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SUSTAINABILITY OF THE MULTI-CHANNEL SYSTEM IN THE WESTERSCHELDE UNDER INFLUENCE OF DREDGING AND DISPOSAL

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ABSTRACT

This paper presents an on-going study meant to improve our knowledge on the morphological development of estuaries for supporting estuarine management considering accessibility for navigation and the ecological value. We focus on the question whether a multi-channel system in the Westerschelde can be sustained under pressure of future deepening and maintenance. After reviewing the previous work on this subject the remaining questions are inventoried and further research for answering each question is proposed. The results of the proposed study will directly be applicable for developing better strategies for disposal dredged sediments, supporting decision making concerning sand mining and further deepening of navigation channels, and for monitoring the effects of human activities on the morphological development in the estuary.

Keywords: Tidal channel, Estuary, Morphodynamics, Stability

1. INTRODUCTION

The Schelde is a tide-dominated estuary that is situated in the southwest of the Netherlands and Belgium. It includes the entire gradient from fresh to salt water areas providing various habitats for flora and fauna. In addition to these ecological values, the estuary is of large economic importance as it provides navigation routes to the ports of Antwerp, Gent, Terneuzen and Vlissingen. Conflicting interests between accessibility and nature conservation and safety against flooding make the sustainable management of the estuary a complex task. Collaboration of the Dutch and Belgium government has resulted in the formulation of a Long-Term Vision, hereafter referred to as LTV, for the Schelde estuary. In view of sustainability, a primary management objective for the estuary is preservation of the physical characteristics and dynamics of the system of channels and shoals in the part of the estuary between Vlissingen and the border between The Netherlands and Belgium, referred to as the Westerschelde.

The morphology of the Westerschelde displays a regular repetitive pattern that consists of mutually evasive meandering ebb channels and straight flood channels. These main channels are separated by sub and intertidal shoals and linked by connecting channels. (e.g., Van Veen et al., 2005; Van den Berg et al., 1996; Jeuken, 2000; Toffolon and Crosato, 2007). This morphology is also referred to as a ‘multi-channel system’. Winterwerp et al. (2001) schematized this system into a chain of so-called macro-cells and meso-cells (Fig. 1), based on morphological characteristics and numerically computed patterns of tide averaged sand transports. Each macro-cell consists of a main ebb channel and a main flood channel, displaying a characteristic morphologic behaviour that is associated with net sediment exchanges between the macro-cells. Smaller-scale connecting channels link the large ebb and flood channels in macro-cells, forming meso-cells. These smaller channels often display a quasi-cyclic morphologic behaviour, characterized by processes of channel origination, migration and degeneration at a timescale of years to decades (e.g., Van Veen et al., 2005; Jeuken, 2000).

Both natural processes and human interferences have influenced the morphological evolution of the estuary over the past two centuries (e.g., Van den Berg et al., 1996; Van der Spek, 1997). Initially the human interference mainly consisted of reclaiming land that largely silted up by natural processes. This reclamation resulted in a permanent loss of intertidal areas, a rather erratic pattern of embankments and a fixation of the large-scale alignment of the estuary. Since the beginning of the twentieth century the human interference shifted from land reclamation to sand extraction (since 1955 about 2 million m^3yr^{-1}) and dredging and disposal to deepen and maintain the navigation route to the port of Antwerp. During the first deepening in the seventies the depth of the shallow sills in the navigation route was increased with 2 to 3 m from 12 to 14.5 m. During the second deepening, carried out in 1997/1998, these depths were increased with another 1 to 1.5 m and included also channel-widening at several locations. With the third deepening, established in 2010-2011, a depth, independent of tide, of 13.1 m was established. As a result of this the maintenance dredging increased from less than 0.5 million m^3yr^{-1} before 1950 to about 7–10 million m^3yr^{-1} at present. The dredging and disposal operations at least enhanced (a) the long-term deepening of the channels, the large ebb channels in particular, (b) the loss of shallow water areas, (c) the raise of intertidal shoals and (d) the partial disappearance of connecting channels (Swinkels et al., 2009, De

Vriend et al., 2011). From the perspective of maintaining the physical characteristics of the Westerschelde these changes are perceived as undesirable developments. The estuarine managers in the Netherlands and Flanders wish to prevent further deterioration of the multi-channel system and wish to develop a well-considered strategy for future dredging and disposal operations.

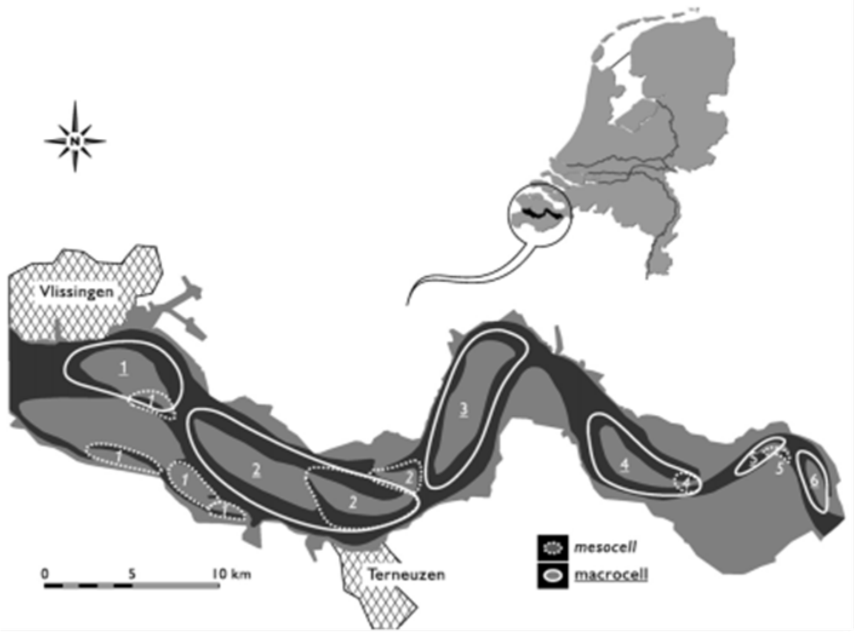

Figure 1. Western Schelde, a chain of morphological cells forming a two-channel estuary (after Jeuken and Wang, 2010).

2. PREVIOUS WORK ON STABILITY OF MULTI-CHANNEL SYSTEM

The stability analysis presented by Wang and Winterwerp (2001, see also Appendix of Jeuken and Wang, 2010) may be used to design a sustainable strategy for disposal in multi-channel systems with an erodible, non-cohesive sediment bed. Accordingly, for a stable channel system in equilibrium a critical level for the amount of sediment disposal exists that amounts to 5% to 10% of the gross sand transport capacity. Long-term sediment disposal exceeding this level may result in a degeneration of the multi-channel system towards a single channel system. Jeuken and Wang (2010) made an attempt to verify this theoretical concept using morphological observations dating back to 1955 and discussed the application of the concept in designing a strategy for disposal in tidal channel systems.

The basis of the stability analysis for a two-channel system, a flood-ebb channel cell, is the stability analysis on river bifurcations by Wang et al. (1995). In this analysis an idealised two-channel model is used, i.e. each of the two bifurcating river branches is considered as a single element. Based on quasi-steady flow assumption a system of two coupled differential equations is derived for the development of the depths of the two channels. It is shown that whether a river bifurcation will be stable (both branches open) or unstable (one of the branches closes) depends on how the sediment transport distribution at the bifurcation depends on the discharge distribution (Wang et al, 1995, Bolla Pittaluga and Tubino, 2002, Kleinhans and Sloff, 2006). Wang and Winterwerp (2001) extended the analysis by Wang et al. (1995) by including the influence of dredging and disposal in the two-channel model. They show that a naturally stable two-channel system can become unstable if the disposal rate in one of the channels exceeds a critical level, of about 5% to 10% of the total sediment transport capacity through the two channels, depending whether or not the other channel is dredged. They argue that, although the analysis is for steady flow, this conclusion also applies to a flood-ebb channel system if the tidal-integrated sediment transport capacity is used. This argument is made plausible by Jeuken and Wang (2010) by considering the tidal flow as an alternating steady flow (steady during ebb as well as during flood but in opposite direction). However, considering the tidal flow as alternating steady flow excludes the effect of tidally induced circulation (see Buschman et al., 2010).

Jeuken and Wang (2010) verified the conclusion from the stability analysis using field observations and numerical modelling. A one-dimensional network model, with one single flood-ebb channel cell and the rest of the estuary schematised into a single branch, is used for the numerical verification showing that the conclusion from the stability analysis for steady flow case can indeed be applied for the tidal flow case. Using historical bathymetry data and dredging & disposal records they confirm the existence and the approximate magnitude of the critical level for disposal that follows from the stability analysis. They also demonstrated that the verification of the theoretical results using field observations is not straightforward as the morphology of tidal channel often changes as a result of both natural processes and human interferences, i.e. the channels are not in equilibrium. The theoretical analysis does not give information how to deal with the morphological changes when the system is not in equilibrium. Therefore they had to consider each of the macro-cells in the estuary separately and could only verify the theoretical results qualitatively and determine the threshold of disposal rate approximately. In addition, the morphological timescales associated with channel degeneration are large (decades to centuries), and have not been determined. It is argued that models used up to now cannot determine these morphological time scales correctly because they only include sand transport and not mud transport. Even though the sediment in the Westerschelde mainly consists of sand, especially in the channels, mud can play an essential role in the final stage of the degeneration of a two-channel system, as mud deposition can be the major part of sedimentation in channels far from equilibrium (Van Ledden et al., 2004). In the stability analysis as well as the verification with field observations only a single macro-cell has been considered as isolated from other cells. Interactions between the neighbouring cells have not been considered so far. Another shortcoming of the studies up to now is that little attention is paid to the smaller scale morphological development within a macro-cell; although the schematisation presented by Winterwerp et al. (2001) explicitly includes meso-cells within the macro-cells the analyses do not include the conceptually described interaction within and between cells as presented in Jeuken (2000). The analyses focus on the development of the two large channels in a macro-cell while it is believed that the interaction between the channels and the tidal flat between them is important. The stability analysis did not take into account the effects of various meso-scale characteristics of a macro-cell, e.g. different sizes of the two channels (length, width, depth). In summary, the study to the stability of the multi-channel system in an estuary like the Westerschelde still needs improvement.

Addressing the remaining fundamental problems related to the stability of the multi-channel system in estuaries like the Westerschelde will not be straightforward but scientifically challenging. The problems involve morphological changes on various spatial scales ranging from channel-shoal interaction to the full estuary scale. Especially the interactions between the developments at different scales are important. As an example, the larger scale development of the two bifurcating channels is determined by the local sediment transport distribution at the bifurcation (Wang et al., 1995). However, in the recent years substantial progress is made in studying the morphological development in the Westerschelde. Especially the LTV V&T studies (Reports to be found at e.g. http://www.vnsc.eu/organisatie/werkgroepen/onderzoek-en-monitoring/rapporten.html) have resulted in improved insights into the system. The behaviour of the system has been extensively analysed using field-data analyses and modelling. Various process-based models, including morphodynamic models, have been set-up and constantly improved (Hibma et al., 2003, 2008; Van der Wegen et al., 2008, Reports of LTV V&T studies). Field data collection has been intensified, especially related to the strategies for disposal dredged material (like on the edge of tidal flats). The new insights into the morphological system, the improved model suits, and the extensive available data form a solid basis for improving the study to the stability of the multi-channel system in the Westerschelde.

In summary it is clear that the existing theory on the impact of human activities to the stability of the multi-channel system in the Westerschelde Estuary still need to be improved. The following questions remain to be answered:

(1) What is multi-channel stability in a changing environment?

(2) How does mud influence the stability of the two-channel stability?

(3) Does a macro-cell influence the stability of its neighbouring cells?

(4) What is the role of channel-shoal interaction on the stability of the two-channel system?

In the following these questions are elaborated and the required research to answer them is proposed.

3. REMAINING PROBLEMS AND FURTHER RESEARCH

3.1 Multi-channel stability in a changing environment

The critical level for disposal by Wang and Winterwerp (2001) is expressed as a fraction of the gross sediment transport capacity. For larger disposals, the multi-channel system shifts to a single-channel system. Strictly speaking the sediment transport capacity needs to be determined at the equilibrium state of the system. This causes a major difficulty for the application of the theory, as an estuary like the Westerschelde is never in equilibrium and always changing under influence of more or less natural processes and human interferences. Jeuken and Wang (2010) use the sediment transport capacity determined at the ‘present’ state and made corrections for each of the macro-cells. The corrections are based on especially the on-going morphological changes in the channel receiving disposal, thus considering local changes rather than the whole estuary as a system. The design rules for dealing with the ‘on-going’ morphological changes in the estuary can be reconsidered by carrying out the following activities:

- Extend and deepen the data analysis of Jeuken and Wang (2010). The up to date field data set can be analysed by structuring the observed development into changes at various spatial and temporal scales, e.g.: the whole estuary (determine e.g. change in averaged depth), per macro-cell, per individual channels in the cells, etc.. The analysis aims to distinguish between autonomous morphological changes and alterations induced by dredging and disposal. Additionally, a morphological quick-scan and inventory of other estuaries exhibiting similar ebb-flood channel systems should be carried out to frame the study in a larger estuarine perspective.

- Analytical and numerical modelling. Analytical modelling (Winterwerp and Wang, 2013, Cai, 2014) can be carried out to investigate the (large-scale) interaction between morphological changes and tidal flow in the estuary. Combined with the results of numerical models this will reveal how the changes at various scales influence the sediment transport and the morphological development.
- Evaluation of the impact of sand-mining. Since 1950's sand-mining has been about 2.5 million m^3yr^{-1}. The policy is now to stop sand-mining in the estuary, based on considerations of potential effects on the sediment budget of the entire Dutch coastal system. The effect of sand-mining on the stability of the multi-channel system has however not been analysed so far. Based on the results of the previous two activities such analysis can be carried out.
- Develop / improve rules to account for the 'autonomous development' when assessing the stability of the channel system and the influence of dredging and disposal.

3.2 The influence of mud on the multi-channel stability

Previous analyses on the stability of the multi-channel system are based on sand transport only. This seems plausible as the sediment in the Westerschelde, especially in the channels, mainly consists of sand. However, mud transport can be very important for morphological changes of a tidal channel when the flow through the channel becomes weak. As an example, the tidal volume in the channel Zoutkamperlaag (in the Friesche Zeegat, a tidal inlet in the Dutch Wadden Sea) was decreased by about 1/3 due to the closure of the Lauwerszee. Van Ledden et al. (2004) show that serious sedimentation in the channel occurred directly following the closure and it is mainly due to mud deposition, even though the channel was sandy before the closure. Comparatively, field observations indicate that the long-term accreting ebb channel of Macrocel 3 (Middelgat-Ossenisse, see Figure 1) is composed of finer sediments than the adjacent channels (Jeuken, 2000). We hypothesize that mud deposition will be essential in the final phase for a channel to disappear. Therefore it is necessary to extend the analysis and modelling by including mud in order to be able to answer the question how long it would take for a two-channel system to degenerate when it becomes unstable. This can be done in the following steps:

- Carry out mud-transport modelling to obtain better insight into the mud transport in the estuary and to determine the key elements and parameters in the next step.
- Develop a conceptual model in order to extend the stability analysis for the two-channel system by Wang and Winterwerp (2001) with the transport of mud.
- Carry out the stability analysis with the extended model to examine if and how mud transport influences the stability of the multi-channel system.
- Improve the formulation to predict the morphological time scale of changes in channel stability taking into account the influence of mud transport and deposition. This can be done by applying the extended two-channel model and by carrying out simulations with a process-based model (e.g. Delft3D) for a schematised two-channel system using the development of macro-cell 3 as reference.

3.3 Interaction between macro-cells (Macro-scale)

The stability analyses so far only consider one macro-cell as an isolated two-channel system. The interaction between adjacent macro-cells has not been considered yet, whereas it is expected that the interaction is important. It is proposed to investigate the cell-cell interaction in a case study for the area around the macro-cell Middelgat–Gat van Ossenisse, indicated as cell 3 in Fig.1. The motivation for choosing this case is the special development of this cell in the last decades. Following a long-term presumably natural process of meandering and bend cut-off, the flood channel became the main navigation channel in 1981. Cell 3 is the only macro-cell in Westerschelde in which the flood-channel is used as the main navigation channel. The switching also makes the navigation (or main) channel located at the same side of the estuary in three consecutive cells (2,3&4), instead of alternating from one side to another in the natural situation. Recently (since 1997), rapid sedimentation occurred in Middelgat, endangering the integrity of the two-channel system in this cell. The following activities are suggested:

- Analyse the development of cell 3 with special attention to the distinction between 'autonomous' development and impact of dredging & disposal. One of the hypotheses is that the two-channel system in cell 3 is becoming unstable even without any disposal activities in the Middelgat. The analysis can be based on field data and results from process-based morphodynamic modelling for this area.
- Investigate the risk of the formation of a long cell by merging cells 2,3&4. After switching the navigation route to the flood channel Gat van Ossenisse the three cells have the main channel at the same side of the estuary. This

causes a risk that the three cells merge to a single long cell which is expected to be unfavourable for the stability of the multi-channel system (see also (4)). The possibility of such a cell-merging can be investigated by analysing the morphological development around the transition/connecting areas between the cells 2-3 and 3-4, based on historical data and model results. The hypothetical case of merged cells can be simulated with a process-based model to analyse the consequence of the merging.

- Investigate the effect to the neighbouring cells 2 and 4 if Middelgat is silted up. The investigation can be based on process-based modelling for schematised case as well as for the real geometry.

3.4 Channel-shoal interaction

The stability analysis for the multi-channel stability is based on an extension of the analysis on a river bifurcation (Wang 1995). The tidal flat between the two channels, including the connecting channels through it, is not considered in this analysis. Other characteristics like the length of the cell (channels) and asymmetry between the two channels have not been considered either. Therefore the following activities are proposed:

- Investigate the effect of length of cell on the stability of the two-channel system. Dredging and disposal activities like switching the navigation channel (see topic 3) and disposal at the edge of a tidal flat (a recent developed disposal strategy) can change the length of a macro-cell. Inspired by the development in the Yangtze Estuary (De Vriend et al., 2011) it is hypothesised that the length of a macro-cell has influence on the stability of the two-channel system. The investigation can be carried out based on the analysis of the formation of sills in the channels, by schematizing the geometry of the channel, in a similar way as the analysis on tidal watersheds in the Wadden Sea (Wang et al., 2013). The sills in tidal channels are similar as the tidal watersheds in the sense that their locations are related to minimum of tidal flow velocity, and can therefore be studied by analytical and numerical modelling of the tidal wave propagation as for the case of tidal watersheds by Wang et al. (2013). A natural ebb-channel has a sill at the seawards end and a flood channel at the landwards end (Van Veen et al., 2005). Deviation from this situation (e.g. the sill in a channel moved from the end to the middle, or development of sills at both ends like the case of Middelgat at present) will negatively influence the stability of the two-channel system.
- Extend the stability analysis by including the exchange of water and sediment within the cell via the tidal flat and the connecting channels. This will allow the analysis of the influence of the height of the tidal flat and the presence of the connecting channels. The hypothesis is that lower tidal flat and presence of connecting channels are favourable for the stability. The analysis needs to be supported and verified by process-based modelling.
- Analyse sensitivity of a number of characteristics of a macro-cell to the stability of the two-channel system. The characteristics include different sizes of the two channels (length, width, depth).

4. CONCLUDING REMARK

The proposed further study will improve our knowledge on the morphological development of estuaries for supporting estuarine management considering accessibility for navigation and the ecological value. The results of the study will directly be applicable for developing better strategies for disposal dredged sediments, supporting decision making concerning sand mining and further deepening of navigation channels, and for monitoring the effects of human activities on the morphological development in the estuary.

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