

## MORPHOLOGICAL RESPONSE OF ESTUARIES TO NODAL TIDE VARIATION

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**Abstract:** Nodal tide variation causes a periodic change of the mean tidal range with a period of 18.6 years and amplitude of about 4%. As the cross-sectional area of the channels in estuaries is related to the tidal prism, such a variation of the tidal range can significantly influence the morphological development of tide-dominated estuaries. Field observations from the Westerschelde estuary in The Netherlands and the Humber estuary in England confirm that there is indeed an 18.6 year cycle in the evolution of the total water volume of the estuaries. Especially in the Humber estuary, with a relatively small morphological time scale, the response to the nodal tide variation appears to dominate the long-term large-scale sediment budget changes of the estuary. Even in the Westerschelde, with a much larger morphological time scale, the response of the estuary to the nodal tide variation can be clearly observed in the historical record of estuarine volume changes. The semi-empirical model ESTMORF can explain these observations. Numerical results from the models for the two estuaries reproduce the observed amplitude and phase lag (relative to the variation of the tidal amplitude) of the morphological response well. The amplitude of the morphological response strongly depends on the morphological time scale of the estuary. The phase lag hardly depends on this time-scale. This remarkable phenomenon is analytically explained using a simplified model based on the ESTMORF theory.

**Key words:** Westerschelde, Humber estuary, Sediment budget, Nodal tides, Modelling, Field observations

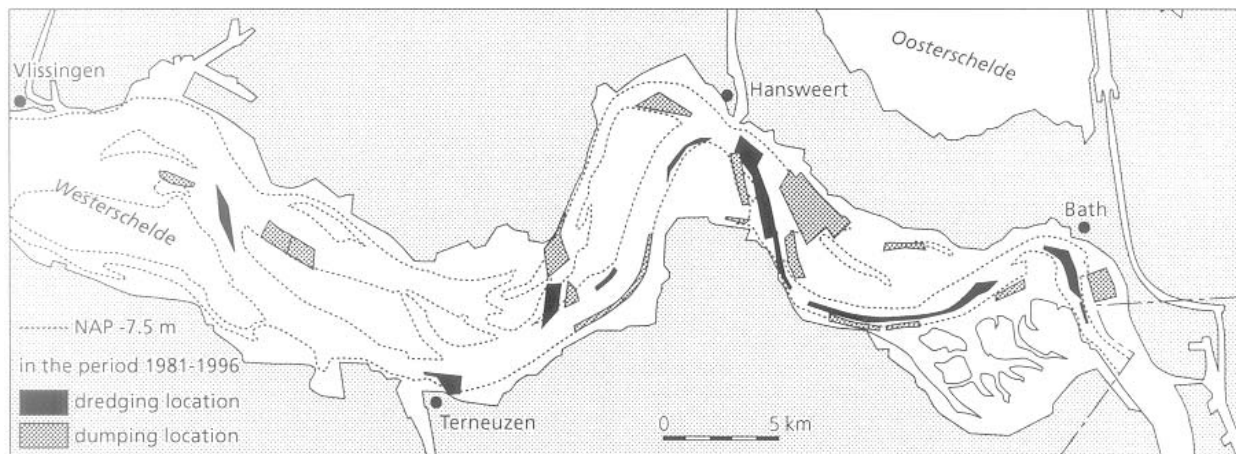
### 1. INTRODUCTION

Estuaries are common features along many coasts all over the world. They provide natural navigation channels and sheltered mooring places as well as habitats for marine flora and fauna. Long-term import or export of sediments, i.e. drowning or accretion of the estuary, may threaten these valuable properties. Therefore insight into the long-term evolution of the estuarine volume and the processes that influence this development is important for the management of these coastal systems. The 18.6 year nodal cycle is an external forcing that may influence the sedimentation in estuaries and tidal basins (see e.g. Oost et al., 1993). Nodal tide variation causes a periodic change of the mean tidal range with a period of 18.6 year and amplitude of about 4%. As a result the tidal prism in estuaries and tidal basins will increase and decrease with this variation in tidal range. The cross-sectional area of the channels in an estuary is related to the tidal volume. Therefore the nodal tide variation may significantly influence the morphological evolution of tide-dominated estuaries. Field

observations from the Westerschelde estuary in The Netherlands and the Humber estuary in England are used to study this potential influence of the 18.6 year nodal cycle. In addition, results of the semi-empirical model ESTMORF (Wang et al, 1998; Wang and Roelfzema, 2001) are considered to further investigate and explain the observed and simulated morphologic response.

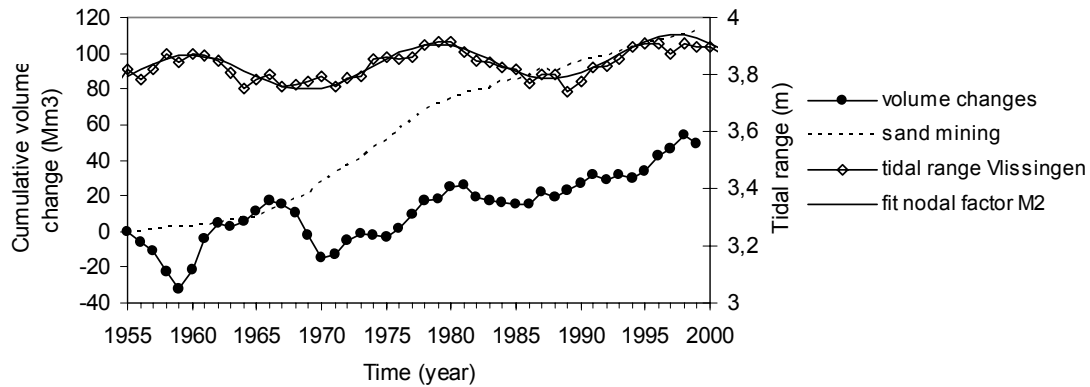
## 2. THE WESTERSCHELDE

The Westerschelde is the seaward, marine part of the Schelde estuary and is located in the South-western part of the Netherlands (Fig. 1). With a tidal range of nearly 4 m near the estuarine mouth (at Vlissingen, Fig. 1), a tidal prism of about  $1 \times 10^9 \text{ m}^3$  and a mean annual river discharge of some  $120 \text{ m}^3/\text{s}$ , the estuary can be characterised as tide-dominated with a meso-tidal regime. The estuarine morphology displays a regular system of large tidal channels that are separated by shoals and linked by some smaller-scale channels. For an overview of the hydrodynamic and morphologic evolution of the estuary at various temporal and spatial scales, see e.g. Van den Berg et al. (1996), Van der Spek (1997) and Jeuken (2000).



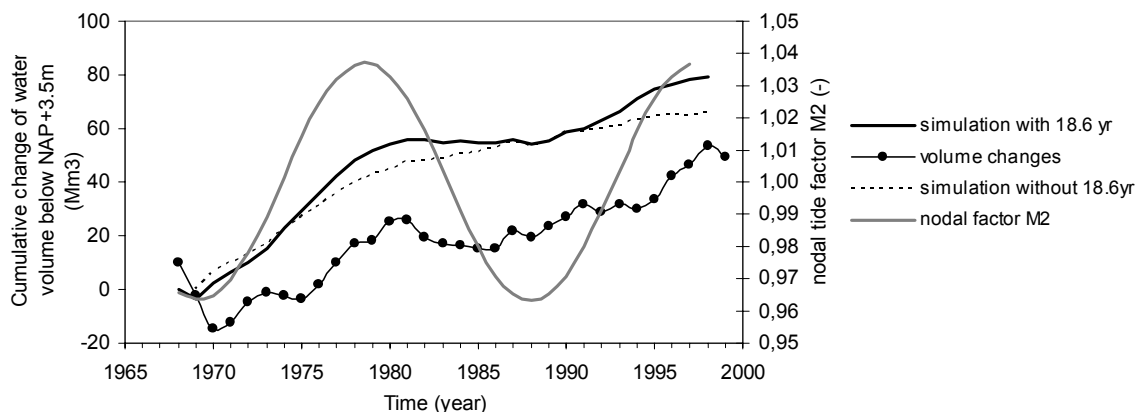
**Fig. 1** The Westerschelde area with its system of channels and shoals (modified from Jeuken, 2000)

Available bathymetric maps of the Westerschelde over the period 1955-1999, with approximately a two year interval, were used to determine the changes of the total water volume below  $\text{NAP}+3.5 \text{ m}$  (NAP is the Dutch ordnance level and approximates mean sea level). The computed volumes were interpolated to annual values. The obtained time-series of volume changes include the net effect of human interference which primarily consists of sand mining. The sediment that is dredged to maintain the shipping lane to the harbors of Vlissingen and Antwerp, some  $10 \text{ M m}^3/\text{yr}$  in the Westerschelde since the early seventies is disposed at different locations within the estuary. Fig. 2 displays the observed change of the water volume relative to 1955 together with the measured tidal range near the mouth of the estuary and the cumulative volume of sand that is mined since 1955. It shows a steady increase of the total water volume in time of  $1.7 \text{ M m}^3/\text{year}$  on average. Superimposed on this long-term trend the estuarine volume displays a cyclic variation with a period of some 18 years and amplitude of about  $7 \text{ M m}^3$ . This cyclic variation in the estuarine water volume lags behind the nodal variation in the vertical tide with about 2 years. The water volume increases with increasing tidal range and vice versa.



**Fig. 2** Observed volume changes and cumulative sand mining in the Westerschelde since 1955. The mean annual tidal range at Vlissingen (see Fig. 1) displays a clear nodal tide variation

The calibrated ESTMORF model for the estuary was used to further investigate the influence of the nodal tide variation on the volume changes in the estuary (Jeuken et al., 2002). For this purpose the nodal tide was included in the morphologic hindcast simulation for the period 1968-1998. Fig. 3 displays the computed volume changes and compares the predicted values with the observed alterations and the results of the reference simulation without the nodal tide. The computed volume changes confirm the observations: a long-term trend and superimposed on this trend a cyclic variation with a period of about 18 years and amplitude of 6-7 M m<sup>3</sup>.



**Fig. 3** Simulated and observed volume changes of the Westerschelde. The adjustment of the seaward hydrodynamic boundary, to include the effect of the nodal tide variation, was based on the nodal factor for the M<sub>2</sub>-constituent

The long-term trend of erosion is slightly larger in the simulation with the nodal tide than in the reference simulation without the 18.6 year cycle. This phenomenon is due to an artifact that is inherent to the way the cross-sectional profile is schematized in ESTMORF: the lowest point in the profile represents the channel bed in such a way that the cross-sectional area below low water is correct. The slope of the channel banks are however, not properly described. As a result of this, fluctuations of the low water level, e.g. due to nodal tide variation, induce an artificial erosion of the inter-tidal area. Initially this erosion does not influence the mass-balance (sediment from the shoals is deposited in the channels). However, the associated increase of the tidal prism imply an increase of the equilibrium cross-sectional area of the channels and hence erosion of the channels. The results in Fig. 3 indicate that this channel erosion manifests itself within 5-10 years in the Westerschelde model.

### 3. HUMBER ESTUARY

The Humber estuary is a tide-dominated estuary that is situated along the east coast of England. A macro-tidal regime, with a mean tidal range of 4.4 m near the mouth and average fresh water flow of  $250\text{m}^3/\text{s}$ , characterizes the estuary. The Humber estuary exhibits a morphologically dynamic system of parallel-aligned tidal channels that are separated by muddy inter-tidal shoals. Townend and Whitehead (2003) give an overview of the morphologic and hydrodynamic characteristics of the estuary.

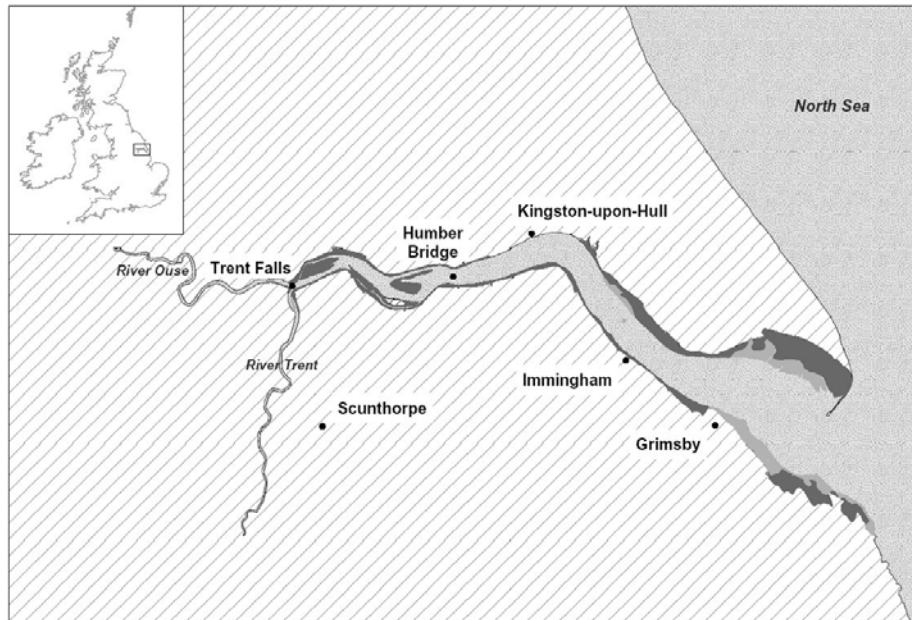
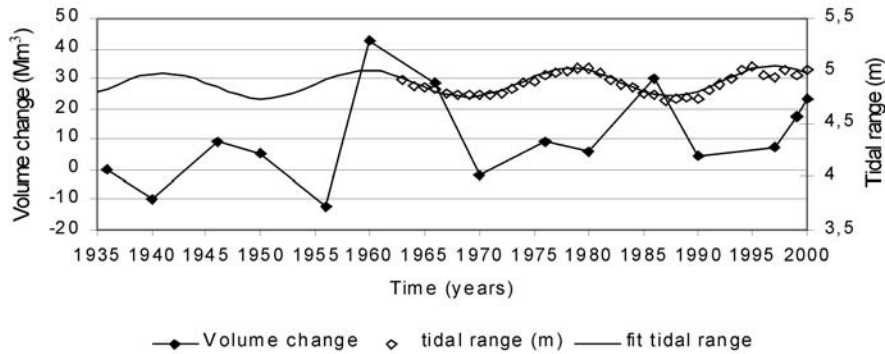


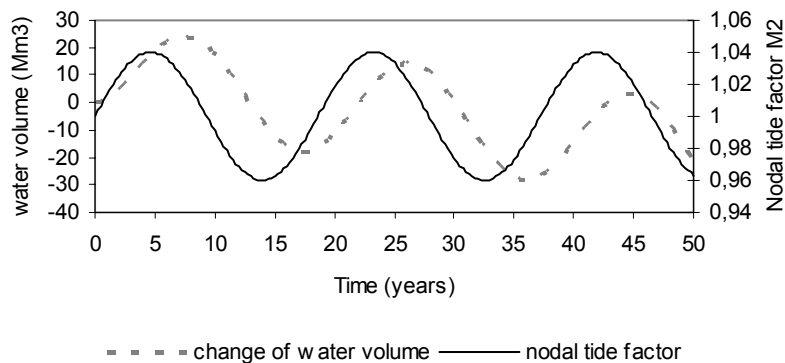
Fig. 4 The Humber estuary

Earlier studies for the Humber shoreline management plan identified a possible link between the nodal tide and changes in estuary volume (ABP, 2000). To investigate this further, a more recent study, ABP (2003), has determined the volume changes at approximately 5 years intervals over the period 1936-2000, and explored the link to the nodal tide for the estuary as a whole and over individual reaches. A non-uniform high water spring level in 2000, computed with a depth-averaged hydrodynamic model, was used as reference level. In the estuary sediment is dredged to maintain the shipping lane and the harbors, on average  $7.3 \text{ M m}^3/\text{yr}$  during the period 1960-1994 (Townend and Whitehead, 2003). Practically all dredged sediments are disposed at nearby located spoil grounds within the estuary. Structural sand mining is absent. Therefore the total volume changes are less influenced by this kind of human interference than in the Schelde estuary. Fig. 5 displays the results of the volume calculations. Over the period 1935 to 2000 the data reveal a small long-term trend of an increasing water volume ( $0,2 \text{ M m}^3/\text{yr}$ ), confirming the conclusions of Townend and Whitehead (2003) that estuarine sediment budget is finely balanced. Large fluctuations with amplitude of  $10\text{-}20 \text{ Mm}^3$  are superimposed on this trend. The period of the fluctuations, 15-18 years, can not be determined precisely because of the relatively large interval (about 5 years) between successive observations. For the same reason it is difficult to determine the phase lag between the nodal tide variation in the tidal range and the fluctuations in the water volume. It seems to approximate 5 years for the estuary as whole.



**Fig. 5** Observed volume changes and tidal range variations in the Humber estuary. Tidal range observations are from Immingham, near the mouth of the estuary

A simulation of 50 years with the ESTMORF model of the Humber was carried out to further investigate the influence of the nodal tide variation. Fig. 6 depicts the results of the simulation with nodal tide variation. It reveals periodic fluctuations in the water volume, with amplitudes of 15-20  $Mm^3$  and a period of 18.6 years, which lag 4 years behind the nodal tide variation in the tidal range. These values approximate the above-mentioned observations.



**Fig. 6** Simulated future volume change in the Humber estuary under the influence of sea level rise and the 18.6 year nodal cycle

#### 4. DISCUSSION

The nodal cycle is the only known hydrodynamic cycle with a period between 18 and 19 years, which is able to strongly influence the tidal currents in tide-dominated estuaries. Therefore it is inferred that the observed and simulated cyclic variation in the estuarine water volume found in the Westerschelde and Humber is the result of regular changes of the tidal prism and current velocities induced by the nodal tide. An increase of the tidal range is associated with an increase of the tidal prism and velocities and results in a larger estuarine water volume (i.e. erosion), whereas a decrease of the tidal range is followed by a temporal reduction of the water volume (sedimentation). Especially in the Humber estuary, with a relatively small morphological time scale, the response to the nodal tide variation appears to dominate the long-term large-scale volume changes of the estuary. Even in the Westerschelde, with a much larger morphological time scale, the response of the estuary to the nodal tide variation can be clearly observed. The amplitude of the morphologic response in the Humber estuary is about twice as large as in the Westerschelde estuary. In both estuaries the morphologic response lags about 3 to 5 years behind the hydrodynamic forcing.

A theoretical analysis based on a simplified model can be used to understand this observed and simulated morphological response of estuaries to the nodal tide variation. In this simplified model the estuary as a whole is considered as a single element and its morphological state is represented by its total wet volume under a certain (high water) level  $V$ . Based on the same model concept as ESTMORF a differential equation for  $V$  can be derived, of which the linearized form reads as (Kragtwijk et al, 2003, Stive and Wang, 2003):

$$T \frac{dV}{dt} + V = V_e \quad (1)$$

Herein

$$\begin{aligned} T &= \text{morphological time scale of the estuary,} \\ t &= \text{time,} \\ V_e &= \text{equilibrium value of } V. \end{aligned}$$

According to the model concept the equilibrium volume  $V_e$  is directly related to the tidal volume, thus also to the tidal range. This means that the nodal tide variation can be represented by

$$V_e = \hat{V}e^{i\omega t} + V_0 \quad (2)$$

Where,

$$\begin{aligned} \hat{V} &= \text{amplitude of the nodal tide variation in } V_e, \\ \omega &= \text{frequency of nodal tide variation, thus equal to } 2\pi/18.6 \text{ year}^{-1} \\ V_0 &= V_e \text{ value at averaged tide (long-term mean).} \end{aligned}$$

The solution of Eq. (1) can then be written as

$$V = C\hat{V}e^{i\omega t} + V_0 \quad (3)$$

In which  $C$  is a complex coefficient, which can be determined by substituting Eq. (3) into Eq.(1).

$$i\omega TC + C = 1 \quad (4)$$

so

$$C = \frac{1}{1+i\omega T} \quad (5)$$

The modulus of  $C$  represents the damping factor, i.e. the ration between the amplitude of  $V$  and that of  $V_e$ , and the argument represents the phase-lag, thus

$$\text{damping factor} = \text{mod } C = \frac{1}{\sqrt{1+(\omega T)^2}} \quad (6)$$

And

$$\text{phase-lag} = -\arg C = \arctan(\omega T) \quad (7)$$

Figure 7 shows the latter two relations. It reveals that the damping factor thus also the amplitude of the morphological response decreases as  $\omega T$  increases and that the phase-lag rapidly approaches  $\pi/2$  as  $\omega T$  increases. The morphological time scale of the Humber estuary is of the order of magnitude of 35 years (so  $\omega T$  is about 12) (Wang and Roelfzema, 2001), and that of the Westerschelde estuary is much larger, with the order of magnitude of a century. For large values of  $\omega T$  the damping factor is approximately inversely proportional to  $\omega T$  and the phase-lag is practically  $\pi/2$  representing a time-lag of 4.65 year. This explains why the amplitude of the morphologic response in the Humber is larger than in the Westerschelde and why the phase lag approximates 3 to 5 years in both estuaries.

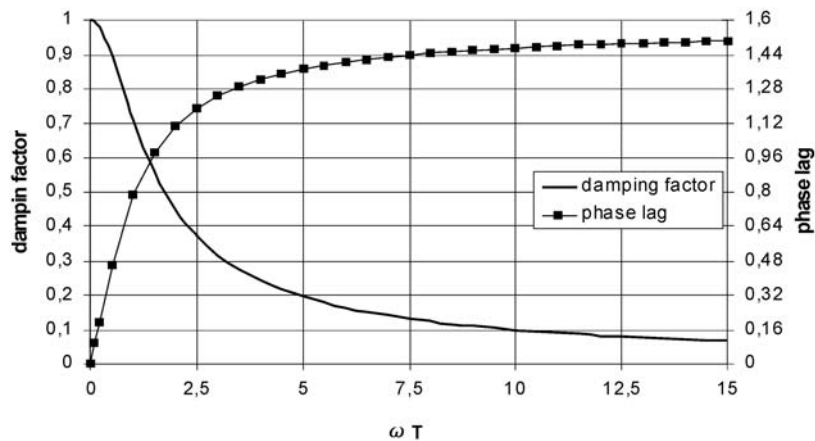


Fig. 7 Damping factor and phase-lag of morphological response of estuaries to nodal tide variation

## 5. CONCLUSIONS

The 18.6 year nodal cycle influences the overall sediment balance of tide-dominated estuaries. The impact of the nodal tide variation depends on the morphological time-scale of the estuary. A small timescale, i.e. a dynamic system, displays a morphologic response with large amplitude. The phase difference between the hydrodynamic forcing and the morphologic response only slightly depends on the morphologic time-scale. Field observations, model results and theoretical considerations show that the maximum phase difference approximates a quarter of the period in the hydrodynamic forcing, i.e.  $18.6/4=4.65$  yrs. The results of the present study imply that 18.6 year nodal cycle should be accounted for in the monitoring of estuaries and sediment balance studies.

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