RESPONSE TIME SCALES FOR DUTCH WADDEN SEA

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REPORT PREPARED FOR
RIJKSWATERSTAAT/RIKZ

MARCH 2000

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0. SUMMARY

Morphological response times depend on both the magnitude of the disturbance and the size of the area.
In general morphological disturbances can be classified in two classes:
. man made changes
. natural developments.
In the first group large response time scales are associated with large scale disturbances such as the closing of Zuiderzee and Lauwerszee, respectively in 1932 and 1969. The morphological response process to these two projects is still in progress and is discussed in this paper.
The second group includes morphological response to a change in sea level rise and to other gradual changes in North Sea boundary conditions.
The morphological adjustment of the Inlet of Texel, its tidal basin and its ebb-tidal delta, is of importance in relationship to erosive processes on the adjacent shorelines of Texel and North-Holland. Considering the gorge of the inlet it seems likely that its cross-section is presently in equilibrium with the present values of its tidal prism and sediment transport (Gerritsen, 1999). However it is likely that on a long term basis further adjustments in tidal flow and sediment demand of the tidal basin will occur and will induce further adjustments in the gorge of the inlet.
In many cases the response of a certain area to an abrupt change takes place in the form of a decay function. As the adaptation progresses the rate of adjustment becomes smaller.
The morphological adjustments of the Inlet of Texel and the Frisian Inlet after the tidal closures show that the morphological adjustments start in the region of the gorge and then propagate inland where channel adjustments develop at a later date.
It is noted that areas in the back of the basins (this is particularly true for the Texel Inlet) have a longer response time than the areas adjacent to the inlet. It is difficult to predict how much more sedimentation can be expected in the back basin of the Texel Inlet and how further adaptation will develop with time.
During the adaptation process the asymmetric tide, which is partly responsible for a dominant flood transport, gradually changes to a more symmetrical form with a less important M_4 component. Furthermore observations show that the areas near the inlet first "take what they need" for the sedimentation of tidal channels in their restoration process and let pass to other stations further inward the excess quantities of sediment flux.(Van Dongeren, 1992).
It may also be noted that the grain size of the imported sediment deposited in the main channel, gets smaller at greater distance from the inlet.
There is evidence that the filling of the Texel Inlet basin after the closure of the Zuiderzee takes place in the form of a long, non linear and damped sand wave at the channel bottom.

The report also discusses the response of the Western Wadden Sea to an increased rate of sea level rise. In the calculations it has been assumed that the long term average concentration of sediment in the sea outside the ebb tidal delta remains unchanged.
On that basis a model formulation is developed, resulting in a response time somewhat higher than half a century.
The adaptation process in a situation of continuous change, such as an increase in sea level rise, is different from the adaptation after an abrupt change such as induced by a tidal closure. However the response characteristic is still a function of the response time scale valid for a small sudden change.

Response calculations make it possible to calculate the level difference between bottom and sea at various times in the future and the sediment demand of the basin depending on various scenarios of change in sea level rise.
In most reports about morphological response the contribution of silt in the restoration process is neglected. This may not be justified for certain regions such as for areas located in the back of the Texel basin, where sedimentation from silt could presently be a factor in the ongoing adaptation response process.
At present calculations seem to indicate that the resultant import of sediment through the inlet has become much smaller than in the past (Van Marion, 1999) and may even have converted to a resultant ebb transport (Steijn, 1997).
Robaczewska et al (1991) have shown that an Eulerian residual south going flow exists through the Western Wadden Sea, generating a residual ebb flow through the Texel basin of 910 m3/s (= 40.6 mill.m3 per tidal cycle).
The influx of fine sediment (silt) as a result of this flow across the tidal divide could be a contributing factor in the sediment balance which may not be entirely negligible. However in the present calculations this aspect has been neglected.

Man made changes of lesser magnitude are dredging operations to keep navigational channels at required depths and the mining of sand for industrial purposes. The latter operations are usually from confined sandpits in localized areas where suitable sand is available.

Man made interventions vary from small to very large and it is reasonable to expect that the times required for the morphological adjustment to the original or new equilibrium condition also vary from small (years) to large (many decades).

Morphological responses also develop with respect to land subsidence from oil and/or gas mining. Two types of response behavior occur from the mining process. During the mining operations response to the subsiding sea bottom develops in way similar to the response to sea level rise. After the mining has stopped the response behavior changes to a decay type of adjustment after a sudden bottom change.
A comprehensive study on the effects of gas mining has been conducted by a group of scientists from different organizations (Oost et al, 1998). Reference is particularly made to the contributions by Oost (1998) and Eysink (1998).

Various models are available to describe the morphological adaptation process from which the response time scale or adaptation time scale can be calculated. Three main groups of models can be distinguished : dynamic models or process models, dynamic-empirical models and fully empirical models.
For the purposes of this study with emphasis on response time scales the ASMITA and ESTMORF models appeared to be particularly useful. These models can best be classified under the group of dynamic-empirical models.
The ASMITA model is a behavior oriented model designed for the interaction between a tidal basin and the adjacent coast. (Stive and Wang, 1996). The behavior of the system elements are described on an aggregated scale. Their state variables are total volume and area relative to mean sea level. The five system elements are:
Tidal basin, consisting of tidal channels and flats
Tidal Inlet

Ebb-tidal delta
Adjacent coasts
The basic concepts of the model are the same as of the ESTMORF model (Wang et al 1998, Stive et al, 1998, and Fokkink et al, 1998).

The ESTMORF model simulates the morphological development of a channel network in an estuary. It is coupled to a hydrodynamic model to simulate the water flow. The empirical part of the model relates the water flow to equilibrium profiles of the channels. From this information, an equilibrium concentration field is derived. (Fokkink and Van der Weck, 1998).
The dynamic part of the model is based on the advection - diffusion equation which also describes the mass balance for suspended sediment.
The concept of equilibrium concentration is based on the work of Di Sivio (1989)

The most important conclusions of this study are:
The ASMITA model for aggregated morphological units gives good results in predicting response times for different types of morphological disturbances with different magnitudes and time scales, ranging from the filling in of dredging pits from sand mining to the adaptation of tidal basins to changes in sea level rise. Despite the fairly crude schematization used in the models the results agree surprisingly well with observed data and reasonable expectations. It is important that required model parameters be assigned physically realistic values.

1. Satisfactory results are obtained when in the model formulation the resultant advective transport component is neglected in comparison with the dispersive transport.
2. Response time scales, as defined in the report, vary from small to large depending on the size of the disturbance.
3. The following orders of magnitude of the response time scale have been arrived at:
   Filling in of dredge pits: years – one decade
   Man-made changes in tidal basins (tidal closures): 2-4 decades.
   Increase in the rate of sea level rise for Wadden Sea: ~ 5 decades.
4. Results may be less reliable in relatively small disturbances in which residual advective transports can not be neglected. An example is the filling in of a dredge pit in the Western Scheldt. Although on first impression model results seemed to agree with field observations, further analysis showed that the actual distribution of sediment concentration did not correspond with model assumptions. This causes a lack of confidence in this model application.
5. Detailed discussion on the response time scale associated with oil and gas mining will not be given in this report, but will be treated in a separate paper.

Finally a number of recommendations for further research are presented in this report.

1. INTRODUCTION.

The Dutch Wadden Sea, as it existed before the closing of the Zuiderzee, developed into a system of channels and tidal flats during the 5th to the 7th century A.D. (Louters and Gerritsen 1994). A few large tidal inlets formed the connection between the North Sea and the tidal basins behind the barrier islands. The largest of these basins, the former Zuiderzee, was connected to the North Sea by one large inlet: the Vlie Inlet. A second large inlet was the Ameland Inlet which reached far into the present Province of Friesland.
Over the years many changes have characterized the developing landscape of the Wadden Sea, the coastlines of the barrier islands and the tidal inlets.
For most of its history the changes that occurred were of natural origin, with the rising sea level being one of the most important causes of change during all of its history.
At the end of the first millennium interventions by men started to influence the natural developments when dikes were being built to protect against high tides and to form polders for agriculture, resulting in changes in the tides and in the morphological landscape.
Outside of the dikes sedimentation and land reclamation was promoted by the construction of a system of primitive tidal flow barriers and flow channels.
The most important man made change in the Wadden Sea was the closure of the Zuiderzee, in the years 1928 – 1932, which had a dramatic impact on the morphological conditions particularly of the Western Wadden Sea.. One of the most significant changes was the increase of the tidal range in the basin north of the closure dam, resulting in the increase in the tidal prisms of the Texel Inlet and of the Vlie Inlet and in significant changes in the morphology of the tidal basin including the shoaling of the former flow channels north of the closure dam..
A later and somewhat less dramatic impact occurred after the closure of the Lauwerszee in 1969. The impact was largely limited to morphological changes in the storage basin of the Frisian Inlet. In this case the tidal basin shoaled and the size of the Frisian Inlet decreased over time. Simultaneously changes occurred in the coastline sections adjacent to the inlets and in the sand volumes of the ebb tidal deltas.

Another man made effect on the morphology of the Wadden Sea is the lowering of the bottom of a tidal basin due to the mining of oil or gas from deeper layers directly underneath or in the vicinity of the Wadden Sea. This is a development of practical interest with respect to the impact of these operations to the Wadden Sea itself, as well as to the stability of the coastal areas of the North Sea adjacent to the inlets.

We mentioned earlier that the rise of the mean sea level over time has had a determining influence on the historic natural development of the Wadden Sea and of the barrier islands. Over the past decades The Wadden Sea has been under the influence of sea level rise, whereby sedimentation on the tidal flats takes place by the movement of sediment from the channels onto the flats.
Most scientists agree that the observed warming of the atmosphere will continue and most likely will result in an increase in the rate of sea level rise with an impact on the Wadden Sea as a whole.
A new equilibrium situation may ultimately develop if the (average) rate of sedimentation in the Wadden Sea equals the (average) rate of sea level rise over a period of time. Such an equilibrium will not develop if the required supply of sediments is not adequate to compensate for the

increase in depth from sea level rise. This is an important issue that has received the attention of many researchers.
The developments of tidal basins prior to 5000y. BC have shown that supply and deposition of sediments has its upper limits. From this it has been concluded that when the rate in sea level rise exceeds a rate of 3mm /year parts of the inter tidal flats remote from the channels may start to drown. (Beets and Van der Spek, 1996). However this seems not to be the case for the salt marshes area. Dijkema (1996) found that in general the salt marsh zone in the Wadden Sea can cope with a sea level rise of 5mm per year for barrier islands and 10 mm per year for the mainland side of the Wadden Sea.

For the calculation of the time required for a disturbed morphological condition to adapt back to the situation that occurred before the disturbance took place phenomenological models are used to describe the response process in smaller or larger detail.
In some cases of large man made impacts such as the closing of the Zuiderzee the morphological situation does not convert back to the former equilibrium condition but to a new, not a priori known equilibrium situation. A similar situation develops (long) after the rate of sea level rise has increased.

In dynamic models mathematical formulations are used to describe the transport of water and of sediment, from which changes in bottom level are calculated.
In dynamic-empirical models the water motion is calculated from a physical-mathematical model, whereas bottom changes or channel cross-sections are found from experimentally established relationships between water motion and morphological parameters.
A fully empirical model is strictly based on empirical relationships.

For the prediction of morphological response processes dynamic-empirical models are the preferred type, because they are steered by empirical morphological relationships and are therefore more suitable to describe long term processes.
The Estmorf and Asmita models recognize an overall equilibrium concentration and a "local equilibrium concentration" the value of which is determined by the hydrodynamic condition.

Response is nature's way of adjusting itself from a disturbed situation to its previous equilibrium condition or to a new equilibrium, if such a condition exists.
The latter is not necessarily the case because the natural morphological condition may be subject to a slow and gradual change, that is not fully known
However in the following discussions it is assumed that such an overall equilibrium condition exists. This assumption is usually justified when a small scale disturbance is restored to its original condition, such as the natural sedimentation in a small dredging pit, but may not be fully valid for large scale natural changes or man made interventions.

In the morphological adjustment processes of the Dutch Wadden Sea different response time scales can be observed for different types of disturbances. Short time scales of a few years are observed in the adjustment of dredging pits after the dredging has been terminated, whereas long response times (many decades) have been observed after the closures of Zuiderzee and Lauwerszee. Very long response times (over half a century) will be present when the morphological changes deal with large areas and small disturbances, such as the response of the entire Wadden Sea to an increase in sea level rise.

The tidal inlets of the Dutch Wadden Sea are shown in Figure 1.1.
When comparing the morphological response of the tidal basins of the Texel Inlet and the Frisian Inlet, after the closures of Zuiderzee and Lauwerszee, it may be noted that these two basins have responded in different ways.
In the case of the Texel Inlet the tidal prism increased as a result of the closing, whereas in the case of the Frisian Inlet the tidal prism decreased after the closing operation. As a result the tidal channels in the western part of the tidal basin of the Inlet of Texel have been subject to erosion where the eastern part of this basin was subjected to sedimentation. Inside the Frisian Inlet sedimentation took place and the inlet decreased in size. In this case the eastern (most landward) portion of the main channel increased somewhat in size due to enlargement of the tidal basin.

In this report we have used the Asmita and Estmorf model formulations for the calculation of the response time scales for different problem situations. The Asmita model is a behavior oriented model designed for the interaction between tidal basin and adjacent coast.(Stive and Wang, 1998, Wang,1997). It is a particularly useful model for our purpose because it deals with large aggregated units. The Estmorf model simulates the morphological development of a channel network in an estuary (Fokkink et al, 1998, Fokkink and Van der Weck 1998). In both models sediment transport is governed by the diffusion-advection equation for suspended sediment, where transports are integrated over a tidal cycle and diffusion (dispersion) aspects become important features. Basic concepts are the assumption of an overall equilibrium concentration and a local equilibrium concentration, determined by the hydrodynamic condition.(Di Silvio, 1989).

This report will include the following subjects:
. Morphological response processes at local disturbances.
. Morphological response of the Frisian Inlet basin after closing of Lauwerszee.
. Morphological response of the Texel Inlet basin after the closing of the Zuider Zee.
. Response of Wadden Sea to sea level rise.
. Basin response to gas mining (full discussion will be given in a separate report)
. Conclusions and recommendations.

The paper will not include discussions on the impact of biological activity on sediment size and transport behavior, and does not deal with the effect of subsidence of the Wadden Sea bottom on the biosphere. Although these topics are of practical interest, they are outside the scope of this investigation.

2. MORPHOLOGICAL RESPONSE PROCESSES AND RESPONSE TIME SCALES.

An excellent description of the ESTMORF model is given in Wang et al (1998) to which we like to make reference. It is to be noted that the ASMITA model is based on a similar formulation regarding the definition of the equilibrium state and the sediment transport process except that in ASMITA the transport equation is simplified and has no time derivative for the concentration. Furthermore the ASMITA model deals with aggregated areas.
The ESTMORF model described by Wang et al uses an existing one-dimensional flow model to simulate the flow in a schematized network consisting of branches.
Our approach is concerned with entire morphological units for which an ASMITA type approach is most be suitable.
The most important hypothesis in both the ESTMORF and ASMITA model concepts is that an overall equilibrium concentration characterizes a morphological system. For each morphological element of the system a local equilibrium concentration can be defined which depends on the hydrodynamic condition. An empirical relation is required for each element to define the morphological equilibrium state of this element.
The concept of equilibrium concentration is based on the pioneering work of Di Silvio (1989). If all elements of the morphological system are in equilibrium they have the same sediment concentration and there is no more transport between sections. This value of the concentration is called overall equilibrium concentration, CE. The local equilibrium concentration is identified by Ce.
The concept of "equilibrium concentration" is based on the long term average of the sediment concentration including a variety of current and wave conditions. Suggestions on how to arrive at values for CE are given in Stive et al (1998).
If a unit of the system is out of equilibrium the system will strive toward restoration of the equilibrium state by means of sediment transport from one unit to the other. During the adaptation process the sediment concentration C at any time can be either smaller or larger than the equilibrium concentration Ce. When C>Ce, sedimentation takes place; when C<Ce, erosion develops.
For a more detailed description of these models reference is made to Wang (1997), Fokkink et al, (!998) and Fokkink and Van der Weck (1998).

The evolution of the actual morphological state to its equilibrium usually behaves as an exponential decay process, defined by a response time scale ,ι.
When the sediment concentrations of adjacent units have different values sediment transport takes place between these units. It is assumed that the transport of sediment takes place in the form of suspended sediment, which is governed by the advection-diffusion equation. .
The transport quantities used in the model are integrated values over a full tidal cycle. When tide-averaged concentration values are used and equal tidal flows in ebb and flood direction are assumed advective transports in the flood and ebb direction cancel each other out whereby the resultant transport between adjacent sections is governed by diffusion or dispersion. Consequently diffusion or dispersion plays a dominant role in the exchange of sediments between sections in our model formulation. (See Appendix C for a discussion on the value of the dispersion coefficient to be used in the model).

The notion that the response process develops in the form of an exponential decay function is based on the assumption that the rate of adaptation of a disturbance to its equilibrium condition is proportional to the remaining size of the disturbance. In the beginning the adaptation develops rapidly and at the end very slowly. Observations show that adaptation processes usually develop in this fashion.
Let us use the natural sedimentation in a dredge pit after the dredging has stopped as an example of an adaptation process from which we can derive a definition of adaptation time or more correctly of response time scale.
Let us assume that the initial volume of the pit equals the value V_0. After a time ,t, the remaining volume is reduced to V, and the assumption is made that the rate of further decrease in volume , dV/dt , is proportional to V. Then the process is described by the following differential equation:

$$dV/dt = -(1/\iota)\,V \qquad (2.1)$$

where $(1/\iota)$ is a proportionality constant the value of which determines the speed at which the dredge site fills up.
The solution is:

$$V/V_0 = e^{(-t/\iota)} \qquad (2.2)$$

The parameter ι defines the time scale at which adaptation takes place and is defined as the response time scale of the adaptation process. Equation (2.2) allows to determine the value of the adaptation time scale from observed or calculated values of V/V_0.
The equation also shows that the adaptation time ι defines the time t that is needed to reduce the size of the disturbance to a value (1/e) V = 0.37 Vo. At a time $\iota = 2t$ the remaining volume is reduced to 0.14 Vo and at $\iota = 3t$ to the value 0.05 Vo.
At $t = 3\iota$, the disturbance is then reduced to 5 % of its original value.

From:

$$dV/dt = -(V_0/\iota)\; e^{(-t/\iota)}$$

it follows that

$$\iota = -\; V_0 / (dV/dt)_{t=0} \qquad (2.3)$$

The value $-(dV/dt)_{t=0}$ represents the rate of decrease of the pit-volume ***at the time t = 0***, which can be determined analytically and/or from observations. The value $-(dV/dt)_{t=0}$ also equals the transport into the pit at the beginning of the process, after the dredging has stopped. For the calculation of ι in an assumed exponential decay function we only need to know the beginning value of the transport rate and not the entire process from beginning to end.

When more than one of a series of units, e.g. sections of a tidal channel are out of equilibrium the adaptation process not necessarily develops according to an exponential decay function.
An example of this will be discussed in the report (Chapter 6).

The discussion in this report centers around the changes that have occurred in the Dutch portion of the Wadden Sea. These changes are partly due to natural processes and partly due to interference of these processes by man.
The natural processes have included the formation of the Wadden Sea in the early part of this millenium and the general extension of the Western Wadden Sea by the development of the connecting Zuiderzee over the years. With this process the tidal inlets of the Western Wadden Sea slowly increased in size and the tidal basin increased in depth. (Figure 2.1).
During this period the major inlets of the Western Wadden Sea, the Texel Inlet and the Vlie Inlet must have been ebb-dominant, meaning that the ebb flow carried more sediment to the North Sea than the flood flow carried into the basin.
The closing of the Zuiderzee in 1932 had a dramatic impact on the hydrography and morphology of the Western Wadden Sea. The morphological response process still continues to-day particularly in the land ward parts of the present tidal basin indicating that the large basin requires a long time (large response time scale) to restore the morphology of the basin to the new equilibrium condition which is in tune with the changed hydraulic conditions. This process is also interactive: the changes in morphology in turn induce a response in tide conditions.
An interesting question is whether or not the Western Wadden Sea was in morphologic equilibrium before the closing of the Zuiderzee. An answer to this question can not be given with certainty because the relationship between tidal flow and sediment transport is not known with enough accuracy to predict morphological developments on a long time scale.
It is likely that the tidal basin as a whole was still in a state of slow morphologic evolution but that the size of each one of the inlets to the Western Wadden Sea was in equilibrium with their tidal flow at the time.
The closure of the former Lauwerszee in 1969 generated a large morphological disturbance in the tidal basin of the Frisian Inlet of which the Lauwerszee was a part. The response to this change also continues to cause morphological adjustments to that area to-day.

Regarding the effect of an increase in the rate of sea level rise on the morphology of the Wadden Sea the following should be noted. The filling in of a dredge-pit (after dredging has stopped) represents adaptation after a sudden change. Response to a change in sea level rise represents adaptation to a condition (water level) which is continuously changing. This represents a different process and requires a different solution.

The response to bottom level reduction as a result of oil and gas mining from underground reservoirs under the Wadden Sea is a topic of special public interest.
A considerable effort by a group of scientists of various organizations provides a valuable source of information on this issue.. (Oost et al, (1998), Oost, (1998), Eysink, (1998)).
This topic will be further dealt with in a separate paper.

3. SEDIMENTATION OF DREDGE SITES IN WADDEN SEA

During recent years dredging operations have been carried out at specific sites in the Dutch Wadden Sea with the objective to mine suitable sand for various purposes. After the required amounts of sand had been removed and the dredging had stopped these dredging sites were left to themselves and became subject of natural sedimentation. The Rijkswaterstaat Office in Hoorn has documented the sedimentation process of a number of these sites and has calculated the response time scales for these pits. These values were verified and sometimes adjusted by Oost (Oost,1997) and are summarized in Table 1.

The schematics of the situation are given in Figure 3.1 assuming a circular plan form.
For a diameter L of the dredge pit the response time scale can be calculated from the formula:

$$\iota = [1 / (CE(1- \alpha))] . [hdo /ws + (hdo / hi) (L^2 / 4D)] \quad (3.1)$$

in which

$$\alpha = (hi / (hi + hdo))^n$$

The obtained values are in seconds
A derivation of this equation is given in Appendix A.

For the calculation of ι the field parameters hi, hdo and L must be known, and the values of the morphological parameters CE, D , n and ws must be estimated and verified from calibration.
To compare "observed" and calculated response times four sites have been selected from Table 1: Boontjes, Griend, Terschelling 1 and Vlieter.

The following process assumptions were made.
The dredge-pits Boontjes, Griend and Terschelling 1 are located in fairly well protected areas with original depths (before dredging) between 0.6 and 3.0 m and low flow velocities.
The Vlieter had a larger original depth and larger velocities.
The dredging pits are depressions surrounded by areas with shallower depths, and are schematized having a circular plan form as shown in Figure 3.1.
In the adaptation process it is assumed that the dredge-pit is filled from the surrounding area by dispersive transport, and that the contribution of advective transport to the sedimentation can be neglected. The concentration gradient is taken as the difference in sediment concentration between the surrounding area and the dredging pit, divided by the length L.
It is also assumed, and this is important, that at the surrounding area near the dredge sites current velocities remain under the critical value for bed load transport so that the bottom around the pit remains stable and is not subject to erosion during the process of sedimentation.

The morphological parameters need to be given assigned values.

In ASMITA (as in ESTMORF) the time scale depends on the parameters D, CE, n and ws.
We have selected the following parameter values:
$CE = 10^{-5}$; ws = 0.01m/s or 0.005 m/s; n =3; D = 250 m^2/s.
The values of these parameters have been estimated by comparing with values used in Fokkink and Van der Weck (1998).

Location	τ-value	Surface Area m2	Volume Pit m3	Orig. Sed. Size (mμ)	Fill Size (m μ)	Orig. Depth (m – NAP)	Max. vel. (estimate) (m/s)
Vlieter	16	1000000	4000000	200	100	-4	0,4?
Boontjes	3,4	175000	956000	125		-2 tot -3	0,4
Griend	5,2	46000	278000	125		-0,2	0,4
Terschelling 1	7,9-9	14000	161000	125	90	-0,6	0,3?
Terschelling 3	10,4-13,5	20000	190000	125		-0,3	0,2?
Terschelling 4	4,7-6,2	19000	152000	125	90	-0,7	0,3?
Terschelling 5	2,9-3,9	12500	152000	125		-0,7	0,3?
Terschelling 6	7,6-16,5	37000	270000	125		-0,1	0,2?
Oosterbierum	0,5	200000	458000	110	96	-1,5 tot -2	sterk variabel
Kikkertgat	0,6	76000	346500	154	144	-1,3 tot -3 (geul)/ -0,6 tot -1,3 (plaat)	0,8
Paesensrede	1,5	200000	1060000	143	142		0,7-0,8?
Buiten Eider Noordgeul	0,9	150000	650000		100	-2	0,6
Buiten Eider Zuidgeul I	1,2	230000	1160000		100	-5	0,6
Buiten Eider Zuidgeul II	3,8	160000	1160000		100	-2	0,5

Table 1 : Response time scales for sedimentation areas (data RWS – Hoorn)

It may be of interest to compare formulation (3.1) with a purely empirical formulation derived by Oost from the data of Table 1 (Oost,1997).
He suggested the following relationship (coefficient reduced to rounded number):

$$\iota = 0.00297\ Vo / (\sqrt{Ao}\ .\ hi) \text{ (in years) **} \qquad (3.2)$$

in which Vo represents the initial value of the dredge pit and Ao its surface area.
Writing

$$Vo = Ao\ .\ hdo$$

and setting

$$Ao = \tfrac{1}{4}\ \pi L^2$$

equation (3.2) can be written as

$$\iota = 0.00263\ L\ (hdo / hi)$$

In equation (3.1) the first term is dominant for large depths and small surface areas whereas the second term dominates for large sites and shallow depths. For an average size dredge pit both terms may carry equal weight. We compare the empirical expression with the second term of equation (3.1) and notice that comparable results may be possible if the dispersion coefficient, D, is taken proportional to the diameter of the pit, L.
For assumed values $\alpha = 0.125$ and $CE = 10^{-5}$ we have

$$D \sim 0.53\ L\ .$$

This gives the following values for D:

Boontjes	$D = 250\ m^2/s$
Griend	$D = 128\ m^2/s$
Tersch. 1	$D = 70\ m^2/s$
Vlieter	$D = 598\ m^2/s$
Average	$D = 261\ m^2/s$

In our calculations we have not followed this path of variable D but we have instead assumed a constant value of $D = 250\ m^2/s$ for all cases, also using the same values for CE and n.
The results of the calculations are not very sensitive as to the selected value of n in equation (3.1).
A further comparison requires that the assumed values for D and CE are not independent from each other..
In Wang (1997), $CE = 10^{-5}$ was used with $D = 5000\ m^2/s$, whereas in Fokkink and Van der Weck (1998) the values $CE = 10^{-4}$ and $CE = 5.\ 10^{-5}$ were selected, with lower D-values ranging from 250 to 1000 m^2/s. For a higher value of CE a lower value of D is required to provide acceptable agreement between observed and calculated values of the response time scale.
A further discussion on the parameter D is given in Appendix C.
Seo and Cheong have analyzed a great number of data sets for natural streams and derived a dimensionless expression for the value of D (equation (C.12), which shows that D is a function of width and depth of the flow channel. In the case of a circular dredging site the width of the

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- **In Oost (1998) this expression was modified to:

$$\iota = 0.00293761\ .\ (Vo / \sqrt{Ao}\ .\ hi) + 9.36141 - 0.07\ .\ (Vo / \sqrt{Ao}\ .\ hi)^2$$

We have used the earlier version of this equation for reason of simplicity.

channel is the circumference of the circle which is proportional to its diameter. The assumption of a relationship between D and L therefore has some experimental justification.

Regarding the parameter ws, two different values were used: ws = 0.01 m/s and ws = 0.005 m/s, which both seem reasonable values for the areas considered.
The results of calculations based on equation (3.1) for the selected cases are presented in Table 2.

For the sites Boontjes, Griend and Terschelling 1, there is a reasonable agreement between "observed" and calculated values for the selected model parameters with only ws varying between ws = 0.01 m/s and 0.005 m/s.

However for the site named Vlieter observed and calculated values are not in reasonably close agreement, suggesting the possibility that the process assumptions for the model equation may deviate from the actual conditions in the field.

TABLE 2

DREDGE SITE	OBSERVED VALUES (YRS)	CALCULATED WS = 0.01 M/S	CALCULATED WS = 0.005 M/S
BOONTJES	3.4	3.4*	5.2
GRIEND**	5.2	3.8	5.7*
TERSCHELLING 1	7.9 – 9.0	4.7	8.4*
VLIETER	16	6.1	7.6*

OBSERVED AND CALCULATED RESPONSE TIME SCALES

- * Results closest to observed values
- ** Initial depth hi adjusted because of high tidal flat elevation
  Observed data are from Oost, (1997).
  Parameter values: $CE = 10^{-5}$; $D = 250\ m^2/s$; $n = 3$.

Discussion

In the derivation of equation (3.1) use is made of the ASMITA (and ESTMORF) concepts of equilibrium concentrations CE and Ce., whereby it was assumed that in the areas surrounding the dredge site the sediment concentration would be equal to CE whereas within the dredge site a local equilibrium concentration, Ce , could be defined which is related to CE by

$$Ce = CE\,(Ve/V)^n = CE\,(he/h)^n$$

where Ve and he are respectively equilibrium volume and depth and V and h the actual volume and depth. During the filling in of the site the actual sediment concentration, C, in the pit is

smaller than CE and larger than Ce, conditions necessary for the dispersive transport to the pit and the sedimentation inside of it.
The above definition of Ce is related to the hydrodynamic condition. Its form is derived from a sediment transport formulation whereby sediment transport is proportional to velocity to the power n+1. In order for this condition to be valid the depth-width ratio of the dredge site should be small.

For shallow dredge sites with a large surface area the second term in equation (3.1) becomes dominant over the first term. Neglecting the (small) variations in the factor $(1-\alpha)$ in this equation and assuming that the dispersion coefficient is proportional to the length L (L/D = constant), equation (3.1) can be simplified to the form:

$$\iota = \text{constant}_1 \, . \, (hdo/hi) \, (L/ (4D/L) = \text{constant}_2 \, . \, Vo / (\sqrt{Ao}/ hi) \qquad (3.3)$$

which makes equation (3.1) similar to Oost's empirical equation (3.2) and gives support to the model concept.

When dealing with deep and narrow dredge sites the formulation for the local equilibrium concentration as used in the model concept may not longer conform to the physical reality. Such may be the case in the topic of the next chapter.

4. SEDIMENTATION AT A SHIP WRECK SITE IN THE WESTERN SCHELDT

In the " Pas van Terneuzen", a channel in the Western Scheldt Estuary, the ship wreck "Zamosc" was recovered in July 1980 , which required significant dredging that created a relatively long and narrow trench of about 7 ½ m maximum depth below channel bottom. This dredging pit gradually filled up with sand and silt.

An analysis of the sedimentation of the ship wreck site was undertaken by Rijkswaterstaat to obtain information on this process which was important with respect to the prediction of the rate of sedimentation of a planned dredged trench for the placement of tunnel segments under the Western Scheldt in that region.
In the above mentioned analysis detailed current and concentration measurements were undertaken in addition to hydrographic surveys of the site and adjacent channel bottom at semi-monthly time intervals (De Jong, 1982).
Figure 4.1 presents the hydrographic situation at the wreck site and shows the locations at which current and sediment concentration measurements were taken.
Part of the depression at the dredged site consists of an oblong channel with parallel banks forming a trench. The traverses 5, 6 and 7 run across this channel at distances of 20 m covering 60 m of this channel. This channel section was selected for the analysis. The changes of bottom level over time in Traverse 6 as presented in De Jong's study are shown in
Figure 4.2. Rates of sedimentation were calculated from the hydrographic surveys and were compared with calculated values from current and concentration measurements.
The cross-sections at Traverse 6 are shown at three different measurement dates.

In our study we will use the same channel section and calculate the response time scale for this section in a manner similar to the method applied to the dredge pits in the Wadden Sea as discussed in Chapter 3 and we will compare observed and calculated values.
Because of the availability of measurement information on current and sediment concentration we will be able to verify some of the model assumptions regarding the transport and sedimentation process from the field data.

Response time scale

The development of an expression for time scale is again based on the Asmita-Estmorf concept (Wang, 1997) and follows the same lines as for the dredge pits in the Wadden Sea. The difference between this situation and that of the previous chapter is that we are now dealing with flow, (more or less) perpendicular to a trench which can be schematized to a two-dimensional (2DV) situation. The channel section has parallel banks and is subject to inflow from the two banks. The schematics and dimensions of the section are shown in Figure 4.3.

We will first discuss the results of the measurements by Rijkswaterstaat as reported by De Jong (1982)

From the hydrographic surveys the following amounts of sedimentation were found:

Period: September 8 - September 22, 1980 (first period):

Sand + silt = 2423 m^3

(Calculated : Sand 1394 m^3; silt 910 m^3; sand + silt = 2304 m^3).

Period: September 22 - October 6 ,1980 (second period):
Sand + silt = 1736 m3

(Calculated: Sand 1011 m^3; silt 90 m^3; sand + silt = 1101 m^3)

From Figure 4.2 the volume of the dredging pit over a channel section of 60 m at the beginning of the first period is calculated at 28140 m^3.
The calculated sedimentation is obtained from measurements of currents and sediment concentrations at the stations 1, 2 and 3 of Figure 4.1. During the first measuring period calculated values are close to observed rates of sedimentation, which gives us confidence in using the data from the hydrographic surveys as input for the calculation. Considering the sedimentation during the first period as the initial rate of sedimentation we can then calculate the response time from equation (2.3)

$\iota = - Vo / (dV/dt)_{t=0}$, which gives with $(dV/dt)_{t=0} = 2304\ m^3 / ½$ month:

$\iota = 28140/ 2423 = 11.6$ (½ month) = 5.8 month ≈ ½ year

This value will be compared with the calculated response time scale.

We will consider the sedimentation of he trench by means of dispersive transport into the trench per unit of length from both sides. For the derivation of an expression for the response time scale reference is made to Appendix A.
The response time scale can be calculated from:

$$\iota = 1/ ((1- \alpha) CE) [hdo / ws + (hdo/hi) (L^2/2 D)] \qquad (4.1)$$

This equation is similar to equation (3.1), derived for a circular dredge site, but with a different numerical factor in the second term of the expression between parenthesis.

For the calculation of the response time scales we will start by using the same parameters as used in Chapter 3:

$CE = 10^{-5}$, ws = 0.01 m/s, $D = 250\ m^2/s$, n = 3.

From site information we have hi = 9.60 m, and hdo = 3.13 m., which gives $\alpha = 0.429$.
Introducing the above values into equation (4.1) gives

$\iota = 5.73 \cdot 10^7$ sec. = 1.8 years

Because the sediment flow into the pit consists of over 2/3 of sand and less than 1/3 of silt, and local velocities at times exceed 1 m/s, it may be meaningful to raise the value for ws to 0.02 m/s, for which we find:

$\iota = 0.95$ year

Because of the larger initial depth compared to the Wadden dredge sites it may be reasonable to raise the value of D to 500 m^2/s; we then find:

$\iota = 0.48$ year ≈ ½ year

This value is equal to the response time scale calculated from the field observations.
These results show that with a reasonable adjustment of the model parameters ws and D, agreement between observed and calculated response times can be obtained.

Comparison between the values of model parameters and physical quantities.

It will be of interest to determine if the model process and the selected parameters are in agreement with the physical conditions at the site.
In the Asmita model (Wang, 1987) the transport mechanism includes both dispersive and advective transport. The advective transport in this model is only of interest, if in a given cross-section the ebb flow differs from the flood flow.

In our model it has been assumed that the tide-integrated values of the advective transport on each side of the pit are equal to zero. (This assumption has not been verified for this case).
The transport and deposit calculations in De Jong (1982), which were compared with measured sedimentation, were based on advective transport and included certain assumptions regarding the amounts deposited in the trench during flood and ebb flow.
The assumptions on which our calculations are based include the condition that the sediment concentration within the trench is smaller than in the region outside the dredged area, (so that a dispersive transport can develop from the surrounding area into the trench).
Measurements indicate, however, that this assumption does not correspond with reality, at least not on the days when measurements were carried out, because the measured concentrations in the trench were higher than outside.
The physical reality therefore appeared to be different from the model assumptions.
Reference is made to Figures 4.4 and 4.5 taken from De Jong's report.
In Figure 4.4 current velocities, sand concentrations and silt concentrations are shown for measuring sites 2 and 3 during ebb, at selected times, the flow running from point 3 outside the trench to point 2 inside the trench.
In Figure 4.5 the same is shown for points 1 and 2, with point 1 situated outside the trench and 2 again inside the trench. Please note that the depths at points 1 and 3 outside the trench are much shallower than at measuring point 2 inside the trench.
The overall concentrations are of order 200-300 mg/l, which correspond to volumetric concentrations of $(1 - 1.5) \cdot 10^{-4}$ which is an order of magnitude higher than the parametric values for CE used in the calculation.

In the preceding chapter it has been suggested that the formulation used to calculate the local equilibrium concentration, Ce, requires a low depth to width (hi/L) ratio to give realistic values for Ce. With a maximum depth of about 7 meters and a trench width of 150 meters the question is whether or not this criterion was met and consequently if the formulation used for Ce was justified.

We may conclude that the sedimentation process in the actual situation is considerably more complicated than the conceptual process in the model, so that a more sophisticated model formulation may be required.
Additional research will be necessary to clarify this uncertainty.

Other modeling approaches

A different modeling approach is the "Sutrench model"(Van Rijn, 1986) ; it is a two-dimensional vertical (2DV) mathematical model for the simulation of bed load and suspended load transport under conditions of combined quasi-steady currents and wind induced waves over a sediment bed This model is applicable to dredged trenches. In addition to the Sutrench model, Delft Hydraulics has developed two additional models, the "Unibest-TC 2.0". which is based on a local equilibrium approach and the "Delft- 2D/3D" model which can also model the vertical structure of the transport processes based on a depth-integrated appr.oach. The use of these models is described in Walstra, Van Rijn and Aarninkhof (1998).
These three models are all process-based models, simulating bed-load and suspended load transport and associated bed level changes. An important consideration is that silt transport apparently plays an important role in the sedimentation process.
Another application of 2DH and 2DV modeling is described by Mead (1999), in which a 2DH and 2DV solution are compared in the study of a hypothetical trench in the Conwy Estuary, United Kingdom.
The advantages of 2DV models over 2DH models include the ability of 2DV models to simulate the vertical eddies which form in steep sided trenches. Furthermore , 2DV models have more sophisticated means of representing vertical turbulent mixing than do 2DH models. (Mead, 1999)
Comparison between the model results of Mead (1999) have indicated that that differences in the model formulations lead to qualitatively different sedimentation predictions.
To overcome the limitations of the 2DH and 2DV models the application of fully three-dimensional models will be necessary.
Because transports and deposits of silt play a role of importance in the sedimentation process in addition to the movement of sand this aspect needs to be taken into consideration.

Discussion

Although the applied model seemed to provide adequate agreement between model results and observed data a further analysis based on field data showed that the process assumptions for the model were not quite the same as the actual field conditions.
The obtained agreement is possibly accidental and can not be relied upon as a measure of verification.
It is recommended that further research be undertaken to develop a more sophisticated model for a narrow trench.

5. MORPHOLOGICAL TIME-SCALES FOR TIDAL FLATS AND -CHANNELS

Tidal flats are important parts of tidal basins and it may therefore be of interest to consider the response of changes in these areas due to different causes.
Examples of possible causes are the change of surface area due to land reclamation or changes in surface elevation due to ground movement or to a change in the rise of sea level.
For the analysis we will use the Estmorf formulation as described in Wang et al (1998) which is suitable for this problem.
The following assumptions are made regarding the physical process
We assume that the tidal flat is bounded by high land on one side and by a flow channel on the other side.

We also assume that the sediment moves from the channel to the flat or visa versa in a direction perpendicular to the channel in the form of dispersion of suspended sediments.
We neglect the effect of any current parallel to the channel on sedimentation or erosion. The flux of sediment between channel and tidal flat is governed by the average concentration gradient between channel and tidal flat. There is no exchange of sediment between adjacent flat sections.

We will calculate the response time scale for two hypothetical situations which differ in the way the adjacent channel responds relative to the changes occurring on the tidal flat.

In the first case we assume that the cross-section of the channel and the sediment concentration in it do not change. The schematics for this situation are shown in Figure 5.1.This can occur when sediment losses or gains in the channel from the exchange with the adjoining flat are entirely compensated by transport in the direction of the channel.
In the second case along-channel transport does not occur (the channel fulfills the function of basin) so that the exchange of sediments between channel and tidal flat also results in changes in the channel volume and cross-section. This situation is shown in Figure 5.2.
Both situations may actually occur in the field.

Detailed derivations are given in Appendix B; the final equations are given below.

a. *First condition: no changes in cross-sectional area of channel and constant concentration in channel.*

Reference is made to Figure 5.1.

The response time scale calculated for this case is expressed by

$$\iota = [1/(n\,CE)].\,[(h_2/ws) + L(L+B)/(2D)] \qquad (5.1)$$

in which

h_2 = initial mean depth on tidal flat (changing)
L = width of tidal flat (constant)
B = width of channel (constant)
CE = overall equilibrium concentration
ws = vertical exchange velocity

D = dispersion coefficient (exchange coefficient)

It may be noted that in expression (5.1) the depth h_1 does not appear, because this value is not relevant under the assumptions made for this case.

b. *Second condition: Sediment for tidal flat is derived from the adjacent section of the tidal channel without the effect of longitudinal transport compensation in channel.*

This situation is schematically shown in Figure 5.2

The response time scale for this situation is given by the following expression:

$$\iota = 1 / (n\, CE\ \delta) \left[(h_2 / ws) (1 + L/B) + L (L + B)/(2 D) \right] \qquad (5.2)$$

in which the factor δ is equal to

$$\delta = 1 + (\Delta h_1 / \Delta h_2). (h_2 / h_1)$$

Here it may be noted that, in the factor δ, depths h_1 and h_2 are both included in the formulation. A detailed derivation of this equation is given in Appendix B.

It is evident that the two approaches have different solutions indicating that the behavior of the channel (or adjacent basin) has a distinct influence on the response time scale of the flat. Furthermore it can be seen that the response time scales are very much affected by the horizontal dimension of the tidal flat, L, and the channel width, B.

In the following time response scale values have been calculated for assumed values of L, B, h_1 and h_2. The two criteria differ in the way the channel section and the flat section work together in the adaptation process.

To apply these formulations to actual situations, assumptions have to be made for the values of the exchange coefficient D and for the morphological parameters CE , n and ws.

The computations have been based on the following parameter values:
$CE = 2.10^{-5}$, $ws = 0.01\ ms^{-1}$, $n = 4$, and $D = 500\ m^2 s^{-1}$. Assumed depth values are $h_1 = 10$ m and $h_2 = 2$ m. The assumed CE-value is based on a sediment concentration of 30 mg/l and a pore content of the deposited sediment of 0.4.

Table 3

Dimensions of tidal flat (L) And channel width (B)	Equation (5.1) (case a) Response time (years)	Equation (5.2) (case b) Response time (years)
L = 1000 m B = 1000 m	0.9	0.8
L = 5000 m B = 2000 m	14	9
L = 10000 m B = 5000 m	60	43

Response times for tidal flats for selected flat dimensions

The selected channel and flat dimensions for which the calculations have been made are shown in column 1 of Table 3; the results of the calculations are shown in the columns 2 and 3.
The value of the dispersion coefficient has significant influence on the outcome of the calculations. A value $D = 500\ m^2/s$ was selected.
In the schematization the tidal flats have been given a horizontal bottom. This does not conform with reality but the influence of this simplification is small, since the outcome of the calculations is dominated by the second term in equations (5.1) and (5.2), in which the depth does not appear.

Table 3 shows that the two approaches lead to different results, with case "a" leading to higher values of the response time than case "b". If the tidal channel accumulates material from eroding flats or if the channel bottom erodes to provide sediment for the sedimentation on the flats, response times are lower than in the case of a non changing channel volume.
The results of this exercise have to be considered primarily of qualitative importance. The actual values of the response time scale depend on the assumed values of the morphological parameters which were used in the calculations and may vary for different values of these parameters.
The calculations show that for small tidal flat areas with widths smaller than 1 km response time is less than one year. The response time quickly increases for wider tidal flats.

Other possible applications

The above derivations may allow application to a different situation such as the exchange of sediments between an ebb tidal delta and a tidal basin, for which the inlet system need to be schematized to a one-dimensional channel. The seaward basin (ebb tidal delta) can then be characterized by a depth h_1 and the tidal basin by a depth h_2, whereas length dimensions need to be assigned according to the situation studied. This potential application will be further analyzed in Chapter 8.

6. MORPHOLOGICAL RESPONSE TO THE CLOSURE OF THE LAUWERSZEE

Shoaling in a tidal basin may occur when a part of this basin is removed from tidal activity by the construction of a dam. An example of such activity is the damming up of the Lauwerszee in 1969. The geographical situation is shown in Figure 6.1.

The development of the Frisian Inlet and the morphological adjustment of its tidal basin to the closure of the Lauwerszee have provided a well documented case for the study and application of various morphological adaptation models. The tidal basin of the Frisian Inlet is a reasonably well contained basin of relatively small dimensions, (compared to the dimensions of the entire Waddenzee), where numerous hydrographic surveys at various time intervals have provided an excellent data base for the development of this basin after closure. (Biegel, 1991).
It is outside the scope of this paper to give a full description of all the research that has been conducted in association with this closure operation. Various different models have been applied to this case. A selected number are briefly discussed below.

It is important to note that if a certain research effort is not listed in this overview this does not reflect in any way upon the scientific value of such effort. It must be kept in mind that the objective of this paper is not to give a full account of all relevant research efforts described in the literature in regard to the closure of the Lauwerszee, but to choose selected approaches for the evaluation of response time scales in order to compare their results with more simplified formulations such as discussed in Chapter 8.

Van Dongeren (1992)."A model of the morphological behaviour and stability of channels and flats in tidal basins" (M.Sc. Thesis)
Van Dongeren developed two models applicable to tidal basin shoaling, a morphodynamic model for a one-dimensonal channel, and a tidal basin model based on empirical relations. He applied the first approach to a generalized condition and the second one specifically to the Frisian Inlet.
The first model is based on hydrodynamic equations for water flow (tides and currents), and on equations for sediment transport and sediment conservation to determine the changes in bottom elevation.
The model uses the asymmetry of the tidal wave to calculate the resultant flood transport of sediment into the tidal basin.
The combination of the M_2–tide and its M_4 component with a lead of M_4 relative to M_2 of 90 degrees induces an asymmetry in the tidal velocities and a flood dominance of the current induced sediment transport.
The component Mo, which represents circulation, is not taken into consideration. (In certain cases this component may be of interest.).
For additional discussion on tide induced residual transport reference is made to Ligtenberg (1998), Dronkers (1998), and Fokkink et al, (1998).
The second (tidal basin) model of Van Dongeren's paper describes the morphological behavior of a channel-flats system in a tidal basin. The distribution of sediment is here based on a set of empirical relations.
The basis of this model is the assumption that the main variables in the system, the channel cross-sectional area and the flats' surface area, tend to their equilibrium values according to a first order differential equation, represented by the decay function.

For the channel's cross-sectional area, A, this equation reads

$$\partial A / \partial t = -(A - Ae)/ \iota \tag{6.1}$$

in which

A = cross-sectional area at time t,
Ae = equilibrium area
ι = morphological time scale

The equation expresses the empirical finding that as A gets closer to Ae the rate of adaptation decreases.
In the model it is assumed that the flats will try to maintain a certain depth (over-depth) below high water.
The adaptation of channel cross-section according to equation (6.1) can only take place if sufficient sediment is supplied to that section. This condition may form a restriction to the adaptation process. Otherwise the change in cross-section depends on the gradient of the sediment transport, S, in the channel direction, x :

$$\partial A/\partial t = \partial S / \partial x \tag{6.2}$$

The inflow or outflow of sediment at the ocean side of the model is governed by an empirical equation relating the exchange to the difference between the equilibrium flats' area and total flats' area at time t.
The tidal basin model can handle different scenarios such as: closure of part of the basin, sea level rise, land subsidence (due to sand and gas mining) and variations in tidal range due to the 18.6 –year tidal periodicity.
The evolution of a tidal channel after closure of part of the basin calculated from this model is shown in Figure 6.2, from Van Dongeren (1992). The letters indicate different stages in the shoaling process which ultimately leads to a sloping surface with zero depth at the landward end of the basin. The process underlying the development of the bottom as shown in this figure is that of a progressive sand wave entering the basin from the North Sea.
The reality of the Frisian Inlet basin is somewhat different from the model condition because a flow channel in the eastern part of the basin is not closed off after the closure of the Lauwerszee. This branch actually increased in size after the closure.

Wang et al, (1998). "A dynamical-empirical model for estuarine morphology"

In this paper the basis for the ESTMORF- model is laid out.
The Estmorf- model is developed by RIJKSWATERSTAAT in collaboration with DELFT HYDRUALICS; it is built on empirical morphological relationships, and includes the concept of equilibrium concentration following the work of Di Silvio (1989).
Di Silvio postulated that in a tidal system three parts can be distinguished, each with its own characteristic long term average concentration: the tidal flats and shoals, the channel and the littoral environment outside the inlet. Transport of sediment between these parts is equal to the exchange volume between two parts times the difference in the average sediment concentration.
The model distinguishes between on overall equilibrium concentration CE and a local equilibrium concentration, Ce.

In Wang et al (1998) the equilibrium state is defined for three variables: the cross-sectional area of the channel, the height of the low flat and the height of the high flat. For the Wadden Sea information for these equilibrium variables is given by Eysink (1992).
When local parts of the system are in equilibrium but the system as a whole is not, sediment will be exchanged between the parts and morphological changes will occur. The sedimentation and/or erosion rate is assumed to be proportional to the deficit/excess of the local sediment concentration, following the formulation of Galappatti and Vreugdenhill (1985).
The bed level change is then described by the relation:

$$\partial z / \partial t = ws\,(C - Ce) \qquad (6.3)$$

in which z = bed level, ws vertical exchange velocity, t = morphological time, and Ce = local and instantaneous equilibrium volumetric sediment concentration.
In order for this equation to be valid the volumetric concentrations need to be defined to include pores.
The local equilibrium sediment concentration is defined by the hydrodynamic condition and reads for the channel cross-section:

$$Ce = CE\,(Ae / A)^n \qquad (6.4)$$

The exponent n in (6.4) is related to the exponent N of the tidal velocity in an exponential transport formula ($n = N - 1$).

In addition to the above mentioned two types of equilibrium sediment concentration the model also recognizes a third type of concentration, the instantaneous local concentration C.

Mass balance equations are written for the channel, and for the low and high parts of the tidal flats. The mass balance equation for the channel is the advection-diffusion equation, which balances the transport gradients of suspended transport with the sedimentation or erosion at the bottom. It may be written as:

$$\partial AC/\partial t + \partial AuC/\partial x + (\partial/\partial x)\,(A\,D.\partial C/ \partial x) = W\,ws\,(Ce - C) + Fk \qquad (6.5)$$

in which
- x = the direction along the channel axis
- A = channel cross-section
- u = velocity
- W = width of channel (at the surface) ,and
- Fk = sediment flux from the tidal flat to the channel
- ws = vertical exchange velocity
- D = dispersion coefficient

The behavior of the model can be evaluated by considering a simplified case: the filling in of a rectangular tidal basin with one end open to the sea and the other end closed. The results depict a development, similar to what was found in Van Dongeren (1992) and are shown here as Figure 6.3.
The morphological time-scale (also named characteristic time scale, response time scale or adaptation time scale) is defined as the time in which the disturbance decreases its initial amplitude by a factor 1/e (e = basis of natural logarithm). If residual flow is neglected the time scale for a small disturbance in a system in equilibrium is expressed by

$$\iota = (1/\,CE.\,n)\,[(h/ws + 1/(k^2D)] \qquad (6.6)$$

in which

h = equilibrium depth
n = constant (between 3 and 5)
CE = overall equilibrium concentration
k = wave number of disturbance

The Estmorf model is applied to the morphological developments after the closure of the Lauwerszee. The model is set up as a one-dimensional (1D) network and gives a reasonable representation of the evolution of the channel's cross-sectional areas.

De Swart and Blaas (1998), "Morphological evolutions in a 1D model for a dissipative tidal embayment"
This study describes tidal water motion, sediment transport and bottom changes in a semi-enclosed rectangular channel with fixed coastlines and an erodible bottom. It is investigated which role bottom friction and the boundary condition for sediment concentration on the landward side play in the shape of the bottom profile.
Different shapes of bed profiles may be observed in several tidal channels in the Dutch Wadden Sea, as is shown in Figure 6.4, taken from this study.

Van de Kreeke (1998)"Adaptation of the Frisian Inlet to a reduction in basin area with special reference to the cross-sectional area of the inlet channel"
This model describes the adaptation process of the inlet channel based on the assumption that the littoral drift is the "disturbing force" that attempt to close the inlet with the ebb-tidal current acting as the "restoring force" keeping the inlet from closing. The same model serves to define equilibrium and stability of tidal inlets.
The resulting expression for the relaxation or adaptation time scale is:

$$\iota = L\,Ae/(Mn) \qquad (6.7)$$

It is suggested that in the application of equation (6.7) the quantity M not only includes the portion of the littoral drift that enters into the inlet but also the sediment transport component due to the flood current into the inlet. It is furthermore suggested that L may be taken as the average length of the tidal channel defined by

$$L = V/A \qquad (6.8)$$

where A represents the cross-section at the gorge and V the volume of the channel below mean sea level.
Van de Kreeke concludes with a relaxation time for the inlet channel of 30 years (Figure 6.5). which is longer than the value determined by Van Dongeren (1992),who found a relaxation time of 15 years.

Some additional discussion on the response time scale for the Frisian Inlet system is presented in Chapter 8.

7. RESPONSE TIME FOR TEXEL INLET BASIN

It may be expected that the response time scales for the Texel basin are larger than the values for the Frisian Inlet basin. The following factors play a role:

(1) The inlet has a larger tidal prism and cross-section, which is in agreement with larger basin dimensions. It also has a larger and deeper ebb tidal delta.
(2) The closure of the Zuiderzee caused an increase in tidal prism for the inlet and the connecting channels, and a decrease in tidal prism for the channel cross-sections further inside the basin.
(3) In the Frisian Inlet the tidal prism decreased throughout the basin as a result of the closure of the Lauwerszee.
(4) The initial response of the cross-section at the gorge of the Texel Inlet (cross-section 3 of figure 7.1) to the closure of the Zuiderzee was a (significant) decrease in area rather than an increase in cross-section; the latter would have been expected as a result of the increased value of the tidal prism after the closure. The increase in tidal prism can be explained by the change in character of the resulting tidal wave (superposition of incoming wave and reflected wave) in the basin after closure. The initial decrease of the cross-section can be explained by the presence of a sand wave entering the basin from the littoral zone.

An important source of information for the response of the inlet and the basin is the recent study by Van Marion (1999), which shows the adaptation of various sections of the inlet system (including the ebb tidal delta) after the closure of the Zuiderzee in 1932.
Figure 7.2 from Van Marion (1999) shows the different regions for which gains or losses in volume have been calculated.
Gains and losses have also been calculated in clustered form for the total areas inside and outside the gorge. The results of these calculations, taken from Van Marion's report are shown in Figure 7.3. Figure 7.3a shows the increase in volume and in average depth for the outer region (outside the gorge), whereas Figure 7.3b shows the changes for the entire basin inside the gorge.
In an attempt to explain these figures a difficulty arises when considering the basin as a whole. Figure 7.3b represents volume changes in aggregated form, and does not distinguish between parts of the basin which are eroding, located in the most seaward portion, and parts which are accreting in the more land ward portion. (Data on individual sections are given in different graphs of Van Marion's report). Although taking Figure 7.3b as a measure of the development of the whole basin could possibly lead to a less accurate interpretation, the data show a clear presentation of the overall trend, which can be used as a basis for an overall average response time scale for the basin.

Van Marion's report also presents calculated values of the resultant sand transport through the Marsdiep based on the Inverse Sediment Transport Model (ISTM), (Mulder, 1993). These calculations seem representative of the actual transports. The calculations show an average import of 7.5 mill. m^3 per year for the period 1931-1949, which is reduced to a value between 0 and 1 mill. m^3 per year for the period 1991-1997. Under certain assumptions the latter value can actually become negative, meaning that the residual transport could be in the ebb direction.
In the above calculations transport of sediment (silt) across tidal divide is not included. This contribution may not be insignificant because of the silt carrying residual ebb flow through the basin entering the basin across the tidal divide.
We may notice from Figure 7.3b that the decrease in volume over time corresponds reasonably well with an exponential decay function. This observation can be used to calculate an overall

value (a sort of weighted average) of the response time scale for this basin. The figure suggests that the system is tending to an equilibrium situation. This may not be entirely correct since in the rear of the basin additional sedimentation is likely to continue. A possible explanation is that deposition of sediment in the eastern part of the basin is counterbalanced by further erosion near the mouth of the inlet.
The inlet section itself is increasing in volume (in agreement with the increase in tidal prism). Its actual response characteristics may be close to the developments shown for the outer region in Figure 7.3a. This graph shows that an equilibrium situation has not entire been reached and that some further increase in volume can be expected.

Based on Figure 7.3b, the equilibrium depth of the tidal basin is assumed at 4.15 m below MSL. This value gives a reasonably good agreement between an exponential decay curve and the data points for depth. On this basis a response time scale of ~35 years has been determined. (See Figure 7.4).
This result can be compared with the figures for the import of sediment as discussed in the preceding section. With reference to equation (2.3) the response time scale can be computed from the quotient of the total volume, Vo, and the rate of decrease in volume, $(dV/dt)_{t=0}$.
Using the values:

$Vo = (4.55 - 4.15)$. (basin area) $= 0.40 \ . \ 657 \ . \ 10^6 = 263. \ 10^6 \ m^3$,

$(dV/dt)_{t=0} = 7.5 \ . \ 10^6 \ m^3/$ year (see above), we find

$\iota = 35$ years

This number is in agreement with the value obtained in Figure 7.4 from the tangent to the sedimentation curve.

This value is likely to represent a sort of weighted average for the entire basin, but certainly does not necessarily represent the response time scale for the back portion of the basin. Observations show that developments in that part of the basin conform to a much longer response time scale.

A usual assumption regarding the sedimentation process in the basin is that all the required sediment is supplied through the inlet. Under this assumption supply to the back basin will only materialize after more seaward located sections have adjusted themselves to the available sediment flux. In other words: the sediment flux to the back portion is restricted.
Local circulation may also have an influence on the sedimentation in the back portion of the basin. This may have two opposing results: it may sustain channel development in that area as well as contribute to additional sedimentation.

Gerritsen and Louters (1994) calculated the response time scale for the Texel Inlet from profile changes, assuming the response was following a decay function. They found a response time scale of 40 years for the inlet and 115 years for the back region.
The value for the inlet corresponds reasonably with the value of 35 years, found above. However there is a significant discrepancy of values with regard to the back portion of the tidal basin.
The value of 115 years for the back region is probably too high. Most likely assumptions made for these calculations were not realistic. Particularly the assumption of an exponential decay function for the response is questionable for this region.

With an exponential decay function $e^{-(t/\iota)}$, at a time $t = \iota$ the magnitude of the disturbance is reduced to 0.368 of its initial value and at $t = 1.6\ \iota$ to 0.20. For $t = 2\ \iota$, this figure is further reduced to 0.135 and at $t = 3\ \iota$, to below 5 %.

Presently the channel cross-section through the gorge of the inlet has approximately the same value it had before the closing of the Zuiderzee. Since the tidal prism increased after the closure of the Zuiderzee, some further increase in cross-sectional area can still be expected, based on an assumed empirical morphological relationships between tidal prism and cross-section.
Such a development would be in general correspondence with a response curve as shown in Figure 7.4 indicating that at present ($t = 2\ \iota$) about 87 % of the expected adaptation would be completed.
Additional discussion on the response time scale for this inlet is given in Chapter 8.

It is feasible that more than one time scale can be identified in the response of a system to a disturbance. It can be shown mathematically that the number of time scales in the system is at least equal to the number of elements in the system (Stive et al, 1998).
It can also be shown (Di Silvio 1989) that when a system has several components the decay function is not necessarily a realistic representation of reality.
This situation may actually exist for the gorge of the Texel Inlet; in the years following the closing the size of its cross-section decreased despite the increase of the tidal prism.

Equilibrium of Ebb tidal delta

Earlier research (Walton and Adams, (1976) and Marina and Mehta (1987)) has shown that the volume of sand of the ebb tidal delta (measured with reference to the continuous shoreline) increases with the increase in tidal prism.
The erosion of the outer region at the Texel Inlet after the closure of the Zuiderzee and the increase of the tidal prism, seem to be in disagreement with these investigations. However, this may not necessarily the case if the receding shoreline is taken into consideration (recent investigations by Rijkswaterstaat (Oost. 1999,Biegel, 1999)).
However the results of the volume measurements of the entire outer region as depicted in Figure 7.3a, show a distinct water volume increase for the entire outer region compared to a decrease in water volume for the inner region as shown in Figure 7.3b.

Sand wave.

Based on the information in Van Marion(1999) an attempt has been made to explain the erosion-sedimentation development in the inlet and in its connecting basins from a morphological perspective. Data from Van Marion (1999) have been used to sketch the behavior of a bottom sand wave propagating through the inlet into the basin. (See Figure 7.5). The existence of such a wave can explain the sedimentation in the gorge of the inlet immediately after the closing of the Zuiderzee (Gerritsen and Louters 1993), corresponding with the decrease in cross-section of the gorge in the years following the closing. As time develops the sand wave, after first causing the inlet cross-section to shoal later causes the inlet to deepen. Simultaneously the eastern part of the main channel system of the basin is subject to shoaling.
A sketch for this potential wave development (not to scale) is presented in Figure 7.5.

More detailed information on the behavior of the sand wave could be obtained by dividing the sections Schulpengat, Marsdiep, Texelstroom I and Texelstroom II into shorter sections e.g. of 2 km length so that the sand wave behavior can be analyzed in greater detail.
The sand wave phenomenon is also in agreement with the concept that the development of the back basin is well in phase behind with respect to the developments near the gorge (see also Van Dongeren, 1992). On a longer time frame, slow further sedimentation in the back basin is likely to take place.

Effect of silt transport

The import of silt across the tidal divide has been neglected in the calculations. Silt transport connected with a residual flow in ebb direction through the basin may have played a not insignificant role in the sedimentation of certain parts of the basin.
Observations show (Oost, 1998), Van Marion (1998)), that sediment deposits in the Western Wadden Sea, e.g. in the Vlieter, (an earlier flow channel to the former Zuiderzee), contain a fairly high percentage of silt.

A portion of the measured sedimentation in the Western Wadden Sea is in the form of silt. Part of this may have been transported across the tidal divide between the Texel and Vlie Inlet. Such residual transport, if it is important, will reduce the need for sediment supplied through the Texel Inlet for the observed sedimentation of the Texel basin.

8. MORPHOLOGICAL TIME SCALES FOR TIDAL BASINS USING THE CONCEPTUAL FORMULATIONS OF CHAPTER 5.

In this chapter we will investigate if conceptual formulas can be used for the overall adaptation of tidal basins.

In the approach of Chapter 5 two different criteria were used, one in which the sediment concentration in the channels remained the same and one in which tidal flats and channel were adjusted simultaneously.
We will investigate if these formulations can be applied to tidal basins as a whole with special reference to the Frisian Texel Inlets, using realistic model parameters.

Table 3 in Chapter 5 shows that the response time scale is strongly dependent on the length dimension of the flat perpendicular to the channel. It was assumed that the transport of sediment to and from the tidal flats takes place only in a direction perpendicular to the channel and that no exchange of sediment takes place from one tidal flat section to an adjacent section in a direction parallel to the channel.
The value of the dispersion coefficient is very important and need to be carefully selected. Its estimated value used in Chapter 5 is based on the small water depth over the shoals. In this simplified model the tidal flats have a horizontal surface, which does not fully reflects reality. However the influence of this assumption on the results is small, since the second term in equations (5.1) and (5.2), in which the depth does not appear, dominates the outcome of the calculations.
The results show that the two approaches a and b lead to different values. Approach 'a' makes the sediment concentration in the channel a constant and independent of its value on the flats. In approach 'b' sediment required on the tidal flat is derived from the channel without the effect of longitudinal transport compensation in the channel. In the latter case a lower response time is obtained.
It may be feasible that equations (5.1) and (5.2) are applicable to an entire tidal basin, if the channel portion, characterized by width B and depth h_1, represents the region of the ebb tidal delta, whereas the tidal flat portion, characterized by length L and depth h_2 characterizes the length and average depth of the tidal basin. The system is then schematized to a one-dimensional system.
Model parameters must be adjusted for this situation; in particular the dispersion coefficient is expected to have a much greater value since the exchange of sediments between ebb tidal delta and tidal basin takes place through the deep gorge.

For the determination of D we make use of the study of Seo and Cheong (1998) " Prediction longitudinal dispersion coefficient in natural streams" in which the authors evaluated previous works on this subject and came up with a new dimensionless expression for the value of the dispersion coefficient in natural streams (see Appendix C):

$$D/(h\,U_*) = 5.915\,(W/h)^{0.620}\,(U/U_*)^{1.428} \qquad (8.1)$$

in which W/h is the width to depth ratio, U the mean velocity and U^* = shear velocity, defined by

$$U_* = (\tau/\rho)^{1/2} = (g\,R\,S)^{1/2} = (g^{1/2}/C)\,U$$

where τ is bed shear stress, ρ the density of water and C the Chezy coefficient.
It is hereby assumed that the longitudinal dispersion coefficient for tidal inlets is of the same nature and magnitude as for natural streams.
The scale relationship $D/(h\, U^*)$ of equation (8.1) scales the dimensionless D to the dimensionless quantities (W/h) and (U/U_*).
Using equation (8.1) the values for D for the Frisian Inlet and for the Texel Inlet have been calculated, whereby it is assumed that the tide averaged velocity is representative for the dispersion process. It is noted that the values of D obtained for the inlets in this way are much higher than the values used for the tidal flats.
The result of the calculations are shown in Table 4. The dimensions on which the calculations are based are listed in the table. The morphological parameters are: $CE = 2.\ 10^{-5}$; n=4 ; ws = 0.01 m/s.

Table 4

INLET	Equation (5.1) Response time scale (years) Case 'a'	Equation (5.2) Response time scale (years) Case 'b'
Texel Inlet $h_1 = 8.7$ m; $\Delta h_1 = 1.3$ m $h_2 = 4.15$ m; $\Delta h_2 = 0.40$ m L = 38750 m B = 9400 m D = 6270 $m^2\ s^{-1}$	59	24
Frisian Inlet $h_1 = 6.0$m; $h_2 = 3.0$ m $\Delta h_1 = 0.48$m; $\Delta h_2 = 0.24$ m L = 18000 m B = 9000 m D = 4150 $m^2\ s^{-1}$	24	12

Response times for Texel Inlet and Frisian Inlet based on different equations

As expected the response times for the second approach (third column) are shorter than for the first approach (second column). This is in agreement with the notion that the system reacts quickest when two neighboring elements have the opposite disturbance (Stive et al, 1998), which is the case here where the shoaling of a tidal basin goes hand in hand with the erosion of the corresponding ebb tidal delta.
When we compare the values of the response time scales in the second and the third column for each case with values of the response time scales found in Chapters 6 and 7 for the two inlet-basins, we may conclude that the values found from field observations lie somewhere in between the values found in the second and third column of Table 3.
For the Texel Inlet we refer to Figure 7.4, which is derived from Figure 7.3b which suggests a response time scale of 35 years. This value is in between the values found in Table 3 but closer to the value in column 3.

For the Frisian Inlet reference is made to Figure 8.1 which shows the development against time of a channel cross-section at a certain distance from the inlet. The data points in the figure are from Van de Kreeke, (1998) (Figure 6.5) and can give rise to two different interpretations:
For the first interpretation we consider the response curve as shown in Figure 8.1. For the channel cross-section to which it applies, (inside the basin),we may distinguish two successive adaptation periods.
From 1970-1974 the cross-sectional area decreased slowly. This can be explained by the fact that insufficient sediment is transported to this particular section from the more seaward located section, because the sediment demand of the latter section has not yet been satisfied.
The initial slow rate of sedimentation during the first adaptation period can be attributed to sediment supply from erosion of the adjacent tidal flats.
The faster rate of sedimentation can only start when the sand wave entering the basin has reached the section under consideration, approximately in 1974, after which time an exponential decay process can start to develop. (A similar explanation for the adaptation process of certain cross-sections for the Frisian Inlet was given in Van Dongeren (1992)).
The assumption is further made that for the inlet proper the exponential decay portion of the curve can be shifted backwards in time. Under this procedure the decay-type response starts in 1974 for this section, from which we then find a response time scale value of 19 years for the inlet section. This value is about in the middle of the values in columns 2 and 3 of Table 3 for this inlet.
In the second interpretation a distinction between two periods with different adaptation rate is not made. Van de Kreeke (1998) follows this route. He considers the differences between individual data points and the average response curve as experimental errors and considers an average curve through all the points. In this approach the curve in Figure 6.5 would be representative for the basin as a whole which can have a larger response time scale than the inlet proper.
In his analysis Van de Kreeke uses a somewhat smaller value of the equilibrium cross-section and arrives at a response time scale of 30 years.
The two types of interpretations may be combined in that a shorter response time scale (order 15-19 years) could be appropriate for the inlet section whereas the larger value (order 30 years or less) could be realistic for the basin as a whole.
Detailed information on the dynamics and sedimentary development of the Dutch Wadden Sea, with emphasis on the Frisian Inlet can be found in Oost,1995 (Ph.D. Thesis).

It may be concluded that the values obtained with the two simplified models for the Frisian and Texel Inlets, as listed in Table 4, give the right order of magnitude for the response time scales but the results show the need for further refinement of the models for more precise results.

9. RESPONSE OF WADDEN BASIN TO SEA LEVEL RISE

The Dutch Wadden Sea in its present form is relatively young and has been subject to large changes. Even at the beginning of the Christian era the coastline in the northern part of the country was located several kilometers seaward of its present location.
At that time the mean sea level was 1.5m lower than the present level.
The changes that have developed over the years have been greatly influenced by the rise of the mean sea level. At the present time the rate of mean sea level rise for The Netherlands is about 0.18 m per century (0.0018 m per year).
The Intergovernmental Panel on Climate Change (IPCC) has come to the conclusion that because of the observed heating of the atmosphere and the melting of the polar icecap an increase in the rate of sea level rise must be expected. For the coming century the expected rate of sea level rise for The Netherlands may increase to the order of 60 cm per century, but higher or lower values are also possible. The value of 60 cm per century will be used in our calculations.

In previous chapters the response of tidal basins to abrupt changes (closures) in the system were analyzed. The response was based on the assumption that relaxation would take place according to a differential equation of the type of equation (6.1), with solution:

$$(A - Ae) / (Ao - Ae) = e^{-(t/\iota)} \qquad (9.1)$$

in which

- $A = A(t)$ = cross-sectional area of inlet channel,
- Ao = initial area
- Ae = equilibrium cross-section
- ι = response time scale, also called characteristic response time

If a change in sea level rise occurs, the Wadden Sea morphologic system will react to such a change. The difference between the response to a change in the rate of sea level rise and the response to an abrupt change is that with sea level rise the new condition is not a fixed situation but a varying situation in the form of a rising sea level.
The change in the rate of sea level rise can occur over a relatively short time span.
The formulation for the response of a tidal basin to increased sea level rise is given in Gerritsen and Louters (1994):

$$Z = s \, . \, t \qquad (9.2a)$$

$$Zb = s\,(t - \iota\,(1 - e^{-t/\iota})) \qquad (9.2b)$$

in which

- $Z = s\,t$ = increase in sea level rise (compared to present condition)
- Zb = rise in bottom level in Wadden Sea (response)
- t = time
- s = increase in rate of sea level rise
- ι = response time scale (as in equation (9.1))

The response curve represented by equation (9.2b) is schematically shown in Figure 9.1.
In order to calculate the rise of the sea bottom in the Wadden Sea the value of the response time scale must be known. This value can be calculated from the response to a small sudden rise in sea level, and a corresponding increase in overall depth of the Wadden Sea.

Although tidal flats and channels respond differently to a change in waterlevel (see Chapter 5) for the overall response of the basin we consider the Wadden Sea as one basin with an average depth.

As a basis for the calculations we assume that a such a change in depth does not affect the value of the equilibrium sediment concentration in the littoral zone outside the tidal inlets (CE). This zone is an area of high energy (waves and currents) with a rapid response to a small change in depth.
Inside the inlets the rise in sea level (Δh_e) induces a decrease in local equilibrium concentration from the increase in depth according to

$$Ce = CE\,[(h_e / (h_e + \Delta h_e)]^n \qquad (9.3)$$

With Δh_e positive, Ce < CE so that a flux of sediment will start to develop from the littoral zone into the tidal basin through the inlets. Assuming that this sediment transport takes place in the form of suspended load, transport and sedimentation are governed by the advection-diffusion equation, derived from the mass conservation equation for sediment:

$$\underset{(1)}{\partial C/\partial t} + \underset{(2)}{U\,\partial C/\partial x} + \underset{(3)}{(\partial/\partial x)(D.\partial C/\partial x)} = (ws/h)\,(Ce - C) \qquad (9.4)$$

in which

C = sediment concentration
Ce = local equilibrium concentration
U = depth-average velocity
h = depth
D = dispersion coefficient
x = distance in flow direction
t = time
ws = vertical exchange velocity

The sediment flux into the basin has two components: dispersive transport and advective transport as expressed by the second and third terms of equation (9.4).
In the Asmita and Estmorf models the concentration values CE and Ce are defined as long term averages, which are characteristic for a certain area, and include a variety of morphological conditions. Equation (9.4) can be integrated over the entire cross-section of a channel and over a full tidal cycle. As concentration values do not vary within a tidal cycle, for harmonic tidal motion the advective transport term (second term of equation (9.4)) becomes zero when integrated over a full tidal cycle and the sediment transport is fully determined by the dispersive component (3rd term of equation (9.4)).
In the physical reality of tidal flow and sediment transport in a tidal basin, sediment concentrations do vary within a tidal cycle. Overall they are higher during flood than during ebb generating a residual transport in the flood direction and sedimentation in the basin. On this basis of consideration advective transport becomes the main transport component.

In agreement with the two approaches, as discussed above, we will follow two different paths for the calculation of residual sediment transport into the basin. The first one is based on dispersive transport and the second one on advective tansport.
The dispersive approach was used in the previous chapters.

a. Calculation of response time scale based on dispersive transport

Because the sedimentation process from sea level rise is a slow process the time derivative (first term) is neglected.
Assume that the overall equilibrium concentration, CE is maintained in the littoral zone outside of the inlets. Assume furthermore that an instantaneous average concentration, C < CE, is present in the tidal basin inside of the inlet. Due to the concentration gradient sediment will move from the littoral zone into the basin in the form of dispersive transport. This flux equals

$$\text{Dispersive transport} = (D\ A/\ L)\,(CE - C) \quad (m^3/s) \tag{9.5}$$

The transport is in m^3/s if the concentration is in volumetric units. The length L in (9.5) must be chosen so that (CE - C)/L represents the average concentration gradient between the littoral zone and the tidal basin.
Furthermore deposition of sediment inside the entire basin can be expressed conform equation (9.4):

$$\text{Deposits} = ws\ \ Ab\ \ (C - Ce) \tag{9.6}$$

where Ab represents the horizontal surface area of the bay and Ce the local equilibrium sediment concentration at the beginning of the adaptation process.
The value of the response time scale is found from:

$$\iota = (\Delta h_e)/\,(ws.\ (C - Ce)), \tag{9.7}$$

This equation is only valid if the volumetric concentration includes the pore volume. Otherwise equation (9.7) needs to be corrected by a factor expressing the pore content of the deposits.

From these expressions the value of ι can be calculated (see for method Appendix B):

$$\iota = 1/\,(nCE)\,[\,h_e/ws + h_e(Ab/A)\,(L/D)\,] \tag{9.8}$$

In the procedure that follows we calculate the response time scale for sea level rise in the Texel tidal basin using the dimensions of this basin, and assume that the results are equally applicable to the Wadden Sea as a whole.
For the tidal basin of the Texel Inlet we will use the following characteristic dimensions:
$h_e = 4.15m$; $Ab = 657 \,.\, 10^6\, m^2$; $A = 60{,}000\ m^2$; $L = 18{,}000$ m. The equilibrium depth is an estimated value (see Chapter 7, Figure 7.3b).
Selected model parameters are: $D = 6270\ m^2/s$; $CE = 2.\ 10^{-5}$; $n = 4$; $ws = 0.01\ ms^{-1}$

For the value of the dispersion coefficient we refer to Chapter 8, equation (8.1), and Appendix C.
Introducing these numbers into equation (9.10) gives : $\iota = 51.9$ years.
In comparison with earlier found response time scale values, such as in Chapters 7 and 8 this seems a realistic value.

Using equation (9.2b) the obtained value for ι allows us to calculate the rise in bottom level, the difference between sea level and bottom and the sediment demand for various scenarios of sea level rise.
Figure 9.1 describes the process. It is to be noted that in the beginning of this process the bottom rises only slowly; after $t = \iota$, the bottom begins to rise at a faster pace ultimately rising at the same speed as the (increased) rise in sea level, however at a lower elevation. The difference between mean sea level and bottom (= water depth) ultimately reaches a maximum value, at $t \rightarrow \infty$,

$$(Z - Zb)_{max} = s \, . \, \iota \qquad (9.09)$$

The response of the basin to increased sea level rise has to be taken in addition to the response of the basin to man made changes such as the closure of the Zuiderzee.

b. Calculation of response time scale based on advective transport.

Again we assume that the average concentration in the littoral zone, outside of the inlets, equals CE, and inside the basin the average concentration is C. For the calculation of the flow of sediment we now follow Di Silvio's (1989) methodology.
Let the tidal prism of the inlet be P and neglect the large scale circulation through the basin of the Western Wadden Sea. The values for P will then be the same for flood and ebb.
For the import of sediment into the basin during the flood period we may write:

$$\text{Influx} = P \, . CE$$

For the export during the ebb portion of the tidal cycle we have

$$\text{Export} = P \, . \, C$$

The resulting import during a tidal cycle is then equal to

$$\text{Res. Import} = P \, (CE-C) \qquad (9.10)$$

The rate of sedimentation during a tidal cycle is given by:

$$\text{Sedimentation} = ws. \, Ab \, . \, (C-Ce) \, . \, T \qquad (9.11)$$

The equation for the response time scale is the same as for case "a", and is expressed by equation (9.7).
From these equations the value of the response time scale can be determined:

$$\iota = 1/(n \, CE) \, [\, he / ws + he \, (Ab \, T)/P \,] \qquad (9.12)$$

Using the same dimensions and parameters as for case "a" and in addition $P = 957 \, .10^6 \, m^3$ and $T = 44640$ sec, we find $\iota = 50.6$ years.
It will be interesting to note that both approaches give approximately the same values for the response time scale, which can be rounded to 50 years.

The values obtained for the response time scale in the above analysis depend very much on the values assumed for the morphological parameters. Reference is made to the discussion paragraph below.

In the following we will calculate some characteristic numbers in the adaptation process.
For this we will use data from the Texel basin.
The sediment demand of the Texel basin caused by increase in sea level rise is calculated at a time $t = \iota = 50$ years; the sea level rises to a rate of 0.0058 m per year. The present rate is taken at 0.0018 m per year.
The additional sediment demand for the Texel basin due to the increase in rate of sea level rise can be calculated from

$$Qs = Ab \,.\, dZb/dt \qquad (9.13)$$

where $dZb/dt = s\,(1 - e^{(-t/\iota)})$ (from equation (9.2b) (9.14)

Qs is the required sediment transport in m^3 /year (including pores).
For the present we have, based on a sea level rise of 0.0018 m /y:

$$Qs = 0.0018 \,.\, 657\ 10^6 = 1.18 \text{ mill. } m^3 \text{ per year}$$

Based on equations (9.13) and (9.14), with $s = 0.0058 - 0.0018 = 0.004$ m/y and at $t = \iota = 50$ years:

$$Qs' = s\,(1 - 1/e)\,Ab = 0.004 \,.\, 0.632 \,.\, 657\ 10^6 = 1.66 \text{ mill } m^3 \text{ per year}$$

In total

$$Qs + Qs' = 2.84 \text{ mill. } m^3 /y$$

At $t = \iota$ the sea level has risen an additional distance of

$$Z = s\,\iota = 0.004 \,.\, 50 \text{ m} = 0.20 \text{ m},$$

whereas the sea bottom has had an additional rise of

$$Zb = s\,\iota\ (1 - 1/e) = 0.004 \,.\, 50 \,.\, 0.368 = 0.074 \text{ m}$$

The additional submergence of the mean bottom level is then 0.20 m - 0.07 m = 0.13 m.

On a very long term $t \rightarrow \infty$, the bottom will rise at the same rate as the sea level provided there is sufficient sediment available from the coastal sections to raise the bottom at the required speed.

At a rate of sea level rise of 0.0058 m per year and an increase in bottom elevation of the same magnitude the corresponding sediment demand for the Texel basin is $0.0058 \,.\, 657 \,.10^6\ m^3$ / year $= 3.81.10^6\ m^3$ / year, which is considerably less than the calculated influx of sediment of $7.5 \,.10^6\ m^3$ / year, after the closing of the Zuiderzee during the period 1931-1949 (see Van Marion, 1999 and Chapter 7). It is therefore likely that with the above increased rate of sea level rise the sediment demand of the Texel basin can be met, ultimately at the cost of eroding shorelines in the region.

During the process of accelerated sea level rise the sedimentation will not be equally distributed over the tidal basin but the flats will receive more material than the channels. There will be some movement of sediment from the channels toward the flats, making the channels relatively deeper. This is supported by observations which indicate that tidal flats are preferred areas for sediment deposition, particularly the higher parts near the land boundaries under the added influence of wave action.

Other aspects of possible importance for the potential of sedimentation are biological factors, such as primary production or filter feeding activity and the influence of mussel populations on tidal flats.

It may be expected that the Vlie basin has a comparable response time to increased sea level rise with reference to the Texel basin, because both inlets have approximately the same tidal prism. The eastern part of the Wadden Sea which is narrower, is expected to have a somewhat smaller response time scale than the western part.

A detailed and informative discussion on the sediment balance of the Wadden system including the effect of sedimentation in the Wadden Sea on the stability of the North Sea Coast is presented in Oost (1998).

Discussion

The results of the calculations of the response time scale very much depend on the morphological parameters used in the calculations.
With respect to the value of the exchange velocity, ws, this parameter only appears in terms which are small compared to the other terms in the equation for the response time scale, and is therefore of less significance for the response time scale for large areas.
For the value of n, $n = 4$ is selected. This parameter relates to the power of the velocity in the sediment transport equation, N, where $n = N-1$.
The Engelund Hansen formula, which has $N = 5$, includes both bed load and suspended load transport for sand sized particles, whereas the advection-diffusion equation, which is used in this model, deals exclusively with the transport of fine-grained sediments.
A related issue is the role of the bed load transport in the sediment balance and in the value of the overall equilibrium concentration.

The second method for the determination of the response time scale makes use of the advective sediment transport rates during flood and ebb. This method can be used to "back-calibrate" the CE- value from the observed influx of sediment through the Texel Inlet after closure of the Zuiderzee. For this Van Marion (1999) found for the first years after closure $7.5 \,.\, 10^6$ m^3/year. However in order to do this calculation we have to estimate the fraction of bed load transport in this quantity and deduct this from the total value. A rough approximation is 50 %. On that basis CE can be calculated from equations (9.10) and (9.11) for which we find $CE = 1.8 \,.\, 10^{-5}$. The selected value $CE = 2.0 \,.\, 10^{-5}$ fits this approach.
The values for CE, Ce and C include pore contents in order to be able to express deposited quantities in volume of soil. If we assume for the pore content a generally accepted value of 40%, the volumetric concentration expressed in terms of solids becomes $(1\text{-}0.4) \,.\, 2 \,.\, 10^{-5} = 1.2 \,.\, 10^{-5}$.
For a specific density $\rho_s = 2650$ kg/m^3, we find CE equivalent to 0.032 kg/m^3 = 32 mg/l.
In order to determine if this result represents a physically realistic value we will compare this result with some studies presented in the professional literature.

Oost (1995) lists for the average sedimentation concentration in the North Sea, based on investigations of Eisma and Kalff, a value of 10 mg/l.

Van Vessem (1998) reports for the sediment concentration in the mouth of the Haringvliet Estuary (outside of the dam) 30-70 mg/l, whereas Dronkers (1984) reports for the Oosterschelde basin (before closing) an average concentration of ~ 25 mg/l.
A landward increase in the suspended sediment concentration is generally observed in basins where sediment is imported from the sea (Dronkers,1984, Postma, 1967,Ridderinkhof, 1998). This trend is attributed to the effect of wave action (Dronkers,1984, Ridderinkhof ,1998) and can be observed in the Wadden Sea.
Oost (1995) records for the sediment concentrations in the Vlie basin a value of 50 mg/l., whereas Donkers (1984) mentions near surface concentration values between 25 and 70 mg/l for the same basin. (For the eastern part of the Wadden Sea, south of "Rottumer Plaat" Dronkers reports considerably higher concentration values, up to 250 mg/l)
Our estimate of CE was based on the conditions for the Texel basin, for which concentration values are generally lower than for the more northerly basins.
From extensive measurements Postma (1954) arrived at an average concentration of suspended silt in the Texel basin of 18 mg/l. The average concentration of sand is about 5 mg/l so that the total average amount for that basin amounts to 23 mg/l. Postma lists for the North Sea side of the Texel Inlet average silt concentrations of 7-8 mg/l.

Based on increasing sediment concentrations in northward direction it may be expected that CE values will not be the same for all inlets of the Wadden Sea but will also increase in that direction.
In order to have sediment imported into the basin the concentration in the littoral zone which we use as reference concentration, CE, must be larger than the average concentration inside the basin.
We used the Texel basin as a reference basin to evaluate the aspects of increased sea level rise. Based on Postma's data a littoral zone concentration of 32 mg/l corresponding to $CE = 2 \,.\, 10^{-5}$ seems an acceptable value.

Dronkers (1984) made a detailed analysis of the various mechanisms that may contribute to the import of sediment in tidal basins. He finds that the landward increase in sediment concentration cannot be explained by the action of tidal currents and that a long term averaged landward increase of suspended sediment concentration can only be explained by the influence of wave action.

Ridderinkhof (1998) studied the transport and sediment concentration of the Ems – Dollard basin in a simplified mathematical model. He found that a landward increase in the concentration distribution can be simulated only if the effect of wind waves is taken into account. His studies also showed that net fluxes are influenced by the interaction between tidal asymmetries and the hysteresis in the concentration-velocity curve of suspended sediments.

In view of the complicated mechanisms of sediment distribution and transport the models used in this study are only schematic representations of the real physical world.
Nevertheless they show insight into some large scale problems and provide us with workable data.

10. RESPONSE TO BOTTOM SUBSIDENCE (OIL AND GAS MINING)

The response of the tidal system to bottom subsidence from oil and/or gas mining is dependent on a number of factors : the size of the area involved, the magnitude of the subsidence and the way the subsidence develops during mining and after the mining has stopped.
The response to the mining operation may be considered to consists of two phases. If during the mining the bottom subsides in a linear fashion the response of the sea bottom is similar to the response of the sea bottom to sea level rise. This is the first phase. The second phase sets in after the mining has stopped. The response during the second phase is the restoration of depth after a sudden change and is similar to the filling in of a dredging pit after the dredging has stopped..

The mining of gas below or near the Wadden Sea is presently a subject of special public interest and will be further discussed in a separate paper.

11. CONCLUSIONS AND RECOMMENDATIONS

Conclusions

In this report morphological response processes of different kinds at different time and space scales are reviewed and some new approaches are suggested. Most situations considered are located in the Dutch Wadden Sea, but the sedimentation of a ship wreck removal site in the Western Scheldt Estuary is included for comparison.
The smallest disturbances are dredging pits of limited dimensions used for the mining of sand for commercial uses but also from the mining of sea shells from natural deposits.
It has been shown that for dredged sand pits, based on an Asmita-Estmorf formulation, calculated response times are in good agreement with observed values when the pits are well contained depressions in areas with small residual tidal currents so that the transport of fine sediment to these sites is governed by dispersion. When those conditions are not met agreement between model results and observed response times becomes problematic. An example in case is the sedimentation of a site called "De Vlieter", which is a deposition area of one square kilometer in size, which forms a part of a much larger sedimentation area in a major flow channel to the former Zuiderzee. It is characterized by tidal currents of medium strength which influence the sedimentation characteristics. Agreement between observed and calculated response times is less than adequate for this site.

An interesting case is the sedimentation of a trench in the Western Scheldt Estuary dredged for the removal of a ship wreck (the "Zamosc") in July,1980.
After the wreck removal the research department of the Rijkswaterstaat at Vlissingen conducted extensive investigations on the adaptation process including velocity and sediment concentration measurements. The simplified model, developed for the Wadden pits and applied to this case gave very reasonable results, but the physical process as documented by the measurements appeared to be quite different from the assumptions underlying the simplified model. It appears that the sedimentation process in a situation of this type is quite complicated when strong tidal currents pass over the site. The possibility of using more detailed 2DH, 2DV, or 2D/3D- models need to be considered for similar cases.

The report gives much attention to the morphological adaptation processes of the Frisian Inlet basin and the Texel Inlet basin after the closure of the Lauwerszee in 1969 and of the Zuiderzee in 1932. Different approaches to evaluate the adaptation processes have been described. A considerable data base is available for the Frisian Inlet, which has served as a basis for analysis. For the Texel Inlet and its basin, detailed information about the hydrographic development is provided in Van Marion (1999), obtained from hydrographic surveys at different times.
Based on an Asmita-Estmorf formulation a simplified model is presented for the response of the tidal basins (more specifically only the portion of the basin under the direct influence of the inlet), which provides response times comparable to observed values.
It has been suggested in the report that in the filling of the Texel basin after the closure of the Zuiderzee bed load transport in the form of a progressive non linear (damped) sand wave at the bottom of the channel has played a major role in the adaptation process.
It also has been emphasized that the back parts of the basin respond differently from the parts closer to the inlet, because after a certain time the transporting agents (tides, currents, dispersion) may no longer be able to facilitate the required transport of sediment into the back basin. One of

these transporting agents is the tidal asymmetry caused by the superposition of the M_2 and M_4 components of the tide, which is affected by the sedimentation process.
Particularly with respect to the Texel Inlet basin the possible further sedimentation of the back basin area needs further study. It is expected that the response of this region has reached about 80 % of its ultimate value. For the back basin area response times are much higher and slow sedimentation can still be expected for a long time to come provided this further filling can be facilitated by the governing processes.
It has been suggested in the report that the role of the transport of silt across the tidal divide north of the basin, facilitated by a residual tidal flow toward the Texel Inlet, may have played a greater role in the sediment balance than so far acknowledged.
Attention also has been paid to the expected response of the Wadden Sea to an increase in the rate of sea level rise. The response time calculated from a simplified formulation gives reasonable results. The formulation allows the calculation of the expected sediment demand of the basin for different scenarios of increased sea level rise.
In the report some attention is paid to value of morphological parameters used in the models with respect to the actual physical conditions in the field..

Recommendations

1. The complicated case of the sedimentation of a dredged trench, when strong tidal currents are present, needs further study through a combination of field experiments (physical), model experiments and mathematical model formulation.
2. It is recommended that the role of the bottom sand wave in the filling of the Texel basin after the closure of the Zuiderzee be investigated by dividing the area into smaller sections of about 2 km along the axis of the channel and by calculating the change in volume of these areas from survey data.
3. The roles of bed load transport and of silt transport in the sediment balance of the Texel Inlet basin need to be further investigated by means of field measurements.
4. The detailed physical processes dealing with the sedimentation of tidal flats need further study (including the exchange between channel and tidal flats), and the role of roughness and erosivity at tidal flats in the exchange process needs further analysis. The role biological activities play in the sedimentation process also needs further clarification.
5. The interaction between ebb tidal delta and the adjacent coastlines is only globally known and needs attention in further studies. Of particular importance is the response of coastlines to changes in the adjacent ebb tidal delta, in regard to developing strategic plans for coast conservation and protection.

12. ACKNOWLEDGMENTS

The author wants to express his appreciation to Rijkswaterstaat/RIKZ for the opportunity to participate in the important K2000*TX project (Opdrachtbonnummer 22982613).
He particularly wants to thank Dr D.W. Dunsbergen of RIKZ for his support, including the review of the manuscript.
In addition he wants to acknowledge the input of Dr. J van de Kreeke and Dr. A.P. Oost who have provided valuable comments during the writing of this report.
The author also appreciates Dr. Per Bruun's comments and suggestions.

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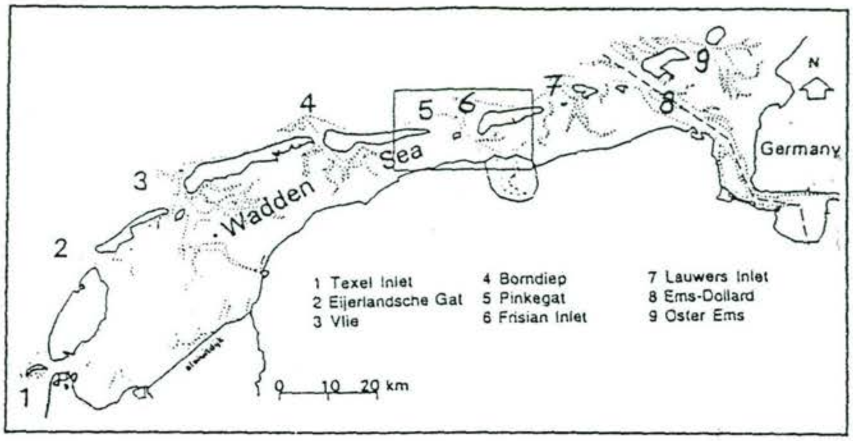


Figure 1.1. Tidal Inlets in the Dutch Wadden Sea

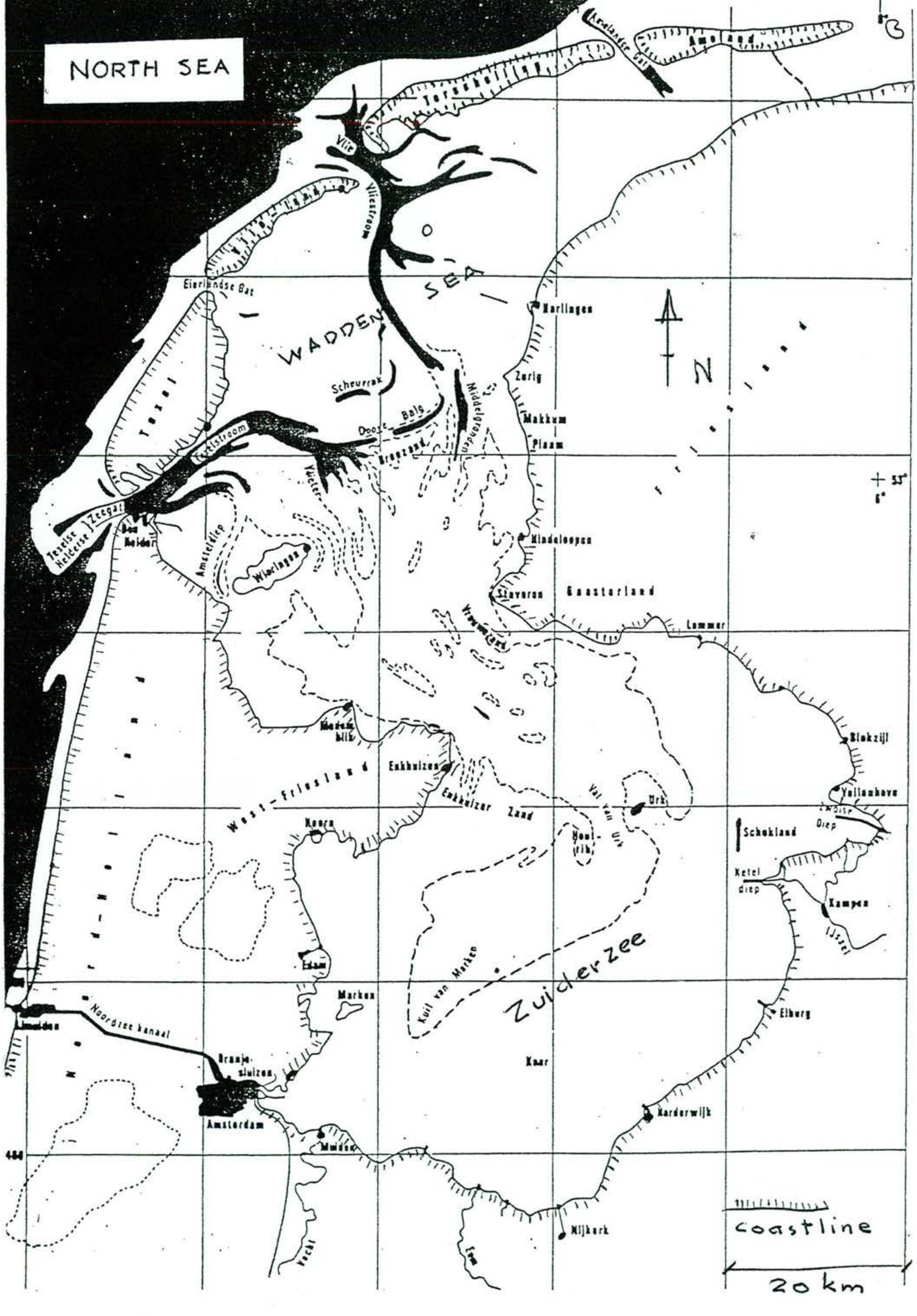


Figure 2.1. Western Wadden Sea and former Zuiderzee

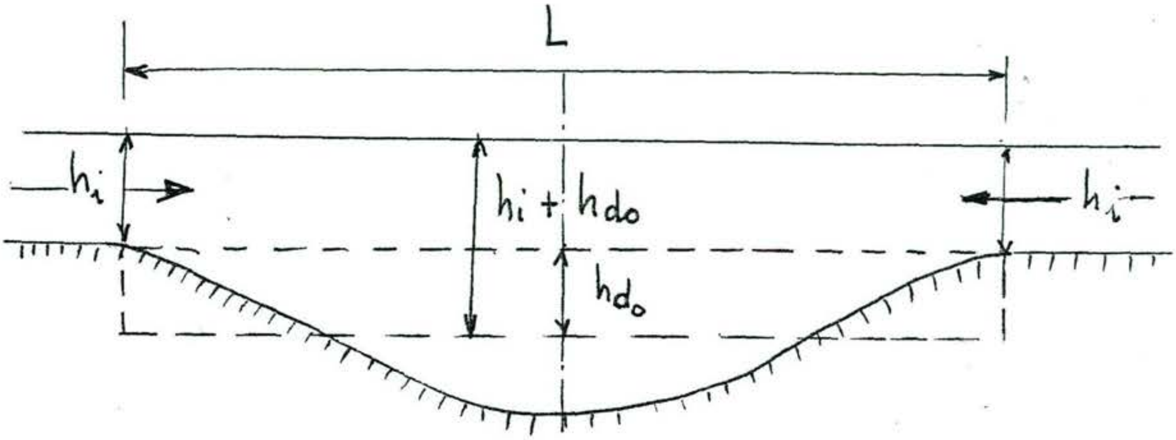


Figure 3.1. Circular dredging pit in Wadden Sea

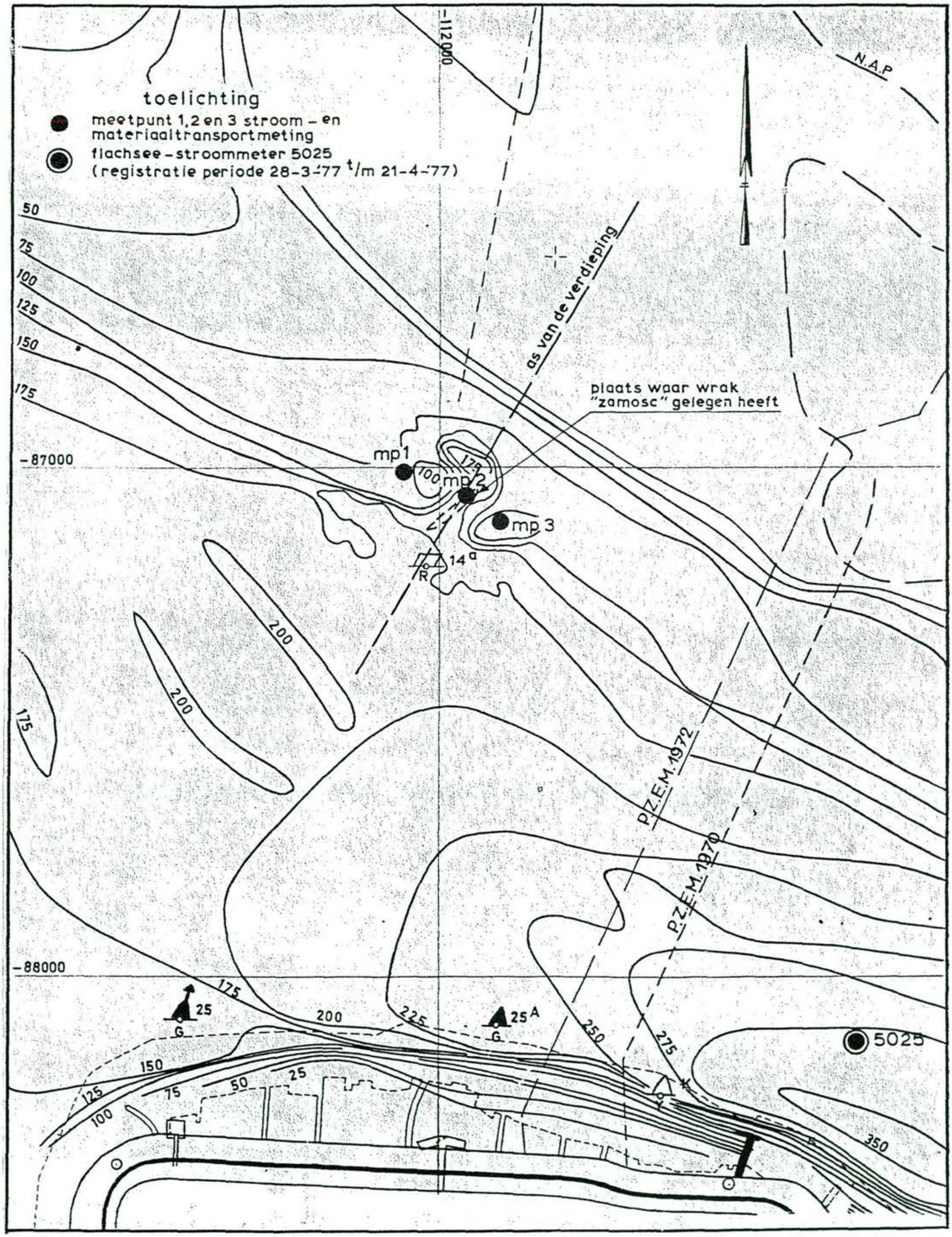


Figure 4.1. Hydrographic situation at wreck site in Western Scheldt (After De Jong, 1982)

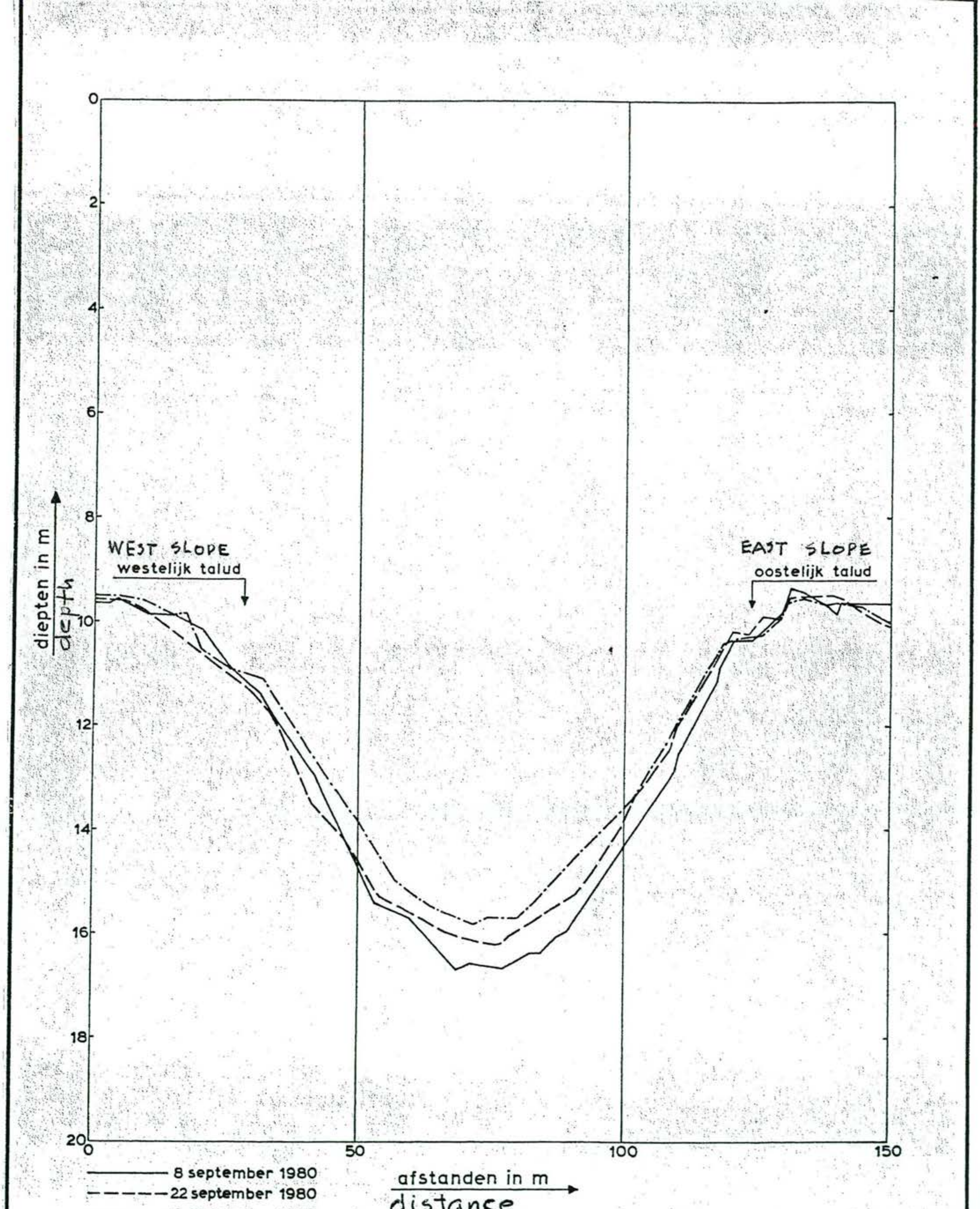


Figure 4.2. Cross-sections at Traverse 6 at wreck site at different times (After De Jong, 1982)

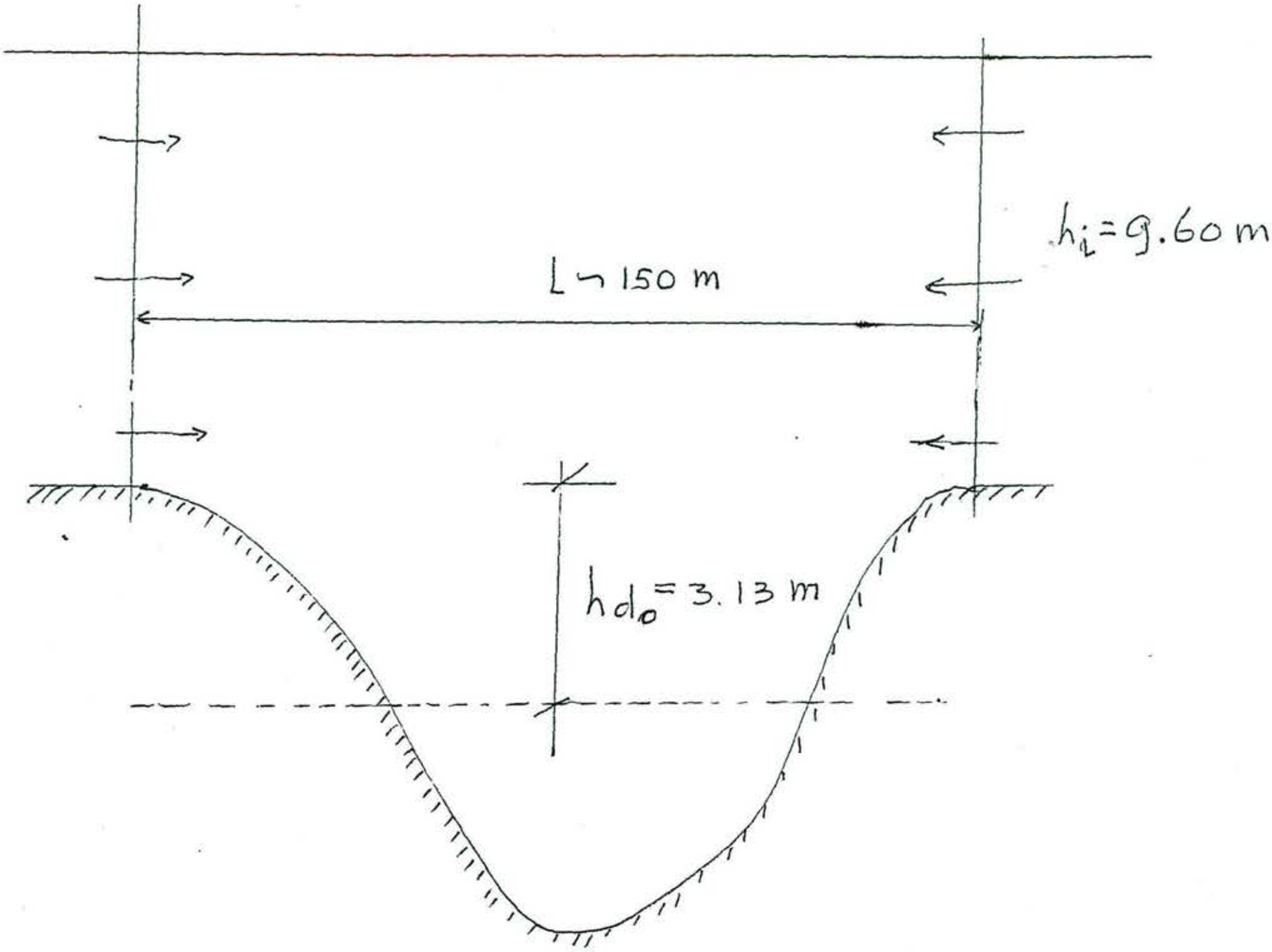


Figure 4.3. Cross-section at wreck site (schematic)

(Trench)

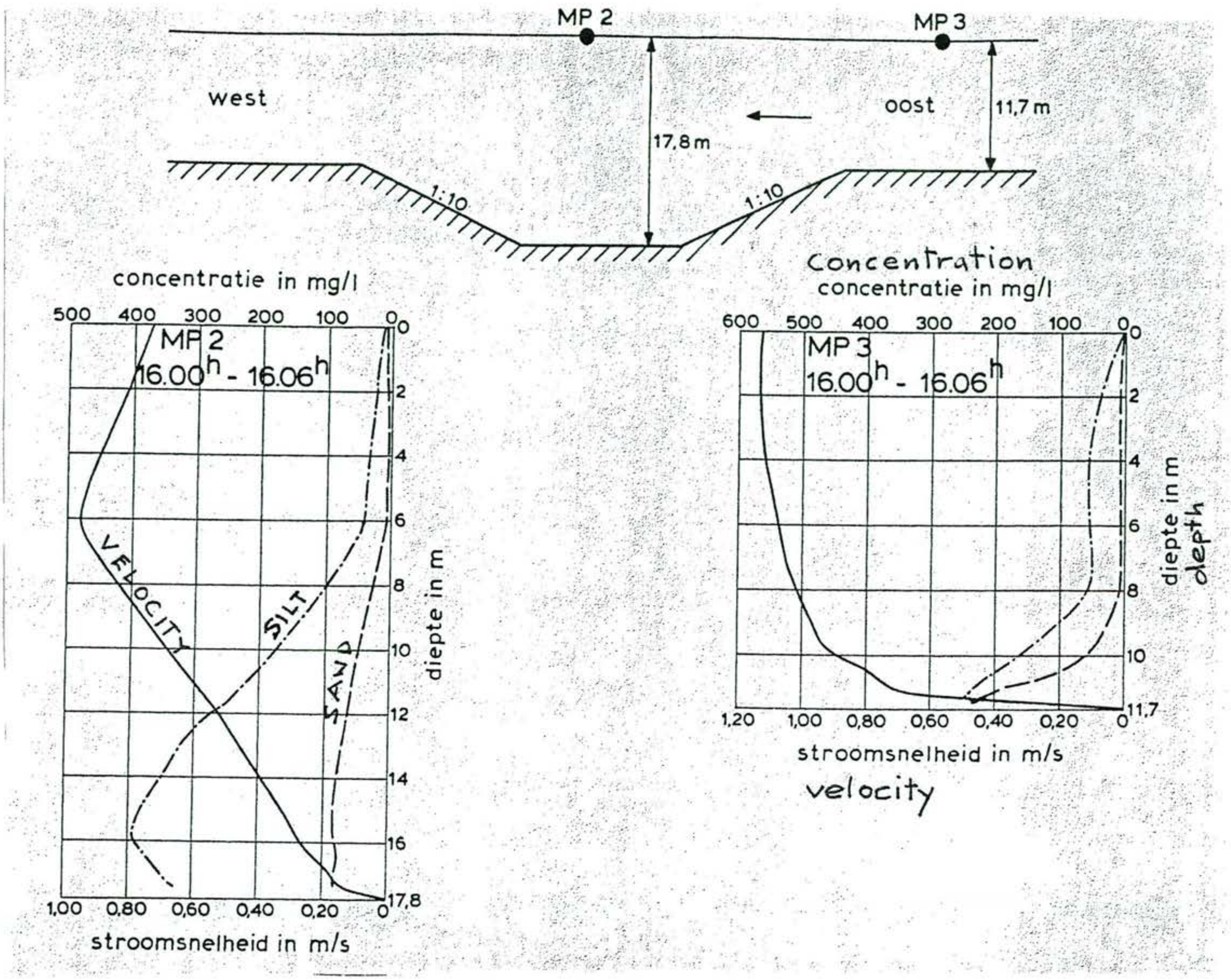


Figure 4.4. Current velocities and sediment concentration at wreck site (stations 2 and 3) (After De Jong, 1982)

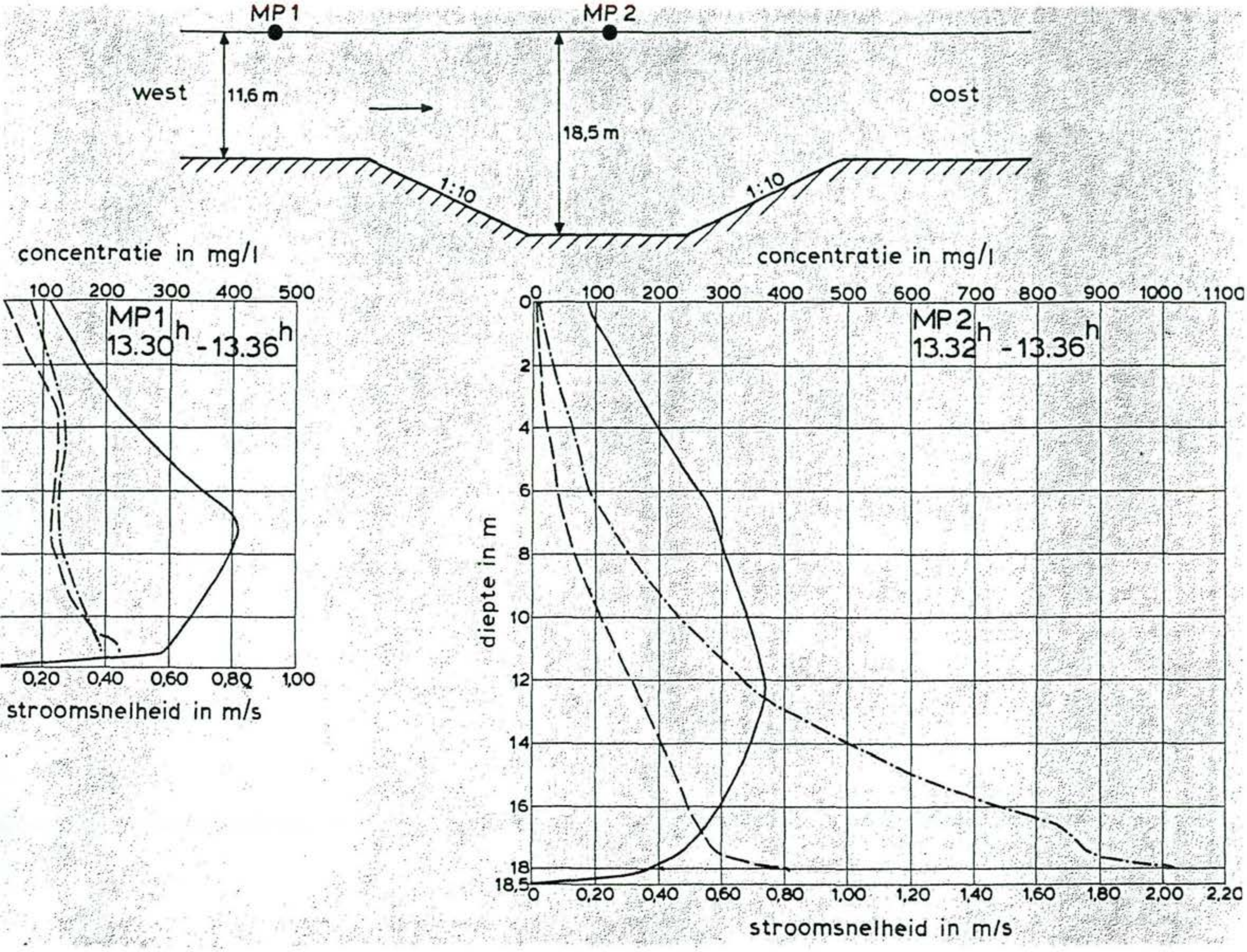


Figure 4.5. Current velocities and sediment concentration at wreck site (stations 1 and 2) (After De Jong, 1982)

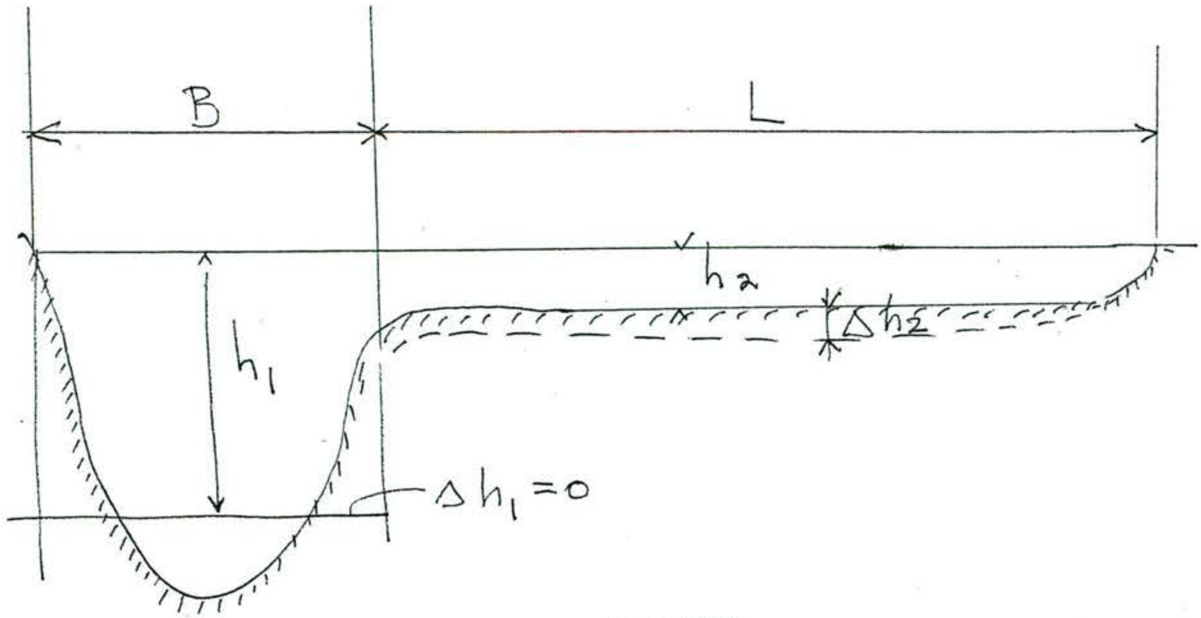


Figure 5.1. Adaptation of tidal flat

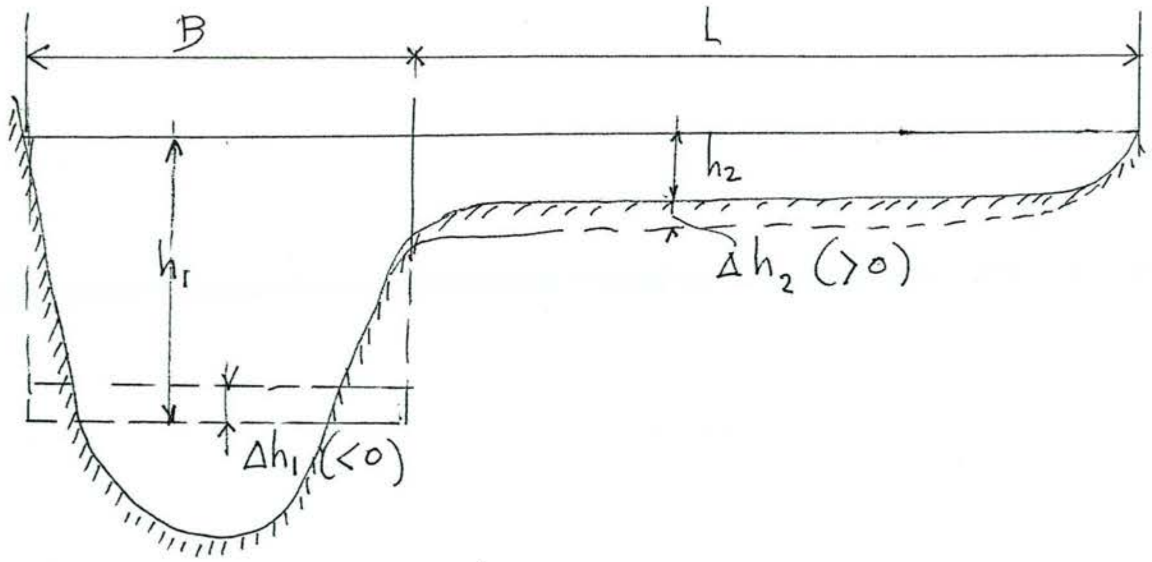
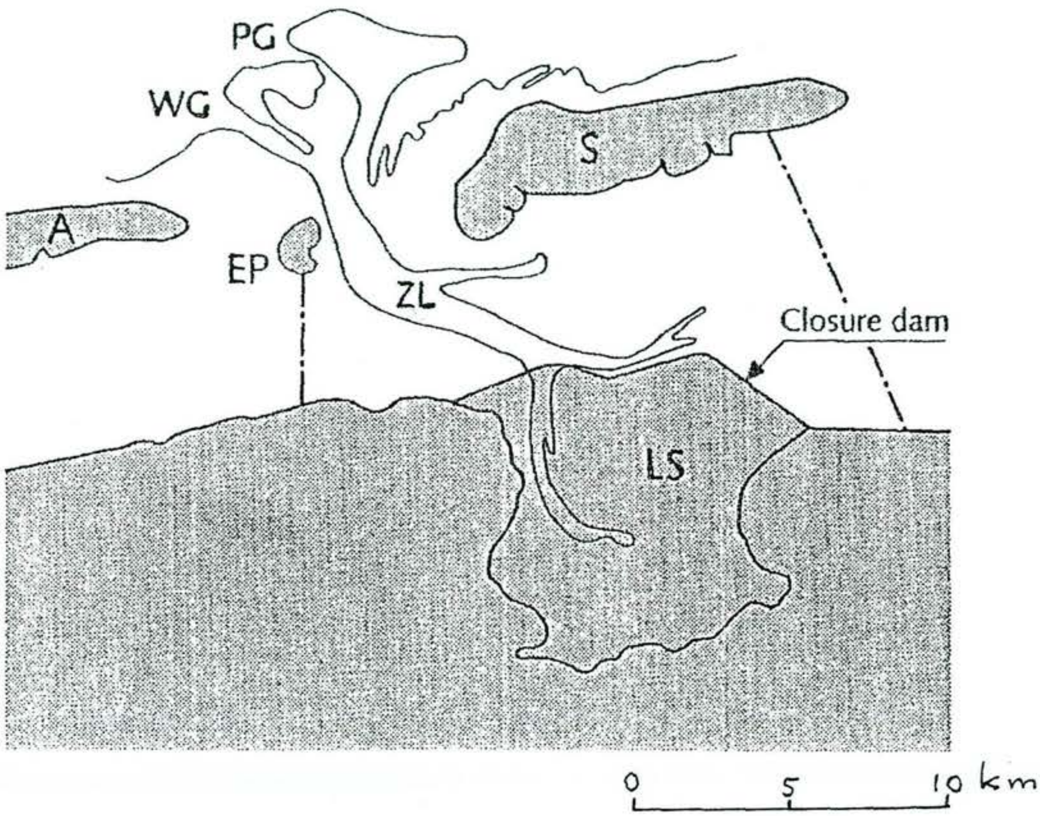
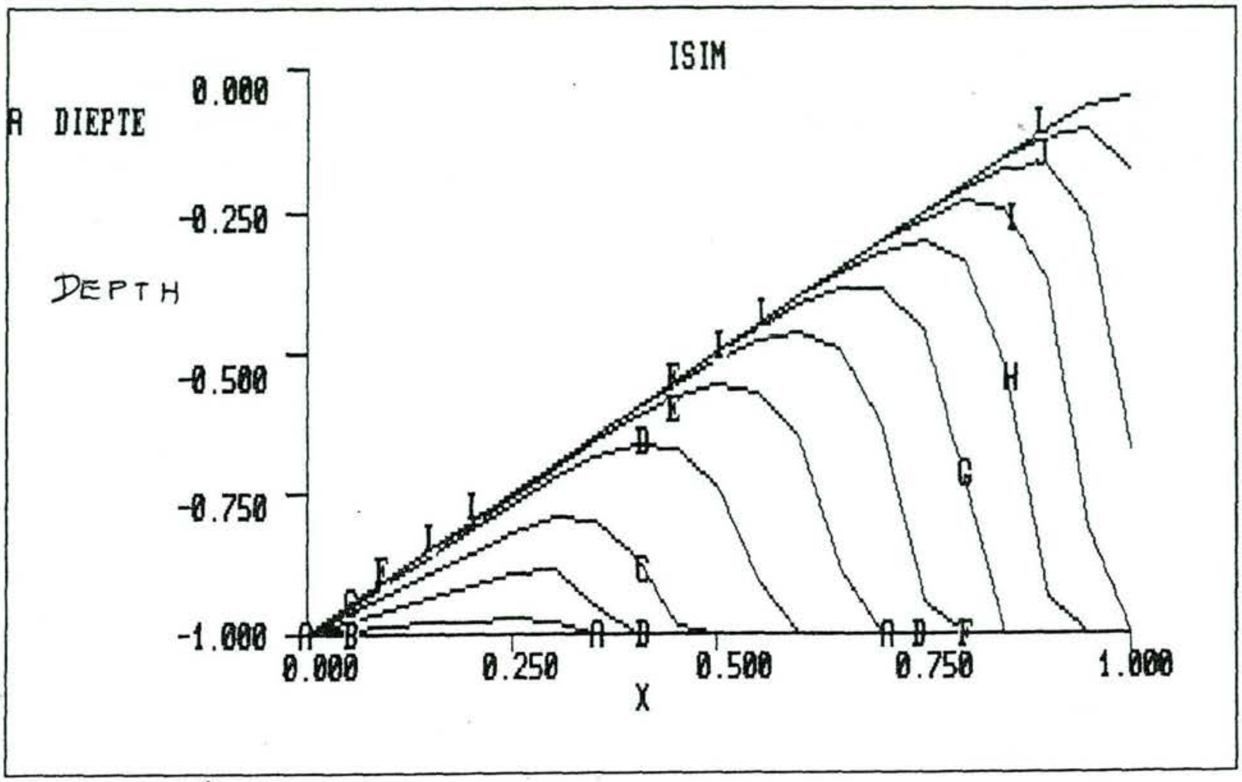


Figure 5.2. Adaptation of tidal flat – channel; (sand for flat is derived from channel)



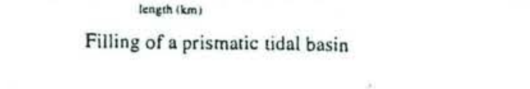
Frisian Inlet. A = Ameland, S = Schiermonnikoog, EP = Engelsman Plaat, LS = Louwers Sea. WG = Westgat, PG = Plaatgat, ZL = Zoutkamperlaag. Dashed-dot lines represent approximate basin boundaries for the Frisian Inlet.

Figure 6.1 Frisian Inlet and former Lauwerszee



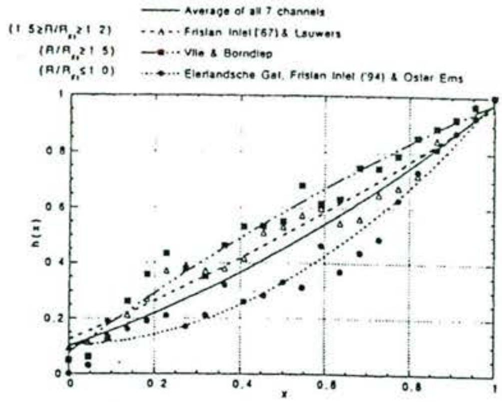
Time-evolution with constant τ. The letters indicate different stages in the shoaling process.

Figure 6.2. Evolution of tidal channel after closing part of the basin (After Van Dongeren ,1992)



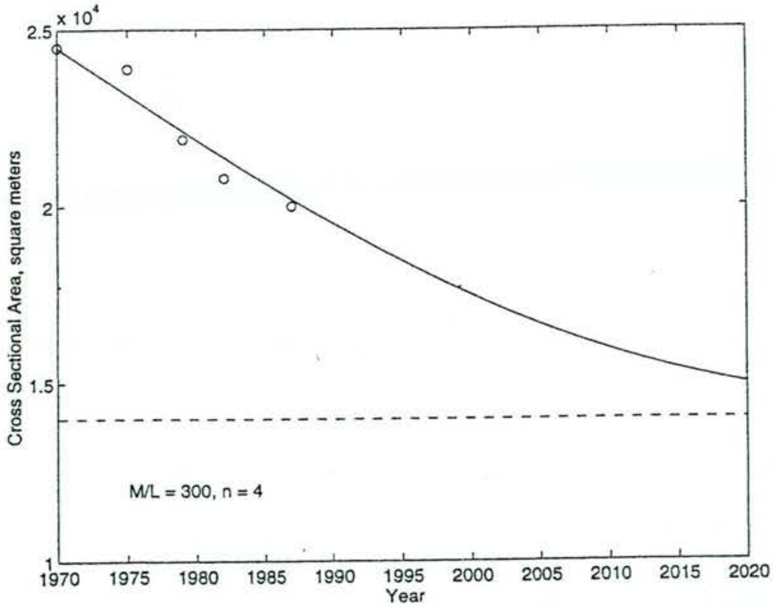
Filling of a prismatic tidal basin

Figure 6.3. Filling of prismatic channel (Aafter Wang et al, 1998)



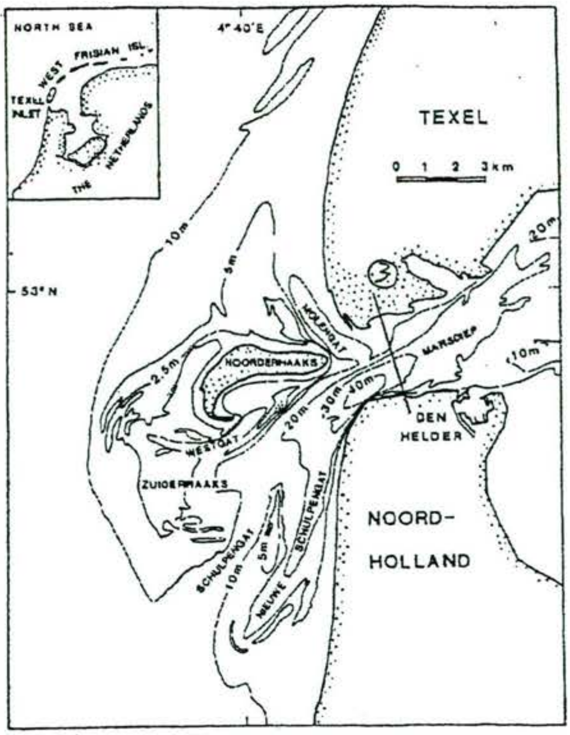
Scaled along-channel bed profiles of several tidal channels in the Dutch Wadden Sea. Markers indicate actual data, curves are the best fits with quadratic polynomials.

Figure 6.4. Channel bed profiles for different inlets in Wadden Sea (After De Swart and Blaas, 1998)



. Adaptation of Inlet Channel Cross-sectional Area. o observations, ———— theory (Eq. (10) with $A_e = 14{,}000\ m^2$ M/L = 300 m^2/year and n = 4), ------ equilibrium cross-sectional area A_e.

Figure 6.5. Adaptation cross-sectional area Frisian Inlet (After Van de Kreeke, 1998)



Ligging platen en geulen in buitendelta (heden) [Sha, 1990].

Figure 7.1 Texel Inlet (After Sha, 1990)

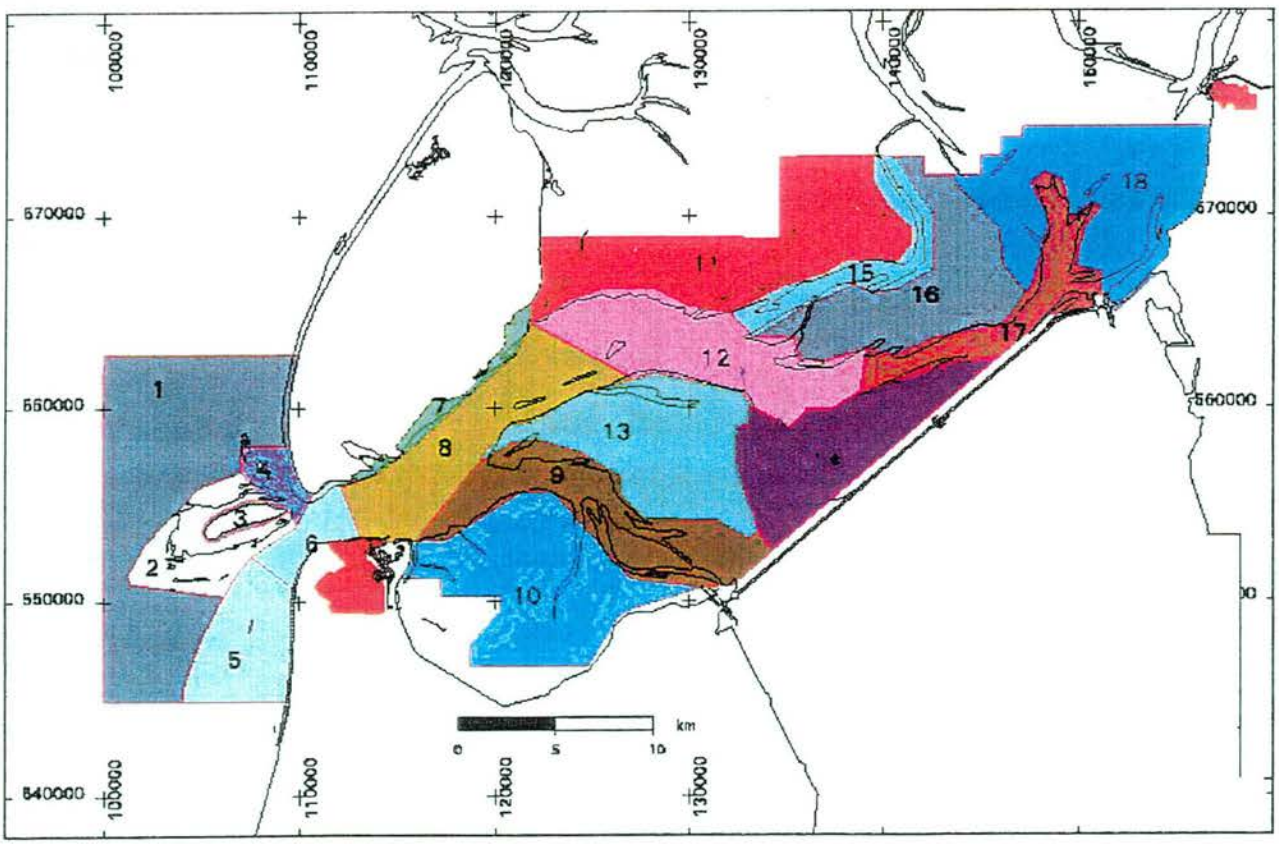


Figure 7.2. Morphological units in Texel Inlet basin (After Van Marion, 1999)

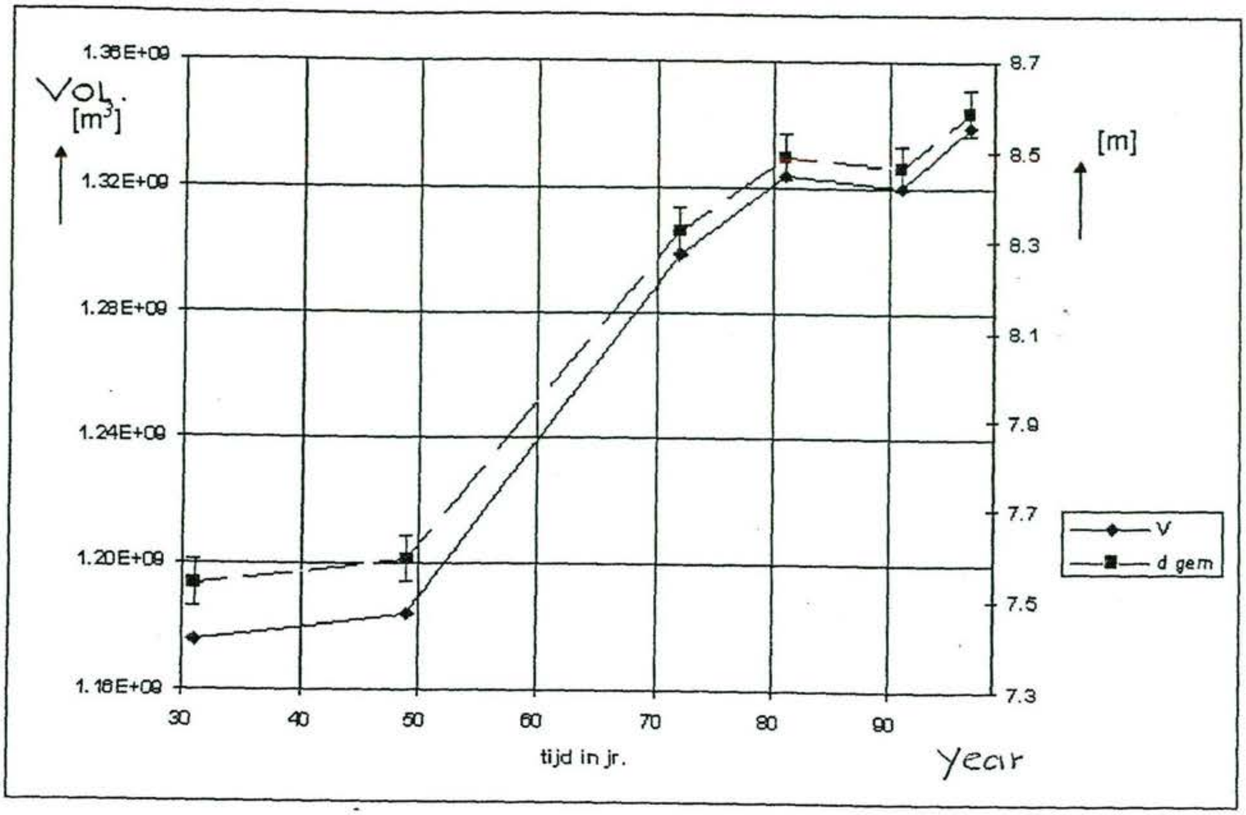


Figure 7.3a. **Change in volume and average depth of outer region, Texel Inlet (After Van Marion, 1999)**

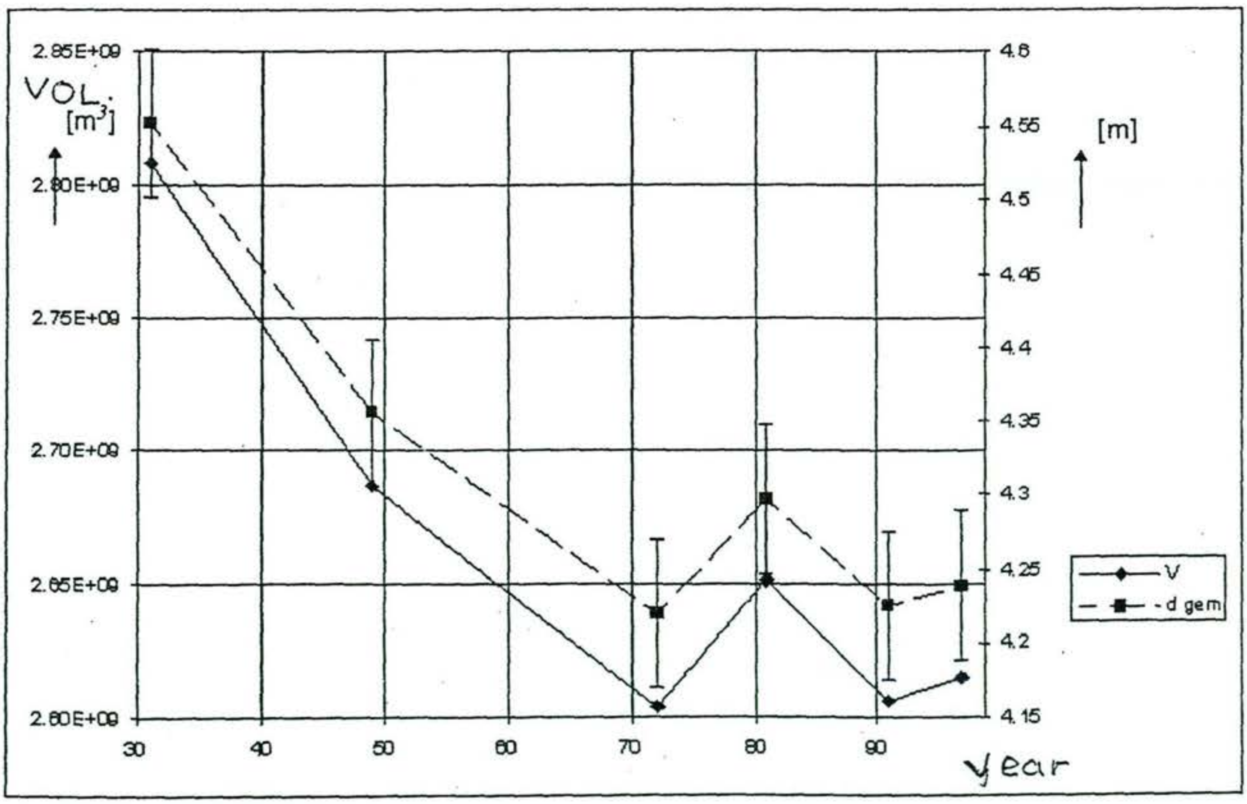


Figure 7.3b. **Change in volume and in average depth of tidal basin of Texel Inlet (After Van Marion, 1999)**

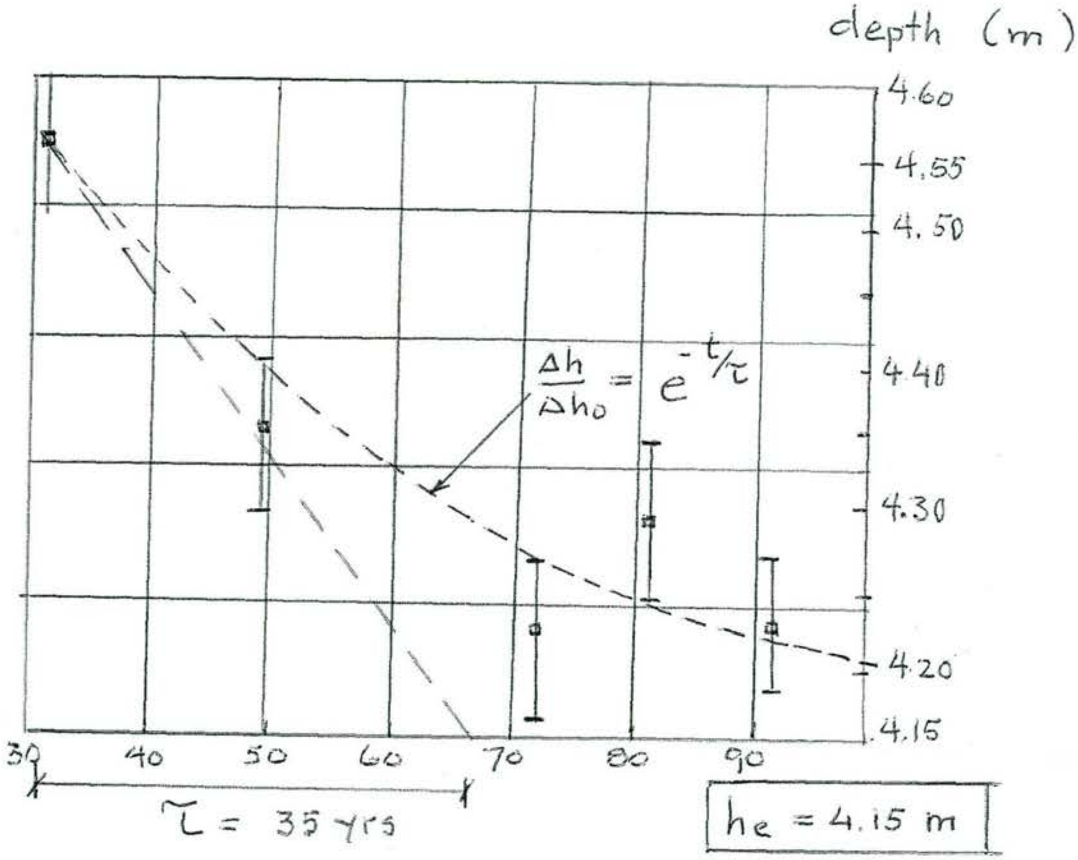


Figure 7.4 Response curve for tidalbasin of Texel Inlet (Based on data Van Marion)

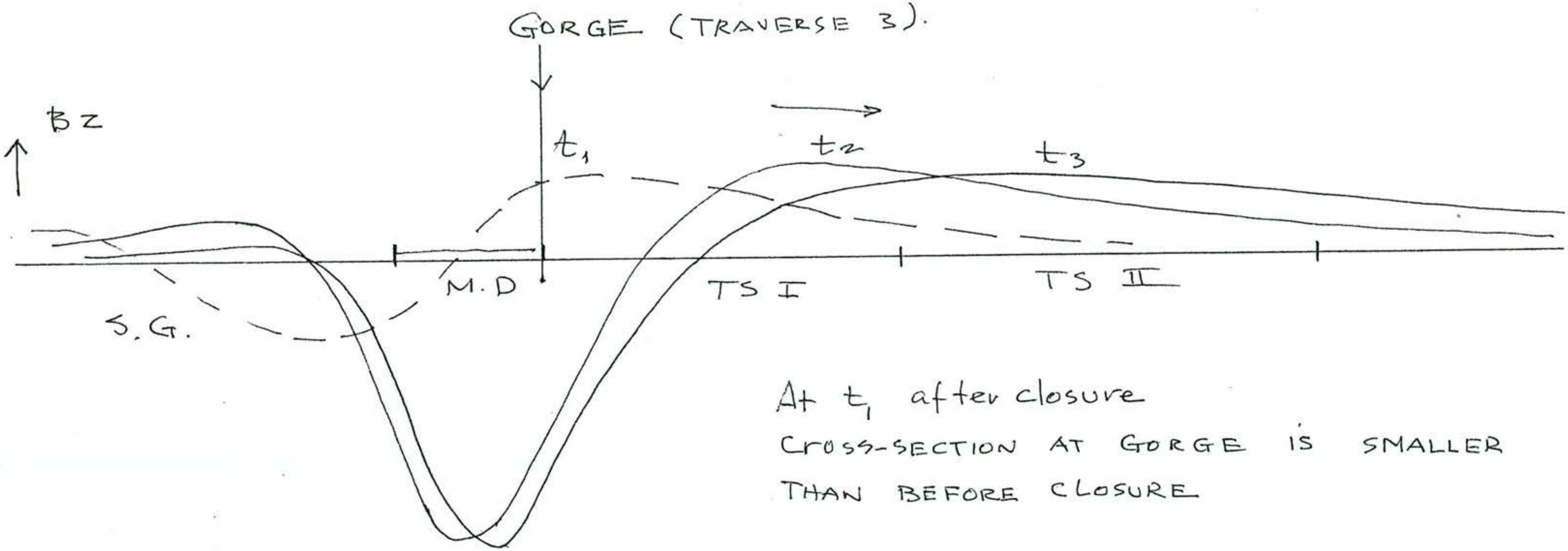


Figure 7.5. Schematic propagation of sand wave, Texel Inlet

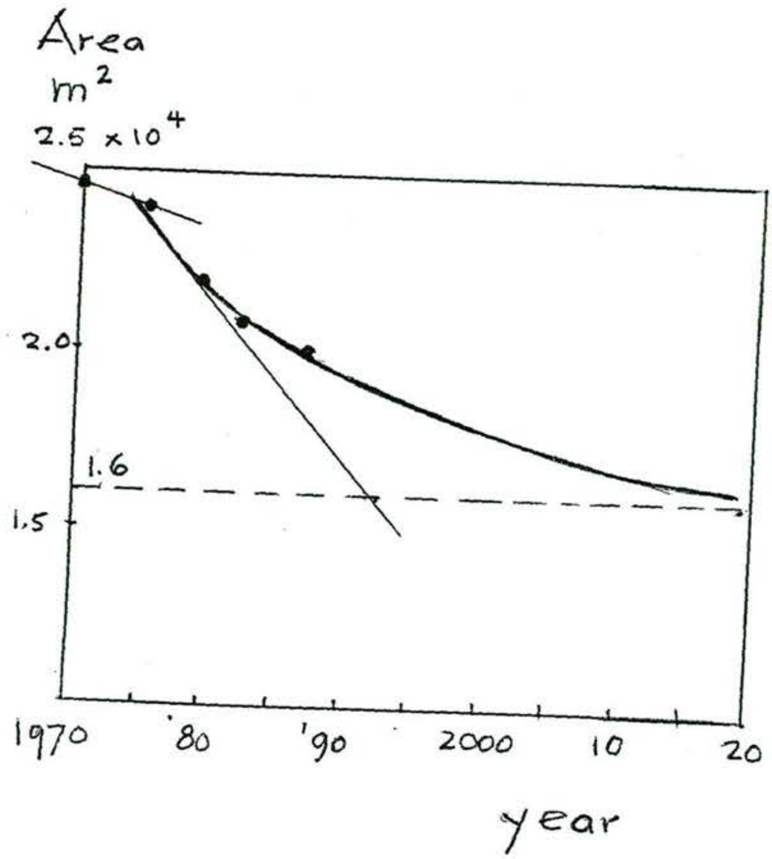
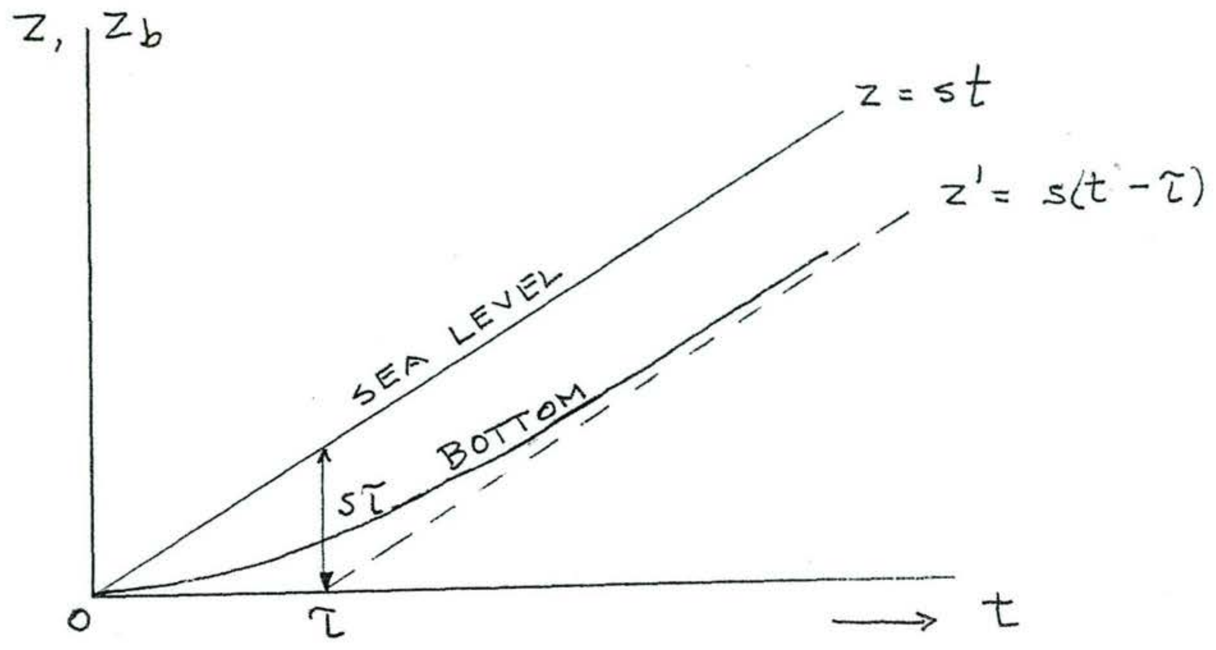


Figure 8.1. **Adaptation cross-sectional area Frisian Inlet. (Data from Van de Kreeke, 1998)**



z = increase rise in sealevel
z_b = in crease rise of sea bottom (Wadden)
t = time
τ = characteristic response time
s = rate of increase in sea level

$$z_b = f(s, t, \tau)$$

$$z_b = s\left(t - \tau\left(1 - e^{-t/\tau}\right)\right)$$

Figure 9.1. Adaptation of Wadden Sea bottom to sea level rise

APPENDIX A

Chapter 3. Derivation of expression for response time scale for circular dredge-pit

In the following section an expression for the time scale is derived based on the Estmorf and Asmita approach. These approaches are based on the assumption of the existence of an overall equilibrium concentration CE for an entire morphological system in equilibrium and of a local equilibrium concentration Ce for sections of the system which relate to the hydraulic condition. Ce is related to CE by the expression:

$$Ce = CE\ (Ve/V)^{n} \qquad \text{(A.1)}$$

in which Ve is the equilibrium volume and V the actual (wet) volume of an element.

The exponent n is related to the power of the velocity that generates the concentration of sediment; its value varies between 2 and 4. For fine grained sediment which is usually found in dredging pits, the value $n = 3$, which is in agreement with Bagnold"s transport equation for suspended transport, is selected in the analysis of Chapter 3.
In the derivation it is assumed that the advective transport components during ebb and flood either can be neglected or cancel each other out during a tidal cycle, so that the transport is completely governed by the dispersive transport component..
The rate of sedimentation is determined by the fall velocity of the sediment and by the difference between the actual concentration and the local equilibrium concentration.
We assume that the dredging pit is of circular form, with dimensions as in Figure 3.1of the text. We further assume that tidal velocities are small and will not erode the original sea bottom around the edge of the site. In other words, the horizontal dimensions of the pit and the flow depth near the edge will not change.

The sediment concentration in the environment outside the dredge site is CE and is based on the consideration that before dredging the bottom was in morphologic equilibrium.
The sediment concentration inside the pit is C, whereby $Ce < C < CE$.
Ce is the local equilibrium concentration, defined by equation (A1):

It is furthermore assumed that the concentration gradient can be taken as $(CE - C)/L$, and that the term $\partial C/\partial t$ can be neglected in the calculation.

The influx of sediment from the surrounding area into the circular dredging pit due to the concentration gradient is then:

$$\text{Influx} = [(D\ \pi\ L\ hi)/L]\ (CE - C) = D\ \pi\ hi\ (CE - C)$$

in which D is the dispersion coefficient.
The rate of sedimentation (deposits) in the dredging pit with horizontal area Ao is given by

$$\text{Dep.} = Ao\ ws\ (C - Ce)$$

ws is a sediment exchange coefficient, which can be positive or negative, whether we are dealing with sedimentation or erosion. In the sedimentation of a dredging pit it represents the fall velocity of the sediment.

Because of the conservation of mass, input must equal deposit, because it was assumed that the variation of concentration with time could be neglected.
Thus we have:

$$\pi \; D\,hi\;(CE - C) = Ao\;ws\;(C - Ce) \qquad (A.2)$$

Solving C from equation (A.2) gives

$$C = (\pi D\;hi\;CE + Ao\;ws\;Ce) / (Ao\;ws + \pi\;D\;hi) \qquad (A.3)$$

From equation (A.1)

$$Ve / V = he / h \qquad \text{(circular area does not change)}$$

and

$$he = hi \text{ (from Figure 3.1) (circular edge does not erode)}$$

so that

$$Ce = (he / h)^n \,.\, CE = [hi / (hi + hdo)]^n \,.\, CE = \alpha\, CE$$

In Chapter 2, a formulation was derived for the response time scale:

$$\iota = Vo / -(dV/dt)_{t=0} \qquad (2.3)$$

Referring to equation (A.2) we may write

$$(dV/dt)_{t=0} = Ao\;ws\;(C - Ce)$$

provided concentration is defined as volumetric concentration, *including pore contents.*
If the concentration is defined as volume sand over volume water, the pore ratio needs to be taken into consideration.
Applying equation (2.3) to the problem at hand, we obtain :

$\iota = hdo / (ws\;(C - Ce))$, and, after introducing C from equation (A.3):

$$\iota = [\,hdo / (ws\;CE\;(1 - \alpha))] \,.\, [\,(Ao\;ws / (\pi\;D\;hi)) + 1\,]$$

It is to be noted that ι is defined by the rate of sedimentation at the beginning of the adaptation process. Therefore the value of Ce also refers to the beginning stage and has consequently a specific value. (As the process develops Ce gets larger with time as Ce $\to$ CE).

With $Ao = (\pi / 4)\; L^2$ (circular plan form), this results in

$$\iota = [\,1 / (CE\,(1 - \alpha))] \,.\, [\,hdo / ws + (hdo/ hi)\,(L^2 / 4D)] \qquad (A.4)$$

$$\text{with } \alpha = (hi / (hi + hdo))^n$$

For the calculation of ι the field parameters hi, hdo, and L must be known and the values of the morphological parameters CE , D, n and ws must be estimated or determined from calibration.

Chapter 4. Derivation of expression for response time scale for a long trench

The derivations are based on the same concepts as in Chapter 3.
The difference is that we are here dealing with the movement of sediment into a section of a channel which reduces the problem to a two-dimensional situation with the flow entering the channel from both sides, as schematically shown in Figure 4.3.
We consider the sedimentation per unit of length of trench:

Influx of sediment (from two sides): ((2 D hi)/L) (CE - C)

Deposition of sediment : ws L (C - Ce)
The conservation of mass requires that:

$$2\,D\,hi\,/L\,(CE - C) = ws\;L\;(C - Ce) \qquad (A.5)$$

From equation (A.5) it follows that the concentration C can be expressed in terms of CE and Ce.
Furthermore we have:

$$Ce = (he / h)^n . CE = \alpha\, CE$$

In the same way as for the circular dredging site the response time scale is calculated from:

$$\iota = hdo\; / (ws\; (C - Ce)$$

Calculating C from equation (A.5) and inserting the result in the expression for ι, we find:

$$\iota = 1/ ((1- \alpha)\, CE)\, [\; hdo / ws + (L^2 / 2\, D)\, (hdo/hi)\,] \qquad (A.6)$$

APPENDIX B

Derivation of equation (5.1)

Reference is made to Figure 5.1.

We assume that a tidal flat is being restored from a lower level to its original equilibrium depth h_2 by means of a sediment flux from the adjoining channel.

The flux of sediment per unit length of channel, I, moving towards the flat region can be expressed by

$$I = [(D\, h_2)/((L + B)/2)]\,(CE - C) = [2\, D\, h_2 / (L+B)]\,(CE - C) \qquad (B.1)$$

In this approach it is assumed that in the channel the overall equilibrium concentration CE is present and is not affected by the flow of sediment to the tidal flat where the local sediment concentration is C.
Conservation of sediment requires that the flux of sediment to the tidal flat equals the amount deposited on the flat, (Dep), which per unit of length can be expressed by.

$$Dep = L\, ws\,(C - Ce) \qquad (B.2)$$

In equation (B.2) Ce represents a local equilibrium concentration which value is determined by the hydrodynamic condition as expressed in the Estmorf formulation.

Equalizing (B.1) and (B.2) gives:

$$[(2\, D\, h_2)/(L + B)]\,.\,(CE - C) = L\, ws\,(C - Ce) \qquad (B.3)$$

The unknown value of C can now be expressed in terms of the values CE and Ce.
Defining furthermore the characteristic adaptation time ι by

$$\iota = \Delta h_2 / [\, ws(C - Ce)] \qquad (B.4)$$

where Ce represents the value of this parameter at the beginning of the adaptation process.
Introducing the value of C, obtained from solving equation (B3) for C, gives after some algebra

$$\iota = [1/(n\, CE)\,].\,[\,(h_2/ws) + L(L + B)/(2D)] \qquad (B.5)$$

in which h_2 represents the equilibrium depth on the tidal flats.
This expression allows us to calculate the adaptation time for the conditions specified for this situation.

Derivation of equation (5.2)

Reference is made to Figure (5.2)

This situation is different from the one in Figure 5.1 in that the increase in flat elevation goes hand in hand with an increase in channel depth.
The time dependent concentrations in channel and on tidal flat are respectively C_1 and C_2.
The sediment flux from the channel to the flat is fully deposited on the flat and is derived from erosion in the channel.
Conservation of mass requires two set of equations. The first one states that the sediment flux from the channel toward the flat is equal to the amount of sand deposited on the flat:

$$[D\, h_2 / ((L + B)/2)\,].\,(C_1 - C_2) \;=\; ws\, L\, (\, C_2 \;-\; Ce_2) \qquad \text{(B.6)}$$

The second equation states that this flux also equals the amount of erosion from the channel:

$$[D\, h_2 / ((\, L+B)/2\,].\,(C_1 - C_2\,) = ws\, B\, (Ce_1 - C_1) \qquad \text{(B.7)}$$

In the equations (B.6) and (B.7) the parameter ws represents an exchange velocity between fluid and sediment (bottom). (Can be positive and negative).

The response time scale for the tidal flat is calculated from the equation:

$$\iota \;=\; h_2 / [\; ws\, (\, C_2 - Ce_2)\,] \qquad \text{(B.8)}$$

We could write a similar equation for the channel, but in this analysis we limit ourselves to deriving an expression for the flats.

In order to solve the equations we need to introduce the values for Ce_1 and Ce_2:

$$Ce_2 = CE\, [h_2 / (h_2 + \Delta h_2)]^n \qquad \text{(B.9)}$$

Assuming $\Delta h_2 << h_2$, equation (B.9) can be approximated by

$$Ce_2 \;=\; CE\, (\, 1 - n\, (\Delta h_2 / h_2\,)) \qquad \text{(B.10)}$$

A similar expression can be developed for Ce_1.

The solution process goes as follows:

. C_1 is solved from equation (B.7) and expressed in terms of C_2 and Ce_1,

. C_2 is solved from equation (B.6) and expressed in terms of Ce_1 and Ce_2 (and other parameters)

. ι is solved from equation (B.8) (gives response time scale for tidal flat).

After some algebra the following result is obtained:

$$\iota \;=\; 1/\,(n\, CE\, \delta)\,.\,[\,(h_2 / ws)\,(\,1 + L/B) \;+\; L\,(L + B)/\,(2D)\,] \qquad \text{(B.11)}$$

in which

$$\delta = \; 1 + (\,\Delta h_1 / \,\Delta h_2)\,(h_2/h_1)$$

APPENDIX C

Estimation of dispersion coefficient

In the calculations of the response time scale while using the Asmita or Estmorf formulation the value of the dispersion coefficient D plays an essential role in the dispersion of sediment from regions of higher concentration to areas of lower concentration. This is particularly important in tidal regions where the advective transport in flood direction is (more or less) compensated by sediment transport in the ebb direction.
The estimate of the dispersion coefficient is one of the more difficult tasks in the calculation process.
We will discuss the following aspects of the problem:
. distinction between diffusion and dispersion
. longitudinal dispersion in natural channels
. scale of eddy diffusion
. applications

Diffusion and dispersion

In diffusion the basic problem is the transport of some quantity in a flowing fluid.
We distinguish convective or advective transport in which the moving fluid is the transporting component and the diffusive transport whereby transport takes place between adjacent fluid particles, either in the form of molecular diffusion or in the form of turbulent diffusion.
The problem is approached by way of considering the mass balance of the transported quantity.
Molecular diffusion is based on Fick's (1855) equation:

$$\partial c / \partial t + u \; \partial c / \partial x = D_m \; \nabla^2 c \qquad \text{(C.1)}$$

in which D_m is the coefficient of molecular diffusion, c the concentration and u the velocity in the direction of flow (x-direction).
If the transport takes place in turbulent flow with velocity fluctuations u', v' and w' in the x,y and z directions, and concentration fluctuations of c', additional transport takes place due to the turbulent motion, represented by the extra terms $\partial(-\overline{u'c'})/\partial x$, etc.
It has been confirmed experimentally that for many occasions this convective type of transport follows a diffusive type law analogous to Fick's law, i.e. the transport associated with the turbulent fluctuations is proportional to the gradient of the average concentration c.
By analogy to molecular diffusion turbulent diffusion coefficients D_{tx} ,etc. are introduced:

$$-\overline{u'c'} = D_{tx} \; (\partial c / \partial x)$$

Similar expressions are introduced for $-\overline{v'c'}$ and for $-\overline{w'c'}$, which gives

$$\partial c/\partial t + u \, \partial c/\partial x = (D_m + D_{tx}) \, \partial^2 c/\partial x^2 + (D_m + D_{ty}) \, \partial^2 c/\partial y^2 + (D_m + D_{tz}) \, \partial^2 c/\partial y^2 \qquad \text{(C.2)}$$

in which u and c represent time-averaged values and D_{tx} , etc are assumed to be constant.
Equation C.2 is the mass balance equation for turbulent flow in terms of the time-averaged quantities and a process called turbulent diffusion.
A well presented and more detailed description of molecular and turbulent diffusion can be found in Tamai (1972), which has partly been used as a reference for this description

Longitudinal dispersion

If a tracer cloud moves downstream in a pipe or natural channel, it continues to spread out until at some time the cloud fills the entire cross-section. After lateral mixing has taken place the primary variation of profile averaged concentration is just in one direction, which is the direction of the flow. In that case a strictly one-dimensional equation is preferred rather than the previous equation.
This one-dimensional equation can be obtained by integrating and averaging Eq. C.2 over the cross-sectional area after substituting $u = \overline{u} + u''$ and $c = \overline{c} + c''$, where u'' and c'' represent the deviations of $\overline{u}$ and $\overline{c}$ from their average values in different locations of the cross-section.
Taylor (1953) showed that the convection associated with u'' is proportional to the longitudinal gradient of c, and can be incorporated in the value of the turbulent diffusion coefficient. The resulting equation is called longitudinal dispersion.
Both the velocity distribution over the cross-section and the lateral diffusion contribute to the longitudinal dispersion.
We may furthermore note that in natural streams the molecular diffusion is usually an order of magnitude smaller than the turbulent and spatial diffusion, so that the former can be neglected with respect to the latter.
Ultimately the equation can be written as

$$\partial c/\partial t + u \ \partial c/\partial x = D \ \partial^2 c/\partial x^2 \qquad (C.3)$$

in which D represents the longitudinal dispersion coefficient (considered constant) and u and c are time and cross-section averaged values of an assumed uniform flow in a channel.
The duration of the time averaging is very short compared to the period of a slowly varying current such as a tidal current.

Theoretical analysis supported by observations shows that the longitudinal dispersion coefficient in natural channels is not constant but varies with x. The advection-dispersion relationship should therefore be written as

$$\partial c/\partial t + u \ \partial c/\partial x = \partial/\partial x \, (D \ \partial c/\partial x) \qquad (C.4a)$$

In the above discussion both the terms diffusion and dispersion were used.
The transport associated with molecular and turbulent action was called diffusion whereas the transport associated with the variation of the velocity across the flow section was called dispersion.(Tamai,1966). The latter is relevant after the concentration of a substance is present over the entire cross-section of the flow.
In a natural channel an uneven distribution of flow across the flow (over the width of the channel) contributes significantly to the longitudinal dispersion of matter in the channel.

If the cross-section of a channel varies in the flow direction and mass is preserved the 1D dispersion equation is

$$A\, \partial c/\partial t + uA\, \partial c/\partial x = \partial/\partial x\, (DA\, \partial c/\partial x) \qquad \text{(C.4b)}$$

in which A = the cross-section average concentration, u = the cross-section average velocity, D the dispersion coefficient, t = time and x = the direction of the mean flow.
The use of the 1D dispersion equation is limited to locations far from a source of injected material.

Formulations for the longitudinal dispersion coefficient

Taylor (1954) through theoretical analysis predicted that in pipe flow dispersion along the pipe relative to a point moving with the mean speed of flow would be as though it were due to a virtual coefficient of longitudinal diffusivity

$$D = 10.1\, r\, u_* \qquad \text{(C.5)}$$

in which r is the radius of the pipe and u_* the shear velocity defined by

$$u_* = \sqrt{(gRS)}$$

where g = gravitational acceleration, R = hydraulic radius and S = slope of energy grade line.

Elder (1959) extended Taylor's method to uniform flow in an open channel of infinite width. He arrived at

$$D = 5.93\, h\, u_* \qquad \text{(C.6)}$$

in which h = the depth of flow.
Elder's equation has been widely used because it is simple and has a sound theoretical background. However it has been shown that Elder's equation significantly underestimates the dispersion in natural streams.(Fisher et al, 1979).
Using the lateral velocity profile rather than the vertical velocity distribution Fisher developed an integral relation for the dispersion coefficient, which however was difficult to solve because detailed information on the horizontal velocity information was required.
Fisher (1975) developed a simpler equation, making a number of assumptions in his integral formula. He found:

$$D = 0.011\, (u^2 B^2)/\, (h\, u_*) \qquad \text{(C.7)}$$

Equation C.7 has the advantage of simplicity in that it only uses data that can easily obtained for a natural stream.
Liu (1977) derived a similar equation. He started with Fisher's equation taking into account the role of lateral velocity gradients in natural streams and replacing the coefficient 0.011 by a variable parameter β representing a function of the cross-section's shape. By least-square fitting field data of others he deduced the expression:

$$\beta = 0.18\ (u_*/u)^{1.5}$$

Inserting this expression into Fisher's equation and writing it in dimensionless form Liu's formula becomes:

$$D/\,(hu_*) = 0.18\, (u/u_*)^{0.5}\, (B/h)^2 \qquad \text{(C.8)}$$

In comparing results with field data it appears that both Fisher's method and Liu's formula tend to overestimate the value of the dispersion coefficient for large widths of streams, suggesting that the second power of the parameter (B/h) in these formulas may be too high.

Iwasa and Aya (1991), by analyzing their laboratory data and previous field data by Nordin and Sabol (1974) and others arrived at the following equation for D:

$$D/(hu_*) = 2.0\ (B/h)^{1.5} \tag{C.9}$$

in which the power of (B/h) is reduced to1.5. For very high values of B/h the power is likely to be further reduced.

Most natural streams are considerably wider than deep and the presence of transverse variation in the downstream velocity will provide the dominant mechanism for longitudinal dispersion. Since material in the high velocity zone is carried downstream faster than in the low velocity zone, the effect is a stretching out of the suspended or dissolved substance. (Tamai, 1972).

Other authors have proposed expressions for the dispersion coefficient in natural streams, and this information is reviewed in Seo and Cheong (1998). This publication, together with the survey paper of Tamai (1972) have provided essential information for this overview.

Further analysis by Seo and Cheong

In order to test the behavior of existing dispersion coefficient equations Seo and Cheong have used 59 data sets measured in 26 streams in the United States from published reports.
By using dimensional analysis they found that the dispersion coefficient in dimensionless form could be expressed as a function of the following dimensionless parameters:

$$D/(hu_*) = f\left((\rho u h/\mu),\ u/u_*,\ B/h,\ Sf,\ Sn\right) \tag{C.10}$$

in which:

$D/(hu_*)$ = dimensionless dispersion coefficient
$\rho hu/\mu$ = Reynolds number
B/h = width to depth ratio,
u/u_* = friction term, defined by $(8/f)^{0.5}$ (f = friction coefficient = Darcy – Weisbach factor)
Sf = bed shape factor , and
Sn = sinuosity

The bed shape factor and the sinuosity are vertical and transverse irregularities in natural streams which cause secondary currents and shear flow that affect the hydraulic mixing process in streams.
In Seo and Cheong (1998) these two parameters were dropped because they cannot easily be estimated for natural streams. They are also partly included in the friction term.
Furthermore the effect of the Reynolds number is negligible in natural streams.
Equation C.10 is then reduced to:

$$D/(h u_*) = f(u/u_*, B/h) \qquad (C.11)$$

This equation has the same structure as the (rewritten) equation of Liu (C.8).
Seo and Cheong used a regression method to find an equation with the least statistical error.
For this they used the one-step method developed by Huber (1981) and got the following results:

$$D/(hu_*) = 5.915 \; (B/h)^{0.620} \; (u/u_*)^{1.428} \qquad (C.12)$$

In deriving this equation the correlation coefficient was 0.75.
The regression equation derived by the least square method gave a different equation with different exponents on the right hand side and a different numerical coefficient. The correlation coefficient for this approach had a smaller value (0.66).
Seo and Cheong compared their result (equation C.12) with the results of three other methods for 24 field data sets. They found the accuracy of their formula considerably higher than that of the other formulas.
It appears that other variables may play a role as may be concluded from the study by Hunt (1999).

The effect of horizontal scale

Hunt (1999) proposed a variable dispersion coefficient model based on measurements in five different rivers and streams in the mountains of the South Island in New Zealand by Day (1974, 1975). Day found that the dispersion coefficient for his field experiments continued to increase indefinitely with distance downstream from the point of tracer release.
Because the dispersion coefficient has the dimension of the product of a velocity and a length Hunt considered it reasonable to consider the following equation:

$$\partial c/\partial t + u \, \partial c/\partial x = \partial/\partial x \, (\varepsilon \, u \, x \;\; \partial c/\partial x) \qquad (C.13)$$

where ε = a dimensionless constant.
This dimensional argument could also be used to justify the depth rather than the x, as a characteristic length, such as was done in the previous section. However such a choice would not agree with the results of Day's experiments, because depth does not increase indefinitely with distance downstream. For this reason x is selected by Hunt as the characteristic length parameter.
ε represents the dimensionless dispersion coefficient defined by

$$\varepsilon = D / u \, x \qquad (C.14)$$

Hunt derived an equation for ε in implicit form:

$$\varepsilon / [(1-\varepsilon)^2 (1-2\varepsilon)] = \xi \; (h/B)^2 \qquad (C.15)$$

in which the dimensionless coefficient ξ is not a constant but varies (widely) for the different rivers. Hunt also proves that the values for ε are bounded by

$$0 < \varepsilon < ½$$

Equation C.15 confirms what was found in the previous section that the dimensionless form of the dispersion coefficient includes a function of the width to depth ratio.

It may be of interest to compare Hunt's results with the findings of Cheo and Cheong.
In equation C.12 the dispersion coefficient is made dimensionless by dividing it by the product ($h\,u_*$). This equation can be rewritten by replacing u_* by the average velocity u.
Replacing u_* by u makes sense because mixing in the horizontal plane is likely to dominate the dispersion and because Day and Hunt found that the dispersion increases in the direction of the flow. Equation C.12 in the rewritten form is:

$$D/\,hu \;=\; 5.915\,(B/h)^{0.620}\,(u/u_*)^{0.428} \qquad (C.16)$$

Comparing equations C.14 with C.16 we can write expressions for ε as follows

$$\varepsilon = 5.915\;(B/h)^{\,0.620}\,(u\,/\,u_*)^{0.428}\,(h/x) \qquad (C.17a)$$

or

$$\varepsilon = 5.915\;(h/B)^{0.380}\,(u\,/\,u_*)^{\,0.428}\,(B/x) \qquad (C.17b)$$

Comparing equations C.17b and C.15 we notice that in both equations ε is a function of (h/B).
Furthermore the variable dimensionless coefficient ξ may be expressed as a function of the parameters (u/u_*) and (B/x).
Since $u/u_* = C/\sqrt{g}$, (C = Chezy coefficient), this value is determined by logarithm of the ratio of depth and bottom roughness and may vary only to a relatively small degree. Consequently ξ is dominated by the ratio (B/x) which may explain the differences for this parameter for the different rivers (Values of ξ were 120, 10.4 and 10 for three rivers in Hunt's paper).
We may conclude that there are no fundamental contradictions when we compare the results of Hunt's 1999 paper with the findings of Seo and Cheong (1998).
In order to apply the above results to tidal streams we have to make the additional step from uniform river flow to tidal flow. Since tidal flow is a slowly varying phenomenon we have made the assumption that results found for rivers may be applicable to a tidal flow situation if we chose for velocity the tidal mean of the profile average velocity.

Dispersion coefficient related to the scale of turbulence

One of the important aspects of turbulent diffusion is the relationship between eddy diffusivity and the physical characteristics of the system in which diffusion takes place. One of these characteristics is the scale of the eddies of the turbulent motion.
In agreement with Kolmogoroff's theory Batchelor (1950) has shown that the turbulent diffusion coefficient depends on G, which is the average rate of energy dissipation per unit of mass of fluid, and on l , a measure of the mean size of eddies participating in the diffusion process.
The relationship is in the form:

$$D_t \;=\; (\text{const})\; G^{1/3}\, l^{\,4/3} \qquad (C18)$$

This relationship can be seen as a theoretical justification for the empirical "four-thirds law" suggested by Richardson (1926).
Equation C.18 has been confirmed experimentally by Orlob (1959) in a study of particle dispersion in a two-dimensional field of homogeneous turbulence.

In a natural stream with horizontal and vertical velocity distributions the longitudinal dispersion is in addition affected by these phenomena.
Taylor's equation for longitudinal dispersion in a pipe (equation C.5) can be transformed for uniform free surface flow into

$$D = 14.3\, R\sqrt{2gRS}$$

in which R is the hydraulic radius and S the slope of the energy equation.
Using the Chezy relationship $S = u^2/(C^2R)$, in which C is the Chezy coefficient, the expression for the longitudinal dispersion coefficient develops into:

$$D = [(14.3\sqrt{2g})/C]\, u\, R \qquad \text{(C.19)}$$

This equation can also be expressed in terms of the rate of energy dissipation per unit of mass fluid for open channel flow (see Harleman, 1966). The resulting equation is

$$D = [(20.2\, g^{1/6})/C^{1/3}]\, R^{4/3}\, G^{1/3} \qquad \text{(C20)}$$

where

$$G = gu^3/C^2R$$

The Taylor longitudinal dispersion equation therefore has the same form as Kolmogoroff's similarity equation (C.18).
It is to be noted that the basis for this analysis is Taylor's equation for pipe flow, where the scale of the turbulence is restricted by the radius or diameter of the pipe. In the transformation to open channel flow the restricting dimension would translate into depth or hydraulic radius.
The research by Hunt has shown that this is not necessarily correct because in natural streams the horizontal velocity distribution which is related to the width-depth ratio plays a role in the horizontal dispersion whereby the longitudinal dispersion coefficient grows with the horizontal distance x in the flow direction.
It may be expected that vertical dimensions as well as horizontal dimensions will play a role in the final outcome.
A comparison may be made with Figure C-1, taken from Wiegel (1964), and originally published in Orlob (1959) in which the majority of the data support a four-thirds power relationship between the lateral eddy diffusion coefficient and the scale of the eddy diffusion phenomenon. Batchelor and Townsend (1956) obtained a four-third relationship from theoretical studies but stipulated a restriction in that the distance between two particle had to be small for the relationship to be valid. In experimental experiments in a laboratory channel (which effectively limits the size of the larger eddies) Orlob (1956) found that close to the injection source the width of the dispersion pattern increased about in proportion to the three-halves power of the distance from the source, whereas relatively far from the source the width increased to the one-halve power of the distance to the source.
The latter result may be influenced by the fact that the experiments were conducted in a laboratory channel, in which the growth of eddies is limited and turbulent energy is dissipated in the flow direction. In Wiegel (1964) it is suggested that the eddy diffusion coefficient actually becomes a constant at some distance from the source.
A comparison with Hunt's studies may lead to a different conclusion.

Hunt's (1999) research deals with the longitudinal dispersion coefficient in natural streams, in which depth and width also induce restrictions in the growth of eddies. His finding that the longitudinal dispersion coefficient in rivers is linearly proportional to the distance in the downstream direction, may still fit within the context of the above mentioned studies.
In the ocean the scale of the turbulence can be large and the four-thirds power law may be applicable for engineering purposes.(Wiegel, 1964)

Estimation of longitudinal dispersion coefficient in tidal inlets and tidal channels.

In various chapters of the main report the Asmita-Estmorf formulations have been used to calculate response time scales for different types of disturbances, ranging from relatively small dredge pits to entire tidal basins.
Considering the property of increasing dispersion coefficients with increasing scale of the phenomenon it is necessity to adjust the value of the dispersion coefficient to the size of the sections in the modeling process. Consequently we have to use a range of D-values for different problem situations.
In Chapter 9 calculations on response time scales are made for the entire Texel Inlet basin in relationship to the aspects of sea level rise, in which the dispersive transport through the tidal inlet needs to be estimated in view of the assumptions that this transport takes place primarily in the form of suspended matter and that the advective flood transport is cancelled out by an equal value of the ebb transport from the oscillating tidal flow.
For the estimation of the dispersion coefficient, we turn to the results of Cheo and Cheong (equation C.12), on the longitudinal dispersion coefficient in natural streams. We assume that the results for streams are also valid for tidal channels, if the tidal mean velocity of the cross-section average velocity is used to replace the mean stream velocity.
The statistically derived equation C.12 seems the best available source for the estimation of the longitudinal dispersion coefficient. The tidal inlet is connected with a large size tidal channel (the Texelstroom), which combination may be considered a "natural stream".
This equation reads:

$$D/(hu_*) = 5.915\,(B/h)^{0.620}\,(u/u_*)^{1.428} \qquad \text{(C.12)}$$

For the Texel Inlet we have the following data from different sources (see Gerritsen, 1999, in Chapter 13: References):
$B = 2700$ m; $h = 21.9$ m; $u = 0.72$ m/s ; $C = 54.4\ m^{1/2}$ /s (Chezy coefficient).
In equation C.12, u_* is defined by $u_* = \sqrt{(\iota/\rho)} = \sqrt{g}\,.\,(u/C)$.
Using the above numbers gives:

$$D = 6270\ m^2/s$$

This is a relatively high value but considering the large dimensions of the stream and of the area under consideration with a potential for large horizontal eddies, the calculated value is not unrealistic.
In terms of order of magnitude it compares reasonably well with experimentally determined values for D in the studies of the Western Scheldt by Fokkink et al, 1998 and Wang, 1997. (See Chapter 13:References).

A similar approach has been followed for the Frisian Inlet.
Results have been given in Chapter 8 of the report.

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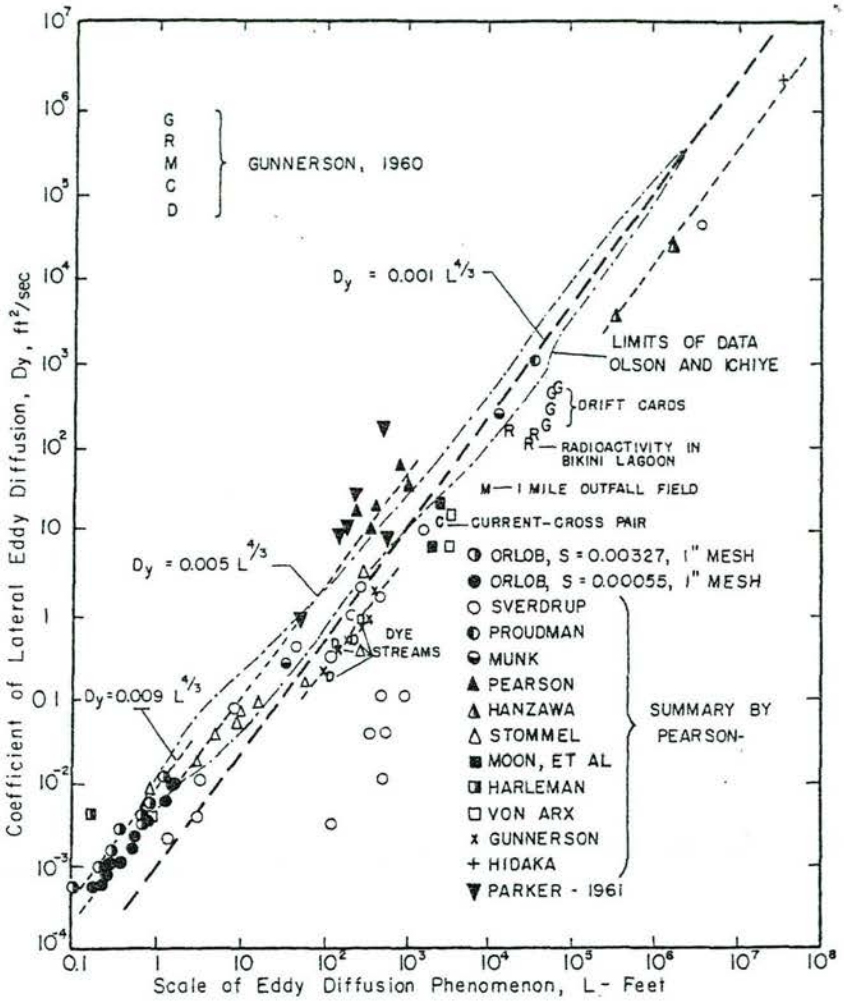

Fig C-1

Eddy diffusion as a function of scale; summary of reported investigations (after Orlob, 1959)

From: Wiegel (1964)