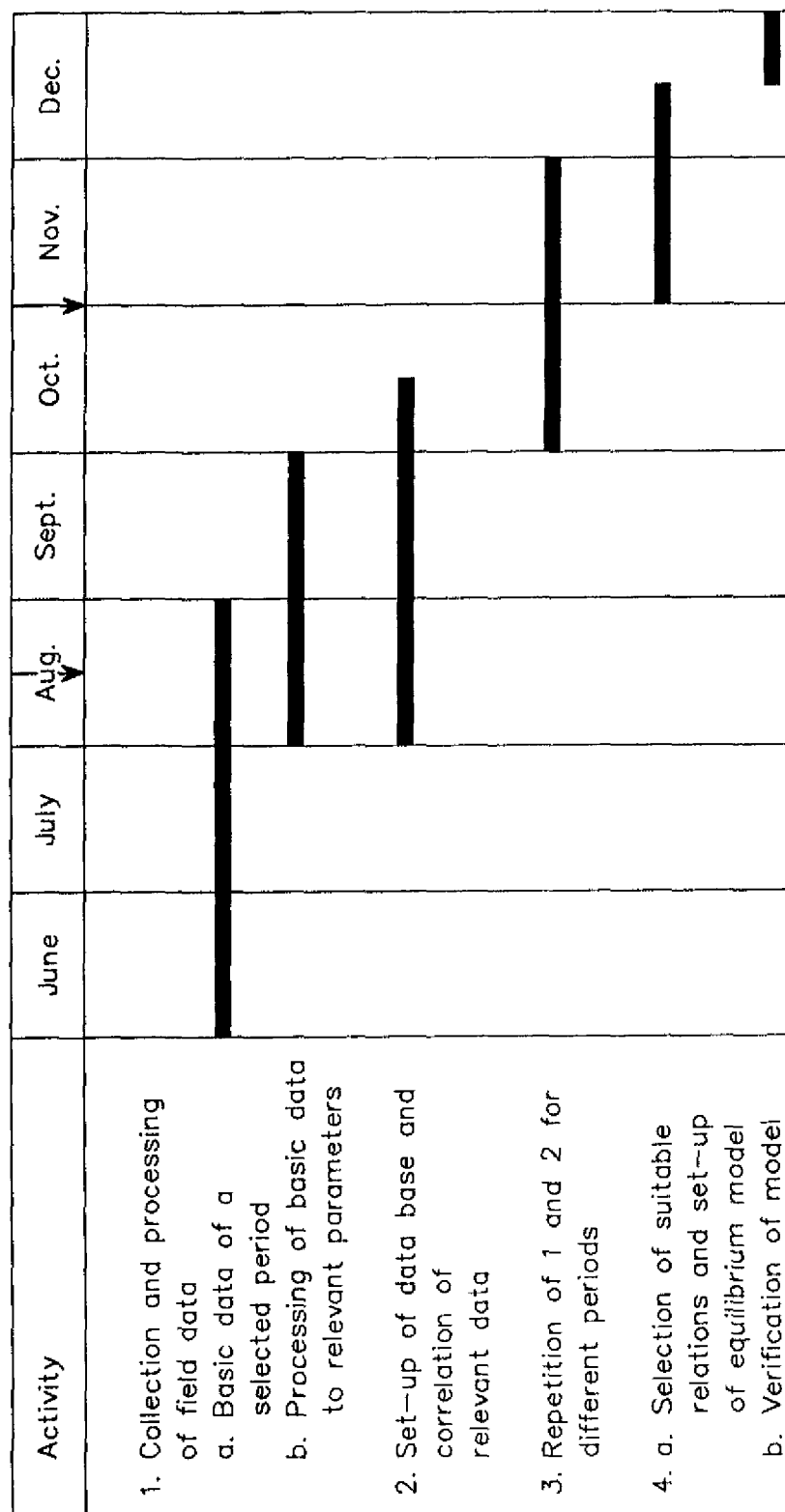
LONGTERM WATER LEVEL RECORDS OF STATIONS
IN THE DUTCH WADDEN SEA

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FIG. 6



meeting

TENTATIVE TIME SCHEDULE OF PHASE 2

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FIG. 7



main office
Rotterdamseweg 185
p.o. box 177
2600 MH Delft
The Netherlands
telephone (31) 15 - 56 93 53
telefax (31) 15 - 61 96 74
telex 38176 hydel-nl

location 'De Voorst'
Voorsterweg 28, Marknesse
p.o. box 152
8300 AD Emmeloord
The Netherlands
telephone (31) 5274 - 29 22
telefax (31) 5274 - 35 73
telex 42290 hylvo-nl

