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Tidal asymmetry and sediment transport in the Westerschelde estuary

a desk study

November 2000

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C. Jeuken
Z.B. Wang

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ABSTRACT:

Based on field observations as well as results of hydrodynamic and sediment transport models, the relation between the asymmetry of the horizontal tide and that of the vertical tide and the relation between the asymmetry of the horizontal tide and the residual sediment transport in the Westerschelde have been analysed. This analysis has the objective to identify the significance of the tidal asymmetry for the morphological development in the estuary.

For the local residual sediment transport, the residual current, i.e. the M0 component of the flow velocity, is the dominating factor of the asymmetry of the horizontal tide. The residual current is determined by the bathymetric characteristics and the phase difference between the horizontal tide and the vertical tide, rather than the overtides. For the integrated residual sediment transport through the estuary, both the residual current and the overtides are important. Further it is concluded that for the residual sediment transport the sixth-diurnal tide is as important as the quarter-diurnal tide.

REFERENCES:

VER.	ORIGINATOR		DATE	REMARKS	REVIEW		APPROVED BY	
1	C. Jeuken		17 October 2000		Z.B. Wang			
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1 Introduction

1.1 Background

The Westerschelde is one of the remaining open estuaries in The Netherlands that is strongly influenced by man. Land reclamation has reduced the size of the estuary by 40 % in less than 300 years. In this century the dredging and dumping activities have increased from less than 0.5 Mm^3/year in 1950 to over 15 Mm^3/year in 1975 (Vroon et al, 1997, Van den Berg et al., 1996). In recent years, a large dredging and dumping program has been executed to enlarge and maintain the navigation route to Antwerp. Since 1997 a deepening program is in progress and a new dredging and dumping program is initiated. For the various water management aspects, e.g. flood control and ecological functioning of the estuary, it is important to understand the impacts of human interference on the morphological development of the estuary in combination with the ever changing natural forcing, e.g. via tide, sea level rise etc.

The natural morphological development is the result of interactions between water motion, sediment transport and bed topography. In an estuary like the Westerschelde where tidal action is an important forcing factor, it is the residual sediment transport that determines the morphological development. Therefore insight into the processes and mechanisms influencing the residual sediment transport plays a key role in the understanding of the morphological development of the estuary under the influence of changing natural conditions and human interference.

An important factor causing residual sediment transport in estuaries is tidal asymmetry. In the Westerschelde it is possibly a principal factor influencing the sediment exchange between the ebb tidal delta and the estuary, as well as between the various parts of the estuary. Analyses of the historical data on tide and morphological development in the Westerschelde (Gerritsen et al., 1999) indicate that there is a clear relation between the change of asymmetry of the vertical tide and the morphological development in the estuary. They also show that there is probably a relation between the asymmetry of the vertical tide and the net sediment flux. Insight into the generation of tidal asymmetry and its influence on the residual sediment transport is required for answering questions like:

- will the estuary drown under the influence of sea level rise or will it silt up fast enough to keep up with the sea level?
- will there be a return flow of sediment between the dumping locations in the western part of the estuary and the dredging sites in the eastern part and what are the involved time-scales?
- can sand mining be continued without affecting the system to an unacceptable extent?

In the last few decades a large number of publications have appeared on tidal asymmetry and its effects on the sediment transport and morphological development in estuaries. A literature survey and desk study has been carried out by Wang et al (1999), who summarise the knowledge related to tidal asymmetry, sediment transport and morphological development in estuaries, as published in the last several decades. In the desk study the concepts / theories found in the literature haven been investigated for the particular situation of the Westerschelde. The present report describes the continuation of the desk study as described in Wang et al (1999).

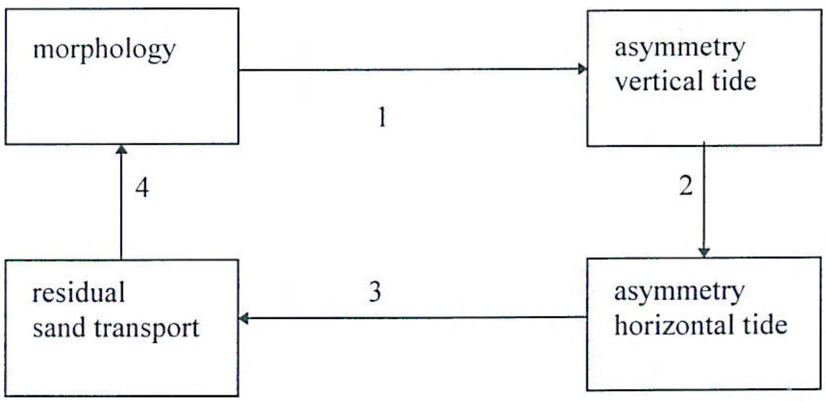
1.2 Objective of the study

The objective of the present study is

- to evaluate the significance of the tidal asymmetry for the morphological system of the Westerschelde estuary;
- to make recommendations for further studies which will lead to a better understanding of the tidal motion and the morphological development in the Westerschelde estuary.

1.3 Set up of the study

The approach applied in the present study is schematically depicted below. Four different aspects have to be considered in order to evaluate the importance of the tidal asymmetry for the estuarine morphology. All four aspects were discussed by Wang et al. (1999) on the basis of a literature review and some data analyses. However, the relationship between the asymmetry of the horizontal tide and the sand transport was only briefly addressed. This issue that is the key element for evaluating the significance of the tidal asymmetry for the morphological system of the Westerschelde, is subject of this study. Based on the study of Wang et al. (1999) the following hypothesis was used as first guideline in the present study: The tidal asymmetry that is related to the generation of residual currents, the so-called subharmonics, determine the residual sand transport at the spatial scale of the estuarine section (see also Ch. 2). The velocity asymmetry related to the generation of the higher harmonics control the sediment exchange between estuarine sections.



First a conceptual model concerning the residual sediment transport in the Westerschelde is presented in Chapter 2. It results in a framework for the aforementioned hypothesis and the formulation of underlying hypotheses. These basic hypotheses in this conceptual model are checked with field data and / or model results in Chapter 3. The conclusions from the study and recommendations for further research are given in Chapter 4.

1.4 Acknowledgement

The present study is carried out by Mrs. C. Jeuken, and Dr. Z.B. Wang from Delft Hydraulics in close co-operation with Mr. B.A. Kornman from RIKZ-RWS.

2 Considerations on residual sediment transport in the Westerschelde

2.1 Definitions

Sediment transport in a estuary can be considered on various time- and space scales. On different time scales distinction can be made between the instantaneous transport, the ebb-transport, the flood-transport, and the residual transport. The ebb- and flood-transport are the integral of the instantaneous transport over the ebb and flood period respectively. The residual transport is the integral of the instantaneous transport over the whole tidal period and is thus equal to the difference between the ebb- and flood-transport.

$$se = \int_{T_{ebb}} |s| \mathrm{dt} \qquad (2.1)$$

$$sf = \int_{T_{flood}} |s| \mathrm{dt} \qquad (2.2)$$

$$sr = \int_0^T s \mathrm{dt} = sf - se \qquad (2.3)$$

In these equations

s	=	instantaneous sediment transport (positive in flood direction)
se	=	ebb-transport
sf	=	flood-transport
sr	=	residual transport (positive in flood direction)
T_{ebb}	=	flood period
T_{flood}	=	ebb period
T	=	tidal period
t	=	time

On the different spatial scales, the pattern of circulation cells in the residual transport field is interesting. The most important circulation cells are those in the various macro-scale ebb- and flood-channel systems. Such a ebb and flood-channel system consists of two large, parallel-aligned channels, divided by a tidal flat or a tidal flat complex. The Westerschelde estuary consists of a chain of such ebb- and flood-channel systems, also referred to as estuarine sections (see e.g. Jeuken, 2000 and Winterwerp et al., 2000). From the head towards the mouth of the Westerschelde six sections can be identified (EC=ebb channel, FC=flood channel, see Jeuken 2000 for an overview of the morphologic evolutions within each section, Fig. 2.1):

1. Het vaarwater boven Bath (EC) - Appelzak (FC).

2. Het Nauw van Bath (EC) - Schaar van Noord (FC).
3. Het Zuidergat / Overloop van Valkenisse (EC) - Schaar van Valkenisse (FC).
4. Het Gat van Ossenisse (EC) - Middelgat (FC)
5. De Pas van Terneuzen (EC) - Everingen (FC)
6. De Honte (EC) - Schaar van Spijkerplaat (FC).

By integrating the residual sediment transport over the channels, the total residual transport through the individual ebb- and flood-channels can be obtained. Integrating the residual transport over the whole cross-section of the estuary gives the total residual transport through the estuary. Similarly, one can obtain the ebb- and flood-transport through the channels and through the whole estuary.

$$S_{r,ebb} = \int_{ebb-channel} sr\,\mathrm{dy} \tag{2.4}$$

$$S_{r,flood} = \int_{flood-channel} sr\,\mathrm{dy} \tag{2.5}$$

$$S_r = \int_{cross-section} sr\,\mathrm{dy} = S_{r,ebb} + S_{r,flood} \tag{2.6}$$

Herein

$S_{r,\,ebb}$	=	residual transport trough the ebb channel
$S_{r,\,flood}$	=	residual transport trough the flood channel
S_r	=	residual transport trough the estuary
y	=	lateral co-ordinate

The demarcation of ebb and flood channels within a certain cross channel can be based on bathymetric considerations, i.e. the location of the highest point in the profile. Though it should be noted that the demarcation of ebb and flood channels is not always unambiguous. The residual transport in an ebb-flood channel system can thus be considered as consisting of a circulating component and a net residual component through the estuary,

$$S_{r,circulation} = (S_{r_{ebb}} + S_{r_{flood}})\,/\,2 \tag{2.7}$$

$$S_{r,net} = S_{r_{ebb}} - S_{r_{flood}} \tag{2.8}$$

2.2 Significance for morphological development

Sediment transport in the Westerschelde is mainly driven by the tidal flow. This has the consequence that the ebb- and flood transport are almost equal to each other, which means that the magnitude of the residual transport is an order of smaller than that of the ebb- or flood-transport. This applies to all spatial scales.

$$se >> |sr| \qquad sf >> |sr| \tag{2.9}$$

Within an ebb- and flood-channel system in the Westerschelde the circulating component of the residual transport is much larger than the net throughflows.

$$|S_{r,circulation}| >> |S_{r,net}| \tag{2.10}$$

The various transports as discussed above each have their own influence on the morphological development in the estuary. It can be stated that the component of the residual transport through the estuary $S_{r,net}$ is responsible for the morphological development on the mega-scale, whereas the circulation component $S_{r,circulation}$ is responsible for the macro-scale morphological development.

Obviously the morphological development is determined by the residual sediment transport. However, also the ebb- and flood-transports are important for studying the morphological development, especially under the influence of human interference. The change of the residual transport induced by human interference (a deepened area by dredging) is related to the magnitude of the ebb- and flood-transports under non-disturbed condition. So the time scale of the morphological development induced by the interference is related to the ebb- and flood-transports.

2.3 Relation to tidal asymmetry

Local residual sediment transport is directly related to the asymmetry of the horizontal tide. As shown by Van de Kreeke and Robaczewska (1993) the long-term mean bed-load transport is determined by the flow velocities associated with M_0, M_2 and its overtides. The dimensionless expression for the tidally averaged bed-load transport reads as

$$\frac{\langle q \rangle}{\hat{u}^3 f} = \frac{3}{2}\varepsilon_0 \qquad M_2, M_0$$

$$+\frac{3}{4}\varepsilon_4 \cos\beta \qquad M_2, M_4$$

$$+\frac{3}{4}\varepsilon_4\varepsilon_6 \cos(\beta-\gamma) \qquad M_2, M_4, M_6$$

(2.11)

with

q	=	volumetric rate of sand transport per unit width
$\hat{u}$	=	amplitude of the M_2 tidal current
$\varepsilon_0, \varepsilon_4, \varepsilon_6$	=	amplitude ratio of the residual, M_0, M_4, M_6 and the M_2 tidal current respectively

f	=	function of sediment and fluid characteristics
γ	=	phase of tidal current M_6 relative to the M_2 tidal current
β	=	phase of tidal current M_4 relative to the M_2 tidal current

An approximate analysis of the tidal and residual suspended sediment transport, based on cross-sectionally averaged velocities computed with a 1D-model, indicates that for the residual suspended transport of coarse sediment more or less the same applies as for the bed-load transport (not shown).

The residual transport in the ebb- and flood-channels, $S_{r,ebb}$ and $S_{r,flood}$, and thus the circulation in the morphological cells, is mainly determined by the residual flow velocity or the tidal rectification, i.e. the M_0 constituent of the horizontal tide. The residual transport through the estuary S_r is closely related to the overtides of M_2.

The overtide of M_2 in terms of flow velocity is related to the asymmetry of the vertical tide whereas the M_0 component is mainly geometry and bathymetry induced.

Thus the circulation component of the residual sediment transport is mainly induced by the bathymetry difference between the ebb- and flood-channel. The residual transport through the estuary is closely related to the asymmetry of the vertical tide in the estuary. This means that the asymmetry of the vertical tide is important for the morphological development on the mega-scale whereas the residual currents (=tidal rectification) induced by bathymetry is important for the morphological development on the macro-scale, i.e. the estuarine sections.

2.4 Summary working hypotheses

In summary the following hypotheses have been proposed in the previous sections (see also Fig 2.2):

1. The residual sediment transport, local, through a channel or through the whole estuary, is much smaller in magnitude than the corresponding ebb- or flood transport.
2. The residual sediment transport through an ebb- and/or a flood channel is much larger than the residual transport through the estuary. In other words, the circulating component of the residual transport is much larger than the component through the estuary.
3. The circulating component of the residual transport is mainly related to the residual flow field and much less to the overtides.
4. The component through the estuary of the residual transport is closely related to the overtides of the flow velocity.
5. The circulating component of the residual transport is responsible for the macro-scale morphological development, i.e. the morphologic evolution of a system of two parallel main channels. For the macro-scale morphological development the residual flow (M_0) is therefore much more important than the overtides (M_4, M_6, etc.) of the flow velocity.
6. The net throughput of sediment over the entire estuarine cross-section is responsible for the mega-scale morphological development, i.e. the sediment exchange between estuarine sections and larger stretches of the estuary. The overtides of the flow velocity therefore play a significant role in the mega-scale morphological development.

3 Elaboration of the hypotheses on the basis of observations

3.1 Introduction

Basically, the following information is available to evaluate the hypotheses as formulated in the previous chapter:

- Sand transport measurements.
- Results of large-scale sediment budget analyses
- Sediment transports from the Delft3D-MOR runs carried out within the long-term vision Westerschelde project (Winterwerp et al., 2000).
- Results from 1D tidal model (Schoeman, 2000)
- Flow velocity data in individual main channels near Terneuzen (Jeuken, 2000)

These observations are addressed below, focusing on the hypotheses.

3.2 Large scale residual sediment transport in the estuary

3.2.1 Field Data

Field data on large scale sediment transport in the Westerschelde are scarce. Allersma (1992) and Storm (1996) present some data for a number of cross sections in the estuary based on direct measurement of (suspended) sediment transport. These all concern 13 hour (one tide) measurements at a limited number of verticals for each cross-section. These data give a good indication of the magnitude of the total (ebb + flood) transport through the cross-sections but cannot be considered to be accurate for the determination of the residual transport through the cross sections. This is probably the reason why Storm (1996) only presented the total transport through the cross sections but not the residual transport. Moreover, the tidal conditions during the measurements are seldom cyclic, resulting in a bias of the transports.

The most complete data on the long-term large-scale residual sediment transport are those based on the sediment-balance studies. Uit den Bogaard (1995) constructed a sediment-balance for the six parts of the estuary based on the data of the morphological development and dredging / dumping records. The results for the residual sediment transport are shown in Fig.3.1. The upper panel of the figure shows the residual transport at the mouth into the estuary, from the western part to the central part (vak4-vak3) and from the central part to the eastern part. In the lower panel the 5-year moving average of the transports at the same cross sections is shown. The averaging was done to smooth out errors in the data. Furthermore, it should be noted that the sediment balance is based on the assumption that the sediment exchange at the border between The Netherlands and Belgium can be ignored.

It also emphasised that the observations relate to both sand and mud. It reveals the following features:

- The positive transport at the mouth (positive = import) decreases until 1985, especially in the period 1978-1983, after 1985, more or less constant around 0.
- In the period 1975-1980 there is a net sediment transport from the western part to the central of the estuary part that increases with time. The sediment exchange reduces in 1982-1986. Since then it is more or less constant.
- A qualitatively similar temporal variation in sediment exchange can be observed between the budget sections 3 and 2 ('vak3-vak2' in Fig. 3.5), the central and landward part of the estuary.

Huijs (1996) has analysed the data of the morphological development and the dredging / dumping records on a more detailed scale by dividing the estuary into morphological units of channels and tidal flats. However, from this analysis it is not possible to determine the sediment exchange between the units. Moreover, the applied schematisation of the channels and shoals is not same for subsequent years. This is a complicating factor in interpretation of the results.

3.2.2 Relation to the asymmetry of vertical tide

The tidal asymmetry parameters are presented in Wang et al (1999). The M4 related to the M2 tide is shown in Fig.3.2 together with the large-scale sediment transport. Comparison of the two figures shows that there is not an unambiguous relationship between the asymmetry of the vertical tide and the large-scale sediment transport in the estuary (this contrasts with the observations of Gerritsen et al., 1998). This indicates that, if present, the relation between the direction of large-scale sediment transport and asymmetry of the vertical tide is a complicated one. Possible reasons for this complexity are:

- The direction of change in the tidal asymmetry at different stations is different. At Hansweert it becomes less ebb-dominant whereas at Bath it becomes less flood-dominant.
- The relation between the asymmetry of the horizontal tide and that of the vertical tide is complicated. The discharge at a cross-section is related to the water level variation in the whole estuary upstream of the cross-section, including the Zeeschelde.
- The residual sediment transport through the estuary is an integral of the local residual transport through individual ebb and flood channels (see Eq.1.6). This local residual transport strongly depends on the residual velocity (Van de Kreeke and Robacewska, 1993). In other words, the sediment exchange between estuarine sections may be influenced by 2D (or even 3D) channel processes. For instance, the study of Jeuken (in press) shows that the sediment exchange between the estuarine sections 4 and 3 is effectively influenced/determined by the behaviour of connecting channels in the bar area of the main flood channel Everingen. This implies that relatively small-scale processes, i.e. medium-scale channel behaviour, can be involved in the large-scale sediment transport in the estuary.

3.3 Results of a one-dimensional model

Schoeman (2000) set up a one-dimensional model to study the relation between the tidal asymmetry and the morphology in the Western Scheldt. The results of one of the simulations of this model, with the realistic bathymetry of 1996, is used here to analyse the relation between the asymmetry of the horizontal tide and that of the vertical tide, and the relation between the residual sediment transport and the asymmetry of horizontal tide.

The amplitude ratio between the M4 tide and the M2 tide as well as the phase lag between M4 and M2 for water level, discharge and flow velocity (cross-section averaged) are shown in Fig.3.3.

- The amplitude ratio between M4 and M2 for the cross-sectionally integrated discharge is larger than 2 times that for the water level, whereas the amplitude ratio for the velocity is smaller than 2 times that for the water level. This agrees with the analysis on the non-linear effects due to the hypsometry (Wang et al, 1999).
- The difference of the phase of M2 relative to that of M4 between the horizontal tide and the vertical tide is about 80°. There is also a difference between the phase lag for the flow velocity and that for the discharge. This difference varies from about -10° at the mouth to about 10° at the upstream end of the Westerschelde.

The amplitude ratio between the M6 tide and the M2 tide as well as the phase lag between M6 and M2 for water level, discharge and flow velocity (cross-section averaged) are shown in Fig.3.4.

- The amplitude ratios between M6 and M2 for the discharge as well as for the flow velocity are about 3 times that for the water level. Also this is in agreement with the results of the analysis carried out by Wang et al. (1999).
- The phase lag between M6 and M2 for the vertical tide decreases from about 70° at the mouth to about 0° at the upstream end, whereas the phase lag for the horizontal tide, for the discharge as well as the flow velocity, is almost constant through the whole estuary: about 160°.

The three terms in the long-term averaged sediment transport (eq. 2.11) derived from the results of the flow velocity are shown in Fig.3.5.

- It is remarkable that even the results of such a 1D single-branch model show a M0 component for the flow velocity. The term related to this component is the largest one of the three. The ebb-dominant current even without upstream river discharge is due to the fact that ebb-flow occurs at a lower water level than the flood-flow. This confirms the concept of Bakker and De Vriend (1995).
- The contribution due to the M4 component is in the same order of magnitude as that of the M6 component. The contribution of M4 is negative (export) in the western part and positive in the eastern part. The contribution of the M6 component is the other way around.
- If all three terms are taken into account the calculated residual transport is negative. If only the overtides are taken into account it is slightly positive (flood-dominant) in almost the whole estuary.

- Note that for the calculation of the transport the variation of the (transport) width, which will make the transport somewhat (5-10%) more positive because the water level during flood is higher than during ebb, is not taken into account.

It is also noted that for all the cross sections the ebb and flood transport are of the same order of magnitude, and both much larger than the residual transport (not shown).

3.4 Tidal and residual transport within channels

3.4.1 Velocity observations from the field

The results of a discharge measurement and some long-term current observations in the system of main channels near Terneuzen (Jeuken, 2000) were harmonically analysed (for locations see Figure 3.6). The relative contribution of the depth-averaged residual current and the quarter and sixth-diurnal velocity components to the sand transport were determined following Van de Kreeke and Robaczewska (1993, see equation 2.11).

Point observations

The results of the long-term current meter observations are depicted in Figure 3.7. For both the main ebb channel and the main flood channel three locations are indicated, viz.: the entrance of the channel (E), the central part (C) and the bar area (B, see figure 3.6).

The main ebb channel is characterised by strongly ebb-dominant residual currents. In the central part of the channel the amplitude of M_4 relative to M_2 amounts 0.15. The amplitude ratio of M_6 is considerably smaller. The relative phases approximate 100 and 140 degrees respectively. The contribution to the residual sand transport (lower panel) shows that the residual currents determine the ebb-dominant direction of the net transport in the central part of the channel. Remarkable is the ebb-dominant direction of the interaction between M_2 and M_4. The triple-interaction between M_2, M_4 and M_6 is associated with a flood-dominant direction. In the bar area (B) and the entrance (E) where the channel exhibits a curved-channel alignment, the ellipses of the overtides M_4 and M_6 are strongly inclined with respect to the M_2-ellips. As a result it is not meaningful to consider the interaction between M_2 and its overtides in the main flow direction. Presumably this phenomenon of strong inclination of the ellipses is due to transverse secondary flows.

At the three locations (E, C,B) in the straight main flood channel Everingen this phenomenom of inclined current ellipses is absent, which seems to confirm the above interpretation. Figure 3.7 reveals a large spatial variation in the relative magnitude of the residual currents and the overtides. In the deep central part a small ebb-dominant residual current exists, whereas clearly flood-dominant residuals occur in the entrance and bar area of the channel. Except for the entrance of the channel, where M_4 is relatively large, M_4 and M_6 are of similar relative magnitude. The phase differences relative to M_2 range between some 100 and 160 degrees respectively (middle panel). The direction of residual sand transport is determined by the effect of the residual currents. Remarkable is the negative contribution of the interaction M_2M_4 and the flood-dominance of the triple interaction $M_2M_4M_6$.

Discharge measurement

In 1996 a discharge measurement has been carried out with an Acoustic Doppler Current meter in the central part of Terneuzen section during strong spring tidal conditions (with practically cyclic tides, transect 7 in Fig. 3.6).

The results of the harmonic analysis show a small ebb-dominant residual current, similar to the 1D-model. This current is probably due to the phase differences between the horizontal and vertical tide. Because of this phase differences the maximum ebb currents occur at lower water level and smaller cross-sectional area than the maximum ebb flow. This favours an ebb-dominant residual current. Furthermore, an approximately equal contribution of the M_4 and M_6 overtides in the horizontal tide can be observed (Fig. 3.8). The magnitude of the asymmetry in the horizontal tide, indicated by the amplitude ratio (upper panel), is larger than that of the vertical tide: the asymmetry in the discharges and velocities is two to three times larger than in the water levels. This more or less confirms the previous analyses of Wang et al. (1999) and the 1D model results described in section 3.2. Similar to the 1D-model results (for mean tidal conditions), the asymmetry related to the quarter-diurnal component is slightly larger than that of the sixth-diurnal one. Also the relative phase difference between M_2 and the overtides M_4 and M_6 are similar, i.e. some 90 and 140 degrees respectively.

The relative contribution of the various components to the residual transport of coarse sediment (lower panel) shows again a strong influence of the residual currents, both for the entire estuarine cross-section and for the individual main ebb and flood channels. The relatively small residual current (see upper panel) largely determines the direction of the net transports. The contribution of the overtides to the residual transport is several times smaller. Averaged over the entire cross-section the interaction between M_2 and M_4 is attended with a small flood-dominant transport, whereas the triple interaction ($M_2M_4M_6$) induces a small ebb-dominant transport. The contribution of the overtides in the individual main channels is opposite: in the flood channel the interaction between M_2 and M_4 yields a flood-dominant transport whereas it induces an ebb-dominant transport in the ebb channel. The triple interaction between M_2, M_4 and M_6 is attended with a small ebb-dominant transport in the flood channel and an flood-dominant transport in the flood channel. This emphasises the large spatial variation as pointed out in the previous section.

3.4.2 Results from 2DH-transport modelling

The sediment transport through some cross-sections in the estuary has been determined from computed sediment transport fields that were carried out within the framework Long-term Vision project (Winterwerp, 2000). The results of some transects were analysed to obtain an impression of the tidal and residual transports within and through a system of two parallel ebb and flood channels. For each of the three seaward located estuarine sections (numbers 3-6, see section 2.1) two representative cross-sections were selected which clearly separate the main ebb channel from the main flood channel. The results in terms of ebb, flood and residual transport, in individual channels and in the system of channels as a whole, are shown in Figure 3.9. It is emphasised that the distinction between ebb and flood channels in Figure 3.9 is based on morphologic arguments: the ebb channel has a bar at its seaward end, whereas the flood channel has a bar at its landward end. The lateral demarcation between the channels follows the 'watershed' across the elongate shoals between the two channels. This implies that when ebb and flood-dominant transports occur within the same channel (e.g. in the flood channel Gat van Ossenisse), the sum of these transports is presented. Furthermore, the magnitude of the transport depends on the transport formulation chosen (Engelund-Hansen) and on the sediment parameter settings (grainsize of 240 μm). Hence the results give an indication of the order of magnitude of the various transport constituents and their relative magnitude.

Figure 3.9 gives rise to the following observations:

- The main ebb channels (EC) exhibit an ebb-dominant transport, whereas the main flood channels (FC) are clearly flood-dominant.
- The tidal and residual transport in the main flood channels (FC) tend to exceed those in the main ebb channel, resulting in a net flood-dominant residual transport through the system of two parallel main channels. This net component is smaller than the individual ebb and flood transport rates, though in five of the six cross-sections it is of same order of magnitude.
- A similar observation applies to the sand transport in the individual channels. The magnitude of the net transport through a channel resembles the magnitude of the subordinate, i.e. smallest tidal (ebb or flood), transport.

Similar observations are made by Jeuken (2000). She further concludes that the direction of the ebb-dominated transport in the (main) ebb channel is due to the ebb-dominant residual currents. The generally large, flood-dominant transport in the flood channel coincides with flood-dominant residual currents and an overall, i.e. in both main channels, flood-dominant asymmetry of the maximum velocity.

3.5 Residual flow and bathymetry

In the previous sections it has been shown that the residual velocity plays an essential role in the residual sediment transport. Therefore an analysis will be carried out in order to identify the factors determining the residual current.

3.5.1 Single branch consideration

The results of the one-dimensional model, as well as the field measurements, show that there is a residual current in the ebb-direction, even when there is no upstream discharge (so no residual discharge in the 1D-model). This is due to the fact that the ebb flow occurs at a lower water level than the flood flow. This can be demonstrated as follows. In case that there is no residual discharge, the ebb-volume must be equal to the flood volume:

$$\int^{T_{ebb}} |Q| dt = \int^{T_{flood}} |Q| dt \qquad (3.1)$$

The residual current in the ebb-direction is equal to

$$v_r = \frac{1}{T_{ebb} + T_{flood}} \left(\int^{T_{ebb}} \frac{|Q|}{A_{ebb}} dt - \int^{T_{flood}} \frac{|Q|}{A_{flood}} dt \right) \quad (3.2)$$

Since A_{flood}>A_{ebb} the residual current v_r is always negative, i.e. in the ebb-direction, independent of the ebb- and flood duration and hence independent of the maximum ebb- and flood discharge. The factor determining the cross-sectional averaged residual current is thus the phase lag between the horizontal tide and the vertical tide.

3.5.2 Two-branches consideration

In an ebb- and flood-channel system, the residual flow through the channels can be explained by simplifying the tidal flow to two steady-flow periods, one in the flood direction and one in the ebb direction, both with the same discharge Q_{tot}. Furthermore, it is assumed that the widths of the two channels are equal. If the water level during flood is δ above the reference level and the water level during ebb is δ under the reference level, the discharge through the flood channel during flood follows from

$$Q_{f1} = \frac{(h_1 + \delta)^\alpha}{(h_1 + \delta)^\alpha + (h_2 + \delta)^\alpha} Q_{tot} \quad (3.1)$$

During ebb it is

$$Q_{e1} = \frac{(h_1 - \delta)^\alpha}{(h_1 - \delta)^\alpha + (h_2 - \delta)^\alpha} Q_{tot} \quad (3.2)$$

In these two equations

- h_1 = depth of the flood channel with respect to the reference level
- h_2 = depth of the ebb channel with respect to the reference level
- α = power depending on formulation for bed shear stress, for Manning it is 5/3

The residual discharge through the flood channel then becomes

$$\frac{\Delta Q}{Q_{tot}} = \frac{1}{1 + \left(\frac{\frac{h_2}{h_1} + \frac{\delta}{h_1}}{1 + \frac{\delta}{h_1}} \right)^\alpha} - \frac{1}{1 + \left(\frac{\frac{h_2}{h_1} - \frac{\delta}{h_1}}{1 - \frac{\delta}{h_1}} \right)^\alpha} \quad (3.3)$$

So there are two parameters determining the residual discharge through the system of channels: h_2/h_1, characterising the bathymetry of the system, and δ/h_1, where δ is determined by the phase lag between the horizontal tide and the vertical tide. If the flood channel is shallower than the ebb channel and the water level during flood is higher than during ebb the residual discharge in the flood channel is in the flood direction.

The expression (3.3) is depicted in the upper panel of Figure 3.10. The residual discharge normalised with the total discharge through the system is more or less proportional to δ/h_1. It is remarkable that the relative residual discharge increases with h_2/h_1 but the increase becomes smaller when its value approaches 2. This is made better visible in the lower panel of Figure 3.10, in which the derivative of the expression to δ/h_1 is depicted as function of h_2/h_1. This derivative has a maximum value when h_2/h_1 is about 2.

Finally, it is noted that there are also other geometric parameters, i.e. the length of the channels, influencing the discharge distribution through the channels and thereby the circulation discharge in the ebb and flood channel system. Another mechanism generating such a circulation is due to the width variation of the channels (the width of the flood channel increases in the upstream direction) as demonstrated by Van Kerckhoven (1995). However, in general it can be concluded that the residual circulation is determined by the geometric and bathymetric characteristics of the estuary and by the phase lag between the horizontal tide and the vertical tide.

4 Discussion, conclusions and recommendations

4.1 Discussion and conclusions

First the hypotheses as summarised in 2.4 are evaluated based on the findings in Chapter 3.

Hypothesis 1: *The residual sediment transport, local, through a channel or through the whole estuary, is much smaller in magnitude than the corresponding ebb- or flood transport.*

This hypothesis is supported by the 1D model results, but not fully supported by the results from the 2DH model. According to the 2DH model, the residual transport through a cross section can be of the same order of magnitude as the smallest of the ebb- and the flood-transport, depending on the location of the cross-section. The hypothesis is thus confirmed when the whole estuary is considered, and rejected when the individual channels are considered.

Hypothesis 2: *The residual sediment transport through an ebb- and/or a flood channel is much larger than the residual transport through the estuary. In other words, the circulating component of the residual transport is much larger than the component through the estuary.*

This hypothesis has been proven false. The circulating component and the component through the estuary of the residual transport can be of the same order of magnitude.

Hypothesis 3: *The circulating component of the residual transport is mainly related to the residual flow field and much less to the overtides.*

This hypothesis is fully supported by all data available and can therefore be considered as proven true.

Hypothesis 4: *The component through the estuary of the residual transport is closely related to the overtides of the flow velocity.*

No conclusion about this hypothesis can be drawn yet. It is shown that there is a relation between the (vertical) overtides and the residual sediment transport through the estuary, but it is also shown that the residual flow plays an important role in the residual transport. Even according to the single-branch 1D model, the residual current gives a predominant contribution to the residual transport. This raises doubt about whether it is justified to relate the cross-sectional averaged sediment transport to the cross-sectional averaged flow velocity. If this is done, the 1D model will always give a residual transport in the ebb-direction, even if all the characteristics of the tidal asymmetry are reproduced. This is clearly not in agreement with the reality. At this moment, only the following conclusion can be drawn: *The residual transport through the estuary is the integral of the local residual transport over a cross-section of the estuary. The local transport is dominated by the circulating residual flow, but the integral can be influenced by the residual flow as well as the overtides.*

Hypothesis 5: *The circulating component of the residual transport is responsible for the macro-scale morphological development, i.e. the morphologic evolution of a system of two parallel main channels. For the macro-scale morphological development the residual flow (M_0) is therefore much more important than the overtides (M_4, M_6, etc.) of the flow velocity.*

This hypothesis can be considered as proven true.

Hypothesis 6: *The net throughput of sediment over the entire estuarine cross-section is responsible for the mega-scale morphological development, i.e. the sediment exchange between estuarine sections and larger stretches of the estuary. The overtides of the flow velocity therefore play a significant role in the mega-scale morphological development.*

This hypothesis should be modified as (see the evaluation of hypothesis 4): *The net throughput of sediment over the entire estuarine cross-section is responsible for the mega-scale morphological development. The overtides of the flow velocity therefore play a significant role in the mega-scale morphological development,* ***in addition to the residual flow.***

Further the following conclusions have been drawn:

- In the residual sediment transport and hence also in the morphological development of the Westerschelde estuary, the residual current plays a very important role.
- For the residual sediment transport the quarter-diurnal and sixth-diurnal component of the tide are equally important.
- The residual current is determined by the geometric and bathymetric characteristics of the estuary, and by the differences in water level during flood and during ebb. The latter is determined by the phase difference between the horizontal tide and the vertical tide in the estuary.

In the analysis by Wang et al. (1999) it has been demonstrated that the mega-scale morphological development influences the asymmetry of the vertical tide. The present study shows that the most important characteristic of the asymmetry of the horizontal tide is the residual current (the M0 component). It is noted that the bathymetric characteristic influencing the residual current, the depth difference between the flood channels and the ebb channels, is also strongly influenced by the human interference, such as dredging and dumping activities. Therefore, more insight into the residual current and the residual sediment transport mechanisms under the influence of the bathymetric characteristics is necessary for studying the impact of human interference.

4.2 Recommendations

Based on the findings of the present study, the following recommendations are made for further studies:

- Study the relation between the residual current and the bathymetry in more detail with 2Dh and 3D models. Use 1D network models to explore the influence of bathymetric changes on the asymmetry of the vertical tide.
- Pay more attention to the M6 component in the studies. Up to now only the M4 component has been analysed in relation to the morphology.
- Use 2DH sediment transport models to analyse the relative importance of the overtides (as compared with the residual current) to the residual sediment transport, especially the net throughput of sediment over the entire estuarine cross-section.
- Analyse the morphologic evolution of the individual channels within the estuarine sections (Jeuken, 2000).

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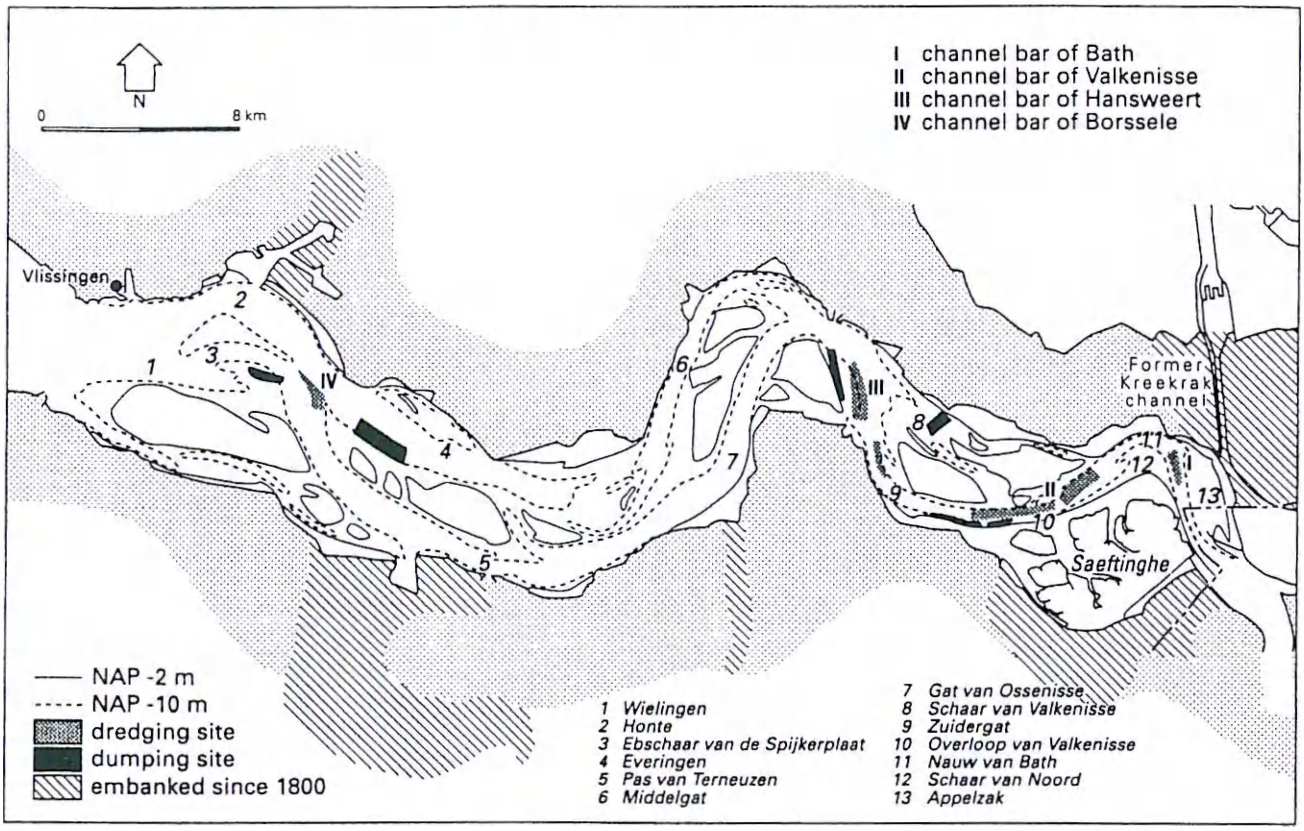
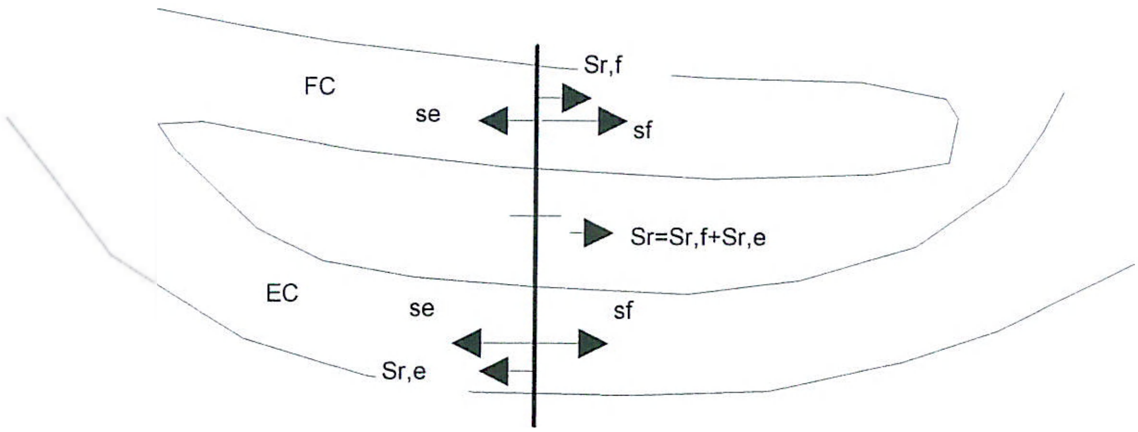
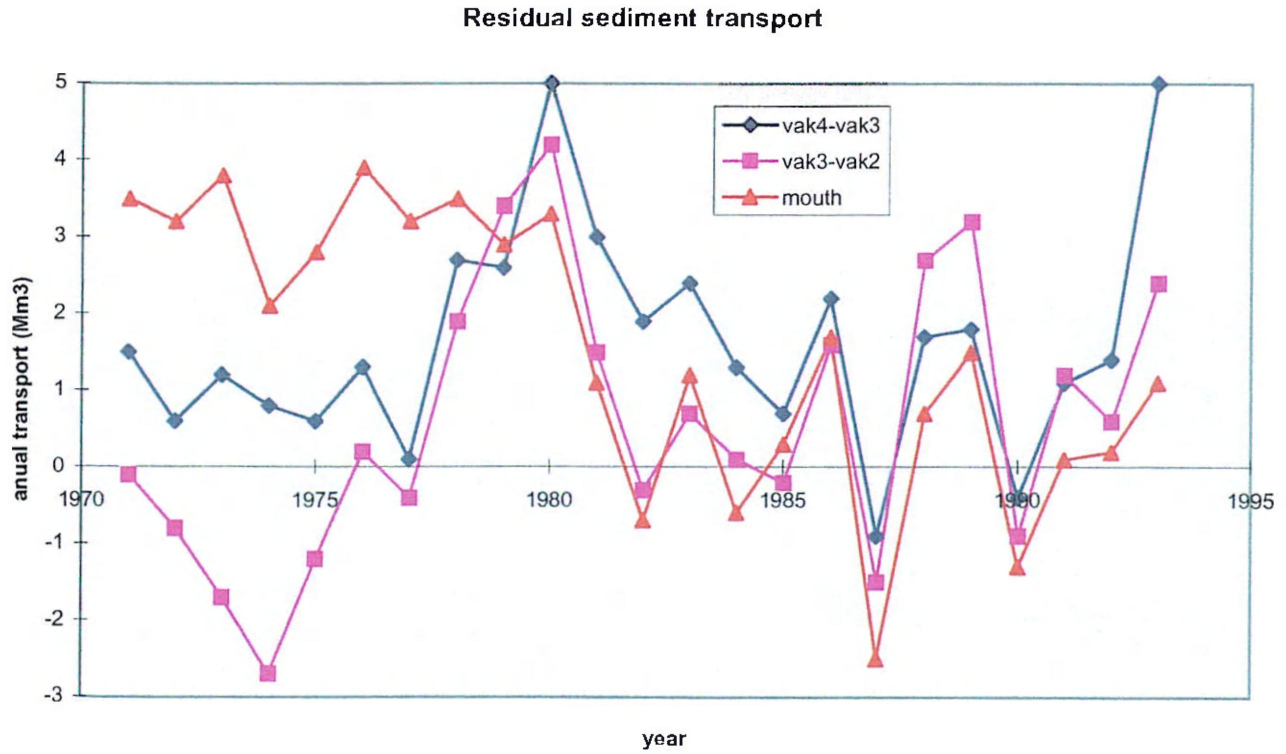


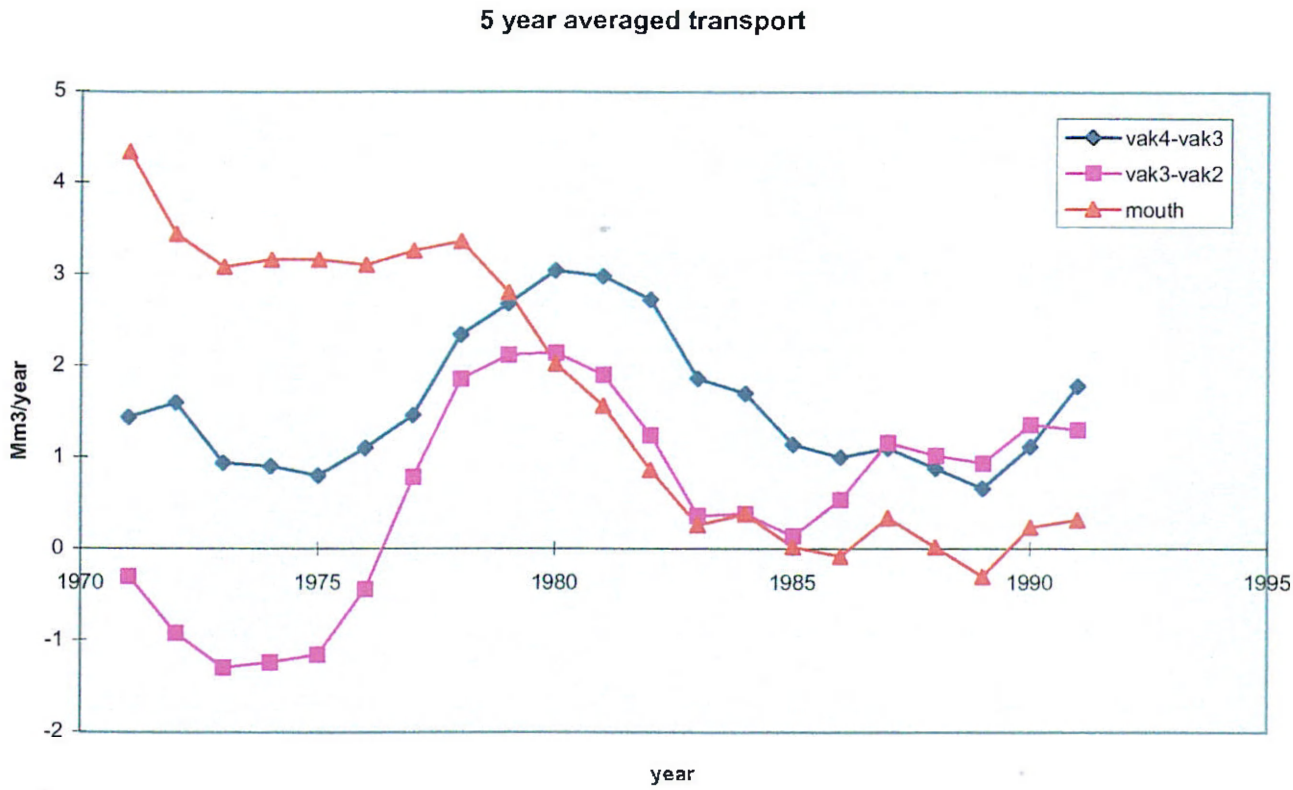
Location of various main ebb and flood channels in the Westerschelde in 1992 (from Van den Berg et al., 1996)	Z2864
	11/2000
WL | DELFT HYDRAULICS	Fig.2.1



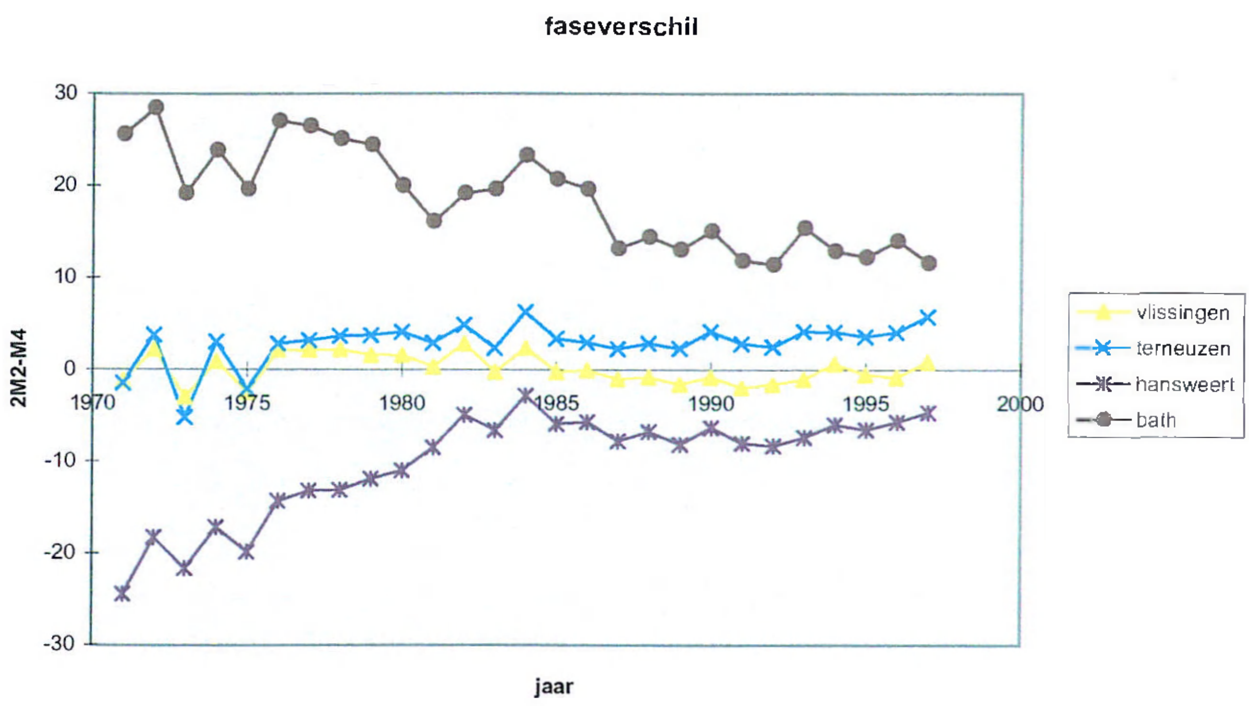
se = ebb transport through channel
sf = flood transport through channel
Sr,f= residual transport through flood channel FC
Sr,e = residual transport through ebb channel EC
Sr=residual transport through entire cross-section, i.e. Sr,f+Sr,e.
EC= main ebb channel
FC= main flood channel

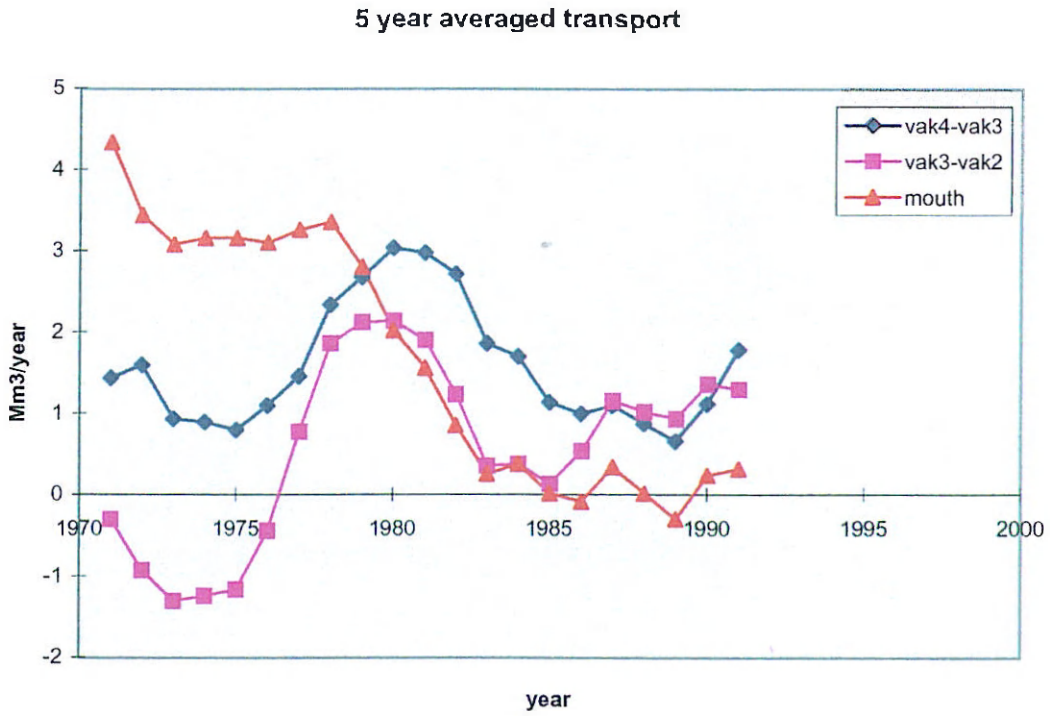
Schematic representation of the residual sediment transport at the spatial scale of an estuarine section.	Z2864	
	11/2000	
WL | DELFT HYDRAULICS	Fig.2.2	



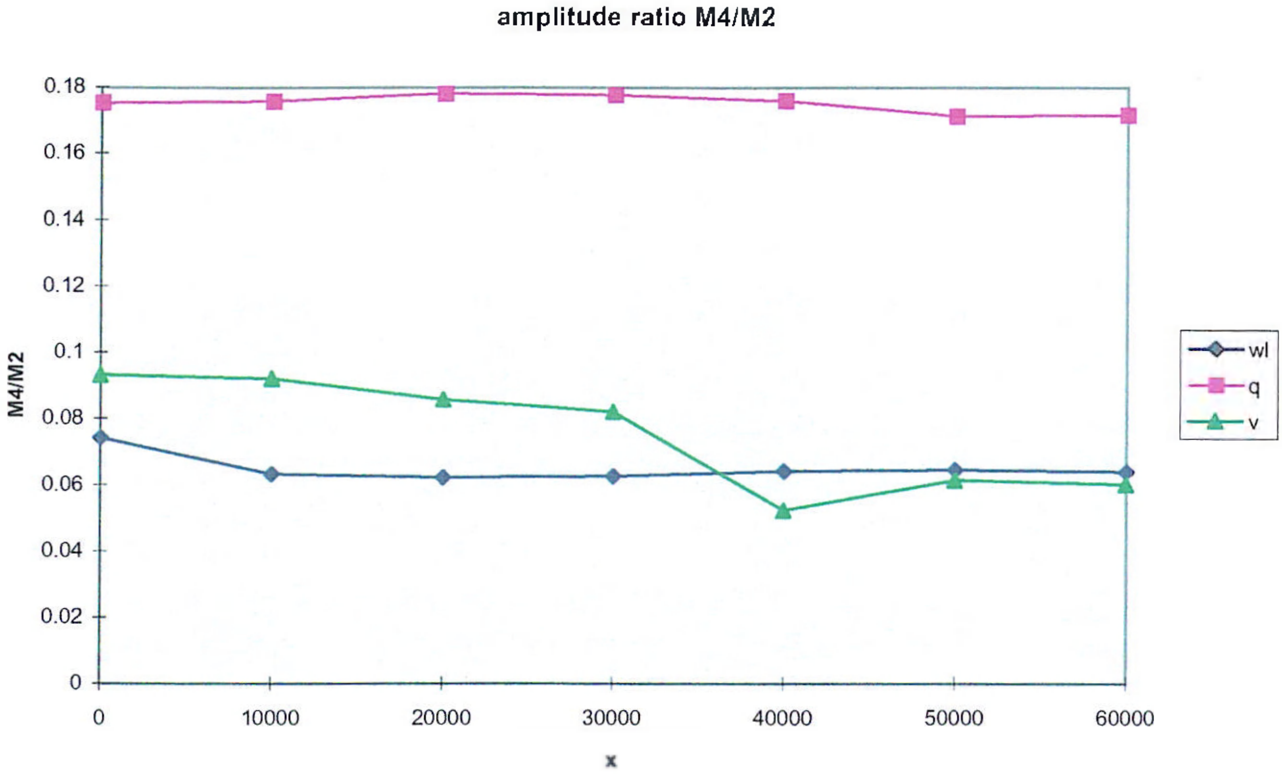


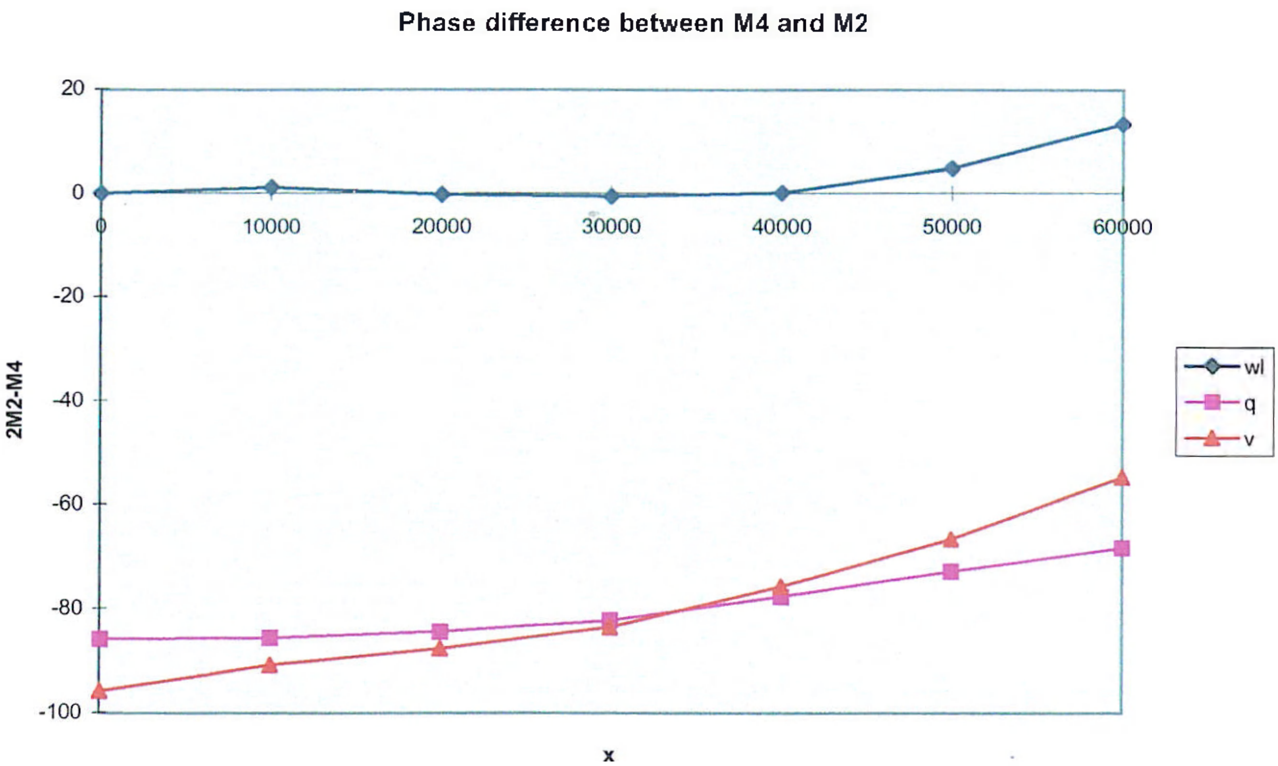
Net sediment transport inferred from a large-scale sediment budget study (Uit den Bogaard, 1995). + = landward directed transport, -=seaward directed transport.	Z2864
	oktober2000
WL | DELFT HYDRAULICS	Fig.3.1



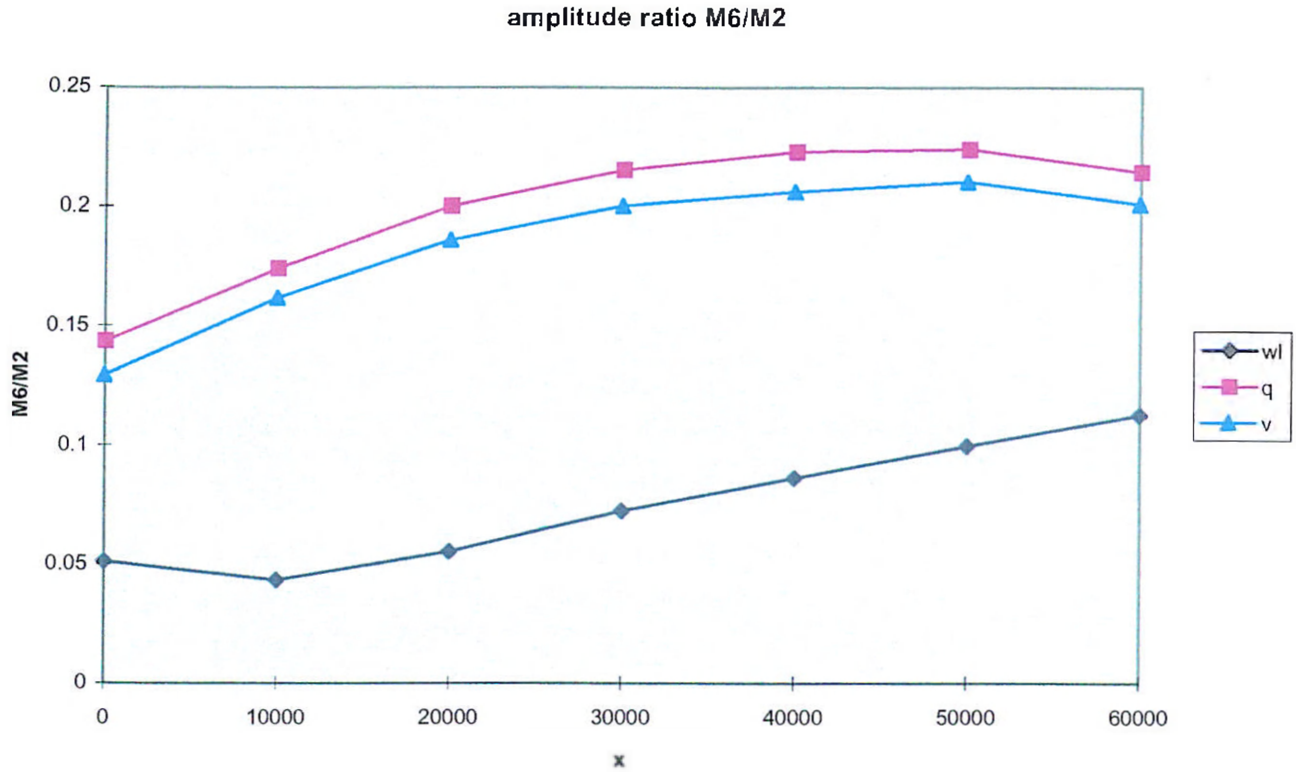


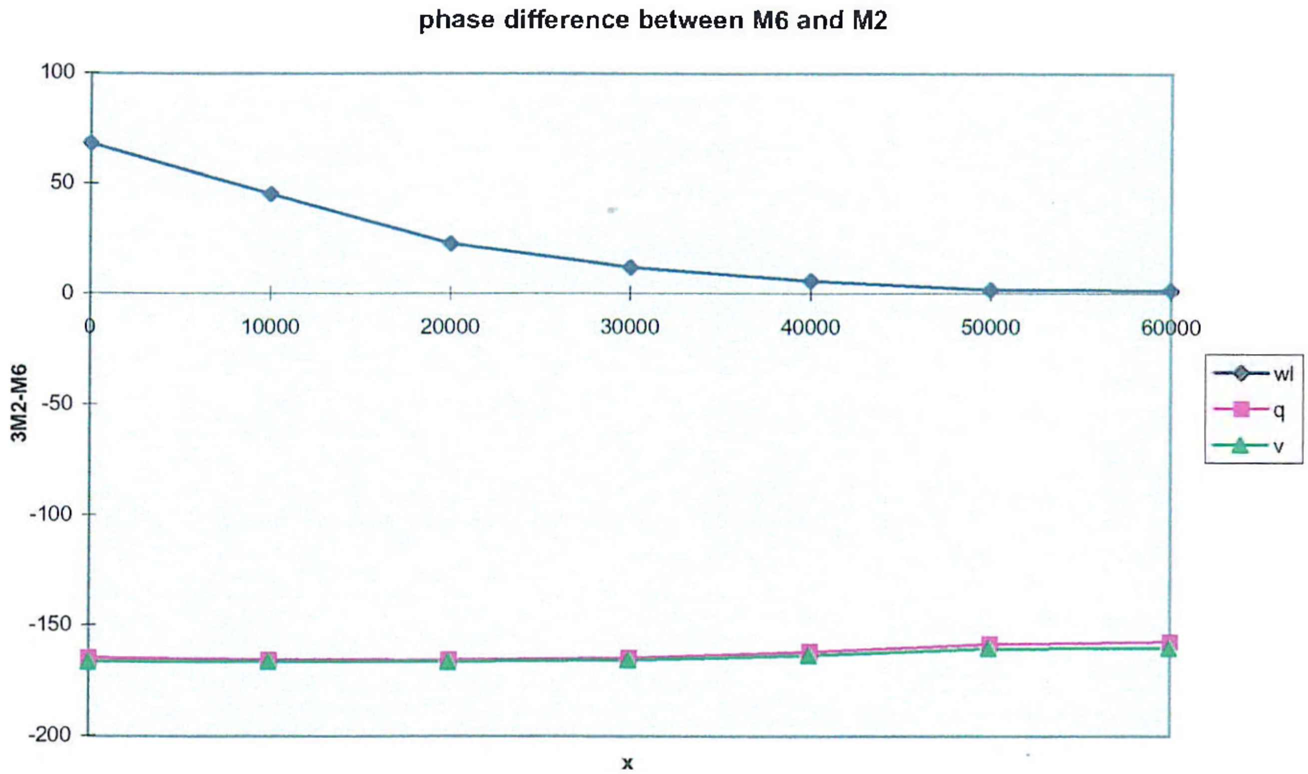
Asymmetry of the vertical tide related to the generation of M4 and the large-scale sediment transport in the estuary.	Z2864
	11/2000
WL | DELFT HYDRAULICS	Fig.3.2





Asymmetry of the vertical and horizontal tide related to generation of M4 inferred from 1D model results. wl=water level, q=discharge and cross-sectionally averaged velocity.	Z2864	
	11/ 2000	
WL | DELFT HYDRAULICS	Fig.3.3	





Asymmetry of the vertical and horizontal tide related to generation of M6 inferred from 1D model results. wl=water level, q=discharge and cross-sectionally averaged velocity.	Z2864
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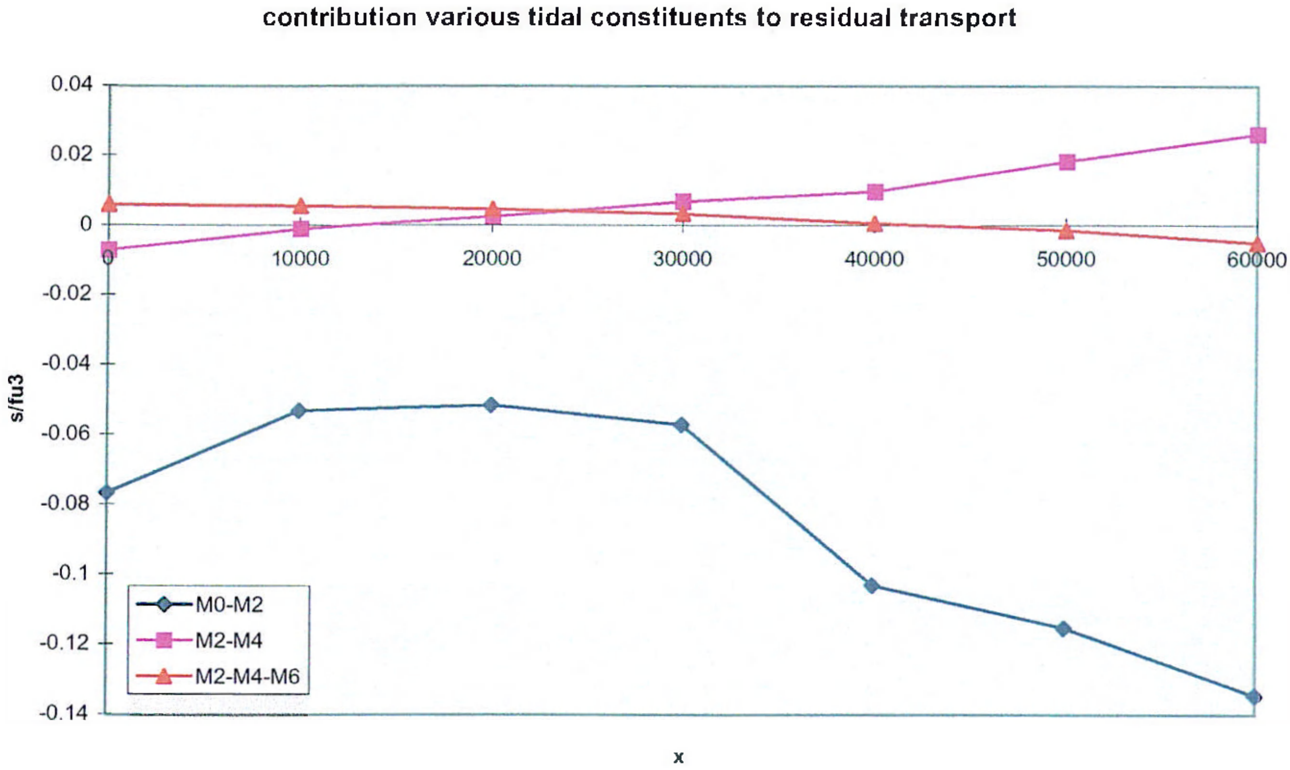
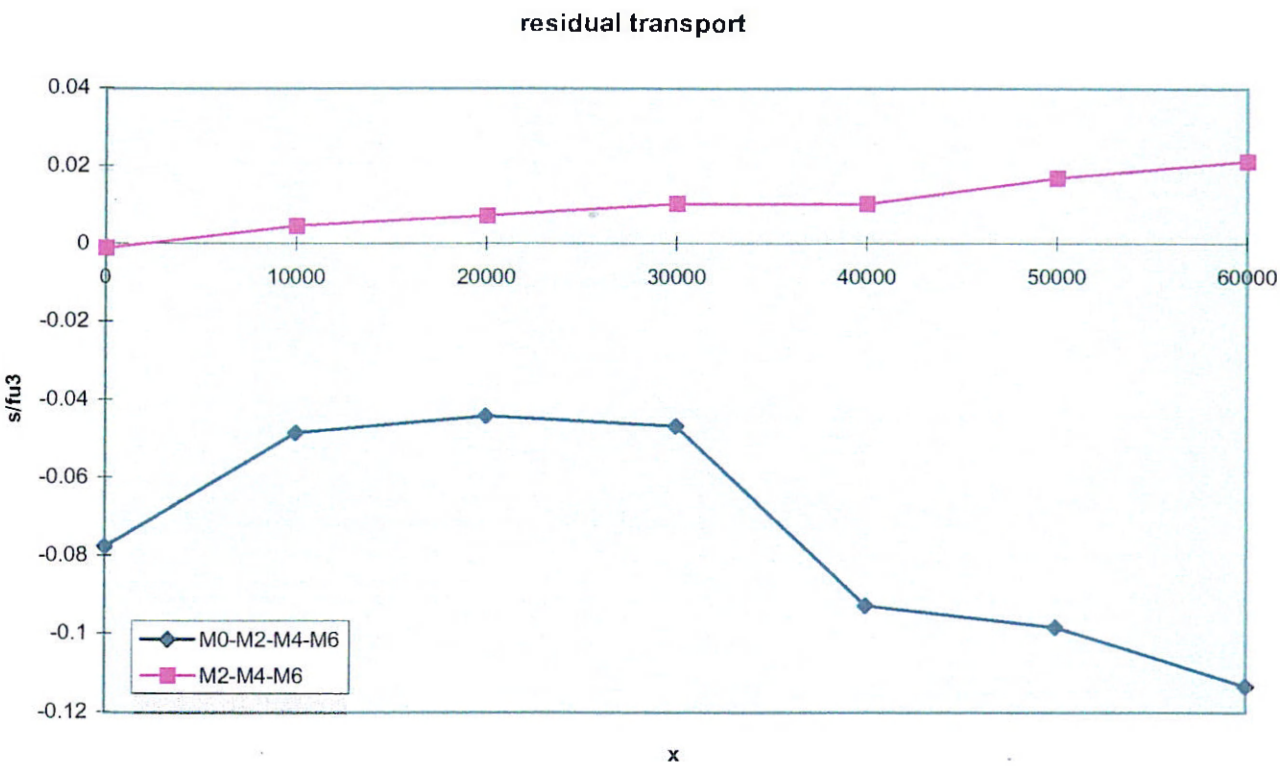
WL | DELFT HYDRAULICS	Fig.3.4





1D model results Contribution of various components to the residual sediment transport according to equation 2.9.	Z2864
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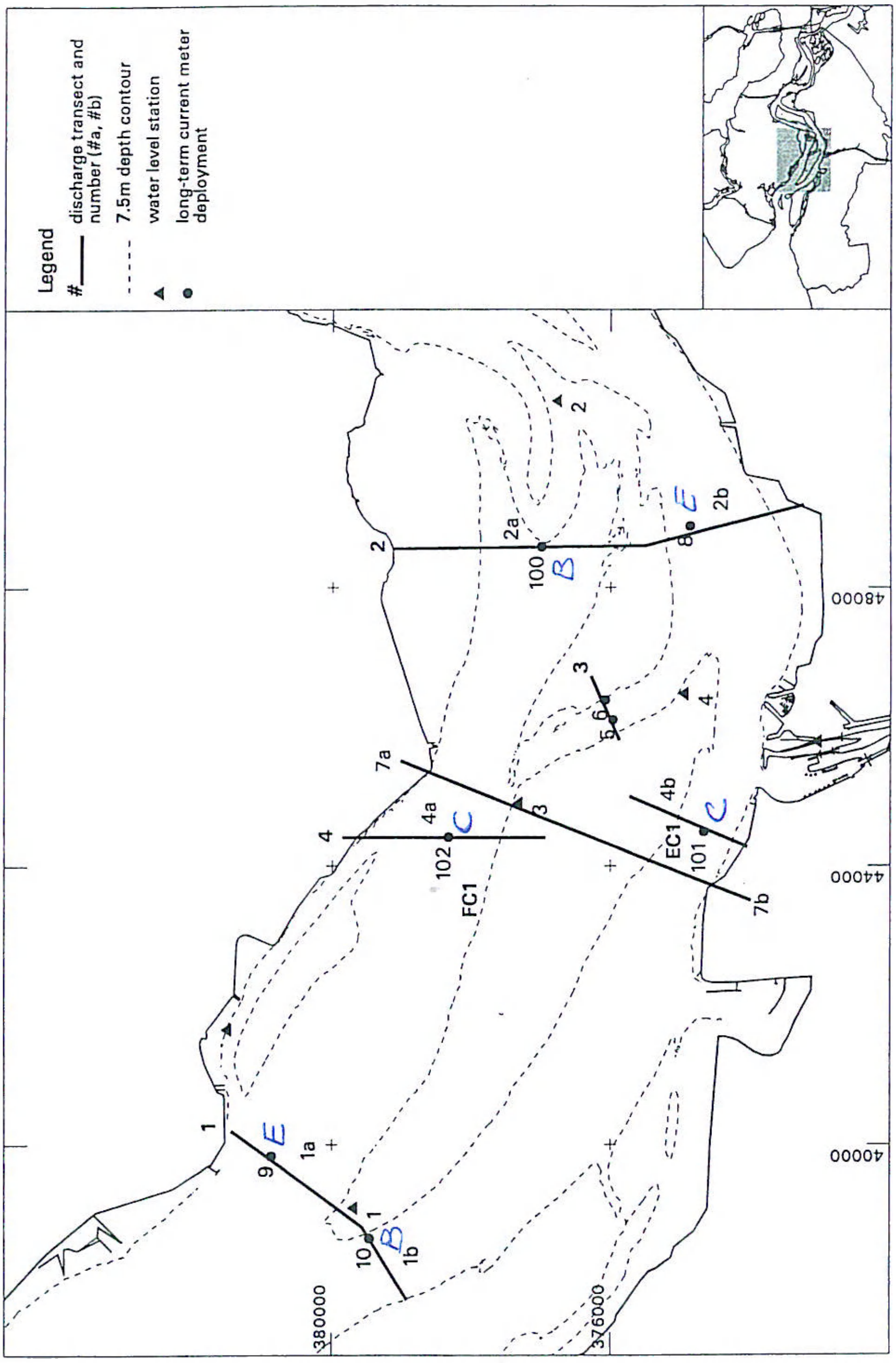
WL | DELFT HYDRAULICS	Fig.3.5



Location of long-term current meters (9, 102,100, 10,101 and 8) and discharge transect 7(a+b). (From Jeuken, 2000).
FC1=flood channel, EC1=ebb channel.

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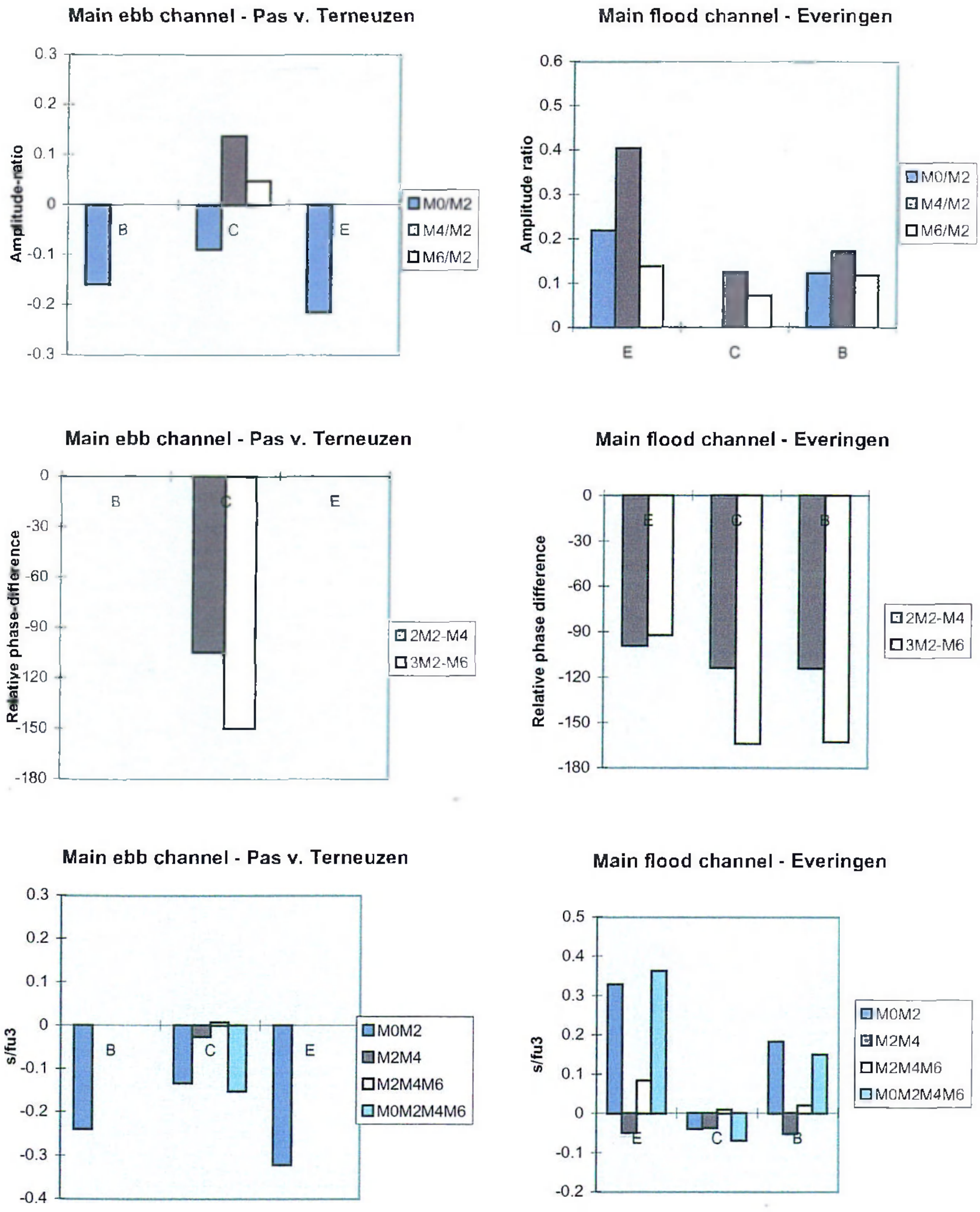
WL | DELFT HYDRAULICS	Fig.3.6



Results of long-term current measurements in the Terneuzen section. E=entrance, C=central part, B= bar area of main channel. For locations see Fig. 3.6.

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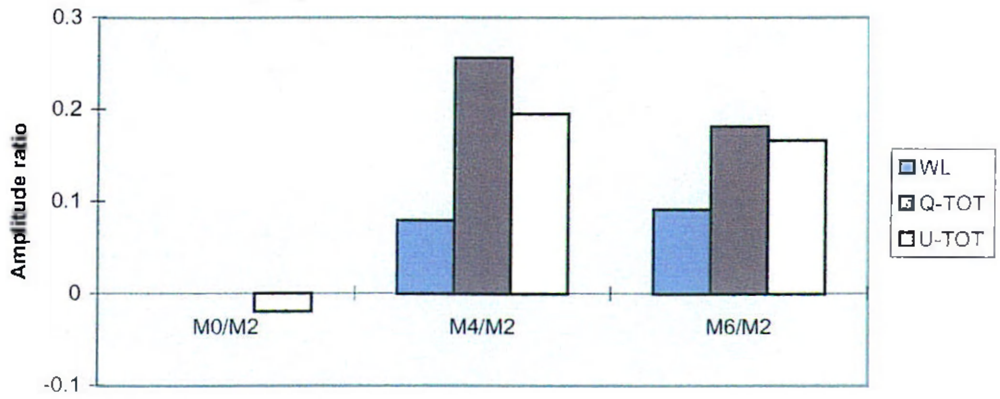
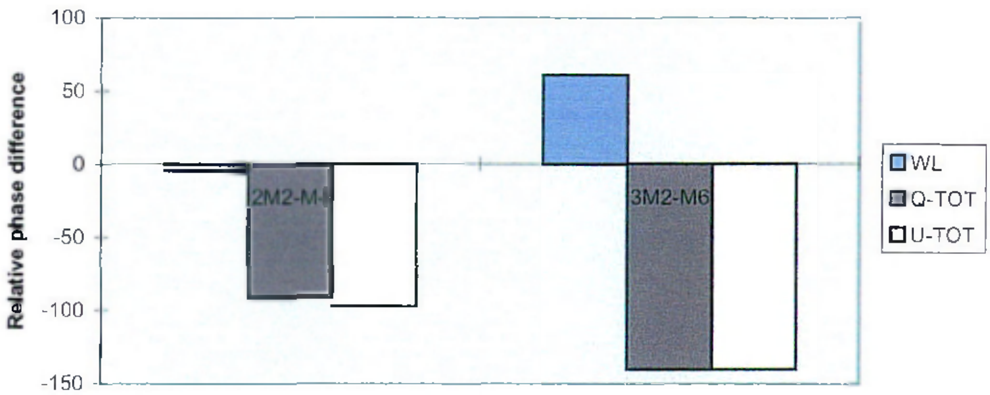
WL | DELFT HYDRAULICS

Fig.3.7

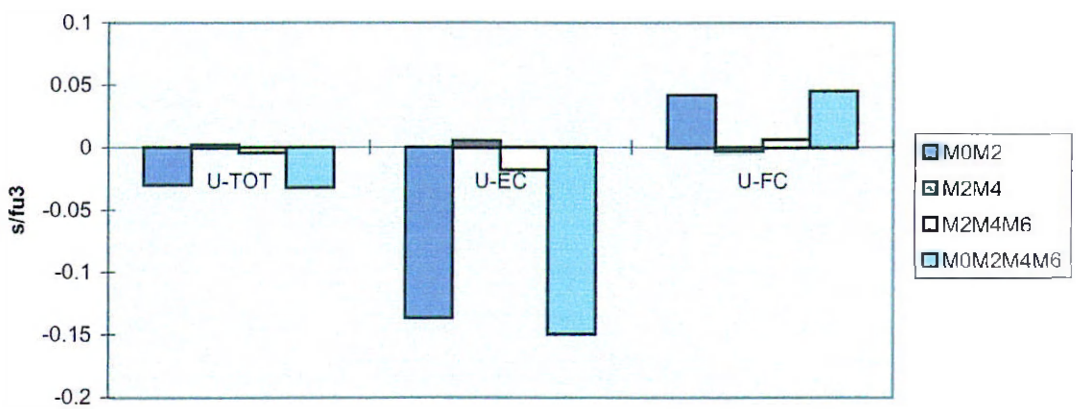
Discharge transect 7



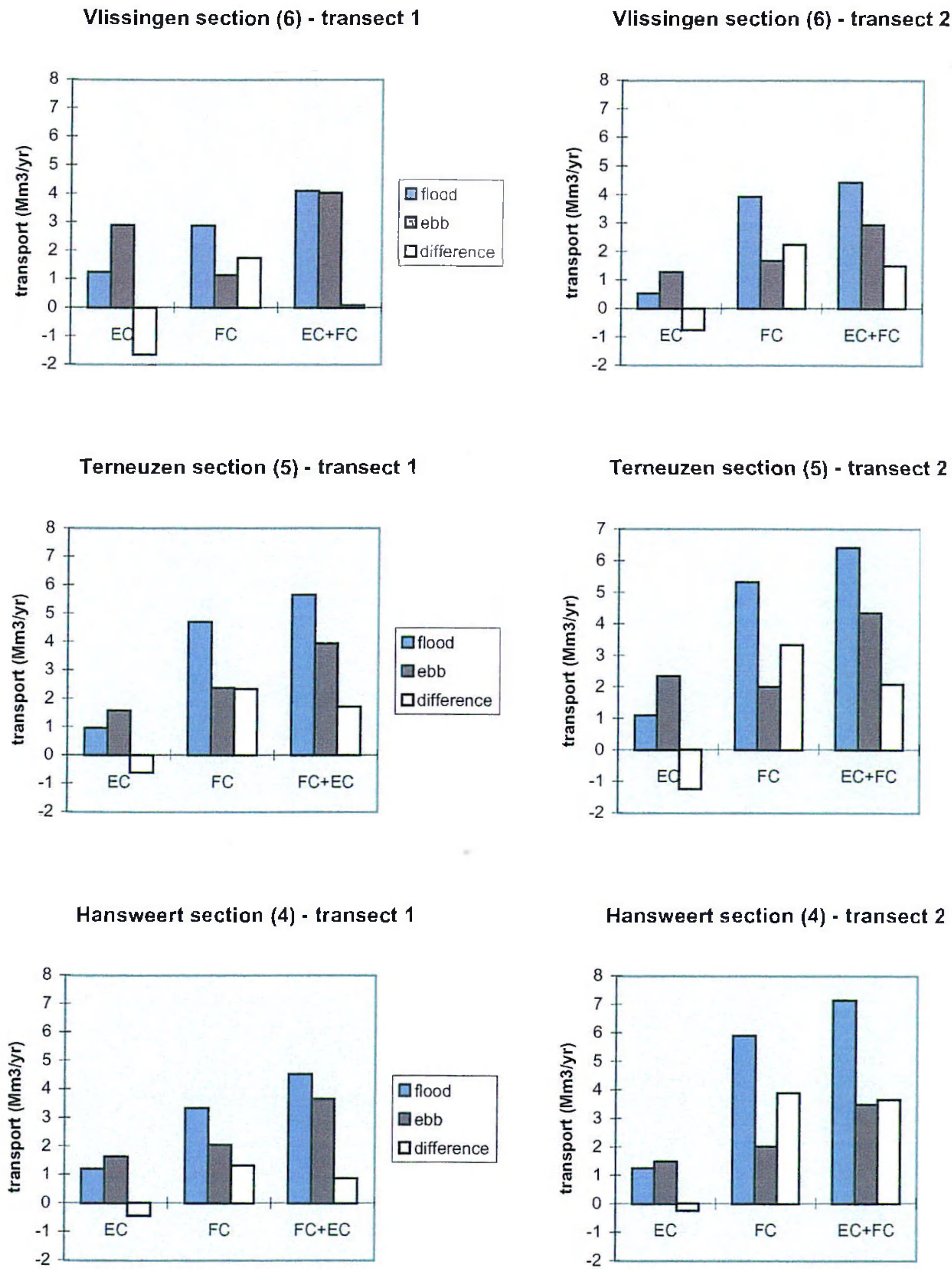
Discharge transect 7



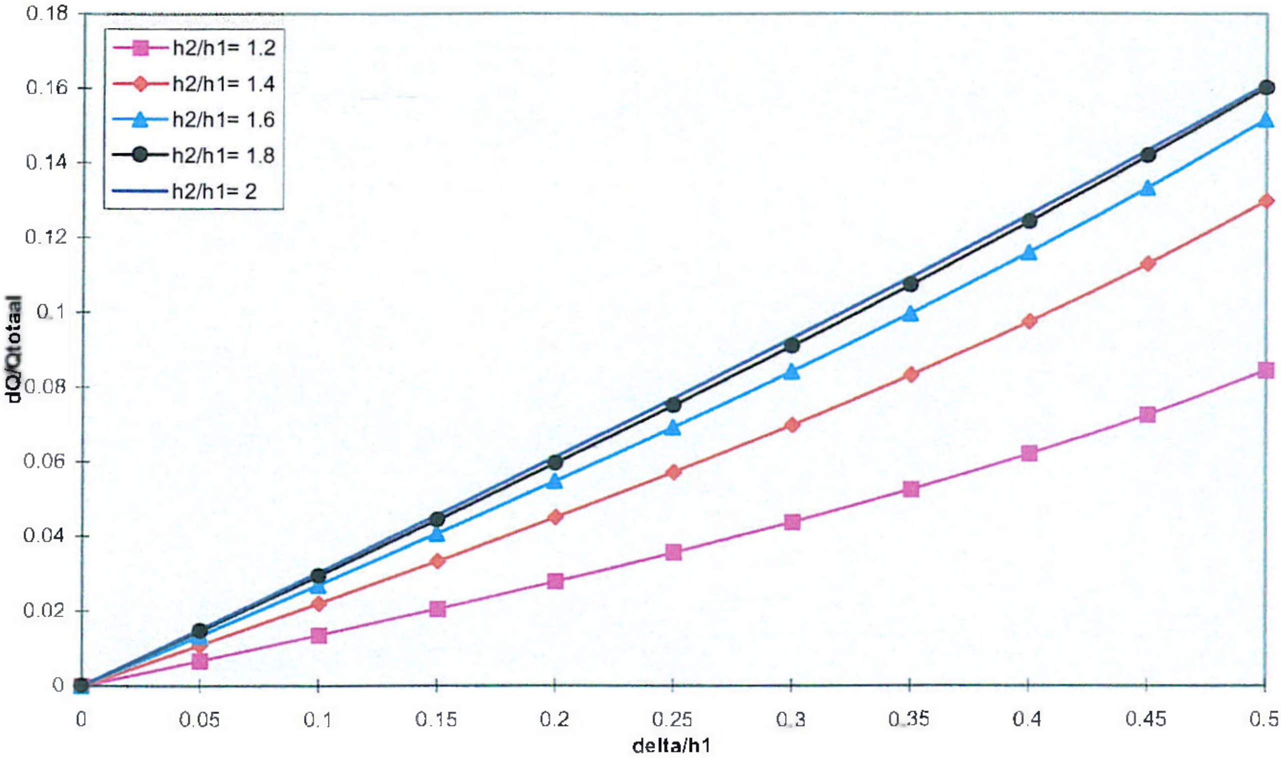
Discharge transect 7



Results of discarge measurement near Terneuzen. WL=water level, Q-tot and U-tot=discharge and velocity through entire estuarine cross-section. U-EC=velocity in ebb channel, U-FC=velocity in flood channel	Z2864 oktober 2000
WL | DELFT HYDRAULICS	Fig.3.8



Results of 2DH sediment transport model. EC=ebb channel, FC=flood channel	Z2864	
	oktober 2000	
WL | DELFT HYDRAULICS	Fig.3.9	



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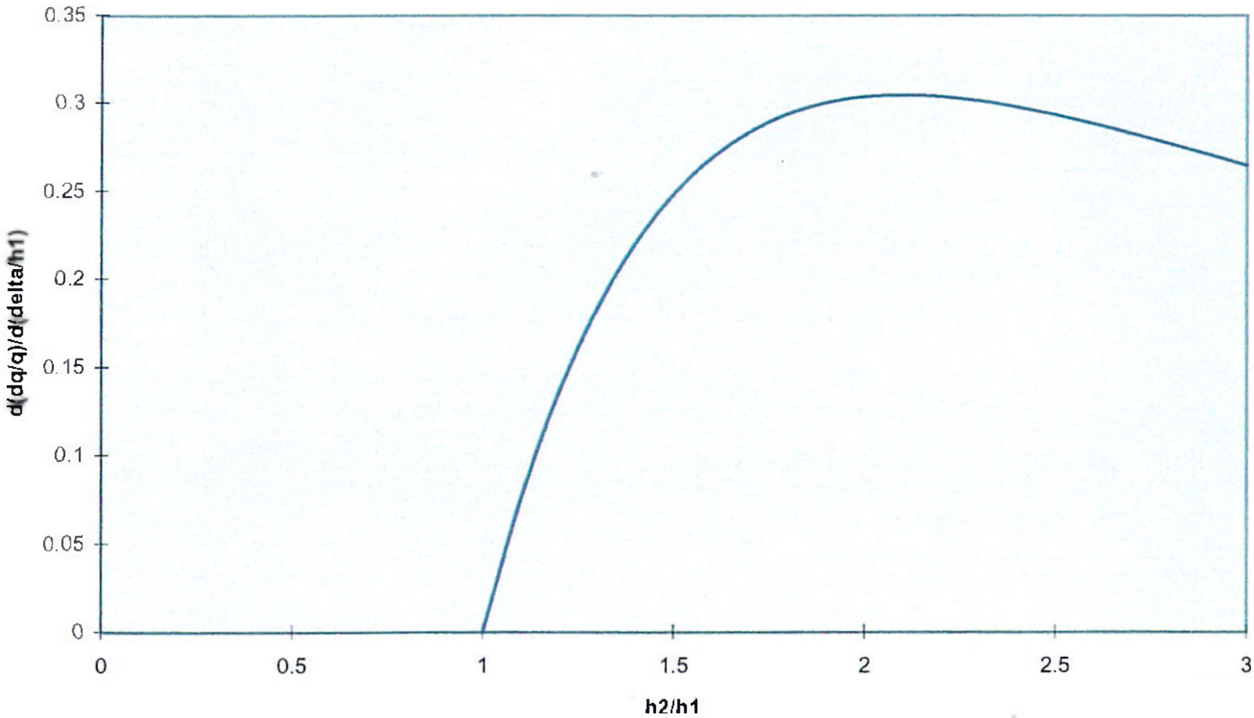

Residual flow circulating in a flood- and ebb channel system and the role of the channel depth.	Z2864
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WL | DELFT HYDRAULICS	Fig.3.10

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Rotterdamseweg 185
postbus 177
2600 MH Delft
telefoon 015 285 85 85
telefax 015 285 85 82
e-mail info@wldelft.nl
internet www.wldelft.nl

Rotterdamseweg 185
p.o. box 177
2600 MH Delft
The Netherlands
telephone +31 15 285 85 85
telefax +31 15 285 85 82
e-mail info@wldelft.nl
internet www.wldelft.nl