PERGAMON

Available online at www.sciencedirect.com

SCIENCE DIRECT

Continental Shelf Research 22 (2002) 2599–2609

CONTINENTAL SHELF RESEARCH

www.elsevier.com/locate/csr

Morphology and asymmetry of the vertical tide in the Westerschelde estuary

Z.B. Wang[a,b,*], M.C.J.L. Jeuken[a], H. Gerritsen[a], H.J. de Vriend[a,b], B.A. Kornman[c]

[a] *WL/Delft Hydraulics, Partner in Delft Cluster, P.O. Box 177, 2600 MH Delft, The Netherlands*
[b] *Delft University of Technology, Faculty of Civil Engineering and Geosciences, Partner in Delft Cluster, Delft, The Netherlands*
[c] *National Institute for Coastal and Marine Man., P.O. Box 8039, 4330 EA Middelburg, The Netherlands*

Received 16 February 2001; accepted 9 August 2002

Abstract

Observations on the changes of the large-scale morphology and tidal asymmetry in the Westerschelde estuary were used to evaluate the applicability of existing relationships between estuarine morphology and the asymmetry of the vertical tide. The results of the analyses show that shallow parts tend to be more flood-dominant than deeper areas. This tendency agrees with the findings of earlier studies of tidal asymmetry (e.g. Coastal Shelf Sci., 27 (1988) 521). Historical changes and spatial variations of the asymmetry of the vertical tide can be explained by the variation of the ratio of tidal amplitude to mean channel depth. The results can be used to assess the impact of, for instance, a channel deepening on the asymmetry of the vertical tide.
© 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Estuaries; Tidal asymmetry; Shallow water tides; Geomorphology; Hypsometric curves; The Netherlands; Westerschelde estuary

1. Introduction

The Westerschelde (see Fig. 1) is the seaward, marine part of the tide-dominated Schelde estuary. It is located in the SW part of the Netherlands. Land reclamation, damming, dredging and other kinds of human interference influenced the natural evolution of the estuary during the last centuries. At present, some $10 \times 10^6\,m^3$ of sediments are annually dredged to maintain the shipping lane to the harbours of Antwerpen, Gent and Vlissingen. Besides this channel maintenance, two additional dredging programs have been carried out in the periods 1971–1974 and 1997–1998. During the last program the minimal water depth at the bars in the main ebb channels was increased from 14.5 to 16.0 m below NAP (Dutch ordnance level ≈ mean sea level). A new deepening program has been proposed for the near future. The deepening, and thereby increasing maintenance, of the navigation channel will inevitably have an impact: (i) on the morphological evolution and associated large-scale processes of erosion and sedimentation;

*Corresponding author. WL/Delft Hydraulics, Partner in Delft Cluster, P.O. Box 177, 2600 MH Delft, The Netherlands. Tel.: +31-15-2858585; fax: +31-15-28558710.
E-mail address: zheng.wang@wldelft.nl (Z.B. Wang).

0278-4343/02/$ - see front matter © 2002 Elsevier Science Ltd. All rights reserved.
PII: S 0 2 7 8 - 4 3 4 3 (0 2) 0 0 1 3 4 - 6

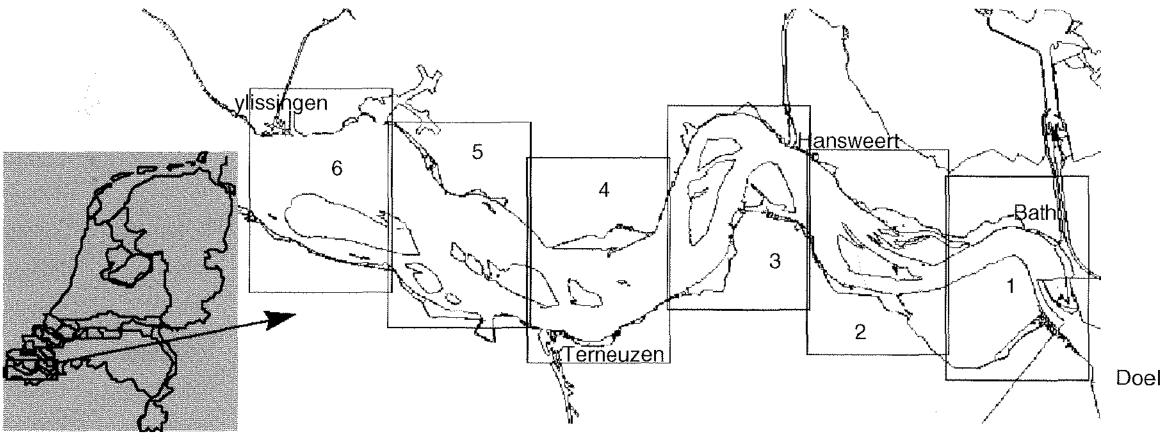

Fig. 1. The Westerschelde and the six echo-sounding sections.

(ii) on the tidal wave propagation; and (iii) on the ecological system in the estuary. A minimisation of possible negative effects requires an understanding of this impact

The asymmetry of the tide is one of the controlling factors for the residual sediment transport and hence the morphological development in estuaries and tidal basins (e.g. Aubrey, 1986; Dronkers, 1986). In the Westerschelde, where the tidal flow is the major driving force for the morphological development, it may even control the sediment exchange between the ebb tidal delta and the estuary, as well as between the various parts of the estuary.

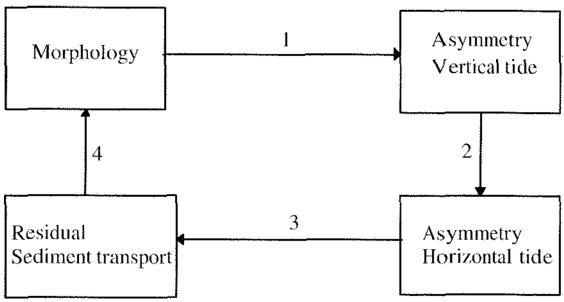

Fig. 2. Schematic representation of the interaction between morphology and tidal asymmetry.

The interaction between the morphology and the tidal asymmetry is schematically depicted in Fig. 2. In the past, different aspects of this interaction were investigated for short tidal basins in particular. For instance, Boon and Byrne (1981), Speer and Aubrey (1985), Friedrichs and Aubrey (1988, 1994), Dronkers (1986, 1998), Speer et al. (1991), Friedrichs et al. (1992), Van der Spek (1997) and Lanzoni and Seminara (1998) consider the influence of basin morphology on the asymmetry of the vertical and horizontal tide. They show that the mean depth of the tidal basin and the relative volume and height of inter-tidal shoals are the principal morphologic parameters affecting the tidal asymmetry: shallow systems with large inter-tidal basin storage tend to be flood-dominant and enhance landward near-bed transport, whereas deep tidal basins with little inter-tidal basin storage tend to be ebb-dominant. The vertical tide is flood-dominant if the rising-tide time is shorter than the falling-tide time, and ebb-dominant if the opposite is true. Considerable attention has been paid to the effect of tidal current asymmetry on the residual transport (3 in Fig. 2) of fine grain (e.g. Postma, 1967; Groen, 1967; Dronkers, 1985, 1986; Ridderinkhof, 1997; Schuttelaars and De Swart, 2000) and coarse grain sediments (e.g. Aubrey, 1986; Dronkers, 1986; Friedrichs and Aubrey, 1988; Van de Kreeke and Robaczewska, 1993; Van de Kreeke and Dunsbergen, 2000). In some of these studies, the relationship between tidal asymmetry and morphology is addressed in terms of inferred large-scale net sediment transport directions and the observed tendencies of sediment import or export (e.g. Dronkers, 1986; Van de Kreeke and Dunsbergen, 2000).

This paper addresses the influence of the morphology on the asymmetry of the vertical tide in the Westerschelde estuary (1 in Fig. 2) on the basis of field observations of the large-scale morphological development and the changes of the tidal asymmetry during the last 3–4 decades. It aims to evaluate the applicability of the existing relationship between tidal asymmetry and estuarine morphology on the basis of these observations. This study differs from previous ones in two ways. Firstly, the Westerschelde is a long estuary, or tidal basin, where the tidal wave propagation is influenced by both friction and inertia. Secondly, field observations of both morphology and tidal asymmetry over a period of decades are analysed to address the influence of morphology on tidal asymmetry.

2. General characteristics of the estuary

2.1. Morphology

The Schelde estuary resembles the morphologic descriptions of Hayes (1975), Dalrymple et al. (1992) and Wells (1995) for tide-dominated estuaries with a meso- to macro-tidal regime. Morphogenetically, the estuary is a young coastal plain estuary (Bokuniewicz, 1995) that was only formed some thousands years ago by sea flooding of the low relief river valley.

The present day estuary has a funnel-shaped geometry, where the estuarine width reduces from about 6 km near the mouth, via 2–3 km near Bath to less than 100 m near the estuary head. Its length from Vlissingen up to the sluices in Gent is about 160 km. Its cross-sectional area decreases exponentially from the mouth to the estuary head. The width-averaged depth decreases from some 15 m at Vlissingen to only 3 m near Gent.

The Westerschelde is the seaward, marine part of the estuary. This part of the estuary exhibits a well-developed system of channels and shoals. The larger main channels in the estuary display a repetitive pattern, referred to as estuarine sections (Jeuken, 2000). Each of these consists of a meandering ebb channel and a straight flood channel. In most sections these channels are separated by inter-tidal shoals and linked by smaller connecting channels. In the Westerschelde six estuarine sections can be identified. Channel evolution in the three sections near the head of the Westerschelde, i.e. the area between Hansweert and Doel (Fig. 1), is strongly influenced by dredging and dumping activities. Until 1997 natural processes dominated the evolution of the channel and shoal system in the seaward reach of the Westerschelde, between Vlissingen and Hansweert, though dredging and dumping occur also in this area. Van den Berg et al. (1996) and Jeuken (2000) give overviews of the long-term morphologic channel behaviour within the estuarine sections. The Westerschelde, having a length of about 60 km, is the study area of this paper.

2.2. Hydrodynamics

The water motion in the estuary is forced by a semi-diurnal tide. The mean river outflow is about 120 m^3/s or $5 \times 10^6\,m^3$ of water per semi-diurnal tide. This is less than 1% of the tidal prism of about $2 \times 10^9\,m^3$. Water level observations along the estuary show an increase in mean tidal range between Vlissingen and Antwerpen (78 km further upstream) from 3.8 to 5.2 m. This amplification of the tide is due to convergence, shoaling and partial reflections (Jeuken, 2000). Landward of Antwerpen, the tidal range decreases. The duration of falling tide exceeds that of rising tide, and this flood-dominant asymmetry of the vertical tide increases in the landward direction (see e.g. Jeuken, 2000). At Vlissingen the duration difference between falling and rising tide amounts to about half an hour. Near Antwerpen it approximates 2 h and further increases to almost 4 h near the tidal limit at Gent.

The phase difference between the vertical and horizontal tide is about 2.5 h. The maximum depth-averaged current velocities in the channels are typically in the order of 1–1.5 m/s. These velocities, in combination with medium to fine sands (200 μm on average), induce a sediment transport that is dominated by suspended load.

3. Available data and analyses

3.1. Morphology

De Jong (2000) describes changes in the net sediment budget over the period 1955–1999 for six areas in the Westerschelde (Fig. 1). The distributions of the water volume as a function of depth, i.e. the hypsometric curves, for each of the six echo-sounding sections in 1955 and 1996 are given by Mol et al. (1997).

These hypsometric curves were analysed by means of curve fitting. It appears that the water volume below a vertical reference level z can be described by

$$V = C(d+z)^{\alpha}, \tag{1}$$

where V is the water volume (in $10^6\,\mathrm{m}^3$) below reference level z (in m relative to NAP), C is a coefficient, d is the maximum depth below the reference level (NAP) and α is a dimensionless coefficient. This equation can also be written as

$$V = Cd^{\alpha}\left(1+\frac{z}{d}\right)^{\alpha}. \tag{2}$$

The coefficients Cd^{α} and α for the six echo-sounding areas are given in Table 1. The coefficient Cd^{α} is the water volume at the reference level (Dutch ordnance level NAP). The fit appears to be very good (Fig. 3). The uniformity of the curves for the various parts is intriguing. It might be explained by the regular and repetitive pattern of channels and shoals, i.e. the occurrence of the estuarine sections (see Section 2.1). From Eq. (1) it follows that the water surface area F at a certain level is

$$F = \frac{\partial V}{\partial z} = \alpha C(d+z)^{\alpha-1}. \tag{3}$$

Eqs. (1) and (3) can be used to derive the dimensionless parameters a/h and V_s/V_c as defined by e.g. Friedrichs and Aubrey (1988). For the water volume on the inter-tidal shoals V_s we have

$$V_s = V(a) - V(-a) - 2F(-a)a, \tag{4}$$

Table 1
Parameters characterising the hypsometry of the channel and shoal system. For locations of sections see Fig. 1

Section	1955			1996		
	d (m)	α (1)	Cd^{α} (m^3)	d (m)	α (1)	Cd^{α} (m^3)
1	20	2.70	131.9	20	1.94	182.5
2	20	2.57	254.8	20	2.16	270.0
3	30	2.47	503.0	30	2.67	472.8
4	40	3.59	441.3	40	3.59	441.3
5	50	3.99	670.7	50	4.42	691.3
6	40	3.43	631.2	40	3.43	631.2

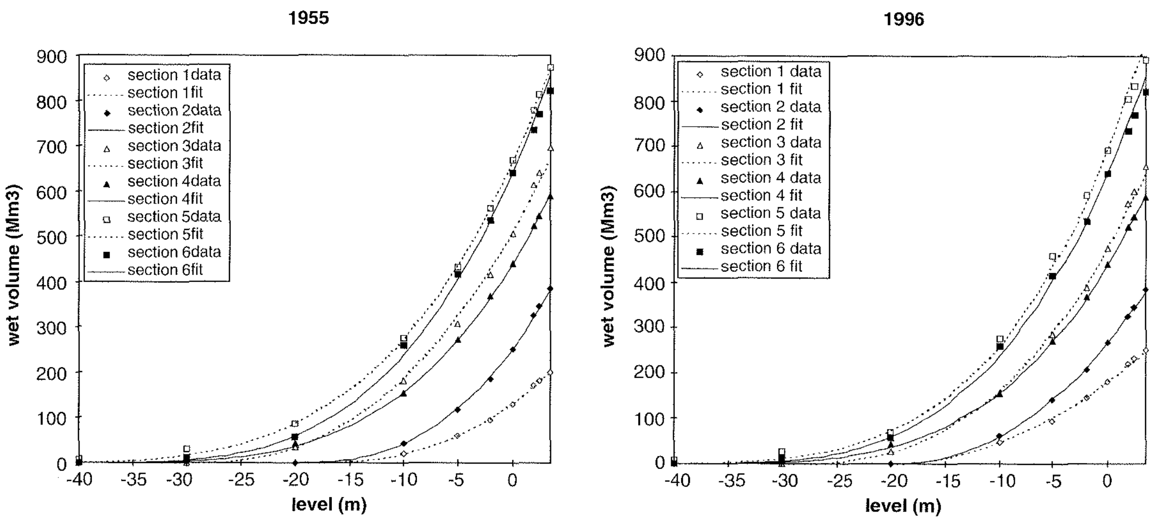

Fig. 3. Hypsometric curves for all the echo-soundings sections 2 and 3 in 1955 and 1996. For locations see Fig. 1.

where a is the amplitude of the dominant semi-diurnal M_2 tide. The channel volume below mean sea level V_c is defined as

$$V_c = V(-a) + aF(-a). \tag{5}$$

The mean channel depth h follows from

$$h = \frac{V_c}{F(-a)} = \frac{V(-a)}{F(-a)} + a. \tag{6}$$

Substitution of Eq. (1) for V and Eq. (3) for F yields the two parameters a/h and V_s/V_c:

$$\frac{a}{h} = \frac{\alpha a/d}{1 + (\alpha - 1)(a/d)}, \tag{7}$$

$$\frac{V_s}{V_c} = \frac{(1 + a/d)^{\alpha}}{(1 - a/d)^{\alpha} + (a/d)(1 - a/d)^{\alpha - 1}} - 1 - \frac{\alpha a/d}{1 + (\alpha - 1)(a/d)}. \tag{8}$$

The spatial and temporal variations of these morphologic parameters were determined to assess the influence of large-scale morphologic changes on the asymmetry of the vertical tide.

3.2. Vertical tide

Along the Westerschelde, water levels are being measured since 1885. For the four water level stations, Vlissingen, Terneuzen, Hansweert and Bath (Fig. 1), time series with a sampling interval of 1 h (until 1987) and 10 min (since 1987) are available from 1971 onwards. For the stations Vlissingen, Terneuzen and Hansweert, water level observations with a sampling interval of 3 h are available over the period 1955–1970. The observations over the period 1971–1996 were analysed by the Ministry of Transport, Public Works and Water Management, when 94 harmonic components were determined for each year of measurements. An additional harmonic analysis was carried out for the water level observations at Vlissingen, Terneuzen and Hansweert for the year 1955, using 53 components.

The results of the harmonic analyses over the period 1971–1997 were used to quantify the annual changes of the asymmetry of the vertical tide. Usually, the asymmetry of the vertical tide refers to the distortion of the predominant semi-diurnal tide as a result of overtides. A direct measure of non-linear distortion is the M_4 to M_2 amplitude ratio (a_4/a_2). The nature of the asymmetry can be defined as the phase of M_4 relative to M_2 ($2\varphi_2 - \varphi_4$). A relative phase between 0° and 180° indicates that the duration of water level fall exceeds water level rise, i.e. the tide is flood-dominant, and otherwise it is ebb-dominant. The amplitudes and phases of M_2 and M_4 at the four stations are given in Table 2.

The tidal asymmetry inside the estuary is influenced by the asymmetry of the tide at the seaward boundary of the estuarine system (e.g. Dronkers, 1986, 1998; van der Spek, 1997). Similarly, it is likely that the asymmetry of the vertical tide at a certain station is influenced by the asymmetry of the tide in a section downstream. Based on this assumption the following hypothesis is put forward: the spatial change of the tidal asymmetry in a certain part of the estuary, rather

Table 2
Amplitude (m) and phases (°) of M_2 and M4 at the four stations

Year	Vlissingen				Terneuzen				Hansweert				Bath			
	M_2		M_4		M_2		M_4		M_2		M_4		M_2		M_4	
	a	φ	a	φ	a	φ	a	φ	a	φ	a	φ	a	φ	a	φ
1971	1.72	59	0.12	119	1.85	69	0.11	140	1.95	80	0.12	185	1.97	95	0.13	163
1976	1.72	60	0.13	119	1.85	70	0.11	137	1.95	82	0.12	177	2.02	95	0.12	163
1981	1.73	60	0.13	120	1.86	69	0.12	135	1.99	79	0.12	167	2.10	94	0.12	172
1986	1.73	58	0.13	116	1.86	68	0.12	133	1.95	79	0.12	163	2.08	92	0.12	165
1991	1.75	59	0.13	121	1.88	69	0.12	135	1.98	80	0.12	167	2.10	93	0.12	174
1996	1.75	60	0.13	120	1.88	69	0.12	134	1.98	81	0.11	167	2.09	94	0.12	173

than the tidal asymmetry at a specific location, should be related to the morphologic characteristics of the considered area. The spatial change of the tidal asymmetry between two stations is represented by the ratio of the amplitude ratios and the difference between the relative phase differences, respectively:

$$A = \frac{(a_4/a_2)_{station\ 2}}{(a_4/a_2)_{station\ 1}}, \tag{10}$$

$$P = (2\varphi_2 - \varphi_4)_{station\ 2} - (2\varphi_2 - \varphi_4)_{station\ 1}. \tag{11}$$

The temporal variations of the parameters A and P and their relationship with the large-scale morphologic changes are addressed in the following sections.

4. Results

4.1. Large-scale morphologic changes

The cumulative net sediment budget changes in three parts of the estuary point to some large-scale morphologic changes over the period 1955–1996 (Fig. 4). The western, seaward part of the Westerschelde experienced a net erosion of some $20 \times 10^6\,m^3$, whereas in the central part about $30 \times 10^6\,m^3$ volume of sediment was deposited. In this latter area, the main ebb channel was cut off by the main flood channel. This natural process was associated with a substantial sedimentation of the main ebb channel that exceeded the erosion of the main flood channel (see e.g. Jeuken, 2000). Relatively large morphologic alterations occurred in the period 1955–1996. The eastern part of the

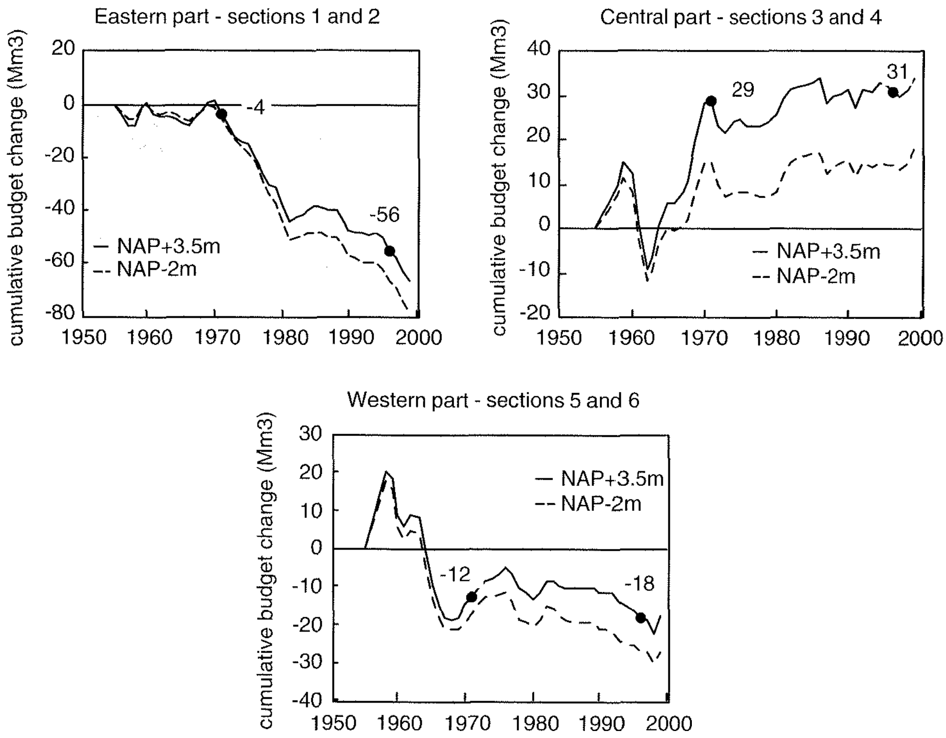

Fig. 4. Evolution of the sediment budgets in the eastern (sections 1 and 2), central (sections 3 and 4) and western (sections 5 and 6) parts of the estuary below NAP + 3.5 m and NAP−2 m (approximately LW). Labels indicate the cumulative sediment budget changes (in Mm^3) since 1955 in 1971 and 1996. A negative value indicates an erosion with respect to 1955, whereas a positive value points at sedimentation. For section location see Fig. 1.

estuary eroded with almost $60 \times 10^6\,m^3$, mainly as a result of the large-scale channel deepening and the maintenance dredging and dumping since 1971. In this area the man-made local deepening of the bars in the main ebb channel was followed by an erosion of the adjacent channel sections.

4.2. Development of the asymmetry of the vertical tide

The tidal asymmetry in the Westerschelde changed over the last decades (see Fig. 5, Table 3). Near the mouth of the estuary, at Vlissingen, the small asymmetry of the vertical tide hardly changed: the phase difference $2\varphi_2 - \varphi_4$ fluctuates with a few degrees around zero. The same applies to the slightly flood-dominant tide at Terneuzen. The largest alterations of the tidal asymmetry are observed at Hansweert and Bath. Over the entire period 1955–1996, the asymmetry of the vertical tide slightly decreased (Fig. 5, Table 3). The phase difference $2\varphi_2 - \varphi_4$ at Hansweert is negative. Its magnitude decreases between 1955 and 1982 indicating a small decrease of the slightly ebb-dominant asymmetry of the vertical tide at Hansweert. Since 1982 the phase difference at this station varied around -6° (Fig. 5). At Bath the flood-dominant asymmetry reduced between 1971 and 1987. Since then it has hardly changed. The temporal variation of P displays similar but smoother changes (Fig. 5). The intensity of the

Table 3
Relative phase difference $2\varphi_2 - \varphi_4$ of the vertical tide at Vlissingen, Terneuzen Hansweert and Bath in 1955 and 1996

	Vlissingen	Terneuzen	Hansweert	Bath
1955	1	3	−10	unknown
1996	−0.8	4.1	−5.7	11.6

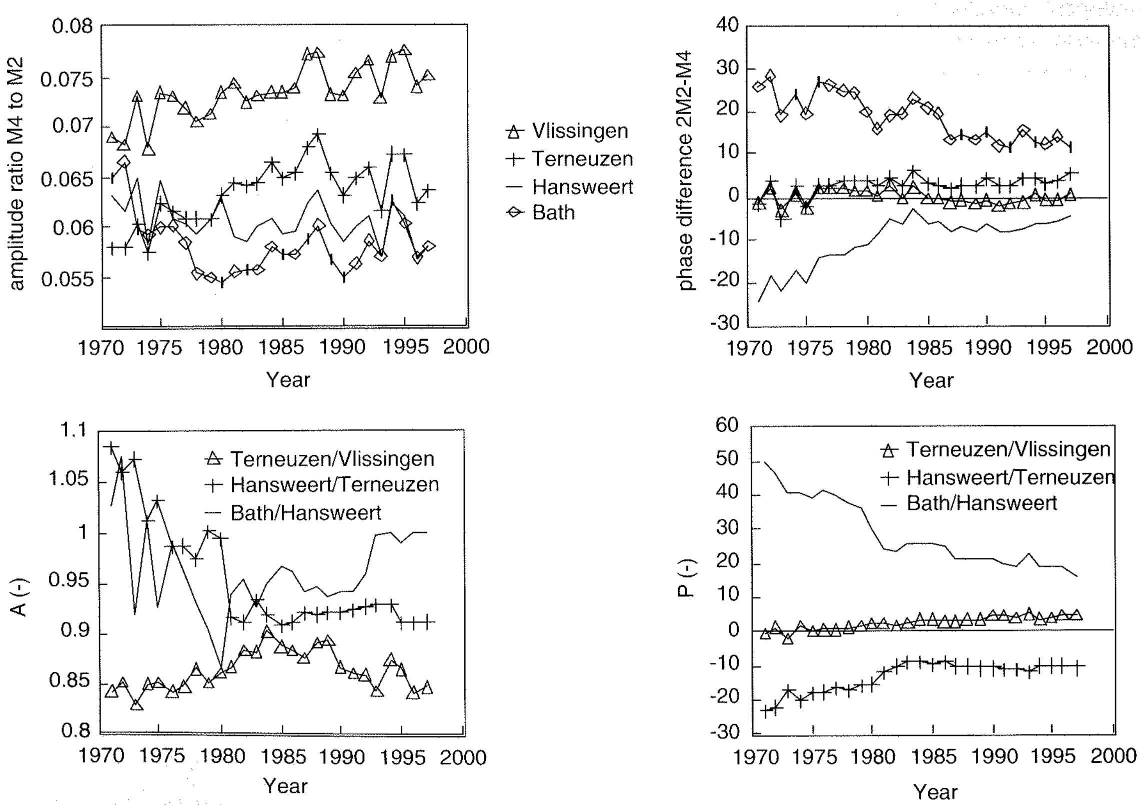

Fig. 5. Changes of the asymmetry of the vertical tide over the period 1971–1996.

degree of asymmetry, a_4/a_2, at the four stations roughly varies between 0.05 and 0.08. It is larger near the mouth and smaller near the head of the estuary. This spatial variation is due to the increase of the M_2 tide towards the head of the Westerschelde, which is not followed by the M_4. At Vlissingen and Terneuzen a_4/a_2 slightly increased between 1971 and 1988. This finds expression in the temporal changes of the parameter A (Fig. 5).

4.3. Relationship between morphology and tidal asymmetry

The previously described sediment budget changes and alterations of the asymmetry of the vertical tide point at a clear correlation in two different ways. Firstly, the largest morphologic changes in the eastern part of the estuary are accompanied by the largest alterations in the asymmetry of the vertical tide. In the eastern part the depth increased and the flood-dominant asymmetry reduced, whereas in the central part the mean water depth decreased and the slightly ebb-dominant asymmetry of the vertical tide reduced. These opposite evolutions in the two areas qualitatively confirm Friedrichs and Aubrey's (1988) findings (see also Speer et al., 1991): deep tidal basins tend be more ebb-dominant than shallow systems. It is noted that the study of Friedrichs and Aubrey concerns short basins. Apparently a basic mechanism of the change/generation of tidal asymmetry in an estuary applies for short as well as for long basins. This mechanism is the deformation of the tidal wave during its propagation. The deformation occurs when the top (HW) and the trough (LW) of the wave do not have the same propagation speed. Faster HW causes flood dominance and faster LW generates ebb dominance. Further, the analysis will be made from section to section, taking into account that the tide at the downstream end of the section is not symmetric. Each of these sections can be considered as short (relative to the length of tidal wave).

Fig. 6 compares the morphologic parameters V_s/V_c and a/h in the area between two adjacent water level stations for the situations 1955 and 1996 with the tidal asymmetry P in 1955 (1971 for sections 1 and 2) and 1996 as shown in Fig. 5 and Table 3. The comparison of the asymmetry in 1971 and the morphology in 1955 for sections 1 and 2 is not ideal but information of the tidal asymmetry at Bath in 1955 is not available. However, in the eastern part, net sediment budget changes, in the channel (below NAP−2 m) as well as on the intertidal flats (between NAP−2 m and NAP+3.5 m), in the period 1955–1971, were small when compared to the period 1971–1996 (Fig. 4). This indicates that for this area it is possible to relate

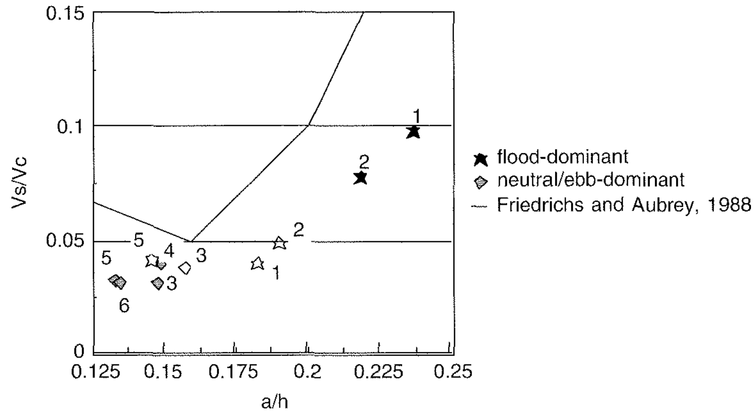

Fig. 6. Relationship between the morphologic parameters a/h and V_s/V_c and the tidal asymmetry. Solid markers—1955; open markers—1996; labels—section numbers in Fig. 1.

the overall morphology of 1955 to the asymmetry in 1971. Fig. 6 shows that the most flood-dominant eastern part of the estuary exhibits relatively large values of a/h, whereas smaller values of this parameter in the central and western part of the estuary tend to be associated with a neutral to small ebb-dominant asymmetry of the vertical tide. The thin lines in Fig. 6 represents Friedrichs and Aubrey's (1988) separation between ebb and flood dominance. For the Westerschelde, this line does not clearly separate the areas with a flood-dominant asymmetry from the ones with a neutral to ebb-dominant asymmetry. The existing theory thus applies qualitatively but not quantitatively to the Westerschelde. This is not surprising because the Westerschelde is a long estuary where the tidal water motion is determined by both friction and inertia, whereas Friedrichs and Aubrey (1988) considered short, friction-dominated tidal basins.

The upper panels in Fig. 7 quantify the changes of the parameters V_s/V_c and a/h for the six echo-sounding sections over the period 1955–1996. It reveals large morphologic changes in the eastern part of the estuary (sections 1 and 2), whereas the smallest differences are observed in echo-sounding section 4. The bottom panels show the spatially averaged temporal changes of P as a function of the changes of the parameters V_s/V_c and a/h in the eastern (sections 1 and 2), the central (sections 3 and 4) and the western part (sections 5 and 6) of the estuary (Fig. 7). The change of the tidal asymmetry in the three areas correlates well with the morphologic parameters. The correlation with a/h agrees well with the theory in literature: an increase of the parameter corresponds with more flood-dominance. Also an increase of V_s/V_c corresponds with more flood-dominance, which seems to be contradictory to the theory. This is probably due to the fact that the two parameters V_s/V_c and a/h are dependent, at least for the Westerschelde estuary with its specific hypsometry. For instance, an increase of the tidal amplitude causes an increase of both V_s/V_c and a/h. Furthermore, the value of V_s/V_c is small in the Westerschelde, for all parts and during the whole period under consideration. Apparently, for this particular estuary, a/h is the most suitable parameter to indicate asymmetry of the vertical tide.

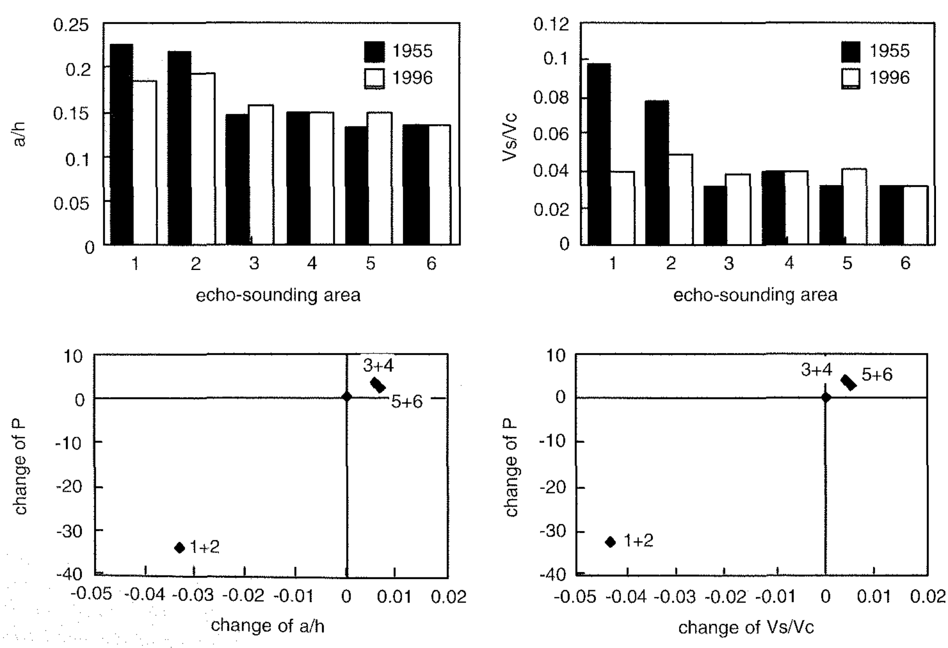

Fig. 7. Relationship between the temporal changes of the morphologic parameters a/h and V_s/V_c and the tidal asymmetry P.

5. Discussion and conclusions

The present study aimed to investigate and evaluate the existing relationship between morphology and the asymmetry of the vertical tide for the Westerschelde estuary on the basis of long-term field observations. Previous studies (Dronkers, 1986; Friedrichs and Aubrey, 1988; Speer et al. 1991; Friedrichs et al., 1992) show that shallow systems tend to be flood-dominant, whereas deep tidal basins tend to be ebb-dominant. The observed temporal and spatial variations in the morphology and the tidal asymmetry in the Westerschelde qualitatively confirm this relationship. Changes in the asymmetry of the vertical tide over a period of decades could be correlated to changes in the ratio of tidal amplitude to mean channel depth, a/h. Especially, for the area near the head of the Westerschelde, this relationship is clearly present. The substantial dredging activities in this area since 1971 are associated with a deepening of the channel system and a reduction of the flood-dominant asymmetry of the vertical tide. This finding can be used to assess the impact of future human activities on the asymmetry of the vertical tide.

A basic mechanism for generating tidal asymmetry is the deformation of the tidal wave during its propagation. The deformation occurs when the top (HW) and the trough (LW) of the wave do not have the same propagation speed. Faster HW causes flood dominance and faster LW generates ebb dominance. This mechanism applies for short as well as for long basins. This is probably the reason why the existing theory for short basins qualitatively applies to the relatively long Westerschelde estuary. It is also found that existing theory do not apply quantitatively.

The observations for the Westerschelde indicate that the two morphologic parameters V_s/V_c and a/h are mutually dependent. This can be a disadvantage when studying the relationship between morphology and tidal asymmetry. A possible set of independent parameters containing the same information is, for instance, the ratio a/h and the ratio of horizontal area of the inter-tidal shoals to total surface area, F_f/F. The analyses of Li and O'Donnell (1997) on tidal rectification suggest that three additional parameters may be used to quantify the relationship between morphology and tidal asymmetry, viz.: (a) the ratio between the length of the estuary and the wave length of the tide, (b) the ratio of a length-scale of the morphological variation along the estuary (e.g. the change of width) to the wave length of tide, and (c) the ratio of the tidal period to the decay time induced by friction. For future research, it is recommended to evaluate the influence of these parameters on the tidal asymmetry.

Finally, the results presented in this study only considered the asymmetry of the dominant vertical tide M_2 related to the generation of the overtide M_4. In the Westerschelde estuary, the sixth-diurnal tide M_6 also affects the asymmetry of the tide. However, theories that relate tidal asymmetry caused by the sixth-diurnal tide to estuarine morphology are still lacking. Therefore, for future research, investigation of the tidal asymmetry caused by this group of constituents and its relationship with the estuarine morphology is recommended.

References

Aubrey, D.G., 1986. Hydrodynamic controls on sediment transport in well-mixed bays and estuaries. In: van de Kreeke, J. (Ed.), Physics of Shallow Estuaries and Bays. Springer, Berlin, pp. 245–258.

Bokuniewicz, K., 1995. Sedimentary systems of coastal-plain estuaries. In: Perillo, G.M.E. (Ed.), Geomorphology and Sedimentology of Estuaries, Developments in Sedimentology, Vol. 53. Amsterdam, Elsevier, pp. 49–64.

Boon, J.D., Byrne, R.J., 1981. On basin hypsometry and the morphodynamic response of coastal inlet systems. Marine Geology, 27–48.

Dalrymple, R.W., Zaitlin, B.A., Boyd, R., 1992. Estuarine facies models: conceptual basis and stratigraphic implications. Journal of Sedimentary Petrology, 1130–1146.

De Jong, J.E.A., 2000. Zandbalans Westerschelde en monding, periode 1955–1999. Rijkswaterstaat, Directie Zeeland, Middelburg, Report NWL-00.16.

Dronkers, J., 1985. Tide-induced residual transport of fine sediment. In: van de Kreeke, J. (Ed.), Physics of Shallow Estuaries and Bays. Lecture Notes on Coastal and Estuarine Studies, Vol. 16. Springer, New York, pp. 228–244.

Dronkers, J., 1986. Tidal asymmetry and estuarine morphology. Netherlands Journal of Sea Research 20, 117–131.

Dronkers, J., 1998. Morphodynamics of the Dutch delta. In: Dronkers, J., Scheffers, M. (Eds.), Physics of estuaries and coastal seas. Rotterdam, Balkema, pp. 297–304.

Friedrichs, C.T., Aubrey, D.G., 1988. Non-linear tidal distortion in shallow well-mixed estuaries: a synthesis, estuarine. Coastal and Shelf Science 27, 521–545.

Friedrichs, C.T., Aubrey, D.G., 1994. Tidal propagation in strongly convergent channels. Journal of Geophysical Research 99 (C2), 3321–3336.

Friedrichs, C.T., Lynch, D.R., Aubrey, D.G., 1992. Velocity asymmetries in frictionally dominated tidal embayments: longitudinal and lateral variability. In: Prandle, D. (Ed.), Dynamics and Exchanges in Estuaries and the Coastal Zone. AGU, Washington, DC, pp. 277–312.

Groen, P., 1967. On the residual transport of suspended matter by an alternating tidal current. Netherlands Journal of Sea Research 3–4, 564–574.

Hayes, M., 1975. Morphology of sand accumulation in estuaries: an introduction to the symposium. In: Cronin, L.E. (Ed.), Estuarine Research, Geology and Engineering. Academic Press, New York, 2, pp. 3–12.

Jeuken, M.C.J.L., 2000. On the morphological behaviour of tidal channels in the Westerschelde estuary. Ph.D. Thesis, Utrecht University.

Lanzoni, S., Seminara, G., 1998. On tide propagation in convergent estuaries. Journal of Geophysical Research C 103, 30793–30812.

Li, C., O'Donnell, J., 1997. Tidally driven residual circulation in shallow estuaries with lateral depth variation. Journal of Geophysical Research 102 (C13), 27915–27929.

Mol, G., Van Berchum, A.M., Krijger, G.M., 1997. The state of the Western Scheldt at the beginning of the deepening 48′/43′, Rijkswaterstaat Report RIKZ-97-049 (in Dutch)

Postma, H., 1967. Sediment transport and sedimentation in the estuarine environment. American Association of Advanced Science Publications, 158–179.

Ridderinkhof, H., 1997. The effect of tidal asymmetries on the net transport of sediments in the Ems Dollard estuary. Journal of Coastal Research, 41–48.

Schuttelaars, H.M., De Swart, H.E., 2000. Multiple morphodinamic equilibria in tidal embayments. Journal of Geophysical Research C 105, 24105–24118.

Speer, P.E., Aubrey, D.G., 1985. A study of non-linear tidal propagation in shallow inlet/estuarine systems, Part II: theory, estuarine. Coastal and Shelf Science 21, 207–224.

Speer, P.E., Aubrey, D.G., Friedrichs, C.T., 1991. Nonlinear hydrodynamics of shallow tidal inlet/bay systems. In: Parker, B.B. (Ed.), Tidal Hydrodynamics. Wiley, New York.

Van den Berg, J.H., Jeuken, M.C.J.L., Van der Spek, A.F.J., 1996. Hydraulic processes affecting the morphology and evolution of the Westerschelde estuary. In: Nordstrom, K.F., Roman, C.T. (Eds.), Estuarine shores: Evolution, Environments and Human Alterations. Wiley, London, pp. 157–184.

Van de Kreeke, J., Dunsbergen, D.W., 2000. Tidal asymmetry and sediment transport in Frisian Inlet. In: Yanagi, T. (Ed.), Interactions Between Estuaries, Coastal Seas and Shelf Seas. Terra Scientific Publishing Company, Tokyo, 2000.

Van de Kreeke, J., Robaczewska, K.B., 1993. Tide induced residual transport of coarse sediment; application to the Ems estuary. Netha J. of Sea Res. 31 (3), 209–220.

Van der Spek, A.J.F., 1997. Tidal asymmetry and long-term evolution of Holocene tidal basins in the Netherlands: simulation of paleo-tides in the Schelde estuary. Marine Geology, 71–90.

Wells, J.T., 1995. Tide-dominated estuaries and tidal rivers. In: Perillo, G.M.E. (Ed.), Geomorphology and Sedimentology of Estuaries, Developments in Sedimentology, Vol. 53. Amsterdam, Elsevier, pp. 179–206.