

A NEW MORPHOLOGICAL SCHEMATIZATION OF THE WESTERN SCHELDT ESTUARY, THE NETHERLANDS

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ABSTRACT: The present paper describes an analysis of the morphological integrity of the multiple channel system (MCS) of the Western Scheldt estuary. The tidal flats and surrounding ebb and flood channels form morphological cells, and the entire MCS can be schematized as a chain of such cells. The major ebb and flood channels have lost their one time function to feed and drain large tidal basins along the estuary. It is hypothesized that the MCS is now self-preserving as a result of the large gross sediment transport rates through these channels and the asymmetry of the channel system. From a stability analysis and computation of the gross sediment transports through the channels, the local and overall capacity of the estuary could be established to accommodate for the dumping of sediments dredged in the fairways of the estuary to safeguard navigation. This capacity compared favorably with the experience of the managing authorities. The scheme is used to evaluate a series of managing scenarios.

1. INTRODUCTION

The Scheldt estuary consists of an ebb tidal delta facing the North Sea and the Western Scheldt (60 km), both on Netherlands territory, and the Zeeschelde (30 km) and Bovenschelde (70 km) on Belgium/Flemish territory. The Western Scheldt, which is the focus of the present paper, forms the access to the Port of Antwerp, situated along the lower reaches of the Zeeschelde. Navigation to the Port is hindered by a series of shallow sills in the fairways of the Western Scheldt, which therefore requires regular maintenance dredging. The dredged material cannot be removed from the system, as a continuous depletion of available sediments may lead to the drowning of the estuary. It has therefore to be dumped somewhere in the estuary, away from the dredging site. This, however, appears to have an adverse effect on the dynamic behavior of the system.

The continuing increase in draught of the vessels accommodated by the Port initiated a joint Netherlands/Flemish study into the impact of further deepening of the fairways on the natural system. From discussions between the managing authorities and scientists it was concluded that the preservation of the current multiple channel system, characteristic for the Western Scheldt is a necessary condition for preserving

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the natural system as to safeguard all interests in the system, and in particular those related to navigation, nature conservation and safety against flooding. Details of this policy making process have been reported by Arends and Winterwerp (2001).

The present paper presents the analysis of the impact of a further deepening of the fairways on the stability of the characteristic morphological features of the Western Scheldt, i.e. the multiple channel system. First an overview is presented on the origin of the multiple channel system on the basis of a description of the historical developments of the estuary. Section 3 describes the hypothesis, on which the morphological analyses are based, yielding a new morphological schematization of the Western Scheldt in the form of a chain of morphological cells. This schematization accounts for the stability of the individual cells of the chain, its analysis is presented in an accompanying paper (Wang and Winterwerp, 2001). The schematization is used to assess the impact of further deepening on the stability of the multiple channel system over a time span of three decades, taking into account autonomous developments like the current or augmented sea level rise.

2. PHENOMENOLOGICAL DESCRIPTION OF THE ESTUARY

The first historical data on the Scheldt estuary date from AD 1000, when the estuary was wide and shallow, though much smaller, and known as De Honte. The river Scheldt then drained further north into a sea arm, presently known as the Eastern Scheldt. In the next five centuries, the estuary increased rapidly in size because of natural processes (storms, floods, subsidence and a continuing sea level rise) and human interference (peat mining). In this period the present sinusoidal plan form of the estuary was probably established by bank protections near settlements. Also the major channel system, as it is still known today, developed in that period to feed the new large tidal basins along the estuary.

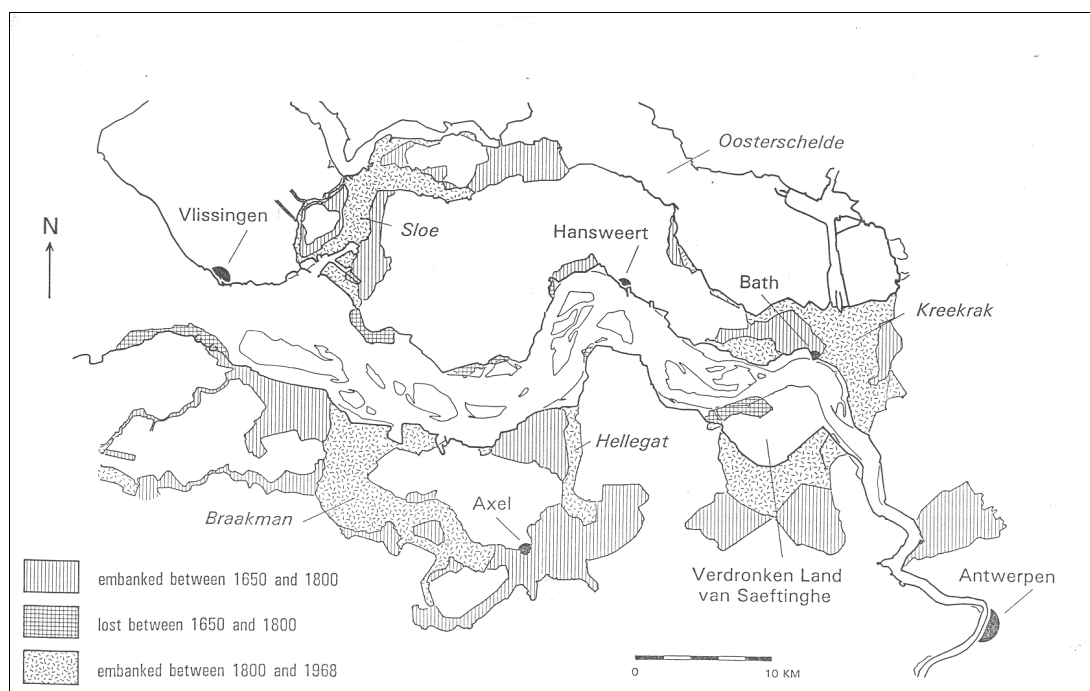


Fig. 1: Historical decrease of the Western Scheldt (Van der Spek, 1994).

In the following five centuries the size of the estuary gradually decreased again by natural processes (land formation from salt marsh evolutions) and human interference (poldering and embanking). An impression of these developments is given in Fig. 1, as established by Van der Spek (1994).

These developments led to the current geometry of the estuary, characterized by its sinusoidal plan form with relative short straight flood channels and more or less continuous curved ebb channels. The spatial scale of the major channels in between the crests and troughs of the sinus can be regarded as the macro scale of the estuary. In between the ebb and flood channels large intertidal flats are found which are intersected by numerous stable and/or migrating secondary channels. These morphological entities have dimensions at the meso scale of the estuary. The ebb and flood channels join at highly dynamic, shallow areas, forming more or less closed topographic units (e.g. Van Veen, 1950). From a conceptual point of view, these units, i.e. the ebb and flood channels and the enclosed intertidal flats, can be regarded as morphological cells - see Fig. 2a.

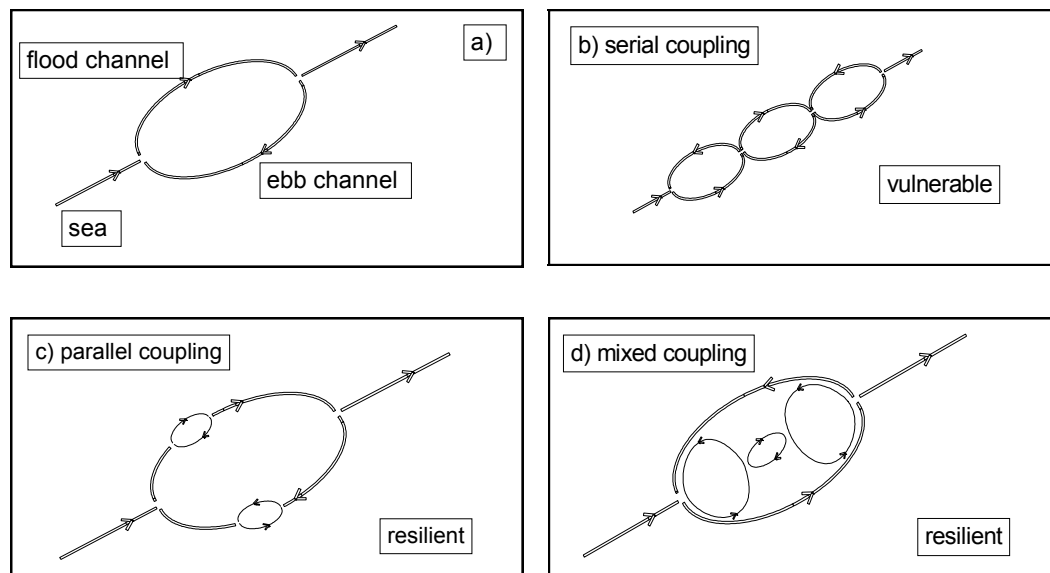


Fig. 2: Sketch of morphological cells and their mutual coupling.

The shallow areas, where ebb and flood channels meet, are the aforementioned sills. Some of these have to be dredged regularly to safeguard navigation. Along the shores of the estuary, which is fully embanked at present, intertidal mudflats and salt marshes are found. Their preservation is of particular importance with respect to the ecological functioning of the system.

For more details on the current morphodynamics and historical developments, the reader is referred to Van der Spek (1994), Van Eck (1999), and Jeuken (2000).

Since 1950 poldering activities have ceased. However, human interference is still significant, which can be appreciated by comparing natural and antropogenic sediment movements. The net annual sediment import into the estuary, prior to the recent deepening, is estimated at 1.3 Mton, whereas about 3.5 Mton of sand is mined annually for commercial purposes, and about 9 to 13 Mton of sediment is dredged at the sills to safeguard navigation and dumped each year at various locations in the estuary (Van der Spek, 1997).

3. SCHEMATIZING THE MULTIPLE CHANNEL SYSTEM IN CELLS

The morphological cells are characterized by very large gross water and sediment transport rates through their branches. Because of the asymmetry of the system, these transports result in significant residual transports circulating through the cells, in the direction of the flood c.q. ebb dominance of the branches. Sediment transport computations show that these residual transports are an order of magnitude smaller than the gross transports through the branches of the cells (i.e. the ebb and flood channels). However, these residual transports are much larger than the longitudinal net transport through the estuary, hence between neighboring cells. Therefore, the stability of the entire multiple channel system can be studied by analyzing the stability of the individual cells. It is reasonable to assume that such a cell is preserved as long as the large circulating sediment transport through its branches is preserved. Moreover, the asymmetry of the system is the driving force for the (re)generation of the secondary channels. This reasoning leads to the basic hypothesis of the present study, that is that the integrity of the multiple channel system of the Western Scheldt estuary is preserved at all scales, if the cell structure of the ebb-flood channel systems at the macro scale is preserved.

These morphological cells can be coupled in a number of ways, as sketched in Fig. 2. A serial coupling (Fig. 2b) is not very resilient in the sense that the degeneration of one branch will lead to the degeneration of the relevant cell, hence of the overall multiple channel configuration. When cells are coupled in a parallel way (Fig. 2c), degeneration of a branch at the meso scale will not affect the overall structure. This degeneration is probably reversible as the mechanisms at the macro scale, driving the generation of such a secondary cell, are maintained. Configurations with a mixed coupling of cells (Fig. 2d) are probably fairly resilient as the driving mechanisms at the macro scale are preserved to regenerate the cells in case of a degeneration of one of the branches.

In the accompanying paper (Wang and Winterwerp, 2001) a stability analysis of an individual morphological cell (e.g. Fig. 2a) is presented. It is shown that a relatively small undeeptening of one branch, resulting from the dumping of sediments dredged elsewhere in the estuary, is neutralized as the local narrowing of that branch will result in an increase in sediment transport capacity, eroding the dumped sediments. However, when the dumping rate in a branch exceeds about 10 % of its gross sediment transport capacity, the hydraulic resistance of that branch increases rapidly, decreasing its flow rate and transport capacity. This results in a positive feed back and a degeneration of the cell.

A deepening of one of the branches of a cell appears not to affect the stability of that cell. Hence, dredging by itself does not endanger the survival of the multiple channel system. However, the enclosed intertidal flat lowers, and its banks steepen, which may be unfavorable side effects from an ecological point of view.

To schematize the Western Scheldt bathymetry in morphological cells, the residual sediment transport field is analyzed, as established from averaging the computed instantaneous sediment transport over a tidal cycle. The sediment transport computations are carried out with DELFT3D (Roelvink and Van Banning, 1994) on a curvi-linear grid with the 1996 bathymetry of the estuary, covering the estuary from its ebb-tidal delta to slightly beyond Antwerp. The grid size varies from about $20 \times 20 \text{ m}^2$ in the narrow channels to about $500 \times 500 \text{ m}^2$ in the sea region, yielding 542×569 grid

points. The time step for the hydrodynamic computations is set at 0.5 min, and for the sediment transport computations at 10 min. The (time-varying) boundary conditions for water level and flow rate have been obtained from other hydrodynamic models that cover part of the North Sea and the entire Scheldt estuary up to its tidal limit. The computations are carried out for a so-called morphological tide, established with the method of Latteux (1995), which yields a cyclical tide with an amplitude of 2 m, 10 % above mean tidal range. The river flow is small and set at 300 m³/s.

The bed roughness is modeled with a Manning coefficient of 0.022 - 0.026 s/m^{1/3}. A typical value of the grain size in the estuary is 240 µm; it is appreciated that the grain size varies somewhat in space, but this effect is omitted at present. The sediment transport is computed with the method of Engelund-Hansen (1967), yielding total sediment transport rates as a function of the hydrodynamics. Comparison of the computed transport rates with some scarce field data is satisfactory; the results are not presented here though.

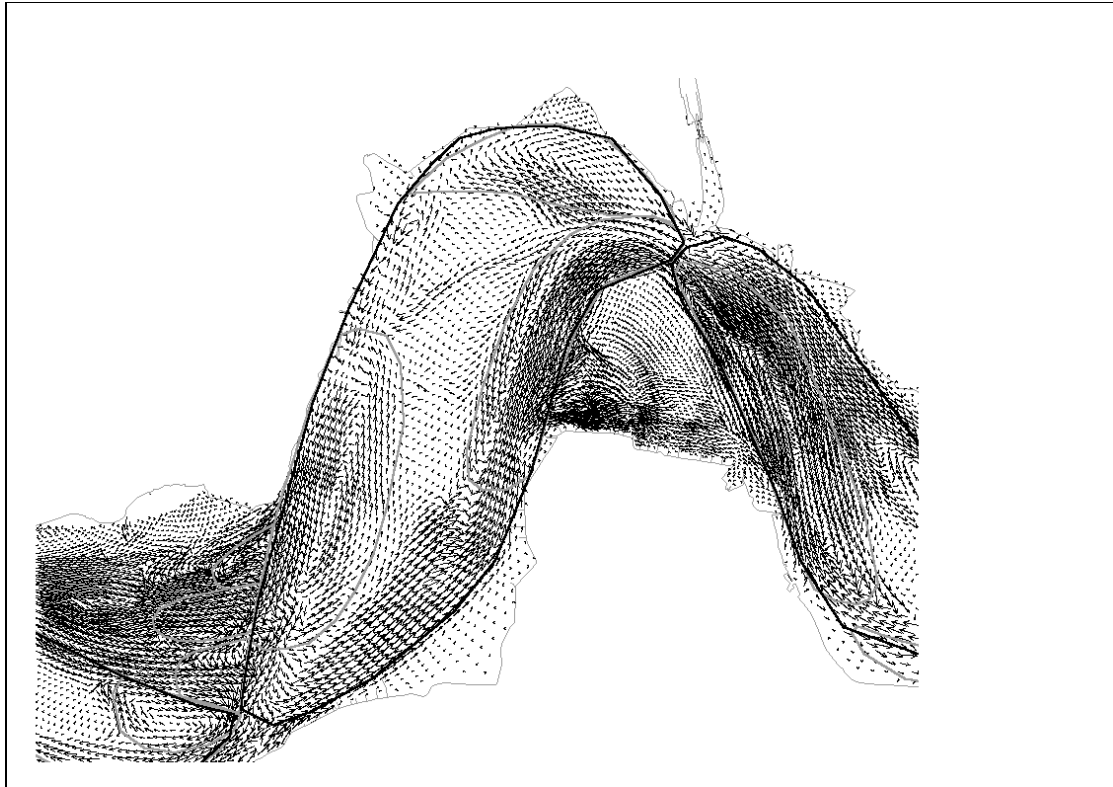


Fig. 3: Example of computed sediment transport field (Cell 4, Fig. 4).

A typical example (for cell 4, e.g. Fig. 4) of the computed residual sediment transport field is given in the vector diagram in Fig. 3, showing recirculating residual transport patterns at various scales. These patterns have been elaborated further through a thorough morphological analysis of detailed bathymetrical maps, i.e. distinguishing ebb and flood channel systems. On the basis of these two analyses, which yielded almost identical results, the morphological schematization of the Western Scheldt multiple channel system in a chain of cells was drawn. The result is presented in Fig. 4, showing the configuration of macro and meso cells.

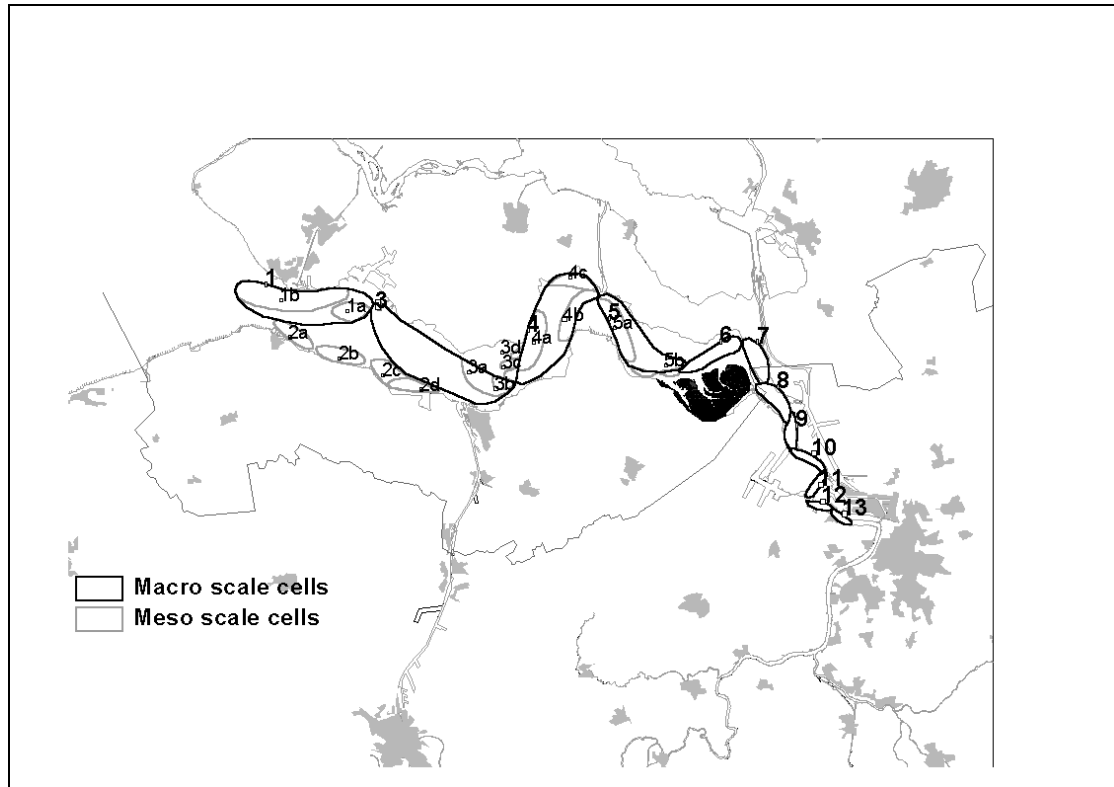


Fig. 4: Schematization of Western Scheldt in morphological cells.

4. ACCOMMODATION FOR CAPACITY DREDGED SEDIMENTS

The accommodation capacity of each individual morphological cell can be established from the stability analysis referred to Section 3 and the computed gross sediment transport for a given bathymetry of the estuary. The accommodation capacity is defined as the amount of sediment that can be dumped in one of the branches of the cell without endangering the integrity of that cell. Evaluation of this capacity should be done over a time span covering the typical time scale of the relevant ebb-flood channel system, which is decades for the morphological entities at the macro scale. In other words, an exceedance of the dumping capacity for a number of years is probably allowable, provided that the system gets time to recover again so that no irreversible degeneration of the cell will take place.

It is noted that the accommodation capacity is different for situations where sediment, dumped in one of the branches from a cell, is originating from dredging at locations outside the cell, and situations where sediment is dredged in one branch, and dumped in the other branch. The implications of these alternative situations are not elaborated in detail here, but have been incorporated in the analyses presented in the following paragraphs of this section.

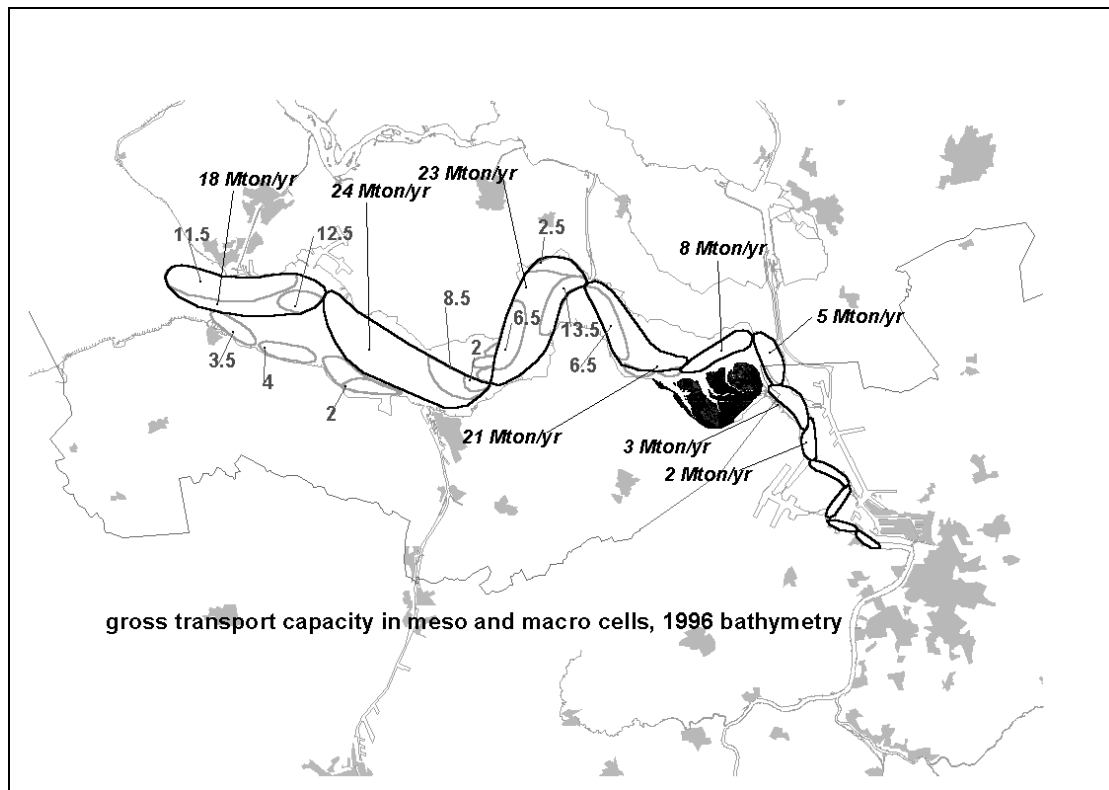


Fig. 5: Gross transport capacity for 1996-reference conditions.

Fig. 5 presents the gross sediment transport capacity, defined as the integral over the tidal period of the absolute value of the computed instantaneous sediment transport, for the 1996-reference situation. Such a picture allows managing authorities to establish the local accommodation capacity for dredged sediments in the Western Scheldt estuary, as elaborated below.

In the flood channel of cell 6 (Fig. 4, “Schaar van de Noord”) large amounts of sediments, dredged in the ebb channel of this cell, have been dumped in the period 1980 - 1985, exceeding the computed accommodation capacity of the cell by a factor of three. It appeared that the channel system silted up significantly, endangering the integrity of the ebb-flood channel system of cell 6. At present no sediments are dumped at this location anymore and the system seems to restore.

Dredging and dumping of sand effectively influenced the channel evolution in cell 5. The large-scale deepening of the sill in the navigation channel in the period 1971-1975 and its maintenance since 1975 were accompanied by a net erosion of the entire main ebb channel. The dumping of the dredged sediments in the main flood channel exceeded the local accommodation capacity with a factor two in the period 1975-1996, to a factor five in the period 1971-1975. The sediment dumping is associated with a net shoaling of the flood channel and an accelerated accretion of the inter-tidal shoals.

Recently another dredging-dumping strategy was implemented consisting of dumping much more sediments in the western part of the Western Scheldt. In the ebb channel of cell 1a (Fig. 4, “Schaar van de Spijkerplaat”) the local accommodation capacity is exceeded by a factor four. In a few years this channel became so shallow that the dredging vessels are reported to have large problems depositing the sediments in this area.

At other locations the accommodation capacity has not been exceeded, and no degeneration problems of channels have been observed.

These observations may be regarded as a qualitative verification of the new cell concept to establish the accommodation capacity for depositing sediments. This concept can be used to analyze various dredging-dumping strategies, and the impact of developments in the estuary.

The current accommodation capacity, summed over all cells, amounts to about 5 to 10 Mton, depending on the dumping strategy. This would imply that the current amount of dredging, to safeguard navigation, of about 9 to 13 Mton, can only be accommodated for because of the sand mining activities at a rate of 3.5 Mton per year.

Next, the impact of various alternative scenarios is studied, amongst which a further deepening of the fairway, depoldering to re-enlarge the tidal volume of the basin, and an augmented sea level rise as a result of global heating. A major problem in evaluating such alternatives is the establishment of the amount of dredging required. This amount is assessed with the hybrid model ESTMORF, which simulates the morphodynamic developments of estuaries as a function of natural processes and antropogenic influence (e.g. dredging and dumping), see Wang et al. (1998). As an example of these scenarios, the computed gross transport capacity for a fairway of 14 m depth is presented in Fig. 6, showing a total accommodation capacity of about 4.5 to 9 Mton per year, a little smaller than the present capacity.

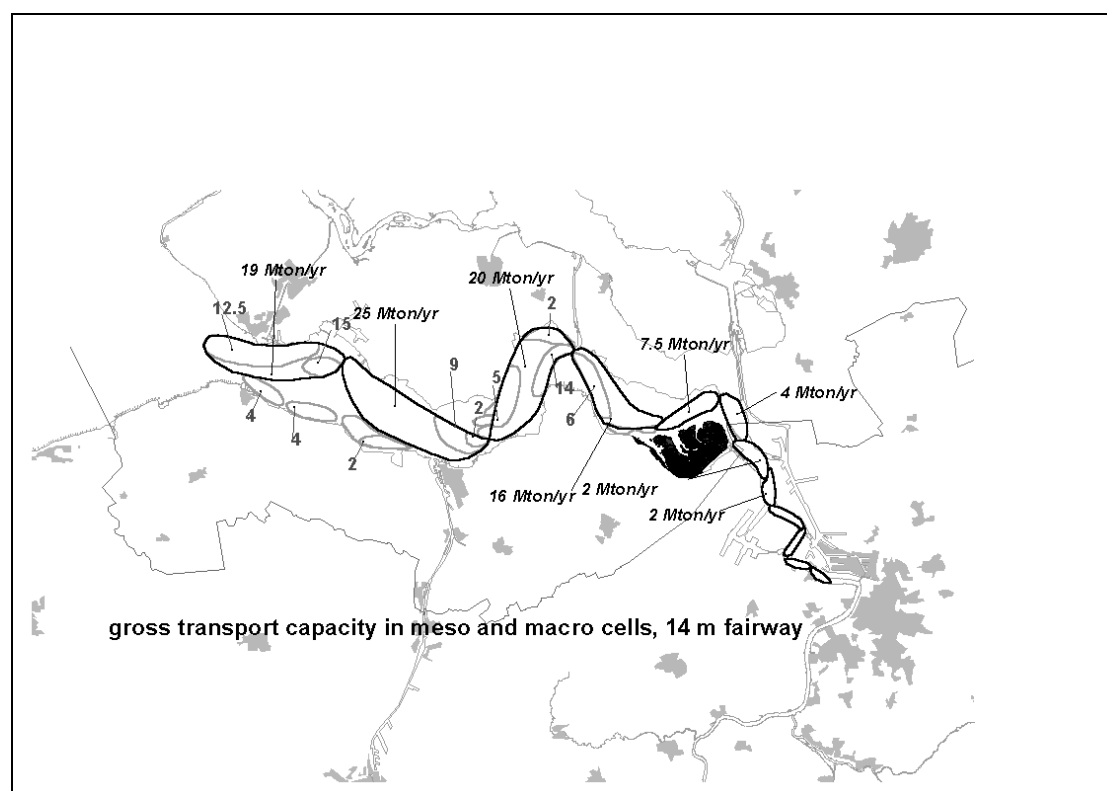


Fig. 6: Gross transport capacity for a 14 m deep fairway.

The maintenance volume is computed with ESTMORF to amount to about 8 to 13 Mton, comparable to the current situation. However, deepening of the fairway requires capital dredging of about 75 to 120 Mton. In the present analysis it is assumed that

this amount of sediment is withdrawn from the system, as a result of which the estuary will be in a process of adaptation to this large depletion of sediment for a period of many decades, and possibly beyond. This explains why the computed maintenance dredging is fairly low in comparison with the current situation with a 12 m deep fairway.

5. DISCUSSION AND CONCLUSIONS

It is reasoned that the current multiple channel system in the Western Scheldt estuary is the remainder of a period that these channels had to feed and drain large tidal basins along the estuary. As a major part of these basins has disappeared, these channels lost their original function. It is hypothesized that the multiple channel system is self-preserving at present as a result of the large gross sediment transport rates through the channels and the overall asymmetry of the system. Conservation of this multiple channel system requires the preservation of the integrity of the individual morphological cells, formed by the ebb and flood channels, and the intertidal flats enclosed.

The schematization of the Western Scheldt in a chain of such morphological cells provides a simple and useful tool to establish the capacity of the estuary to accommodate for the dumping of sediments dredged from the fairway to safeguard navigation. Application of the methodology requires the use of a morphodynamic model to predict the volumes to be dredged for various alternative managing scenarios.

The computed accommodation capacity for the 1996-reference situation compares favorably with experience from the managing authorities at two locations within the system. The dumping of dredged sediments appears to be the factor controlling the integrity of the individual cells, hence of the multiple channel system.

The cell concept should be considered as a tool for the analysis and interpretation of dredging and dumping strategies; it structures the complicated multiple channel system dynamics and the effects of gross, net and residual sediment transports. This concept may be applicable to other long, wide estuaries with a significant tidal influence and a low river flow. However, such applicability has not yet been studied.

Important issues to be addressed for a sustainable management of the Western Scheldt concern the overall stability of the estuary at the mega scale and the influence of large scale artificial sand movements as a result of dredging and dumping activities, and the sediment exchange between the estuary and the ebb tidal delta. As these issues are not incorporated in the cell concept, they are subject of further studies

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