



## Abstract

This report is meant to give an overview of the achievements of the project 'Salt marsh cycles'. These inter tidal areas are very valuable from an ecological perspective and may be under threat due to for example dredging activities in the Western Scheldt and gas extraction in the Waddensea. The European habitat directive requires compensating measures if it can't be proven that no negative effects result from these developments. This means that there is a need for tools to predict the effect on the saltmarshes of planned activities. More general is there the question of how to manage these areas, such that the ecological value is preserved.

The aim of the project is to understand and quantify the ecological and morphological conditions favouring the formation and degradation of salt marshes, to identify the relevant physical and ecological processes as well as their interaction under a variety of environmental conditions, and to assess the role of salt marshes in the development of the estuary as a whole. This is to provide knowledge that contribute to solve managerial problems concerning salt marshes.

The report does not provide an in-depth discussion of its contents. It consists of a collection of abstracts and summaries of papers and reports produced within this project. Links to where the full text can be found, digital or written, are given. Unfortunately not all the abstracts and reports are available in the English language since some of the research has been done for Dutch clients.

The project consists of a number of more or less independent sub-projects that look at the subject from different points of view. They can be clustered as follows:

1. Interaction between salt marshes and other parts of the estuary.
2. Morphological development
3. Interaction between vegetation and morphology
4. Modelling and case-studies
5. Validation data-base
6. Applications abroad: Magroves and Feiyun Estuary (China)

Each of the chapters contains a summary of the work done in one of the above mentioned themes. A chapter starts with the original scope as put in the project plan and ends with a list of products. In the final chapter an overview of the project spin off is given.

PROJECT NAME:	<b>Salt Marsh cycles</b>	PROJECT CODE:	<b>03.01.06</b>
BASEPROJECT NAME:	<b>Salt Marsh cycles</b>	BASEPROJECT CODE:	<b>03.01</b>
THEME NAME:	<b>Coast and river</b>	THEME CODE:	<b>03</b>

## Executive Summary

This report is meant to give an overview of the achievements of the project 'Salt marsh cycles'. These inter tidal areas are very valuable from an ecological perspective and may be under threat due to for example dredging activities in the Western Scheldt and gas extraction in the Waddensea. The European habitat directive requires compensating measures if it can't be proven that no negative effects result from these developments. This means that there is a need for tools to predict the effect on the saltmarshes of planned activities. More general is there the question of how to manage these areas, such that the ecological value is preserved

Salt marshes can be generated in two ways, via sedimentation of lower inter tidal areas or via drowning of land (retreat of flood protection). They can also disappear in two ways, by (usually cliff) erosion and from excessive sedimentation which turns salt marshes into land. Processes and mechanisms influencing the cycle of generation, development and disappearance of the salt marshes and the interaction with the whole estuarine system are the subjects of the present study. A bottom-up (i.e. process oriented) and a top-down approach (i.e. starting from the overall system) will be followed, as this is the most promising approach to address in a convergent way the large scale issues and the local interactions.

The aim of the project is to understand and quantify the ecological and morphological conditions favouring the formation and degradation of salt marshes, to identify the relevant physical and ecological processes as well as their interaction under a variety of environmental conditions, and to assess the role of salt marshes in the development of the estuary as a whole.

Quantification implies the development of a set of model descriptions; these models can be highly empirical and based on a sound understanding of the processes, hybrid and/or deterministic; they are tested against data and applied to case studies.

This report is meant to give an overview of the achievements of the project 'Salt marsh cycles'. It does not provide an in-depth discussion of its contents. It consists of a collection of abstracts and summaries of papers and reports produced within this project. Links to where the full text can be found, digital or written, are given. Unfortunately not all the abstracts and reports are available in the English language since some of the research has been done for Dutch clients.

### Findings relevant for managers

1. The outcome of the conceptual model for salt marshes suggests that the de- or regeneration of these areas is an autogenous process which is not necessarily the result of changed external conditions. Hence, erosion found in salt marshes does not necessarily require remediation actions, as it is possible the results of natural development processes within salt marshes. An 'indicator' for this situation is the occurrence of simultaneous cliff erosion and regrowth of vegetation before the cliff.
2. The study on the SCALWEST model for the Westerschelde has improved the models reproduction of currents in the intertidal areas in the Western Scheldt. Hereto the friction factor is related to the geomorphological unit such that for new models the bottom friction in inter tidal areas can easily be obtained using new geomorphological maps. These results are beneficial to assess the ecological impact of future new measures in the Western Scheldt, like a further deepening of the fairway.
3. The adapted Delft3D-model that accounts for the effect of vegetation on water motion, in combination with the experimental knowledge gained in this project can help to assess the possibilities of 'bioengineering' as a method for salt marsh and coastal protection.
4. The sand-mud model as developed by van Ledden has increased the understanding and the modelling capabilities for large-scale sand-mud segregations in estuaries and tidal basins. This is relevant for salt marshes since the mud content of the sediment is an important parameter. The model can be used to estimate the effect of human interventions and natural changes on the development of the large-scale

bed level and composition in time and space.

5. The study on the Slik van Waarde shows that only a small percentage of dumped material in a channel actually reaches the mudflat and only at the edge of the channel/mudflat. Only when the dumping location is very close to the mudflat does the material has a significant effect on the flat.
6. The theoretical stability analysis on the stability of channels on mud flats provides knowledge on how to 'design' the creek (channel) system in artificial salt marshes, as, for example, present in the Wadden Sea. It shows that that a sufficient large tidal prism is required for a channel to maintain itself. The tidal prism is influenced by:
  - a) the density of the channels  
The relatively high density of especially the smallest channels in the artificial salt marshes in the Wadden Sea compared tot that of the natural salt marshes, has the consequence that the tidal prism per channel become too small to maintain the channels.
  - b) the realtive depth of the channels  
A relatively deep channel attracts more flow than a shallower one next too it making the tidal prism through it larger. This explains why a deeper channel can better be maintained than a shallower one.
7. In the 'krekenproof' a number of adaptations to the drainage system has been tested that were made to 1) reduce the total length of the ditches which compared to natural systems is too large, and 2) to improve the naturalness. Its results are of direct interest for managers of such areas.
8. At present, low sand flats dominate the Wadden Sea. All that remains from the once expansive salt marshes are narrow fringes on the landward side of the tidal basins, and coastal peat bogs have disappeared altogether. The study on the long term development of the Lauwerszee estuary shows that the development is linked to the behaviour of tidal-inlet-related channel systems and to human activities such as the reclamation of salt marshes and cultivation of peat land are the cause.
9. The analysis of the dataset of Rijkswaterstaat to study the correlation between benthic animals and spatial and temporal dynamics of sediment characteristics, shows that the temporal and spatial variations are such that one should be carefull in drawing conclusions based on limited sample locations. Moreover, does it imply that one should be hesitant in using a site for reference purposes when studying the impact of, for example, human intervention. It is better too do measurements at the same location before and after the intervention takes place. To account for the temporal variation one should do this on a long enough scale. The analysis also suggests that it is important that sampling should be done at random locations each year and that for each locations also measurements of environment variables such as sediment characteristics are measured. All measurements including those of the local environmental variables, have to be done several times.

### **Scientific spin-off**

1. In the process based Delft3D-FLOW/3DMOR module an adaptation has been made to account of the effect of plants on water flow. Also an approach has been developed to account for the wave damping effect of vegetation. A model of the salt marsh Paulina Polder has been constructed and validated on available data (see below). This model will made available on the internet.
2. A conceptual model has been developed to explain the development of salt marshes in time taking into account the interaction between morphology and vegetation.
3. A numerical prototype of the process-based sand-mud model has been developed by extending the three-dimensional software package Delft3D from WLdelft hydraulics.
4. The study on the SCALWEST model for the Westerschelde has improved the reproduction of currents in the intertidal areas in the Western Scheldt. Hereto the friction factor is related to the geomorphological unit such that for new models the bottom friction in inter tidal areas can easily obtained using new geomorphological maps.
5. A number of datasets have been put together:

- a) A database of Alterra sediment budget studies from five different salt marshes in the Netherlands was made. This data may be used for modelling purposes after consultation with Alterra.
  - b) A long-term (months) high-resolution (4 Hz) hydrodynamic data set, and, linked to this, a biological description of the organisms on the mudflat and the Paulina Polder marsh, have been collected. After analysis this data will be put on the web to be used in other studies.
  - c) The changes in vegetation, soil level, sedimentation and the development of the creek system the man-made salt marshes of the salt marsh works along the Wadden Sea coast of Groningen and Friesland were measured for 4 years for different adaptations, made to the drainage system in order to reduce the total length of the ditches and to improve the naturalness.
  - d) In order to learn more about salt marsh morphodynamics, with regard to the interactions between sedimentation and vegetation, measurements were done in salt marshes in the Netherlands with a different history and which are submitted to different tidal conditions. The results can be used for salt marsh management. Furthermore they give an indication about the possible effect of sea-level rise on salt marshes and the succession/regression of the vegetation. Since 1993 the sedimentation is measured in several salt marshes along the Wadden Sea.
  - e) Integration of seismic data of the period since 0 AD on the Lauwerszee with reconstructions of the changing estuary.
  - f) Data on the height of the clay layer along the salt-marsh developmental gradient was compiled and classified by age.
6. The following existing datasets have been analysed
- a) For the salt marsh the 'Slik van Waarde' a data analyses of the development in the period 1951-2000 has been conducted
  - b) The interaction between benthos, hydrodynamics and sediment structure was study at two different spatial scales. At the scale of the estuary, an existing large datasets of Rijkswaterstaat was used to analyse the degree to which benthic animals correlate with spatial and temporal dynamics of sediment characteristics. This analysis is based on long-term (7 year) monitoring of a large number of transects in the Westerschelde. Monthly measurements of elevation along the transects, yearly measurement of sediment composition and half-yearly sampling of macrobenthos at the same sites were combined in the analysis.

### Suggestions for future research

1. In the study on the macro-scale morphological characterisation of the Western Scheldt an important first step has been made to identify a number of easily-assessable parameters, which can be used as *quantitative indicators* to be used by managers for the assessment of the morphological quality of tidal systems. The link between morphological quality and potentiality for certain ecotopes allows then to set up a tool for the *ecological characterisation* of tidal systems.

The major suggestion for future research arises from the limitations encountered in the study. Some of the improvements needed by the models will be reached in a short time, and have been discussed in the previous sections. In particular, in the author's opinion, the development of a model able to handle morphological cells with channels and shoals, and capable to assess the residual effects, is desirable and necessary.

A further suggestion which is not related to the theoretical aspects of the analysis, but to the practical management of the information, is to share the existing database of the Western Scheldt estuary, for example on a web site open to the public, and to try to merge it with the data of the Belgian part of the estuary. Many researches are working on this subject and the possibility to have access to such a tool would be broadly appreciated.

3. In the research on process based models, as presented in the report, the effect of vegetation on flow and waves, and its effect on morphology, has been studied separately. This was partly due to the available data of Paulina Schor, in which waves only played a minor role. The combined effect should be studied as well. This would require validation of the model on a case where waves play a more dominant role.
4. Parameterisation to larger scale models and behaviour oriented modelling. Research has to be done on how the results of the process based models can be parameterised and implemented in larger scale predictive models which can be used in practical problems. Knowledge and insight from the process research can be implemented / used in behaviour oriented, i.e. (semi-) empirical models for estuaries including salt marshes
5. This was originally planned for the present project but has been omitted due to time constraints.
6. The conceptual modelling approach is now used to study, whether the creation of creek/channel pattern can be coupled to the interaction between mud and vegetation. This is done on different scales and for both the salt marsh and the mudflats. Channels, gullies or channels play an important role in the development of intertidal areas. Insight in their behaviour is therefore relevant when managing these areas.

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# **Salt Marsh cycles, an achievement report**

**DC-project 3.01.06**

June, 2003

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# I Introduction

## I.1 Background

### I.1.1 The Delft Cluster programme

It has been estimated that some 80% of the world's population will live in delta and coastal areas by 2050. In this context the Delft Cluster programme focuses on the sustainable development of densely populated delta areas. The scope of work includes planning and design, through to construction and management. Delft Cluster (DC) aims to develop the know-how that those involved with civil- and hydraulic engineering require to increase the return on investment in the infrastructure of delta areas. The ultimate societal aim is to reduce uncertainties involved with the implementation of future, large-scale infrastructural works and intervention in the spatial structure. The DC project tries to reach its aim by a strengthening of the existing knowledge infrastructure by means of:

- the generation of knowledge by the setting up and carrying out of a long-term fundamental, strategic research programme, and
- the preservation of knowledge by collecting, making available and transferring existing and developed knowledge.

Seven themes were defined in the DC programme around which research effort was clustered. Each theme is further subdivided into several base-projects, each of which on its turn consists of a number of connected projects that together form a complete, coherent, extensive long-term research programme.

Theme 3, "Coast and River" is dedicated to the sustainable development of rivers and coastal areas. In line with the Businessplan Delft Cluster and the Addendum, the focus of this theme is on the improvement of our knowledge of the natural system, but placed in a particular context. This context concerns the enhancement of our predictive capability in view of large-scale developments of and interventions in coastal and riverine systems, typical of The Netherlands. Theme 3 is restricted to the natural (physical and ecological) components of these systems. Moreover, this work should contribute to a world-wide recognition of the capabilities of Dutch knowledge institutes, consultants and contractors.

### I.1.2 Salt marsh cycles

This project comprises the second phase of the Delft Cluster Project 'Ecomorphology of Estuaries and Coasts'. Ecomorphology, or bio-geomorphology, studies the interaction between biology and morphology or more general physical processes.

The first phase of this project was conducted in 2000 and consisted of an inventory of the managerial questions and relevant processes in the Delta area and the Wadden Sea area regarding this subject (Brouwer et.al., 2001). As a result the second phase concentrated on the salt marshes ('schorren en kwelders') in the above mentioned regions. These inter tidal areas are very valuable from an ecological perspective and may be under threat due to for

example dredging activities in the Western Scheldt and gas extraction in the Waddensea. The European habitat directive requires compensating measures if it can't be proven that no negative effects result from these developments. This means that there is a need for tools to predict the effect on the saltmarshes of planned activities. More general is there the question of how to manage these areas, such that the ecological value is preserved.

Participants in this project are: Alterra, NIOO-CEME, IHE, TNO-MEP, TNO-NITG, TUD, UU, WLIDH, Haskoning, RIKZ and RIZA. 'Natuur Monumenten' does participate in the role of reviewer. They are very interested in its findings.

## **1.2 Aim of the project**

The aim of the project is to understand and quantify the ecological and morphological conditions favouring the formation and degradation of salt marshes, to identify the relevant physical and ecological processes as well as their interaction under a variety of environmental conditions, and to assess the role of salt marshes in the development of the estuary as a whole.

Quantification implies the development of a set of model descriptions; these models can be highly empirical and based on a sound understanding of the processes, hybrid and/or deterministic; they are tested against data and applied to case studies.

## **1.3 Set-up of the study**

From the point of view of the management of estuaries like the Western Scheldt Rijkswaterstaat and Natuurmonumenten wants to know how the various human activities influence the salt marshes in the estuary and how the salt marshes influence the estuarine system. Furthermore Natuurmonumenten wants to know how the existing salt marshes can be preserved and new ones develop. The existing knowledge is insufficient to answer these questions. As examples, during the experts meeting discussing the measures for protecting the Zuidgors Schor and the Schor van Waarde it did not become clear what exactly have been the causes of the accelerated cliff erosion, and consequently it was not possible to accurately judge the proposed measures. To cope with this management need the present study is defined, with the objective to obtain/increase knowledge concerning the cycle of generation, development and disappearance of the salt marshes and its interaction with the whole estuarine system. The set up of the study takes into account the specific need of the managers and users of the estuarine and coastal water systems in The Netherlands. In this way the study will also anticipate on the ongoing research programmes.

Salt marshes can be generated in two ways, via sedimentation of lower inter tidal areas or via drowning of land (retreat of flood protection). They can also disappear in two ways, by (usually cliff) erosion and from excessive sedimentation which turns salt marshes into land. Processes and mechanisms influencing the cycle of generation, development and disappearance of the salt marshes and the interaction with the whole estuarine system are the subjects of the present study. A bottom-up (i.e. process oriented) and a top-down approach (i.e. starting from the overall system) will be followed, as this is the most promising approach to address in a convergent way the large scale issues and the local interactions.

## **I.4 Guidelines for the reader**

This report is meant to give an overview of the achievements of the project 'Salt marsh cycles'. It does not provide an in-depth discussion of its contents. It consists of a collection of abstracts and summaries of papers and reports produced within this project. Links to where the full text can be found, digital or written, are given. Unfortunately not all the abstracts and reports are available in the English language since some of the research has been done for Dutch clients.

The project consists of a number of more or less independent sub-projects that look at the subject from different points of view. They can be clustered as follows:

Interaction between salt marshes and other parts of the estuary.

Morphological development

Interaction between vegetation and morphology

Modelling and case-studies

Validation data-base

Applications abroad: Magroves and Feiyun Estuary (China)

Each of the chapters contains a summary of the work done in one of the above mentioned themes, p.e: chapter 2 deals with 'Interaction between saltmarshes and other parts of the estuary', etc. A chapter starts with the original scope as put in the projectplan and ends with a list of products. In chapter 8 some general results not related to a specific project, are presented. Chapter 9 contains an overview of the spin-off of the project and provides some suggestions for future research.

## **I.5 Website**

There is a project website that can be reached via the delftcluster website. It gives general information on the project and its participants. When available pdf-versions of the publications can be found there.

## 2 Interaction with other parts of the estuaries

### 2.1 General

The works in this task will focus on the role of the salt marshes in the water system as a whole. This means that the problem will be approached from a larger scale (top down approach) rather than restricted to the salt marshes themselves.

### 2.2 Transport of sand-mud mixtures.

Fundamental research on the erosion, deposition and transport processes of sand-mud mixtures will be carried by combining the efforts of an ongoing STW-PhD research at TuD and a R&D project at WL. The goal of this task is to improve the understanding of and to develop prediction tools for horizontal and vertical segregation of sand and mud in estuaries and tidal lagoons. *Participating partners: TuD, WL.*

#### Sand-mud segregation in estuaries and tidal basins

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Large-scale sand-mud segregation, i.e. mud content ( $\% < 0.063$  mm) variations in the horizontal direction at a spatial scale of kilometers, is found in estuaries and tidal basins all over the world. Understanding and predicting the distribution of sand and mud in these systems is important because of management issues such as the maintenance of navigation channels, the sediment bed quality and the distribution of flora and fauna. This research aims at proposing a process-based sand-mud model which can be used for describing morphological behaviour in estuaries and tidal basins including the effect of sand-mud segregation.

A key element in a process-based sand-mud model is an erosion formulation for sand-mud mixtures. Recently, several erosion experiments have demonstrated that the erosion behaviour of these mixtures can change dramatically when a small amount of mud is added to a sand bed or vice versa. Therefore, a classification and erosion formulations have been proposed for the behaviour of sand-mud mixtures. A comparison with a limited number of laboratory and field experiments has shown that the usefulness of the classification, and the applicability of the erosion formulations in a sand-mud model as a first step.

A three-dimensional process-based morphodynamic sand-mud model has been proposed. It extends the currently used morphodynamic models as follows: i) the erosion characteristics of sand and mud depend on the mud content at the bed surface, ii) temporal and spatial variations in mud content are taken into account, and iii) bed level changes depend on sand and mud exchange at the bed surface. Consolidation and flocculation processes have not yet been included explicitly in the model set-up. A numerical prototype of the process-based

sand-mud model has been developed by extending the three-dimensional software package Delft3D from WL|delft hydraulics.

Large-scale sand-mud patterns in estuaries and tidal basins have been investigated by analysing three idealised situations with the process-based sand-mud model: a local situation, a reservoir and a tidal basin. The analysis of the local situation has provided an expression for the equilibrium mud content at the bed surface under tidal conditions. The equilibrium mud content turns out to be the upper envelope of the observed mud content in a large number of points at the Molenplaat, an intertidal flat in the Western Scheldt estuary (the Netherlands). The initial morphological behaviour of the reservoir and the tidal basin has shown separate deposition waves of sand and mud. A clear distinction can be made between areas in which the low mud content at the bed surface is explained by the relatively high bed shear stress ('flow-limited') and by the low supply of sediment ('supply-limited'). The presence of mud on the long-term morphological development of the reservoir and the tidal basin gives rise to two opposing observations. On the one hand, the morphological adaptation time scale decreases, due to the extra availability of sediment and the high mud deposition near the head of the basin. On the other hand, the bed level profile in the equilibrium situation is quite similar to the equilibrium bed level profiles for sand only. The occurrence and shape of the deposition patterns of sand and mud in the reservoir have been validated qualitatively by the sediment balances in the Rhine-Meuse estuary (the Netherlands) after the construction of the Haringvliet Sluices (1970). Qualitatively, the bed level and bed composition profile in the equilibrium state of the basin agree well with the observations in the Dutch and German Wadden Sea.

Finally, the Friesche Zeegat (the Netherlands) has been taken as a real-world case to hindcast the morphological response of the system quantitatively for the period 1970 - 1994 after the closure of the Lauwerszee (1969). Starting with a geometry in 1970, the computed net deposition in the deep channels and at the intertidal area of the basin and the net erosion in between agree qualitatively with the observations. Unfortunately, the observed net erosion in the ebb-tidal delta just after the closure and the observed decreasing import rate in the basin are not predicted correctly. These discrepancies are presumably the result of neglecting wavedriven currents in the model set-up and a poor quantitative prediction of the changes in the hypsometry of the basin. The computed distribution of sand and mud in the Friesche Zeegat appears to be realistic. The ebb-tidal delta is dominated by sand, due to the relatively high bed shear stress. In the basin, sand deposition is mainly found at the entrance of the main channel, whereas mud deposition occurs in the deeper parts of the main channel, in the shallow areas near the borders and in particular in the channel near the dike of the Lauwerszee.

Summarising, the present research has resulted in an increased understanding of and greater modelling capabilities for large-scale sand-mud segregation in estuaries and tidal basins. An innovative three-dimensional process-based model for sand and mud has been developed and good qualitative agreement has generally been obtained between model results and field data. In principle, the sand-mud model is applicable to other water systems (e.g. rivers, coastal seas). The model can be used to estimate the effects of human interventions and/or natural changes on the large-scale bed level and the bed composition development in time and space. An important restriction of its applicability is that the bed has to consist of a nearly uniform sand grain size and a mud fraction with a constant clay/silt ratio. Furthermore, the application of the model requires bed level and bed composition data to

verify the model results. Recommendations for future work include a new set of erosion experiments with sand-mud mixtures to improve the erosion formulations, an extension of the analysis of idealised situations by investigating other boundary conditions, geometries and processes, and the application of the model to new realistic cases with abundant bed level and bed composition data.

### **Acknowledgements**

This research has been supported by the Technology Foundation STW, applied division of NWO and the technology programme of the Ministry of Economic Affairs under contract number DCT.4895. The project has also been embedded in the Delft Cluster project DC 03.01.02 "Ecomorphology in estuaries and coasts". Prof dr H.J. de Vriend, dr Z.B. Wang and dr. J.C. Winterwerp are highly acknowledged for the ideas, discussions and comments during this PhD research.

### **Products**

See: <http://www.waterbouw.tudelft.nl/public/ledden/>

Van Ledden, M., Wang, Z.B., Winterwerp, J.C., De Vriend, H.J., accepted. *Sand-mud morphodynamics in a short tidal basin (Abstract)*. Physics of estuaries and Coastal Seas (PECS2002), Hamburg, Germany.

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Van Ledden, M. & Wang, Z.B., 2001. *Sand-mud morphodynamics in an estuary (pdf)*. In: Proceedings 2nd symposium on River, Coastal and Estuarine Morphodynamics Conference, Obihiro, Japan, 505 - 514.

#### Reports:

Van Ledden, M., 2002. *Modelling of sand-mud mixtures. Erosion behaviour and Application to a tidal basin*. WL | DELFT HYDRAULICS (Z2840), The Netherlands. Software, Ph.D thesis

Van Ledden, M., 2001. *Modelling of sand-mud mixtures. Part II: A process-based sand-mud model (pdf)*. WL | Delft Hydraulics (Z2840), The Netherlands.

Van Ledden, M., 2000. *Sediment segregation in estuaries and tidal lagoons, a literature review (pdf)*. Delft University of Technology, The Netherlands

#### PhD thesis

Ledden, van Ledden, 2003, 'Sand-mud segregation in estuaries and tidal basins', Ph-D thesis Delft University of Technology.

#### Other

Delft3D sand-mud module

## 2.3 Analysis of the morphological characteristic of tidal basins

Analysis of the morphological characteristic of tidal basins, in terms of channel patterns and occurrence of intertidal flat, in relation to the general geometric (size of basin), hydrodynamic (e.g. tidal range) and sedimentological (e.g. grain size) conditions. Starting point of the analysis is the result of (linear and non-linear) stability analyses using idealised models. *Participating partners: WL, TUD, UU.*

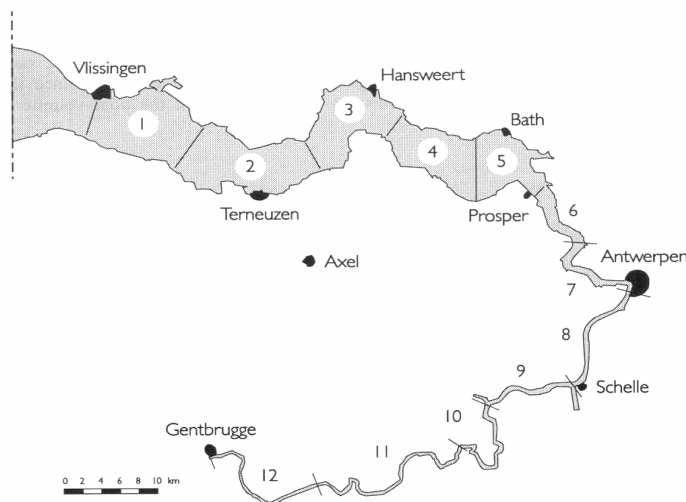
TOWARDS THE DEFINITION OF MEASURING TOOLS FOR THE PHYSICAL CHARACTERIZATION OF DUTCH TIDAL SYSTEMS FROM AN ECOLOGICAL PERSPECTIVE

Alessandra Crosato, Marco Toffolon, Claire Jeuken, Mindert de Vries  
WLI Delft Hydraulics, TU Delft. University of Trento

An estuary or lagoon can be morphologically altered in such a way that the local biology is negatively affected, even though water and sediment are both clean. For management purposes it is thus important to be able to measure the *morphological quality* of a water system, which would allow to quantify the level of damage caused exclusively by physical changes and establish acceptability limits.

Chemical pollution is easily quantifiable and many standards are currently available. Instead, purely *hydro-morphological deterioration* is still difficult to quantify. Chemical pollution has often visible and direct effects on water and organisms, while the effects of morphological changes are slow and not immediately visible. They can manifest themselves after a long period, in the form of alterations in the typical succession stages of salt marshes or as erosion of banks and of intertidal areas. For this reason men have first concentrated their efforts in identifying and treating chemical pollution and only at a later stage have realised the importance of recognising and treating morphological deterioration.

The present study aims at the definition of tools to be used by managers for the assessment of the morphological quality of tidal systems: graphs or tables with thresholds that discriminate different situations. For this purpose it is necessary to identify a number of easily-assessable parameters, which can be used as *quantitative indicators* of the morphological quality, and a reference situation. The link between morphological quality and potentiality for certain ecotopes allows then to set up a tool for the *ecological characterisation* of tidal systems.



The Scheldt estuary from Vlissingen to Gentbrugge, subdivided into 12 sections (after van der Spek, 1994. Large-scale evolution of Holocene tidal basins in the Netherlands, PhD Thesis, University of Utrecht).

The work carried out in 2001 is the result of a joint effort between WL | Delft Hydraulics, TUDelft and University of Trento, in the framework of the Delft Cluster activities, and focused on the morphological characterisation of single sections (macro-scale characterisation) of the Scheldt estuary. The selection of the most promising approaches and especially of the parameters to be used to construct the measuring tools were the core of the work.

## Summary

### *MACRO-SCALE MORFOLOGICAL CHARACTERISATION OF THE WESTERN SCHELDT*

Marco Toffolon

## Introduction

The problem of tidal morphodynamics has not been completely solved yet. In the last decades, great advances have been made in understanding morphological phenomena, especially in the fluvial case, even though there are still some open questions waiting for a solution. Empirical relationships have been explained in a conceptual framework and the underlying dynamics have been clarified. One of the most successful examples (as pointed out by S. Ikeda in the preface of the proceedings of the 2<sup>nd</sup> IAHR Symposium on River, Coastal and Estuarine Morphodynamics, 2001, which collect the state of the art in the field of morphodynamics) is given by the comprehension of the basic mechanisms of meandering in rivers: starting from the first explanations in terms of several factors, now we are able to understand the most relevant aspects and to predict the behaviour of such systems fairly well. On the other hand, empirical relationships in tidal environments (e.g. between tidal prism and cross section area, see O'Brien, 1969 and Jarrett, 1976) are still matter of investigation.

This work does not claim to give an explanation of the questions related to the problems of tidal morphodynamics. It aims to provide a set of *parameters* (i.e. combinations of variables, like velocity, depth, width etc.) able to identify different morphological situations, exploiting the results obtained so far. This is the first step of a long-term project, which finally should result into an ecological characterisation of an estuary.

The local biology of an estuary or lagoon is affected by the morphology: even though the chemical properties of both water and sediments are favourable, the natural environment can be damaged by physical changes. Moreover, they typically occur on a time scale that is slow if compared with the effect of chemical pollution and probably this can explain why such problems have been tackled only in the last few years.

The purpose of the project is to measure the *morphological quality*, providing graphs or tables, based on easily assessable parameters, where threshold lines separate different morphological features (e.g. presence of intertidal areas, islands, single channels etc.) and the related ecological environments. These quantitative indicators should be a useful support for decisions in the management of estuaries.

Actually, the present study has the intermediate goal to determine the most important state variables involved in the problem, without fixing the threshold lines, whose identification is likely to require a stronger effort, both in data analysis and in model formulation.

The definition of controlling parameters presumes that we can grasp the physical mechanisms that drive the evolution of estuarine systems. Unfortunately, this is not completely true, because tidal environments are very complex and, therefore, the most profitable approach to this kind of problem is probably the analysis of data. Of course, a collection of data is not useful itself, but it should be done in the light of a conceptual model. A model is a simplified description of reality and selects few basic aspects of the natural system; looking at its sensitivity with respect to the range of variation of the variables, it is possible to estimate the role of the different factors. Nowadays, although suitable models are not available, we can use partial information to identify a few parameters that certainly play a crucial role in estuarine morphology. In this way it is possible to select the important variables. Data can be compared in space, among different locations, or in time, considering the local evolution of the system.

The present study focuses on the *Western Scheldt estuary*, where radical changes from a situation resembling a river delta to a funnel shaped estuary occurred in the last centuries, strongly affected by human activities; historical comparisons can be made only when considering the last two centuries, after the construction of the major part of the dykes.

### Conclusions

The aim of the study, the morphological characterisation of the Scheldt estuary, has not been completely reached by the present analysis, due to the lack of both data and theories suitable to handle such a kind of complex environment. However, several indications have been found about the importance of different physical factors, which have been quantified using dimensionless parameters.

The selection of the most relevant parameters arises from the choice of the suitable variables to measure the physical characteristics of the morphological elements. The variables have been grouped into a restricted number of parameters, chosen among those used by available theoretical models. The parameters have been further selected on the basis of their role in the morphological evolution, their range of variation inside the estuary and the feasibility of their measurement.

In particular, ratios between geometrical variables (width, depth, tidal range etc.) have been considered for their significance and because they are easily evaluated using bathymetric data and other accessible information. The definitions proposed refer mainly to macro-scale averaged lengths. It is worthwhile to note that their definition is not univocal and depends on the scale and the phenomena that we are studying.

The analysis of the available data of the Scheldt estuary allows to recognize three morphological zones using:

1. the ratio between wetted planimetric surfaces at high and low water level during the tidal cycle,
2. the ratio between the tidal range and the depth,
3. the aspect ratio of the estuarine section (ratio between width and depth).

Three clusters of these parameters can be, corresponding to a qualitative subdivision into multiple-channel, two-channel and single-channel systems. This subdivision had been proposed also independently.

The definition of the thresholds among these zones is not achievable by means of the analysis of data of a single estuary, because also several other factors are supposed to play a role, and their importance is assessable only when a comparison among different cases is made. Indeed, the number of degrees of freedom of the analysis cannot be much larger than the number of estuaries considered: if we want to investigate the role of several parameters, we must study a wider range of their variation.

Besides, also the mega-scale classification of the estuaries is crucial for the macro-scale characterisation. The mega-scale classification is based also on other parameters, those affecting the longer-time evolution, thus the results of the present analysis are valid only for a given type, namely the macro-tidal estuary.

Theoretical models are able to give some indications about the most important factors, even though they are quite simplified and cannot tackle the complexity of the real configurations. As found in previous analogous analyses about river morphology (Schoor et al., 1999, and Middelkoop et al., 2001), the main controlling parameter seems to be the aspect ratio, which is related also with the number of channels in the cross section. Indeed, if we consider both the sensitivity of the models to the parameters and the range of their variation along the estuary, the macro-scale ratio between width and depth (aspect ratio) results to be the fundamental factor characterizing the morphology of the estuarine section.

Another relevant remark concerns the importance of a proper evaluation of the friction factor and hence of the bottom shear stress, especially in the dimensionless form of the Shields number. This parameter has been used also in the fluvial characterisation, for example by Schoor et al. (1999).

The most important new element, typical of tidal embayment, is the variation of the water level due to the propagation of the tidal wave. The ratio between tidal range and averaged depth seems to be meaningful with respect to the presence of intertidal areas, in combination with the number of channels of the estuarine section, which is probably related to the aspect ratio.

Besides, the phase lag between discharge and water level can introduce a morphological asymmetry during the tidal cycle, shifting the bed-forming conditions from the mean water level (and the corresponding aspect ratio) towards the ebb or flood phases, when the aspect ratio can vary. The role of this parameter is currently investigated by the author.

The tidal asymmetry, which has been showed to control the mega-scale evolution (for a short discussion, is not as crucial in the macro-scale characterisation as the previous parameters, at least in the author's opinion. For a more sound evaluation, comparisons between estuaries with a different residual effect are necessary.

The sediment composition can be an important factor as well, but its variation inside the Scheldt estuary and the lack of models dealing with cohesive sediments does not allow to fully recognize its role.

### **Limitations of the analysis**

As pointed out in the previous chapters, at present we do not have any theory able to predict the overall behaviour of tidal environments. The main limitations are:

almost all the theoretical models are linear and can handle only a configuration of the bed that is slightly different from a schematic single channel;

numerical models can be used to estimate the evolution of the system only for relatively short times, because several uncertainties arise when considering long simulations (tens or hundreds of years);

suitable idealised models to describe tidal morphological cells are not available yet.

Furthermore, it is not always easy to separate the scales of the problems, i.e. to distinguish the macro-scale from the upper (mega-scale) and lower (meso-scale) scales. Tidal systems are typically different from rivers and concentrate a large variation of length scales in a limited space: lagoons are extreme examples of hydrographic networks concentrated in few tens of kilometres, with a fast transition between large channels and drainage gulleys. Even if the characteristic length of an estuary is larger, relevant feedback mechanisms occur between the mega- and the meso-scale evolution, on a time scale that is probably similar to the scale of evolution typical of the macro-scale morphological elements. In this way, separate macro-scale features are determinable with difficulty.

Finally, the role of vegetation on the morphological evolution of tidal environments is not clear yet. This topic should be investigated with the combined effort of morphologists, biologists and ecologists, since the feedback mechanisms between the biotic and abiotic components are supposed to be strong.

### **Suggestions for future research**

The major suggestion for future research arises from the limitations encountered in the present analysis. Some of the improvements needed by the models will be reached in a short time, and have been discussed in the previous sections. In particular, in the author's opinion, the development of a model able to handle morphological cells with channels and shoals, and capable to assess the residual effects, is desirable and necessary.

A further suggestion which is not related to the theoretical aspects of the analysis, but to the practical management of the information, is to share the existing database of the Western Scheldt estuary, for example on a web site open to the public, and to try to merge it with the data of the Belgian part of the estuary. Many researches are working on this subject and the possibility to have access to such a tool would be broadly appreciated.

### **products**

1. Toffolon, M., 2002, '*Macro-scale morfological characterisation of the Western Scheldt*', Report TUDelft, scientific paper is in preparation.
2. WL | Delft Hydraulics report Z2941
3. H.M. Schuttelaars<sup>1</sup>, J.G. Bonekamp<sup>3</sup>, and J.A. Roelvink<sup>4</sup>, 2003, 'ROLE OF TIDES IN GENERATING DOWNDRIFT-ORIENTED CHANNELS ON EBBTIDAL DELTAS', Coastal sediments 2003
4. Z.B. Wang<sup>a,b\*</sup>, C. Jeuken<sup>a</sup>, H. Gerritsen<sup>a</sup>, H.J. de Vriend<sup>a,b</sup>, B.A. Kornman, 2002, '*Morphology and asymmetry of the vertical tide in the Westerschelde estuary*', Continental Shelf Research 22 (2002), 2599-2609. Available online at [www.sciencedirect.com](http://www.sciencedirect.com)

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## Abstracts

### ROLE OF TIDES IN GENERATING DOWNDRIFT-ORIENTED CHANNELS ON EBBTIDAL DELTAS

H.M. Schuttelaars<sup>1,2</sup>, J.G. Bonekamp<sup>3</sup>, and J.A. Roelvink<sup>4</sup>

The influence of tides on the orientation of channels on ebb-tidal deltas is investigated using the state-of-the-art numerical model Delft3D-MOR in a highly schematized geometry. The water motion is described by the depth-averaged shallow water equations. It is forced with a limited number of tidal constituents at boundaries far away from the inlet. Due to the interaction of the water motion and the erodible bed, tidally averaged sediment fluxes occur which result in bedform changes. The sediment transport is modeled using a total load formula. The resulting bathymetry resembles that of an ebb-tidal delta. If the sea surface is forced with a semi-diurnal (M2) constituent only, the main channel on the ebb-tidal delta is always oriented

downdrift with respect to the direction of propagation of the M2 tidal wave. When forcing the sea surface with both an M2 and mean component, both channel orientations are observed: if the difference in mean sea surface level is positive over the inlet, the resulting channel will be updrift oriented. A negative difference of mean sea surface level results in a downdrift-oriented channel. The apparent relation between channel orientation and difference in mean sea surface level over the inlet seems to be supported by an analysis of quasi-realistic simulations of tidal motion in the Dutch Wadden Sea.

### Morphology and asymmetry of the vertical tide in the Westerschelde estuary

Z.B. Wang<sup>a,b\*</sup>, C. Jeuken<sup>a</sup>, H. Gerritsen<sup>a</sup>, H.J. de Vriend<sup>a,b</sup>, B.A. Kornman<sup>c</sup>

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

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## 2.4 Analysis of morphological development on the scale of tidal basins in relation to sea level rise.

The Lauwerszee, a small estuary in the northern Netherlands, gradually formed after 0 AD. By 1000 AD it had reached its widest extension. The landward part comprised of extensive tidal flats and salt marshes, that were partially embanked since then. In 1967 the landward part of the estuary was dammed off, creating a freshwater lake on the landward side of the dam and a predominantly sandy tidal-flat area on the seaward side. The former tidal inlet and large tidal channels of this estuary and of its many precursors, are known from detailed seismic surveys in the area. Interpretation of additional seismics and integration of recently acquired radiocarbon datings into the reconstruction of the evolution of the estuary will refine the evolutionary model of this type of estuaries. This model will be published in the international literature. *Participating partners: TNO-NITG, TNO-MEP.*

### Summary

LONG-TERM EVOLUTION OF A SMALL ESTUARY: THE LAUWERSZEE (NORTHERN NETHERLANDS)

S. van Heteren en A.J.F. van der Spek

### Introduction

The Lauwerszee, a small estuary in the northern Netherlands, formed gradually after 0 AD. Roughly 1000 yr later, it had reached its largest extent. The landward part of the estuary consisted of extensive tidal flats and salt marshes, most of which have been embanked since then. In 1967, part of the estuary was separated from the Wadden Sea by a dam, creating a freshwater lake on the landward side of the dam and a predominantly sandy tidal-flat area on its seaward side.

The development of the Lauwerszee estuary is linked to the behavior of tidal-inlet-related channel systems and to human activities. The former tidal inlet and major tidal channels of this estuary and its many precursors are known from detailed seismic surveys in the area. Integration of these seismic data with reconstructions of the changing estuary will increase our understanding of the factors governing estuarine development.

Within the framework of Delft Cluster project "Salt-Marsh Cycles", this type of analysis is important, as it sheds light on processes and parameters determining the formation, expansion, and decay of salt marshes. Here, we analyze spatial and temporal changes to the salt-marsh zone fringing the Lauwerszee estuary and adjacent coastal areas, and explain the decay and increasingly static nature of this zone since the Middle Ages using a simple model.

### Conclusions

The development of the Lauwerszee estuary is linked to the behavior of tidal-inlet-related channel systems and to human activities.

At present, low sand flats dominate the Wadden Sea. All that remains from the once expansive salt marshes are narrow fringes on the landward side of the tidal basins, and

coastal peat bogs have disappeared altogether. Reclamation of salt marshes and cultivation of peatland are the cause.

An early salt-marsh area in the Lauwerszee area was aeroded following the breach that formed the Lauwers-system during the 8<sup>th</sup> or 9<sup>th</sup> century, and was probably linked to extensive peat excavation by a rapidly increasing local population between 700 and 900 AD. As a result, accommodation space increased and the erosion-resistant clay layer protecting the peat was disturbed. Water entering the area during storm surges could easily erode peat that was no longer protected by a clay layer. The Lauwers-system probably reached its maximum size at about 1000 AD.

In subsequent centuries, the area submerged during the Lauwers breach was reclaimed by dike construction. At about 1500 AD, most of the salt-marsh area had been changed into a polder landscape. Until that time, conditions favorable to salt-marsh development were met in many areas, resulting in extensive and highly dynamic areas occupied by salt marshes in various stages of development (pioneer zone, low marsh, high marsh). The construction of dikes eliminated extensive salt-marsh-dominated areas from the coastal system. Existing salt marshes could commonly survive on the seaward side of these dikes by keeping up with sea-level rise, but they could hardly expand in a seaward direction, as high mud flats disappeared and the transition between the marshes and adjacent sand flats became increasingly steep.

On seismic profiles, four sub-recent, deeply incised channel systems can be distinguished. These channel systems are probably associated with former tidal inlets. The mobility and limited life spans of these systems undoubtedly affected the adjacent coastal salt marshes, with erosion occurring near newly formed channels and salt-marsh expansion in areas marked by a reduction in energy conditions.

## Products

S. van Heteren A.J.F. van der Spek, 2003, '*Long-term evolution of a small estuary: the Lauwerszee (northern Netherlands)*', TNO-report 005.31036

## 2.5 Interaction between channels and intertidal areas.

Fundamental research on processes and mechanisms responsible for the sediment exchange between channels and intertidal flats will be investigated within the framework of the ongoing PhD research. *Participating partners: TuD, ALTERRA.*

## Summary

Willem van der Duim en Norbert Dankers (Alterra)

A database of Alterra sedimentbudget studies from five different salt marshes in the Netherlands was made and sent to Delft Hydraulics for further use (validation/calibration of model).

In the years 1979-1996 measurements were done in:

1. The Dollard (Groningen, northeast coast)

2. The Slufter (Texel)
3. Neerlands Reid (Ameland)
4. Schor van Waarde (Western Scheldt Zeeland, southwest coast)
5. Peazemerlannen (Friesland, north coast).

Location	Period	Low tides	Sub marsh tides	Over marsh tides	Storm tides	Total
<i>Dollard</i>	1979-1980	5	10	4	4	23
<i>The Slufter</i>	1991-1992	5	12	0	1	18
<i>Neerlands Reid</i>	1993-1994	2	20	1	0	23
<i>Schor van Waarde</i>	1993-1994	7	11	0	0	18
<i>Peazemerlannen</i>	1994-1996	1	10	4	1	16

For the model it was important that the water level (m+NAP) and water current velocities (m/s) (and if possible the amount of suspended sediment in mg/l) were measured during several tides.

Depending on the location measurements were done every 30 minutes (Dollard en Slufter), every 5 minutes (Neerlands Reid and Waarde) or every minute (Peazemerlannen). Data from the creek profiles are also available.

➤ Contribution to Salt Marsh Cycles:

Production of a database and background information to be used for modelling purposes.

## Products

Alterra – Database on sedimentbudget studies; This data is not public (yet) but may be used for modelling purposes after consultation with Alterra.

## 2.6 Analysis of a large data-set collected by Rijkswaterstaat

Analysis of a large data-set collected by Rijkswaterstaat on the sedimentation, erosion, sediment composition and macrobenthic community composition in the Westerschelde. This data set consists of a number of transects across intertidal flats, some of which are situated in front of saltmarshes, whereas others are situated within the estuary. The analysis of this data set will investigate whether the seasonal accumulation of silt on intertidal flats (e.g. observed at the Molenplaat - Herman et al., in press) is a generally observed phenomenon. We want to investigate whether this process could be responsible for the pronounced seasonal cycle in suspended matter concentrations (more than a factor two difference between winter and summer in the Westerschelde). Moreover, we want to investigate a possible relation between the remobilisation of mud from the intertidal flats and the winter peak in sedimentation rates on salt marshes. Results of this investigation will be used to model the (possible) role of intertidal flat processes (which are documented to be considerably influenced by faunal activities) and the accretion rate of salt marshes. *Participating partners: NIOO, RIKZ.*

## Interaction between benthos, hydrodynamics and sediment structure

We studied the interaction between benthos, hydrodynamics and sediment structure at two different spatial scales. At the scale of the estuary, we used existing large datasets of Rijkswaterstaat to analyse the degree to which benthic animals correlate with spatial and temporal dynamics of sediment characteristics. This analysis is based on long-term (7 year) monitoring of a large number of transects in the Westerschelde. Monthly measurements of elevation along the transects, yearly measurement of sediment composition and half-yearly sampling of macrobenthos at the same sites were combined in the analysis.

At the scale of a single tidal flat, we analysed the spatial structure of macrobenthos data in relation with the important environmental factors. The question is how important spatial autocorrelation in the data is for the analysis. We demonstrate that trend in the environment at a scale > 100m is the most important factor explaining occurrence of macrobenthic populations. At smaller scales, there is probably influence of biological interactions. This cannot be related (at least with present data) to morphology or structure of the sediment bed.

### products

Scientific papers

- 1 Spatial and temporal variation in macrobenthic species and assemblages in an estuarine, intertidal soft sediment environment. (published in shortened form, here reported as internal report) **Tom Ysebaert\*** & **Peter M.J. Herman**
- 2 Spatial variability in soft-sediment benthic macrofauna: controlling factors at the scale of a tidal flat. (submitted) **Tom Ysebaert<sup>1\*</sup>**, **Peter M.J. Herman<sup>1</sup>**, **Judi E. Hewitt<sup>2</sup>** & **Simon F. Thrush<sup>2</sup>**

### Abstracts

SPATIAL AND TEMPORAL VARIATION IN MACROBENTHIC SPECIES AND ASSEMBLAGES IN AN ESTUARINE, INTERTIDAL SOFT SEDIMENT ENVIRONMENT.

Tom Ysebaert & Peter M.J. Herman  
Netherlands Institute of Ecology (NIOO-KNAW).

A hierarchical approach was used to reveal macrobenthic distribution and abundance/biomass patterns at different spatio-temporal scales in an estuarine, intertidal soft-sediment environment in the Schelde estuary, The Netherlands. Yearly, hierarchically scaled surveys were conducted in the study area in the period 1994-2000, covering four different spatial scales: region ( $10^4$  m), transect ( $10^3$  m), station ( $10^2$  m), and replicate samples ( $10^1$  m).

We used univariate ANOVA-based analyses for the dominant species, and multivariate analyses of the assemblage. We also confronted a variance-decomposition approach with regression-based models describing the dependence of assemblage patterns on environmental variables. Our approach also explicitly addressed the problem of interacting spatial and temporal variation.

Regional and transect differences were only apparent for a few dominant species, although for the assemblages as a whole inter-regional differences were clear. In the case of temporal

variation between years, there were a number of dominant species showing significant synchronicity in temporal development between stations. For most species variations at the scale of stations, and year\*station interactions were the most important components of variability. A substantial part of the total variation, both in density of individual species and in composition of the assemblage (as revealed in the multivariate studies) was explained by the observed environmental variables. In this dependence on environmental variables, a large difference between the spatial and temporal component of variation in the environment was observed. Subdivision of the environmental variables into a long-term average and a temporal component always showed that the long-term averages were much more important than the short-term deviations from this average.

Some implications for the design of monitoring programmes are being discussed.

#### SPATIAL VARIABILITY IN SOFT-SEDIMENT BENTHIC MACROFAUNA: CONTROLLING FACTORS AT THE SCALE OF A TIDAL FLAT

**Tom Ysebaert<sup>1\*</sup>, Peter M.J. Herman<sup>1</sup>, Judi E. Hewitt<sup>2</sup> & Simon F. Thrush<sup>2</sup>**

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We explored the use of a spatial, geostatistical analysis approach to predict the distribution of species abundance data as a response to environmental variables by combining estimates of the large-scale pattern and local deviations from this pattern estimated by median polish kriging. We focus on spatial patterns of benthic macrofauna within a single tidal flat of 1.5 km<sup>2</sup> (Schelde estuary, The Netherlands). The survey encompassed 92 sampling stations on a rectangular grid, with a node spacing of ca. 120 m. The results were generalized by comparison with results from an intertidal flat in Manukau Harbour (New Zealand). The form of spatial pattern of both environmental variables (bed shear stress, bathymetry, mud content, etc.) and several macrobenthic species (with different feeding modes and settlement mechanisms) was investigated using a combination of autocorrelograms and variograms, kriging and mapping. As anisotropy and non-stationarity of the variables was obvious, we used an interpolation method based on a decomposition of the data into large- and small-scale variation (median polishing kriging). Large-scale variation (systematic trends across the study site) was the dominant spatial structure in patterns of abundance in both estuaries, with at least twice as much variance attributable to it than to small-scale spatial structure, suggesting that over such scales small-scale autocorrelation will not interfere with our ability to determine relationships. Regression models revealed strong correlations between species distributions and the environment for both tidal flats, although stronger regressions were obtained for the Schelde data. Taking into account the spatial structure of the data only slightly improved the modeling results for the Schelde data. Improvement was higher for the Manukau data where non-spatially structured variance was high. Results of our geostatistical technique on the Manukau data were also generally comparable with results obtained by Legendre et al. (1997) who incorporated space as a polynomial surface in multiple regression. However, the geostatistical technique generally explained more

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variability and allowed us to separate the variability due to spatial structure of the dependent variable from that of the environmental variables.

## 3 Morphological development of salt marshes.

### 3.1 Analysis of development of size, shape and locations of the channels on salt marshes.

Field observations suggest that the channels are often eroding at the one side and accreting at the other. On the other hand, long-term data seem to suggest that the locations of the channels are more or less fixed. *Participating partners: ALTERRA.*

#### Summary

ANALYSIS OF DEVELOPMENT OF SIZE, SHAPE AND LOCATIONS OF THE CHANNELS ON SALT MARSHES. MEASUREMENTS IN THE WADDEN, 'KREKENPROEF'

Willem van der Duim, Alterra

Compared to natural salt marshes the creek system of the man-made salt marshes of the salt marsh works along the Wadden Sea coast of Groningen and Friesland is over-sized. The management policy for these salt marshes is increasing the naturalness. In an experiment, the "Krekenproef", adaptations were made to the drainage system in order to reduce the total length of the ditches and to improve the naturalness. The adaptations that were tested in different parts of the salt marsh were: reducing the small ditches with 50%, improving the dichotomous structure by damming of main ditches or connecting ditches, digging new diagonal ditches ('fish-bone'-pattern) and emphasizing the drainage through the main ditches.

Together with the departement of Civil Works (Rijkswaterstaat) the changes in vegetation, soil level, sedimentation and the development of the creek system were measured. After four years the effects and effectiveness of the adaptations to the drainage system were evaluated.

The main conclusions are:

- None of the tested adaptations scored clearly the best,
- No loss of salt marsh was recorded nor pools of stagnant water due to bad drainage,
- On the bare mudflat and in the pioneer zone the applied changes to the creek system silted up very quickly. Blocking main creeks was not very successful because they were very susceptible to erosion. Combining creeks and the 'fishbone'-pattern were successful on the vegetated parts,
- Many of the low-lying ditches (< 1.4 m +NAP) silted up (partially). Usually the cross section area was rather low at the start of the experiment (<<0,5 m<sup>2</sup>) or they were overdimensioned at the start. The silting up of these ditches did not influence the drainage or vegetation in a negative way so far,
- From a soil level of ca. 1,4 m+NAP the ditches didn't silt up fully, but a small meandering gully remained in the part of the ditch with the highest water current,
- From a soil level of ca. 1,6 m+NAP the ditches hardly changed compared to the start of the experiment,

- The sedimentation was very high (up to 6 cm/y). This was partly caused by the fact that sedimentation was measured near ditches. However, other salt marshes (e.g. Neerlands Reid on Ameland) showed a same high sedimentation over the same period,
- The spread of *Puccinellia maritima* was very fast due to the high sedimentation in and near the ditches. Whether the silting up of (part of ) the ditches will inhibit the drainage can't be predicted at this moment,
- The total area of salt marsh extended while the pioneer zone was reduced (succession). The total area of pre-pioneer zone was reduced while the area bare mudflat extended (regression) and the salt marsh area extended (succession).
- A fast vegetation succession from *Salicornia spec* to *Puccinellia maritima* and from *Puccinellia maritima* to *Elymus athericus* was observed.

➤ Contribution to Salt Marsh Cycles:

Knowledge about the morphological development of salt marshes; the collected data on creek profiles may be of use in a model to be developed by Delft Hydraulics.

## Products

Management directed report (in dutch) of the matching project "De Krekenproef" January 2003, in Dutch. Duin, W.E. van & KS. Dijkema: . *Proef met de onderhoudsarme ontwatering in de kwelderwerken: 'De Krekenproef'; Evaluatie 1997-2002* Gepubliceerd in 2003; 138 pp

This report can be found on the Alterra website: [www.alterra.nl](http://www.alterra.nl). (go to publicaties en producten, rapporten, zoek rapport, rapportnr. 634)

## 3.2 Theoretical analysis on the stability of channels on salt marshes

There is field evidence that an initially too wide (man-made) channel on a salt marsh will disappear due to sedimentation, whereas a narrower channel can persist or even erode. Apparently there is a critical size of a stable channel. With the help of the results of 2a a theoretical analysis on this phenomenon will be carried out, in order to increase the insight into the morphology of the channels. *Participating partners: WL, ALTERRA.*

### Product

Wang Z.B., 2003, 'Channels on mud flats and creeks on salt marshes' WLDelft Hydraulics reportnr. Z2827.60, Paper is in preparation.

### Summary

CHANNELS ON MUD FLATS AND CREEKS ON SALT MARSHES

Zheng Bing Wang (WLDelft Hydraulics)

#### introduction

Salt marshes can originate from a mud flat when the flat becomes sufficiently high and vegetated. Vegetation on a marsh stimulate sedimentation. So whether or not a mud flat can become a salt marsh will strongly depend on whether or not pioneer vegetation can survive. Once the pioneer vegetation survive the sedimentation accelerates and more vegetation will

grow, and eventually a salt marsh will develop. A vital condition for the pioneer vegetation to survive is sufficient drainage on the mud flat. Drainage of the higher part of the mud flat strongly depends on the channels on it. Therefore artificial channels are created on the mud flat in the Wadden Sea in order to stimulate the formation of salt marshes. In such areas it is observed that some channels can maintain it self whereas other channels disappear after oneseason due to sedimentation.

The present study is directly inspired by the studies to the artificial salt marshes in the Wadden Sea (Reents, 1995, Van Duin and Dijkema, 2003), especially the comparison of these marshes to the natural salt marshes. The man-made channels in these artificial marshes, especially the smaller (higher order) ones, need to be dredged for the maintenance. This is in contrast to the creeks in the natural salt marshes, which usually can be maintained themselves by the flow through it. Observations also suggest that deeper channels can often be maintained and shallower channels often disappear.

### **objective**

The objective of the analysis carried out in this study is to obtain more understanding of the behaviour creeks / channels in (natural as well as artificial) salt marshes and on mud flats. It will be investigated if the observations made in the salt marshes concerning the creeks / channels can be explained theoretically. It will also be investigated which are the factors influencing the behaviours of channels in salt marshes and on mud flats.

### **Conclusions**

The theoretical analysis shows that a stable channel on a mud flat requires two necessary conditions:

1. The mud flat must be sufficiently large in order to generate sufficiently large tidal flow velocity.
2. The depth of the channel has to exceed a critical value which depends on the density of the channels.

The critical value of the channel depth increases rapidly with decreasing density of the channels. This has the consequence that only relatively small channels with relatively high densities (closely located to each other) can possibly be formed on mud flats, because the required disturbance for developing a larger channel is too large to occur under natural circumstances.

Based on the results of the stability analysis it is concluded that the most important factor influencing the behaviour of the creeks / channels on salt marshes the tidal prism. A sufficient large tidal prism is required for a creek / channel to maintain itself. Both the density of the creeks / channels and their depth have influence on the tidal prism. The too high density of especially the smallest channels in the artificial salt marshes in the Wadden Sea compared tot that of the highest order creeks in natural salt marshes has the consequence that the tidal prism per channel become too small to maintain the channels. A relatively deeper channel attracts relatively more flow than a shallower one next too it making the tidal prism through it larger. This explains why a deeper channel can better be maintained than a shallower one.

### 3.3 Conceptual modelling

A theoretical investigation will be carried out to analyse which are the conditions for cyclic development to occur. The investigation should identify the most important processes determining large-scale salt-marsh changes. The results should provide a basis for directing the implementation of the appropriate mechanisms into predictive models. The theoretical investigation will be based on relatively simple models that will be implemented in a vertical cross-section of an estuary. They will describe growth of the vegetation in conjunction with deposition/erosion of sediment, using formulations that will, initially, be kept as simple and qualitative as possible. In different steps, the formulations will be extended to express more details in the dynamics of vegetation growth and erosion/deposition processes; the importance of these mechanisms for the dynamics of the system will be investigated. The aim of the analysis is to derive the most parsimonious system of equations capable of describing the essence of salt marsh development in time. Use will be made of an existing database on vegetation structure of salt marshes in Zeeland, in order to provide empirical evidence for the temporal evolution (succession) of salt marshes, as well as for the medium and long-term reaction of salt marsh vegetation to changes in the physical forcing (e.g. Oosterschelde: change in tidal amplitude; Westerschelde: change in mean sea level, change in tidal amplitude). *Participating partners: IHE, NIOO.*

#### Summary

##### COMPLEXITY IN SALT MARSHES

Johan van de Koppel (IHE, NIOO-CEME)

A spatially explicit, 1D model of the interaction of the growth of salt-marsh vegetation and silt accumulation has been developed. For more details the reader is referred to the abstract below.

##### Relevance to the stakeholders

The model shows the occurrence of simultaneous cliff erosion and regrowth of vegetation before the cliff. This suggests that, in the model, salt marsh de/regeneration is an autogenous process, and is not necessarily the result of changed external conditions. Hence, erosion found in salt marshes does not necessarily require remediation action, as it is possible the results of natural development processes within salt marshes.

An indicator of natural developments is regrowth of the vegetation in front of the eroding salt marsh cliff.

#### products

1. Koppel van de, Johan, Wal van der, Daphne, Bakker, Jan P., and Herman, Petr M.J., 2003, '*Self-organization and criticality in salt marsh ecosystems explained by positive feedback*' (working title), paper in preparation
2. Computer code (Matlab based)
3. A short movie is supplied that illustrates the development of a salt-marsh, as predicted by the conceptual mathematical model. This movie shows that the model described in

the paper/report is able to describe the complete development and retrogression of the salt marsh, based on a feedback between plant growth and sedimentation.

4. A meta-database.

Data on the height of the clay layer along the salt-marsh developmental gradient was compiled and classified by age. For a full description of the data and the methods of sampling, see Van de Koppel et al in this report.

## Abstracts

*'SELF-ORGANIZATION AND CRITICALITY IN SALT MARSH ECOSYSTEMS EXPLAINED BY POSITIVE FEEDBACK'* (working title)

Koppel van de, Johan<sup>1,2</sup>, Wal van der, Daphne<sup>2</sup>, Bakker, Jan P.<sup>3</sup> and Herman, Peter M.J.<sup>2</sup>, (1: IHE, 2: NIOO-CEME, 3:RUG)

A spatially explicit, 1D model of the interaction of the growth of salt-marsh vegetation and silt accumulation has been developed. This model is able to simulate, in an abstract manner, the basic development of a salt marsh. The analysis indicates that, in undisturbed situations, a salt-marsh develops increasingly steep slope which stabilizes before a cliff is formed. Disturbances may trigger the formation of a cliff. This cliff initiates a strong retrogression of the entire salt marsh, until regrowth in front of the cliff arrests further erosion. The newly formed salt marsh again develops a steep slope, repeating the evolution described above.

Validations of the concept put forward by the model were based on case studies on salt-marsh development. We used a data set consisting of 30 transects along the natural developmental gradient on the salt marsh of Schiermonnikoog to show that the seaward edge of the salt marsh becomes increasingly steep, as is predicted by the model. This agrees with studies on other salt-marshes (often anecdotal), reported in the literature.

GIS analysis of aerial images of the salt marshes found at Paulinapolder in the Westerschelde revealed that, conform the model predictions, erosion and regeneration of salt marsh may occur simultaneously.

## 4 Interaction between vegetation and morphology of salt marshes

### 4.1 Physical-mathematical formulations for the influences of biological / ecological processes on hydrodynamics, sediment transport and geo-morphological development.

Physical-mathematical formulations for the influences of biological / ecological processes on hydrodynamics, sediment transport and geo-morphological development. Emphasis will be put on the influence of vegetation. Fundamental process research will be carried out on the influence of vegetation on turbulence, bed shear stress, flow resistance, and deposition of sediment. The present study will focus on quantitative formulations which can readily be used in numerical models, based on the available qualitative knowledge. An in-depth literature survey will be a part of this task. *Participating partners: WL, ALTERRA, NIOO.*

#### Products

Crosato, A., Táncoz, I, de Vries M, Wang, Z.B., (2002), '*Quantification of biogeomorphological Variables for Dutch Tidal systems*', WL Delft Hydraulics Report no. Z2837/z2827,. Pdf-file is available at the project website.

#### Summary

QUANTIFICATION OF BIOGEORMORPHOLOGICAL VARIABLES FOR DUTCH TIDAL SYSTEMS

A. Crosato, I. Táncoz, M. de Vries and Z.B. Wang

In recent years biological components have been recognised as potential important factors for the morphodynamic behaviour of estuarine systems. Studies like INTRMUD, ECOFLAT and wood (2000) point in that direction. However, for a large part the magnitude of these effects including the associated spatial and temporal scales are not yet known. One way to assess the size and reach of the impact of biota is to incorporate them in a morphodynamic model. To do this an assessment of the state-of-the-art on the quantifications of biogeomorphological interactions in estuarine systems has been made.

The implementation of biological components into the morphodynamic modelling package Delft3D is one of the goals of the projects "Salt marsh cycles" (Z2827), and "Quantification Biomorphological Variables Westerschelde" (Z2837). The first project is done within the framework of the Delft Cluster research while the latter is part of the 'doelfinancierings-programme' of Delft Hydraulics and RIKZ.

Incorporating biota in a morphodynamic model requires input of both biologists and morphologists. An important aspect therefor is an exchange of knowledge. An important

goal of this report is to provide an introduction into each others specialisms for experts in both fields. In Chapter 2 an overview is given of the biological components of Dutch estuarine systems while in Chapter 3 some aspects of morphodynamic modelling are discussed. In this Chapter also a short introduction of the Delft3D modelling package is given. A more comprehensive description can be found in Appendix D. Next an overview is given of the state-of-the-art in the research into bio-geomorphological interactions. This entails the results of a literature study and of an account of the 'inhouse' experience of Delft Hydraulics.

The literature study focused on the quantification of the biological impact on the morphodynamic processes of estuaries, considering all the typical biological components of the Dutch intertidal areas, from salt marsh vegetation to zoobenthos. Papers and reports were selected on the basis of their usefulness for quantifications. General descriptions of the biological components and qualitative analyses were thus disregarded, unless of particular relevance for other aspects of the study, such as the model schematisation.

## 4.2 Process-based small scale modelling research

The results of task 3a (or part of it) will be implemented in e.g. a research version of Delft3D. The modified software will be used to do modelling research for a schematised basin of a main channel of a salt marsh, in order to identify the relevance of various processes and mechanisms for the generation-development-disappearance cycle of salt marshes. *Participating partners: WL.*

### Summary

#### MODELLING THE INTERACTION BETWEEN VEGETATION AND HYDRODYNAMICS

M. de Vries (WL), I. Tánzos (WL), A. Karanxha (IHE), A. Luijendijk (WL), R. Uittenbogaard (WL), A. Mol (UT), L. Kusters (TUD), I. Moeller (University of Cambridge)

In the latter years WL | Delft Hydraulics has, in collaboration with other institutes, conducted a number of studies on the subject of the interaction between vegetation and morphology. Next to Delft Cluster this work has been done within the framework of the 'doelsubsidie', the European fifth Framework project DELOS and the english contract research project ESTPROC.

If one is primarily interested in the effects of macrophytes on the mean velocity and water levels of, for example, a river reach a 2D-approach is sufficient. In that case the effects of vegetation can be simply incorporated in the bottom roughness, represented by, for instance, the Chézy-coefficient. The disadvantage of this approach for a three-dimensional computation is that the extra resistance introduced to reproduce the effects of vegetation would negatively affect the modelling of the cells close to the bottom. Moreover, the increased bottom roughness appears in the sediment transport calculations too. These are based on the assumption that the bottom consists of sediment only and consequently an increased bottom roughness may result in an overestimation of the transported sediment.

To study the impact of biota on the estuarine morphodynamics it is necessary to model salt marsh processes accurately and therefore the sediment transport should be simulated as

good as possible. This means that the described 2D-approach is, for the purpose of this study, not sufficient. The choice is therefore that of implementing a routine to incorporate vegetation in the three-dimensional model Delft3D, instead. This is obtained by adapting the vertical flow distribution and turbulence according to an already tested 1DV-model approach.

### *Effects on waves*

Next to the effects on flow velocity and turbulent mixing, vegetation causes wave damping and general energy dissipation (Tánczos and Cornelisse, 1999, Verheij et al. 1994 and 1995). The module Delft-3D-WAVE computes wave height and wave energy spectrum for every grid-cell. Energy dissipation is obtained by adding the bottom dissipation due to the combination of orbital flow and currents to the dissipation due to wave breaking. An approach has been developed to adapt the Collins Friction factor such that it accounts for the effect of vegetation on waves.

### **products**

1. Arjan Mol, 2003, '*Wave Attenuation by Vegetation*', WLIDelft Hydraulics Rapportnr Z3040, 'stageverslag' UT. This report will be reorganised to be submitted as a paper to a scientific paper. (see also 6.2)
2. Andi Karanxha, 2002, '*On the interaction between vegetation-flow-sediment transport and morphology*', M.sc. Thesis, IHE.
3. Kusters, L., Msc Thesis Linda, in prep
4. Roelvink, J.A., Duin, M.J.P., and De Vries, M.B., 2002, DELOS; *Improved morphodynamic modelling and application to cases*, Rapportnr Z2937, DELOS deliverable 27, 42. Also look at [www.delos.unibo.it](http://www.delos.unibo.it)
5. Kusters, L., 2003, Data report, Paulinaschor
6. Turner, R., Möller, I. and Spencer, T., 2003, *Application of SWAN-model to vegetated surfaces*, CCRU. This report is based on a collaborative workshop that took place from February 24<sup>th</sup> to March 7<sup>th</sup> 2003 at WLI Delft Hydraulics, Delft, Netherlands, as part of the EA/DEFRA funded project. (see also 6.2)
7. I.C. Tánczos, A. Crosato and M. de Vries' '*Micro scale modelling and practical issues*', RipFor Workshop, Trento 20-22 February, 2003
8. Adaption to the Delft3D-ONLINE SED module to include the effect of vegetation,

### **Abstracts**

#### WAVE ATTENUATION BY VEGETATION

Arjan Mol

Measurements have been carried out at the Paulinaschor, a salt marsh in the Westerschelde, to obtain information of the effect of vegetation on wave attenuation. The data have been analyzed. It appears that wave height is strongly reduced by the vegetation, especially for low water depths. Further analysis of the data has been done, to achieve wave energy dissipation. An attempt has been made to formulate a theoretical approach, which is suitable for calculating wave energy dissipation due to vegetation on the basis of certain vegetation characteristics such as stem diameter, plant height and plant density. This theory has been tested by a comparison between the theoretical dissipations and the – so called – observed

dissipations. This resulted in quite satisfying correlations; correlation coefficients of about 0.6 – 0.8 were calculated. By means of this analysis is a friction coefficient determined, describing the friction exerted by the vegetation. This coefficient depends on the various vegetation characteristics as mentioned before, but also at a second friction factor, that is more plant specific.

Subsequently, the wave model SWAN has been suited for modelling waves over vegetation areas. The Collins friction factor is used for calibration. Values for this factor turned out to be 2 orders of magnitude bigger than the default value, for bare bottoms. A further study on this Collins coefficient showed that this coefficient is, except for a constant factor, the same as the friction coefficient that was calculated on the basis of the various characteristics. Using these calculated friction coefficients, converted to Collins coefficients, the SWAN model has been validated. The model results showed a good agreement with reality. Only the wave attenuation at the edge of the salt marsh did not correspond very well with the observed attenuation. A possible explanation could be that vegetation is modelled in SWAN through an enlarged bottom friction, instead of 3D obstacles. Also due to the fact that the development of the orbital velocity in the vegetation is not known exactly, deviations between model outcome and observed attenuation may occur.

### 4.3 Data collection / analysis

Field measurements will be carried out which focus on sedimentation in different *salt marsh types* (man-made: Friesian and Groninger coast; barrier island: Ameland, and (former) summer polders: Peazemerlannen, Holwerd, Noard-Fryslân Bûtendyks) with different *management* (grazing intensity), *vegetation type and structure*, and *drainage system*. The measurements (with sedimentation-erosion bar [SEB], and filters) will give an idea of sedimentation on *different time scales*: events, season, year, and decades. On filters sediment deposition of one or more tides can be measured. By doing three measurements per year (in March after the winter storms, in August after the summer drought, and in November/December before the winter storms) the SEB is a good tool to measure the changes in soil level between seasons, years, and when monitoring continues long enough. The Rijkswaterstaat data set (starting in 1960) about vegetation and sedimentation along the Friesian and Groninger coast will also provide information about fluctuations in sedimentation and vegetation development on different time scales and about the effect of changes in management. The mean high tide line in the Wadden sea area over that same period provides an extra tool for explanation of the occurring changes. Besides collecting data on sedimentation also data creek profiles and length of the drainage system will be collected in (part of) the sites. *Participating partners: ALTERRA, RIKZ.*

### Summary

#### FIELD MEASUREMENTS ON SEDIMENTATION IN DIFFERENT SALT MARSH TYPES

W.E. van Duin (Alterra)

In order to learn more about salt marsh morphodynamics, with regard to the interactions between sedimentation and vegetation, measurements were done in salt marshes in the Netherlands with a different history and which are submitted to different tidal conditions.

The results can be used for salt marsh management. Furthermore they give an indication about the possible effect of sea-level rise on salt marshes and the succession/regression of the vegetation.

Since 1993 the sedimentation is measured in several salt marshes along the Wadden Sea:

- on Ameland: 24 pq's on 'Neerlands Reid' since May 1993 and 15 pq's on 'De Hon' since August 1995;
- 30 pq's in the 'Peazemerlannen' (Friesland) since Januari 1995;
- in the 'salt marsh works': 15 near the 'Negenboerenpolder' since June 1994, 20 pq's near the 'Julianapolder' since March 1998, 74 pq's on the salt marshes near Holwerd (the 'Krekenproef') since March 1998; 15 pq's near the Noordpolder (since May 1994) were abandoned after heavy damage due to maintenance work and trampling by horses in 1995.
- 105 pq's in the restoration site and adjacent summerpolder and saltmarsh of 'Noard Fryslân Bûtendyks' since December 2000.

Information about the sedimentation on the salt marshes in the 'Krekenproef' can be found in Van Duin & Dijkema (2003). Additional information on the results from Ameland can be found in Eysink *et al.* (2000) and from the Peazemerlannen in Van Duin *et al.* (1997). The data series from 'Noard Fryslân Bûtendyks' is still too small to be presented.

The sedimentation was measured three times per year with the Sedimentation-Erosion Bar.

Some results and conclusions:

- By measuring several times per year seasonal effects were discovered,
- In all summers shrinkage of the soil was measured (especially in 1995 and 1999). In autumn recovery of this phenomenon occurs, because of swelling of the soil by rain or flooding,
- Usually the sedimentation in the winter is very high (especially in 1998/99 and 1999/2000),
- The winter of 1995/1996 was exceptional, because of the mainly easterly wind causing low tides with hardly any sediment input,
- Changes in drainage seem to have a quicker effect on the vegetation than changes in soil level,
- Not only the number of floodings (soil level), but also the distance to creeks and the bare mudflat influence the sedimentation rate,
- The mean sedimentation over the periode 1993-2002 on Nieuwlandsrijd is high for a barrier island salt marsh in the Wadden Sea,
- The mean sedimentation in the salt marsh Peazemerlannen is normal for a mainland marsh and twice as high as in the comparable zones on Nieuwlandsrijd (Ameland),
- A positive sedimentation balance leads to succession and eventually to a climax vegetation. Soil subsidence by gas extraction seems to slow down this process,
- Shrinkage of the soil and lack of floodings in the summerpolder of the Peazemerlannen causes a continuous lowering of the soil level. By removing (part of) the summerdike the salt marsh dynamics could be restored in the future.

Besides data about the sedimentation additional information about vegetation is collected and a comparison between the different salt marshes is made. The data gives insight on the sedimentation in salt marshes of different origin and the survival possibilities in case of sea-level rise.

## Products

Report (2003) in prep.

## 5 Modelling and case-studies

### 5.1 Developments around Schor van Waarde and Zuidgors Schor.

The preservation of these two salt marshes in the Western Scheldt is at this moment an hot issue for the management of the Western Scheldt analysis. Analysis of historical data is being carried out in order to identify the causes of the cliff erosion endangering the two marshes. Modelling of the hydrodynamic and sediment transport processes in the surrounding areas will be carried out in order to test / verify the hypotheses derived from the data analysis, and to evaluate the proposed measures for preserving the two marshes. *Participating partners: RIKZ.*

#### Products

Liek, G. J., & Kornman B., (2001), '*De morfologische ontwikkeling van het slik en schor van Waarde in de periode 1957-2000*', Werkdocument RIKZ/AB/2001/802x.

Admiraal, N. (2002), '*Slinkend Slik. Morfologische ontwikkeling rodn het slik van Waarde van 1951 tot 2000*', Werkdocument RIKZ/OS/2002.806x

The data in these two reports are used to write a paper.

#### Abstracts

“Morfologische ontwikkeling rond het slik van Waarde van 1951 tot 2000”

Door Nico Admiraal (RIKZ)

In het voor u liggende document wordt de morfodynamische interactie tussen de geulen en het slik van Waarde voor de periode van 1951-2000 beschreven. Deze geulen voor het slik zijn de Schaar van Waarde, de Schaar van Valkenisse (vloedscharen) en de Zimmermangeul (ebschaar). Het document beschrijft nader onderzoek dat een vervolg is op het werkdocument van Liek & Kornman (2001). Hierin wordt ingegaan op de ontwikkelingen van het slik en het schor van Waarde in de periode 1957-2000. Naar aanleiding van de daar gepresenteerde data over het slik zijn enkele vragen / hypothesen naar voren gekomen over de oorzaak van de ontwikkelingen op het slik. In dit document zullen deze en andere daarmee verband houdende hypothesen getoetst worden. Het gaat hier voornamelijk om de achterliggende morfodynamische processen van het geulensysteem voor het slik in relatie tot de ontwikkeling op het slik.

Eerst is door middel van een uitvoerige data-analyse de ontwikkeling van het slik van Waarde in de periode 1951-2000 in kaart gebracht. Er is voor gekozen om deze ontwikkeling in perioden van 4 jaar te beschrijven om een gedetailleerd beeld te krijgen. Naast de ontwikkeling van de slikrand en de slikhoogte is in dit document ook de ontwikkeling van de slikinhoud onderzocht. De ontwikkeling van de slikinhoud geeft een nauwkeurig beeld van de ontwikkeling op het slik.

Uit bovengenoemde data-analyse en de data uit Liek & Kornman (2001) zijn twee hypothesen geformuleerd die getoetst zijn door modelberekeningen.

1. Zimmermangeul: Erosie in het oostelijk deel van het slik wordt veroorzaakt door een vermindering van de inhoud van de Zimmermangeul. Sedimentatie wordt veroorzaakt door een toename van de inhoud.
2. Storten: Het water dat over het slik stroomt is onderverzadigd wat tot erosie leidt.. Door te storten kan de stroom weer verzadigd worden, zodat er op het slik geen erosie meer optreedt. Eventueel kan het slik zelfs weer aangroeien.

## Hypothese Zimmermangeul

De Zimmermangeul verliest duidelijk aan betekenis in de periode '80-'88. Het kleiner worden van de Zimmermangeul gaat in 75% van de jaren 1951-2000 samen met toename van de slikhoogte / slikinhoud. Hieruit blijkt dat het aangenomen verband tussen het verondiepen van de Zimmermangeul en de erosie in het oostelijk deel onjuist is. Het omgekeerde is aannemelijker. De verwachte ontwikkeling van de Zimmermangeul kan dus juist tot sedimentatie op het oostelijk deel van het slik leiden.

### *Hypothese storten*

Uit het onderzoek blijkt dat storten vooral een korte termijn invloed op het slik van Waarde heeft. Een klein percentage van het gestorte materiaal komt ook daadwerkelijk op het slik terecht en dan vooral bij de geul-/slikrand. Alleen veel storten, dichtbij het slik heeft een merkbaar positief effect op aangroei van het slik.

### **Morfologische processen voor het slik.**

De belangrijkste verklaring voor de ontwikkelingen in en rond het slik van Waarde is het west-oost gerichte sedimenttransport door de dominante vloedstroom. Morfologische fenomenen, zoals het ontstaan van landtongen voor het slik, maar ook gestorte materialen verplaatsen zich vanuit het westen naar het oosten. Ook voor de erosieverschijnselen geldt dit. Erosie die eerst in het westelijk deel van het slik is opgetreden, treedt in een volgende periode in het oostelijk deel op. De vloedstroom is de primaire oorzaak voor de morfologische ontwikkelingen rond het slik van Waarde. Een secundaire oorzaak is de verandering in het geulenpatroon (Zimmermangeul, de Schaar van Valkenisse) voor het slik. Deze verandert in de loop van de tijd, waardoor de stroming soms meer, soms minder erosieve kracht vertoont. Vooral na '88 is te zien dat deze de ontwikkeling op het slik in positieve zin kan beïnvloeden, d.w.z. vermindering van de erosiedruk op het westelijk deel van het slik, aangroei op het oostelijk deel. De Schaar van Valkenisse neemt dan namelijk sterk toe qua getij-volume ten kosten van de Zimmermangeul, die zijn erosieve kracht op het oostelijk deel van het slik hierdoor verliest. Daarnaast is de stroming in het westelijk deel niet meer direct langs het slik georiënteerd, maar meer naar het zuiden. Deze recente ontwikkelingen hebben dus een positief effect op het slik. Ondanks deze secundaire ontwikkeling, blijft de west-oost georiënteerde dominante vloedstroom, de belangrijkste verklaring voor de ontwikkelingen van het slik van Waarde.

## 5.2 Hydrodynamic modelling intertidal area Western Scheldt.

The hydrodynamic model for the Western Scheldt presently operational at Rijkswaterstaat is not sufficiently accurate for the flows on intertidal areas. research will be carried out to improve the performance of the model for intertidal areas. *Participating partners: RIKZ.*

### Summary

MODELLING INTER TIDAL AREAS IN THE WESTERN SCHELDT

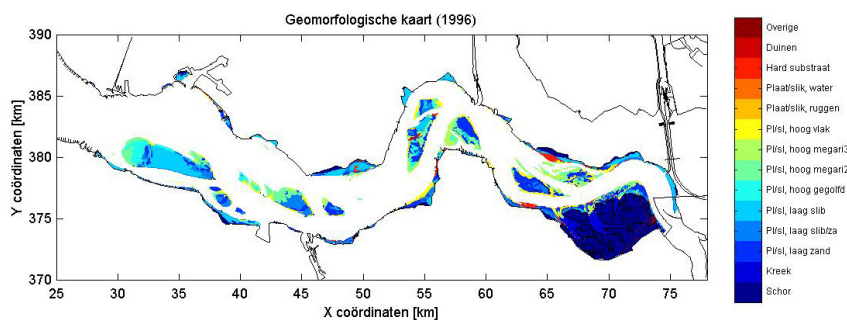
RIKZ/Svašek Hydraulics  
Maarten Jansen/Gerard Dam

In the last years the Dutch government was developing hydraulic numerical models for use in daily circumstances and actual questions. These numerical models were calibrated for the global water levels and currents in deep canals. The models are used to calculate water levels and currents in daily and in storm circumstances.

The currents in inter tidal areas were not calibrated because the measurements were poor and because of a lack of interest in the reproduction of currents in inter tidal areas.

Nowadays ecological aspects are more important and there is a growing interest in the currents and water levels in the inter tidal areas. A good reproduction of the currents is necessary.

The SCALWEST model is a 2DH hydraulic numerical model of the Western Scheldt. It is based upon WAQUA in SIMONA, a numerical program developed by the Dutch government.



Svašek

investigated for RWS/RIKZ the reproduction of the SCALWEST model in inter tidal areas. The conclusion was drawn that the reproduction of currents in the SCALWEST model was poor in mud flat areas and tolerably on plates. One of the parameters which can improve the results was the local bottom friction. A local bottom friction related to the geomorphological unit of that area gives better results for currents in inter tidal areas.

For most units the SCALWEST model is calibrated again with these friction parameters. The calibration is an iterative process because of the use of currents in the production of geomorphological maps. For some geomorphological units no measurements were available, so the friction value is based on literature.

In the SCALWEST model the same friction is used in parallel canals. This is not realistic because of the different shape and currents of both canals. It can also be concluded from measurements. Different friction will lead to different water levels and maybe different currents on plates between the canals. However it was found that the influence of different friction in parallel canals on currents at the plates is small. This experiment took place in the Everingen en Pas van Terneuzen.

At two places in the Western Scheldt vertical measurements of the currents at mud flats are available. These measurements were used to calculate the bottom friction. It was assumed that the current in the vertical has a logarithmic profile. From measurements it could be concluded that this was a correct assumption for both the Plaat van Baarland and the Molenplaat. The calculated friction at the Molenplaat and the friction in the SCALWEST model were in the same order of magnitude. The calculated friction at the Plaat van Baarland differs from the friction in the model.

The SCALWEST model will be used in the future for daily and storm situations. Therefore the changes in friction in the inter tidal areas may not lead to different water levels and currents in deep canals. Comparison of water levels in storm situation gives a difference of 3 cm on high water levels. This is a small difference compared to the inaccuracy of the model. The friction at inter tidal areas does not have a large impact on the water levels during storm.

### Importance of the study

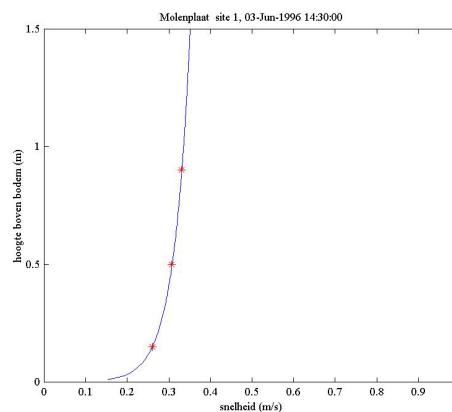
Next years the ecological impact of new measures in the Western Scheldt, like a further deepening of the fairway, must be clear. The results of this study have improved the reproduction of currents in the inter tidal areas in the Western Scheldt. Also for new models the bottom friction in inter tidal areas can easily be obtained using new geomorphological maps. A further optimisation is necessary and therefore new measurements in the inter tidal areas are required.

### Products:

Svašek, 1999, Het SCALWEST model in het intergetijdengebied, een eerste verkenning naar afwijkingen tussen model en veldmetingen, rapport 99321/1115.

Svašek & Alkyon, 2000: ECOMORF, De modellering van de hydrodynamica in het intergetijdengebied, rapport 00327/1165-A647.

Svašek, 2002: Verbeteren van het SCALWEST model, deelrapport 1, Optimaliseren stroming intergetijdengebied, rapport 1206/R01513/GD/Rott2b



## 5.3 Parameterisation to larger scale models and behaviour oriented modelling.

Research will be carried out how the results from tasks 3b and 3c can be parameterised and implemented in larger scale predictive models which can be used in practical problems. Knowledge and insight from the process research will be implemented / used in behaviour

oriented, i.e. (semi-) empirical models for estuaries including salt marshes. *Participating partners: WL.*

This part of the research has been skipped, the ICES-contribution has been refunded.

## 6 Set up of a validation case.

### 6.1 General

In the project plan the object of this task has been described as:

‘A data base with corresponding documentation will be set up in order to serve as a validation case for future studies on salt marshes. A particular salt marsh will be selected on the basis of aspects e.g. data availability. All relevant data concerning all aspects about the salt marsh will be collected, stored in the data set and documented. The validation case will be made available via the internet.’

A search has been made for available and suitable data. As mentioned in 3.2 Alterra has provided a data set for this purpose. However, to validate the developed process based 3D-model developed a more detailed data set was needed. Therefore a measuring campaign was set-up by NIOO-CEME, WL|Delft Hydraulics, RIKZ, RIZA and TUD on the Paulina Saltmarsh. The University of Leuven also participated. The data base including a model of the area is to be made public when the analysis is ready.

Next to the field campaign laboratory measurements at NIOO-CEME and WL|delft Hydraulics have been conducted.

*Participating partners: WL, ALTERRA, NIOO, IHE, RIKZ, RIZA.*

### 6.2 Interaction between plants hydrodynamics and sediment transport.

In the project, the interaction between plants, hydrodynamics and sediment transport was studied in *i)* the field, *ii)* a wave flume and *iii)* a laminar flow flume. We identified general hydrodynamic relationships that can be used to make habitat characterisations for mudflats and salt marshes. We also demonstrate the importance of shoot density and leaf stiffness for hydrodynamics and sediment transport. The combination of the various studies facilitates the inclusion of these ecological processes in hydrodynamic and morphological modelling and answers fundamental ecological questions. Below, we listed the scientific papers that are currently submitted or in preparation. Parts of these data have already been published in internal reports.

#### Products

1. Hydrodynamic measurements on a mudflat and in salt marsh vegetation: identifying general relationships for habitat characterisations. **T.J. Bouma\***, **M.B. De Vries**, **E. Low**, **L. Kusters**, **P.M.J. Herman**, **I.C. Tánzos**, **A. Hesselink**, **S. Temmerman**, **P. Meire**, **S. van Regenmortel.**, submitted to HYDROBIOLOGIA
2. Linking plant traits to the capacity for ecosystem-engineering and facilitation: effects on wave attenuation. (*in prep.*) **T.J. Bouma\***, **M.B. De Vries**, **E. Low**, **P.M.J. Herman**, **I.C. Tánzos**, **G. Peralta**.

3. Effects of leaf stiffness and shoot density on flow and turbulence within seagrass canopies. (in prep.) **G. Peralta**\*, **L.A. van Duren**, **T.J. Bouma**.
4. Identifying the critical vegetation density for bioengineering by *Spartina anglica*. (in prep.) **T.J. Bouma**\*, **C. Feranc**, **J. van Soelen**, **B.P. Koutstaal**, **A. Blanco**, **P.M.J. Herman**, **T. Ysebaert**, **L.A. van Duren**, **M.B. De Vries**.
5. NIOO-CEME: *Sea wave attenuation by salt marsh vegetation*. (2002) **Elinor Low**
6. Arjan Mol, 2003, 'Wave Attenuation by Vegetation', WLI Delft Hydraulics Rapportnr Z3040, 'stageverslag' UT. This report will be reorganised to be submitted as a paper to a scientific paper. (see also 4.3)
7. Kusters, L., 2003, Data report, Paulinaschor
8. Turner, R., Möller, I. and Spencer, T., 2003, *Application of SWAN-model to vegetated surfaces*, CCRU. This report is based on a collaborative workshop that took place from February 24<sup>th</sup> to March 7<sup>th</sup> 2003 at WLI Delft Hydraulics, Delft, Netherlands, as part of the EA/DEFRA funded project. (see also 4.3)
9. I.C. Táncoz, A. Crosato and M. de Vries 'Micro scale modelling and practical issues', RipFor Workshop, Trento 20-22 February, 2003

## Abstracts

HYDRODYNAMIC MEASUREMENTS ON A MUDFLAT AND IN SALT MARSH VEGETATION: IDENTIFYING GENERAL RELATIONSHIPS FOR HABITAT CHARACTERISATIONS.

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**key words:** current velocity, marsh vegetation, mudflat, velocity profiles, waves

We present an overview of a large collaborative field campaign, in which we collected a long-term (months) high-resolution (4 Hz) hydrodynamic data set and linked this to a biological description of the organisms on the mudflat and the marsh. In this paper, the data base was used to identify (1) general relationships that can be used for making hydrodynamic characterisations of mudflat-salt marsh ecosystems and (2) the minimal set of measurements needed to fit such relationship for a particular area. We observed a linear relation between tidal amplitude and the maximum current velocity, both at the mudflat as well as within the marsh vegetation. Velocities in the vegetation were however a magnitude lower than those on the mudflat. This relationship offers possibilities for making hydrodynamic habitat characterizations and for validating hydrodynamic models. E.g., present results imply that making a hydrodynamic characterisation of a mudflat-salt marsh ecosystem requires measuring velocities during a limited number of neap and spring tides, and regressing the maximum velocities against inundation height. However, questions remain to be resolved regarding the importance of spatial variation in velocities and the importance of extreme hydrodynamic conditions during short events such as e.g. storms.

## LINKING PLANT TRAITS TO THE CAPACITY FOR ECOSYSTEM-ENGINEERING AND FACILITATION: EFFECTS ON WAVE ATTENUATION

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**key words:** current velocity, marsh vegetation, *Spartina*, *Salicornia*, waves, *Zostera*

The combined effect of daily inundation with saline water, wave impact and strong current velocities make mudflat-salt marsh ecosystems an extremely hostile environment for plant growth. Because of the stressful conditions, the transition of a mudflat into a salt marsh depends strongly on a combination of bioengineering and facilitation. Regardless, the plant species that dominate the pioneer zone in the SW Netherlands (*Spartina anglica*, *Salicornia europaea* and *Zostera noltii*) show a remarkable contrast with respect to leaf stiffness and leaf density, even though they grow closely together at a similar height along the elevational gradient. The objective of our study was (1) to identify which plant traits make a plant species a successful bioengineer and facilitator and (2) to establish the costs associated to having these traits. In a flume, we mimicked the wave conditions typical for estuarine marshes in the Schelde estuary. Wave attenuation was quantified both for different densities of *Spartina*, *Salicornia* and *Zostera* plants and for different densities of plant mimics with a stiffness comparable to either *Spartina* or *Zostera*, but that exclude all other morphological differences between these species. Our results show that wave energy decreases linearly with a logarithmic increase of the number of plant structures. The dissipation of wave energy was however a magnitude higher in vegetations with stiff leaves than those with flexible leaves. The results of our flume measurements were comparable to the wave attenuation that we measured in a *Spartina* marsh. Costs associated to having stiff leaves at a high density are in tissue construction, demands for anchoring, internal shading and a relative slow lateral expansion.

## EFFECTS OF LEAF STIFFNESS AND SHOOT DENSITY ON FLOW AND TURBULENCE WITHIN SEAGRASS CANOPIES.

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Seagrass meadows affect and are affected by the local hydrodynamic conditions. The interaction strongly depends on i) the size and shape of the leaves, ii) the spacing in between shoots and iii) the biomechanical properties of the plants, which varies among seagrass species. We studied how these seagrass characteristics affect local hydrodynamics within and above the vegetation, using a unidirectional flow flume to simulate low (5 cm s<sup>-1</sup>) and high (30 cm s<sup>-1</sup>) velocities in the habitat of *Zostera noltii*. Using artificial seagrass plants enabled us to separate effects of density (500 vs. 2500 shoots m<sup>-2</sup>) and leaf stiffness (stiff vs. flexible materials) on velocities and the turbulence levels, without having to account for complicating effects of other morphological properties. Subsequently the findings of the artificial plants were validated on a vegetation of *Zostera noltii*. In all measurements, we observed skimming flow, with very low, uniform velocities inside the canopy. The

logarithmic boundary layer was well developed on top of the canopy, but the velocity decreased significantly within the meadow, showing stronger reductions at higher densities. The stiff leaves showed uniform flow from the base of the leaves right to the top of the canopy (10 cm), while in the flexible leaves the vertical velocity gradient started developing several centimeters below the top of the canopy, due to the bending of the shoots. In general, the vertical Reynolds stress showed a negative peak on the top of the canopy, that could be interpreted as positive rates of transport within the canopies (i.e. sedimentation). However, under high velocity and sparse density, the stiff material showed a second positive peak on vertical Reynolds stress, increasing the chance for erosion. In the other cases, where this second peak was not detected, the values of vertical Reynold stress turned to zero within the canopy, due to the absence of a velocity gradient. These results were confirmed in the natural vegetations of *Z. noltii*. The relative turbulence intensity increased within the meadow canopies. This effect was most pronounced at low free stream velocities. The increased relative turbulence may benefit the seagrass growth by reducing the diffusive layer around the leaves, which has been suggested as the main limiting step in C and nutrient uptake. The relative turbulence increased both with decreasing shoot density and with increasing leaf stiffness (stiff > flexible). As for seagrasses leaf stiffness increases and shoot density decreases with the increase in plant size, these results suggests that most of the strap-like seagrass populations may benefit from the increased turbulence within the canopy.

IDENTIFYING THE CRITICAL VEGETATION DENSITY FOR BIOENGINEERING BY *SPARTINA ANGLICA*.

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Current velocities and wave impact make the pioneer zone of the salt marsh an extremely hostile environment for plant growth. Self-facilitation by bioengineering is an important factor for the expansion of the in the SW Netherlands most dominant pioneer species *Spartina anglica*. By reducing hydrodynamic forces, *Spartina* is able to trap sediment, which results in dome shaped tussocks that expand simultaneously in height and laterally. The objective of our study is to obtain a better understanding of the importance of stem density for the ecosystem engineering capacities of *Spartina*. At 8 marshes in the SW Netherlands we characterized the dome shape of 20 *Spartina* tussocks with a 1 m radius. Subsequently, we tested at 8 locations if a similar dome shape would arise in an artificial tussock made from bamboo sticks (i.e., .. sticks m<sup>2</sup>). Surprisingly, most tussocks showed erosion instead of sedimentation. Subsequent flume studies revealed that turbulence is enhanced significantly in case of a too low 'vegetation' density, both in case of plant mimics (bamboo sticks and plastic strips) as well as in case of real *Spartina* plants. We conclude that in order to be a successful ecosystem engineer, a species should reach a density of at least .. structures m<sup>-2</sup>, especially when growing as exposed as in a tussock.

## 7 Applications abroad

### 7.1 General

### 7.2 Mangroves

To investigate the relevance of the expertise developed in this project to other climate zones, an exploratory investigation will be carried out on the extent to which processes that dominate ecomorphological interactions in salt-marshes are important to explain development of and succession of plant species in Mangrove ecosystems. This investigation will make use of the literature that is already available on sediment dynamics in Mangrove swamps (e.g., Wolanski 1992, 1995). Furthermore use will be made of data collected in its current study on Mangrove swamps in Thailand (early description: Terrados et al 1997, Panapitukkul 1998) in which a developing Mangrove forest was investigated. *Participating partners: IHE.*

#### Results

The literature on ecomorphological aspects of Mangroves forests proves scarce. Data available to link ecomorphological development in mangrove systems to the conceptual model as describes above was found to insufficient.

### 7.3 Feiyun estuary

YingBiao SHI  
TU Delft.

The long-term morphological development of the Feiyun estuary has been carried out with the ESTMORF model, which belongs to the hybrid class of models. The impact of the bend cut-off in the Feiyun estuary, the construction of the Sanxi reservoir and the diversion project, to the long-term morphological development is studied.

#### Summary

LONG-TERM MORPHOLOGICAL MODELLING FOR FEIYN ESTUARY WITH ESTMORF

#### Introduction

The Feiyun River, with a length of 203 km and a catchment area of 3252 km<sup>2</sup>, is one of eight rivers in Zhejiang Province (see fig.1-1), China. It flows into the East China Sea in Shangwang of Ruian City. The source of Feiyun River is at Xialing located in the border between Zhejiang and Fujian Province. The tidal influence can reach up the river as far as Tanjiao located 59 km from the river mouth in the dry season during spring tide. The

downstream river reach of Tanjiao is called the estuary reach mainly controlled by tidal flow, and its upstream is called river reach controlled by the basin runoff.

The Feiyun Estuary connects the sea to Ruian harbour. There is an old and a new harbour zone near the Feiyun first bridge in Ruian City. The old harbour is only suitable for 300T to 500T ships. A quay berth for 1000T ship is in the new part. With the development of the economics and foreign trade of Ruian City, the harbour is developing rapidly. Therefore, it is necessary for local government to carry out the channel improvement of the Feiyun estuary. A lot of human interference's are going on / planned in the Feiyun estuary. In the upstream reach of the Feiyun River, the large scale Sanxi reservoir has been constructed and began to store water. Further the diversion from the Zhaoshadu reservoir will also be carried out. A bend cut-off project is also in schedule in order to improve the flood defence and create land for Ruian City. It is no doubt that all these human activities will have important effect on the long-term morphological development of the Feiyun estuary, especially for the navigation channel of the downstream section of the Feiyun estuary.

Within the framework of Delft Cluster project Ecomorphology of Estuaries and Coasts, the long-term morphological development of the Feiyun estuary has been carried out with the ESTMORF model, which belongs to the hybrid class of the models. The impact of the bend cut-off in the Feiyun estuary, the construction of the Sanxi reservoir and the diversion project, to the long-term morphological development is studied.

### Conclusions

Based on ESTMORF an long-term morphological model for the Feiyun river estuary has been set up. The model has been calibrated using hydrographic field data as well as data on historical morphological changes. The model has been applied to investigate the impact of the change of river discharge regime due to the construction of reservoirs in the upstream river, and of a land-reclamation / bend cut-off project in the estuary. The following conclusion are drawn from the study:

The morphological development in the estuary is strongly influenced by the upstream river discharge.

An increase of the river discharge will cause erosion and a decrease of the river discharge causes sedimentation in the estuary.

If the present situation of the estuary is considered as in dynamic equilibrium with the ever varying (seasonally and long-year) river discharge, a systematic decrease of the river discharge due to e.g. the diversion from the Zhoushandu reservoir will cause sedimentation in the estuary. The sedimentation process does not establish a new equilibrium and the sedimentation rate seems to be increasing in the first 30 years.

The sedimentation/erosion caused by the change of the upstream discharge is related to the ratio of the upstream discharge and the critical discharge of sedimentation/erosion. Since the effect of the discharge on the riverbed forming is different in every reach of the Feiyun estuary, the volume of the sedimentation/erosion is also different from the upstream to downstream.

Because of the diversion from the Zhaoshandu reservoir with the discharge decreasing from 85m<sup>3</sup>/s to 65m<sup>3</sup>/s in mean year, the sedimentation will cause in the downstream of the Feiyun estuary. The amount of the sedimentation of the upstream, middle and downstream of the Feiyun Estuary is equal to 1.5\*10<sup>6</sup>m<sup>3</sup>, 5.56\*10<sup>6</sup>m<sup>3</sup> and 3.08\*10<sup>6</sup>m<sup>3</sup> for 30 years, respectively. The ratio of the sedimentation to the river volume below mean water level in the middle and downstream river reach is smaller than that in the upstream.

The considered land reclamation and bend cut-off cause sedimentation due to decrease of the tidal volume in the downstream of Baoxiang. Upstream of Xianjiang erosion occurs due to the low water level descending and ebb tidal velocity increasing for the second case and sedimentation occurs due to the low water level rise for the first case. Upstream of the land reclamation or cut-off first sedimentation occurs and later erosion.

The time scale of the first morphological reaction of the estuary to the disturbance caused by the bend cut-off and land reclamation is relatively small, only in the order of about one year. The first reaction causes a disturbance in the estuary of much larger length scale. Therefore there is a second reaction of the estuary with a much larger time scale.

Simulations have also been carried out for the two cases combination with diversion from Zhaoshandu reservoir. It appears that the combination of the diversion and two cases causes a large morphological reaction because the effects of the two are similar.

The ability of the model to predict long-term morphological changes due to human interference's as well as due to natural development such as seasonal change of discharge and sediment is well demonstrated by the application in Feiyun estuary. Due to the empirical-dynamic character of the model it supplies the information of long-term morphological development as well as hydrodynamics conditions, and takes into the interaction between the two. For the morphological development the model gives not only the changes in the channel part of the estuary, but also the changes of the inter tidal areas. So it is demonstrated that the ESTMORF model is a powerful tool for managers of water systems.

## Products

YingBiao SHI, 2003, '*Long-term morphological modelling for Feiyn Estuary with Estmorf*', 2003

Shi, Y. B. and Wang, Z.B., 2003, '*Long-term morphological modelling for Feiyn Estuary with Estmorf*', International Conference on Estuaries and Coasts, ICEC 2003, November 2003, HangZhou, China.

## **8 General achievements**

### **8.1 Folder**

A folder is developed to inform a larger non scientific audience about salt marshes and the research issues as addressed in this project. This is done in collaboration with Natuurmonumenten.

### **8.2 Workshops**

Two major DC-workshops have been organised. The programme and presentations can be found on the project website. The present achievement report and folder are the product of the second workshop. For the related ESTPROC-project an international workshop on the interaction of waves and vegetation has been organised. Minutes of the first DC workshop is available at the website. The ESTPROC workshop minutes are available at [www.estproc.net](http://www.estproc.net).

### **8.3 Collaboration**

An important 'achievement' or result is the collaboration between the participating institutes. Integration of knowledge of experts in morphology and hydraulics with that of experts in the field of biology and ecology forms the basis of biogeomorphology. This collaboration will continue in the future.

## 9 Project Spin-off

The project spin-off can be divided in two parts: 1) results that are relevant voor managers of salt marsh areas, and 2) results that are usefull for scientific use in related fields. Both are discussed below

### 9.1 Findings relevant for managers

1. The outcome of the conceptual model for salt marshes suggests that the de- or regeneration of these areas is an autogenous process which is not necessarily the result of changed external conditions. Hence, erosion found in salt marshes does not necessarily require remediation actions, as it is possible the results of natural development processes within salt marshes. An 'indicator' for this situation is the occurrence of simultaneous cliff erosion and regrowth of vegetation before the cliff.
2. The study on the SCALWEST model for the Westerschelde has improved the models reproduction of currents in the intertidal areas in the Western Scheldt. Hereto the friction factor is related to the geomorphological unit such that for new models the bottom friction in inter tidal areas can easily obtained using new geomorphological maps. These results are beneficial to asses the ecological impact of future new measures in the Western Scheldt, like a further deepening of the fairway.
3. The adapted Delft3D-model that account for the effect of vegetation on watermotion, in combination with the experimental knowledge gained in this project can help to assess the possibilities of 'bioengineering' as method to for salt marsh and coastal protection.
4. The sand-mud model as developed by van Ledden has increased the understanding and the modelling capabilities for large-scale sand-mud segregations in estuaries and tidal basins. This is relevant for salt marshes since the mud content of the sediment is an imprortant parameter. The model can be used to estimate the effect of human interventions and natural changes on the development of the large-scale bed level and composition in time and space.
5. The study on the Slik van Waarde shows that only a small percentage of dumped material in a channel actually reaches the mudflat and only at the edge of the channel/mudflat. Only when the dumping location is very close to the mudflat does the material has a significant effect on the flat.
6. The theoretical stability analysis on the stability of channels on mud flats provides knowledge on how to 'design' the creek (channel) system in artificial salt marshes, as, for example, present in the Wadden Sea. It shows that that a sufficient large tidal prism is required for a channel to maintain itself. The tidal prism is influenced by:
  - a. the density of the channels

The relatively high density of especially the smallest channels in the artificial salt marshes in the Wadden Sea compared tot that of the natural salt marshes, has the consequence that the tidal prism per channel become too small to maintain the channels.
  - b. the relative depth of the channels

A relatively deep channel attracts more flow than a shallower one next too it making the tidal prism through it larger. This explains why a deeper channel can better be maintained than a shallower one.

7. In the 'krekenproef' a number of adaptations to the drainage system has been tested that were made to 1) reduce the total length of the ditches which compared to natural systems is too large, and 2) to improve the naturalness. Its results are of direct interest for managers of such areas.
8. At present, low sand flats dominate the Wadden Sea. All that remains from the once expansive salt marshes are narrow fringes on the landward side of the tidal basins, and coastal peat bogs have disappeared altogether. The study on the long term development of the Lauwerszee estuary shows that the development is linked to the behaviour of tidal-inlet-related channel systems and to human activities such as the reclamation of salt marshes and cultivation of peat land are the cause.
9. The analysis of the dataset of Rijkswaterstaat to study the correlation between benthic animals and spatial and temporal dynamics of sediment characteristics, shows that the temporal and spatial variations are such that one should be careful in drawing conclusions based on limited sample locations. Moreover, does it imply that one should be hesitant in using a site for reference purposes when studying the impact of, for example, human intervention. It is better too do measurements at the same location before and after the intervention takes place. To account for the temporal variation one should do this on a long enough scale. The analysis also suggests that it is important that sampling should be done at random locations each year and that for each locations also measurements of environment variables such as sediment characteristics are measured. All measurements including those of the local environmental variables, have to be done several times.

## 9.2 Scientific spin-off

1. In the process based Delft3D-FLOW/3DMOR module an adaptation has been made to account of the effect of plants on water flow. Also an approach has been developed to account for the wave damping effect of vegetation. A model of the salt marsh Paulina Polder has been constructed and validated on available data (see below). This model will made available on the internet.
2. A conceptual model has been developed to explain the development of salt marshes in time taking into account the interaction between morphology and vegetation.
3. A numerical prototype of the process-based sand-mud model has been developed by extending the three-dimensional software package Delft3D from WLDelft hydraulics.
4. The study on the SCALWEST model for the Westerschelde has improved the reproduction of currents in the intertidal areas in the Western Scheldt. Hereto the friction factor is related to the geomorphological unit such that for new models the bottom friction in inter tidal areas can easily obtained using new geomorphological maps.
5. A number of datasets have been put together:
  - a) A database of Alterra sediment budget studies from five different salt marshes in the Netherlands was made. This data may be used for modelling purposes after consultation with Alterra.
  - b) A long-term (months) high-resolution (4 Hz) hydrodynamic data set, and, linked to this, a biological description of the organisms on the mudflat and the Paulina Polder

marsh, have been collected. After analysis this data will be put on the web to be used in other studies.

- c) The changes in vegetation, soil level, sedimentation and the development of the creek system the man-made salt marshes of the salt marsh works along the Wadden Sea coast of Groningen and Friesland were measured for 4 years for different adaptations, made to the drainage system in order to reduce the total length of the ditches and to improve the naturalness.
  - d) In order to learn more about salt marsh morphodynamics, with regard to the interactions between sedimentation and vegetation, measurements were done in salt marshes in the Netherlands with a different history and which are submitted to different tidal conditions. The results can be used for salt marsh management. Furthermore they give an indication about the possible effect of sea-level rise on salt marshes and the succession/regression of the vegetation. Since 1993 the sedimentation is measured in several salt marshes along the Wadden Sea.
  - e) Integration of seismic data of the period since 0 AD on the Lauwerszee with reconstructions of the changing estuary.
  - f) Data on the height of the clay layer along the salt-marsh developmental gradient was compiled and classified by age.
6. The following existing datasets have been analysed
- a) For the salt marsh the 'Slik van Waarde' a data analyses of the development in the period 1951-2000 has been conducted
  - b) The interaction between benthos, hydrodynamics and sediment structure was study at two different spatial scales. At the scale of the estuary, an existing large datasets of Rijkswaterstaat was used to analyse the degree to which benthic animals correlate with spatial and temporal dynamics of sediment characteristics. This analysis is based on long-term (7 year) monitoring of a large number of transects in the Westerschelde. Monthly measurements of elevation along the transects, yearly measurement of sediment composition and half-yearly sampling of macrobenthos at the same sites were combined in the analysis.

### 9.3 Suggestions for future research

1. In the study on the macro-scale morphological characterisation of the Western Scheldt an important first step has been made to identify a number of easily-assessable parameters, which can be used as *quantitative indicators* to be used by managers for the assessment of the morphological quality of tidal systems. The link between morphological quality and potentiality for certain ecotopes allows then to set up a tool for the *ecological characterisation* of tidal systems.

The major suggestion for future research arises from the limitations encountered in the study. Some of the improvements needed by the models will be reached in a short time, and have been discussed in the previous sections. In particular, in the author's opinion, the development of a model able to handle morphological cells with channels and shoals, and capable to assess the residual effects, is desirable and necessary.

A further suggestion which is not related to the theoretical aspects of the analysis, but to the practical management of the information, is to share the existing database of the Western Scheldt estuary, for example on a web site open to the public, and to try to merge it with the data of the Belgian part of the estuary. Many researches are

working on this subject and the possibility to have access to such a tool would be broadly appreciated.

2. In the research on process based models, as presented in the report, the effect of vegetation on flow and waves, and its effect on morphology, has been studied separately. This was partly due to the available data of Paulina Schor, in which waves only played a minor role. The combined effect should be studied as well. This would require validation of the model on a case where waves play a more dominant role.
3. Parameterisation to larger scale models and behaviour oriented modelling. Research has to be done on how the results of the process based models can be parameterised and implemented in larger scale predictive models which can be used in practical problems. Knowledge and insight from the process research can be implemented / used in behaviour oriented, i.e. (semi-) empirical models for estuaries including salt marshes.

This was originally planned for the present project but has been omitted due to financial and time constraints.

4. The conceptual modelling approach is now used to study, whether the creation of creek/channel pattern can be coupled to the interaction between mud and vegetation. This is done on different scales and for both the salt marsh and the mudflats. Channels, gullies or channels play an important role in the development of intertidal areas. Insight in their behaviour is therefore relevant when managing these areas.

## A Delft Cluster Research Programme Information

This publication is a result of the Delft Cluster research-program 1999-2002 (ICES-KIS-II), that consists of 7 research themes:

- ▶ Soil and structures, ▶ Risks due to flooding, ▶ Coast and river , ▶ Urban infrastructure,
- ▶ Subsurface management, ▶ Integrated water resources management, ▶ Knowledge management.

This publication is part of:

Research Theme	:	Coast and river	
Baseproject name	:	Ecomorphology of Estuaries and Coasts	
Project name	:	Salt Marsh Cycles	
Projectleader/Institute		Dr. ir Z.B. Wang and Dr.ir. I.C. Tánzos	WL   Delft Hydraulics
Project number	:	<a href="#">03.01.06</a>	
Projectduration	:	01-03-2000	- 30-6-2003
Financial sponsor(s)	:	Delft Cluster	
		EU-DELOS	
		ESTPROC (DEFRA/EA)	
		Alterra, NIOO-CEME, IHE, TNO-MEP, TNO-NITG, TUD, WL Delft Hydraulics	
		RIZA	
		RIKZ	
Projectparticipants	:	Alterra, NIOO-CEME, IHE, TNO-MEP, TNO-NITG, TUD, UU, WL Delft Hydraulics, Haskoning, RIKZ, RIZA and 'Natuur Monumenten'	
Total Project-budget	:	€ 1.262.422	
Number of involved PhD-students	:	1	

Delft Cluster is an open knowledge network of five Delft-based institutes for long-term fundamental strategic research focussed on the sustainable development of densely populated delta areas.



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