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Scheldt Estuary
physics and integrated management

Special Session
on of the

36th IAHR
WORLD CONGRESS

28 June – 3 July 2015

Delft & The Hague,
the Netherlands

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Content

Papers

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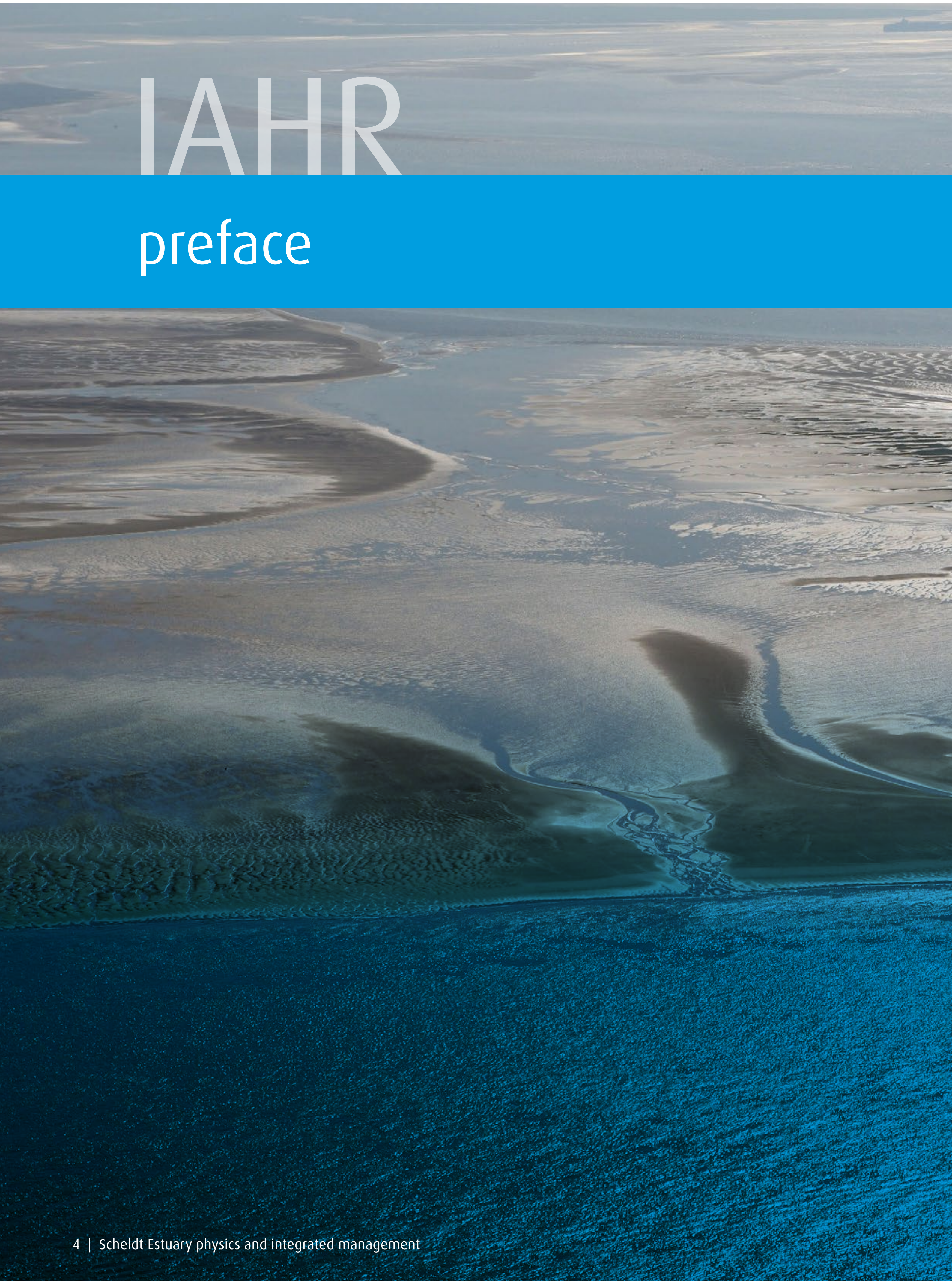
preface



The 36th IAHR world congress was organized in the Netherlands. This was an excellent opportunity to present the state of knowledge on the Scheldt estuary and special sessions were organized on Monday June 29th. The Scheldt estuary is shared by the Netherlands and Flanders, which have agreed to do joint research and monitoring. This is also laid down in the 2005 treaty on cooperation in policy and management of the estuary. The countries collaborate within the framework of the Flemish-Dutch Scheldt Committee.

No less than 17 papers and extended abstracts were submitted and accepted for a presentation. Rijkswaterstaat and the Flemish-Dutch Scheldt Committee are proud of the joint efforts that have been done and supports the special IAHR-sessions and offers this booklet with all submitted papers to all visitors of the special session and all others interested in the state of science on the Scheldt estuary.

Roeland Allewijn
Director Safety and Water Use, Rijkswaterstaat

IAHR

Papers

E-proceedings of the 36th IAHR World Congress
28 June – 3 July, 2015, The Hague, the Netherlands

UNDERSTANDING THE TIDES CRUCIAL FOR JOINT MANAGEMENT OF THE SCHELDT ESTUARY

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ABSTRACT

The Scheldt estuary is situated in the Netherlands and Flanders/Belgium. Both countries collaborate in policy, management and research, as laid down in a treaty of 2005. Preservation of the ‘physical characteristics of the estuary’ plays an important role in formulating objectives, but it is still debated ‘what exactly should be preserved’. What exactly should be preserved’ has a diversity over the various places, as both actual values and driving forces are different along sites. A management plan in such detail is not available.

Recent research has shown which role the tidal intrusion has in these discussions. Tidal intrusion as (an indicator of the) objective for future policy (i) reflects a long term development, (ii) can be linked to changes within the estuary itself, including sediment management and (iii) can be evaluated easily, as for practically all user-functions the increase in tidal amplification is regarded as negative. As a conclusion we pose that we need to accept that from science alone we cannot expect an unambiguous answer when preservation of the ‘physical characteristics of the estuary’ is fulfilled.

Keywords: Estuary, Tidal Amplification, Estuary Management, Delta Governance

1. INTRODUCTION

The Scheldt estuary plays a crucial role in the relationship between the Netherlands and Flanders/Belgium. Both countries require flood protection, need accessibility to large ports (Antwerpen, Gent, Terneuzen, Vlissingen) and value it as one of the few remaining natural estuaries in North West Europe.

2. JOINT ESTUARY MANAGEMENT

The condition for a sustainable and balanced policy was a joint ‘target-view’, laid down in a Long Term Vision on the Scheldt estuary. This vision-document was developed in cooperation between the two countries.. Decision making in the parliaments of the both countries was done by a treaty based on mainly two documents. The first was the Long Term Vision 2030, or LTV (Technical Scheldt Committee, 2001). The second was the ‘Development Sketch’, in Dutch: ‘Ontwikkelingsschets 2010’ or OS2010 (ProSes, 2005), that elaborated a set of measures needed to be started not later than 2010, accomplishing a first phase of the LTV towards the aspiration for 2030.

The Long Term Vision and the Development Sketch 2010 had a threefold objective: improvement of the three user-functions ‘Safety, Accessibility and Naturalness’, with ‘preservation of the physical characteristics of the estuary’ as precondition. Measures that were agreed on included amongst others a further deepening of the shipping fairway, nature restoration (mainly by giving more room to the estuary by depoldering) and a Safety plan for the Sea Scheldt (Sigma plan). It could be concluded that making a Long Term Vision and Development Sketch accelerated getting agreement and decision making for issues that had been highly controversial, like a further deepening of the shipping fairway. It was all part of an integrated plan for the development of the whole estuary.

Together with the treaty on the OS2010, two other treaties were prepared and signed (December, 2005). The ‘Treaty on Cooperation in Policy and Management’ included the agreement to do joint research and monitoring to support policy and management issues. Due to this treaty the Technical Scheldt Committee, a bilateral committee with high level civil servants, was given more powers and became the Flemish Dutch Scheldt Committee (www.vnsc.eu). Parts of the committee functioning were regular meetings and negotiations between the responsible ministers from both countries. A secretariat and a set of working groups were also established. In this framework estuarine managers and researchers of Flanders and Netherlands could cooperate intensively.

The Treaty provided a framework and assured budgets for applied research in both countries on the physical and ecological functioning of the Scheldt estuary, attuned to each other. As the guidance on the research was done by working groups under the VNSC, the relation with decision-making in estuary management was secured. Important decisions were now related to careful preparation of necessary permits and common conclusions on results of monitoring. A special research program named 'Safety and Accessibility', lead to a joint understanding on the long term development of the estuary, its driving forces and how these were influenced by human interventions. It also provided an extensive description of how these large scale developments and driving forces were related to what could be observed on individual channels and intertidal areas (the so-called meso-scale).

The Treaty on Cooperation in Policy and Management was evaluated recently. It was a.o. concluded that the choice for an integrated, bilateral project organization proved to be successful. As one of the most important aspects of this cooperation the evaluation report mentions the '*creation of a common knowledge base*' and the advice was given to '*continue with investments in a common, scientifically grounded, knowledgebase, which can be the foundation for future decision-making*'.

3. Results on tidal response in the research program 'Safety and Accessibility'

The results of the research program have been described in a large set (32) of reports (available at *http://www.vnsc.eu/organisatie/werkgroepen/onderzoek-en-monitoring/rapporten-v-t.html*). As our objective is to describe the outcomes of research on tidal development with its influence on the setting of the agenda for policy and management, we focus on the two most relevant pictures.

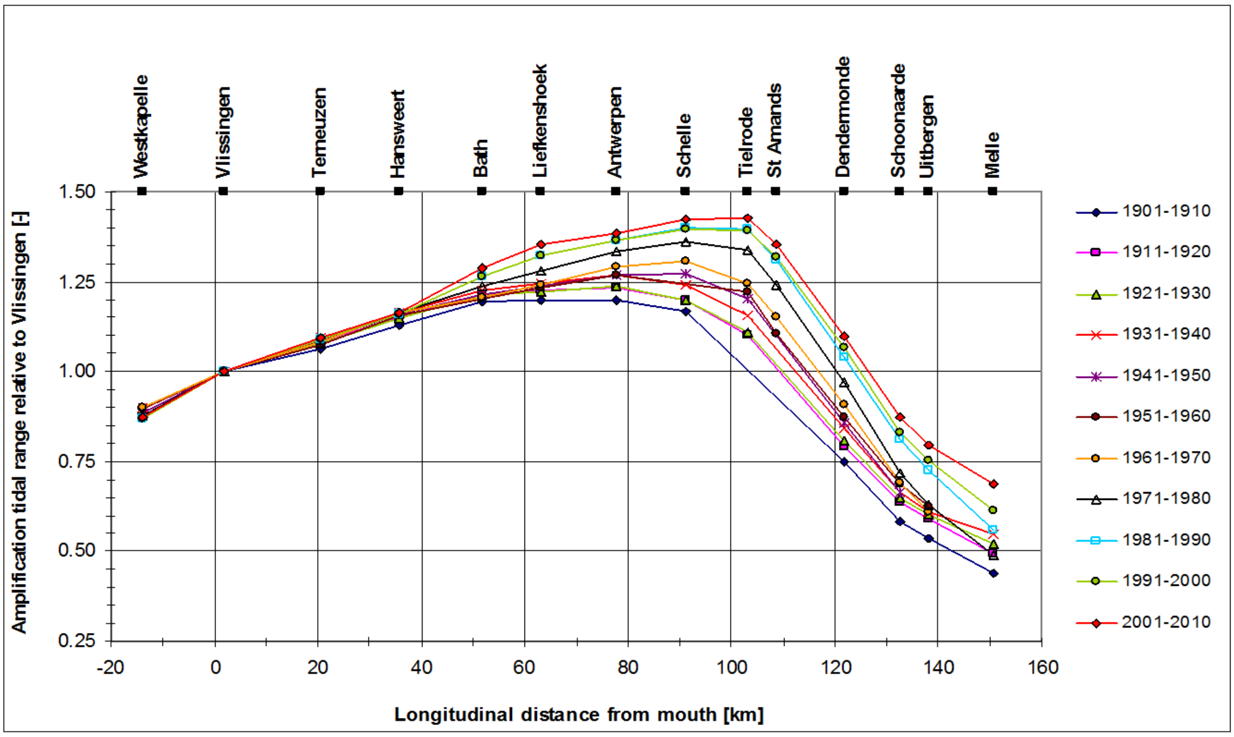

Figure 1: Historical evolution of the amplification of the tide along the Scheldt estuary

Figure 1 shows that the mean tidal range increases nowadays from about 3.8 m at Vlissingen to almost 5.5 m at Tielrode (20 km upstream of Antwerp). More upstream the tidal range decreases to some 2.3 m at Melle near the sluices of Gent. The figure also summarizes the tidal evolution during the last century. In upstream direction the tidal range continuously increased and at the same time the location with maximum amplification shifted in upstream direction over a length of some 40 km. The enhanced intrusion of the tide is even noticeable in Melle, where the tidal range increased with 1 m during the last 100 years.

Theory on estuarine processes predicts that the four most important factors determining tidal intrusion are (i) channel depth / cross section area, (ii) the funnel shape (convergence factor), (iii) the amount of intertidal area and (iv) bed friction. If the Scheldt estuary is evaluated with this in mind, the conclusion can be drawn that during centuries the strategy of reclaiming land and building embankments, played the major role. They made the estuary more funnel-shaped and reduced the amount of intertidal area. During the last half century, however, the channel depth was the most substantial factor, especially in the more eastern parts of the Western Scheldt and in the lower Sea Scheldt.

4. RELATION BETWEEN SEDIMENT BUDGETS AND AMPLIFICATION

Deepening and maintenance of the shipping fairway made the estuary relatively more deep, combined with sand mining and disposal strategies that bring sediment more downstream. Figure 2 illustrates that this was indeed the main cause of increased tidal intrusion from 1970 on. Detailed water level data from the tidal stations of Hansweert and Bath were combined with bathymetrical data. Water levels respond immediately to changes in bathymetry and by analyzing amplification instead of tidal range we exclude the external effects at the boundaries of the estuary (sea level rise, 18.4 year nodal cycle, wind climate on the North Sea) largely.

The graph in the top panel shows that in the last forty years periods of increasing amplification alternated with periods that do not show amplification. A first period of increasing amplification ends around 1980. A second period with increasing amplification starts in the middle of the 1990's and lasts almost one decade. The first period coincides with the first (and largest) deepening of the shipping fairway. The second period starts when the disposal strategy was changed and large volumes of dredged sediments form the eastern part of the estuary were transported to the western part. At the same time sand mining activities were transferred to the Hansweert-Bath area, leading to a further depletion of sediment budgets. Finally a second deepening started in 1997.

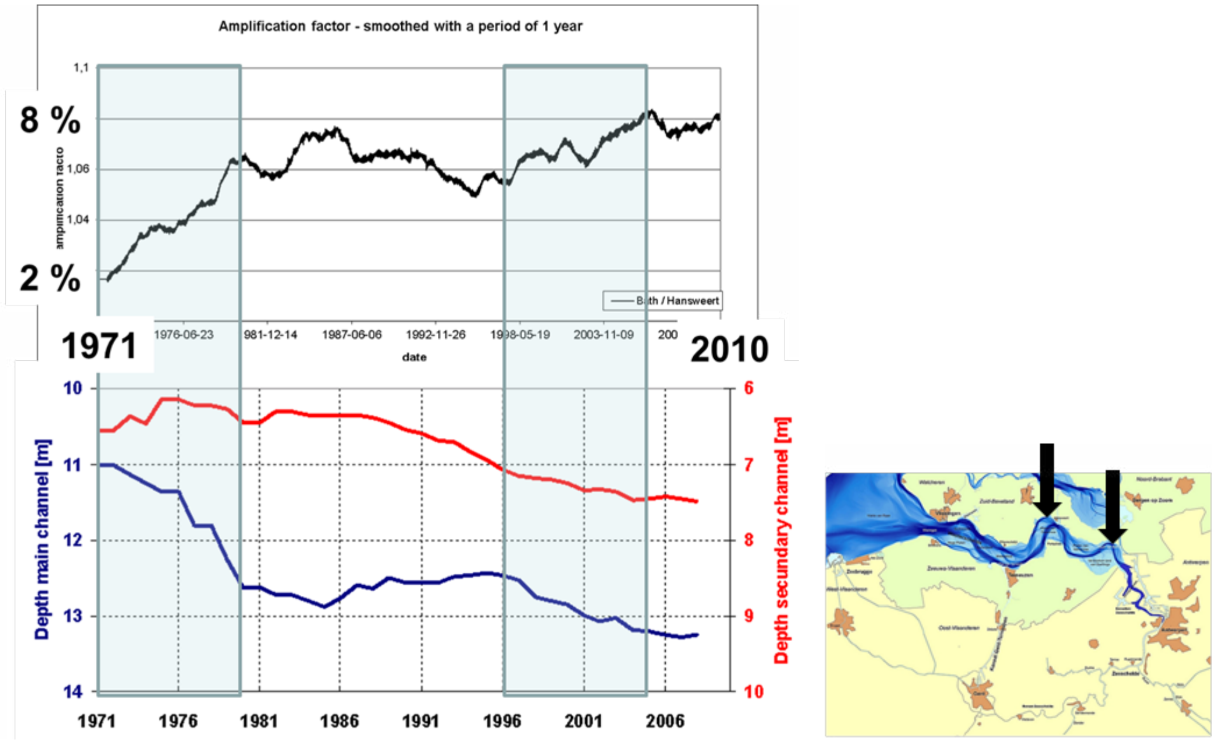

Figure 2: Tidal amplification (top panel) in section Hansweert-Bath and channel depth relative to NAP (Dutch ordnance datum) of the main (blue line) and secondary channels (red line) in the same section (down panel); Scheldt estuary and gauging stations in right panel.

5. THE GROWING ROLE OF TIDAL AMPLIFICATION IN MANAGEMENT OBJECTIVES FOR THE SCHELDT ESTUARY

Within the VNSC it was understood that the tidal regime has strong impacts on safety against flooding, accessibility and ecological values. More tidal intrusion increases the boundary conditions for design of flood protection works, due to higher water levels and changes in the 'foreshore'. The navigability depends on the levels of low water, the deformation of the tidal wave resulting in faster wave propagation and dangerous local cross-currents (during spring tide). The ecological values of the Scheldt estuary are strongly related to the available habitat area, gradients between these and small scale patterns, although the local situations differ strongly, depending a.o. on geometry and historical evolution etc. Finally, increased tidal intrusion may be one of the main factors that has caused a regime shift in comparable estuaries (e.g. the Lower Ems River) with properties that leads to huge import of fine sediments and hyperturbid conditions.

The evaluation of the Treaty on Cooperation in Policy and Management led to an 'Agenda for the Future', describing the issues that need to be dealt with in order to reach the long term objectives. In this agenda there is much attention to 'tidal amplification'. The scientifically grounded conclusions on the development of the tide were probably crucial in getting this on top of the joint political agenda. When the 2005-treaty was evaluated the 'window of opportunity' occurred in which Ministers of both countries needed to take a position on this.

Taking tidal intrusion as (an indicator of the) objective for future policy is attractive for various reasons:

- It reflects a long term development;
- The tidal response changes immediately after changes in the bathymetry / geometry;
- Especially tidal amplification can be linked to changes within the estuary itself;
- For practically all user-functions the increase in tidal amplification is regarded as negative;
- (Part of) the amplification in the past can be linked to human interferences, suggesting that measures must be available to stop or counteract the developments.

6. DILEMMA'S WHEN FORMULATING SEDIMENT STRATEGIES AIMING AT COUNTERACTING TIDAL INTRUSION

The amplification of tidal intrusion in the past suggests that measures must be available to counteract developments. There are, unfortunately, no easy options. Changing the large-scale shape of the estuary would require large interventions or reforming many polders back to estuarine area. The most feasible option seems to be the wise use of dredged material by strategic sediment management. Figures 1 and 2 demonstrate that the most recent amplifications were caused by sediment management as well.

The most prominent challenge for better sediment management is probably in the Sea Scheldt, which has hardly disposal sites for sandy material. The one that is available is kept open by sand mining, implying slowly decreasing sand budgets and probably increasing average cross-sectional area. Also in the more upstream parts of the Western Scheldt preserving or adding sediment to decrease tidal amplification must be done with respect to the shipping demands. There is hardly any space in the main channel upstream Hansweert, hence only secondary channels are available. Disposal in these channels could lead to a (further) shift in the balance between main and secondary channel and is nowadays regarded as a contribution to a gradual change to a one-channel system. This phenomenon induced a different disposal and sand mining strategy in the period 1997 – 2007 (approximately). This was already discussed at figure 2, which shows the profound effects of it on the average depth of the secondary channels between Hansweert and Bath. More tidal intrusion was the side effect, not foreseen at that moment.

There is therefore a large dilemma in weighing various aspects when formulating a sediment strategy, even from a perspective of naturalness and sustainability alone. To complicate it further: the extra costs of a different sediment strategy will probably not easily be accepted, with only the long term changes in the tide to convince decision makers and society. To get to real 'Integrated sediment management' measures must also contribute to (ecosystem) services, both today as in the next decades. At the Dutch coast, for example, the policy of nourishing yearly 12 million m3 is combined with the short term needs, for instance near coastal towns. In the Scheldt estuary these comparable demands on smaller timescales could be the reduction of the costs of safety measures or the creation of ecologically valuable areas. The latter refers to the recent disposals near shoals that are aimed at creating low-dynamic intertidal areas. These, however, do not directly contribute to a decrease of average channel depth.

The Long Term Vision states that preservation of the 'physical characteristics of the estuary' is a prerequisite. One decade later it is still debated 'what exactly should be preserved'. A management plan in such detail is missing. It can, for instance, also be argued that, especially on the long term, a one channel system does not necessarily imply low ecological values. Many other estuaries with one channel have important ecological values, as long as there is 'enough space between the embankments' for the accompanying intertidal areas. Note that for instance in the Ems estuary a change to a one-channel-system, from Eemshaven to Delfzijl, due to siltation Bocht van Watum, is currently not seen as an important management issue.

As a conclusion we pose that we need to accept that from science alone we cannot expect an unambiguous answer when preservation of the 'physical characteristics of the estuary' is fulfilled. It certainly is not meaningful to try to reason towards a 'pristine state' of the estuary or take the 1950's of 1970's as a reference. The choices that have been made on embankments and the situation of ports are an undeniable part of our history. The Scheldt estuary is and will be a modified estuary with safety and accessibility as leading user functions.

The best way forward is to keep on working on specifications of the demands of user functions and agree with stakeholders on a management plan that really defines 'what exactly should be preserved'. This will, undoubtedly, show a diversity along the various places, as both actual values and driving forces are different along sites. To develop such a plan, continuous investments in knowledge of the tides, the morphology and the local hydrodynamics are needed. In this way we may create a way of working that really deserves the name 'Integrated estuary sediment management'.

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TURN THE TIDE: SCIENTIFIC RESEARCH TOWARDS AN INTEGRATED PLAN FOR THE UPPER-SEASCHELDT

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ABSTRACT

During the last 150 years the Scheldt estuary has seen many changes either to claim land for urban or agricultural development or to improve the navigability. From the 1950's onwards the most important changes to the character of the estuary could be attributed to infrastructural works such as dike construction and deepening. Even though cause–effect relationships are difficult to determine it is largely accepted that, besides reclamations, the main contribution to the loss of habitat can be attributed to the increase in tidal amplitude. In various studies the relationship between tidal amplification and large scale engineering works, including deepening, (downstream) sand extraction, embankments and straightening works, has been pointed out. It is clear that anthropogenic changes to the system can have serious consequences to the state of the estuary and that future works need to be prepared in a conscious and sustainable manner in order to avoid further tidal amplification.

Within the framework of the project "Integrated Plan Upper-Seascheldt" commissioned by the Seascheldt division of the Waterwegen & Zeekanaal NV, it is investigated how navigability can be improved (to class Va) without negative effects to nature and safety against flooding. It is the goal of this integrated study to look for synergy in order to mitigate negative impacts of the proposed measures or even to improve the functioning of the system. In the last 10 years already various environmental measures like de-poldering are being implemented under the SIGMA-Plan.

This paper will discuss the evolution of the Seascheldt in relation to historical anthropogenic changes. It will focus on the observed changes in water level, bathymetry, habitats (salt marshes) and sediment concentrations. In addition, the paper will outline the project plan to investigate whether de-poldering projects and other solutions or strategies can be identified that may 'turn the tide'. This study involves applied scientific research to improve knowledge on (ecological) functioning of the Scheldt Estuary by means of a chain of model developments by the project partners (INBO, UA and FHR).

Keywords: *Seascheldt, sediment, habitats, ecology, accessibility*

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FROM STAKEHOLDER TO SHAREHOLDER
– ORGANISING STAKEHOLDER COMMITMENT FOR THE SCHELDE ESTUARY OF THE FUTURE –

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ABSTRACT

The Scheldt Estuary provides the stage for a broad range of stakeholders and (conflicting) interests. These diverging interests led to complex decision-making on estuarine policy and management. The EU Interreg project 'Estuaries on the MOVE' (EMOVE) aims to bring stakeholders together and organize bottom-up commitment for a sustainable Scheldt Estuary of the future, by turning them into shareholders, implying 'ownership' of a particular development or project. Crucial in the approach were: 1) generating a shared understanding on the physical and ecological functioning of estuary and the different perspectives stakeholders have on the estuary and 2) collectively formulating projects and organizing coalitions. The result of the approach was both successful and promising. Five different projects were formulated – ranging from a change in polder regime ('growing land') to a cross-border nature reserve, environmental-friendly sediment disposal techniques, silt agriculture and governance opportunities. The applied methodology of bottom-up project formulation, combined with Group Decision Modelling provided a fruitful ground for measures towards a sustainable Scheldt Estuary that have sufficient support to come to implementation and also important generic lessons for organizing stakeholder commitment in sensitive decision-making environments like estuaries.

Keywords: *stakeholders, shareholders, Schelde, estuary*

1. INTRODUCTION

The Schelde estuary covers both Dutch and Flemish territory. The countries have agreed on joint policy and management of the estuary (laid down in a treaty in 2005). Shipping in the estuary is essential for four major ports, but the estuary also is an extremely valuable, unique and protected nature reserve. Other issues are flood safety, agriculture, salt intrusion and the opportunities for the tourism industry. Due to this multitude of functions, the Schelde estuary is a stage for a broad range of stakeholders and (conflicting) interests. Especially in the past decades these diverging interests led to an extremely tense and complex decision-making process and accompanying implementation. The EU Interreg project 'Estuaries on the MOVE' (EMOVE) has taken up the challenge of bringing stakeholders together and organizing bottom-up commitment in working towards a sustainable Schelde estuary of the future.

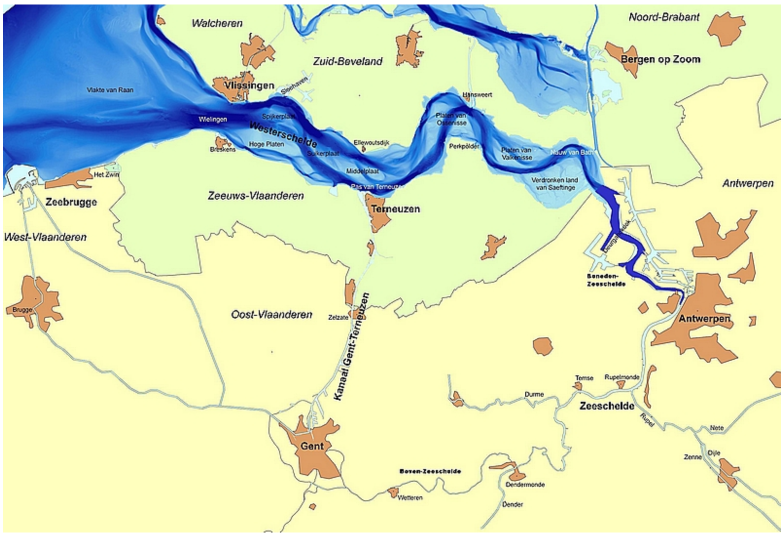

Figure 1: The Schelde estuary, in the Flemish Region of Belgium and The Netherlands, covering approximately 33,000 hectares

An important challenge for the Schelde estuary is 'tidal intrusion'. The tidal regime has strong impacts on the prioritized user functions for both Flanders and the Netherlands: safety against flooding, accessibility and ecological values. However as (Taal et al., 2015) conclude that all these functions have to accept that from science alone we cannot expect an unambiguous answer when tidal intrusion is sufficiently kept under control or which other aspects of the 'physical characteristics of the estuary' should be preserved. Choices that have been made in the past (on embankments, on the situation of ports) are now an undeniable part of our history and part of our objectives for estuarine management. The Schelde estuary therefore is and will be a modified estuary with safety and accessibility as leading user functions.

This means that a major challenge for establishing sustainable management of the Schelde estuary will always be a (political and societal) debate on the possibilities to improve the services the estuary provides. In the past years this debate has been dominated by discussions on nature restoration plans, especially depoldering along the Westerschelde, even though this was part of the 2005 treaty. This issue is off the political agenda since the last court appeal to stop the depoldering of the 'Hedwigepolder' was dismissed in 2014. This final decision and the fact that an official advisory board for the Ministers of Water Management of Flanders and the Netherlands has been (re-)established (Schelderaad, April 2014, including most stakeholders along the Schelde estuary) created opportunities to bring stakeholders together in a more constructive atmosphere than the previous years.

With this context as a starting point, the EU Interreg project 'Estuaries on the MOVE' (EMOVE)[1] started. The main ambition of EMOVE was to turn stakeholders into shareholders, meaning that parties obtain 'ownership' of a particular development or project.

2. ESTUARIES ON THE MOVE (EMOVE)

To reach the ambition described above EMOVE was designed around the following steps:

1. Convening assessment: The purpose of the convening assessment was to gather preliminary information about major issues and expectations that would be relevant for the EMOVE project. The information was used in the design of the project and the stakeholder input process and identify key stakeholders that should be involved.
2. Shared understanding: by means of sharing information and a short process of joint-fact-finding we tried to create a shared foundation of available knowledge.
3. Designing projects and vital coalitions: during this step the stakeholders designed projects and coalitions contributing to a sustainable Schelde estuary.
4. Landing: creating a fertile soil for the projects and coalitions to land on and continue their work after the end of the EMOVE project.

These steps were carried out within the timespan of 12 months, by means of desk research, interviews, bilateral meetings and 4 workshops. In the following sections we describe the 4 steps more elaborately.

2.1 Convening assessment

A convening assessment was held by means of rounds of interviews with stakeholders representing three important user groups: harbours, nature conservation and agriculture. Each time organizations from both Flanders and the Netherlands were interviewed. These interviews did not focus on a 'problem', but asked the respondents open questions with the aim to let them open up for their important interests instead of focusing on problems. By doing so the EMOVE project team wanted to prevent that the project would 'push' the discussion in a direction that was undesired or irrelevant for the stakeholders. Furthermore we asked them in the interviews whether they thought it would be possible for them to identify projects with other stakeholders, and what those could be. Finally we also asked them under what conditions, such as process rules and amount of involvement of stakeholders, they would be willing to work on the identification of potential projects and how they could contribute to this. Finally, because the goal of EMOVE was to create projects in which stakeholders could and wanted to become shareholder, we also tried to identify (potentially) vital project ideas and coalitions. As an illustration table 1 presents an overview of the interests, conditions and opportunities that were identified by the respondents. What we can conclude from these responses is that across all sectors there is a more or less explicit cry out from the stakeholders for convening of the stakeholders and mutual understanding.

Table 1 Interview results concerning interests, conditions, and opportunities

	Harbours	Agriculture	Nature
Interests	– Opportunity to be able to discuss the sustainable development of the Schelde with other stakeholders. – Collaborative knowledge development between the stakeholders. – Gaining insight in the current state of the Schelde system to be able to search for space for development	– to confirm the importance of the economic value of the agricultural sector. – Being able to frame agricultural areas also as having an ecological/nature value – To look abroad for inspiration and also EMOVE should be inspiring.	– Learning from the past before going on. What were the success factors and why did it go wrong with the implementation? – Emove should create support of possible pilots/projects. – Creating mutual understanding between different sectors: not as opponents but as partners.

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[1] For more information on the project and the other estuaries that were involved see: http://www.emove-project.eu

	in a sustainable way.		
Conditions	– Transparency of the process – Use existing knowledge and creating level playing field by sharing knowledge/research. – Pilots/projects should be based on consensus of all the stakeholders.	– Respect towards all stakeholders involved and an curious attitude. No discussion only about conflicting interests. – More attention towards the explanation and communication of the ecological value of the Schelde estuary. – Trying to design projects and pilots that are close to the ‘real’ people and not only – regional scale – policy makers.	– “It takes two to tango” – Willingness to listen to other stakeholders and also some sense for the others interests and ideas. – Being constructive: for example not writing down *who* says something but only *what* has been said. – Decision-makers should respect the outcome of the EMOVE project.
Opportunities	– Creating a shared ‘language’ defining what concepts mean for the Schelde estuary. – Communication between stakeholders has been minimal, EMOVE offers an opportunity to improve this. – Emove should create the shapes of a number of follow up projects or pilots, thus creating a stepping stone for continuity.	– Insight in the effects of salinization and the opportunities this offers for agriculture. – Smart management surplus precipitation. – Growing salt resistant crops. – Insight in the tourist potential of the Schelde estuary.	– Evaluate whether the sediment management is actually reaching the ecological goals it was designed for? – Developing a strategy similar to ‘room for the river’ which combines nature, agriculture and agriculture – Creating an instrument that can be used to test all the projects and plans whether they are: Ecological resilient, economically strong and whether they have societal support

2.2 Shared understanding

To create shared understanding EMOVE used the concept of joint fact-finding. This is described by van Buuren et al (2007). as: *the process in which separate coalitions of scientists and policy-makers and other stakeholders with differing viewpoints and interests work together in order to develop data and information, analyses facts and forecasts, develop common assumptions and informed opinions, and, finally, use the information they have developed to reach decisions together.* However, due to time restraints and the fact that a large joint fact-finding process had already taken place in the Schelde estuary, it was decided to create a ‘pressure cooker approach’. The joint fact-finding had various forms. It started with ‘facts from science’, a memo written by experts on the functioning of the natural system in the Schelde estuary. It also contained a summary of the current governance situation on treaties (Taal, 2014). This memo was also discussed with the stakeholders during their first meeting. Secondly – using the interviews as input – a causal model of the functions and dynamics of the Schelde estuary was designed using Group Model Building (Andersen et al., 2007). This resulted in a diagram that was discussed with the stakeholders. Such a model helps to identify possible feedback loops that could be a topic for projects to be developed by the stakeholders. Finally, also to show how choices from the past still had their impact on the present, a visual narrative of the development of the Schelde estuary from the middle ages until the present was presented and the stakeholders were asked to add to this narrative.

2.3 Designing projects and vital coalitions

During the EMOVE project 4 workshops were organized to take the stakeholders along the path of becoming shareholders. During these 4 workshops the stakeholders designed projects and coalitions contributing to a sustainable Schelde estuary. The workshops are described below.

Workshop 1: Getting on the same page

Due to the fact that the stakeholders came from a period of fierce discussion after the court ruling on the Hedwigepolder, and because the interviews clearly showed a need for an open and trusting approach, the EMOVE project decided that we have to take things slow to deal with this fragile situation. We started the workshop on a personal level and asked all the participants to bring a picture of what the Schelde estuary symbolized for them and asked them to ‘speed-date’ with the other stakeholders that were present. By starting a meeting on a personal note a conflict about more abstract concepts could be prevented. The stakeholders discussed the memo on the state of art (see paragraph 2.1). After that we wanted to make the step to project ideas. To help this we first tried the stakeholders to let them find their mutual gains by identifying in duo's how the Schelde estuary helped them, and where it 'obstructed' them. Starting from these 'gains' more than 50 initiatives were suggested.

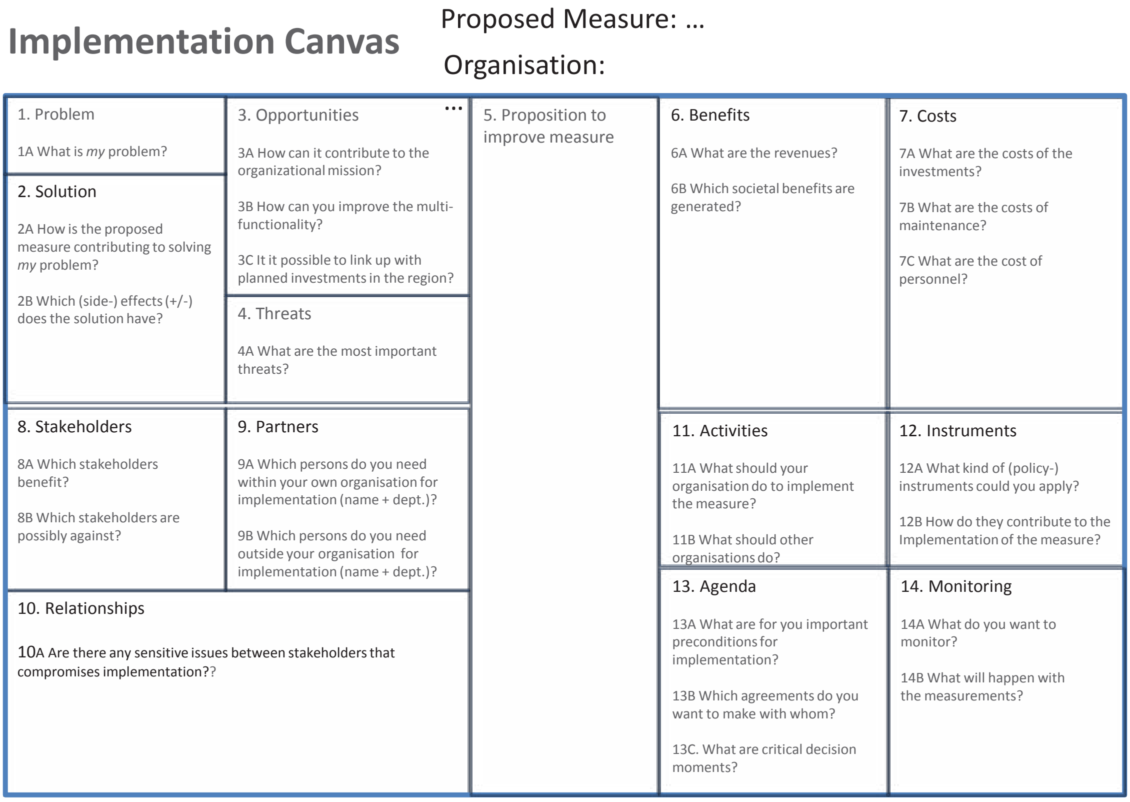
Workshop 2: Selection of projects
There was almost a gap of 2 months between the first and second workshop and some new stakeholders joined the process. Therefore we started the second workshop with 'a step back' and did not directly go to the selection of projects from the first workshop. We feared that we would surprise the stakeholders otherwise too much. Instead, we took extra time for sharing facts, visions and ideas between the stakeholders in three subgroups.

During the second part of the workshop we showed the stakeholders the list of initiatives-from table 3 the first workshop. After that we gave them the opportunity to change or add to this list and they could then also 'vote' for the initiative/project idea that appealed to them the most. Finally we also wanted the stakeholders to trigger in becoming shareholders. We did this by letting the stakeholders take up the ideas/initiatives that they came up with themselves. This was a crucial moment, as they would make the step from stakeholder to active shareholder. For this reason we gave instructions for the next step and asked the stakeholders who wanted to go on with one of the projects to take these instructions and invite others to form a coalition. We also stated that if they picked up the instructions they could join us for an additional working session. Eventually 5 groups picked up the instructions resulting in in five initiatives/active project ideas.

Table 2 Selected initiatives/project ideas that were further developed by stakeholders

Initiatives /Project ideas	**Stakeholders involved**
1) 'Growing land': bringing back dynamics into agricultural polder areas and thus heightening the land, and creating nature areas. At the same creating agricultural polders from nature areas.	Agriculture Nature organisations Harbours Recreation Government (waterways)
2) Creating hydro morphologic measures that contribute to the strengthening of eco system services concerning nature, accessibility and safety in the Schelde estuary.	Government (waterways) Harbours Civil organisations Research
3) Creating a cross boundary nature park including recreational functions.	Municipalities Regional government Nature organisations Agricultural organisations Local recreation entrepreneurs
4) The support engine for the Schelderaad: more a process business case in which the newly formed Schelderaad would be supported by a – activity and agenda setting based – help team.	Government (waterways) Nature organisations Schelderaad members
5) Silt agriculture: growing salt resistant/allowing crops on areas that were influenced by salt intrusion.	Agriculture Nature Municipalities

Workshop 3: Working on the pilots
As we did not want the newly formed coalitions to be left alone for 2 months, we offered help in the start-up phase with an facultative extra work-session for their initiatives. During this session they worked as a coalition on their initiative. We used the implementation canvas (van der Brugge en Ellen, 2013) for this working session. The canvas was used because it quickly brings together important challenges concerning the implementation of measures or the realisation of project ideas.



Implementation Canvas

Proposed Measure: …

Organisation:

1. Problem

1A What is *my* problem?

2. Solution

2A How is the proposed measure contributing to solving *my* problem?

2B Which (side-) effects (+/-) does the solution have?

3. Opportunities …

3A How can it contribute to the organizational mission?

3B How can you improve the multi-functionality?

3C It it possible to link up with planned investments in the region?

4. Threats

4A What are the most important threats?

5. Proposition to improve measure

6. Benefits

6A What are the revenues?

6B Which societal benefits are generated?

7. Costs

7A What are the costs of the investments?

7B What are the costs of maintenance?

7C What are the cost of personnel?

8. Stakeholders

8A Which stakeholders benefit?

8B Which stakeholders are possibly against?

9. Partners

9A Which persons do you need within your own organisation for implementation (name + dept.)?

9B Which persons do you need outside your organisation for implementation (name + dept.)?

10. Relationships

10A Are there any sensitive issues between stakeholders that compromises implementation??

11. Activities

11A What should your organisation do to implement the measure?

11B What should other organisations do?

12. Instruments

12A What kind of (policy-) instruments could you apply?

12B How do they contribute to the Implementation of the measure?

13. Agenda

13A What are for you important preconditions for implementation?

13B Which agreements do you want to make with whom?

13C. What are critical decision moments?

14. Monitoring

14A What do you want to monitor?

14B What will happen with the measurements?

Figure 2 Implementation canvas (Van der Brugge and Ellen, 2013)

Workshop 4: Presenting the results and taking the next step.
In the first part of the final workshop we asked the coalitions to present their projects and use the other stakeholders to improve the projects, with the implementation canvas as the guideline: improving and filling in the blanks. In the second part of the workshop we brought back the joint fact-finding results from the interviews and the workshops by presenting a 'narrative' of the Schelde, where we also included the pictures that the stakeholders took with them for the first workshop.

2.4 Landing and aftermath

Because the EMOVE project wanted to prevent that the projects did not stop after the last workshop EMOVE made sure that the projects were presented to the chairman of the Schelderaad. Also we ensured that the projects would be on the agenda of the next meeting of the Schelderaad, with a request for an official reaction towards the Flemish-Dutch Schelde Committee. By doing so, the EMOVE project safeguarded that the projects would also be brought to the next step of decision-making.

3. CONCLUSIONS and outlook

Looking back on the process of EMOVE we learned the following:

1. Start with the energy/enthusiasm of the stakeholders instead of a large problem or with a strategy that the stakeholders could react upon. We put them a bit off their feet – and also got a lot of questions from the stakeholders like 'where are the solutions we should react on' but it also triggered the stakeholders to come up with innovative ideas.
2. Give the stakeholders the opportunity to bring in the issues that they thought were important for sustainable development of the estuary. We did this in the interviews, but also in the first workshop, in small groups, letting them tell each other what was important for them: where did the Schelde help them?
3. By getting the stakeholders to actually put down their ideas together, they also feel responsible for those ideas, which also helped them to create a coalition.
4. Timing: in our case taking advantage of a 'window of opportunity': the fact that there was recently a new stakeholder platform in the Schelde, which was also looking for activities to undertake, helped us in the EMOVE project substantially. The stakeholders also felt an urgency to act after years of relative impasse.

The lessons above also indicate that trust and opening up for alternative solutions and processes can help to 'break' a deadlock situation. It can be argued that this might – in certain cases be an alternative to more top down oriented approached which usually ask for more time and political urgency. In this sense, a bottom up urgency from an area, region or multi-stakeholder group itself is leading, instead of a political urgency.

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ECOSYSTEM SERVICES, A USEFUL CONCEPT FOR THE RESTORATION OF ESTUARIES?

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ABSTRACT

The Schelde estuary was subjected to major human impacts leading to major environmental problems such as pollution, habitat loss, but also increasing water levels leading to higher risks of inundations. In this paper we describe how an approach using the ecosystems service concept was applied as a basis for restoration of the estuary.

Keywords: Estuarine restoration; ecosystem services, Schelde estuary

1. INTRODUCTION

The Schelde estuary with a length of 160 km, a surface of more than 350 km² and a tidal amplitude of up to 5.5 m on average, was subjected to major human impacts over the past centuries (Meire et al., 2005). Starting already more than 1000 years ago, land reclamation is responsible for an enormous reduction in tidal areas, reducing the estuary to its present size and shape. As shipping became more and more important and especially ship sizes increased, important dredging works further changed the morphology of the estuary. Since the beginning of the 20th century, pollution coming from the catchment and the industry along the estuary lead to a dramatic decrease in water quality with large parts of the estuary being anoxic for most of the year (Meire et al. 2005).

Environmental legislation led to a reduction in emissions and by now water quality improved and no anoxic periods occur anymore. Also measures for habitat restoration are undertaken. Although there are some clear objectives formulated (eg water quality standards, conservation objectives, safety levels, depth of the fairway,..) there is a clear lack of more integrated objectives. Indeed there is a close relation between tidal characteristics and estuarine morphology and between morphology, tidal characteristics and water quality. Restoration of tidal areas might impact both tidal characteristics as well as water quality and ecological functioning. However these aspects are not or rarely taken into account in current policy frameworks and no integrated objectives for estuaries are formulated.

In this paper we explore the concept of ecosystem services and describe how it was used in the restoration of the Schelde estuary. The concept of ecosystems services, the direct and indirect benefits people derive from ecosystems, proved to be a very useful and unifying concept that allows to put forward more integrated objectives and come to more integrated projects.

2. ECOSYSTEM SERVICES

A crucial element is the Ecosystems services (ES) delivered by the biophysical system. ES are simply defined as “the benefits humans derive from nature” (MA 2005). They can be grouped in four major categories: provisioning services include food (fish, game, fruit,…), water (drinking, irrigation, cooling), raw materials (fiber, timber,…), genetic, medicinal and ornamental resources; regulating services as air quality regulation, climate regulation, moderation of extreme events (storms, floods,..), regulation of water flow, waste treatment (water purification), erosion prevention, maintenance of soil fertility, pollination and biological control; habitat services being the maintenance of life cycles of species and maintenance of genetic diversity and finally the cultural services being recreation, aesthetic and spiritual experience, information for cognitive development (TEEB, 2010). The large loss of biodiversity in the last decades resulted in a serious reduction of the ES delivered to men by the remaining ecosystems. This was for the first time clearly shown in the Millennium Ecosystem Assessment, a document prepared by more than 1360 experts from all over the world under the coordination of UNEP (MA, 2005). Crucially important is that in the millennium ecosystem assessment it is clearly shown that there is a tight link between the ES and the constituents of human wellbeing such as security, basic material for good life, health, etc. Indeed, we are to a very large part dependent on these ecosystem services. The importance of these losses of ES, not only in terms of biodiversity loss, but also in economic loss became clear since the very influential paper of Costanza and coworkers in Nature in 1997 (Costanza et al. 1997) where for the first time the economic value of the earth’s ecosystems was calculated and proved to be as large as three times the gross global product. Some of this value comes from direct use values (the prices we pay for marketed ES) but the largest part is due to the indirect use values. This is the price we have to pay to compensate a loss of ecosystem services (the loss of a floodplain might result in flooding of inhabited areas, the cost for infrastructure to protect this area against flooding can be seen as the economic value of the lost flood plain). The concept of ES allows to link on the one hand the ecological aspects and on the other hand the economic aspects and as such might become a crucial element for restoration and sustainable development. Not surprisingly the concept of ES was taken up very quickly by different environmental organizations like IUCN, but also by large bodies like the World Bank, UN and several governments. In Europe the TEEB (The Economics of Ecosystems and biodiversity) study forms a milestone in the development and the application of the concept (TEEB, 2010). It is very likely that it will be taken up in environmental legislation in the near future and that it can become a crucial concept in IWRM (Integrated Water Resources Management). Not taking these into consideration might lead to unprecedented poverty and environmental problems as the biophysical system is the basis for the human society.

3. APPLYING THE ECOSYSTEM SERVICE CONCEPT IN RESTORATION: THE CASE OF THE SCHELDE ESTUARY

Taking into account the whole concept of ES was also the base of the integrated management of the Schelde estuary. As a result of the human interventions in the estuary, most ES delivered by the system are seriously deteriorated resulting in major problems, such as increased risk of flooding, collapse of fisheries, increased erosion, reduced sink function for nutrients and pollutants leading to higher loads going to the coastal sea. The loss of ES was either compensated by very expensive management measures or simply “suffered” (eg the complete loss of recreational and professional fisheries in large parts of the estuary). Insight in the concept of ES resulted in a very fundamental change in the vision of the classical managers and led to the understanding of having a common problem for both economic and ecological management and the need to manage the whole of the estuary as one system based on integrated solutions. An integrated strategy requires the understanding of the ES and their quantification. If we take the tidal marshes as an example, they are important for storage of flood water, sedimentation and as sink or source for nutrients among many other ES (Van Damme et al., 2009). For example silica is a very important element because it is essential for the growth of diatoms that form the basis of the food chain and are the most important group of phytoplankton responsible for most of the primary production. Dissolved silica, taken up by diatoms, is incorporated in biological structures: Biogenic silica. This form cannot be used by diatoms anymore. It enters at high tide with the floodwater in the tidal marshes and is there transformed back into dissolved silica, the form that can be used again by diatoms, and exported at low water to the estuary (Struyf et al. 2005). This recycling of Silica was shown to be very important to sustain the primary production in the summer months. The next crucial step is to determine our objectives. Here it is of utmost importance to move from classical environmental objectives such as basic water quality standards or protection of biodiversity or classical economic objectives such as a fairway of 13 m deep to more integrated objectives including the crucial elements of the system and taking both ecological and economic elements into consideration. In the long term vision made for the Schelde estuary objectives were formulated for accessibility, safety and naturalness of the system. These must be made more precise and can be formulated as: ‘which and how much services the ecosystem must deliver?’ This means a functional approach. This can be seen as determining the carrying capacity not only for species (the classical ecological approach) but also for ES. For example, One can determine a volume of water that should be stored on marshes to control water levels in case of a storm surge or the amount of primary production needed to sustain the nursery function or the productivity in the coastal sea. It can be determined as the retention of nutrients which is needed in the estuary to prevent eutrophication in the coastal sea or how much we want to reduce the increase of the high water level, etc. These objectives, must then be translated into a surface of the habitats (and of a population size of species) delivering these ES. If the goal is to recycle X tons of biogenic to dissolved Silica and we know that mashes transform Y $g.m^{-2}$ the surface needed can be calculated, being X/Y. This exercise can be done for the different ES and will result in a surface of different habitats needed. Of course each habitat delivers several ES which allows us to have many win-win situations and innovative measures can be worked out.

To reach the required safety level for protection against flooding in the Flemish part of the Schelde estuary, it was calculated, using an advanced hydrodynamic model, that 1800 ha of flood control areas (FCA) are needed along the Scheldt estuary to reach the required safety against floodings (Broeckx et al. 2011). Flood control areas are low laying polders near the river, surrounded by dikes. The dike near the estuary is lower than the ring dike to allow overtopping of the dike at high water during storm tides. At low tide, the water is flowing back to the estuary through big sluices in the dike. Similarly, it was calculated that even when the water quality of all tributaries meets the WFD standards, still an additional 1300 ha of marshes and 500 ha of tidal flats in the estuary are needed to avoid Si limitation, reduce N loads, provide enough benthic biomass for migrating and wintering waterbirds etc. On top of that about 4000 ha of non tidal wetlands are required as habitat for rare species, to buffer peak discharges etc (Adriaensens et al. 2005).

The advantages of defining the Conservation Objectives in such a comprehensive and systemic manner are huge. It does not only put the emphasis on protecting and restoring species and habitats, but to a very large extent it also emphasizes the fundamental problems of the system (such as increasing tidal energy) that negatively affect both the ecology and economy of the system. The ES-approach is also an opportunity to link the various environmental legislations (Bird and

Habitat-, Water Framework-, flood directive etc.). This enables a truly integrated approach and makes it much easier to negotiate with all of the different stakeholders.

This approach led also to the development of entirely new concepts such as flood control areas with a restricted controlled tide. A pilot project, the Lippenbroek, was realized in 2006 and since then monitored in detail. During storm tides, water overtops the dike and is stored in the polder having a reducing effect on high water levels, increasing safety. During normal tides a limited amount of water enters the polder through sluices resulting in a much reduced tidal amplitude. However this is enough to allow the major ecological processes like nutrient retention to work very well in that area. In this way several objectives are integrated.

4. LIPPENBROEK: A PILOT STUDY

To derive the surfaces mentioned it is important to combine several services in one habitat. Indeed biodiversity development as well as flood storage and biogeochemical processes, could be combined in the same habitat. This requires new concepts, an example is a flood control area (FCA) with a controlled reduced tide (CRT). For safety reasons FCAs are necessary, however they are flooded only occasionally (once or twice a year on average) during storm surges. It is however, perfectly possible to introduce a tidal regime in a FCA by using culverts in the dike. This is done in such a way that the tidal system allows the development of a marsh system but at the same time the storage capacity of the area for flood water is retained. The tidal amplitude in the FCA is controlled and reduced. This innovative concept of introducing a CRT into a FCA has been implemented in the pilot project “Lippenbroek”, the world’s first FCA-CRT (Cox et al. 2006; Maris et al. 2007). Operational for six years, the Lippenbroek clearly delivers some important ecosystem functions as predicted. Oxygen poor estuarine water that enters the CRT is enriched up to 80 % saturation or more at the outflow. Nutrients are removed, e.g. the total dissolved nitrogen and phosphorus concentrations are reduced during one tidal cycle. The area is a hotspot for primary production and serves as a nursery and feeding ground for fish. This concept is now applied in large parts of the flood control area of Bazel, Kruibeke, Rupelmonde. This area of over 600 ha is essential for flood control. The original plan, dating back to 1976, aimed only at safety and in the 1990 the plan was adapted to accommodate different ES in a true integrated way. A cost benefit analysis, taking into account the ES, clearly proved the overall economic benefits of the integrated plan versus sectorial plans. (Liekens et al., 2009)

5. CONCLUSIONS

Optimization of ecosystem services proved to be a promising approach and should be at the heart of estuarine management. In the case of the Schelde estuary, it was the key factor to convince politicians and decision makers to take ecological restoration seriously and understand the benefits of an integrated approach. However, much more work is needed to identify and quantify ecosystem services and relate these to human well-being and economic parameters. Furthermore, if we want to use the ES approach as a strategy to also protect biodiversity, a better understanding of the relation between functional and structural biodiversity is crucial.

A successful restoration plan should be based on a comparison between the quantified losses and the desired levels of services. This in turn must be translated into the surface and quality of each habitat needed to deliver the required amount of service. Modelling is an indispensable tool and field experiments are crucial to increase our understanding of the system.

The Millennium Ecosystem Assessment can be seen as a milestone and stimulated a lot of new research, the field of ES science is developing exponentially. Although many examples of integrated projects, proofs of concept, already exist, still a major effort is needed to really implement the ES and integrated approach not only in policy documents but in the field. As water is the crucial link between all ecosystems from source to the coastal sea, the water framework directive should apply the ES approach as a cornerstone of integrated water resources management.

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A SMOOTH SCHELDT

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ABSTRACT

The Western Scheldt is the seaward part of the Scheldt estuary with a pronounced multichannel morphology and extensive intertidal flats. Observations of the bathymetry and aerial photographs of the intertidal and supra-tidal environments over the last 60 years reveal distinct transformations of the morphology on various spatial scales. The overall change is from an irregular distribution of intertidal flats with branching channels and shallow areas towards smooth tidal flats in between the main channels. A decline in the number of small tidal channels – ebb- and flood chutes and channels that connect the main ebb- and flood channels, is observed throughout the Western Scheldt. The large number of small tidal flats have merged into a limited number of bigger entities, and the jagged edges of the flats have given way to almost straight water lines. The surface area of the intertidal flats that is covered with mega-ripple fields has decreased. Mechanisms that account for the changes on all scales throughout the Western Scheldt have not been recognized. So far intrinsic pattern development and/or the closure of branching tidal basins are recognized as candidates to explain the changes.

Keywords: Estuary, Morphology, Bed forms

1. INTRODUCTION

The Scheldt estuary is one of Europe's larger estuaries. The estuary has its seaward part – The Western Scheldt- in the Netherlands and the landward parts in Flanders (figure 1). The estuary serves as a shipping lane and hosts major harbors. The estuary is recognized as a wetland of international importance and protected under EU-legislation (the Habitat- and Bird-Directives). The estuary funnels storm surges to the hinterland and thus requires flood-protection schemes to protect the inhabitants and economic activities on its banks. The important (ecosystem) services provided by the estuary require a careful management to balance their often contrasting needs. Ongoing studies of various aspects of estuarine development are an essential element of the estuarine management and this study is one example from many, executed in cooperation between the Netherlands and Flanders.

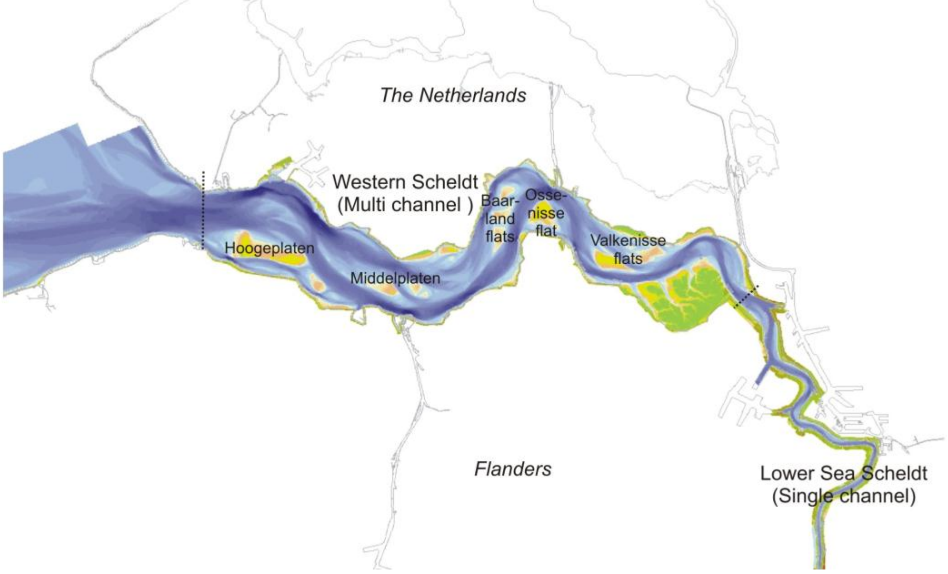

Figure 1. Map of the Scheldt-estuary. The dotted lines mark the boundaries of the Western Scheldt.

Two morphological characteristics of the Western Scheldt are regarded essential for its ecological value. The presence of multiple channels (the main eb- and flood channels and connecting channels) results in intertidal flats that have no connection to the main land and are thus difficult to access. These intertidal flats provide undisturbed feeding grounds for waders during low water. The quality of the intertidal feeding grounds is determined by the presence of macrobenthos (bivalves, worms, crustaceans). One factor that limits the presence of macrobenthos is the reworking of the sediment by tidal currents. Reworking is eminent in areas with migrating mega ripples. Reworking is also thought to limiting the abundance of macrobenthos in areas without distinct bed forms.

The character of the intertidal flats in the Western Scheldt has changed over the past century. The number of interconnecting channels has decreased and the surface area covered with mega ripples has decreased. While the total surface area of the inter tidal flats has been relatively stable, the number of inter tidal flats has decreased and the length of the (low) water line has decreased. The overall appearance of the Western Scheldt inter tidal flats has changed from small with jagged edges to large and smooth. In this extended abstract the observation will be presented along with hypotheses on its origin.

2. DATA AND APPROACH

The data used for the analysis consists of digitized and digital bathymetric data (these cover 1818 to 2012) and the geomorphological maps (1959 to 2012).

The bathymetric data cover the entire Western Scheldt: tidal channels, intertidal flats and supra-tidal areas. The frequency of the soundings has increased over the centuries and since 1996 a bathymetric dataset of channels and intertidal flats is made annually. The digital bathymetric data from 1955 on have an accuracy that is sufficient for quantitative morphological analysis, including the development of the height of intertidal flats, the depths of channels and the development of the sediment volume. The bathymetric data prior to 1955 is used for the comparison of channel patterns, but lacks the accuracy for quantitative morphological analysis.

For this study a visual comparison of the distribution of intertidal flats and connecting channels has been performed. In earlier studies the number of inter tidal flats, the length of the circumference of the intertidal flats and the meso-scale index (= tidal-flat surface area/circumference) have been calculated.

The geomorphological maps cover the intertidal flats and supra-tidal areas and are based on aerial photographs. Different types of photographs have been used for the analysis, from black and white for the older datasets via color images to the false color images that are used from 1996 onwards. Image analysis of the photographs reveals distinct patterns that are mapped and attributed to classes. The geomorphological classes include the presence of marsh vegetation, rocks (artificial), Holocene peat and clay deposits, sandy or silty bed composition and the presence or absence of mega ripples and other large bed forms. Small bed forms (current and wave ripples) cannot be detected because these are smaller than the resolution of the imagery. In the present study the absence or presence of mega-ripples in the geomorphological maps is used. The geomorphological maps from 1996 to 2012 have been used for quantitative comparison, the older maps are used for pattern evaluation.

3. THE EDGE OF THE FLATS

The intertidal flats regarded primarily in this study the complexes surrounded by tidal channels indicated with their names in figure 1. In the detailed map of the Middelplaten complex in figure 2 these areas are marked with 1. The intertidal flats on the banks of Western Scheldt (marked 2 in figure 2) have displayed less marked changes over the years. The number of intertidal flats that are surrounded by tidal channels has decreased from over 50 in 1959 to over 20 in 2004 (Cleveringa, 2007). The total length of the waterline surrounding these intertidal flats has decreased. The geometry of the tidal flats and their number is primarily determined by the tidal channels that surround the flats.

A short introduction in to the typology of the channels helps to understand which changes have occurred. The tidal channels are marked in figure 2, with a subdivision in:

A. The main ebb- and flood channels of the estuary;
B. Connecting channels that connect main channels and thus intersect the intertidal-flat complex;
C. Ebb- and flood chutes.

All of the above channels have undergone changes that have affected the geometry of the tidal flats. The main channels have become more continuous throughout the estuary over the years, because many of the shallows (‘drempels’) that used to exist where the main ebb and flood channels meet have been dredged. With the disappearance of most of the shallows the number of ebb- and flood chutes has also drastically reduced. Ebb- and flood chutes were not restricted to the shallows, they pinched into the flats in other places as well. Such indentations into the flats by ebb- and flood chutes have become rare. The number of connecting channels has also decreased and in fact the map in figure 2 displays all but one of the remaining connecting channels.

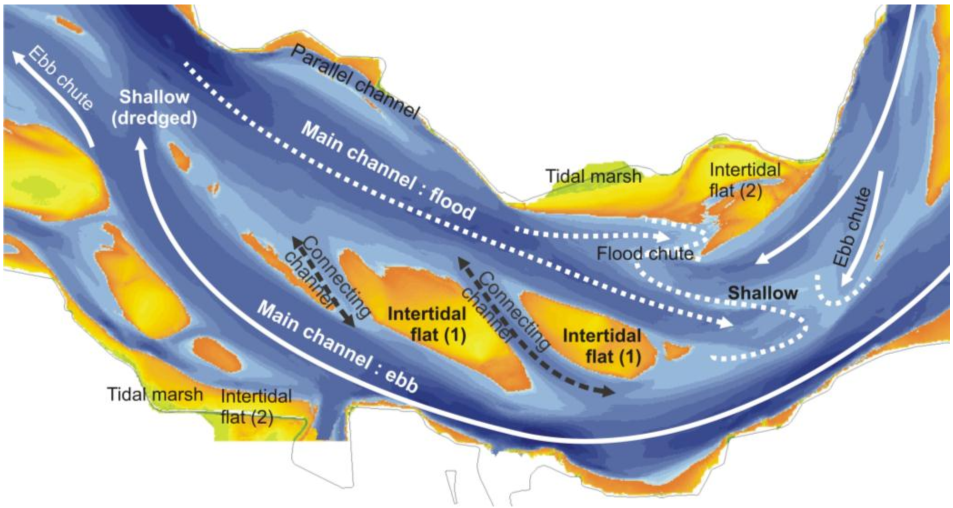

Figure 2. Map of the Middelplaten intertidal flat complex with the surrounding tidal channels (in 2013).

4. MEGA RIPPLE ABUNDANCE

Mega-ripple fields are characteristic elements of the Western Scheldt that range from the intertidal flats into the sub-tidal domain. Western Scheldt scale mapping of the sub-tidal mega-ripple fields has not been performed and therefore the analysis is restricted to the intertidal ranges. The abundance of the mega-ripple fields on the intertidal flats has decreased with several hundred hectares from 1996 to 2012 (figure 3). The graph also shows that the rate of changes varies and includes a massive drop over 400 ha. The recent observations (2011 and 2012) have shown a slight increase in the extent of the mega ripple fields.

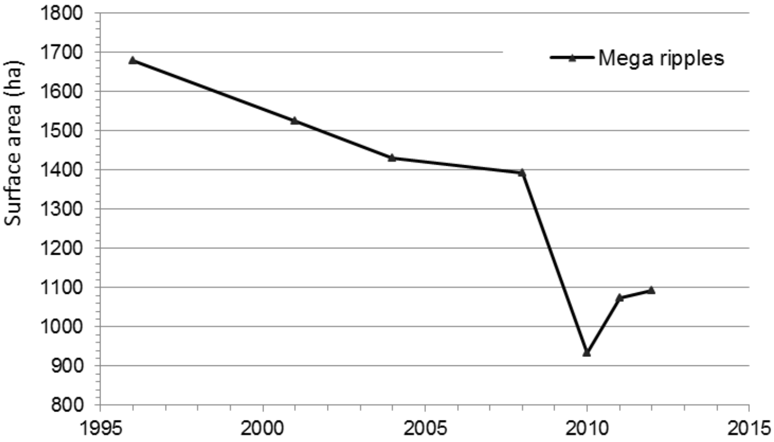

Figure 3. Graph of the extent of mega-ripple fields on the intertidal flats of the Westerns Scheldt (from the geomorphological maps).

Comparison with the older geomorphological maps shows that prior to 1996 mega-ripple fields were even more abundant. A visual comparison of the maps from 1959 and 2012 in figure 4 reveals the decrease of the mega ripple fields. These maps also reveal that the mega-ripple fields are primarily located on the fringes of the intertidal flats that are surrounded by tidal channels. Mega-ripple fields are scarce along the banks of the Western Scheldt.

5. DISCUSSION

The decrease of the number of intertidal flats and the reduction of the length of their water line may have the same causes as the decrease of the mega-ripple fields. The favored location of the mega-ripple fields are the edges of the intertidal flats. And there are less edges now then 60 years ago. The developments relate to the tidal flow and sediment transport along (through the main channels and connecting channels) and onto the intertidal flats (through ebb- and flood chutes and over the mega-ripple fields).However, a mechanism or mechanisms to explain changes in the tidal-flow and sediment transport along and onto the intertidal flats is missing. The observed increase in the height of the intertidal flats may be a component to include in the explanation.

Mechanisms have to be applicable throughout the Western Scheldt because the developments have occurred in the entire realm. That excludes changes in the tidal range, because these have been small in the western side and larger in the east. Similarly, dredging and dumping are unlikely candidates to explain these developments because their intensities have varied on the scale of the Western Scheldt. A mechanism that may account for the developments on this scale is the (slow/delayed) response to the closure of the branches over the last centuries. The pattern of branching tidal channels that intersect the flats in 1959 may be inherited from the older situation where these channels diverged into smaller channels in the branches. Our understanding of the patterns and pattern development of channels in tidal basins is evolving and new experiments with numerical and physical models may shed some light on the likelihood of this and other explanations. This also holds for intrinsic pattern development of tidal channels and flats as a potential explanation for the development of the smooth Scheldt.

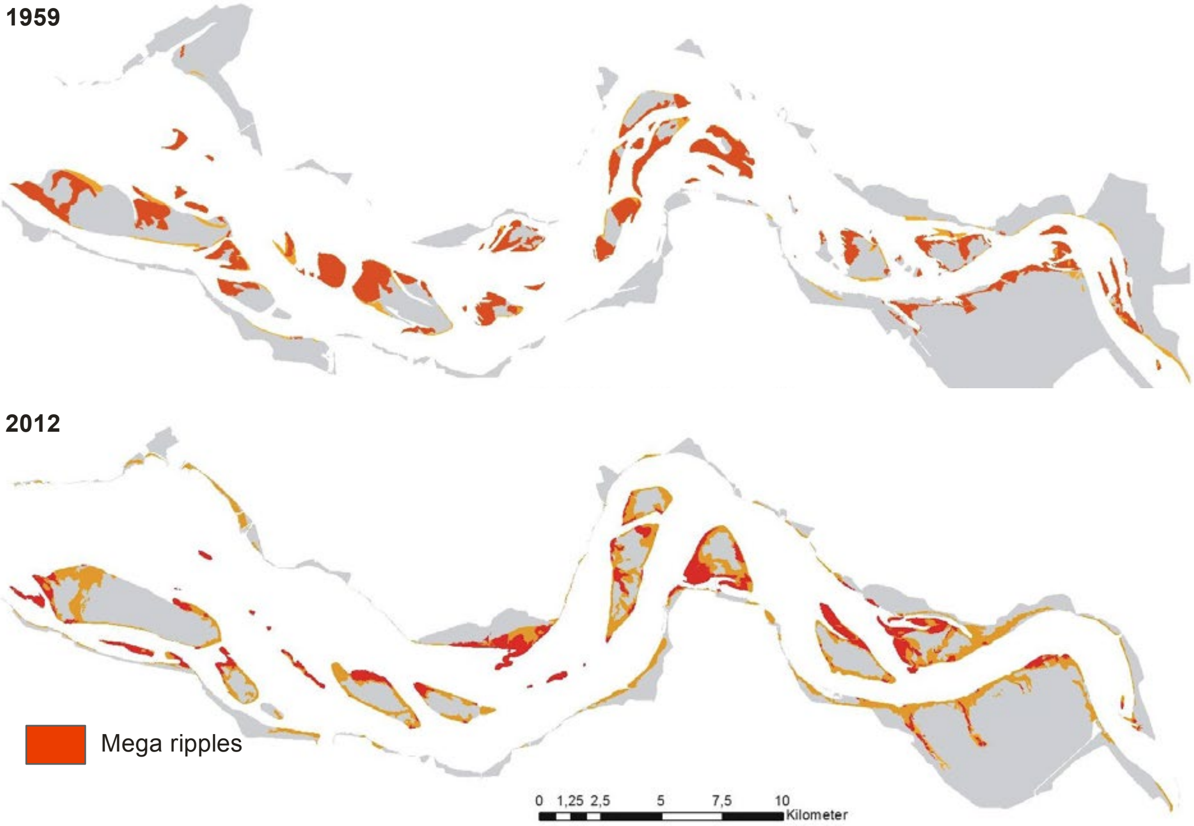

Figure 4. Maps of the intertidal flats and tidal marshes in the Western Scheldt (grey and orange), with the mega ripple fields in red.

It is difficult to assess the appreciation of these developments. The waterline is considered to be of major interest for some waders. Therefore the reduction of its length is not welcomed in view of the ecological value of the estuary. The mega-ripple fields are areas with limited abundance of macro benthos. But the decrease of mega-ripple fields so far has not resulted in an increase of richer feeding grounds for birds and this is as yet not well understood. In terms of policy making and estuarine management the observed developments and lack of explanations make it complex to set goals and realize measures.

6. CONCLUSIONS

The morphology of the Western Scheldt has changed from an irregular distribution of intertidal flats with branching channels and shallow areas towards smooth tidal flats in between the main channels. Small tidal flats have merged and the jagged edges of the flats have given way to almost straight water lines. The surface area of the intertidal flats that is covered with mega-ripple fields has decreased. The developments relate to the tidal flow and sediment transport along (through the main channels and connecting channels) and onto the intertidal flats (through ebb- and flood chutes and over the mega-ripple fields).

ACKNOWLEDGMENTS

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A FIRST PHASE IN THE HABITAT CLASSIFICATION FOR THE ZEESCHELDE : BED FORM CLASSIFICATION.

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ABSTRACT

Within the scope of the long term vision of the Schelde estuary and the Development Outline 2010 low dynamic intertidal and shallow water areas are considered to be of high ecological value. These areas are in fact linked to eutrophic foraging zones for birds and young fish and to refugees for tidal migrators. However, this assumption is based on experiences in other areas and there is no evidence that all parts of the shallow water area are equally valuable. Little is known about the occurrence of such valuable areas in the Schelde estuary, nor are the physical and morphological processes which determine the occurrence of these areas fully understood.

Following research on this topic on the area near the Walsoorden Sandbar in the Westerschelde (the Netherlands) in 2008-2009, a new research project was defined to determine relationships between physical, sedimentological and ecological characteristics in the Zeeschelde (Belgium) and to set up a classification of undeep subtidal and intertidal areas.

A first step in the habitat classification comprised of a detailed analysis of 5 sub areas, each characteristic for a certain salinity zone. The first phase of the analysis of the subareas consisted of an analysis of multibeam echo sounding data in respect to the occurrence of bed forms, which resulted in a classification of each sub area in a limited amount of bed form classes.

In a second phase a numerical hydrodynamic model was used to determine hydrodynamic characteristics for each of the subareas. Based on the results of the first two phases, accordance between hydrodynamic and physical characteristics was sought, but none could be found. However more insight was obtained about the range of bedform sizes and the configuration of hydrodynamic zones. In a last phase data from the first two steps will be combined with ecological parameters to try and find relationships and develop a map of the spatial variation of the ecological value for the different sub areas.

Keywords: Habitat classification, Zeeschelde, Bed forms, Hydrodynamics, ecology

INTRODUCTION

Within the scope of the long term vision of the Schelde estuary and the Development Outline 2010, low dynamic intertidal and shallow water areas are considered to be of high ecological value. These areas are in fact linked to eutrophic foraging zones for birds and young fish and to refugees for tidal migrators as shrimps. However, this assumption is based on experiences in other areas and there is no evidence that all parts of the shallow water area are equally valuable. Little is known about the occurrence of such valuable areas in the Schelde estuary, nor are the physical and morphological processes which determine the occurrence of these areas fully understood. Therefore, a research project was defined in 2008-2009 to investigate the relation between on one hand the bed forms, hydrodynamics and sediment properties and on the other hand the ecological value of the shallow water areas (Plancke, Y. 2009). The project was conducted by NIOO-CEME in collaboration with Flanders Hydraulics and IMARES, and focused on the area near the Walsoorden Sandbar in the Westerschelde (the Netherlands).

This study resulted in a criterion based on abiotic parameters (depth and duration during a full tidal cycle in which flow velocity exceeds 65 cm/s) that was able to predict habitats with a high ecological value. Where this criterion was found for only one specific area of the Schelde estuary, a validation is necessary. Therefore 2 new studies were started: one to validate the criterium in the Westerschelde, a second one to validate it in the Zeeschelde. This paper describes the results of the abiotic analysis in the Zeeschelde. In a first phase a bed form classification was made for 4 specific subareas (spread over the full salinity gradient), based on multibeam echo sounding data. In a second phase the hydrodynamics were analyzed, while in the third phase it was investigated whether relations existed between bed form and hydrodynamic characteristics.

BED FORM ANALYSIS

1.1 Study Area and used data

Within the Zeeschelde detailed research will be conducted in 4 subareas. These subareas were selected in such a way that within each of the salinity zones in the Zeeschelde a vast undeep water area could be analyzed. The selected subareas are (Figure 1):

- Mesohaline : Schaar van Ouden Doel and Galgenschoor
- Oligohaline : Notelaer and Ballooi
- Freshwater with long residence time : Branst
- Freshwater with short residence time : Appels

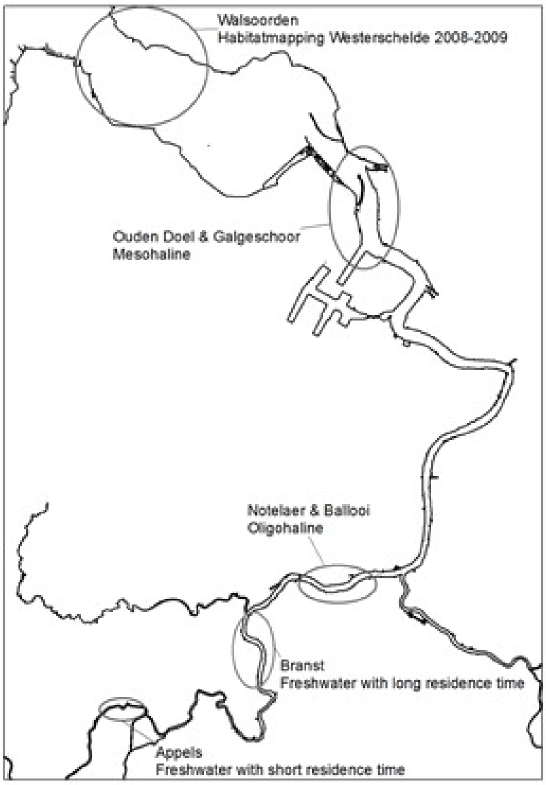

Figure 1. Location of analyzed subareas in the Schelde estuary.

The bathymetry for the Beneden Zeeschelde is based on multibeam echo sounding measurements from 2011, the bathymety for the Boven Zeeschelde was composed of data from 2009, 2010 and 2011. For the intertidal area LIDAR data from 2011 was used.

1.2 Methodology

The analysis was executed using the following steps:

1 Visual classification in zones, starting from the shaded view image of the area

2 Selection of zones without bed forms

3 Definition of several longitudinal transects (along the direction of the flow) within each zone with bed forms

4 Analysis of each transect for following parameters: average length, average height, average asymmetry and average steepness of the bed forms

5 Classification of the sub area in a limited amount of bed form classes

1.2.1 *Visual classification in sub areas*

A so-called “shaded view” map was used as a base for the visual classification in sub areas. This computer-generated map shows a simulated cast shadow of sun upon a raised bathymetry. The angle from which the light shines on the bathymetry was chosen so as to be able to discern the bed forms optimally. The optimal angle was found to be parallel to the direction of the flow, because the direction of bed forms is expected to be perpendicular to the direction of the flow. Based upon this “shaded view” images, different sub areas were delimited (see zoom detail in Figure 3). Boundaries were defined visually in those places where differences in bed forms appeared to occur.

1.2.2 Selection of zones without bed forms

While determining the zones without bed forms, a distinction was made between flat zones and zones with irregular bed forms (caused by geological hard layers or human interference such as sediment disposal or extraction). The difference between zones without bed forms is not always clear on the basis of topo-bathymetric maps. Especially the recognizing of hard layers, which can have both an irregular as a flat gradient, is often not easy. The in situ sediment sampling campaign that was conducted in the scope of this research, made this distinction clearer.

1.2.3 Definition of longitudinal transects

Within every subarea some longitudinal transects were defined, assuming that these sections are representative for the whole subarea. If possible, the length of the transects was made long enough to ensure a sufficient number of bed forms was included in the transect, in order to be able to conduct a representative analysis. The depth values of these sections were exported from a 1m*1m raster covering the study area using GIS-software.

1.2.4 Analysis of the transects to obtain characteristic parameters

For every longitudinal transect following characteristics were deduced:

- Length of the individual bed forms
- Height of the individual bed forms
- Asymmetry of the individual bed forms
- Average steepness of the bed forms per transect

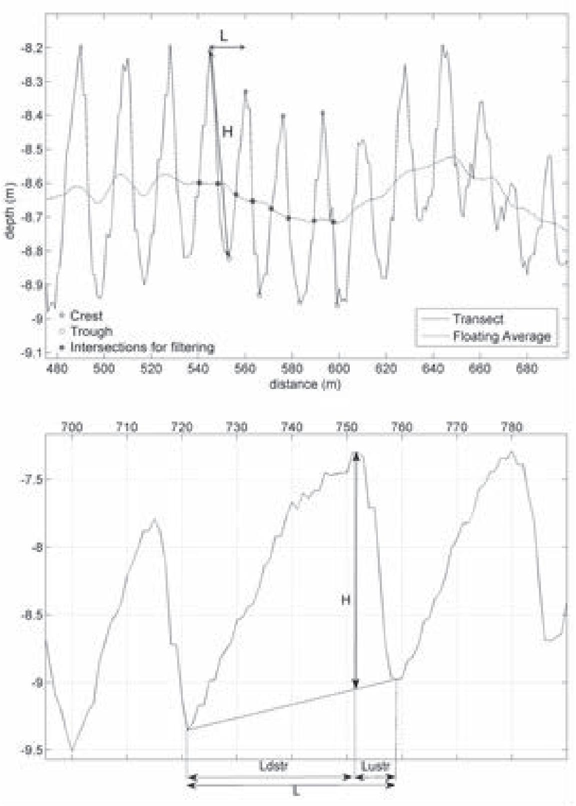

Figure 2. Methodology for determining characteristic parameters, above: step 1 – 4, below: step 5 – 7.

This analysis was executed using a self developed Matlab routine, based on the methodology used in the Bed form Tracking Tool (van der Mark et al. 2007). This routine consists out of the following steps to define the characteristic parameters of the bed forms in a certain transect (Figure 2) :

1 Choosing a period for a floating average to remove trends (large scale depth variation) from the section without loosing the individual bed forms.

2 Detrending of the section by subtracting the floating average from the original data.

3 Determining the intersections of the detrended signal and the zero-line.

4 Determining the crests and troughs, based upon the assumption that between two intersections with the zero-line, a crest or a trough can be found.

5 Determining the length of every individual bed form, defined as the distance between 2 successive crests.

6 Determining the height of every individual bed form, defined as the difference between the height of a crest and the following trough.

7 Determining the asymmetry of every individual bed form, defined as the ratio between the inclination length (Ldstr) and the declination length (Lustr) of the bed form (from trough to trough).

8 Determining the average steepness per transect, defined as the ratio between the average height and the average length of the bed forms (from trough to trough) in that section.

Next, the characteristics of the individual bed forms were averaged per transect. The resulting average values for length, height and asymmetry were filtered to minimize outlier-effects : all values outside the interval [0,25*average : 1,75*average] were discarded and a new average was calculated using the remaining values.

The transects were always defined from down-estuary to up-estuary side. Thus, an asymmetry value greater than 1 implies a bed form where the seaward side is longer than the landward side. This indicates flood dominance. A value smaller than 1 indicates ebb dominance.

1.2.5 *Classification of the study area in a limited amount of bed form classes*

In order to group the different sub areas in a feasible amount of classes, the averaged characteristics were compared to each other and classified according to the classification used in the 2008-2009 Walsoorden research project. This makes it easier to compare the results of the Zeeschelde research project with those of the Westerschelde research project. Table 1 shows the classification based on length and height of the bed forms, table 2 shows an overview of the asymmetry classes.

Table 1. Overview of length/height classes

Class	Length	Height
1	< 10 m	< 5 cm
2	~ 10 m	15 – 30 cm
3	10 – 15 m	30 – 50 cm
4	15 – 25 m	50 – 100 cm
5	15 – 30 m	100 – 150 cm
6	> 30 m	> 150 cm
7	> 30 m	< 100 cm

Table 2. Overview of asymmetry classes

Class	Asymmetry
1	< 0,90 (ebb dominance)
2	0,90 – 1,10 (no dominance)
3	1,10 – 1,50 (flood dominance)
4	> 1,50 (strong flood dominance)

1.3 Results

Based on the mean length, height and asymmetry of the bed forms per transect, each of the zones is attributed to one of the bed form and asymmetry classes. A class 0 is also defined, holding the zones with irregular bed-surface. Where small bed forms are superposed on larger ones (e.g. dunes of class 5 with superposition of ripples of class 2), a combined class number is attributed (e.g. class 5,2). In figure 3 an example of the length/height classification for the subarea Notelaer/Ballooi can be found, figure 4 shows the length/height classification for the subarea Appels.

The subareas Ouden Doel and Galgeschoor in the Beneden Zeeschelde are strongly influenced by human interference (disposal/sand extraction). This means only few zones contain bed forms, which makes it difficult to draw general conclusions on the occurrence of bed forms. Most of the bed forms in this area are small ripples (class 2).

In the other sub areas, in the Beneden Zeeschelde, bed form characteristics are more diverse. Next to zones with smaller ripples, sub areas Notelaer/Ballooi and Branst also contain dunes and dunes with superimposed ripples. In sub area Appels no dunes can be found, but ripples from class 3 are present, next to the small class 2 ripples.

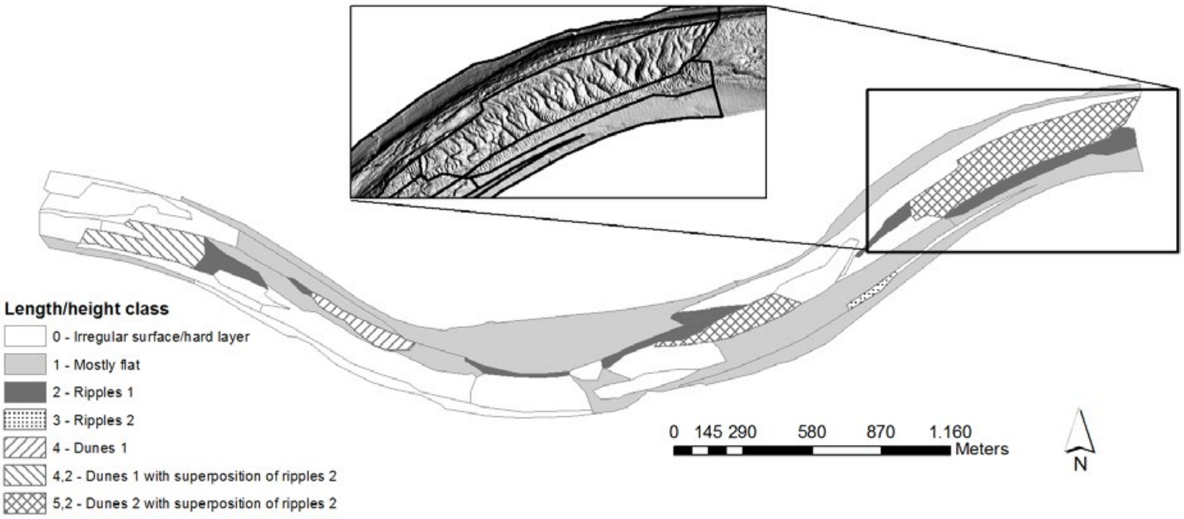

Figure 3. Notelaer and Ballooi: classification in length/height classes, based on shaded view map.

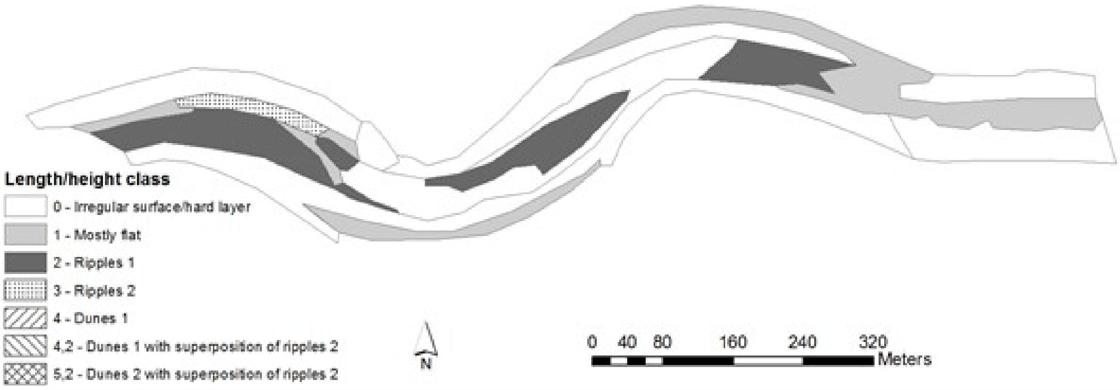

Figure 4. Appels: classification in length/height classes.

It was noticed that most of the classes with bed forms are located in the deeper, central parts of the river.

The classification in asymmetry classes is executed using the classes in table 2. Class 0 is again used for zones with irregular bed surface, while a class 5 was defined for zones where different transects are characterised by different asymmetry.

Most areas are flood dominant, but within each sub area ebb dominant zones (or zones with no dominance) are found. No relationship can be found though between location of the zones and dominance class.

HYDRODYNAMIC ANALYSIS

In a next phase of the study the relation between the occurrence of bed forms and hydrodynamic parameters was analysed.

1.4 Used data

A 2D validated numerical model was used as a base for the hydrodynamic analysis (Maximova, T. 2013). This model is a refined version of the NEVLA-model (Maximova, T. 2009; Verheyen, B. 2012), which was too coarse to be able to predict the velocities in sufficient detail for this study in the upper part of the estuary.

The downstream boundary of the model is located at Walsoorden; the upstream boundary is located at the tidal border. Measured water levels at Walsoorden (HMCZ database) are used as a downstream boundary condition. Measured discharges are used as an upstream boundary condition. The time step used for the model simulations is 3s. For the bathymetry, the multibeam and LIDAR data from the bed form analysis was used in the model.

Every 10 minutes a “map file” with flow fields was exported for the period from 26/06/2009 to 27/06/2009 (spring tide conditions).

1.5 Methodology

Based upon the flow fields, following characteristic hydrodynamic parameters were deduced:

- Average flood velocity
- Average ebb velocity
- Ratio average flood velocity to average ebb velocity
- Maximum flood velocity
- Maximum ebb velocity
- Duration that flow velocities exceed 65 cm/s during one spring tidal cycle (figure 5 shows the duration map for Appels).

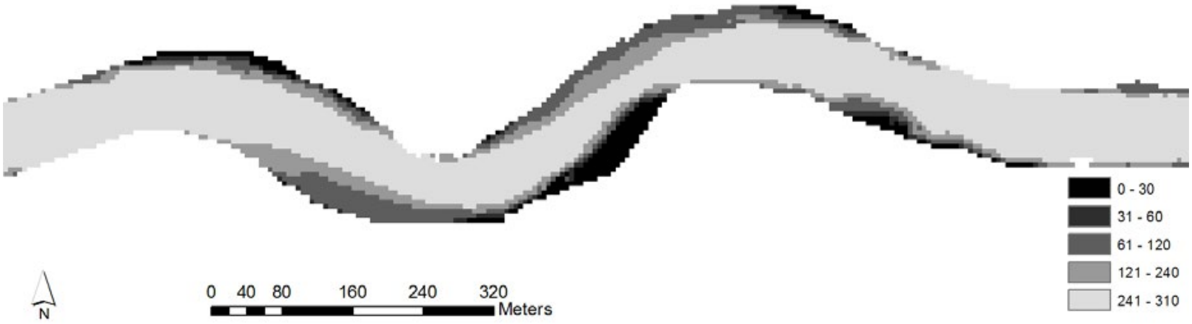

Figure 5. Appels: duration that flow velocities exceed 65 cm/s during one spring tidal cycle.

Similar to the bed form analysis, the hydrodynamic analysis was performed using 2 types of classification: on one hand a classification based on the magnitude of average velocities, on the other hand a classification based on the ratio between average velocities.

For the first classification, the used boundary values are related to characteristic velocity boundaries for e.g. initiation of sediment transport (Flanders Hydraulics Research, 2007) and low vs. high dynamic conditions (Bouma et al., 2005). For every point in the flow field, ebb as well as flood velocity was classified using these boundary values, and based upon the combination of ebb and flood velocity the eventual classification was made.

1.6 Results

The hydrodynamic analysis shows an increase of velocities with increasing depth. The duration during which flow velocities are higher than 65 cm/s exceeds 240 minutes almost everywhere, except along the river banks and on the leeward side of the guiding wall. Flood/ebb ratio shows a similar pattern in all sub areas, namely an alternating pattern of ebb- and flooddominated zones along each river bank.

ON-GOING RESEARCH

Based on the bed form classification the Research Intitute for Nature and Forest took ca. 200 samples, stratified random over the different classes and subareas. At this moment the samples are being analysed on both grain size as the density and number of benthic species. These results will be used to investigate whether relations exists between the abiotic characteristics presented in this paper, and the biotic characteristics.

CONCLUSIONS

Based on the bed form classification and hydrodynamic classification a relationship was sought between both aspects. Therefore the hydrodynamic characteristics were attributed to the bed form classes by calculating the average value per bed form zone for each of the hydrodynamic parameters. Figure 6 shows an example of the classification, based on the ratio between average flood and ebb velocity.

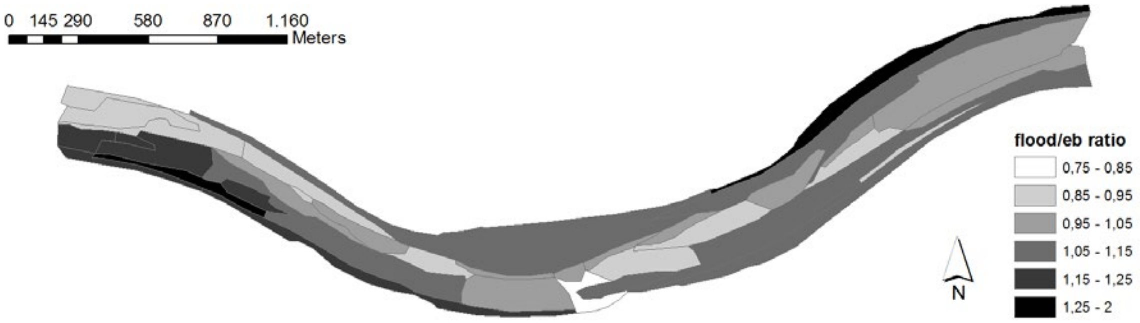

Figure 6. Notelaer and Ballooi: classification in hydrodynamic classes based on flood/eb ratio

Next scatterplots were made to search for a relationship between the occurrence of certain types of bed forms and each of the hydrodynamic characteristics (Figure 7 shows the relationship between height and maximal flood velocity).

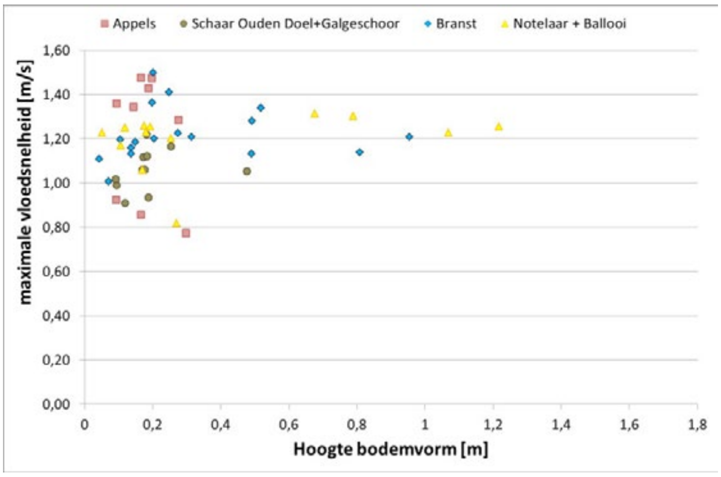

Figure 7. Relationship between height and maximal flood velocity.

A clear relationship between hydrodynamic and bed form characteristics could not be found. A general increase of the size of the bed forms with increasing velocities can be determined, but the scatter is fairly high. However, between depth and bed form size a slightly better relationship can be found ($R^2 = 0{,}568$).

ACKNOWLEDGMENT

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HUMAN VERSUS NATURAL MUD FLUXES IN THE SCHELDT ESTUARY: ARE THEY SIGNIFICANT AND IF SO, HOW CAN THEY BEST BE OPTIMISED?

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ABSTRACT

The mud dynamics of the Scheldt estuary is governed by the interplay between tidal flow, freshwater discharge, marine and fluvial mud supply and local sources and sinks. A question is how large human impacts are on these mud dynamics. Using a process-based mud transport model of the Scheldt estuary, these impacts have been quantified by evaluating different scenarios representative for present or alternative maintenance dredging procedures.

The results show that although the ‘human’ fluxes caused by maintenance dredging are typically small compared to natural gross fluxes, they are very significant compared to natural residual fluxes, notably in the narrower section of the estuary near Antwerp. Here more than half of the available mud is ‘second-hand’, i.e. it has been dredged from and released back into the estuary at least once. This implies that an optimization of the dredging and release cycles, including the smart selection of release locations, offers the perspective of smaller human impacts, possibly even at lower costs.

A down-estuary shift of release locations would be favourable. Also, locations closer tidal flats may contribute to interrupting the vicious circle between dredged mud dispersion and maintenance dredging by enhancing the accretion rate of these flats. However, the surface area of these flats has to be substantial to provide more than just a short-term solution.

Keywords: Scheldt estuary, mud, human impacts

1. INTRODUCTION

The mud dynamics of the Scheldt estuary is governed, like other estuaries, by the interplay between tidal flow, freshwater discharge, marine and fluvial mud supply and local sources and sinks, notably mud flats. Human impacts on the mud dynamics can be either direct or indirect. Direct impacts are caused by harbour and fairway maintenance dredging (i.e. dredging vessels transporting mud from A to B), indirect impacts are caused by human modifications of the estuary such as increasing channel depth by capital dredging or reducing the area of tidal flats by land reclamation, thus modifying the natural flux. The question is whether these impacts are significant compared to the natural estuarine mud dynamics and if so, how they can best be optimised to reduce maintenance cost and to increase the ecological values of the estuary.

2. METHODS

The answer to this question is addressed by using a process-based 3D mud transport model of the Scheldt estuary. This model has been developed in the past few years within the framework of the Belgian-Dutch cooperation on the management of the Scheldt estuary. All technical reports containing details on the development of the Scheldt estuary mud model are publicly available at www.scheldemonitor.be. Also, some journal papers on its development and application have been published (van Kessel *et al.*, 2011a; van der Wal *et al.*, 2010 and Eleveld *et al.*, 2014). Recently, the same modelling approach has been applied to the Ems estuary bordering The Netherlands and Germany (van Maren *et al.*, 2015).

The adopted modelling approach originates from work on the impact of the construction of Maasvlakte-2 land reclamation for the benefit of Rotterdam harbour extension on the mud dynamics and turbidity in the Dutch coastal zone (van Kessel *et al.*, 2011b). Although it has a lot of elements in common with many other mud transport models, it is special in the sense that the model is not only aimed at reproducing the short-term suspended sediment dynamics of the Scheldt estuary, but also at reproducing the long-term mud balance and the evolution of the mud distribution in the bed. The advantage of this approach is that the mud distribution in the bed does not need to be prescribed by the modeller; instead, it is computed by the model. Only mud concentrations at the river and sea boundaries need to be prescribed. Therefore, the mud distribution in the bed is free to respond to changes in navigation channel depth, the construction or extension of tidal docks, a new strategy for maintenance dredging etcetera. Both the short-term and long-term effects of these changes can thus be evaluated. As the mud distribution in the bed only changes slowly (at a timescale of months to years), only direct effects on the suspended sediment concentration play a role on the short term. However, on the long term also the mud distribution may change. Therefore, short-term and long-term effects are not necessarily the same; they even may be opposite. For example, a deepening of a navigation channel may, on the short term, result in lower mud concentration in the water column if the channel velocity decreases. However, on the long term the mud concentration may increase caused by increased estuarine circulation and tidal asymmetry. Classical short-term mud models lack this distinction and can only predict short-term effects correctly.

However, to reduce the computational costs for long-term 3D model computations, the hydrodynamic model is decoupled from the sediment transport model. This makes it possible to re-use the hydrodynamics model results (for example available for a period of a month or a year) for a multi-year sediment transport computation. This advantage comes at a cost: the model is not a morphological model, so the bathymetry of the underlying hydrodynamics is fixed. Also, the effect of suspended sediments on hydrodynamics is neglected, so the approach is only valid for low concentrations (typically < few 100 mg/l). In most of the Scheldt estuary and at most times, the low-concentration requirement is met.

Human impacts are quantified by evaluating different scenarios representative for present and alternative maintenance dredging procedures. The focus of this extended abstract is on the dredging procedure, as this can more easily be modified on the short term than estuarine bathymetry. Both a reversion of land reclamation and channel depth would have large consequences for the economical function of the Scheldt estuary.

3. RESULTS

3.1 Present release locations

Figure 1 shows the computed near surface concentration around Vlissingen harbour in case of harbour sedimentation, maintenance and local release of dredged mud relative to the surface concentration in case of no harbour sedimentation (switched off in the model) and no mud release. The left hand panel is a snapshot during maintenance dredging, the right hand panel between maintenance dredging intervals. It is clear that during dredging the mud concentration increases with respect to the no-intervention case because of mud release, but afterwards it decreases because of harbour sedimentation. Figure 2 shows the time-average effect, which is limited. In seaward direction the presence of the harbour results in a slight decrease of the near-surface concentration (up to a few percent), in up-estuary direction it results in a slight increase of the concentration. According to the right-hand side of Figure 2 about 5% of the suspended mud originates from the harbour, but without the harbour most of this sediment would have remained in suspension. Because of this compensating effect, the net effect remains small.

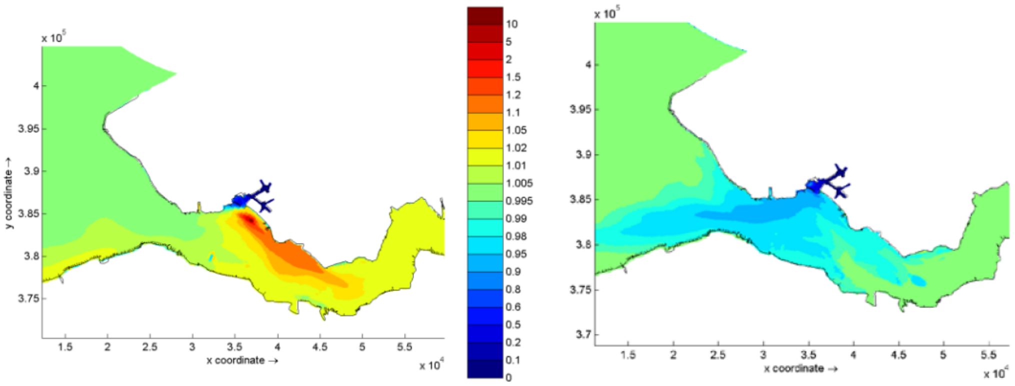

Figure 1. Relative change in near-surface mud concentration for a scenario with harbour with respect to a scenario without harbour. Left: during dredging and release. Right: outside maintenance time window. 1 = no change.

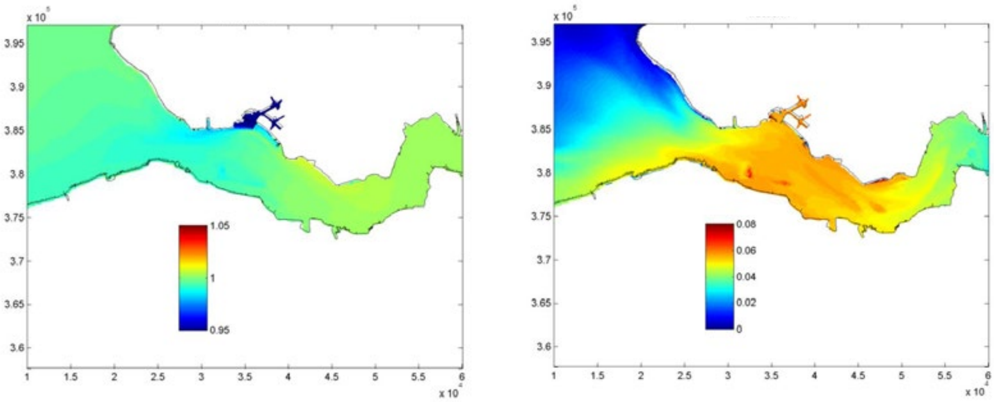

Figure 2. Left: time-average effect of harbour on near-surface concentration. Relative concentration difference with and without harbour. Right: fraction of sediment originating from Vlissingen harbour with respect to the total suspended sediment concentration.

At Antwerp, where the estuary narrows but were the natural suspended sediment concentration is 4-fold larger (about 200 mg/l) because of a local turbidity maximum, the effect of harbours is more distinct. Figure 3 shows a pie chart of the computed origins of the mud at Boei84 near Antwerp. Only about 30% of the mud is 'fresh', i.e. not originating from one of the harbours in the vicinity. About 65% of all mud originates from the harbours and access channels of Antwerp (Zandvliet, Deurganckdok and Kallo, of which DGD has by far the largest contribution). The Dutch harbours contribute only for about 5%. More than 2/3 of all sediments are 'second hand', i.e. have at least once been dredged and released. This suggests that there is a large potential for optimisation of the local dredging strategy.

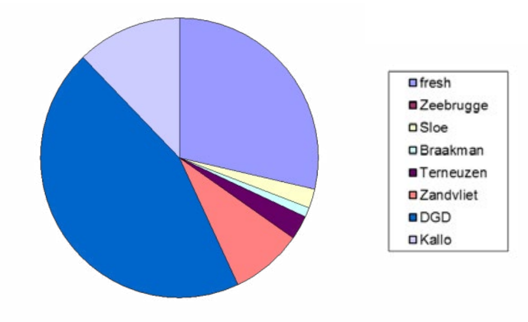

Figure 3. Computed mud origins at Boei84, close to Antwerp harbour. 'Fresh' represents mud not originating from one of the harbours.

3.2 Alternative release locations

Figure 4 shows the results of a sensitivity computation on the effect of a down-estuary shift of the release location for mud originating from maintenance of tidal docks and access channels at Antwerp. The left-hand panel shows the computed time-average suspended mud concentration near the surface for the present maintenance strategy. Note that the observed estuarine turbidity maximum (ETM) near Antwerp is reproduced by the model. When the release location is shifted in down-estuary direction as indicated in the left-hand panel, the time-average concentration increases in down-estuary direction but decreases in up-estuary direction. However, the computed local increase of about 5 to 10% is much smaller than the local decrease (more than 20%), so the overall effect is positive, i.e. on average the mud concentration decreases. This can be explained by two effects: 1) towards the sea the estuary is wide, so the same mud release rate results in a smaller concentration effect and 2) as the concentration at DGD decreases (with about 7% according to Figure 4), also the sedimentation rate decreases, resulting in a smaller dredging effort and mud release rate. Therefore both effects reinforce each other.

With the mud model, a third mechanism that may further reduce mud concentration levels and the return flow of mud towards the harbour basins has not yet been studied. This mechanism is the release of dredged material at a location near low-dynamic tidal mud flats. It may contribute to interrupting the vicious circle between dredged mud release and maintenance dredging by enhancing the accretion rate of these flats. However, the surface area of these flats has to be substantial to provide more than only a short-term solution.

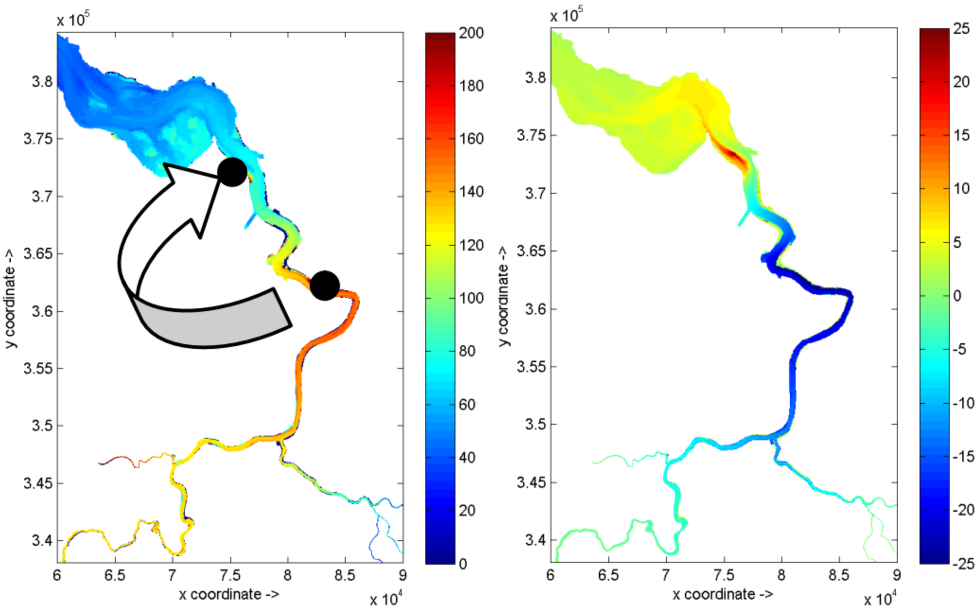

Figure 4. Left: time-average near-surface mud concentration near Antwerp harbour. Right: % change resulting from a down-estuary shift of the release location.

4. CONCLUSIONS

The results show that although the 'human' fluxes caused by maintenance dredging are typically small compared to natural gross fluxes, they are very significant compared to natural residual fluxes, notably in the narrower section of the estuary near Antwerp. Here more than half of the available mud is 'second-hand', i.e. it has been dredged from and released back into the estuary at least once. This implies that an optimisation of the dredging and release cycles, including the smart selection of release locations, offers the perspective of smaller human impacts, possibly even at lower costs. In the Western Scheldt human impacts are smaller, as the estuary is much wider and natural gross fluxes are much larger because of the much larger tidal volume, whereas the volume of maintenance dredging at Vlissingen or Terneuzen is smaller than at Antwerp.

Computations with the mud model show that a down-estuary shift of release locations would be favourable, whereas the present practice is that dredged mud is most often released up-estuary of the harbour or access channel from which it has been dredged. Two mechanisms are responsible for this favourable effect, i.e. 1) a wider estuary results in a smaller concentration effect and 2) a smaller concentration effect results in a lower harbour sedimentation rate and therefore mud release rate. A third mechanism to reduce mud concentration levels would be the selection of release locations close to tidal flats, as the vicious circle between dredged mud dispersion and maintenance dredging may be interrupted by enhancing the accretion rate of these flats.

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MUD DISPOSAL AND SUSPENDED SEDIMENT CONCENTRATION IN THE LOWER SEA SCHELDT – TOWARDS A HYPERTURBID SYSTEM?

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ABSTRACT

In this paper, an analysis of continuous SSC measurements in the Sea Scheldt is presented. Information from different projects that focus on the state of the Scheldt Estuary (Belgium-Netherlands) and the management of dredging and disposal activities, is discussed to increase the insight in the effects of mud disposal and the increasing sediment concentrations (SSC) in the Lower Sea Scheldt.

Keywords: Scheldt estuary; sediment concentration measurements; dredging; mud disposal; water quality

1. INTRODUCTION

Several estuaries in Europe, e.g. the Loire in France and the Ems on the Dutch-German border, have witnessed a transition to a state characterized by very high suspended sediment concentrations, a so-called hyperturbid state. These estuaries underwent a 'regime shift' (Winterwerp, 2012; Winterwerp & Wang, 2013; Winterwerp et al. 2013) as the consequence of deepening, narrowing, rectification and reflection at hard upstream boundaries. These man-made changes to the estuaries led to a tidal amplification and an increase of the tidal asymmetry which resulted in an upward transport of mud. This in turn reduced the effective hydraulic resistance. Finally, this reduction closed a feedback loop as it leads to further tidal amplification.

In the Scheldt Estuary, and especially the Sea Scheldt (i.e. the Flemish part of the Scheldt Estuary, see Figure 1), several elements that contribute to the abovementioned feedback loop are identified. These may indicate that the system is, as other estuaries in the past, evolving towards a hyperturbid system.

2. BACKGROUND

2.1 Man-made interventions in the Scheldt estuary

The estuary has been subject to many historical interventions in the past centuries. Jeuken et al. (2007) and Van Braeckel et al. (2012) provide comprehensive overviews. Many interventions indicate that the Scheldt estuary is a heavily modified system, including activities such as land reclamations (22,000 ha in Belgium since 1100 AD, 40,000 ha in the Netherlands since 1650 AD), rectifications in the Upper Sea Scheldt, execution of flood protection plans, building of locks (Boudewijn lock, Kallo lock, Terneuzen, Dendermonde, Upper Sea Scheldt …), ports (Sloehaven), docks (Deurganckdock) and terminals (Europaterminal, Noordzeeterminal), dredging and sand mining (estimated at ca. 150 million m³ in the Western Scheldt since the 1950s), changes in the upstream input discharges, building of bank protections, groynes, …

The Scheldt estuary now is an intensely shipped area, holding the fairway to the ports of Vlissingen and Terneuzen in the Netherlands and Ghent and Antwerp in Belgium (see inset in Figure 1). In the 1970s and 1990s, the main fairway was deepened several times to allow for increasingly larger ships to access the ports. In 1995, the second deepening allowed tide-independent access to the port of Antwerp for ships up to a draught of 11.6 m.

Already in 2001 (DZL & AWZ, 2001) the Long Term Vision (LTV) for the Scheldt estuary provided a framework for sustainable management of the Scheldt estuary in a political context of Dutch-Flemish cooperation. The focus of the LTV was aimed at three principal functions: safety against flooding; navigable access to harbours; and naturalness of the physical and ecological system. The measures, projects and directives for monitoring needed to achieve the estuarine state described in the LTV were described in the Development Plan 2010 for the Scheldt estuary (Proses, 2005). One of the projects was the deepening and widening of the navigation channel to allow for tide-independent navigation up to a draught of 13.1 m.

In the Western Scheldt (the Dutch part of the estuary), 11 sills and a few shoals were deepened in 2010 to a depth of -14.5 m LAT (Lowest Astronomical Tide), for a total capital dredging volume of 7.7 million m³. Parallel to this, a flexible disposal strategy was devised (Consortium Arcadis-Technum, 2007; VNSC, 2009) to contribute to the morphological equilibrium of the multi-channel system (through less disposal in secondary channels, as practiced in the past), to

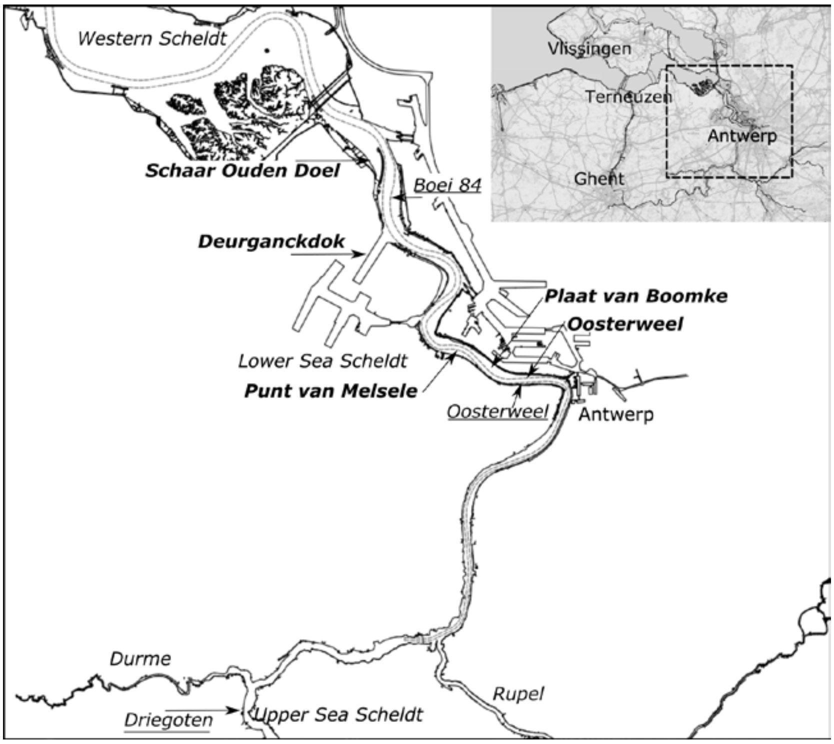

Figure 1: Location map and names of important dredging and disposal locations (bold) and measuring sites (underlined).

contribute to the creation of new ecologically valuable areas near the sand bars (through disposal near sand bars to create low dynamic shallow water and intertidal area), and to conserve existing ecologically valuable areas. This process is monitored closely and reported periodically (Depreiter et al., 2012, 2013; biannual reports, see IMDC, 2014a, 2014b and monthly reports, see e.g. IMDC, 2014c).

In the Sea Scheldt, sills between the Dutch-Flemish border and the Deurganckdock were deepened, a sill at the entrance of the Deurganckdock was removed, and a pivoting area for ships was dredged. The activities took place between 2008 and 2010. In total, about 6.6 million m³ of sediment was dredged.

The Deurganckdock is a tidal dock with a length of 2.7 km, a width of 400 to 450 m. The main construction phase was carried out between 2005 (opening of the dock) and 2007 to early 2008 (extension of the dock). A current deflecting wall was installed at the entrance in 2010-2011 to reduce sedimentation (siltation) in the dock (Roose et al., 2013, Decrop et al., 2013). As of 2011, the maintenance dredging level was deepened to its design level.

2.2 Tidal amplification

During the past century, the tidal range in the estuary has increased significantly (e.g. Kuyper, 2013). The amplification of the tide compared to Vlissingen (near the mouth of the estuary) has increased from a factor 1.2 (1901-1910) near Antwerp (at 78 km from the mouth) to 1.4 (2001-2010) near Tielrode, 30 km further upstream. The most significant breakpoint in the development of high and low water levels, and thus the tidal range, is observed in the 1970s in the eastern part of the Western Scheldt as well as the entire Sea Scheldt. These effects are attributed to the first deepening of the Scheldt. During these works, large amounts of sand were extracted from the estuary. Figure 2 illustrates the peak in total sand volume removed from the estuary in the early 1970s which concurs with the onset of a rapid increase of the tidal range in Antwerp.

2.3 Relevant monitoring programs

In the framework of the Long Term Vision and the Development Plan 2010, the Moneos-T execution plan (Schrijver & Plancke, 2008) was set up for monitoring the effects of the third deepening of the Scheldt. Data analysis and reporting, including the results presented in this paper, is carried out within the framework of the “Monitoring Programme Flexible Disposal” since 2010 (e.g. IMDC, 2014a, 2014b, 2014c) and extensive sedimentation processes monitoring and data analysis “Evaluation of the external effects on the siltation in Deurganckdock” since 2006 (e.g. IMDC, 2014d), both commissioned by the Maritime Access Division of the Flemish Government.

In the Sea Scheldt, the OMES monitoring and research programme was set up after a heavy storm in 1994, to investigate the environmental impact of the Sigma Plan (the flood resilience plan in Flanders) (Meire, 1997). This program is based on periodic (monthly to bimonthly) measurement campaigns, aimed at the functioning of the pelagic ecosystem, mearsuring e.g. the light climate (attenuation of light in the water column and sediment concentrations.

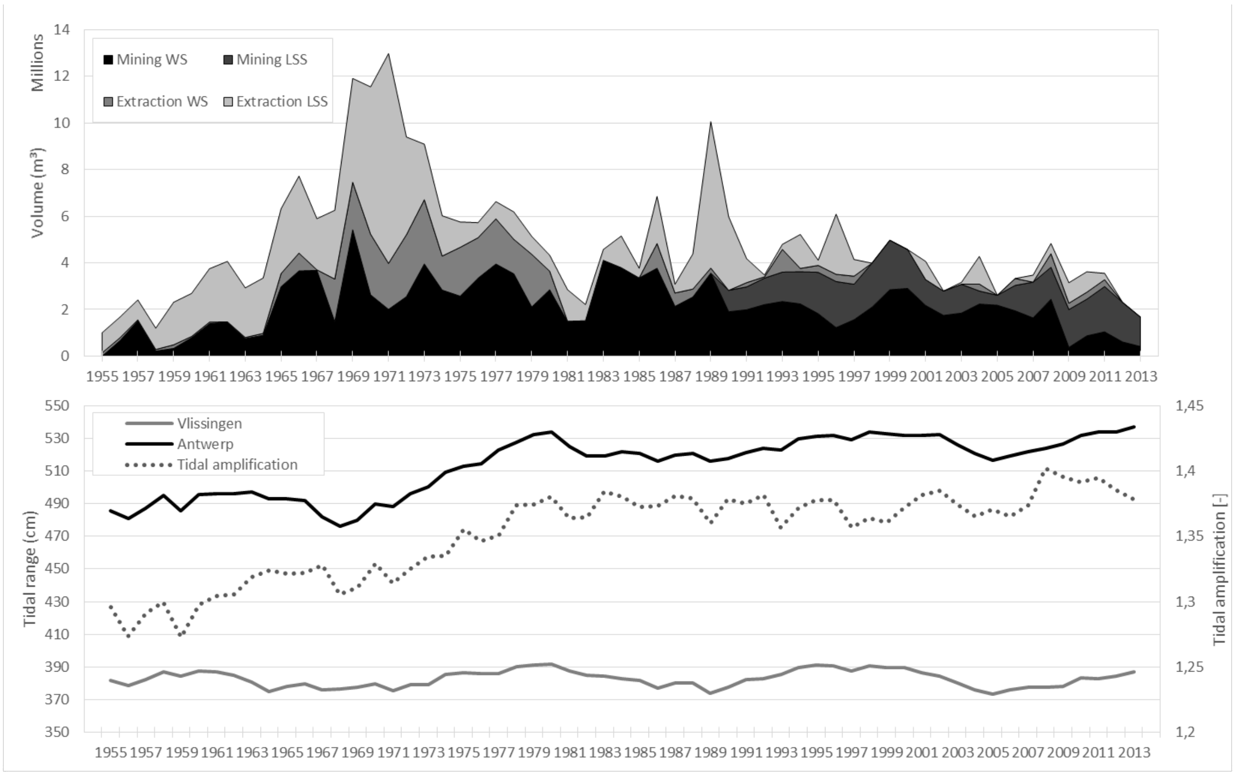

Figure 2: Sand mining and extraction in the Lower Sea Scheldt and Western Scheldt compared to tidal range and amplification between 1955 and 2013. Data from T2009-consortium (2014) and IMDC (2014a).

3. DATA

3.1 Dredging and disposal data

In the Lower Sea Scheldt, dredged mud and sand are (currently) disposed at separate disposal sites. The discrimination between sand and mud is made by the dredger operators per trip, based on the behaviour of the sediment in the ship's hold. Sand is being disposed at the former secondary channel which was closed by a groin in the 1960ies, called "Schaar Ouden Doel", located near the Dutch-Belgian border. This sand is being mined in this location by contractors. Mud disposal sites are situated along shoals west of Antwerp, called "Punt van Melsele" (left bank), "Plaat van Boomke" and "Oosterweel" (two juxtaposed sites on the right bank). In the past, mud had also been disposed at "Schaar Ouden Doel" and other sites.

The dredging and disposal activities in the Lower Sea Scheldt are recorded in the "Bagger Informatie Systeem" (BIS; dredging information system). BIS records consist of ship information, dredged volume, sediment type (sand or mud), dredging and disposal location and other metadata. From this database, the mud disposal volumes through time have been extracted. The volumes (Figure 3) are presented in 'reduced volume' (V'), which is a calculated volume based on a mud density of 2 ton per m³. Mud disposal volumes varies around ~500.000 m³ V' per year before 2000. In 2001-2003, volumes between 2 and 3 million m³ are disposed. Between 2004 and 2008, the mud disposal volume is always lower than 2 million m³ but higher than before 2001. After 2008, the yearly volume increases up to nearly 5 million m³ in 2011, to decrease again in 2012-2013, but remaining 3 million m³ and above any volume recorded before 2011.

These variations, especially the higher values, can be linked to specific interventions. First of all, the high mud disposal volumes in 2001-2003 relate to the deepening and maintenance of sills between Deurganckdock and the Dutch-Belgian border, as preparation to the opening of Deurganckdock. Since 2005, mud is dredged increasingly in Deurganckdock and the sill just north of it ("Drempel van Frederik"), but also the entrances to the Zandvliet- and Berendrecht Lock and the Kallo Lock require more maintenance dredging (Figure 4). In 2011, a peak in the mud dredging volumes occurs mostly due to the deepening of the Deurganckdock and the nearby sill.

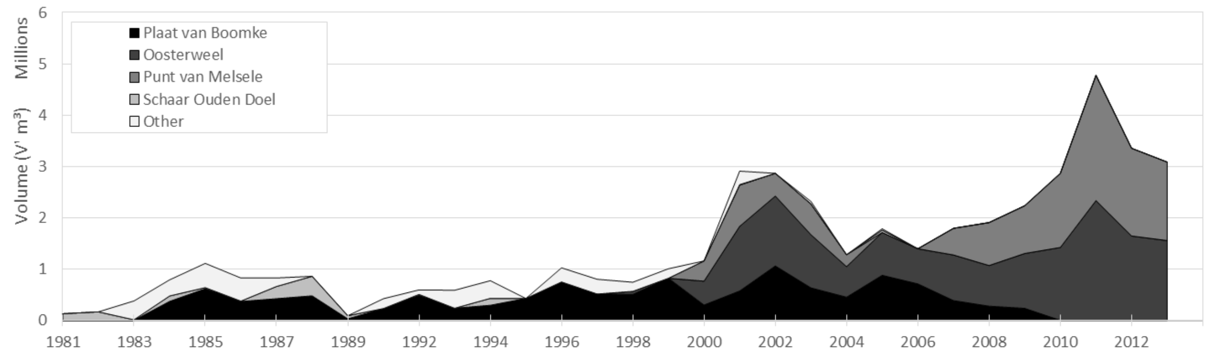

Figure 3: Mud disposal volumes per site in the Lower Sea Scheldt (reduced volume V') from 1980 to 2013. Data from IMDC (2014a).

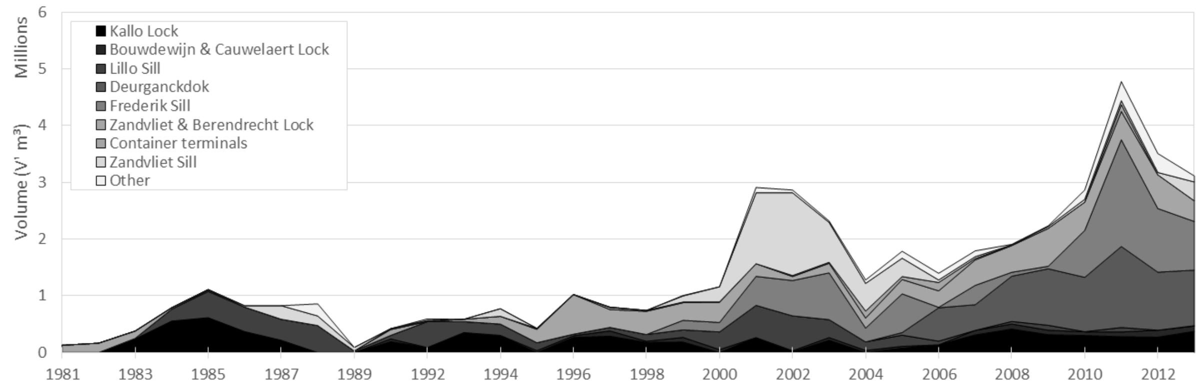

Figure 4: Mud dredging volumes per site in the Lower Sea Scheldt (reduced volume V') from 1980 to 2013. Data from IMDC (2014a).

3.2 Continuous sediment concentration measurements

Continuous turbidity measurements are carried out by Flanders Hydraulics Research at different locations in the Sea Scheldt. Here, we will focus on 3 stations. "Boei 84" is a measuring station near the Dutch-Belgian border. Two turbidity sensors are installed and measure at 0.8 and 3.3 m above the river bed (8.5 m and 6 m below low water level). In the vicinity of the mud disposal sites, the "Oosterweel" station also has two sensors, at 1 m and 4.5 m above the river bed (5.5 m and 2 m below low water level). A third station is further upstream in the Upper Sea Scheldt, "Driegoten". It has one sensor. Measurement data is reported yearly in the framework of the MONEOS project, e.g. Vereecken et al. (2011) and Vanlierde et al. (2013).

All measurement sensors have been replaced at least once through time. As a consequence, the raw turbidity measurements cannot be compared directly. Through calibration to water samples at discrete times, turbidities are converted to suspended sediment concentrations (SSC, in mg/L), as detailed in the MONEOS report by Flanders Hydraulics Research. To reduce tidal variations and noise in the data, two-day averaging has been applied to the data, resulting in a smoother signal.

Another limitation to the data set is the occurrence of saturation or clipping of the signal, due to the range and/or resolution settings in measurement sensors. The clipping has been eliminated through a correlative model of the 25-percentile value of the SSC signal (within a two-day measurement window) and the average of the same signal, within a year without clipping or saturation. Strong correlations (Oosterweel upper sensor: r=0.98; figure 5) were observed. In years with clipped signals, the same correlation (per sensor) was applied to estimate the average SSC based on the behaviour of the 25-percentile SSC value at each moment (see IMDC, 2014a). Figures 6 and 7 display the continuous and two-day averaged SSC values of the Boei 84 and Oosterweel site. Clipped and 'restored' data will be indicated with arrows. Derived statistics are presented in Table 1 and summarized in Table 2. For two sensors with sufficiently long timeseries, 99-percentile trends and values have been determined as well (excluding the years with clipped data).

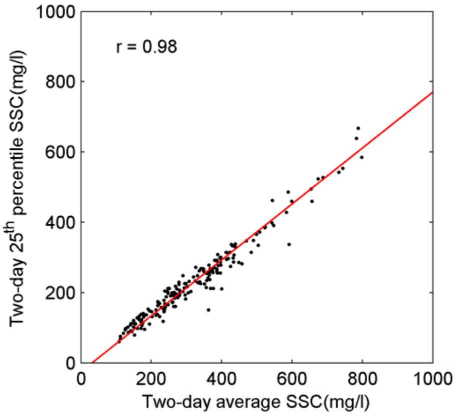

Figure 5: Correlation between bidiurnal 25-percentile and average SSC; Oosterweel upper sensor (IMDC, 2014a).

The data at Oosterweel show a decreasing trend between 2001 and 2005 (11 mg/L) and an increase from 2005 to 2011 (34 mg/L for the upper sensor and 50 mg/L for the low sensor). In 2011-2013, a decrease is observed again (11 mg/L in the upper sensor and 10 mg/L in the lower sensor). The 99th percentile values increase significantly. Measurements upwards of 800 mg/L were increasingly observed in 2013 (3% (upper) and 5% (lower of the time). Before 2007, measurements higher than 800 mg/L never occurred.

At Boei 84, an increase of 13 mg/L was observed during the period 2006-2013. The increase is lower (7 mg/L) in 2011-2013. Here also, the 99th percentile increased significantly (+60 mg/L/year in 2005-2011 and +12 mg/L/year in 2011-2013). 99 percentiles values were higher than at the Oosterweel site, probably because the sensors are closer to the river bed.

Table 1: Statistics derived from continuous SSC measurements: yearly average SSC and standard deviation, 99-percentile SSC and exceedance fraction of 800 mg/L SSC.

Sensor		2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
OOSTERWEEL Upper	Average	133	188	177	113	108	145	177	210	235	244	348	320	327
	Standard dev.	74	98	99	68	63	82	105	112	148	158	160		198
	99th percentile	322	439	426	314	272	375	541	497	668	775	772		962
	% > 800 mg/l	0%	0%	0%	0%	0%	0%	0%	0%	0%	1%	1%		3%
OOSTERWEEL Lower	Average						163	199	248	271		415	350	370
	Standard dev.						90	100	124	159				217
	99th percentile						424	507	576	772				1078
	% > 800 mg/l						0%	0%	0%	1%				5%
BOEI 84 Upper	Average						197	182	209	210	205	212	179	263
	Standard dev.						144	144	166					
	99th percentile						772	742	866					
	% > 800 mg/l						1%	1%	1%					
BOEI 84 Lower	Average						303	293	310	318	352	364	233	377
	Standard dev.						203	214	244	253	266	283		269
	99th percentile						973	975	1128	1177	1227	1234		1258
	% > 800 mg/l						4%	4%	6%	7%	7%	10%		9%
DRIEGOTEN	Average									176	161	377	181	158
	Standard dev.													128
	99th percentile													633
	% > 800 mg/l									2%	0%	16%	0%	0%

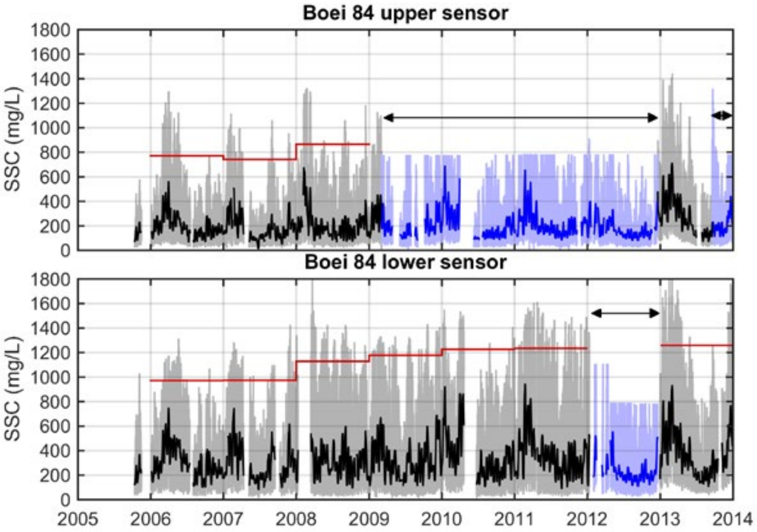

Figure 6: Continuous SSC measurements at Boei 84 site, Lower Sea Scheldt (IMDC, 2014a). Arrows and blue linestyles indicate ranges with saturated data. Light blue and gray are full data range, bold black and blue are two day averages. Red lines represent 99-percentile values.

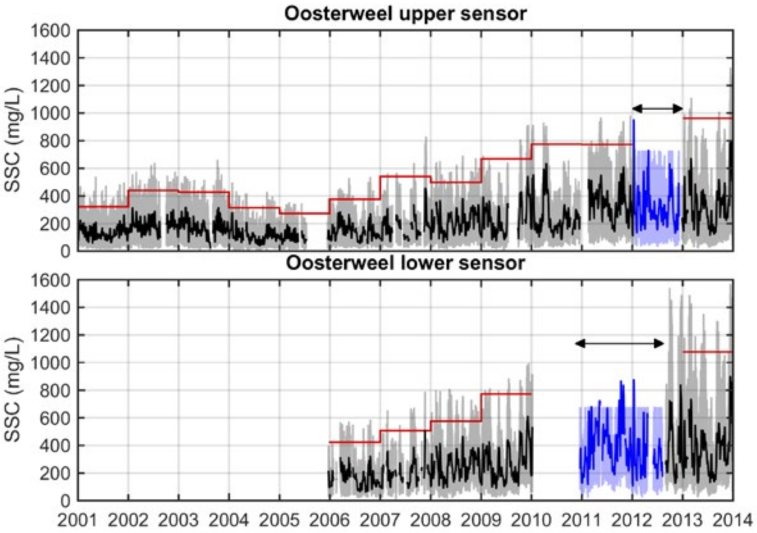

Figure 7 :Continuous SSC measurements at Oosterweel site, Lower Sea Scheldt (IMDC, 2014a). Arrows and blue linestyles indicate ranges with saturated data. Light blue and gray are full data range, bold black and blue are two day averages. Red lines represent 99-percentile values.

Table 2: Summary table showing average trend direction and 99-percentile SSC and 99-percentile values in the Sea Scheldt (Boei 84, Oosterweel, Driegoten stations)

	Trend	**Maximum year SSC average (mg/L)**	**99-percentile trend**	**Maximum year SSC 99-prctile (mg/L)**
B84 Upper	2007-2013 +	2013 (263 mg/L)		
B84 Lower	2007-2013 +	2013 (377 mg/L)	2006-2013 +	2013 (1258 mg/L)
OWL Upper	2005-2013 +	2011 (348 mg/L)	2005-2013 +	2013 (962 mg/L)
OWL Lower	2006-2013 +	2011 (415 mg/L)		
Driegoten		2011 (377 mg/L)		

The data show that the past decade, the average SSC measurements indicate increasing sediment concentrations at Boei 84 and Oosterweel. At the Driegoten site, no trend is observed, but the 2011 year clearly stands out in average SSC. Maximum SSC observations have been observed in 2013 at the Boei 84 and in 2011 in the three other locations. The maximum extreme SSC values (99-percentiles) have been recorded in 2013, following a period of increase since 2005-2006 (Figure 8).

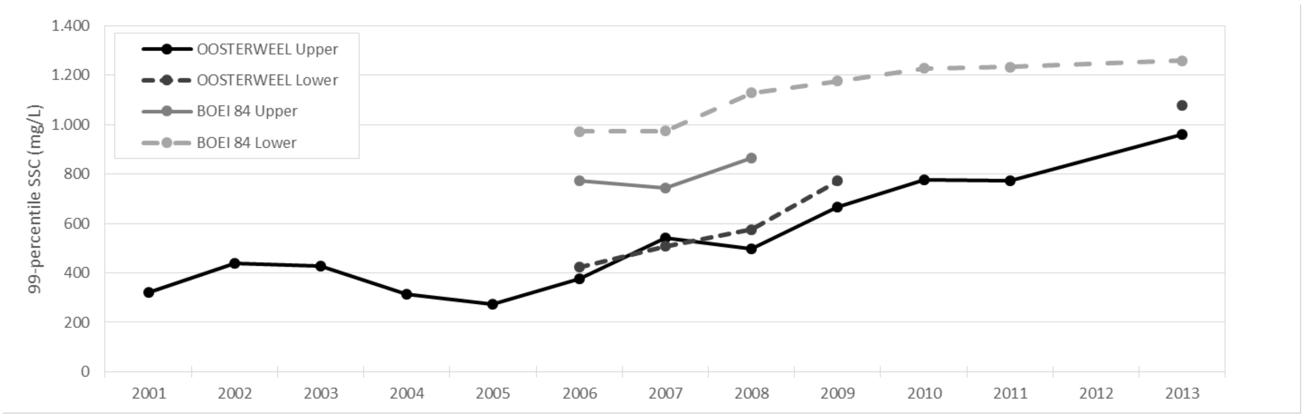

Figure 8: Evolution of the yearly 99-percentile SSC measurements in 4 different sensors.

4. ANALYSIS

4.1 Trends in mud disposal and continuous measurements

In the data description, it is shown that the Oosterweel sensors show peak average SSC in 2011, in parallel to the peak mud disposal in the vicinity (Figure 9). On a longer timescale, a covariation of the timeseries is visible: elevated mud disposal in 2001-2003 corresponds to average SSC values from 130 – 190 mg/L. In 2004-2007, less disposal has taken place, which translates in lower SSC averages. As of 2006, a systematic increase in the mud disposal volumes is observed while a similar trend in the average SSC is observed. In 2012 and 2013, the average SSC is somewhat lower, while the mud disposal volumes are lower as well; both parameters are still higher than in years before 2011. The lower sensor at Oosterweel is less complete but shows similar trends as the top sensor (Figure 10).

This behavior of the SSC signal can be explained by the proximity of the mud disposal locations. Current velocities observed at the Oosterweel lower sensor during spring tide exceed 1 m/s, while at neap time velocities between 50 and 75 cm/s occur (e.g. Taverniers et al., 2012). These velocities are sufficient to resuspend the freshly disposed mud from the Oosterweel disposal locations. Morphological analysis (IMDC, 2013b) indicates that the disposal locations Punt van Melsele and Oosterweel do not show significant accretion but rather deepening. The Plaat van Boomke location has not been used since 2010 as this location did become too shallow. At Oosterweel, there is frequent disposal of sediment, and periods with a high disposal frequency are alternated with periods without sediment disposal. These periods without sediment disposal have a clear effect on the SSC signal at Oosterweel, both in the lower and upper sensors. Figure 12 shows that the SSC signal clearly decreases with the number of days after nearby disposal of sediment ($r = -0.97$, $p < 0.0001$), further corroborating the link between measured SSC at Oosterweel and nearby disposal (Vandenbruwaene et al., 2015).

The measurements at the Boei 84 upper and lower sensors (Figure 11) show an increase in SSC since 2007, although a (visual) correlation with the mud disposal is not present.

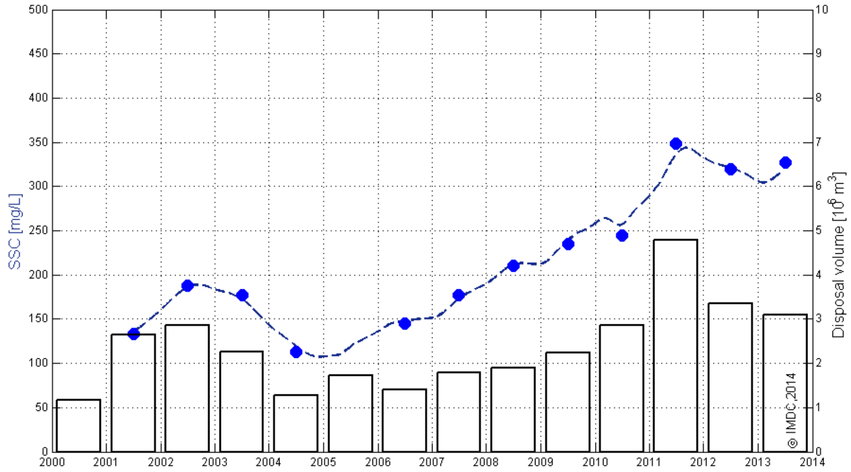

Figure 9: Trend of the yearly mud disposal volume and the year-averaged SSC at Oosterweel top sensor.

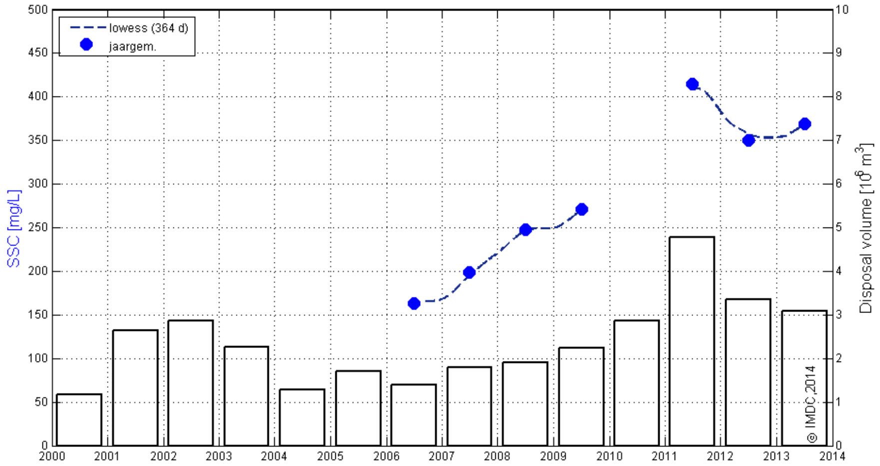

Figure 10: Trend of the yearly mud disposal volume and the year-averaged SSC at Oosterweel lower sensor.

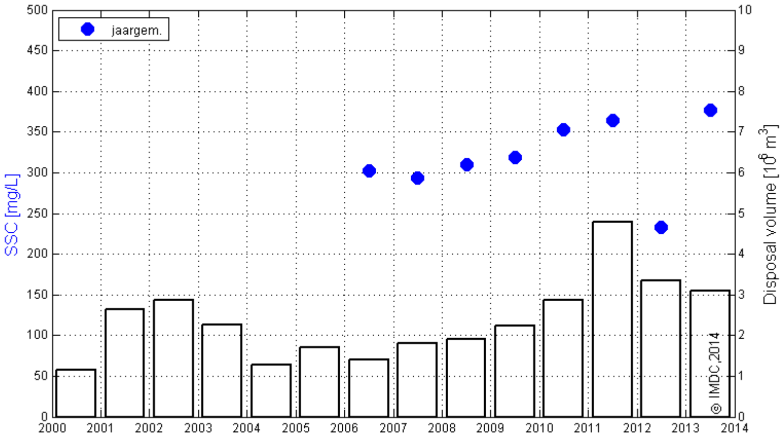

Figure 11: Trend of the yearly mud disposal volume and the year-averaged SSC at Boei 84 lower sensor. The 2012 average SSC is much lower than expected due to missing in the spring season.

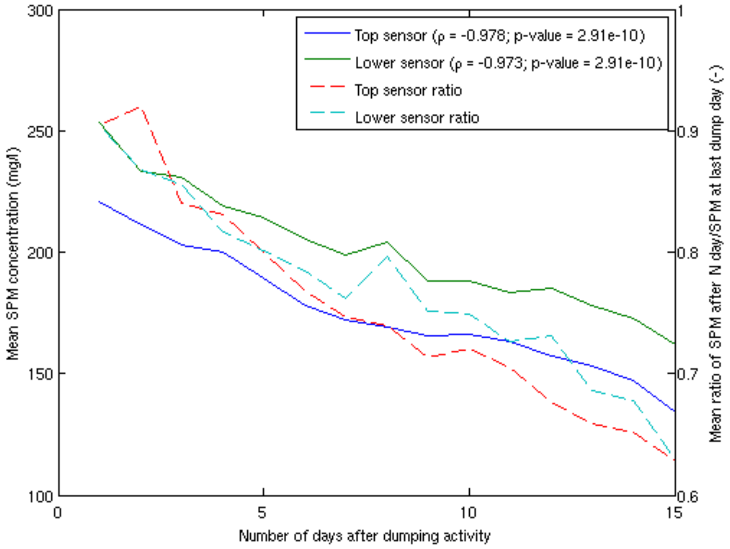

Figure 12: SSC evolution at Oosterweel in the first two weeks after sediment disposal nearby

4.2 Regression analysis

To further elucidate the covarying trends, a multivariate regression analysis has been performed on turbidities measured with RCM9 devices at Oosterweel (top sensor) and Boei 84 (lower sensor) (IMDC, 2013c). For this analysis, it has been chosen not to work with SSC to avoid errors or uncertainty due to calibration between turbidity and SSC. The analysis has been performed on weekly averages because the available mud disposal data is also aggregated at the week level.

The regression models contains following significant terms: a constant term, an autoregressive component (which represents the average turbidity in the previous week; this effect is supported by the relation in Figure 12), tidal components MSF (neap-spring cycle), MM (monthly lunar cycle), SA (yearly cycle, or seasonality) and MF (14 day lunar cycle); the weekly mud disposal volumes and finally a linear trend. Additionally for the Boei 84 lower sensor, the current velocity also significantly contributed to the variation; this was not the case for Oosterweel.

The relative importance of the terms is evaluated through the coefficient of partial determination (Eq. 1, Table 3), defined as

$$r^2_{X_j} = \frac{SSR\ (model) - SSR\ (model\ excl.X_j)}{SSE\ (model\ excl.X_j)} \qquad [1]$$

with $r^2_{X_j}$ the coefficient of partial determination of term X_j, SSR the sum of square of the regression, SSE the sum of the squares of the residuals. The *model* is the complete model, while *model excl.* X_j is the model from which the component or term X_j is omitted.

Table 3: Coefficients of partial determination per component of the regression models

Oosterweel (upper)	$r^2_{X_j}$	**Boei 84 (lower)**	$r^2_{X_j}$
Mud disposal volume	45.1%	Autoregressive component	38.6%
Autoregressive component	45.0%	Neap-spring cycle (MSF)	35.6%
Neap-spring cycle (MSF)	36.0%	Mud disposal volume	34%
Trend	9.6%	Seasonality	15.7%
Monthly lunar cycle (MM)	8.7%	Monthly lunar cycle (MM)	12.1%
Biweekly lunar sycle (MF)	5.0%	Biweekly lunar sycle (MF)	12.0%
Seasonality	3.9%	Current velocity	5.6%
		Trend	2.8%

In the Oosterweel regression model, the mud disposal volumes and the autoregressive components are the strongest terms. The significance of this is that the weekly averaged turbidity strongly depends on the turbidity of the preceding week and the mud disposed in the current week. This observation corroborates the visual interpretation above of the similar trends in SSC and mud disposal volume. Futhermore, it appears that the neap-spring cycle also strongly influences turbidity. This is to be expected as this cycle determines current velocities in the whole system, and thus the potential for erosion and/or resuspension.

The Boei 84 regression model shows that the autoregressive factor and the neap-spring cycle are the strongest factors in the model. The mud disposal volume is a strong third factor in the model. Seasonality and other terms are much weaker in the model. The strong presence of the mud disposal volume in this model is unexpected because the resemblance in trends between SSC and yearly mud disposal was not as striking as in the Oosterweel case.

Both sets of residuals (i.e. the difference between the observations and the model) do not display a trend. A certain amount of variation is still present, however (Figure 13). It is thought that upstream discharge variations and/or suspended sediment loads from the catchments may explain some of these variations as well although they do not show significant trends in the last years.

This analysis confirms that the impact of mud disposal on turbidity (or SSC) in the Lower Sea Scheldt is important. The recent increase in SSC can therefore be related for a large part to the increased mud disposal volumes.

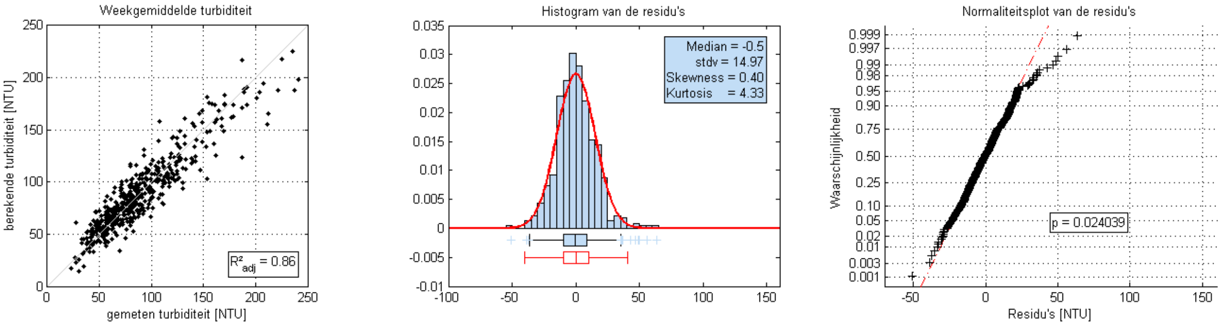

Figure 13: Example of residual analysis of the Oosterweel model. Note the underestimated extreme measured values.

5. DISCUSSION

5.1 Periodic surface sampling and other data sources

The biweekly to monthly sampling and monitoring campaigns in the OMES framework have changed through time, but based on the past years, measurements also indicated that 2011 was a year with higher SSC than preceding years (IMDC, 2013a; Maris et al., 2013; Figure 14). It must be noted however that OMES data has a higher degree of uncertainty due to the independence of tidal phase of the measurements.

Other data sources, also recorded in the framework of the OMES project, corroborate with the 2011 peak SSC data. The light attenuation appeared to be higher on average in 2011 than in 2010 or 2013. Simultaneously, lower algal biomasses and primary production were observed in most stations (Maris et al., 2013).

Vandenbruwaene et al. (2015) also show higher surface SSC values in the OMES dataset in 2011 for the lower Sea Scheldt (in green on Figure 15). In the Western Scheldt, surface SSC was higher in 2010, and in the upper Sea Scheldt in 2009 and 2011. Note the large natural variation in the dataset however.

Flanders Hydraulics Research also performs measurements depending of the tidal phase, at the turning of the tide and at half-tide ebb (Vereecken et al., 2012; Taverniers et al.; 2013a; Vanlierde et al.; 2013, 2014). The highest concentrations are observed at Oosterweel in 2011 and confirm our report above, but so far, no clear temporal trends throughout the Sea Scheldt have been reported.

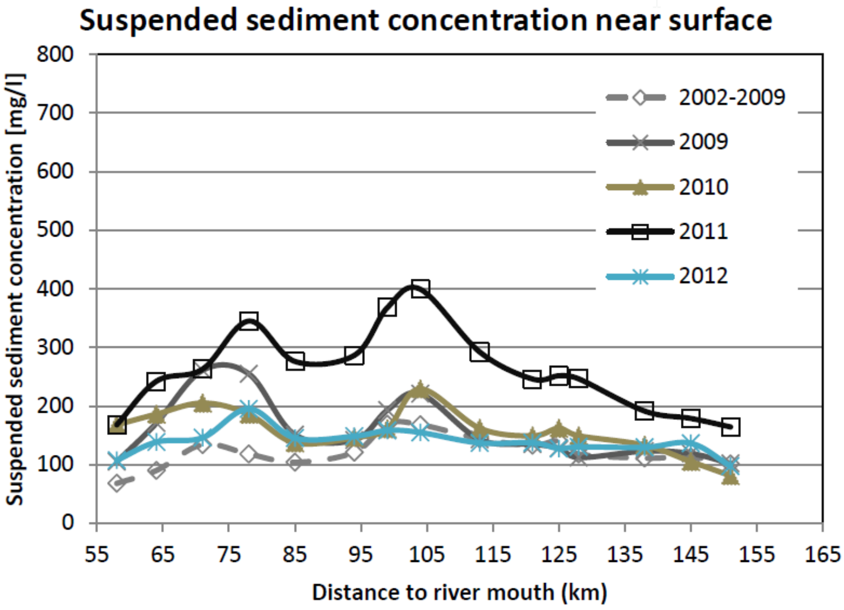

Figure 14: Surface suspended sediment concentrations (source: IMDC, 2013a; Maris et al., 2013).

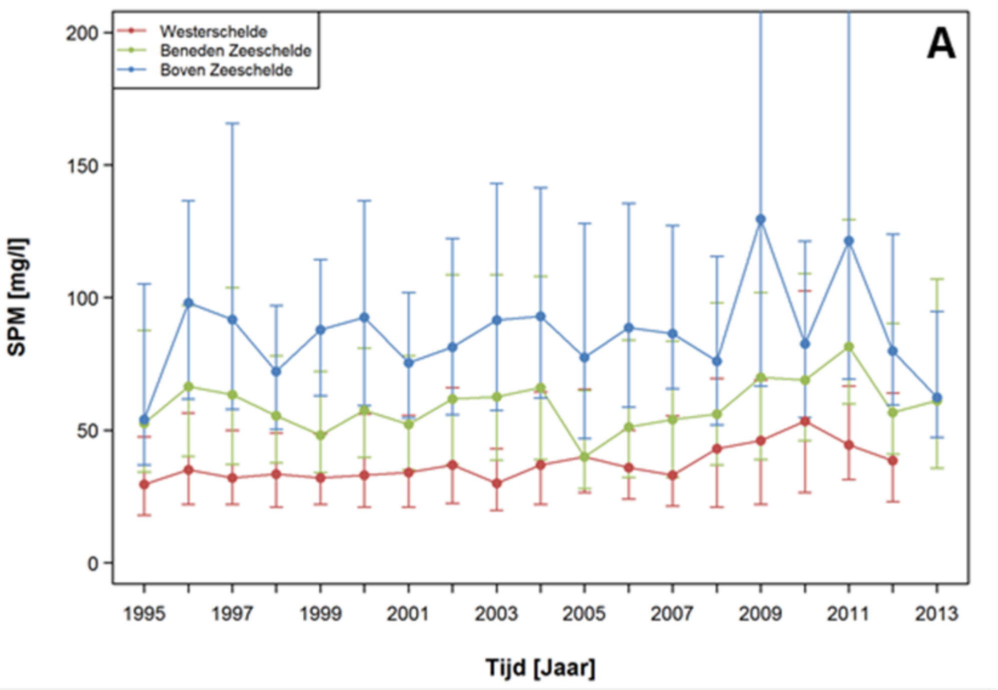

Figure 15: Surface SSC over the period 1995-2013 in the Scheldt estuary. Data from the OMES dataset. Dots represent the median, error bars represent the 25 and 75 percentile.

In the framework of the Long Term Vision research programme, mud dispersion after disposal has been studied to suggest alternative disposal locations (IMDC, 2013b and Van Kessel et al., 2015 (this issue)). This analysis showed that upwards disposal of mud (as is the case now, from the Deurganckdock area to the Oosterweel area) has a strongly increasing effect on SSC (Figure 16). Seaward disposal leads to lower SSC due to increased mixing and dispersion.

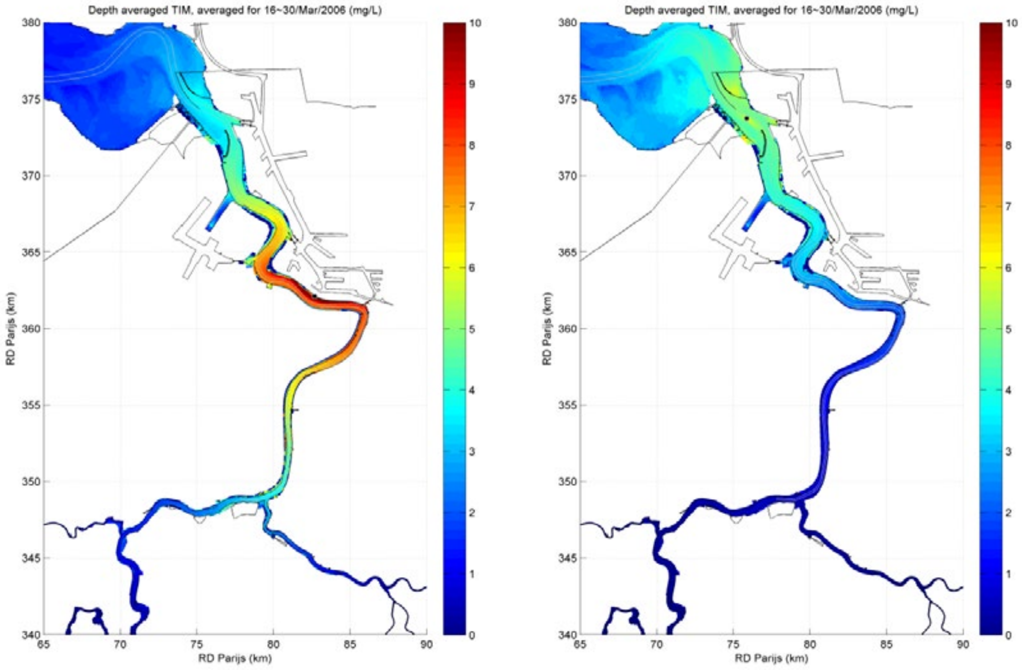

Figure 16: Average suspended sediment concentrations over spring-neap cycle after unit mud disposal at Oosterweel (left image) and Schaar Ouden Doel (right image). (source: IMDC, 2013b).

5.2 Towards a hyperturbid system?

In the Lower Sea Scheldt, processes that make part of the positive feedback loop described by Winterwerp (2012), Winterwerp & Wang (2013), Winterwerp et al. (2013), have been identified. The increase of the tidal amplitude can be explained by the first deepening of the Scheldt estuary during the 1970 that was characterized by large sediment extraction volumes. The increased volume of the estuary undoubtedly led to an increased tidal propagation in the estuary.

In more recent years, increasing suspended sediment concentrations were observed in the continuous SSC measurements. It is proposed that a large part of the variations and increase are explained by the mud disposal increase, in combination with the mud disposal strategy that currently disposes mud against the SSC gradient (towards the sediment concentration maximum, located upwards of Antwerp). A ‘recirculation’ pattern appears to be invoked by this process: mud disposed at the Oosterweel location is resuspended and caught in mud sedimentation areas. Important sedimentation areas are the Deurganckdock and lock entrances and access channels due to the low dynamical conditions. To prevent disturbance of navigation and accessibility, these areas are regularly dredged which leads to redeposition at the Oosterweel site.

At the moment, the mud disposal strategy mostly effects the Lower Sea Scheldt and the influence seems to be reversible (based on the decreased SSC in 2012 and 2013 in the continuous measurements). The numerical modelling (IMDC, 2013b, Van Kessel et al., 2015) suggests possible alternatives by disposing the dredged mud down the SSC gradient. The speed at which the SSC appears to respond may lead to a quick decline in SSC levels, with positive feedback through less deposition in Deurganckdock and lock entrances.

Although this would not resolve the tidal amplitude increase observed in the past decades, the risk for reduction of the hydraulic drag would be effectively reduced. Another question rises however: at which spatial scale does the hyperturbidity feedback loop act? In other words: over which area do SSC need to be increasing to reduce the effective hydraulic drag to induce further tidal amplitude effects? It is not certain whether the effects observed near Oosterweel would suffice to drive this process.

6. CONCLUSIONS

The Scheldt Estuary has undergone vast changes and interventions, not in the least in the past century. It is known from other estuaries and physical theory that these can lead to amplification of the tidal amplitude. A positive feedback loop has been hypothesized and supported by observations in several estuaries, showing that an increase in tidal amplitude may lead to an increase in sediment concentrations, decrease of hydraulic drag resistance and again in tidal amplitude increase. Estuaries that have undergone such transformations are now characterized by hyperturbid conditions, the presence of fluid mud layers and ultimately, a poor ecological state. High turbidity for instance excludes light penetration in the water column and inhibits thus primary production. Stratified fluid mud layers block oxygen transport through the water column leading to anoxic conditions.

In this paper we addressed the state of the Scheldt estuary. The feeds to the positive feedback loop appear to be present: increase of tidal amplitudes in the past decades, and more recently changes in SSC. Although several datasets and proxies (continuous SSC, light attenuation) point to an increased SSC in the (Lower) Sea Scheldt, other analyses (IMDC, 2014; Vandenbruwaene, 2015) indicate that there are no clear long-term trends after removal of known relations and trends such as the spring-neap cycle.

Although the long-term trend may still not be revealed, our analysis and numerical modelling (IMDC, 2013b, Van Kessel et al., 2015 (this issue)) clearly shows that mud disposal in the Low Sea Scheldt influences a larger area. Increased mud disposal leads to rather immediate elevated SSC values. On the other hand, a decrease of mud disposal also resulted in decreased SSC values.

It is suggested that future sediment management choices will partly determine whether SSC will continue to rise in the Sea Scheldt. The topic of hyperturbidity and regime shift is currently researched to a further extent within the research program “Agenda of the Future” and the “Integrated Plan of the Sea Scheldt”. Ultimately, we recommend to further investigate smart mud disposal and management strategies in the Lower Sea Scheldt to avoid an unwanted regime shift.

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TRANSPORT OF FINE SEDIMENTS IN A NARROW CONVERGENGING ESTUARY – THE SEA SCHELDT

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ABSTRACT

In this paper we study the transport of fine sediments by river-induced flushing, estuarine circulation and tidal asymmetry in the Sea Scheldt, Belgium. This study is carried out with an idealized schematization of the river, modeled as an exponentially converging river with constant depth and rectangular cross section, using Delft3D. Sediment is only imported from the lower sea boundary. Values for tidal amplitude and river flow, prescribed at the models' open boundaries are comparable to those in the Scheldt. We show that a turbidity maximum is formed at the head of the salinity intrusion, driven by estuarine circulation, and in balance with river-induced flushing. For the given conditions, the model does not predict any fine sediment transport beyond that turbidity maximum.

Keywords: Estuary, fine sediments, estuarine circulation, tidal asymmetry

1. INTRODUCTION

In three previous papers (Winterwerp, 2011; Winterwerp and Wang, 2013; Winterwerp et al., 2013), we have argue that the Loire and Ems River have evolved into a hyper-turbid state with suspended sediment (SPM) concentrations of many 10s g/l. This evolution is the response to large-scale engineering works, such as narrowing, rectification and deepening, sometimes accompanied by redirection of fresh water as well. Not so long ago, these rivers depicted more classical estuarine features, with a pronounced estuarine turbidity maximum (ETM) at the head of the salinity intrusion, with concentrations of a few 100 mg/l. Hence, the question arose under which conditions this transition towards hyper-turbid conditions may occur, and whether other tidal rivers, such as the Sea Scheldt, may evolve towards such a state. In this paper, we study the role of the river flow in conjunction with tidal asymmetry on such a transition.

The distribution of fine sediments in an estuary is governed by a balance between the down-estuary transport by river-induced flushing and the up-estuary transport by estuarine circulation and tidal asymmetry. The three tidal asymmetries that may affect fine sediment transport are:

1. **Asymmetry in peak velocities**. As sediment transport in alluvial systems is proportional to U^n, with $n > 1$, peak flood velocities larger than peak ebb velocities induce net up-estuary sediment transport (e.g. Friedrichs and Aubrey, 1988).
2. **Internal asymmetry**. As vertical mixing scales with U^2, peak flood velocities larger than peak ebb velocities induce more mixing during flood than during ebb. Sediment is then better mixed over the water column during flood than during ebb, yielding a net up-estuary transport owing to the larger flow velocities higher in the water column (e.g. Jay and Musiak, 1994).
3. **Asymmetry in slack water duration**. We have to distinguish between Eulerian and Lagrangean conditions. In the latter case, flood dominant conditions prevail when the flow velocity decreases towards the head of the estuary, as sediment resides then longer on the bed at high water slack (HWS) than at LWS, e.g. Van Straaten and Kuenen (1958) and Postma (1961). For an Eulerian analysis, the temporal velocity gradient is relevant. If the gradient at high water slack (HWS) is smaller than at LWS, the duration of flow velocities below a critical velocity for erosion is longer during HWS than during LWS. Hence sediment resides on the bed longer during HWS than during LWS, resulting in a net-up-estuary transport (e.g. Dronkers, 1986).

It is important to realize that asymmetries in tidal velocities are not only governed by the higher harmonics of the tide, but also depends on the river flow. At large river flows, peak ebb velocities may exceed the otherwise dominant peak flood velocity. This obvious observation also implies that in up-estuary direction, the net effect of tidal asymmetry ultimately becomes ebb dominant in a converging estuary. Also, the salinity distribution, driving the estuarine circulation, interacts with the tidal asymmetry, in particular with the internal asymmetry. In general, the water column in the area of salinity intrusion is more stratified during ebb than during flood, owing to tidal straining, which adds to the effects of internal tidal asymmetry.

Further, we should appreciate how the various transport processes interact with the state of the sedimentary system. River-induced flushing, estuarine circulation and internal tidal asymmetry work on the sediment in suspension. However, estuarine circulation can only induce net (up-estuary) transport when the suspended sediment depicts a gradient over the water column – estuarine circulation does not induce net transport on homogeneously mixed matter.

Net sediment transport by tidal asymmetry in peak velocities can only occur over an alluvial bed, i.e. the sedimentary bed contains an abundance of fine sediments so that the amount of sediments in the water column scales with the flow velocity through enhanced erosion (mobility) and vertical mixing. In case that only limited amounts of fines are available in/on the sedimentary bed, the timing of mobilization of those sediments into the water column becomes relevant, which is governed by the length of the slack water period. We refer to starved bed conditions.

These starved bed conditions are encountered in most low-concentration estuaries, such as the current Upper Sea Scheldt, whereas alluvial conditions are met in hyper-concentrated rivers, such as the Ems and Loire.

In this study, we investigate whether the three processes of river-induced flushing, estuarine circulation and tidal asymmetry can induce a transition from starved bed conditions to alluvial conditions. For fine sediments, this implies a transition from a "normal" low-concentration estuary to hyper-concentration conditions.

2. SETUP OF THE STUDY

We study this transition with Delft3D simulations of the sediment transport and fate in an idealized schematization of a converging estuary. Its plan form is depicted in Fig. 1, and its dimensions in Table 1. This idealized schematization has similar features as the Scheldt estuary between Bath and Ghent.

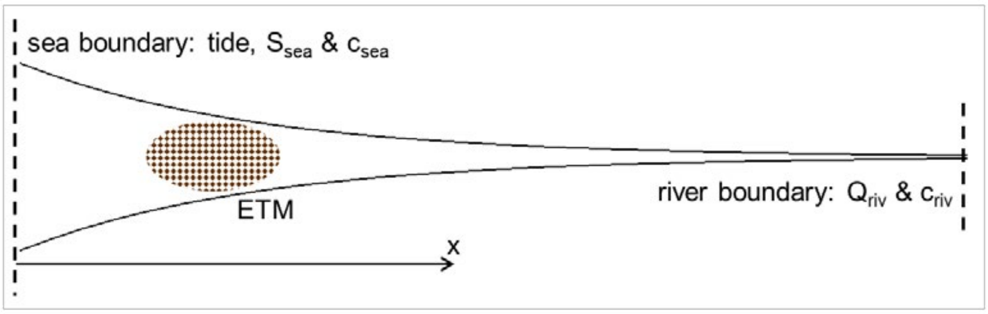

Fig. 1: Plan form of idealized, converging estuary.

Table 1: Reference settings Delft3D simulations; buoyancy coupling means that SPM affects the bulk density of the water-soil mixture, modifying vertical turbulent mixing.

L	estuary length	104 km	S_{sea}	salinity at mouth	20 ppt
h	water depth	6 m	c_{sea}	SPM concentration at mouth	100 mg/l
b_0	width at mouth of estuary	3 km	c_{riv}	SPM concentration at river	0
L_b	convergence length	30 km	W_s	settling velocity	0.5 mm/s
k_s	roughness height	3 cm		water-bed exchange	yes/no
Q_{riv}	river flow	30 m^3/s		buoyancy coupling	yes/no
M_2	amplitude semi-diurnal tide	2.13 m	$\tau_{c,e}$	critical shear stress for erosion	0.3 Pa
ϕ_2	phase semi-diurnal tide	91 deg	M	erosion parameter	0.1 $g/m^2/s$
M_4	amplitude first overtide	0.12 m	c_{gel}	gelling concentration	100 g/l
ϕ_4	phase first overtide	179 deg			

The width of the estuary follows an exponential function $b(x) = b_0 \exp\{-x/L_b\}$. The depth is constant and we do not include any intertidal area – the tide is therefore profoundly flood-dominant. Only the primary semi-diurnal tidal component (M_2) and its first overtide (M_4) are prescribed at the seaward boundary, while their values are equal to the measured values at Bath in the Western Scheldt.

This basically one-dimensional topography is implemented in Delft3D, using curvi-linear coordinates with grid size in longitudinal direction of Δx = 140 m and at the mouth a grid cell Δy = 140 m, decreasing down to 5 m at the river boundary. Over the water column, we use 23 sigma layers; in the lower half mater, the mean layer thickness measures 5 cm, while increasing by a factor 1.3 higher in the water column. We use a time step of 0.5 min, and run the simulations for many months (0.5 – 1 year). In almost all simulations, we start with an "empty" estuary, i.e. all sediment has to enter the system through its sea boundary.

In this study, the following simulations are analysed, varying the model parameters around the reference conditions given in Table 1:

Table 2: Delft3D simulations.

run	description	study objective
1	salinity, SPM, buoyancy coupling, no water-bed exchange	reference
2	same as 1, but no sediment	development overtides
3	same as 1, but no buoyancy coupling	effect SPM-induced stratification
4	same as 1, but with water-bed exchange	effect slack water asymmetry
5	same as 1, but no water-bed exchange, continuing on run 4	effect peak velocity asymmetry
6	same as 1, but no water-bed exchange and initial sediment on bed	effect peak velocity asymmetry
7	same as 1, but larger M_4 amplitude at boundary	effect external overtide
8	same as 1, but smaller river flow	effect river-induced flushing

3. FIRST RESULTS

When this document was drafted, the Delft3D simulations were not yet in equilibrium – the long simulation times required for attaining equilibrium, in conjunction with the high spatial resolution, yields long computational times.

Fig. 2 shows how the tidal asymmetry develops along the idealized estuary. In concordance with theory, a pronounced asymmetry is developed. At the estuary mouth, the peak ebb and peak flood velocity almost are equal (see Table 1: $2\phi_2 - \phi_4 = 3^0$, i.e. at the edge of a transition between ebb to flood-dominant conditions, e.g. Friedrichs and Aubrey, 1988). However, further up-estuary, peak flood velocities are almost twice the peak ebb velocities, as observed in the Upper Sea Scheldt. Hence, the estuary becomes progressively more flood dominant with respect to the peak tidal velocities in up-estuary direction.

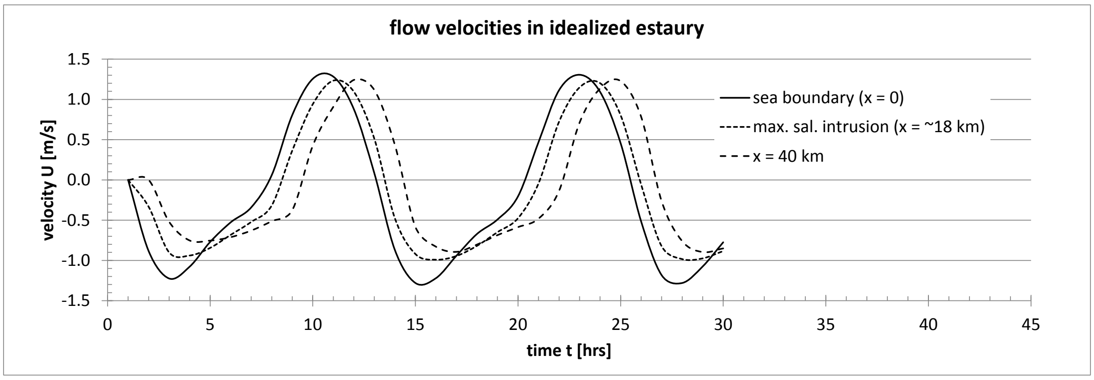

Fig. 2: Development of tidal asymmetry along idealized estuary – positive velocities are up-estuary..

Fig. 2 also shows that the temporal velocity gradient at LWS is larger than at HWS – if we assume a critical velocity U_{cr} = 0.2 m/s, the duration of HWS and LWS are given in Table 3, from which we conclude that with respect to slack water conditions, the idealized estuary is ebb-dominant.

Table 3: Computed duration of slack water period, assuming 02. m/s threshold erosion velocity (run 3).

mouth *x* = 0		maximum salinity distribution		*x* = 40 km	
LWS	HWS	LWS	HWS	LWS	HWS
45 min	24 min	33 min	24 min	24 min	21

Fig. 3 shows an example of the longitudinal and vertical distribution of salinity and SPM in the idealized estuary, with a pronounced estuary turbidity maximum (ETM). Note that this ETM migrates with the tide, the results of which are not shown here. Though salinity is at equilibrium, the SPM distribution is not – sediment continues to be pumped into the estuary. Note the accumulation of fines around the location of maximum salinity intrusion, well exceeding the SPM concentration at the model's boundary. The SPM concentration is well mixed over the water column owing to the absence of sediment-induced buoyancy destruction.

Fig. 3 also shows that no sediment can escape beyond the ETM in up-estuary direction. Apparently, up-estuary transport by estuarine circulation and down-estuary transport by river-induced flushing converge at this ETM-location. As sediment interaction with the bed (erosion and deposition) is not modelled, slack water asymmetry, nor asymmetry in peak velocities contribute to the net fine sediment transport in the estuary.

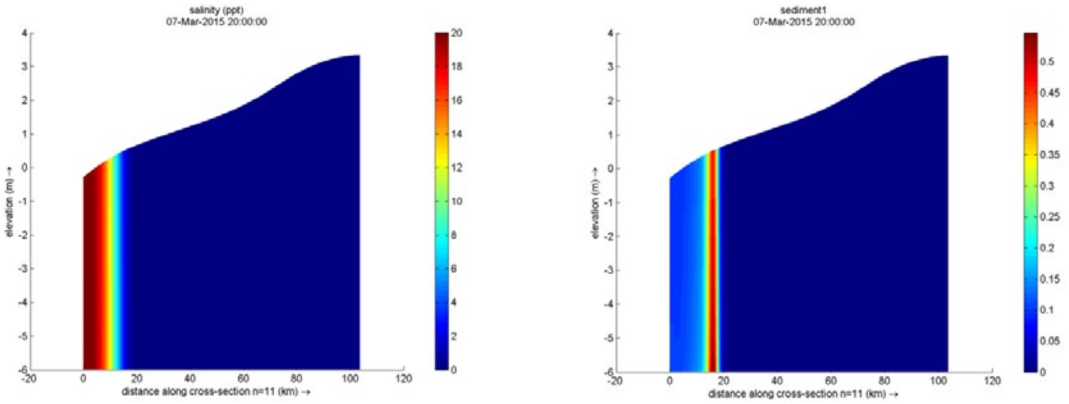

Fig. 3: Longitudinal salinity (left panel) and SPM (right panel) distribution around maximal salinity intrusion, run 3; 7 month simulation time. Colour bars represent salinity [ppt] and SPM [g/l].

These results bear the remarkable conclusion that for starved bed systems in an idealized schematization of a converging estuary, sediment cannot be transported beyond the ETM induced by the longitudinal salinity gradient. This conclusion holds for the boundary conditions prescribed – at this boundary, $t_{LWS} > t_{HWS}$.

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ON THE SHORT- AND LONG-TERM SPM VARIATIONS IN THE SCHELDT ESTUARY

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ABSTRACT

Recently there has been a growing interest in the question whether or not the Scheldt estuary may evolve towards a hyper-turbid system. Typical for such a regime shift is an increase in suspended particle matter (SPM) over a time scale of several decades. In this research we studied the historical evolution of SPM in the Scheldt estuary by the analysis of data over a period of 18 years (1995-2013). We looked at the effect of the tide, riverine discharge, seasons and sediment disposal (short-term) in order to understand the effect of these physical parameters on the SPM signal and its historical evolution (long-term).

Keywords: Scheldt estuary; suspended particle matter (SPM); historical evolution; tide; riverine discharge

1. INTRODUCTION

This study is part of a larger project called ‘mud balance Sea Scheldt’. The project aims to improve the system knowledge of mud and mud behavior in the Scheldt estuary, and assesses the implications on the evolution of estuarine habitats. This requires of thorough analysis of literature, measurements and modeling results, in this way leading to the identification of ‘mud sources’ and ‘mud sinks’ in the estuary. Moreover, a number of management questions (*e.g., is there a long-term increase in SPM?*) are tackled in this project. Present study focuses on the historical evolution of SPM (based on data analysis) and looks at the effect of several physical parameters (e.g., tide, riverine discharge) on the SPM signal.

2. METHODOLOGY

SPM is intensively monitored along the Scheldt estuary and several type of databases are available. The most extensive database contains surface SPM data which were sampled at random time steps (tide-independent). The dataset covers the entire estuary (Figure 1, red dots) and starts in 1995.

In order the evaluate the tide-independent surface SPM dataset in function of the different physical parameters we developed an algorithm which relates the time step of SPM sampling with: (1) the time step of the tidal phase (based on the time difference with the nearest extrema), (2) the neap-spring tide cycle (determined by the tidal range), and (3) the riverine discharge (based on daily values). Moreover, we evaluated the long-term evolution of SPM.

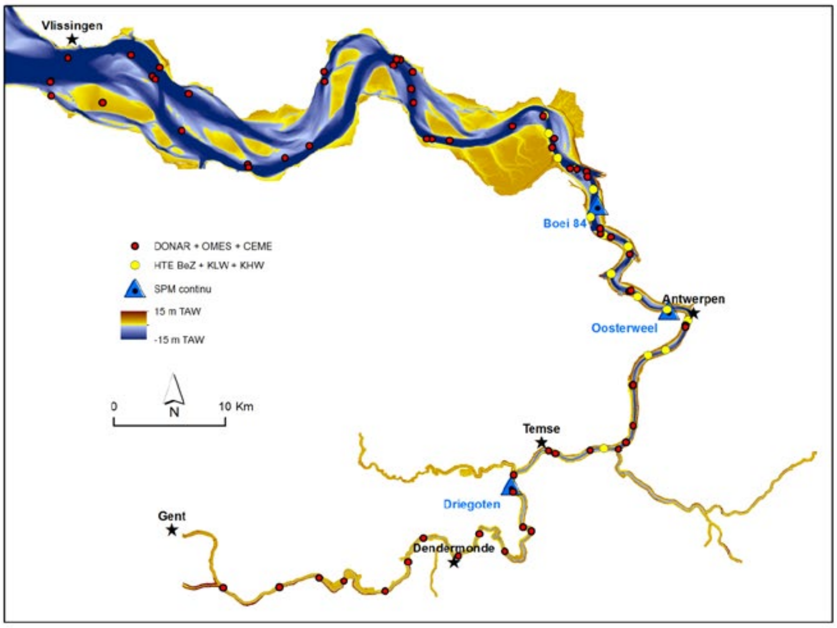

Figure 1. SPM measuring locations along the Scheldt estuary

3. RESULTS AND DISCUSSION

The tide has a clear influence on the SPM signal. Within the short-term of an individual tide we observe lower SPM values just after slack water (Figure 2). At this time flow velocities are strongly reduced which explains the decrease in SPM. As flow velocities increase, higher SPM values are observed. In the Sea Scheldt (i.e. the part of the Scheldt 58-160 km from the mouth) we hereby observe higher SPM values during ebb than during flood, suggesting an ebb-dominated sediment transport. On the longer-term of a neap-spring tide cycle we observe an increase in SPM with increasing tidal range (Figure 3). In general the surface SPM concentration during neap tide is 0.8-0.9 times the median SPM concentration (i.e. the median value of all SPM measurements), while during spring tide this is a factor 1.1-1.3.

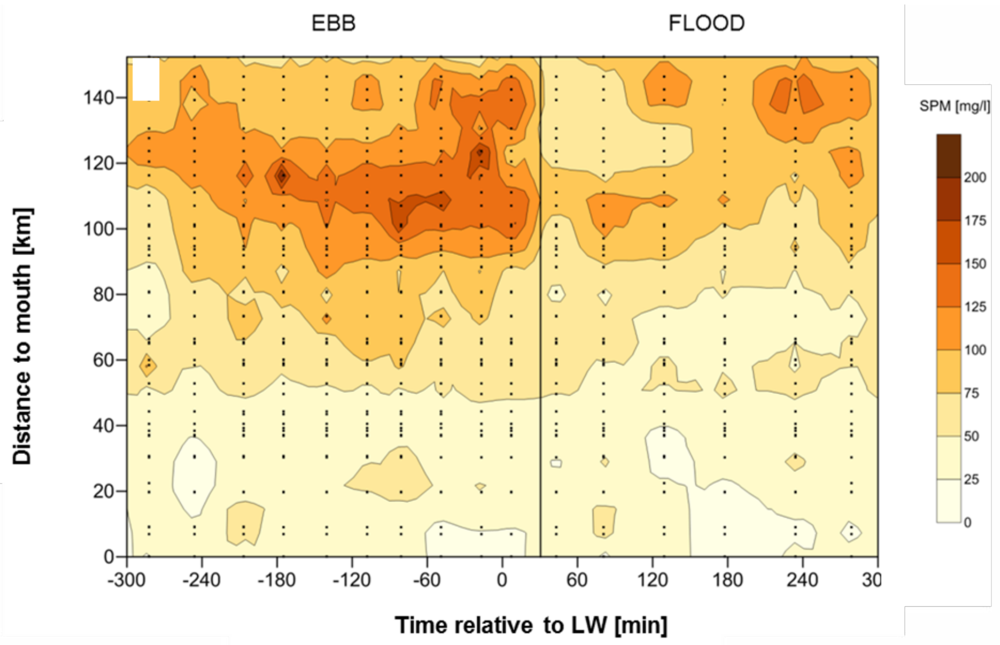

Figure 2. Relationship between the tidal phase (relative to LW) and the surface SPM along the Scheldt estuary. Vertical line which separates the ebb and flood phase represents the time of low water slack.

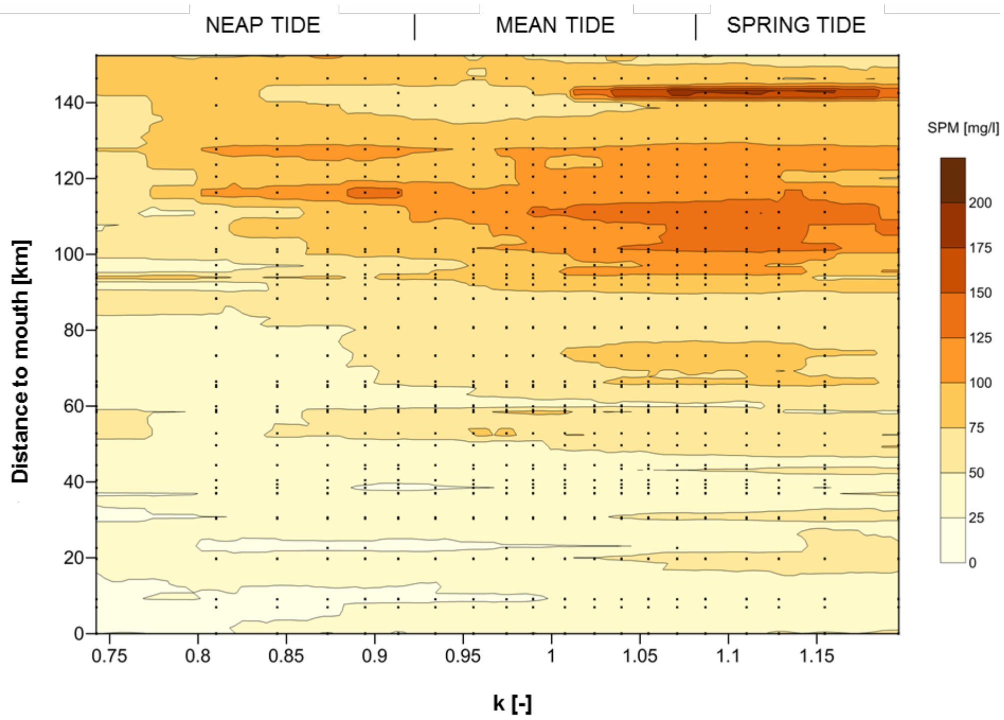

Figure 3. Relationship between the k-value (i.e. the ratio between the observed tidal range and the mean tidal range) and the surface SPM along the Scheldt estuary.

Moreover, we found that riverine discharge plays an important role in the formation of the estuarine turbidity maximum (ETM). If the riverine discharge is low (typical during summer and autumn), a distinct zone of elevated suspended sediment concentrations forms at a distance 100-140 km from the mouth (Figure 4). At higher riverine discharges (around 60 m³/s which is typical for winter conditions) SPM concentration are lower in the upstream parts of the estuary. Flow velocities in the downstream direction are then sufficiently large to transport the suspended solids. However a zone with increased SPM concentrations still occurs at 100-120 km from the mouth. Remarkably, SPM concentrations in the upstream part again increase at extreme high discharges (a discharge >96 m³/s only occurs in 10% of the cases). At these peak discharges the SPM concentration in the river is clearly larger which leads to higher SPM values in the upper part of the estuary.

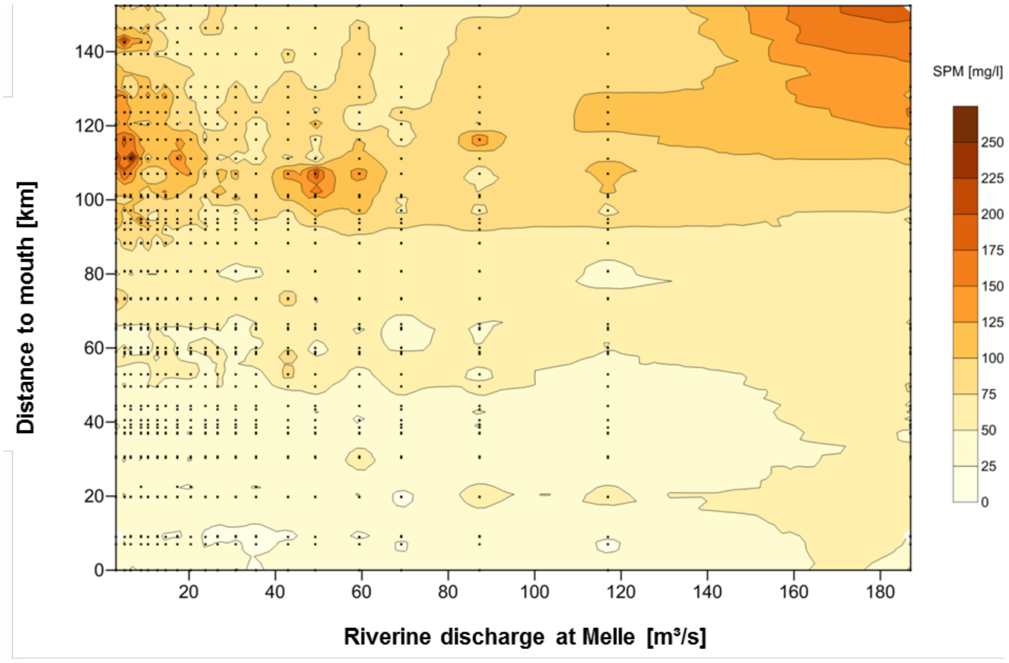

Figure 4. Relationship between the riverine discharge at Melle and the surface SPM along the Scheldt estuary

In the long-term (1995-2013) there is no significant increase or decrease in SPM in the Sea Scheldt. However we do observe an alternation of periods with higher and lower suspended sediment concentrations (Figure 5, red and green circles). Higher SPM values are hereby associated with periods of lower riverine discharge and vice versa (cf. red and green circles in Figure 5 and Figure 6). Riverine discharge thus not only affects the SPM signal on the daily or seasonal scale, but also has an effect in the longer term of years. Our study demonstrates the strong correlation between the physical parameters and the SPM signal, and emphasis that long-term trend analysis of SPM should always be interpreted with care, and in function of the historical changes of the forcing physical parameters.

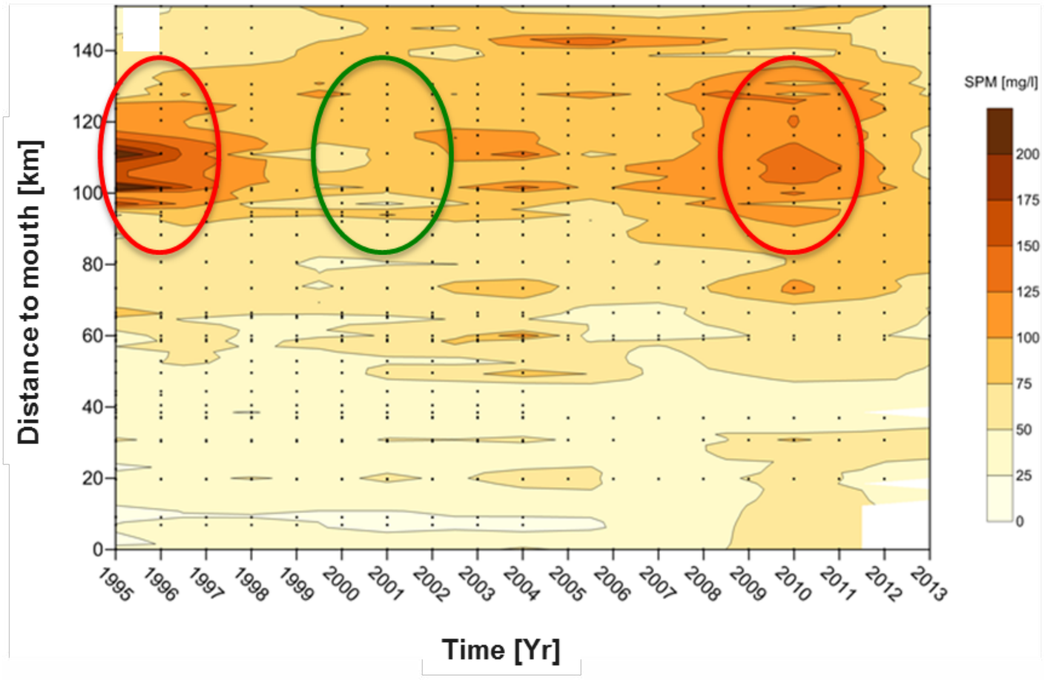

Figure 5. Evolution of surface SPM along the Scheldt estuary over the time period 1995-2013. Red circles indicate periods with higher SPM values in the upstream part of the estuary, the green circle indicates a period with lower SPM values.

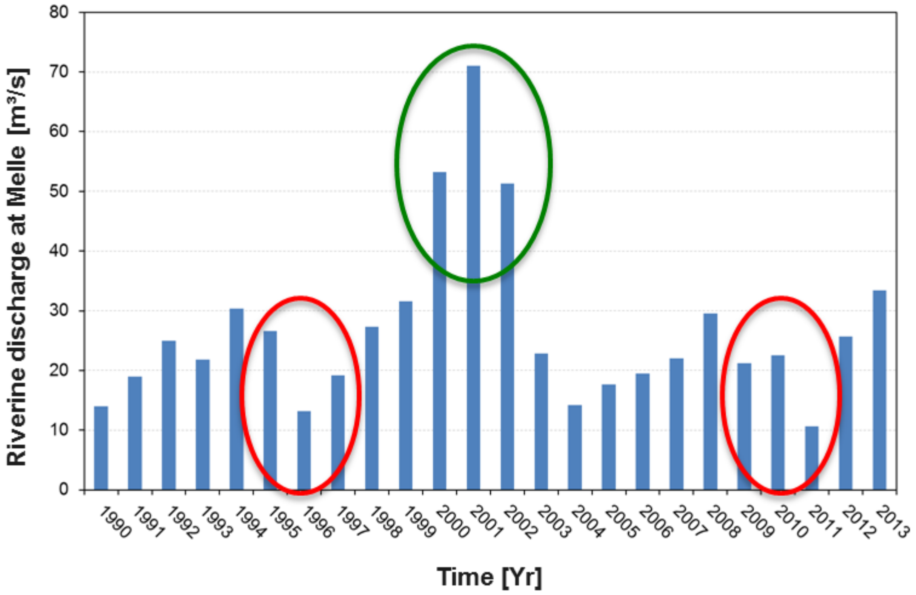

Figure 6. Yearly riverine discharge at Melle.

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HISTORICAL EVOLOTION OF MUD DEPOSITION AND EROSION IN INTERTIDAL AREAS OF THE SCHELDT ESTUARY (BELGIUM AND SW NETHERLANDS)

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ABSTRACT

The mud dynamics in an estuary are recognized as an important element of estuarine functioning, because increasing suspended sediment concentrations may be both harmful for ecological functions (e.g., biomass production by phytoplankton) and deteriorative for human functions (e.g., by siltation of shipping channels). Considering the potential risk of increase in suspended sediment concentration in the Schelde estuary, this study aims to quantify the mud deposition/erosion in different time periods since 1930 to present, different intertidal ecotope types, and different zones along the Schelde estuary, including the Westerschelde and Zeeschelde. We analyzed the height change, volume change, eroded or deposited mud mass, and the overall mud balance. Our results suggested that net mud deposition occurred in intertidal areas in both the Westerschelde and Zeeschelde in almost all time periods. The mud deposition in stable marshes plays an important role. A large amount of mud deposition is also observed in stable intertidal flats and areas that shifted from intertidal flat to marshes or from subtidal zone to intertidal flat. Over 90% of mud erosion is observed in areas that shifted from intertidal flat to subtidal zone. Mud erosion is also observed in areas that shifted from marsh to intertidal flat.

Keywords: mud deposition, mud erosion, intertidal areas, Scheldt estuary, GIS

1. INTRODUCTION

The mud dynamics in an estuary are known to be a key element of estuarine functioning, as increasing suspended sediment concentrations may be both harmful for human functions such as by siltation of shipping channels, as well as a hindrance for ecological functions such as biomass production by phytoplankton. In terms of the potential risk of increase in suspended sediment concentration in the Schelde estuary (Belgium and SW Netherlands, Figure 1), it is relevant to know the historical evolution of the mud deposition/erosion in intertidal areas within the estuary. The aim of this project is to calculate the mud deposition/erosion in different time periods since 1930 to present, for different intertidal ecotope types, and in different zones along the Schelde estuary, including the Westerschelde (Netherlands) and Zeeschelde (Belgium).

2. DATA AND METHODS

We analyzed the height change, volume change, eroded or deposited mud mass, and the overall mud balance in between time steps of around 1930, 1960, 1990, 2000 and 2010. Ecotope maps of different years were compared to get the difference maps of ecotope changes between the different time steps. Elevation data were compared between different years to get the elevation change between the different time steps. Height change in the different ecotope change classes were extracted based on the combination of elevation change maps and ecotope change maps. Volume change in the different ecotope change classes were calculated by multiplying the height change in the different ecotope change classes with the area of different ecotope change classes. Mud volume change was calculated by multiplying the volume change in the different ecotope change classes with mud content data. In the end, mud mass change was calculated by multiplying mud volume change with dry bulk density data.

The Digital Terrain Models (DTMs) in the Westerschelde and Zeeschelde of different time steps were interpolated from the bathymetric data, topographic data and LIDAR data provided by Rijkswaterstaat, aMT (afdeling Maritieme Toegang) and INBO (Instituut voor Natuur- en Bosonderzoek) (Van der Pluijm et al., 1998; Van Heerd et al., 1999; Alkemade, 2004; Temmerman et al., 2004; Rijkswaterstaat, 2011; Van Braeckel et al., 2012; Van Ryckegem et al., 2014). The ecotope maps of marsh, intertidal flat and subtidal zone were generated based on vegetation maps of Westerschelde from Rijkswaterstaat and detailed ecotope maps from INBO, which were extracted from aerial photographs and hydrograhic maps (Huijs, 1995; Van der Pluijm et al., 1998; Reitsma, 2006; Rijkswaterstaat, 2011; Van Braeckel, 2013). Sediment grain size data were collected from different sources, including the data from MOVE project (Plancke et al., 2011), from INBO (Speybroeck et al., 2014) and UA-ECOBE (Temmerman et al., 2003, 2004; Teuchies et al., 2013; Jongepier et al., 2015) during several projects. The dry bulk density is estimated based on measurements on sediment samples from the Scheldt estuary with high mud content, in particular marsh samples (Temmerman et al., 2003; Teuchies et al., 2013). Since no spatial trend in bulk density was observed along the estuary, an average dry bulk density of 500 ± 100 kg/m^3 was used for all zones.

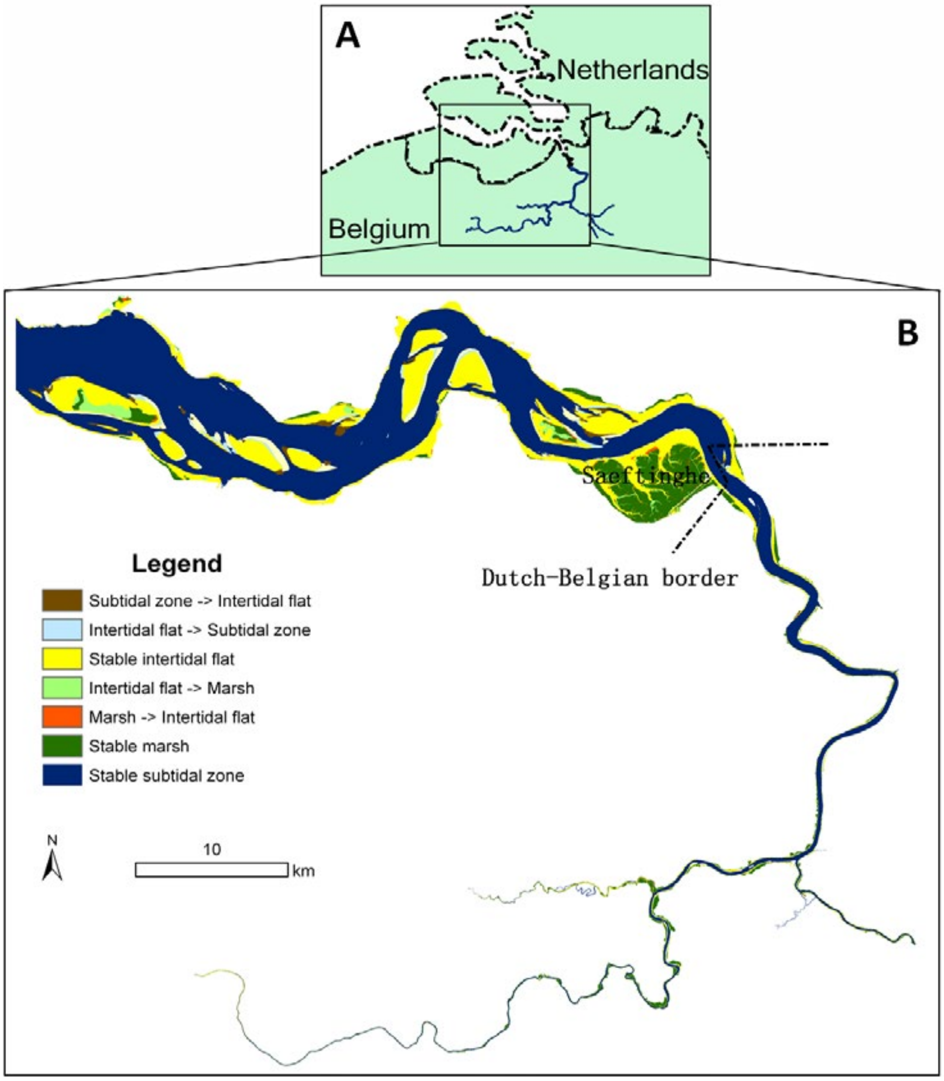

Figure 1. Study area. (A) Location within NW Europe. (B) Location of the Westerschelde (west of the Dutch-Belgian border) and Zeeschelde (southeast of the Dutch-Belgian border). Ecotope changes are mapped for the Westerschelde (2004-2010) and Zeeschelde (2001-2010).

3. RESULTS AND DISCUSSION

Our results suggested that net mud deposition occurred in intertidal areas in both the Westerschelde and Zeeschelde in almost all time periods (Figure 2 and Table 1). For the total mass of mud deposition, intertidal mud deposition is slightly larger in the Westerschelde (on average 42.6 × 10^3 ton/year averaged over all time periods) than in the Zeeschelde (on average 36.2 × 10^3 ton/year), because the intertidal areas of the Westerschelde is much larger than that of the Zeeschelde. The average mud deposition rate in all the intertidal areas is the largest in the periods of 1963-1992 in the Westerschelde (79.5 × 10^3 ton/year) and 1930-1960 in the Zeeschelde (72.0 × 10^3 ton/year). In terms of the relative role of different intertidal ecotope types, the mud deposition in stable marshes plays an important role in both the Westerschelde (on average 68.7 × 10^3 ton/year) and Zeeschelde (on average 44.3 × 10^3 ton/year). The mud deposition in stable marshes in the Westerschelde mainly takes place in Saeftinghe (with 3000 ha the biggest intertidal area in the estuary), especially in the earlier periods before 2004, with mean mud deposition rates of 62.3 × 10^3 to 77.8 × 10^3 ton/year. A large amount of mud deposition is also observed in stable intertidal flats (on average 43.0 ×10^3 ton/year) and areas that shifted from intertidal flat to marshes (on average 22.0 ×10^3 ton/year) or from subtidal zone to intertidal flat (on average 227.3 ×10^3 ton/year) in the Westerschelde. Over 90% of mud erosion is observed in areas that shifted from intertidal flat to subtidal zone in the Westerschelde (on average 307.6 ×10^3 ton/year) and in the Zeeschelde (on average 11.1 ×10^3 ton/year). Mud erosion is also observed in areas that shifted from marsh to intertidal flat in the Westerschelde (on average 10.9 × 10^3 ton/year).

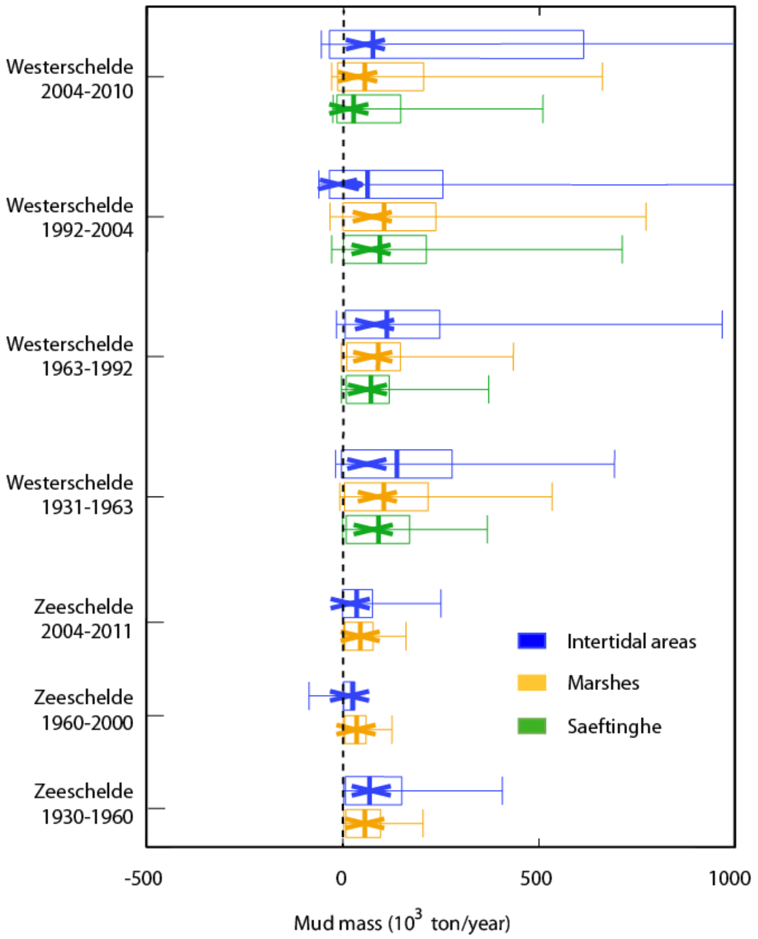

Figure 2. Boxplots of mud balance in the intertidal areas, marshes and Saeftinghe in the Westerschelde and Zeeschelde in different periods. Intertidal areas = onshore tidal flats + offshore tidal flats + tidal marshes. The upper bound and lower bound indicate the 5th percentile and 95th percentile of the values. The box indicates the 25th and 75th percentile. The thick line indicates the 50th percentile, and the cross indicates the mean value. The 95th percentile of the values in the Westerschelde in 2004-2010 and 1992-2004 are 407 × 10^4 ton/year and 249 × 10^4 ton/year, respectively, which are outside of the range of the x-axis.

Table 1 – Average mud erosion/deposition rates in mass and muss per unit in different ecotope types of all sub-division zones in the Westerschelde and Zeeschelde.

	Location	Stable marsh	Stable intertidal flat	Marsh -> Intertidal flat	Intertidal flat -> Marsh	Intertidal flat -> Subtidal zone	Subtidal zone -> Intertidal flat	All intertidal areas
Mass (ton/year)	Westerschelde	68,742	43,081	-10,916	21,964	-307,587	227,345	42,629
	Zeeschelde	44,332	-5,228	1,241	20	-11,135	6,988	36,219
Mass per unit area (ton/ha/year)	Westerschelde	33	4	-59	27	-199	143	4
	Zeeschelde	68	-4	-11	50	-75	3	20

The mud deposition rate per unit area (Table 1) is much larger upstream in the Zeeschelde (with an average of 20 ton/ha/year) than downstream in the Westerschelde (4 ton/ha/year). The same as the total mass of mud deposition, the mass per unit area is also the largest in the periods of 1963-1992 in the Westerschelde (7 ton/ha/year) and 1930-1960 in the Zeeschelde (36 ton/ha/year). The mud deposition per unit area is the highest in stable marshes in both the Westerschelde (33 ton/ha/year) and Zeeschelde (68 ton/ha/year). High deposition rate per unit area is also observed in areas that shifted from subtidal zone to intertidal flat in the Westerschelde (143 ton/ha/year) and areas that shifted from intertidal flat to marshes in the Zeeschelde (50 ton/ha/year). The highest mud erosion rate per unit area is observed in both the Westerschelde (199 ton/ha/year) and the Zeeschelde (75 ton/ha/year) in areas that shifted from intertidal flat to subtidal zone. High erosion rate per unit area is also observed in areas that shifted from marsh to intertidal flat, especially in the Westerschelde (59 ton/ha/year). A positive correlation is expected between the suspended sediment concentration and the deposition rate, because of higher sediment availability for deposition (Temmerman et al., 2003; Vandenbruwaene et al., 2011).

4. CONCLUSIONS

In conclusion, there is a net mud deposition in intertidal areas in both the Westerschelde and Zeeschelde in all time periods from 1930 to 2010. The total mud deposition is slightly larger in the Westerschelde than in the Zeeschelde because of the much larger intertidal area in the Westerschelde, although the mud deposition rate per unit area is the opposite. Both the highest total mass and the highest mass per unit area of the mud deposition are observed in the periods of 1963-1992 in the Westerschelde and 1930-1960 in the Zeeschelde. Stable marshes play an important role in mud deposition, especially in Saeftinghe. Large amount of mud deposition is observed in areas that shifted from subtidal zone to intertidal flat and areas that shifted from intertidal flat to marshes. Large amount of mud erosion is observed in areas that shifted from intertidal flat to subtidal zone and areas that shifted from marshes to intertidal flat. A positive correlation is expected between the deposition rate and the suspended sediment concentration.

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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^{3}yr^{-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^{3}yr^{-1} before 1950 to about 7–10 million m^{3}yr^{-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.

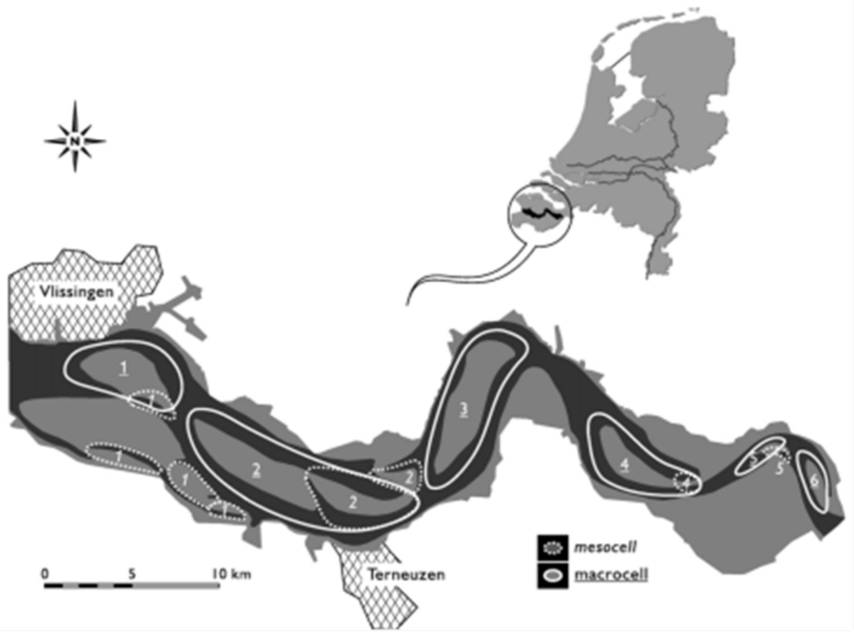

Figure 1. Western Schelde, a chain of morphological cells forming a two-channel estuary (after Jeuken and Wang, 2010).

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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SIMULATION OF LONG-TERM MORPHODYNAMICS OF THE WESTERN SCHELDT

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ABSTRACT

In this paper we use a 2D process-based model to hindcast morphodynamic behavior of the Western Scheldt estuary. The periods of 1860-1970 (110 years) and 1905-1970 (65 years) are simulated. We compare the results to a historically unique dataset of bathymetric maps. The results show that the model results get better over time. The results show that the model is capable of simulating the large scale erosion and sedimentation that has occurred in the considered period. We attribute this to the self-organization of both the model and reality. The interaction between the major tidal forcing and the estuaries' fixed outline overrules other uncertainties over long time scales. Our research shows that process-based models applied in confined environments and under constant forcing conditions may perform well especially on long time scales. This makes them potentially suitable for centennial time scale forecasts related to, for example, climate change.

Keywords: *Morphodynamics, Estuaries, Numerical models, Long-term, Hindcast*

1. INTRODUCTION

Estuaries are located between the river and the sea. Estuaries are important navigational gateways to ports and rivers further upstream. Estuaries have also important ecological functions like the breeding ground for fish or feeding ground for birds. The ecological importance of estuaries is stressed by protecting the intertidal areas. Any negative change in these areas due to natural or antropogenic factors needs to be avoided. It is therefore vitally important to know the potential effect before any measure is executed. Estuaries are more and more under pressure due to human activities and climate change. Dredging of navigational channels is a major anthropogenic influence in estuaries. Reclaiming land from estuaries is seen throughout the world. Sea level rise is another influence that causes concern about the possibility of drowning of intertidal areas.

Managing estuaries requires validated prediction tools for estuarine morphodynamics to assess the future state of estuarine environments as well as the impact of human actions. Since several years process-based morphodynamic models have been developed for these reasons. These process-based models are commonly used by the scientific and engineering community (e.g. for environmental impact assessment studies). Scientific research of these models has mostly been limited to schematized estuaries and short-term modeling exercises in real estuaries with varying success (maximum a few years). In this paper we are interested in the value of process-based morphodynamic models on long-term timescales (decades – centuries). For that reason we hindcast two periods of morphodynamic behavior of the Western Scheldt estuary by means of a 2D, high resolution, process-based model and compare results to a historically unique bathymetric dataset.

2. LONG-TERM MORPHODYNAMICS PREDICTABLE?

Process-based models are based on physical principles (e.g. mass conservation) and use mathematical equations to describe water motion, sediment transport and bottom change. The last decades these models have developed rapidly and are becoming robust tools to calculate morphological changes (Van der Wegen and Roelvink, 2012). A process-based model describes the water motion with a typical time step of seconds to minutes for numerical stability. Using an empirical sediment transport formula (e.g. Engelund and Hansen, 1967) sediment transport is calculated within this time step. The next step is to calculate bottom changes, which are fed back into the water motion the following time step. Since the desired morphological scale is much larger than the hydrodynamic time step these morphological computations typically require a large computational effort. To speed up the computation the bottom change is usually multiplied by a morphological acceleration factor (Roelvink, 2006).

It seems at first hand ambitious to scale up a sediment transport formula that was originally developed on a laboratory scale of seconds to a timescale of years, decades or longer. De Vriend et al. (1993) claim that long-term behavior of models may be inherently unpredictable since the natural system is a nonlinear interaction between water, sediment motion and bed topography.

Stive and Wang (2003) claim that the ability to hindcast or predict the evolution of tidal inlets at decadal to century time scales remains questionable. Furthermore hindcasting decadal-timescale bathymetric change in estuaries is prone to error due to limited data for initial conditions, boundary forcing, and calibration (Ganju et al., 2009). Small deviations in for example parameter settings might cause large errors in the long term since the errors begin to accumulate (Roelvink and Reniers, 2011). Haff (1996) points to different sources of uncertainty or error that arise in attempting to model at longer time scales : (i) model imperfection, (ii) omission of important processes, (iii) lack of knowledge of initial conditions, (iv) sensitivity to initial conditions, (v) unresolved heterogeneity, (vi) occurrence of external forcing, and (vii) inapplicability of the factor of safety concept. Generally hindcast periods greater than a few years are considered unreliable.

These authors suggests that long-term modeling is difficult, if not impossible. On the other hand several studies have shown that realistic patterns emerge if the model starts from a flat bed. Hibma et al. (2003) show that self-organization of pattern formations in a highly schematized estuary can be simulated with a process-based model and gives reasonable resemblance with patterns found in reality. The reason why the model was capable of simulating these patterns is a positive feedback between currents and bathymetry. Van der Wegen and Roelvink 2008, Van der Wegen et al. (2008, 2010) extended this research for millennia timescales and concluded that a relative simple process-based model can describe at least in some degree the morphodynamics of estuaries. The positive feedback mechanism between currents and bathymetry is responsible for more or less stable results after long timescales with little sensitivity to the model settings or sediment transport formula. Van der Wegen and Roelvink (2012) also showed that a process-based model is capable of reproducing the channel-shoal pattern using the Western Scheldt geometry with considerable skill starting from a flat bathymetry. The reason is that the interaction between tidal forcing, sediment availability and the basin geometry plays a major role in the morphological development of a tidal dominated basin. Other researchers also concluded that starting from a flat bed process-based models can produce realistic patterns in tidal inlets (Cayocca, 2001; Marciano et al., 2005; Dastgheib et al., 2008; Dissanayake et al., 2009).

To conclude: most research on long-term timescales using a process-based model has been carried out for schematized estuaries. In these cases the models produce patterns that are observed in reality. Real hindcasts over decadal to century timescales are still scarce. It is therefore important to test these models on these time scales and to know the value of process-based models for scientific and engineering reasons.

3. CASE STUDY: WESTERN SCHELDT ESTUARY

We take the Western Scheldt as a case study to test the ability of process-based morphological models on long time scales. The Scheldt estuary is one of the major estuaries of North-West Europe. The estuary is approximately 160 km long and is located both in Dutch and Belgian territory. The down-estuarine part (last 60 km) is called the Western Scheldt (Figure 1) and is characterized by a width of almost 5 km near the mouth and 1 km near the Dutch-Belgian border. The mean tidal range increases from 3.8 m at the mouth to over 5.0 m near Antwerp almost 80 km from the mouth of the estuary (see Figure 1). The estuary mainly consists of medium to fine sand. Mud is usually only found in intertidal areas. The river discharge is of minor importance since the fresh water discharge, on average 120 m³/s, is only 0.6% of the tidal prism at the mouth (Van der Spek, 1997). The estuary is well-mixed.

The Western Scheldt incorporates large areas of tidal flats and salt marshes. Nature is therefore an important function and stringent EU and national legislation is maintained to safeguard its natural values. Equally important are the functions of the estuary in the safety against flooding and the access to the Port of Antwerp.

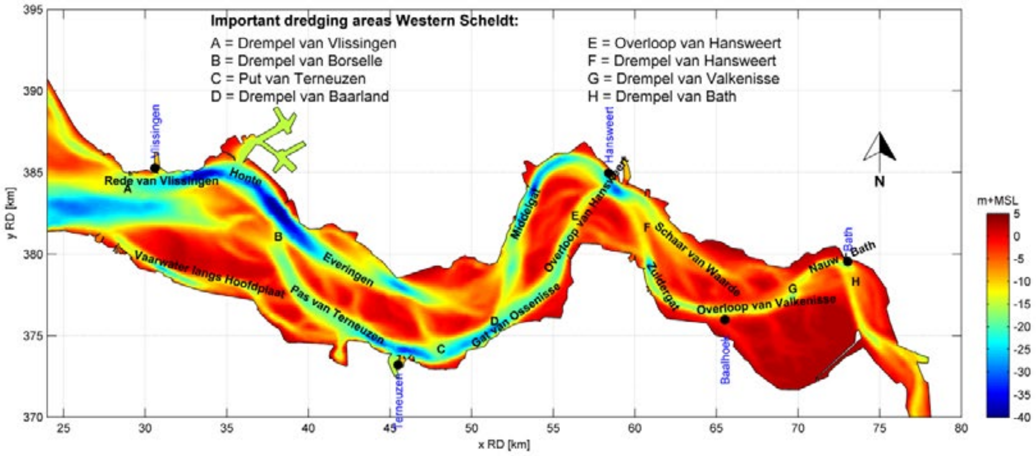


Figure 1. Layout of the Western Scheldt around 1970 with names of important channels and dredging areas and tidal stations

The Western Scheldt has a multiple channel system. Ebb and flood channels show an evasive character separated by inter tidal shoals (Van Veen, 1950). The ebb channel has a meandering character, while the flood channel is straighter. The ebb flow reaches it maximum velocity near mean sea level (MSL), while the flood flow reaches its peak one hour before high water (Van den Berg et al., 1996). As a consequence the ebb flow is more concentrated in the channels, resulting in deeper ebb channels. The ebb channel is therefore generally designated as the navigational channel in the Western Scheldt.

In this paper two periods are considered: 1860-1970 (110 years) and 1905-1970 (65 years). Figure 2 shows the observed bathymetries from 1860 to 1970. In this period large morphodynamic changes have occurred as can be seen from Figure 2. In the 1970's and 1990's a deepening and widening of the navigational channel has been carried out to allow vessels with greater draught to enter the port of Antwerp. Recently, in 2010, a third deepening has been completed. Dredging volumes after 1970 range in the order from 5-14 million m^3 per year in the estuary. Before 1970 the dredging operations concentrated to a few sills in the eastern part of the estuary. The hindcasts are therefore limited till 1970, before the major dredging operations started, in order to answer the question if we are able to hindcast the (relative) natural morphodynamic behavior of the system over this 110 year period.

In the past centuries large land reclamations have narrowed the estuary. The land reclamations in both simulations are taken into account.

The tide and morphology are inter-related. In Wang et al. (2002) this is described by saying that (1) changes in morphology lead to (2) changes in tidal levels, which lead to (3) differences in ebb and flood velocities that (4) causes residual transport of sediment, with a feedback into (1). In principle this feedback loop is described by a process-based model, although its practical value in long-term morphodynamic calculations has not been proven yet.

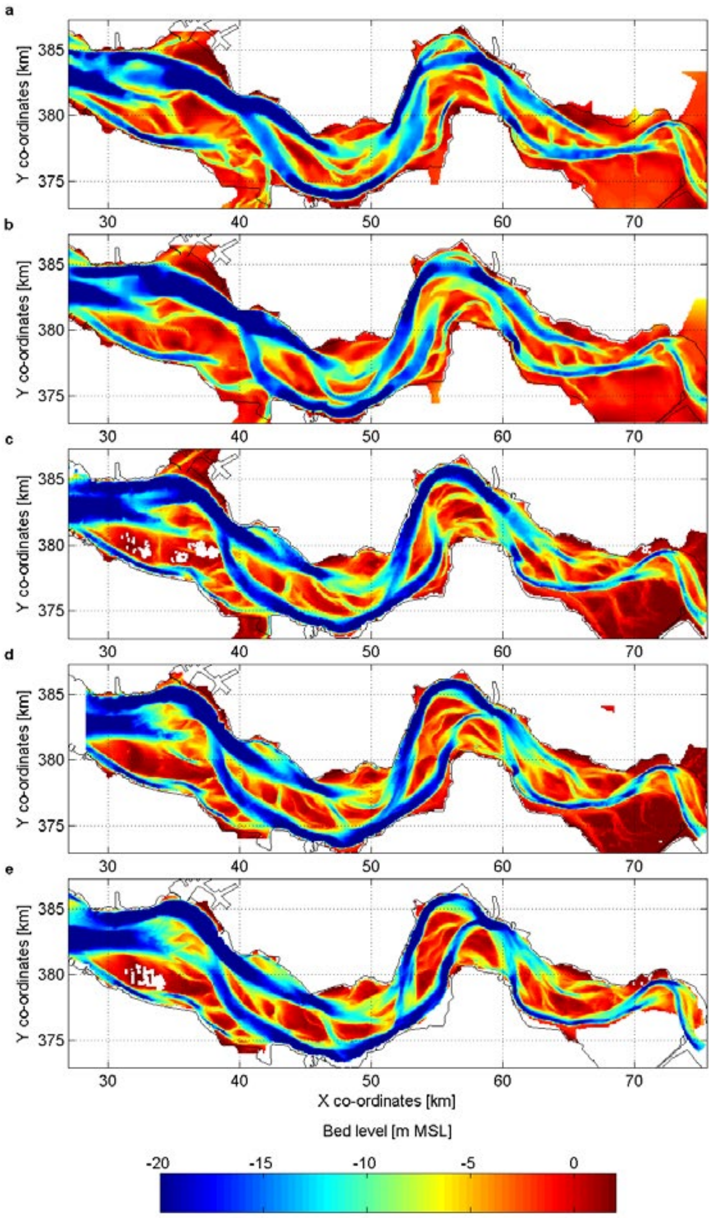


Figure 2. Five measured bed levels with respect to Mean Sea Level (MSL) of the Western Scheldt. a, 1860. b, 1905. c, 1931. d, 1955. e, 1970. Black line indicates the present day plan form. Coordinate system in Dutch National Grid.

4. THE MORPHODYNAMIC MODEL: FINEL2D

The process-based model that is applied in this study is called FINEL2d. The model is a 2DH process-based model based on the finite element method. The depth-integrated shallow water equations are the governing equations of the flow module. For details about FINEL2d reference is made to Dam et al. (2007). Other examples of the FINEL2d model are Dam et al. (2005, 2009, 2013b) and Dam and Bliek (2013).

FINEL2d uses an unstructured triangular grid. The advantage of such a mesh in comparison to for example a finite difference grid is the flexible mesh generation. In FINEL2d no nesting techniques are required in regions of specific interest, where a higher degree of resolution is needed, while arbitrary coastlines and complex geometries can be resolved very well.

The seaward boundaries of the computational mesh of the Western Scheldt are chosen approximately 40 km away from the coastline and coincide with the boundaries of existing models. The latter can be used to obtain the corresponding boundary conditions. The major part of the Scheldt-estuary in Belgium is also included in the schematization. In Figure 3 the overall mesh is shown. In the area of interest, the Western Scheldt, the average grid size is approximately 1.1 ha (~100 by 100m). Near the seaward boundaries the grid size is approximately 2.5 km^2 (~1600 by 1600 m). The total number of elements (triangles) of the mesh is 59,937.

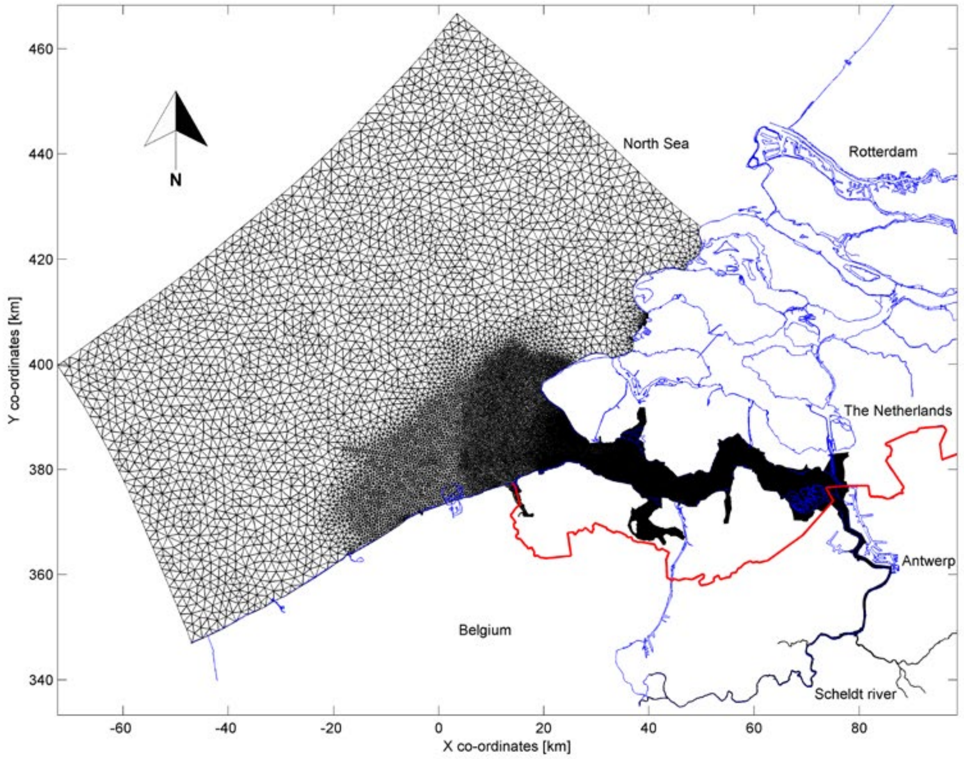


Figure 3. FINEL2d model grid of the Scheldt estuary (1860 outline).

On the seaward side of the grid astronomical tidal boundary conditions are given, while on the river side constant (yearly averaged values) river discharges are taken. Only the influence of the tidal action on the morphology is taken into account. Wave action is ignored for simplicity reasons, although intertidal areas can be influenced by wave action. To speed up the morphological calculation a morphological acceleration factor (MF) is used every timestep to multiply the bed level changes (Roelvink, 2006). In this case a MF of 24.75 is applied in accordance with Dam et al. (2007). One neap-spring cycle for the water motion represents a morphodynamic year with this setting. A parameterization of the spiral flow was implemented according to Kalkwijk and Booij (1986).

The calibration of the model on the water motion and the sandy morphology for the entire Scheldt estuary is carried out in Dam et al. (2007) with an update in 2013 (Consortium Deltares-IMDC-Svasek-Arcadis, 2013). The model was first calibrated on water levels at the main tidal stations (not presented here). This resulted in a global k-nikuradse roughness of 0.01 m. The model was validated for tidal currents in both the channels and inter tidal areas. The model showed good agreement between current observations and model results (Consortium Deltares-IMDC-Svašek-Arcadis, 2013).

Although a dredging module is available in the model (e.g. Dam et al., 2013b), this option is specifically not used in this paper, since we are interested in the (relative) natural behavior of the system before 1970. When dredging is included in the model, the results might be artificially influenced.

The optimal settings for the morphodynamic model found in the calibration are given in Table 1. These settings are used in the model computations discussed in this paper.

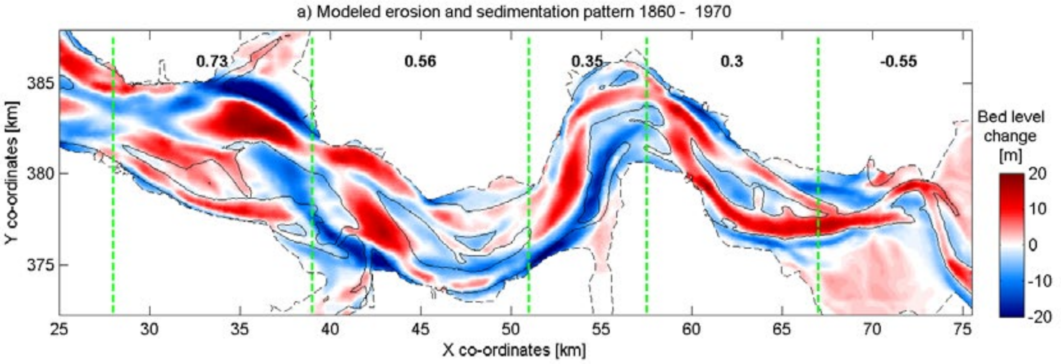
The land reclamations are taken into account in the computation. The borders of the land reclamations coincide with the computational mesh. At the year of closure a weir is implemented in the model, so that this section is closed off from the tidal influence and morphodynamic activity in the closed-off section stops. A hindcast of the years 1965 to 2002 is described in Dam et al. (2007), which was updated recently (Consortium Deltares-IMDC-Svasek-Arcadis, 2013 and Dam et al, 2013b).

Table 1. Model settings.

PARAMETER	VALUE
Sediment transport formula	Engelund- Hansen
Grain size (d_{50})	Variable (150 to 300 μm)
Fall velocity of sand	Variable
Morphological acceleration factor	24.75
Non-erodable layers	From government data
Hydraulic roughness	1 cm
Dredging module	off

5. RESULTS EROSION/SEDIMENTATION PATTERN

Using the model settings as described in the previous section a simulation is carried out for the period 1860-1970. Previous results of the 1860-1970 computation are described in Dam et al. (2013a). Several observed bathymetries are available to compare the model results. Here we limit the comparison to the year 1970. Figure 4 shows the erosion and sedimentation pattern for the 1860-1970 period for both model and measurement (110 years). Figure 5 shows the modeled and measured erosion/sedimentation pattern for the 1905-1970 period (65 years). The results show that the model is capable of simulating most of the observed morphological changes in the estuary. Especially large scale erosion or sedimentation is predicted well by the model. This is valid for both the 1860 as the 1905 computation. On smaller scales still differences can be seen. This means that the astronomical tidal forcing is the dominant forcing for the large scale morphology. Another conclusion is that forcings like storms or large river discharges do not play a large role in the large-scale and long-term development of the estuary. In the next section a more objective method is used to compare the model results with the measurements.


a) Modeled erosion and sedimentation pattern 1860 - 1970

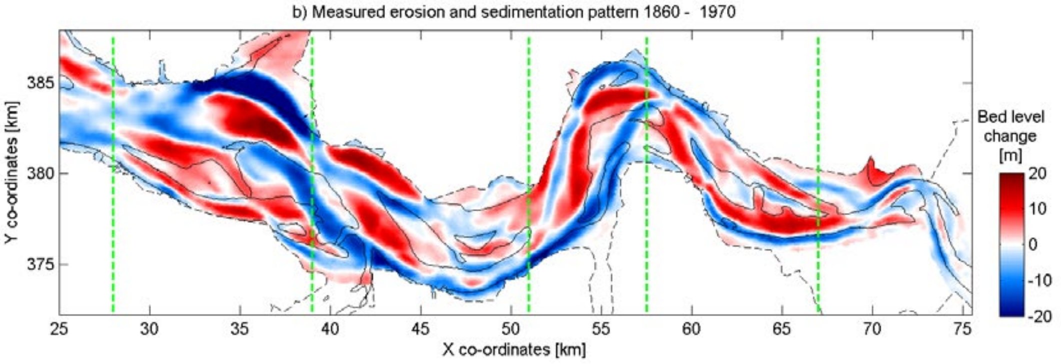
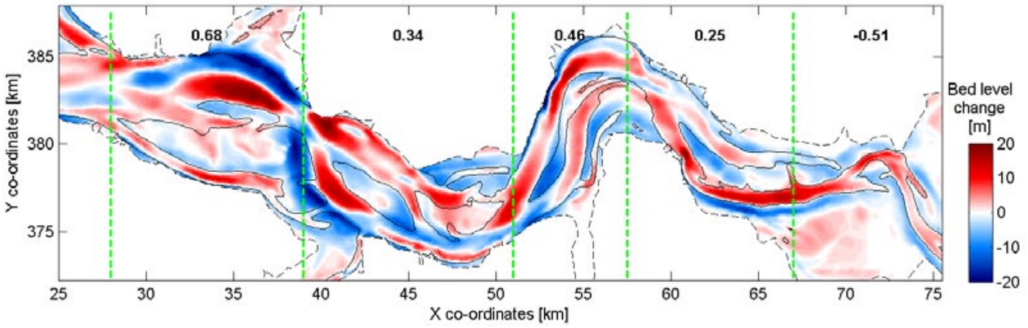

b) Measured erosion and sedimentation pattern 1860 - 1970

Figure 4. Erosion and sedimentation patterns of the 1860-1970 period. a, Modeled. b, Measured. Black dashed line indicates the 1860 plan form. Black solid line indicates the -5m contour line of the 1860 bed level. Black numbers indicate Brier-Skill Scores for sections indicated by the green dashed lines.

a) Modeled erosion and sedimentation pattern 1905 - 1970



b) Measured erosion and sedimentation pattern 1905 - 1970

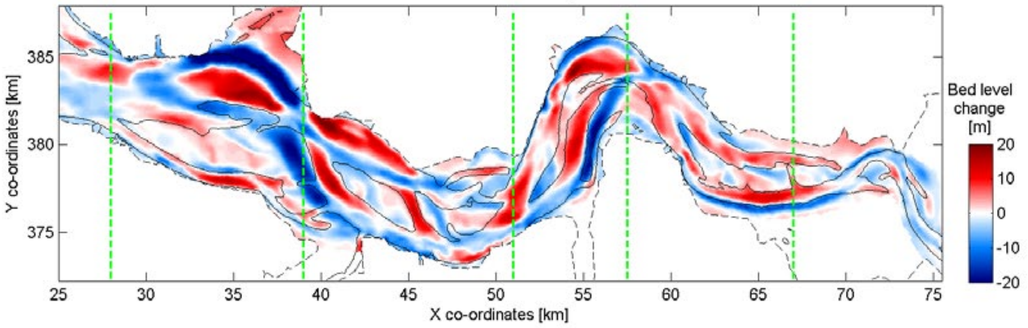


Figure 5. Erosion and sedimentation patterns of the 1905-1970 period. a, Modeled. b, Measured. Black dashed line indicates the 1860 plan form. Black solid line indicates the -5m contour line of the 1860 bed level. Black numbers indicate Brier-Skill Scores for sections indicated by the green dashed lines.

6. RESULTS USING THE BRIER-SKILL SCORE

To objectively compare measured and modeled bed changes, we use the Brier-Skill Score (BSS), see equation (1) (Sutherland et al., 2004).

$$BSS = 1 - \frac{\left\langle (Y - X)^2 \right\rangle}{\left\langle (B - X)^2 \right\rangle} \qquad [1]$$

where:
X= measured bed level [m];
Y= modeled bed level [m];
B= initial bed level [m].

And the <> denote an arithmetic mean, i.e. averaged over the model domain in this case.

The following rating of the BSS for morphological models is used (Sutherland et al., 2004):

Table 2. Rating of Brier-Skill Scores.

RATING	VALUE OF BSS
Bad	<0
Poor	0 - 0.1
Reasonable/Fair	0.1 – 0.3
Good	0.3 – 0.5
Excellent	0.5 – 1.0

As a reference, weather forecasting considers a BSS over 0.2 to be a useful prediction (Murphy and Epstein, 1989).

Figure 6 shows the BSS values for both computations with all available measured bathymetries. The 1860 run shows that the BSS is initially negative (red line) but increases to become 0.52 (excellent) after 110 years for the entire Western Scheldt. The 1905 run shows similar behavior: the BSS is also increasing over time and becomes 0.46 after 65 years of simulating for the complete Western Scheldt. So the conclusion that the model results get better over time is independent of the initial bed level.

In Figure 4 and 5 BSS values are given for different sections of the estuary. The most western section scores the highest BSS value of around 0.7 in both the 1860 as the 1905 computation. Generally BSS values decrease towards the east. The most eastern section scores negative BSS values for both runs. An explanation for this is that in this part of the estuary dredging has taken place in the considered period and this was not included in the simulation.

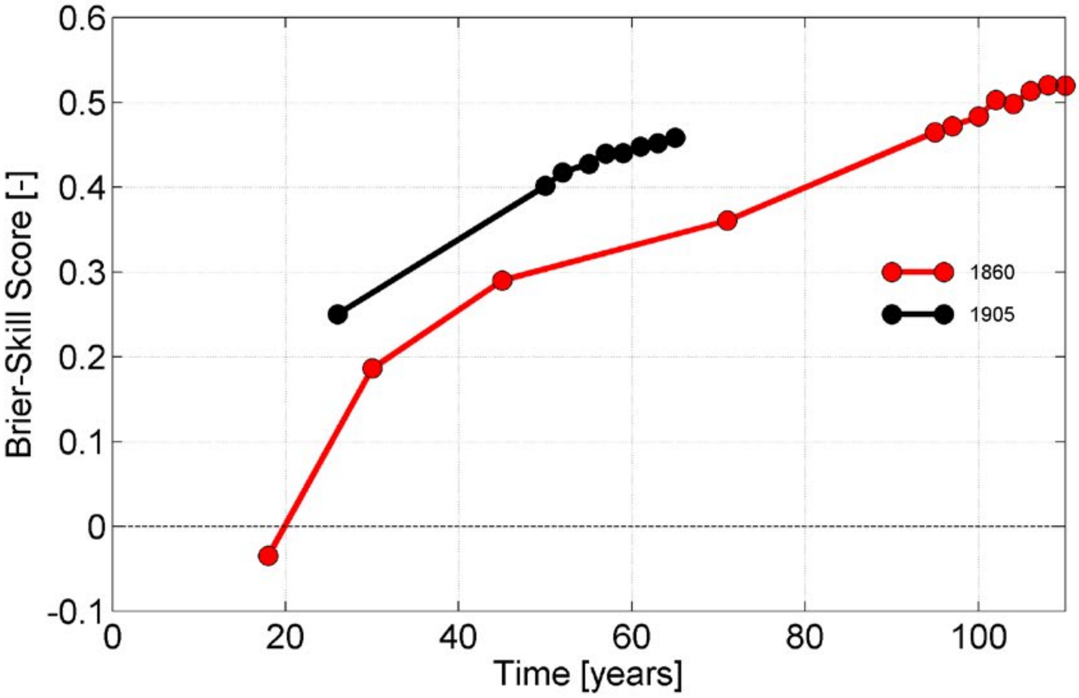


Figure 6. Brier-Skill Score for simulations with startyear 1860 and 1905. Markers indicate comparisons between model and data, solid lines interpolate between subsequent comparisons.

7. CONCLUSIONS

Contrary to common perception the results found in this paper show that long-term morphodynamics in estuaries is predictable. The results in the long-term are better than the short-term. An explanation for the initial low BSS is that the model needs to adjust the (observed) bathymetry according to its unknown parameter settings, boundary forcing and process descriptions.

The number of possible morphological outcomes seems endlessly and unpredictable, but in reality the outcomes are limited due to a few reasons: first of all self-organization is leading the morphological changes, which is reproduced by the model. As a consequence large channels are aligned more efficiently. Secondly the interaction of the tide with the estuarine geometry (i.e. fixed banks and non-erodable layers) is an important process (Van der Wegen and Roelvink, 2012). Thirdly the well predictable tide is the governing forcing. Stochastic forcing like storms and river discharge are limited. This makes that the number of possible morphological outcomes is limited even further.

Process-based models applied in the confined environment of an estuary and subject to constant tidal and river forcing conditions perform well especially on long (> decades) time scales, which makes the approach potentially suitable for centennial time scale forecasts related to for example sea level rise or other gradual changes in forcing with a similar time scale.

ACKNOWLEDGMENTS

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MODELING THE MORPHODYNAMICS OF THE MOUTH OF THE SCHELDT ESTUARY

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ABSTRACT

Recent research on the Scheldt estuary mainly focused on the Western Scheldt. There is now a renewed interest in the mouth of the estuary as the Flemish government explores the feasibility of large-scale morphological interventions in that area. This paper describes the ongoing development of a process-based numerical model (Delft3D) of the Scheldt estuary. The so-called Delft3D-NeVla model computes morphodynamics forced by waves, tide, wind and river discharge, and affected by sediment dredging and dumping to maintain navigation channels at the desired depth. After further calibration and validation, the Delft3D-NeVla model will become an important tool to understand and predict the morphodynamics of the mouth of the estuary due to natural processes and large-scale morphological interventions such as relocation of navigation channels.

Keywords: Delft3D; hydrodynamics; numerical modeling; morphodynamics; Scheldt estuary

1. INTRODUCTION

The Scheldt estuary is situated at the border of The Netherlands and Belgium. It consists of a (tidal) river part from Gent to about Antwerp, an inner estuary (Western Scheldt) from Antwerp to Vlissingen and a mouth or ebb-tidal delta (see Figure 1). The average Scheldt river discharge is about 100 m^3/s. The pre-dominantly semi-diurnal tide amplifies in upstream direction to a tidal range exceeding 5 m near Antwerp, making the Scheldt a tide-dominated estuary.

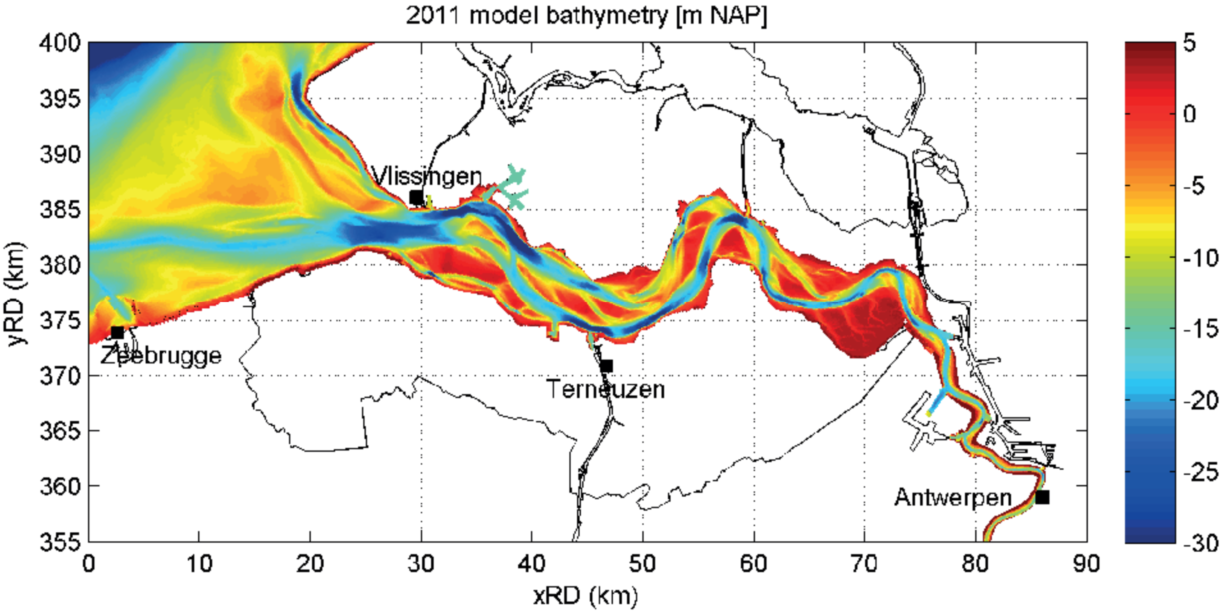


Figure 1. 2011 bathymetry Scheldt estuary.

The Scheldt estuary includes the entire gradient from fresh to salt water providing various habitats for marine 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. Safety against flooding is the third important aspect of the Scheldt estuary.

The morphology of the Western Scheldt displays a regular repetitive pattern of mutually evasive meandering ebb channels and relatively straight flood channels (see Figure 1); also referred to as 'multiple-channel system'. These main channels are separated by intertidal shoals and linked by stable and/or migrating secondary channels. The ebb and flood channels join at dynamic, shallow areas that form sills in the navigation channel, which are dredged regularly. Along the completely embanked shores, intertidal mudflats and salt marshes are found. The mouth or ebb-tidal delta of the Scheldt estuary contains the shallow area called Vlakte van de Raan in the middle and two tidal channels: the Oostgat along the Walcheren coast in the North and the Wielingen, the main entrance to the Western Scheldt, in the South.

Both natural processes and human interferences have influenced the morphological evolution of the estuary over the past two centuries (see e.g. Jeuken & Wang, 2010). Initially, human interferences 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 20th century human interferences shifted from land reclamation to sand extraction and dredging and dumping to deepen and maintain the navigation route to the port of Antwerp. The first deepening took place in the 1970s, the second in 1997/1998 and the last in 2010.

Recent modeling research (e.g. Dam et al., 2007; Van der Wegen & Roelvink, 2012) focused mainly on the Western Scheldt hydro- and morphodynamics. The Flemish government explores large-scale interventions in the mouth in support of safety, navigation and ecology. This requires new knowledge and prediction tools, because the morphodynamics of the mouth and inner part of Scheldt estuary differ. Wave effects are expected to be more important in the mouth, and there is an interaction with coastal morphodynamics. Furthermore, the influence of dredging and dumping activities is probably less pronounced.

This paper describes the set-up of a sophisticated Delft3D numerical model of the entire Scheldt estuary to increase system knowledge and to contribute to estuarine management on the large scale, as well as first model results.

2. DELFT3D MODEL

The Delft3D software solves coupled, wave-averaged equations for waves, currents, sediment transport and bed level change (see Lesser *et al.*, 2004). We have set-up a 2DH (depth-averaged) Delft3D morphodynamic model covering the entire Scheldt estuary including effects of waves, tide, wind and river discharge. Figure 2 shows the computational grid of the so-called Delft3D-NeVla model, since it is based on the NeVla model developed by Flanders Hydraulic Research.

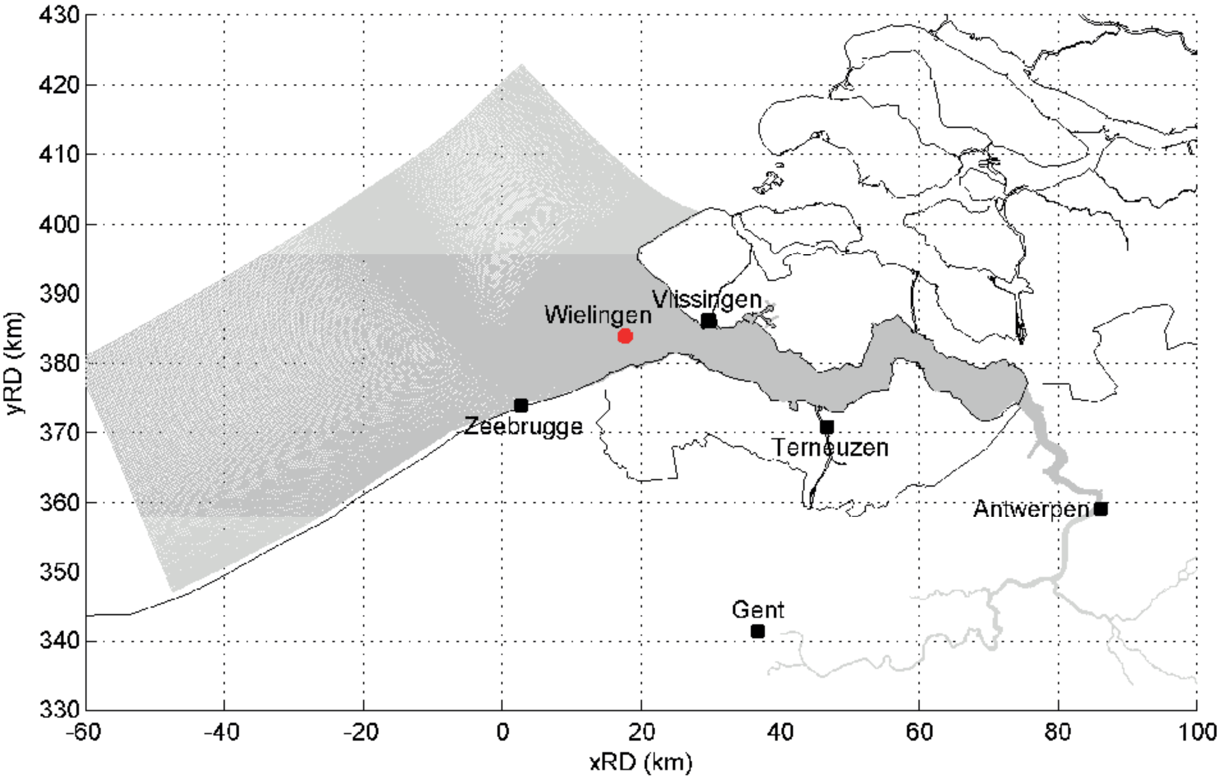


Figure 2. Computational grid Delft3D-NeVla model. The red dot indicates the location of the wave measurement station Wielingen.

The grid resolution varies between ~400 m on the Continental Shelf, to in between 50 and 100 m in the Western Scheldt to ~10 m upstream. The downstream boundary conditions are derived from the DCSM-Zuno model (Zijl *et al.*, 2013; submitted). At the upstream boundary measured discharges are imposed.

The domain of the wave model is smaller; it covers the coastal area and the Western Scheldt up to xRD ≈ 55 km. This was chosen because wave effects become less important further upstream and this study focusses on the mouth of the estuary. The flow and wave field are coupled every 30 minutes.

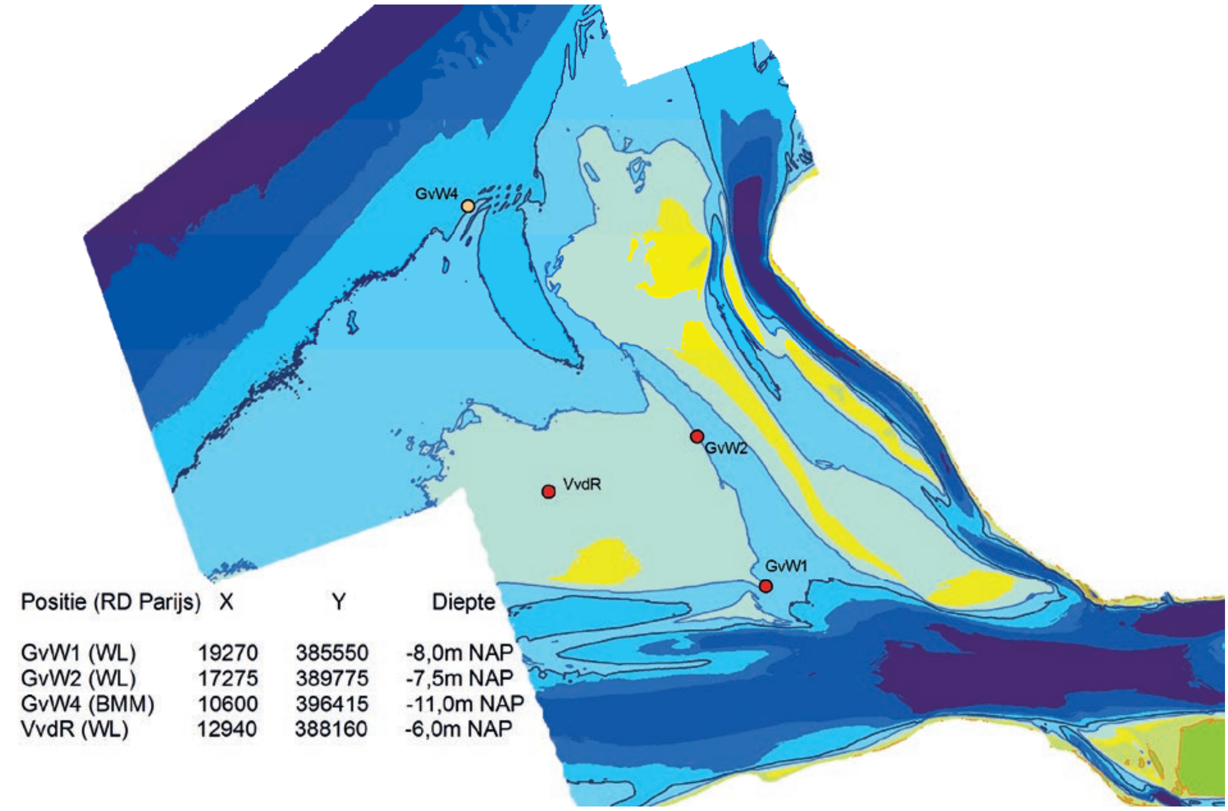
We apply a single grain size with a D50 of 0.2 mm and use the Van Rijn transport formulation. Furthermore, we account for the existence of hard, non-erodible layers and the sediment dredging and dumping activities related to maintenance of navigation channels and harbors.

3. FIRST MODEL RESULTS

The original Delft3D-NeVla model was validated earlier using measurements of water levels, discharges, velocities, maintenance dredging volumes and morphological changes in the Western Scheldt (see Consortium Deltares-IMDC-Svasek-Arcadis, 2013). Given the focus of this study we will now focus the model validation on the mouth of the Scheldt estuary, including waves. This section contains the first example results of the model validation, as well as explorative morphological calculations. We will soon be able to present more results.

3.1 Hydrodynamics

Of particular interest is the measurement campaign that was carried in the summer of 2014 (Plancke et al., 2014). Between 8th of August 8 and 5th of September wave, flow velocity and suspended concentration measurements were carried out at 4 fixed locations on the Vlakte van de Raan. Figure 3 shows the location of the measurement frames.



Positie (RD Parijs)	X	Y	Diepte
GvW1 (WL)	19270	385550	-8,0m NAP
GvW2 (WL)	17275	389775	-7,5m NAP
GvW4 (BMM)	10600	396415	-11,0m NAP
VvdR (WL)	12940	388160	-6,0m NAP

Figure 3. Location measurement frames on the Vlakte van de Raan (VvdR) and the channel Geul van de Walvischstaart (GvdW). Figure adapted from Plancke *et al.* (2014). Color scale indicates bathymetry from deep (dark blue) to shallow (bright yellow).

Figure 4 compares measured and computed velocities at the locations VvdR and GvdW2. These are the results of a first run with astronomical boundary conditions and without waves and further tuning. It is shown that the Delft3D-NeVla model can reproduce the measured velocities reasonably well, although the peak values are underestimated. While the model computes the depth-averaged velocity over the entire water column, the observations only covered the upper half the water column. This is supposed to cause the lower peak velocities in the model.

The spring-neap tidal cycle can be observed in the velocity time-series at both locations with higher velocities during spring tide (around 14th of August) and lower during neap tide (around 20th of August). The velocities in the channel (GvdW2) are ebb dominant; compare e.g. the velocity peak that occurs during ebb tide just before 19th of August with the previous one. This is less apparent in the flow velocity measurement on the Vlakte van de Raan. The depth-averaged velocities are generally lower here than in the channel. Furthermore, one can observe that the velocities never drop to 0 m/s at both locations, but remain 0.1-0.2 m/s during high and low water slack.

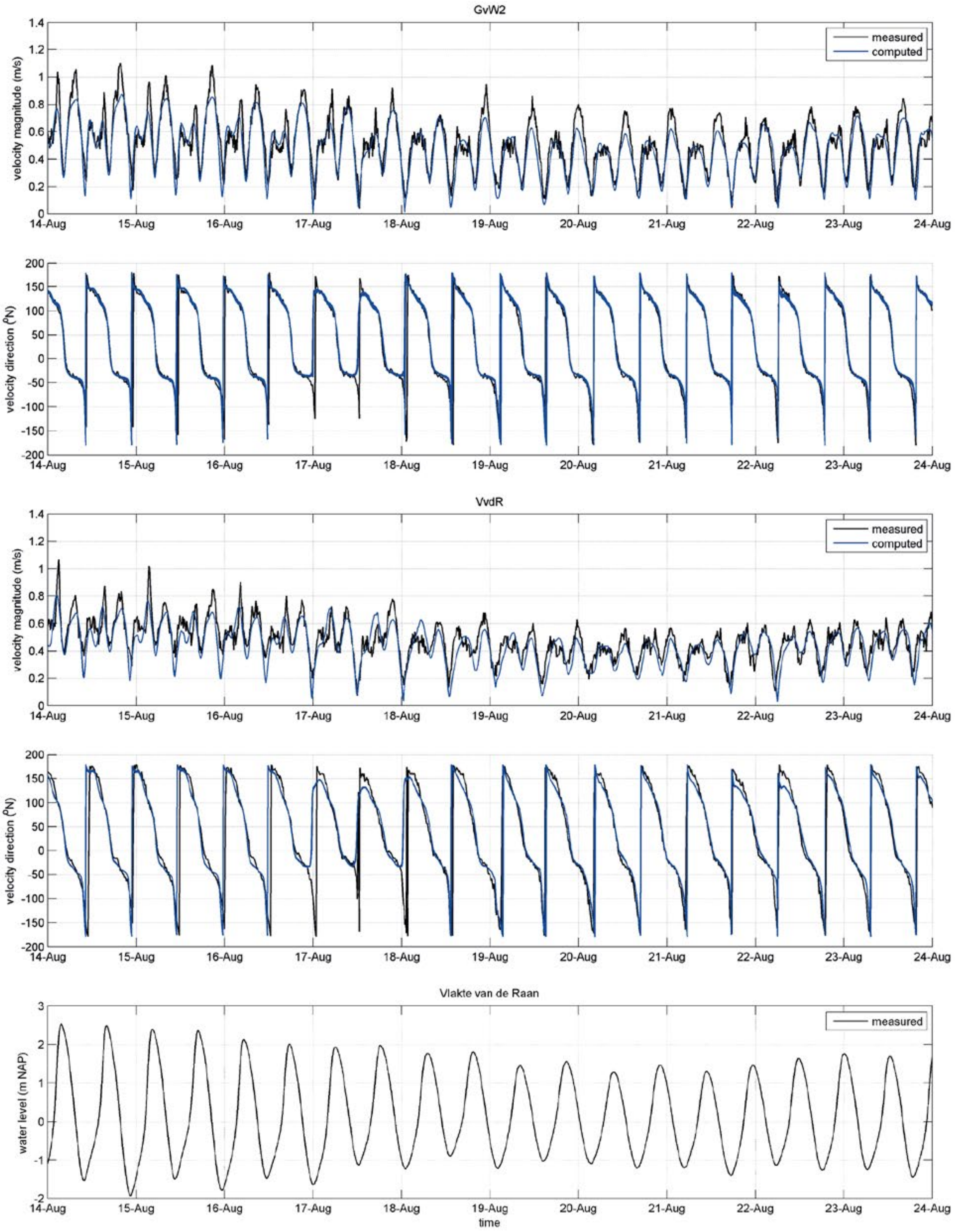


Figure 4. Comparison between measured and computed velocities at the Vlakte van de Raan (VvdR) and in the channel Geul van de Walvischstaart (GvdW2). The lower panel shows the measured water levels at Vlakte van de Raan.

Figure 4 shows that the significant wave height H_{m0} and peak period T_p at Deurloo can be quite well predicted using the Delft3D-NeVla model. Although the model tends to overpredict the wave heights, the increase and decrease during the waxing and waning of the stormy events at 9, 11 and 17 of August is nicely reproduced.

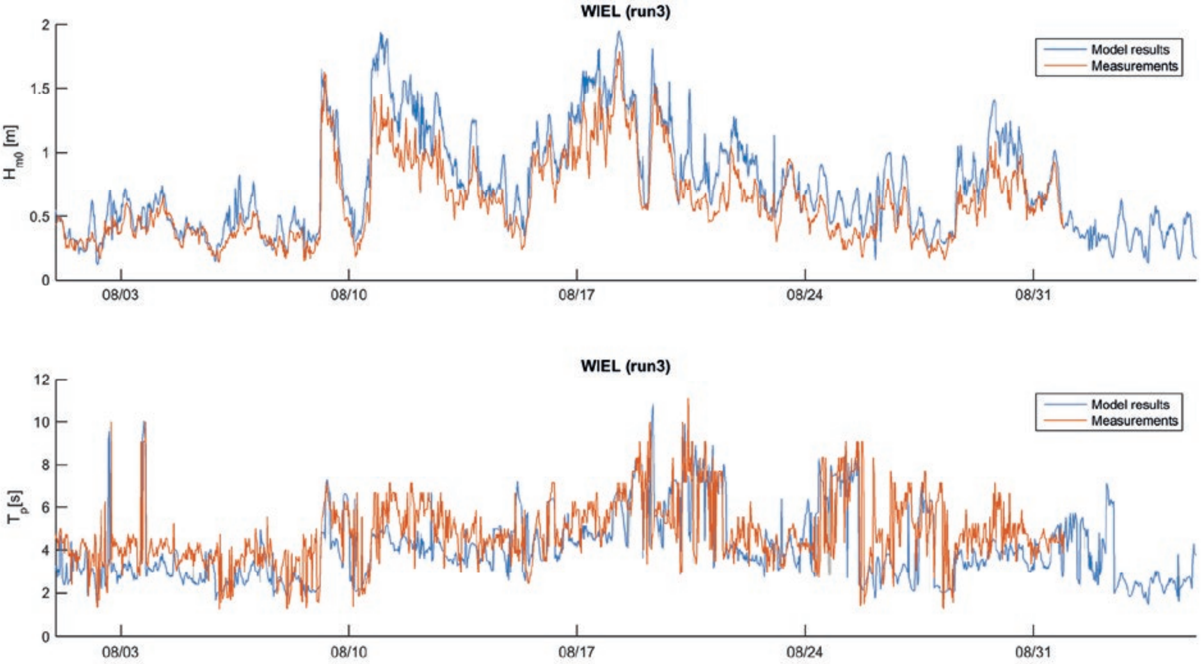


Figure 4. Comparison between measured and computed significant wave height and peak period at Wielingen.

3.2 Morphology

We plan to hindcast the morphological evolution of the mouth and Western Scheldt between 1985 (after the construction of the Zeebrugge harbor) and 2011 to assess the accuracy of the model for long-term morphological simulations. We will compare measured and predicted bed level changes (patterns and magnitude), as well as maintenance dredging volumes. These long-term and large-scale computations are challenging, since they are computationally intensive and the involved physics are very dynamic and complex.

In order to minimize computational time, the model domain is split-up in 5 online-coupled domains using domain decomposition. Flow, sand transport and bed updating are computed every flow time step (online approach). As bed level changes are relatively small during these small time steps, we multiply these with the morphological acceleration factor or morfac (see Roelvink, 2006). We have used morfac = 104, which means that the simulation of one spring-neap flow cycle of ~14 days corresponds to approx. 4 years of morphological change. This saves a lot of computational time.

Under the same assumption we use the parallel online or *mormerge* approach to include wave effects in an efficient way (see Roelvink, 2006). The different wave conditions are run in parallel. They share the same bathymetry that is updated every time step according to the weighted averaged of the bed level changes due to each condition.

Figure 5 compares bed levels computed with a morfac of 104 and 52 (no waves) to analyze the effect of the morfac on the predicted bed level changes. The maximum differences are ±2 m in the Western Scheldt; model results only differ little in the mouth. Compared to the computed bed level changes of around ±10 m, the effect of the morfac is of second order. This is expressed in Figure 6, which show the relative volume changes computed as follows for each time step:

$$\Delta V_{\mathrm{rel}} = \frac{\Sigma\left|\Delta V_{\mathrm{i,morfac=104}} - \Delta V_{\mathrm{i,morfac=52}}\right|}{\Sigma\left|\Delta V_{\mathrm{i,morfac=52}}\right|} \qquad [1]$$

with ΔV_i the volume change per grid cell. The variation in the relative volume difference over time is the result of variable wind and tidal forcing. The relative volume differences are larger for the Vlakte van de Raan and Western Scheldt (domain 2) than for the outer domain (domain 1), because domain 2 is morphologically more dynamic than domain 1. Furthermore, we can see that the differences become smaller in time. After 20 years, the relative volume difference is 2-3% which is very small compared to uncertainties due to the physics, numerics and parameter settings of the Delft3D-NeVla model.

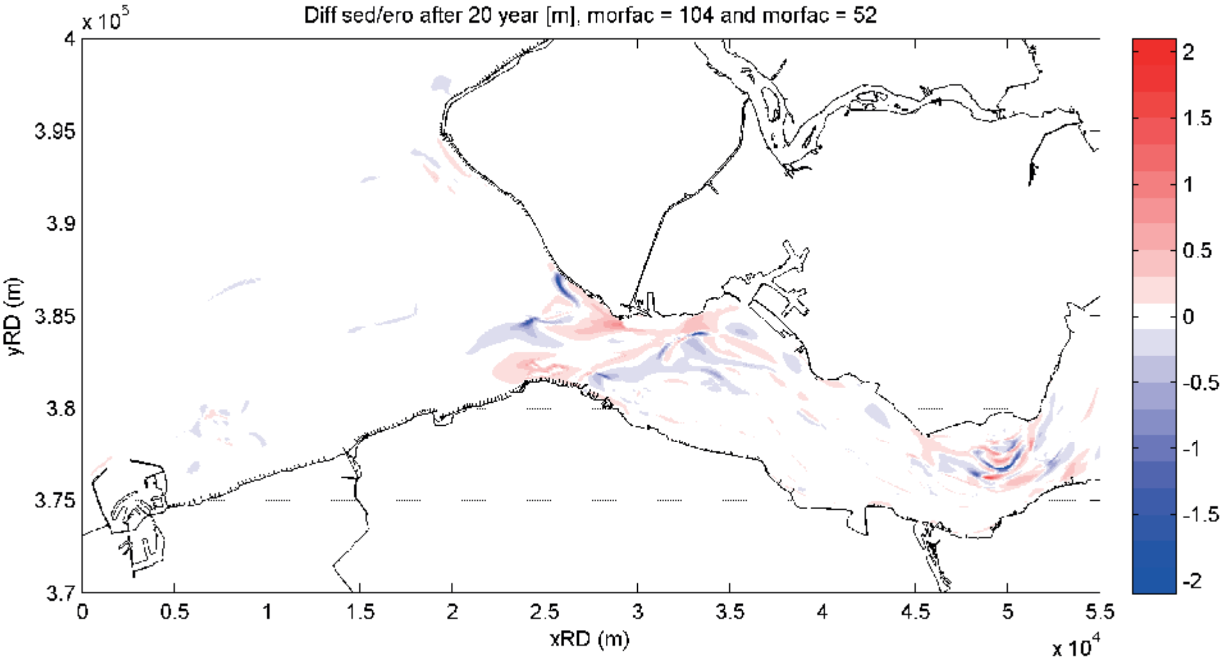


Figure 5. Difference between computed (no waves) sedimentation/erosion after 20 years with morfac = 104 and morfac = 52. Red colors indicate relatively more (less) sedimentation (erosion) with morfac = 104, and blue colors less (more) erosion (sedimentation).

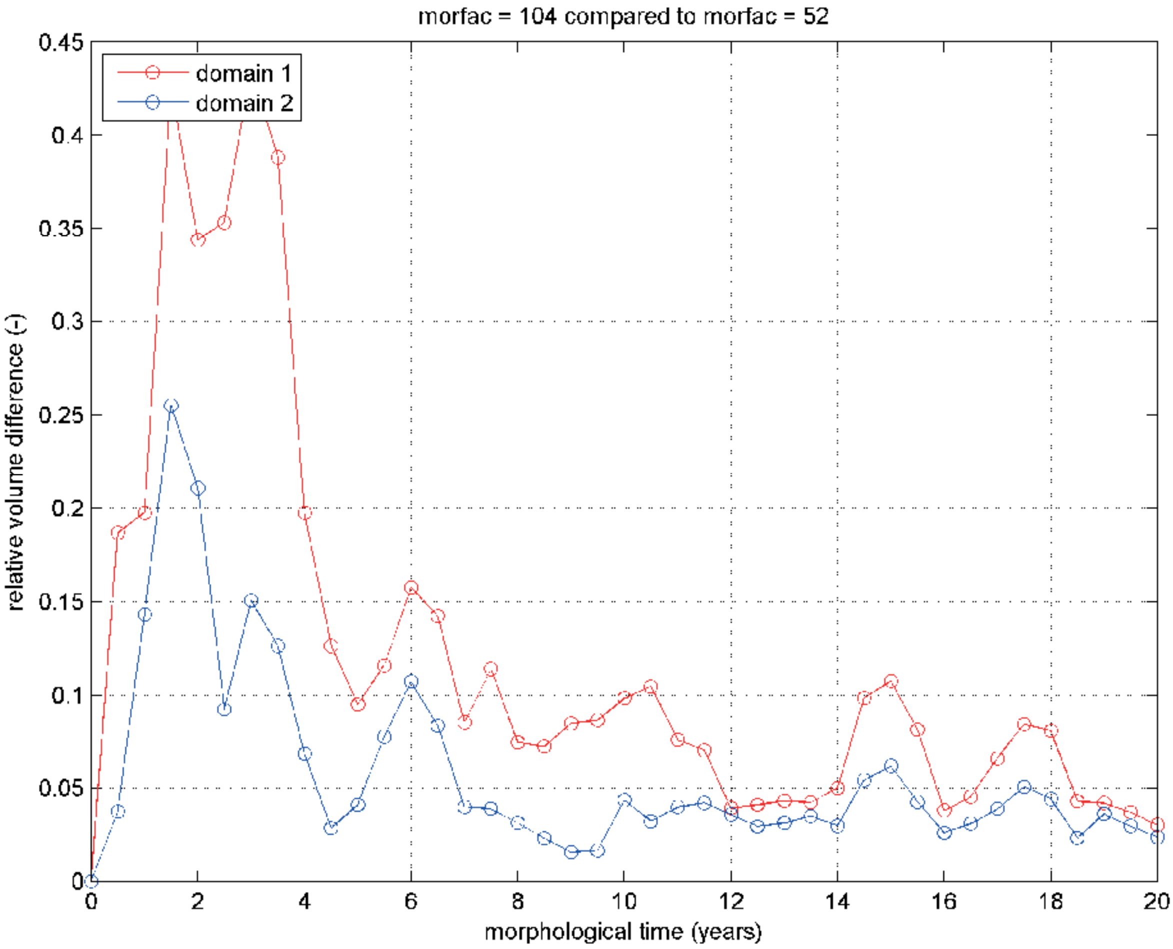


Figure 6. Relative volume difference for a simulation with morfac = 104 compared to a simulation with morfac = 52. Domain 1 refers to the area seaward from the Zeebrugge harbor, and domain 2 to the adjacent domain that extends into the Western Scheldt.

4. DISCUSSION AND CONCLUSIONS

This paper describes the ongoing development of a process-based numerical model (Delft3D) of the Scheldt estuary. The model will become an important tool to understand and predict the morphodynamics of the mouth of the estuary due to natural processes and human interferences. The main features of this 2DH Delft3D-NeVla model are:

- computational domain covers the entire Scheldt estuary from the North Sea to Gent with a relatively high resolution
- tide, waves, wind and river discharge forcing accounted for
- presence of hard, non-erodible bed layers included
- dredging and dumping activities are accounted for
- simulation of large-scale, long-term morphological development made possible by using advanced techniques (morfac, mormerge)

The first simulations show that the Delft3D-NeVla model reproduces measured velocities and wave heights in the mouth of the Scheldt estuary reasonably well. Future steps are:

1. Further calibration and validation against measured water levels, discharges and velocities.
2. Morphological hindcast for the period 1985-2011.
3. Model simulations to study large-scale morphological interventions in the mouth (e.g. relocation navigation channel)
4. Extension to a fully coupled morphological model for sediment mixtures (incl. mud)

ACKNOWLEDGMENTS

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Sediment transport in the Schelde-estuary: a comparison between measurements, transport formula and numerical models

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ABSTRACT

The Schelde-estuary serves different estuarine functions and therefore faces managers with multiple challenges: increasing tidal propagation vs. safety against flooding; sedimentation in the navigation channel vs. port accessability; changing dynamics vs. ecology. Within the Flemish-Dutch Long Term Vision for the Schelde-estuary, a 4 year (2014-2017) research programme was defined, in which 8 topics will be dealt with (e.g. tidal penetration, risk for regime shift, sediment strategies, valueing ecology). Two fundamental tools will be crucial in answering the different questions towards the future management of the estuary: expertise/system understanding and numerical models. At this moment (first year), several projects are ongoing trying to increase the system understanding and improving the state-of-the-art numerical models. Where the numerical models reproduce the hydrodynamics reasonably well, sediment transport and the resulting morphological changes is still a big challenge. Therefore an extensive monitoring campaign was performed in 2014, during which both hydrodynamic and sediment transport measurement were performed in the Schelde-estuary. At more than 10 locations, from the up-estuarine part (Boven-Zeeschelde) to the mouth area (Vlakte van de Raan), measurements were executed over a full tidal cycle (13h). Currents were measured using ADCP, while sediment transport was measured using both direct (Delft Bottle and pump samples) and indirect (OBS, ABS) techniques. This extensive dataset allows an in-depth analysis of the sediment transport processes occuring in the estuary. A comparison will be made with several transport formula (e.g. Bagnold, Engelund-Hansen, Van Rijn, ...). The data will also be used to validate the existing numerical models, allowing a better assesment of the possibilities and limitations of the present numerical models.

KEY WORDS

Sediment transport, measurements, numerical modelling, estuary

THE SCHELDE-ESTUARY

The Schelde-estuary is a macro-tidal estuary with a length of 180 km in Flanders and the southern part of the Netherlands (Figure 1). The Vlakte van de Raan (“mondingsgebied”) connects the estuary with the North Sea and should be seen as an integral part of the estuary. This part is a shallow water area with several channels. The Vlakte van de Raan (-20 KM to 0 KM) connects to the Westerschelde (KM 0 to KM 60), which has a multiple channel system, with ebb and flood channels and intertidal sandbars in between. More up-estuary, near the Dutch-Belgian border, the morphological system changes into a single channel system, the Zeeschelde (KM 60 to KM 160).

The estuary is characterised by semi-diurnal tides, causing ebb and flood currents with important sediment transports of both cohesive as non-cohesive sediments. The Schelde-estuary serves different estuarine functions and therefore faces managers with multiple challenges: increasing tidal propagation vs. safety against flooding; sedimentation in the navigation channel vs. port accessability; changing dynamics vs. ecology. Within the Flemish-Dutch Long Term Vision for the Schelde-estuary, a 4 year (2014-2017) research programme was defined, in which 8 topics will be dealt with (e.g. tidal penetration, risk for regime shift, sediment strategies, valueing ecology).

METHODOLOGY

In order to supply managers with adequate answers, research tools (both expertise/system understanding and numerical models [Peters et al., 2006]) are crucial in answering the different questions. At this moment (first year), several projects are ongoing trying to increase the system understanding and improving the state-of-the-art numerical models. Where the numerical models reproduce the hydrodynamics reasonably well, sediment transport and the resulting morphological changes is still a big challenge. Within the scope of the MONEOS programme [Plancke et al., 2012], discharge and sediment transport measurements are performed at regular basis (going from continuous SPM measurements at several points to yearly sailed transect measurements). In 2014, an additional monitoring campaign was performed, during which both hydrodynamic and sediment transport measurements were performed in the Schelde-estuary. At more than 10 locations measurements were executed over a full tidal cycle (13h): 3 locations at the Vlakte van de Raan, 7 locations at the Zeeschelde and 1 location at the Rupel, a tributary of the Zeeschelde.

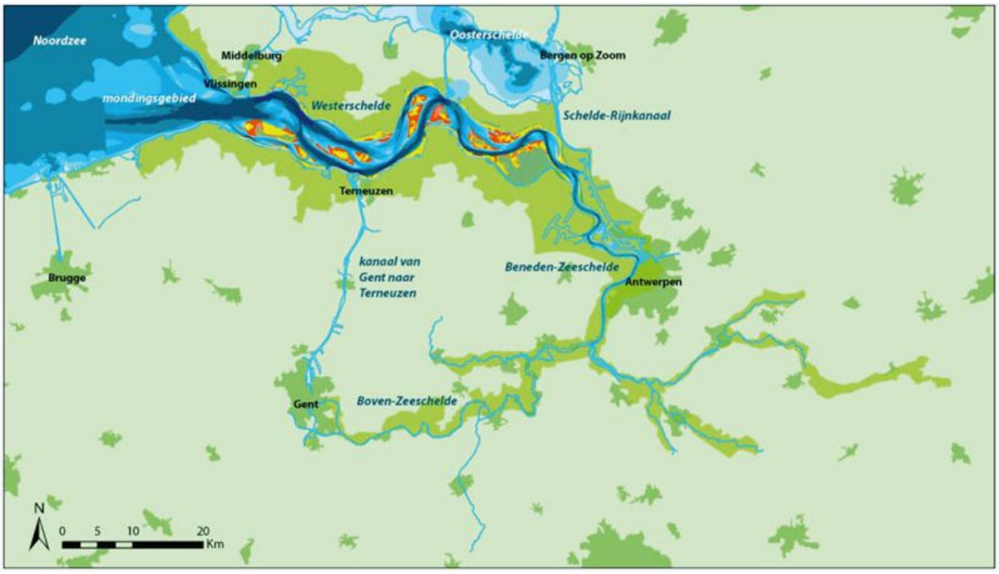

Figure 1 – Overview of the Schelde-estuary (source: http://www.compendiumkustenzee.be)

At each location one or two vessels were used. The first vessel was anchored during the measurement period, performing measurements at a fixed point in the estuary. Currents were measured using ADCP (vertical profile) and Aanderaa Current Meter (point), while sediment transport was measured using both direct (Delft Bottle and pump samples) and indirect (OBS, ABS) techniques. The Delft Bottle technique was used both near-bed (using frame) and in the water column (suspended), at four different positions (bed + 20 cm, bed + 40 cm, bed + 100 cm and bed + 200 cm). Measurements were executed continuously, with sampling times varying from 3 minutes (at peak transport) to 15 minutes (near slack moments). From these measurements total transports were derived every 30 minutes. At those locations where a second vessel was available, additional transects were sailed using ADCP (current and sediment transport from ADCP-backscatter). For the locations at the Vlakte van de Raan, additional frames were placed at the bed, allowing long term (4 weeks) measurements of hydrodynamics (currents and waves) and sediment transport.

The measurements are used to validate the available numerical models. A first project deals with large scale sediment management issues in the down-estuarine part, Vlakte van de Raan (see Van der Werf et al., 2015). A second project focusses on management strategies for the most up-estuarine part, Boven-Zeeschelde (see Maximova et al., 2015). A third project will detail the future sediment strategy in the Beneden-Zeeschelde. Both Delft3D as TELEMAC models are used in these different studies. For the last project a detailed model of the study area has been set up. At this moment, the model is being validated for the sediment transport in the BenedeZeeschelde.

FIELD MEASUREMENTS: RESULTS

Figure 1 shows the hydrodynamic conditions for the different locations in the Zeeschelde. The tidal characteristics change significantly along the estuary: the most down-estuarine locations of the Zeeschelde (Liefkenshoek, Oosterweel) have an almost symmetrical tide; more up-estuary the tidal asymmetry increases, most pronounced at Schellebelle and Schoonaarde. The tidal range increases from the North Sea up to Driegoten due to the funnel shape of the estuary. More up-estuary it decreases due to the damping effect of the undeeper channels. The asymmetry in the vertical tide is translated into the horizontal tide (flow velocities), with a longer ebb-phase and lower flow velocities more up-estuary. Highest flow velocities are found at Oosterweel (ebb and flood phase) and Driegoten (flood phase).

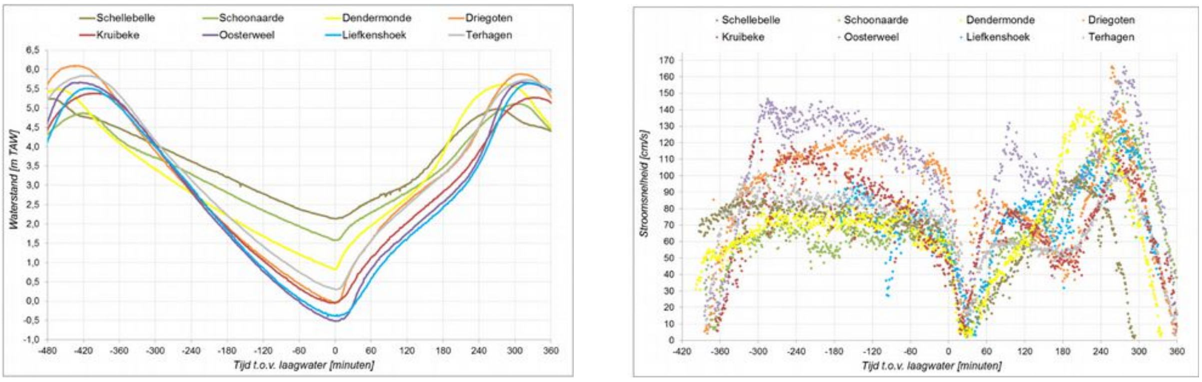

Figure 2 – Overview of tides (left) and flow velocities (right) for locations in Zeeschelde

Figure 3 shows the sediment transport for the different locations in the Zeeschelde. The sediment D50 ranges from very fine sand (near-bed “DBF”) to very fine silt or mud (suspended “SUSP”). Sediment transport patterns are different for different locations, which is related to the position along the estuary and its position on the transect. For Driegoten the sediment transport shows a maximum 1 to 3 hours after low water. The sediment during this period is muddy, with a lot of flocs. Where the flow velocities in this period are low, the peak is probably related to the technique of the Delft Bottle: while this technique is suited for sand, it was found that during period with low flow velocities, currents through the bottle are insufficient to transport mud through the bottle, leading to anomalies in the measured transport.

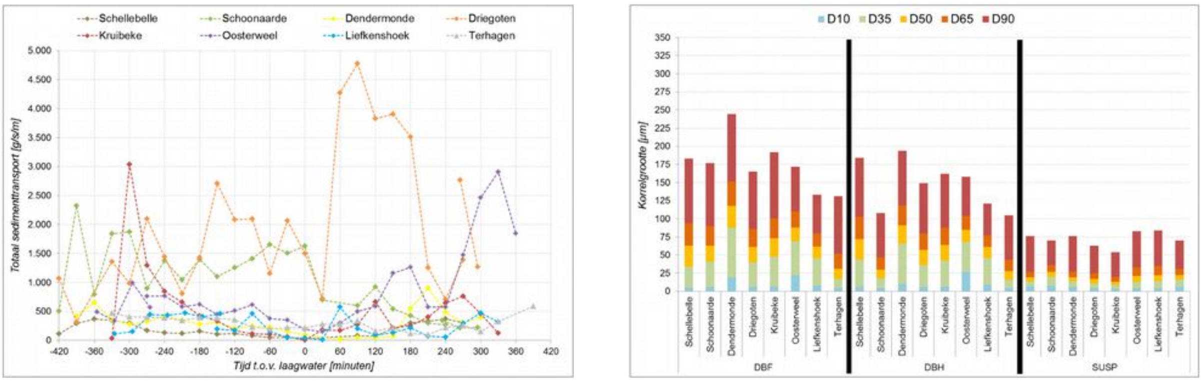

Figure 3 – Overview of total sediment transport (left) and sediment characteristics (right) for locations in Zeeschelde

ONGOING RESEARCH

In 2015 the results of the measurement campaigns are further analysed. A first aspect focusses on the uncertainties of the results from the field measurements. Errors can be introduced during the execution of the measurements (e.g. Sediment capture during lowering and hoisting of bottle) as due to the technique (e.g. muddy sediments) and during the post-processing (e.g. Calculation of total transport). Possible errors are estimated resulting in error bars for the measurement results.

Next, a comparison is made between the measured transport rates and certain sediment transport formulas. A first exploratory comparison, based on the Bagnold approach, shows a rather good agreement for location Boom, while for other locations the agreement is worse.

Finally the measurement data are used the validate state-of-the-art numerical models. In the past, the models have been extensively calibrated and validated for hydrodynamics, but due to lack of available measurement data, sediment transport was never really validated. Sensitivity exercises have indicated the important influence of several numerical parameters. Preliminary results for the Beneden-Zeeschelde show a rather promising agreement (i.e. differences of factor 2 to 3), but further research is necessary and ongoing.

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Numerical modelling of flood control areas with controlled reduced tide

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ABSTRACT

The present paper focuses on the numerical modelling in TELEMAC-3D of flood control areas with controlled reduced tide structures along the Scheldt estuary and coastal zone for the storm event of December 6th, 2013. A new culvert functionality was implemented in the code to better represent the hydrodynamics of the exchange of water between the Scheldt estuary and these flood control areas with controlled reduced tide. Existing source and sink terms included in the code were paired and used as a culvert. The theoretical background to represent the different kind of flows through the culvert was based on the work of Bodhaine (1968). Additionally different head loss coefficients were introduced according to different geometric features of the culverts. The implementation of these new structures inside the 3D numerical model was validated using measured water levels in the estuary and inside the flooding areas , and using discharges (in and out) through the culverts measured only for one full tidal cycle. For the storm surge only measured water levels were available and these were compared with modelled ones.

Keywords: *Scheldt estuary, Storm surge, TELEMAC-3D, Culvert, Flood control area*

1. INTRODUCTION

Estuaries are transitions between riverine systems and the coastal zone. They provide an important link between overseas trading and local economy since they can shelter important harbors and therefore offer work opportunities. Many people live in these lowlands and climate change is increasing the intensity and frequency of storm surges along coast worldwide, posing an immer growing flood risk for these areas (Webster et al., 2005; Temmerman et al., 2013). For instance, storm surges can propagate far inland and induce flood risk for all those living close. The occurrence of storm surges poses huge challenges for the coastal zone management. In order to prevent a number of hazards associated with these events, it is essential to study and analyze the risk of floods in areas along the coast and estuary.

The Scheldt river originates in the north of France (St. Quentin) at 110 m above sea level and flows after 355 km into the North Sea near Vlissingen (The Netherlands). The estuary is well mixed, presenting small or negligible salinity gradients (Baeyens et al., 1998). A storm surge in February 1953 caused many causalities in England, Belgium and in the Netherlands. This was the start for the so called Delta works in the Netherlands, set up with the purpose of protecting the coastline from storm surges. In Belgium it was only after the storm in 1976, causing large floods, that the development of a new flood protection plan, i.e. the Sigma plan, started. The protection against flooding is combined with restoration of a lot of nature areas (Meire et al., 2014). Over the last centuries high water levels have been increasing in the estuary and therefore dike levels have to follow. Because of the large economic value for the port of Antwerp it was decided not to close the estuary with a storm surge barrier.

Instead of raising the dikes or closing the estuary, Flanders chose the option of building flood control areas (FCA's). The flood control areas are areas along the Scheldt estuary surrounded with dykes, like the rest of the estuary and separated from the river by an overflow dyke with a specific level. When a storm surge enters the estuary, the FCA becomes active only when water levels exceed critical thresholds extracting only critical water volumes at the top of the storm tide. These areas can store large amounts of water from the tidal (storm) wave and therefore protect the hinterland from flooding. When the water level drops after a storm tide, outlet culverts evacuate the water out of the FCA back into the river (Figure 1). These outlet culverts have valves to avoid water flowing from the river into the FCA. Moreover, culverts allow a controlled reduced tide (CRT) installed in the FCA creating a tidal nature and therefore improving the ecological value in some of these areas. The elevation and specific geometry of the culvert determines inflow-outflow patterns within the area creating a tidal ecosystem (Maris et al., 2007)

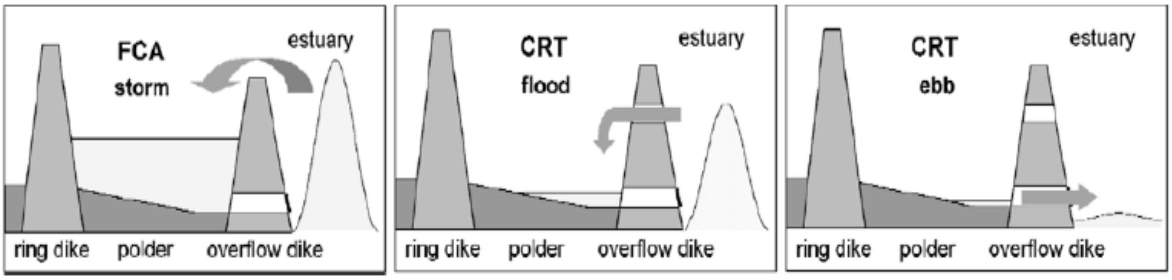

Figure 1 Water overflows the dyke (on the left) and through the culvert (on the middle) from the river into the FCA and evacuates from the FCA into the river through the outlet sluice (on the right). (Source: De Mulder et al. (2013))

When the storm of 6th of December 2013 entered the Scheldt estuary, 13 of these areas were operational and some of them were completely filled (Figure 2). It is expected that by 2030 more than 40 areas will become active.

Figure 2 FCA/CRT 'Bergenmeersen' filled during storm surge of 6th of December 2013 (© Hydrologic Information Centre, Flanders Hydraulics)

The incorporation of these structures in numerical models is essential to better predict and describe the flow hydrodynamics in these areas. The main aim of this work is to analyze how these structures can be taken into account and implemented in the three-dimensional hydrodynamic model TELEMAC-3D.

In the following sections the theoretical background of the different types of flow through a culvert is described. Subsequently, the implementation of this functionality in TELEMAC-3D is discussed. Finally, results of a test case are presented evaluating the numerical model results by comparing them against measurements.

2. NUMERICAL IMPLEMENTATION OF CULVERTS

2.1 Hydrodynamic model – governing equations

The numerical platform TELEMAC-MASCARET was the chosen tool to analyze and study the Scheldt estuarine hydrodynamics. TELEMAC-MASCARET was originally developed by EDF R&D and it includes the three-dimensional circulation model TELEMAC-3D. The model is based on the finite elements method. Assuming the hydrostatic hypothesis, the code solves the three-dimensional RANS equations:

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0 \qquad [1]$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-g\frac{\partial \eta}{\partial x}+v\Delta(U)+F_x \qquad [2]$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-g\frac{\partial \eta}{\partial y}+v\Delta(V)+F_y \qquad [3]$$

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0 \qquad [4]$$

(U, V, W) are the three components of the flow velocity, (u,v) the depth integrated flow velocities, υ the diffusion coefficient, g the gravitational constant and (F_x, F_y) the source and sink terms of the momentum equations ([2] and [3]).

Additionally, TELEMAC-3D gives the possibility of taking into account passive or active tracers in the model domain. The following equation, describing the evolution of tracer concentration (T), is solved:

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}=v_t\Delta(T)+Q' \qquad [5]$$

The tracer diffusion coefficient is given by υ_t and Q' represents the source terms for tracers.

In TELEMAC-3D (v6p3) hydraulic structures such as culverts or tubes are not implemented. The capability of the model to impose source/sink terms in the domain was used as a basis for the implementation of the culverts. Therefore, the inflow and outflow act as a couple of source/sink points (in the code, new terms are added to the second hand side of the depth integrated continuity equation [4]). For instance, when the flow is going from the river to the floodplain, a source term is implemented on the side of the floodplain, i.e., a discharge is imposed, and at the same time a sink term is imposed on the side of the river with a symmetric value of that discharge (e.g. Q_{river}= - $Q_{floodplain}$). Using this method an assumption was made: it is considered that the discharge occurs at the same time in the river and floodplain. The tracer concentration in the model domain is associated to the discharges and volumes at the source and sinks terms and is as such taken into account.

2.2 Flow through culverts

A number of studies regarding the description of flows through the culverts refer to the work of Bodhaine (1968). In his work, the flow that occurs through a culvert is classified into six types, being the discharge calculated in a different way for each kind of flow. The equations are deduced from the continuity and energy equations between the approach section and the downstream section of the culvert. The type of flow depends on whether the culvert flows full or not and whether the flow is controlled by the inlet or outlet.

New equations were then incorporated in the code in order to cover a wide range of the flow conditions that exist through a culvert. The following equations, corresponding to each type of flow presented above, were implemented in TELEMAC-3D. They are based on the equations proposed in Bodhaine (1968) and similar to the ones incorporated in DELFT 3D model. The flow type 1 conditions (described also in Bodhaine (1968)) were not incorporated since they only occur when the culvert slope is larger than the critical flow slope, which is never the case for our FCA/CRT application.

Type 2 – Critical depth at outlet:

$$Q = \mu h_c W \sqrt{2g * \left(S_1 - (z_2 + h_c)\right)} \qquad [6]$$

Type 3 – Tranquil flow:

$$Q = \mu (S_2 - z_2) W \sqrt{2g(S_1 - S_2)} \qquad [7]$$

Type 4 – Submerged outlet:

$$Q = \mu D W \sqrt{2g(S_1 - S_2)} \qquad [8]$$

Type 5 – Rapid flow at inlet:

$$Q = \mu D W \sqrt{2g h_1} \qquad [9]$$

Type 6 – Full flow with free outfall:

$$Q = \mu D W \sqrt{2g(S_1 - (z_2 + D))} \qquad [10]$$

with: Q the discharge through the culvert, W the culvert width, D the culvert height, μ the total head loss coefficient, S_1 the water level on side 1, S_2 the water level on the other side, h_1 the water level above the culvert base on side 1, h_2 the water level above the culvert base on side 2, h_c the critical water level inside the culvert (this is assumed to be close to 2/3 of h_1), z_1 the base level of the culvert at side 1, and z_2 the base level of the culvert at side 2. Most of these variables are shown in a schematic representation of the culvert in Figure 3.

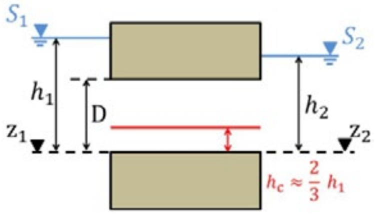

Figure 3 Representation of the different variables used for the culvert equations.

The conditions for each type of flow are given in Table 1. To distinguish between flow type 5 and flow type 6 a constant c, that is dependent on the culvert slope and the ratio culvert W/D, is used. Then if L/D < c, with L the length of the culvert, flow type 5 occurs, otherwise it is flow type 6 (Bodhaine, 1968).

Table 1 Conditions for each type of flow used in TELEMAC-3D

	$\frac{S_1 - z_1}{D}$	$\frac{S_2 - z_2}{D}$	$S_2 - z_2$	L/D
Type 2	<1.5		$< h_c$	
Type 3	<1.5	≤ 1.0	$> h_c$	
Type 4	>1.0	> 1.0		
Type 5	≥ 1.5	≤ 1.0		< c
Type 6	≥ 1.5	≤ 1.0		≥ c

The equations presented above are written to describe flow conditions through a culvert with a single barrel. Nevertheless, additional features are sometimes incorporated in the hydraulic structures, such as weirs in the vicinity of the culvert entrance or exit. Such combined structures have to be taken into account. Then the geometric features of the culvert presented in Figure 3 are modified as shown on Figure 4. The structure becomes more complex. In order to represent these features an equivalent culvert bottom elevation was used, which replaces both the bottom elevations z_1 and z_2 in the formulas described above. The equivalent bottom culvert elevation z is then equal to the mean between z_1 and z_2. The diameter used in the equations will be the one corresponding to the entrance of the culvert, i.e., regarding Figure 4, if the flow goes from left to the right D will be replaced by D_1 and in the opposite direction, the value D_2 will be used.

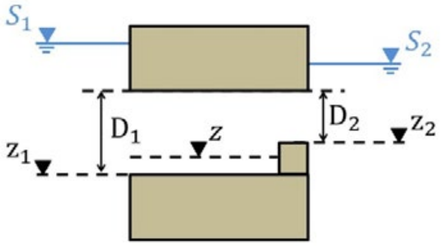

Figure 4 Representation of the different variables used for the combination of a culvert with a weir

The head loss coefficient μ was adapted from the one based on Carlier (1972). New terms were added to account for the extra head loss of additional structures in front and behind the culvert structures, like one-way valves and trash screens (examples in Figure 5 and 6). The head loss due to singularities can be obtained by the general relation (Carlier, 1972; Lencastre, 1961):

$$\Delta H = C\frac{U^2}{2g} \quad \text{or} \quad U = \mu\sqrt{2g\Delta H} \quad \text{with } \mu = \frac{1}{\sqrt{C}} \qquad [11]$$

$C = C_1 + C_2 + C_3 + C_v + C_T + C_p$ represents the sum of the different contributions for the head loss due to singularities.
C_1 represents the head loss due to the contraction of the flow at the entrance of the hydraulic structure which results in a deceleration of the flow immediately after the culvert entrance. Usually C_1 is equal to 0.5 (Larock et al., 2000).

Already in the past, Bodhaine (1968) noticed that the discharge coefficient for type 5 flow had to be lowered comparatively to the other flow types. It seems that the calculated discharge tends to be overestimated when the default equation is applied. In order to take into account that effect, a correction coefficient ($\alpha_1{}^5$) is applied to C_1 when type 5 flow occurs, such that:

$$\Delta H_1 = \alpha_1{}^5 C_1 \frac{U^2}{2g} \qquad [12]$$

With: $4 \leq \alpha_1{}^5 \leq 10$ according to Bodhaine (1968).

C_2 represents the head loss coefficient due to the friction in the structure and is expressed by (Lencastre, 1961):

$$\Delta H_2 = C_2\frac{U^2}{2g} = \frac{2gLn^2}{R^{4/3}}\frac{U^2}{2g} \qquad [13]$$

where *n* the Manning Strickler coefficient for the structures material and *R* the wet cross-shore section in the structure, calculated in the code for each type of flow. An assumption is made when calculating the hydraulic radius since the code does not make any kind of backwater analysis to get the precise water depths in the culvert. C_3 is the head loss coefficient due to expansion of the flow at the exit of the culvert. According to (Lencastre, 1961):

$$\Delta H_3 = \left(1 - \frac{A_s}{A_{s2}}\right)^2 \frac{U^2}{2g} = C_3 \frac{U^2}{2g} \qquad [14]$$

where A_s and A_{s2} are the sections in and just outside the downstream part of the structure. C_v is the head loss coefficient due to the presence of a valve and depends on the type of valve and the degree of opening. When type 5 of flow occurs a correction coefficient (C_{v5}) is also applied to C_v. C_t is the head loss coefficient due to the incorporation of trash screens. The value for C_t can vary between 0, equivalent of not having any trash screens, to 1.4, for which the net flow area is almost equal to the gross rack area.

Sometimes at the entrance of the culverts the flow is divided into two sections caused by two entrance boxes instead of one but then the flow converges into a single culvert barrel. Following Carlier (1972) the head loss coefficient through parallel pillars is given by:

$$C_p = \beta \left(\frac{Lp}{b}\right)^{4/3} sin\theta \qquad [15]$$

Lp is the thickness of the pillars, b the free thickness between two consecutive pillars and β a coefficient dependent on cross-shore section of the pillar.

3. APPLICATION

3.1 Bergenmeersen FCA – CRT description

In order to test the new culvert functionality implemented in TELEMAC-3D, the new version was applied to a field test case, located in the Bergenmeersen area, where there is a flood control area with a controlled reduced tide function. Two simulation periods were chosen in order to analyze the capability of the code to model exchange of water between these areas and the estuary. The first simulation period makes part of a recent measurement campaign carried out from the 10th to the 12th September 2014. Mean water levels inside the flood control area and in the Scheldt river were measured. Data from the outlet and inlet discharges through the culverts were measured during a full tidal cycle on September 11th. In order to analyze the behavior of the model for a storm surge, a second time period, characterized by the storm of December 6th, 2013, was modeled. For the storm period only water levels in both sides of the flood control area and the Scheldt river were available. There were no discharge measurements for that time period.

The area of Bergenmeersen is characterized by a ring dyke with a crest level of 8 m TAW (Belgian reference level, i.e. equal to mean low water sea level) that surrounds the FCA and by an overflow dyke with the crest level of 6.2 m TAW that separates the river from the FCA.

The configuration of the inlet and outlet sluices is quite complex. Three outlet sluices were built with one-way valve installed at the river side. Above these outlet sluices, six smaller inlet sluices were included and at their entrance wooden beams function as a weir at different heights (Figures 5 and 6). The wooden beams control the water level at which water starts flowing in, allowing some space for calibrating the water levels inside the domain and coping with possible future changes in water levels in the estuary. The inlet culverts could be closed by a valve descending from the ceiling. At each inlet and outlet sluice the flow is separated into two parts at the river side and then converges until the FCA side. Additionally, in order to avoid garbage coming into the structure, inlet and outlet structures were provided with trash screens (Figure 6). Table 2 presents an overview of the inlet and outlet sluices geometric characteristics and configuration.

Figure 5 Inlet and outlet sluice configuration in the river side (construction phase) (source: Patrimoniumdatabank W&Z)

Figure 6 View of the inlet sluices from the river side (on the left) and inlet and outlet sluices from the FCA side (on the right)

Table 2 Characteristics of the new inlet and outlet sluices of the new FCA-CRT in Bergenmeersen.

	Inlet (Scheldt side)	**Inlet (FCA side)**	**Outlet (Scheldt side)**	**Outlet (FCA side)**
Number of culverts	6		3	
Culvert width (m)	2.7 2.7		3 3	
Culvert length (m)	9.5		18	
Culvert height (m)	1.6	2.25	1.1	2.25
Level of culvert floor (m TAW)	4.2	2.2	2.7	2.2
Crest level of stop weirs (m TAW)	4.2/ 4.2/ 4.2/ 4.35/ 4.5 / 4.5			

3.2 Model Setup

A mesh resolution of 5 m was set in the river part, while in the floodplain the elements vary from 10 m to 50 m length (Figure 7). Five horizontal planes were imposed in the model. The bathymetric data used in this test case comes from multibeam measurements completed with LIDAR st the shorelines carried out in 2013. The water levels in the Scheldt come from Schoonaarde tidal station. These values were used as boundary condition for the hydrodynamic model.

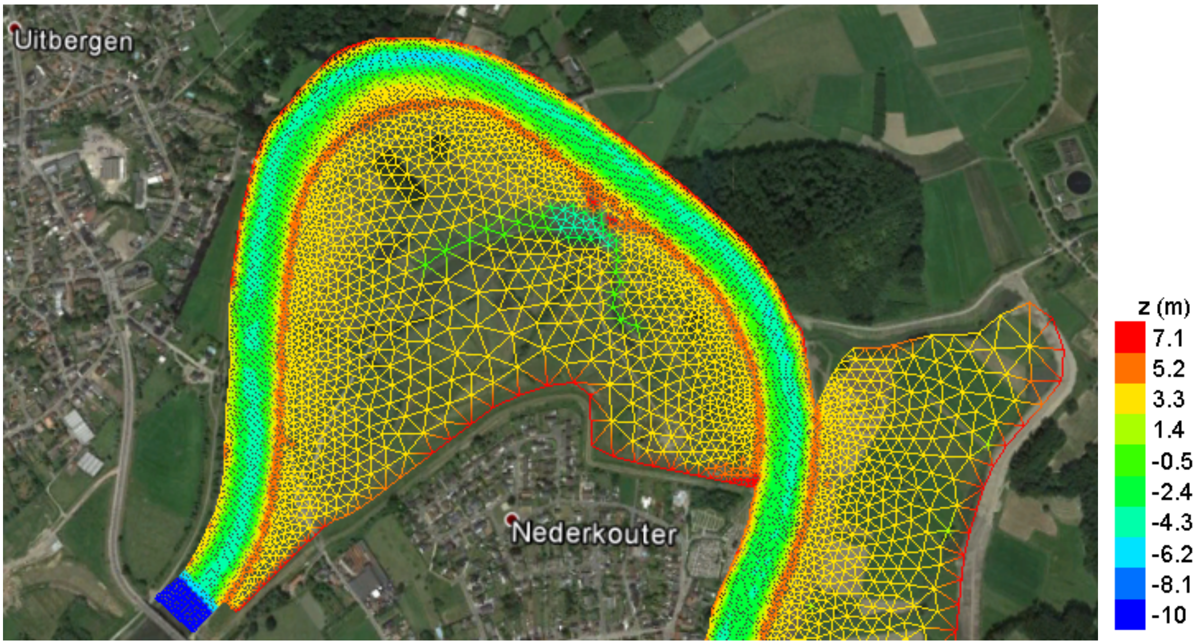

Figure 7 Planview of part of the computational domain to model the FCA-CRT in Bergenmeersen. The colour scale represents de bottom elevation values (m).

The time step was set to 5 s. For the different simulations the parallel version of TELEMAC-3D was used. The bottom friction was taken into account in the model through the Manning Strickler's parameter n. It was assigned a value of n=0.016 (typical value found in the literature for natural channels (French, 1987)). The Smagorinsky turbulence model was chosen to solve the horizontal viscosity while a mixing length model was applied to estimate the vertical turbulence viscosity.

The different geometric features for the inlet and outlet sluices have to be given to the model together with the direction of the flow through the culvert An outlet sluice only allows the flow to go from the floodplain to the river, because it has a one-way valve, and an inlet sluice allows the flow to go in both directions.

Regarding the head loss coefficients at the exit of the inlet and outlet sluices typical values, found in the literature (Lencastre, 1961) were imposed (C_3=1). At the entrance of the inlet sluices the head losses were increased, comparatively with the typical value of C_1= 0.5, in order to take into account the effect of the flow being split into two parts. Following the expression given by Carlier (1972), the head loss due to the presence of pillars is about C_p = 0.4 and therefore C_1 becomes C_1=C_1+C_p. It was considered that the valve at the outlet sluice was ¾ opened when flow was going out, which corresponds to a value of C_v=1 (Bruce et al., 2000). Since there was also flow separation at the exit of the outlet sluice, the value of C_V was increased to take into account this effect. The coefficient to take into account the trash screens was set to C_t =1 both for the inlet and outlet sluices.

Based on values found in the literature (Bodhaine, 1968), a value of *n*=0.015 (typical value for concrete in smooth conditions) was assigned for the Manning Strickler parameter inside the culvert.

3.3 Analysis of results

In the following, comparisons of the numerical model results with experimental data are shown for the simulation period between the 10th till the 12th September. The comparison between the water level on the Scheldt side computed by the model and obtained from experimental data is shown in Figure 8. In general the evolution of the water level in time is fairly well represented by the model. Nevertheless the model underestimates the water level when the water flows from the flood control area to the river. This feature can be confirmed by the underestimation of the outflow that the model presents in Figure 11.

In Figure 9 it can be confirmed that the model gives good result when computing the water level in the flood control area even if it is slightly underestimated when the water flows from the river to the flood control area. Once again this is confirmed by the underestimation of the inflow calculated by the model and is shown in Figure 10.

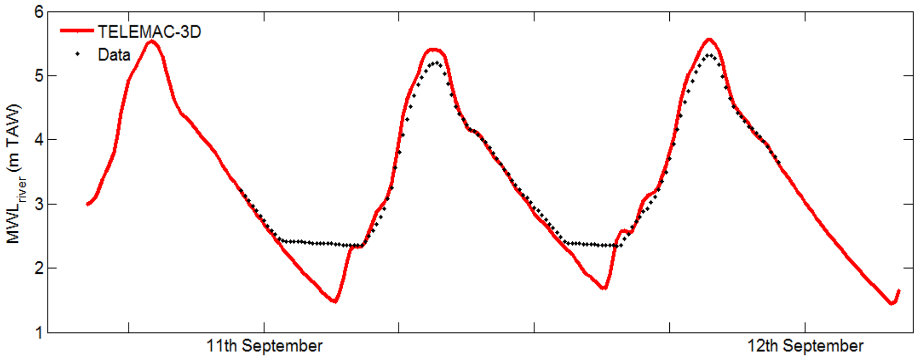

Figure 8 Comparison between water levels measured and computed by the model in the Scheldt river side from the 10th till the 12th September 2014.

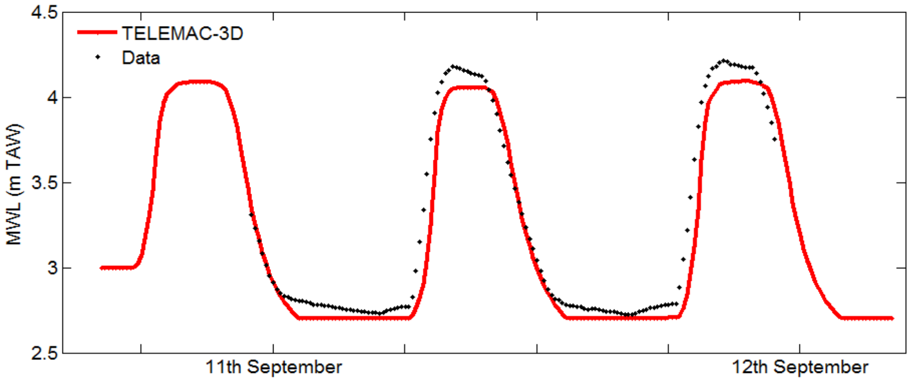

Figure 9 Comparison between water levels measured and computed by the model inside the flood control area in Bergenmeersen from the 10th till the 12th September 2014.

Figures 10 and 11 show that the inlet and outlet discharges computed by the model fit well with the experimental data even if the numerical results overestimate slightly the measurements for both cases.

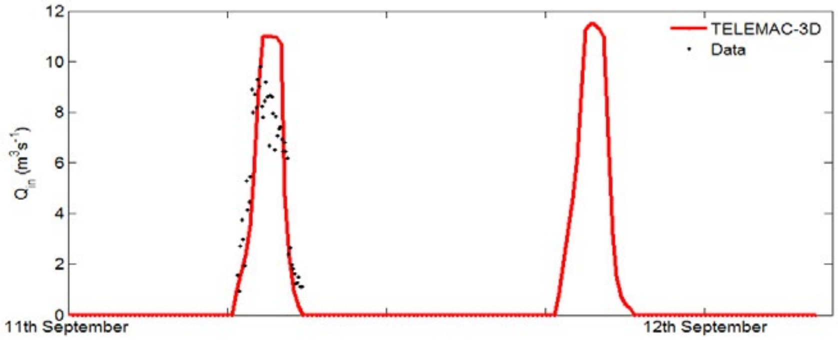

Figure 10 Comparison between inflow measured and computed by the model on September 2014.

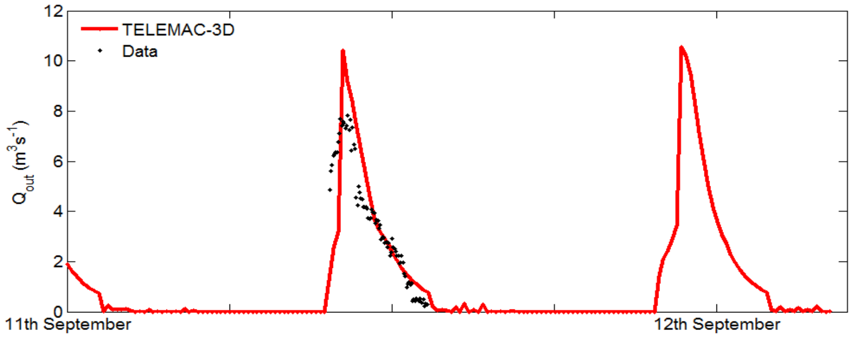

Figure 11 Comparison between ouflow measured and computed by the model on September 2014.

In order to have a more quantitative analysis for the differences found between numerical results and experimental data, the normalized root mean square error value [16] was calculated for the water levels and outlet and inlet discharges (Table 4). It can be verified that the error for the computed water levels is quite low (about 4%). Nevertheless a larger error is found for the inflow and outflow discharges (about 30%).

$$\varphi_i = \sqrt{\frac{\sum_{i=1}^{n}(d_i - m_i)^2}{\sum_{i=1}^{n} {d_i}^2}} \qquad [16]$$

The variable d_j represents the measured values and m_j the computed values.

Table 3 Normalized root mean square error for the water level (MWL_error), outlet discharge (Q_{out}_error) and inlet discharge (Q_{in}_error) computed by TELEMAC-3D.

MWL_error	0.043
Q_{out}_error	0.333
Q_{in}_error	0.306

In order to test the capability of the code to reproduce a storm event, the storm occurred on December 6th, 2013 was modeled. For this time period, measurements of water levels inside the flood control area of Bergenmeersen and in the Scheldt river were available. The model setup was kept the same as for the simulation period of 10th to 12th September, with exception of the imposed water level time series at the boundary

In Figure 12 the water level in the river computed by the hydrodynamic model agrees well with the measurements. In Figure 13 the model underestimates the water level for a normal tide and overestimates it for the peak flow of the storm tide of December 6th. During this period, the water level in the river reached the crest level of the dyke (6.2 m TAW) resulting in the overflow of water inside the flood control area. This behavior can be observed in the model results.

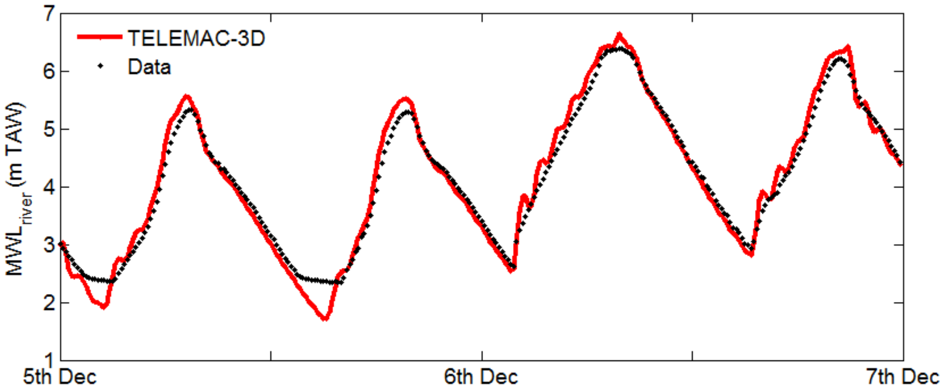

Figure 12 Comparison between water levels measured and computed by the model in the Scheldt river side from the 5th till the 7th December 2013.

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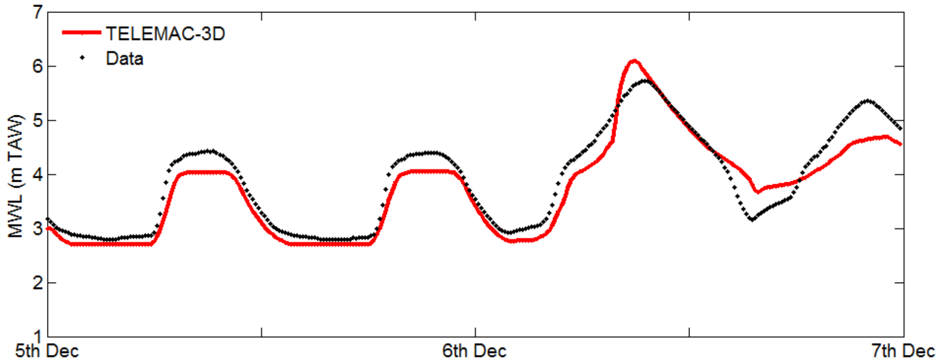

Figure 13 Comparison between water levels measured and computed by the model inside the flood control area in Bergenmeersen from the 5th till the 7th December 2013.

4. CONCLUSIONS

The scope of this paper was the implementation of a new culvert functionality in the three-dimensional hydrodynamic model TELEMAC-3D and its performance in both a normal tide and storm tide situation.

After the implementation in TELEMAC-3D. The culvert works as a couple of source and sink terms in which the discharges are calculated depending on the water levels between the source/sink terms, i.e., on the water levels in the flood control area and in the river. The theoretical framework was based on the work of Bodhaine (1968) together with Lencastre (1961). The model presents some limitations, such as the fact of making approximations on the calculation of water levels inside the culvert and not making a backwater analysis to know exactly the water levels at the entrance, inside and at the exit of the culvert.

A test case was applied to verify numerical results. A flood control area with controlled reduced tide, located in Bergenmeersen, Belgium, was chosen since a set of measurements were made during two time periods: one during the storm event of December 6th, 2013 where water levels were obtained inside the FCA and in the Scheldt river and a second one, made recently, from the 10th till 12th September where not only water levels were assessed but also a 13h measurement of inlet and outlet discharges that occurred through the culverts.

Despite the fact that the model approximates the real bathymetry by a grid (which is coarser inside the FCA) and the possible differences between the sluice construction on paper planview and the real built thing, the numerical results give a good agreement with the measured data. Both the water levels and inlet and outlet discharges during the time period of September and the storm event on December are well reproduced. This shows the potential of the model to simulate this kind of water flows both at a normal spring-neap tidal cycle and for storm surges.

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THE UNSTRUCTURED SCALDIS MODEL: A NEW 3D HIGH RESOLUTION MODEL FOR HYDRODYNAMICS AND SEDIMENT TRANSPORT IN THE TIDAL SCHELDT

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ABSTRACT

In the framework of the projects "Integral Plan for the Upper Sea Scheldt" and "Agenda for the Future", the SCALDIS model, a new unstructured high resolution model of the tidal Scheldt is developed in TELEMAC 3D (Telemac-Mascaret software platform). Starting from the stated model purpose, a weighted dimensionless cost function is set up that attributes equal weight to the vertical and the horizontal tide. By adapting the bottom roughness, the cost function is minimized during model calibration. Quantification of the model skill and cost function calculation is done using the VIMM toolbox which is developed and maintained at Flanders Hydraulics Research. The quantified model skill of the SCALDIS model shows that the model is well suited to assess the effects of changing the bathymetry and geometry of the Scheldt river on water levels, velocities, tracer dispersion and residence times, and that the hydrodynamics can be used as the basis for sediment transport calculations (both cohesive and non-cohesive).

Keywords: Scheldt Estuary, numerical model, VIMM toolbox

1. INTRODUCTION

Within the framework of the project “Integrated Plan Upper Sea Scheldt” commissioned by the Sea Scheldt division of Waterwegen & Zeekanaal NV, it is investigated how navigability can be improved in the upper part of the Sea Scheldt, without negative effects to nature and safety against flooding.

Within the Flemish-Dutch Long Term Vision for the Schelde-estuary, a 4 year (2014-2017) research programme was defined ("Agenda for the Future"), in which 8 topics will be dealt with (e.g. tidal penetration, risk for regime shift, sediment strategies, valueing ecology).

Within these two aforementioned programmes the need was identified to have a hydrodynamics and sediment transport model that covers the entire tidally influenced zone of the Scheldt Estuary and the mouth area, and that has sufficient resolution in the upstream part. The existing NEVLA schematization (Vanlede et al., 2015) that was built and maintained since 2006 at Flanders Hydraulics Research has the needed spatial coverage. Being implemented on a structured grid however, the resolution can only vary smoothly; more specifically from 300m in the North Sea over 65m around Antwerp to 20m at the upstream end. This upstream resolution is not sufficient to accurately describe the hydrodynamics and sediment transport there, taking into account that the river width decreases to 40m around Ghent.

In order to increase the resolution in the upstream part while keeping one model domain for practical reasons (so no nesting or domain decomposition) and with an acceptable computational cost, the natural choice was made to move to an unstructured grid.

2. MODEL PURPOSE

In the framework of the study “Integrated Plan Upper Sea Scheldt”, a set of models are improved or developed by the different project partners.

These models will be used to evaluate the effects of different alternatives (specified morphology of the Scheldt river in a specific state and at a specific time), possible variants (modest changes to an alternative), under different scenarios (a range of boundary conditions that take into account the climate change, sea level rise, increasing or decreasing tidal amplitude, high or low discharge).

Flanders Hydraulics Research develops a new 3D high resolution model for hydrodynamics in the tidal Scheldt estuary (this paper). In a later stage, the hydrodynamics model will be extended to also include sediment transport (both non-cohesive and cohesive). The University of Antwerp (UA) improve on their ecosystems model for primary production in the Scheldt estuary. The Research Institute for Nature and Forest (INBO) builds ecotope and fysiotope maps and models benthos, birds and migratory fish (twaitshad) for the different alternatives.

The alternatives include the current state (2013-2014), a reference state (autonomous development between 2013 and 2050 including the sustainable management plan for class IV inland shipping and decided policy) and states including the future accommodation and maintenance of the fairway.

The different models that are to be used in this project are intricately intertwined. Tracer experiments will be carried out in the 3D hydrodynamic model in order to provide tracer concentration timeseries for calibration of the dispersion coefficient in the 1D model. For this purpose, the 3D model will be spiked with passive tracers, initialised in polygons that correspond to the boxes in the 1D OMES model. This is a similar method as used by Soetaert and Herman (1995) when they calibrated their 1D MOSES model to the SAWES water quality model for the Western Scheldt. The 1D model in turn will be used to calculate initial longitudinal salinity distributions for the 3D model calculations. For the ecotope maps and habitat modelling of INBO, areal coverage of low water 30% and high water 85% exceedance frequency, percentiles of immersion duration, current velocity maps and shear stress maps are derived from runs of the 3D hydrodynamic model.

SPM values from the ensuing sediment transport calculations in the 3D model provide an important input in the 1D ecosystem model of UA, because primary production in the Scheldt estuary is largely limited by light availability. SPM values are also an input in the migratory fish model of INBO. Effects of different alternatives on sand transport give an indication of what morphological changes to expect.

3. MODEL SCHEMATISATION

For the development of this new unstructured schematization, the open source numerical platform TELEMAC-MASCARET was chosen. TELEMAC-MASCARET was originally developed by EDF R&D and it includes the three-dimensional circulation model TELEMAC-3D. The model is based on the finite elements method. Assuming the hydrostatic hypothesis, TELEMAC-3D solves the three-dimensional Reynolds Averaged Navier Stokes (RANS) equations (Hervouet, 2007):

$$\frac{\partial U}{\partial x}+\frac{\partial V}{\partial y}+\frac{\partial W}{\partial z}=0 \qquad [1]$$

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}+W\frac{\partial U}{\partial z}=-g\frac{\partial \eta}{\partial x}+v\Delta(U)+F_x \qquad [2]$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}+W\frac{\partial V}{\partial z}=-g\frac{\partial \eta}{\partial y}+v\Delta(V)+F_y \qquad [3]$$

$$\frac{\partial h}{\partial t}+\frac{\partial (uh)}{\partial x}+\frac{\partial (vh)}{\partial y}=0 \qquad [4]$$

(U, V, W) are the three components of the flow velocity, (u,v) the depth integrated flow velocities, υ the diffusion coefficient, g the gravitational constant and (F_x, F_y) the source and sink terms of the momentum equations ([2] and [3]). The set of equations is closed using the k-ε turbulence model.

TELEMAC provides the possibility of taking into account passive or active tracers in the model domain. The following equation describing the evolution of tracer concentration (T) is solved:

$$\frac{\partial T}{\partial t}+U\frac{\partial T}{\partial x}+V\frac{\partial T}{\partial y}+W\frac{\partial T}{\partial z}=v_t\Delta(T)+Q' \qquad [5]$$

The tracer diffusion coefficient is given by v_t and Q' represents the source terms for tracers.

3.1 Model Grid and Resolution

The model domain (pictured in figure 1) covers the entire tidal Scheldt estuary, including the mouth area and the Belgian Coastal Zone from Dunkerque (France), until Goeree (The Netherlands), including the Eastern Scheldt. Upstream the model extends to the limits of the tidal intrusion. All tributaries of the Scheldt are included.

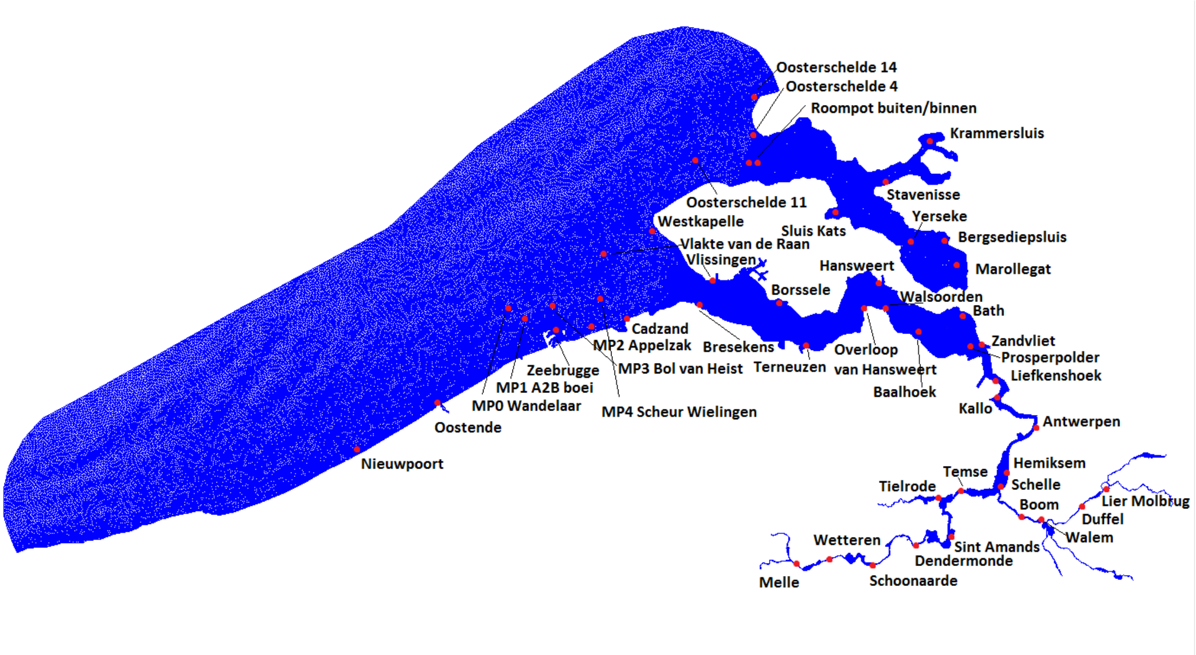


Figure 1: Model domain and output points

Using an unstructured grid allows to combine a large model extent with a high resolution upstream. The grid resolution varies from 7-9m in the Upper Sea Scheldt to 500m at the offshore boundaries.

The model grid consists of +460 000 nodes in the horizontal. The model is 3D with 5 sigma planes over the vertical, which gives a total of +2 300 000 of nodes. The resolution in the coastal area varies from 200 to 500 m depending on waterdepth. The resolution in the Eastern Scheldt is 200 m. In the Western Scheldt the resolution is 120 m. In the Sea Scheldt the resolution increases slowly to 30m near Antwerp and 10m in the Upper Sea Scheldt. Upstream the tributaries the resolution can reach 4m.

3.2 Bathymetry

Figure 2 shows the bathymetry of the SCALDIS model. It was built out of a patchwork of different data sources. The Belgian Continental Shelf and the Belgian coastal zone was measured in 2007-2009 by MDK-aKust. The bathymetry of the Dutch coast (mostly 2010-2012) was measured by Rijkswaterstaat and downloaded from Open Earth. The harbor of Zeebrugge is put at maintenance depth. The bathymetry of the Western Scheldt (2013) and the Eastern Scheldt (2010) was measured by Rijkswaterstaat. For the lower Sea Scheldt, bathymetric data of 2011 was provided by Maritime Access division. Bathymetric data for the Upper Sea Scheldt and Rupel basin (2014) was completed with data for the Dijle and Lower Nete (2010-2013) and for the Zenne and Grote and Kleine Nete (2001) which was provided by W&Z, Sea Scheldt division. For the Flood Control Areas along the river, the topographic data is derived from the Mercator Database.

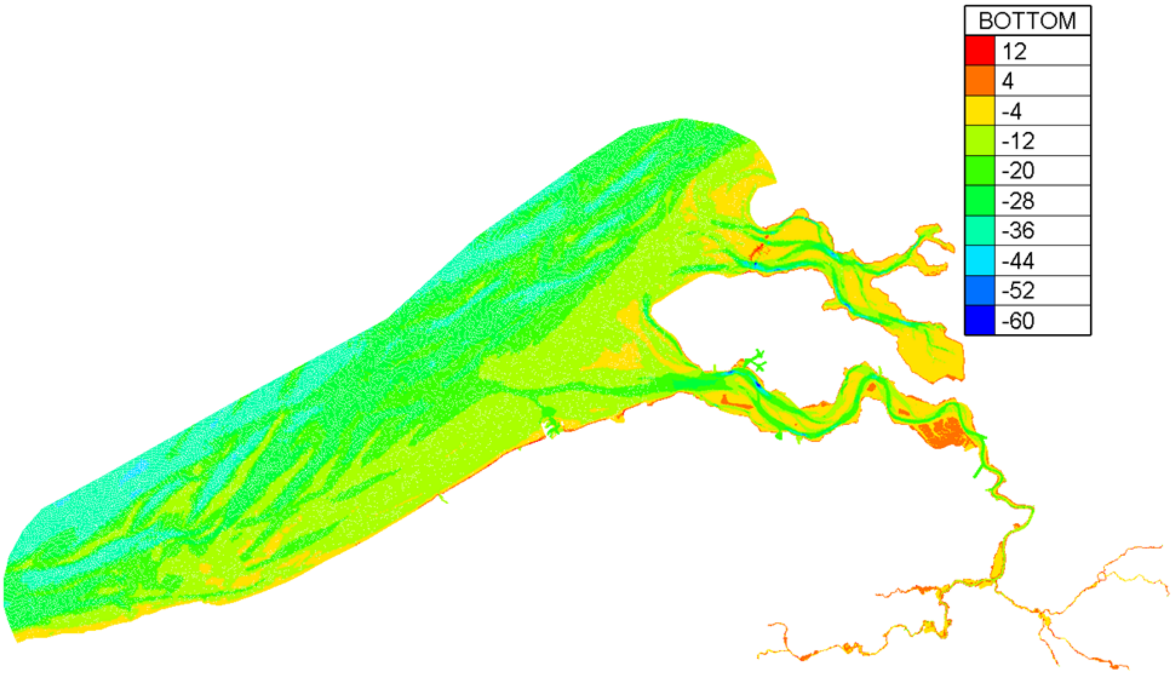


Figure 2: Bathymetry of the SCALDIS model (m TAW)

3.3 Flood Control Areas

In the actualized Sigma Plan for the Sea Scheldt, different restoration techniques are elaborated which combine safety with estuarine restoration (http://www.sigmaplan.be/). One example is flood control areas (FCA's) with our without a controlled reduced tide.

In order to include the FCA's in the SCALDIS model, the existing culvert functionality in TELEMAC was extended to better represent the hydrodynamics of water exchange between the Scheldt estuary and these flood control areas (Smolders, 2014 and Teles, this volume). Discharge coefficients for in- and outlet structures are calibrated against measurement data in Lippenbroek and Bergenmeersen. Using this new schematization, all planned FCA's that are foreseen in the Sigma Plan are included in the model.

3.4 Boundary Conditions

The downstream model boundary is located in the North sea. The SCALDIS model is nested in the ZUNO model (Rijkswaterstaat, 2009) from which it gets the downstream boundary conditions for water level and salinity.

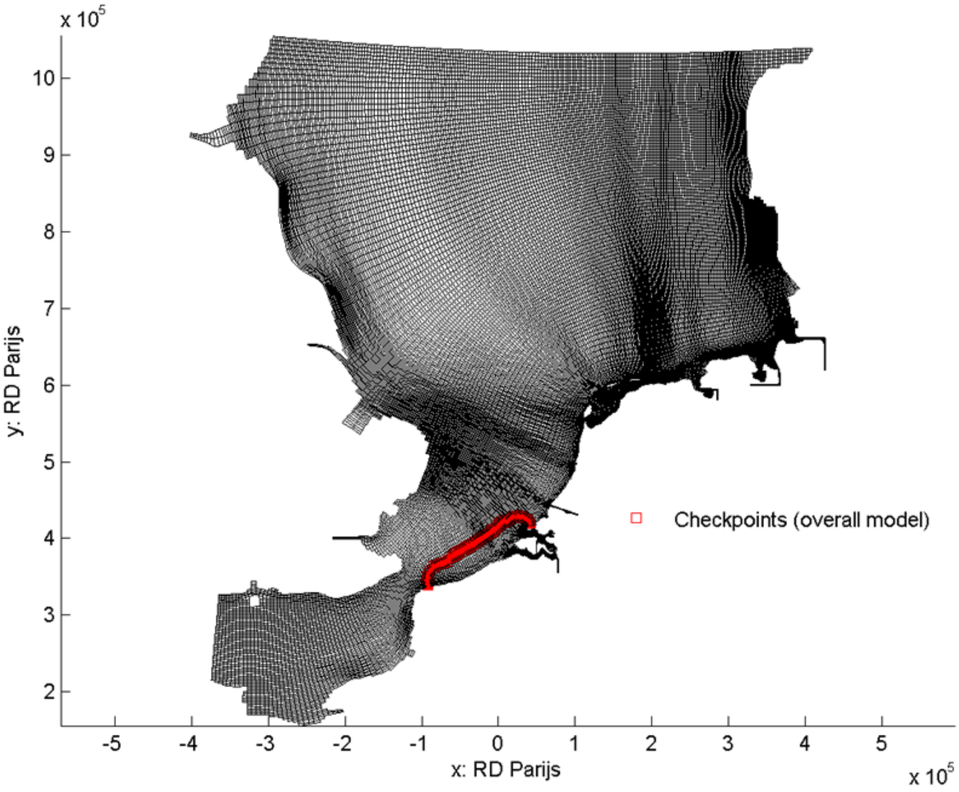


Figure 3: Domain of the ZUNO model (black) and boundary points of the SCALDIS model (red)

A correction of the harmonic components was calculated based on the comparison of the ZUNO results and measurements for a period of 1 year (2013). Phase of M2, M4 and S2 are corrected, together with the average water level Z_0. Details are given in table 1.

Table 1: Correction in harmonic components from values calculated in the ZUNO model

Component	Correction to value from ZUNO
M2 phase	+4°
M4 phase	-6°
S2 phase	+7°
Z_0 (average water level)	-0,21m

Salinities in ZUNO are corrected based on the comparison of the calculated and measured salinity time series at Vlakte van de Raan. Details of the analysis of the hindcast of 2013 in ZUNO (from which downstream boundary conditions are derived) are given in Maximova et al. (2015).

At the upstream boundaries, measured timeseries of fresh water inflow are prescribed. Additional sources of fresh water are included at Bath and Terneuzen.

3.5 Calculation Time and speed-up

A 3D run with salinity as an active tracer runs with a speed-up of 8,5 on 60 cores (Intel Xeon Westmere X5650 - 2.66GHz Six Core). Including the flood control areas activates the culvert functionality that was added to the code. This slows down the calculation to a speed-up of 3,5. This is linked to the way sources and sinks are implemented in the TELEMAC code. The implementation of the new culvert code makes extensive use of the existing sources and sinks subroutine in TELEMAC. Optimising the sources and sinks subfunction will greatly reduce the cost of using the newly developed culvert functionality. This has been reported as a feature request to the developers in the TELEMAC consortium.

4. CALIBRATION

4.1 Bottom Roughness

The modeled horizontal and vertical tide is calibrated by adapting the bottom roughness, which is represented by Manning's equation for the dimensionless friction coefficient C_f.

$$C_f = \frac{2gn^2}{h^{1/3}}$$ [7]

The calibrated roughness field (Manning's n in equation 5) is shown in figure 4.

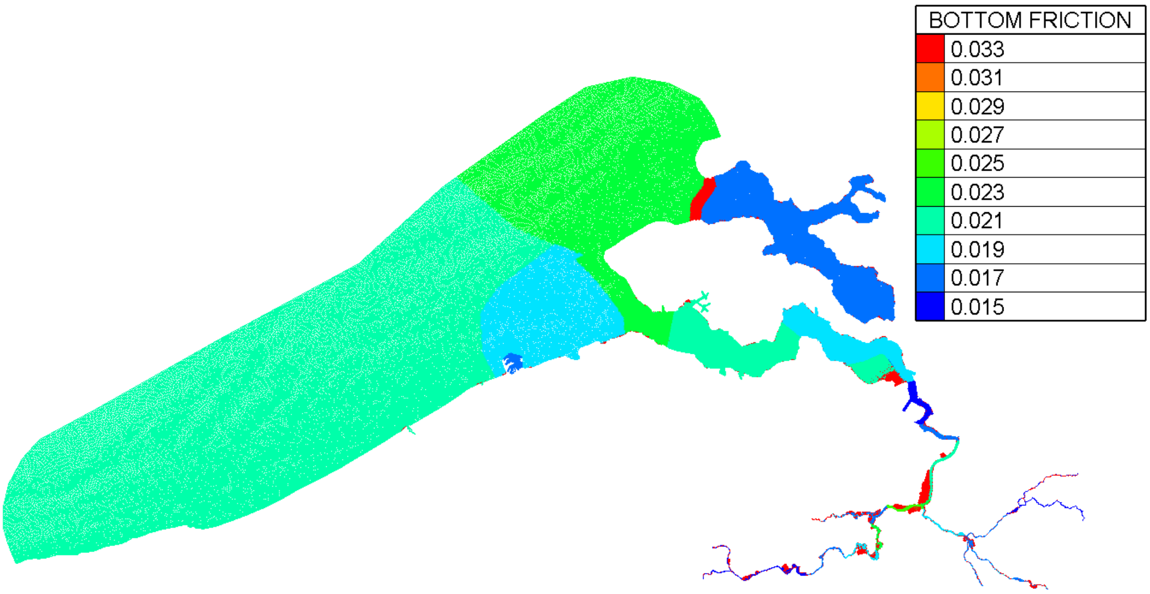


Figure 4: Bed roughness field of the SCALDIS model ($m^{-1/3}s$)

4.2 Cost Function

A weighted dimensionless cost function is calculated for each simulation to assess model performance. Each factor is a particular error statistic with the same unit as the measurements on which they are based. The cost function is made dimensionless by normalizing to the factor score in the reference run. The task of calibration is to minimize this objective function. Within this project we limit the parameter space to roughness in different zones in the model domain.

$$Cost = \sum \frac{Factor_i}{Factor_{i,ref}} * Weight_i$$ [6]

Several parameters are selected as factors for the calculation of the cost function. For the vertical tide, the RMSE (Root Mean Square Error) of the complete timeseries, as well as the RMSE of the level of high waters are taken into account. Both modeled and measured water levels are harmonically analyzed using t_tide (Pawlowicz et al., 2002). A vector difference is aggregated over 6 harmonic components and Z_0 (explained in more detail in §5.1). The difference in M2 amplitude between model and measurement is also a factor. By including the amplitude of M2 both in the vector difference as as a separate factor, the M2 component gains a higher weight in the total cost than the other harmonic components. This is justified by the fact that M2 is the most important harmonic component in the area of interest.

For the horizontal tide RMAE (Root Mean Absolute Error) of sailed ADCP measurements and RMSE of measured discharges are included as factors.

Table 2 lists the weights used in the cost function (equation 6). Note that the horizontal and vertical tide are given the same weight. This stems from the intended model purpose. The model should be able to accurately describe the evolution of water level over time, with extra emphasis on the prediction of high water. It is equally important however that the model is able to accurately reproduce velocities and fluxes, because it is the intention to use this hydrodynamic model as the basis for sediment transport calculations (both cohesive and non-cohesive) and tracer calculations.

Table 2: Weights used in the cost function

	Zone	Objective Function	Weights [%]		
Vertical Tide (Water Levels)	Western Scheldt	RMSE Time Series	3,50%	14,00%	50%
		RMSE Level High Water	3,50%		
		Vector difference	3,50%		
		delta M2 amplitude	3,50%		
	Eastern Scheldt	RMSE Time Series	1,25%	5,00%	
		RMSE Level High Water	1,25%		
		Vector difference	1,25%		
		delta M2 amplitude	1,25%		
	Lower Sea Scheldt	RMSE Time Series	3,50%	14,00%	
		RMSE Level High Water	3,50%		
		Vector difference	3,50%		
		delta M2 amplitude	3,50%		
	Upper Sea Scheldt	RMSE Time Series	4,25%	17,00%	
		RMSE Level High Water	4,25%		
		Vector difference	4,25%		
		delta M2 amplitude	4,25%		
Horizontal Tide (Velocities and Fluxes)	Western Scheldt	RMAE of Sailed ADCP deep zone	10,00%	13,33%	50%
		RMSE of Discharges	3,33%		
	Lower Sea Scheldt	RMAE of Sailed ADCP deep zone	10,00%	15,83%	
		RMAE of Sailed ADCP shallow zone	2,50%		
		RMSE of Discharges	3,33%		
	Upper Sea Scheldt	RMAE of Sailed ADCP deep zone	15,00%	20,83%	
		RMAE of Sailed ADCP shallow zone	2,50%		
		RMSE of Discharges	3,33%		
			100%	100%	100%

Figure 5 shows the evolution of the dimensionless cost function of the different model runs in model calibration. Model run Scaldis_028_0 corresponds to the lowest cost function and is referred to as the calibrated model.

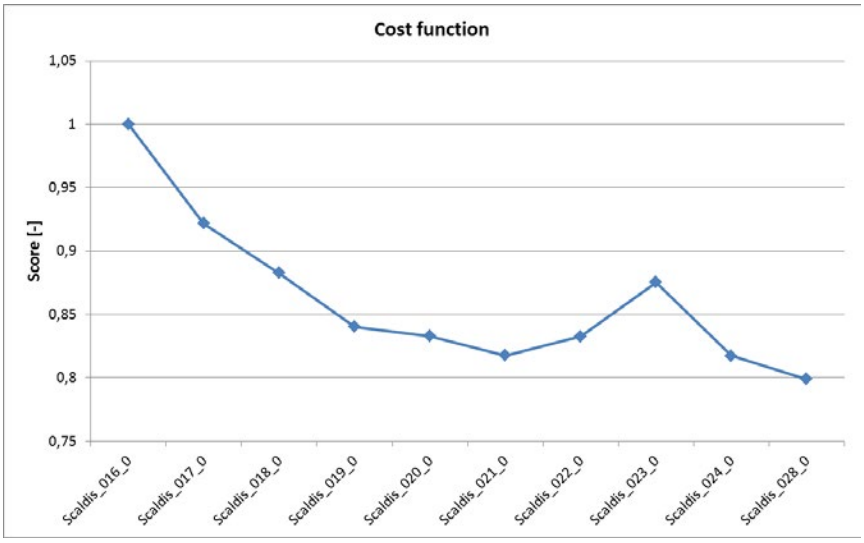


Figure 5: Evaluation of the total dimensionless cost function for the different runs in model calibration. Model run Scaldis_028_0 corresponds to the lowest cost function and is referred to as the calibrated model

5. MODEL SKILL

Model skill is assessed using runs of different periods in 2013. Model and measurements are compared and analyzed using the VIMM toolbox , developed in MATLAB at Flanders Hydraulics Research. This toolbox for skill assessment of hydraulic models automatically determines the difference between a model run and different types of measurements. For this project, more than 5000 figures and 40 tables are generated for each run to give the modeler a deeper insight in the model skill. The toolbox works independently of model software (currently Delft3D, SIMONA and TELEMAC are supported) and measurement data source.

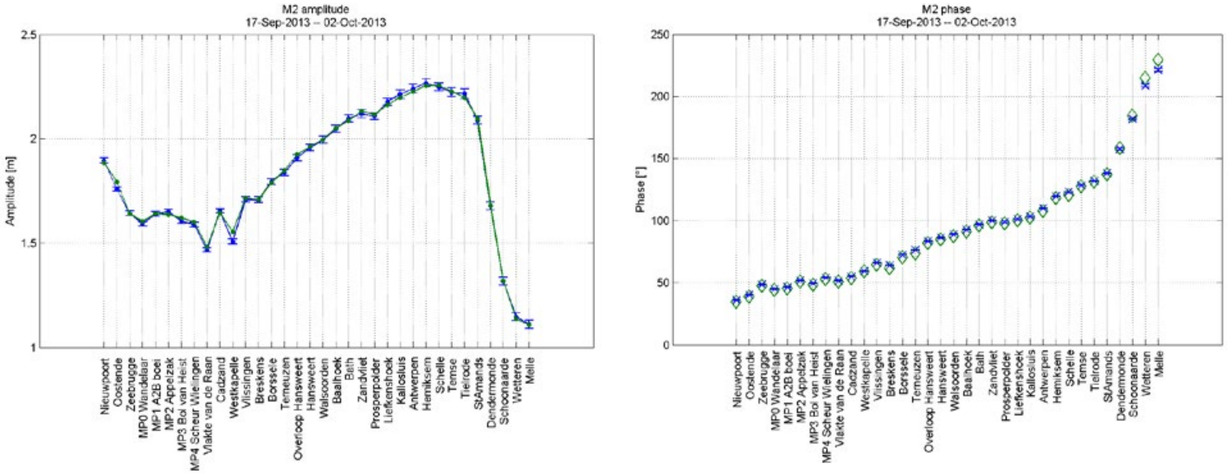
For the sake of readability, of course only a very small subset of these figures can be shown in this article. More detailed information can be found in the technical report (Smolders et al., 2015 and the appendices therein).

5.1 Vertical Tide

The RMSE of high waters and complete water level time series is 7 to 9 cm in the North sea and Western Scheldt, around 10 cm in the Eastern Scheldt and 11 to 14 cm in the Sea Scheldt. The bias of water levels is smaller than 10 cm at most stations.

Modeled and observed tides are harmonically analyzed using t_tide (Pawlowicz et al., 2002). In the region of interest, most tidal energy is present in the M2 tidal component. Figure 6 shows the variation of modelled and measured M2 amplitude and phase along the estuary. The difference between model and measurement in M2 amplitude is smaller than 1 cm in 80% of the stations. The difference in M2 phase is smaller than 2° at 80% of the stations.

From this we can conclude that the model is able to accurately reproduce the celerity of the tidal wave, and the variation of tidal amplitude along the estuary caused by the combination of the funnel shaped system geometry and bottom friction.



M2 amplitude
17-Sep-2013 – 02-Oct-2013

M2 phase
17-Sep-2013 – 02-Oct-2013

Figure 6: M2 amplitude [m] in the left panel and phase [°] in the right panel for different stations in the North sea and along the Scheldt estuary. The error bars indicate the estimated accuracy of the harmonic analysis. Measurements (in blue) and calibrated model (in green).

Calculated and observed amplitude and phase of different harmonic components can be geometrically combined to a vector difference (Gerritsen, 2003), the lengths of which are summed over selected components and averaged over selected stations (equation 8).

$$e = \frac{1}{N_s}\sum_{i=1}^{N_s}\sum_{i=1}^{N_c}\sqrt{\left(A_{c,i}\cos(\varphi_{c,i}) - A_{o,i}\cos(\varphi_{o,i})\right)^2 + \left(A_{c,i}\sin(\varphi_{c,i}) - A_{o,i}\sin(\varphi_{o,i})\right)^2} \qquad [8]$$

e is the total vector difference with $A_{c,i}$ en $\varphi_{c,i}$ the calculated amplitude and phase of harmonic constituent i and $A_{o,i}$ en $\varphi_{o,i}$ the observed amplitude and phase, summed over N_c components and averaged over N_s stations.

Because the vector difference aggregates error information over different frequencies and different stations, it is a powerful tool during model calibration and validation/verification.

Figure 7 gives shows the stacked vector difference over 6 harmonic components plus Z0 (average water level) and 34 stations in the North Sea and the Scheldt estuary. The lower the stacked graph, the higher the model accuracy at that station. This way the stacked vector difference graph describes the evolution of model skill along the estuary. The sudden decrease in model accuracy in the upstream end of the model domain is attributed to the fact that daily values of fresh water inflow are used as upstream boundary condition. In the upstream end of the Scheldt estuary, discharge still has a significant impact on the vertical tide (water levels). Earlier work has shown that hourly values of fresh water inflow are better to reproduce peak inflows and the effect of peak inflow on water levels, but hourly values were not available in the modeled period.

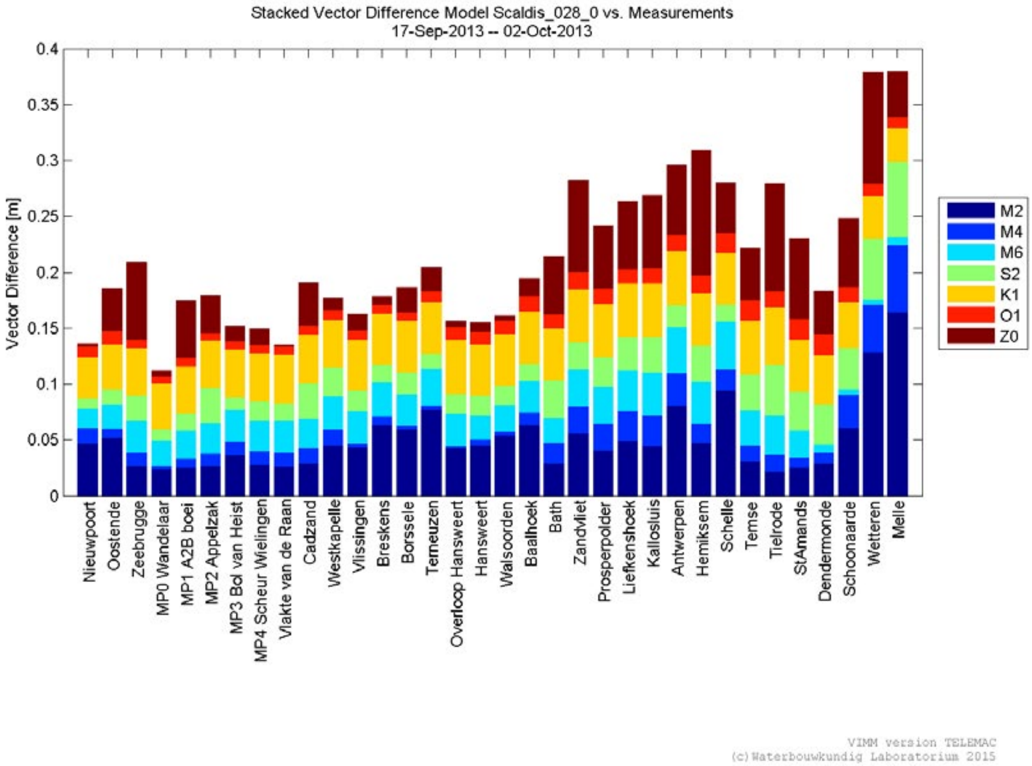


Figure 7: stacked vector difference graph for 34 stations in the North Sea and the Scheldt estuary.

5.2 Horizontal tide

The model is compared to velocity measurements in shallow areas using ensemble analysis or phase averaging where measured and modelled depth averaged velocities are split into individual tidal cycles and averaged out over neap, normal and spring tide.

Phase averaging provides useful information on intratidal dynamics, and focuses the attention on system behavior by averaging out more episodic events.

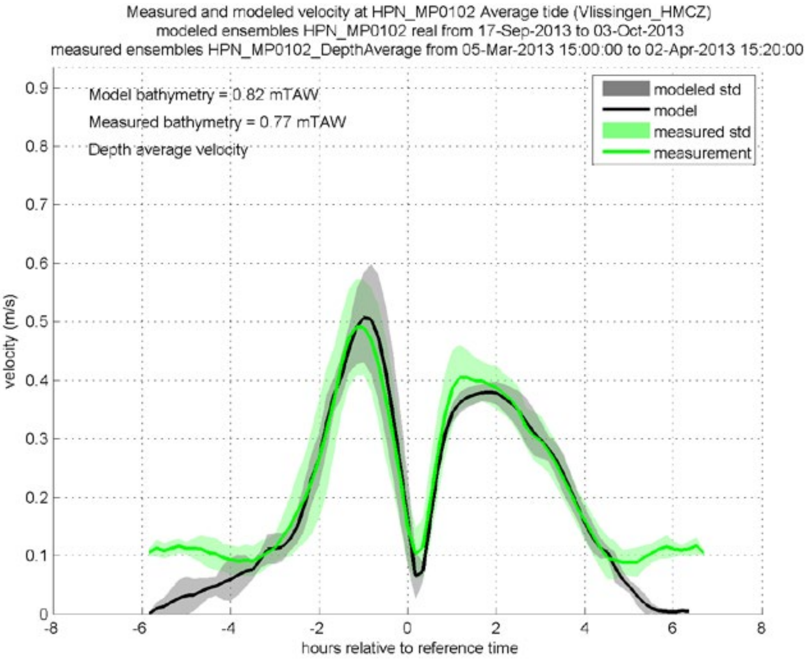


Figure 8: Mean and standard deviation [m/s] over a tidal cycle of the depth averaged current during an average tide at location Hoge Platen Noord in the Western Scheldt.

Figure 8 shows an example of phase averaging applied to depth averaged velocities that are measured by Rijkswaterstaat using a an ADCP that has been dug into a shoal in the Western Scheldt (Hoge Platen Noord).

5.3 Salinity

The salinity at Liefkenshoek is compared between model and measurement in figure 9, showing a good agreement, both in absolute value as in the tidal amplitude of the salinity variation. This model result gives confidence that tracer dispersion and related parameters as residence times are accurately described in the model.

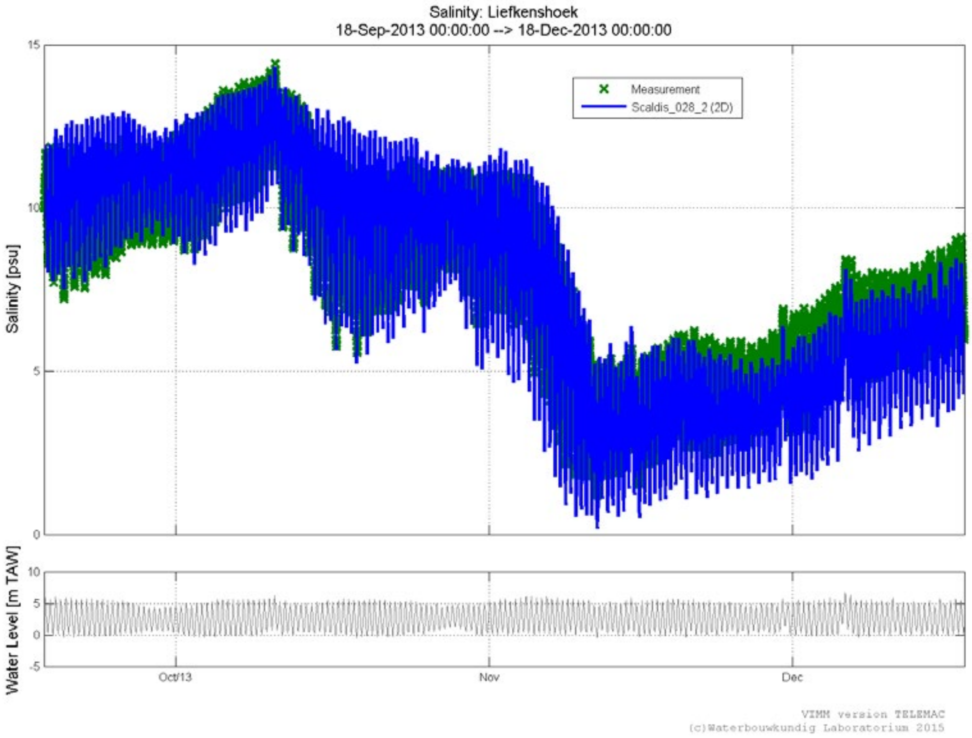


Figure 9: Modelled (blue) and measured (green) salinity. Modelled salinities are depth averaged from the results of the 3D model.

6. CONCLUSIONS

This paper introduces the unstructured SCALDIS model, a new 3D high resolution hydraulics model. Model calibration is done using a weighted dimensionless cost function that attributes equal weight to the horizontal and the vertical tide. The weights are chosen in accordance to the stated model purpose, objectifying and quantifying the process of model calibration.

Assessing model skill can be a tedious and labor intensive work for a modeler. In order to facilitate and partly automate this process, the VIMM toolbox was developed at Flanders Hydraulics Research. This toolbox provides an abstraction layer between the statistical methods that are used for quantifying model skill, the software in which the model schematization is built (currently Delft3D, SIMONA and TELEMAC are supported) and the data source of the measurements. This way, code duplication in between projects and modelers can be avoided. Code quality is guaranteed using a versioning system. By giving the modeler standardized figures and tables that provide a deep insight in model performance, the VIMM toolbox greatly enhances the efficiency of model calibration and quantified skill assessment of hydraulic models.

The quantified model skill of the SCALDIS model shows that the model is well suited to assess the effects of changing the bathymetry and geometry of the Scheldt river on water levels, velocities, tracer dispersion and residence times, and that the hydrodynamics can be used as the basis for sediment transport calculations (both cohesive and non-cohesive).

ACKNOWLEDGMENTS

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