Wave reworking of a delta

Process-based modelling of sediment reworking under wave conditions in the deltaic environment

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MSc thesis

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Abstract

A process-based numerical model was applied to look into wave reworking in the deltaic environment. The two main objectives were (1) to develop this model and (2) consequently apply it to study the effects of wave reworking on the morphology and stratigraphy of a delta. A depth-average Delft3D model with two sediment fractions (fine silt and fine sand) was developed. The initial condition was the morphology and stratigraphy of a pre-defined fluvial-dominated delta. This initial condition was first subjected to gentle perpendicular waves for a period of 44 months, for a situation with no active river discharge, to resemble a degrading delta (base case). Next, the reference model was subjected to waves for the same period and varying riverine water and sediment discharges were added to the model (fluvial input case).
The results of these simulations gave a realistic representation of the processes of sediment reworking by waves in the deltaic environment. The deltaic environment rapidly adjusted to changes in the forcing. The base case showed the effects of delta front erosion, channel infill and sediment sorting. Due to the difference in energy required for stirring up and transport of sediments, sand sediments remained in the deltaic environment while silt sediments were transported. This process of sediment sorting is dominant in sediment reworking by waves and is adequately represented by the model. Sand sediments are deposited on the edges of the delta front and thereby shield the underlying fine sediments. The results for the fluvial input case showed similar realistic behaviour and exhibited a switch towards wave-influenced delta morphology and behaviour, as defined by classical delta classifications. Also deposition of sand-ridges around the river mouth was observed and the process of sediment sorting was present. Sand deposits prevented further erosion of fine sediments of the delta front and sand-ridges shield the deltaic environment behind the ridge. This study also demonstrated that the influence of riverine sediment discharge is a steering factor for channel switching.
The model proved to be robust in the sensitivity analysis and provides greater insight in the coupling of morphology and stratigraphy of deltas and delta behaviour. The model therefore contributes to the understanding of the response to changes of processes in the deltaic environment, which is of increasing importance to help to sustain deltas for future generations.

References

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Preface

This thesis concludes my Master of Science at the faculty of Civil Engineering and Geosciences of Delft University of Technology. The graduation project was carried out at Deltares. The base of this project lies in New Orleans, at the Coastal Sediments conference 2007, where I was introduced to modelling of delta development. It resulted in this graduation thesis which matches my ambition to contribute to the solution of an existing problem with social relevance; the increasing pressure on and increased importance of the deltaic environment. Besides, this thesis combines the fields of hydraulic engineering and sedimentary geology and therefore introduced me to (the basics of) a new discipline.

I want to thank my graduation committee for their interest, enthusiasm and support. I thank prof. Marcel Stive for his personal involvement in both my Master in Hydraulic Engineering in general and this graduation specifically. Joep Storms for his continuous enthusiasm and explanations of the basics in geology, geomorphology, sedimentology, long-term morphodynamics and those other fields related to long-term earth processes. I enjoyed calling Nathanael Geleynse with new ideas on the model and discussing them. I got very good feedback from him on every question and every detail, which I highly appreciated. Finally, special thanks to Dirk Jan Walstra, since I could bother him with every question that came to mind at any time and he would find the time to answer it.

I enjoyed working at Deltares, but that would not have been so much fun without the help of my ‘colleagues’ of HYE; especially Jan Joost and Arjen who I asked ‘just another little question’ every day, but also Hans, Pieter, Tim, Cilia, Bas, Radha, Patricia and everybody else. Also, my graduation at Deltares would not have been the same without my fellow graduation students; Renske, Claartje, Johan, John, Claire, Anna, Carola, Steven, Sepehr, Lars, Thijs, Arend, Wouter, Chris, Reynald and especially Roald. I really enjoyed the ‘Friday-pancake-day’ with you.

I thank my family who have supported me from the start. I want to thank my friends for their support and a wonderful time in Delft. However, most of all I want to thank Jeanine for her continuous enthusiasm, interest, patience and all the help during my graduation!

Marten Hillen

Delft, March 2009

Summary

Deltas are densely populated and highly productive areas which are vulnerable to changes in their environment. Currently these areas are under growing threat, mainly because of human-induced pressure. Increased understanding of the response to changes of processes in the deltaic environment will help to sustain deltas for future generations.

The research of deltas is of interest to both hydraulic engineers and geologists, because of the presence of fluvial processes, the dynamic coastal environment and the presence of hydrocarbons. Both disciplines study the deltaic environment but often different approaches have been and still are applied. Greater understanding of deltaic environments can be achieved if interests of both fields are combined. Due to increased computational power and advanced up-scaling algorithms for sediment dynamics it is possible to bridge the gap between these disciplines by applying hydrodynamic models to simulate processes over longer periods. Therefore, this multidisciplinary study investigates delta development from both a morphologic and stratigraphic perspective on meso-scale (years, kilometers) by applying a process-based numerical model to look into wave reworking in the deltaic environment. The two main objectives are (1) to develop this model and (2) consequently apply it to study the effects of wave reworking on the morphology and stratigraphy of a delta.

The depth-average Delft3D model that has been developed simulates the process of meso-scale sediment reworking by free-surface waves in the deltaic environment. It is applied to investigate the effects of waves on the morphology and stratigraphy of a pre-defined fluvial-dominated delta. In the Delft3D model two sediment fractions are present, one representing fine silt sediments and one representing fine sand. The sediment transport formulation of TRANSPOR2004 is used to model both sediment fractions as suspended load and bed load transport. The online sediment method is applied for the morphodynamic update of the bed level. A constant perpendicular wave climate is generated with the 3rd-generation SWAN model, which regularly communicates with the flow field. As initial condition the morphology and stratigraphy of a pre-defined fluvial-dominated delta are used. This delta was developed in another study under comparable conditions. First, this initial condition is subjected to waves for a period of 44 months, for a situation with no active river discharge, resembling a degrading delta (base case). Next, the reference model is subjected to waves for the same period and varying riverine water and sediment discharges are added to the model (fluvial input case).

The results of these simulations give a realistic representation of the processes of sediment reworking by waves in the deltaic environment. The deltaic environment rapidly adjusts to changes in the forcing. The base case shows the effects of delta front erosion, channel infill and sediment sorting. Because of the difference in energy required for stirring up and transport of sediments, sand sediments remain in the deltaic environment while silt sediments are easier stirred up and transported to the lateral sides of the delta or offshore. This process of sediment sorting is a dominant process in sediment reworking by waves and is adequately represented by the developed model. Bed and suspended load transports develop along the delta front. Sand sediments are deposited on the edges of the delta front and thereby shield the underlying fine sediments. The results for the fluvial input case show similar realistic behaviour and also exhibit a switch towards wave-influenced delta morphology and behaviour. The shape of a symmetric wave-influenced delta (according to the classical classification) is

observed. Also deposition of sand-ridges around the river mouth is observed and again the process of sediment sorting is present. The sand deposits on top of fine sediments prevent further erosion of fine sediments of the delta front and sand-ridges shield the deltaic environment behind the ridge, as expected from real life delta behaviour. This study also demonstrates that the influence of riverine sediment discharge into the deltaic environment is a steering factor for channel switching.

The findings of this study are the next step in extending the current body of knowledge on delta development on meso-scale. With research on meso-scale, phenomena of the stratigraphy can be checked with the corresponding development of the morphology over time. This gives extra insight in the construction of the sedimentary framework and in the formation of partially preserved sediments. The model proves to be robust in the sensitivity analysis and therefore it can be surely applied to case-specific approaches. These findings could stimulate researchers to extend the model to different detaic environments and for different conditions. Future delta researchers need to be aware that the sensitivity analysis of this study confirms the importance of (scaling of) the sediment characteristics, especially of fine sediments, as well as the importance of wave-related transports, which are overestimated within Delft3D.

The developed model offers great possibilities for further elaboration and application in delta research. This study provides greater insight in the coupling of morphology and stratigraphy of deltas and in delta behaviour in general. It thereby contributes to future models that will be able to predict the potential behaviour of deltas and their threats in more detail. Therefore this study contributes both to the understanding and sustaining of deltaic environments, which are unique natural and living environments.

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1 Introduction

Deltas are vulnerable areas formed at river mouths at the boundary of land and water. Due to their unique characteristics, such as fertile soils, the presence of a river and large water bodies (oceans or lakes) and a unique ecological environment, these areas are highly attractive for human settlement and commerce. In the last centuries coasts, deltas and rivers have been increasingly modified by man to create a safe living environment and for economic purposes. Port-, shipping-, fishing- and hydrocarbon (oil and gas) industry can be found in deltas, along with agriculture and tourism. Deltas provide an attractive living environment with high productivity and therefore it is not surprising that many of the world's major cities are situated in deltas (Ericson et al., 2006; Smalls and Nicholls, 2003).

Currently the drawbacks of human engineering have however become apparent, through the loss of unique deltaic habitat, poor water quality and (increased) subsidence in deltaic environments. Clearly a better understanding of natural systems is needed to help sustain deltas and to sustain a safe living environment. This study looks into the complex behaviour of the 'natural' deltaic environment, by using a schematized delta, to obtain better understanding of the deltaic environment and its response to changes. This chapter sets the context of this research and sets the field of study within the research context and current ongoing research. The problem statement and objectives of this study are outlined and a reader's guide for the remaining report is provided.

1.1 Research context

Deltas have many different characteristics on different spatial scales and are found in different climate zones over the world. Figure 1.1 shows the worldwide distribution of 40 major deltas (red dots), their drainage basins (in blue) and large reservoirs therein (small yellow dots) as studied by Ericson et al. (2006). Some of the best known major deltas in the world are the Mississippi delta in North-America, the Amazon delta in South-America, the Rhône delta in Europe, the Niger delta in Africa, the Ganges-Brahmaputra delta and the Mekong delta, both in Asia.

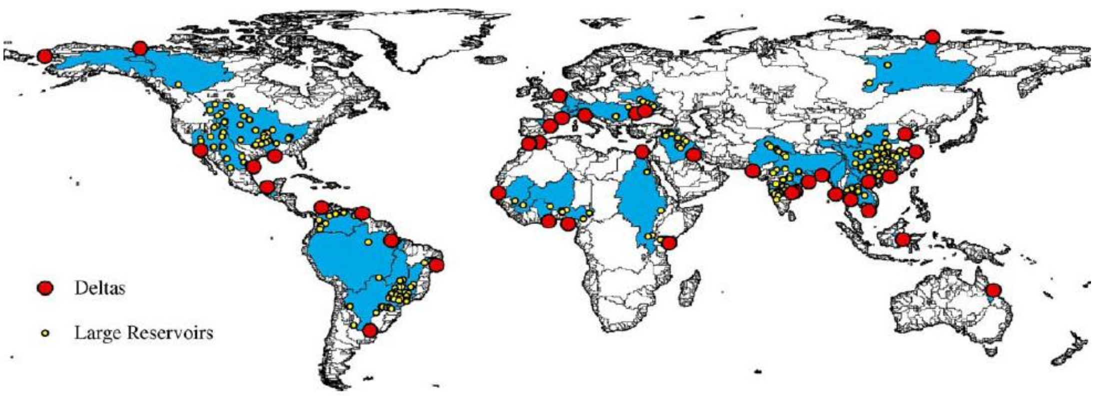

Figure 1.1 Global distribution of 40 large delta systems (Ericson et al., 2006)

Deltas differ from one another in many ways and every deltaic environment has unique characteristics. However, several similarities within the deltaic environment can also be recognized and the general definition of a delta is based on these similar characteristics; a delta is a discrete shoreline protuberance, where a river supplies sediment more rapidly than basinal energy can redistribute it (Reading and Collison, 1996).

Currently increasing attention is paid to deltas and their vulnerability (Ericson et al., 2006; McManus, 2002; Nicholls et al., 2008; Syvitski, 2008; Syvitski and Saito, 2007). Threats to the low-lying deltaic environment are both human and climate induced. These human activities and engineering put increasing pressure on the deltaic environment. The degradation of the delta environment has increased, subsidence of the deltaic area has accelerated and river discharge and river sediment load have changed due to processes such as water extraction, the extraction of hydrocarbons, dredging and modification of river and waterways, the presence of port facilities and other adjustments to the natural environment (Nicholls et al., 2008; Syvitski, 2008; Syvitski and Saito, 2007). An example of these adjustments is given in Figure 1.2 which shows the (expected) deterioration of the Mississippi delta, USA, from 1932 till 2050, with the land loss indicated in red. Human influence is a major contribution to the deterioration of the Mississippi delta (Day et al., 2007).

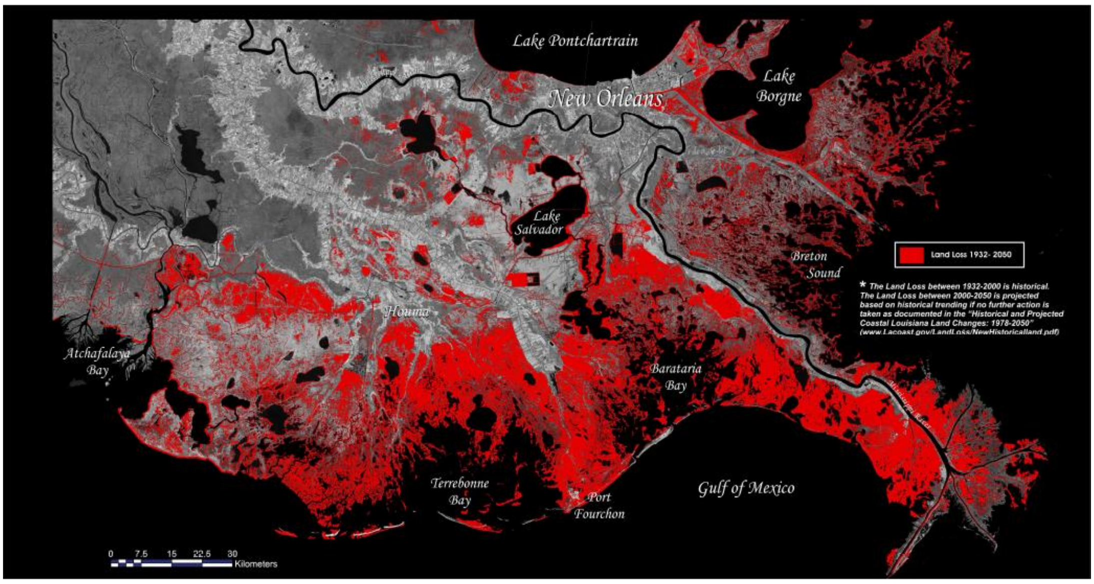

Figure 1.2 Map indicating land loss of the deteriorating Mississippi delta (LaCoast.gov, 2004)

The last decade impacts of storm events in populated deltas such as hurricane Katrina (2005) and cyclone Nargis (2008) highlighted the vulnerability of the deltaic environment. In the future the influence of climate change is also predicted to have a severe impact on deltas (Nicholls et al., 2008). Climate change is predicted to cause sea level rise, change river characteristics, increase the strength and intensity of storms and influence the wave climate (Nicholls et al., 2008). This increased pressure can subject the deltaic environment to flooding, deteriorating and changing environments. Because deltas are densely populated areas and because of their increasing economic importance, better understanding of deltas and the deltaic environment is required.

The causes of threats to deltas have been under investigation by several researchers such as Ericson et al. (2006), Nicholls et al. (2008) and Syvitski (2008). These studies contribute to the body of knowledge on the future pressure on the deltaic environment. By studying deltas, their development and evolution the response of the deltaic environment to these threats and changes can be determined. As deltas are complex dynamic systems a numerical process-based approach should be applied because detailed information is required to study these responses. Therefore, modelling the process of the development of a delta (delta building) and modelling the process of degradation of a delta (delta degradation) can provide insight in the formation and changes of the deltaic environment and the response of the deltaic environment to different forcings. Furthermore the possibility to predict future development of deltas can help to sustain the deltaic living environment and therefore provide an interesting topic of study.

1.2 Field of study and methodology

For hydraulic engineers the hydrodynamics and morphodynamics of the deltaic environment provide a challenging study environment and an important research area . For geologists the unique changing depositional environment and the presence of hydrocarbons in deltas make these areas interesting research areas. Both disciplines study the deltaic environment and the processes under study correspond, or are closely linked to each other, but often different approaches have been and still are applied. Greater understanding of deltaic environments can be achieved if interests of both fields are combined (Storms et al., 2007).

Modelling of the deltaic environment has become more detailed and more elaborated over the last decades. Models of the deltaic environment have been constructed on varying spatial and temporal scales. Geologist use large scale models (10 – 100 kilometers) to study facies sequences formed over long periods of time (10^3 to 10^6 years), where hydrodynamic models that represent the morphologic processes in the coastal and deltaic environment can use a very small scale (millimeters over a period of seconds). Due to increased computational power and advanced upscaling algorithms for sediment dynamics it is possible to bridge the gap between these large scale and small scale models by applying hydrodynamic models to simulate processes over longer periods and thereby acquiring better understanding of processes on meso-scale. In this study meso-scale is defined as the order of magnitude of kilometers (on spatial scale) and years (on temporal scale). On this scale there currently is a lack of understanding between actual measurements (small scales) and stratigraphic data (large scales). This lack of understanding can be regarded as the bridge between the interests of hydraulic engineers and geologists that needs considerable attention (Figure 1.3).

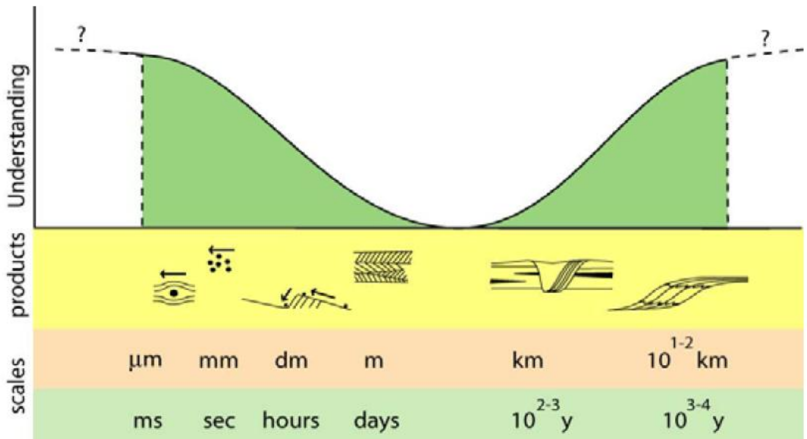

Figure 1.3 Schematization of lack of understanding on meso-scale (Storms et al., 2007)

Processes on meso-scale are important with respect to the evolution of deltas and changes in the morphology and stratigraphy of the deltaic environment. The morphologic processes that determine the sedimentary framework of the deltaic environment shape the delta over a period of years and the size of many deltas and delta lobes is in the order of kilometers. Studying the deltaic environment on this scale can provide extra insight in the processes of sediment deposition and erosion, which cannot always be studied with stratigraphic sequences. These processes occur on relatively small timescales (seconds to years), but have an effect on the facies sequences that have so far only been studied on much larger timescales (10^4 years). The process of erosion, or the process of sediment reworking in the deltaic environment, is interesting to investigate on meso-scale since erosional patterns or degradational sediments are more difficult to determine in the stratigraphy, because only the sediments that are (partially) preserved are found.

Storms et al. (2007) studied the deltaic environment with respect to morphology and stratigraphy on meso-scale. They introduced the use of the hydrodynamic model Delft3D to determine processes on meso-scale and interpret them from both the fields of hydraulic engineering and (sedimentary) geology. Their study illustrated an approach for the initial delta building by river effluents. A recent study by Geleynse builds on this work by focusing on the process of delta building of a fluvial-dominated delta in a well shielded environment (lacustrine environment, or (semi-) enclosed bay), and pays extra attention to the lower part of the alluvial feeder system (Geleynse et al., 2009). The feeder system of a delta is (in most cases, including this one) a river, which transports free-moving (alluvial) land-derived sediments to a basin, such as a lake (lacustrine environment). The characteristics of the delta under study by Geleynse are quite specialized, but in reality several delta systems are found which have corresponding characteristics. Examples of comparable lacustrine deltas, that correspond with the characteristics of the deltas under study by Geleynse, are the Selenga delta in Russia, the Lake St. Clair delta in Canada and the Volga delta in Russia. Plan view images of these deltas in Figure 1.4 show some of these similar characteristics, such as the presence of many distributaries, on different spatial scales.

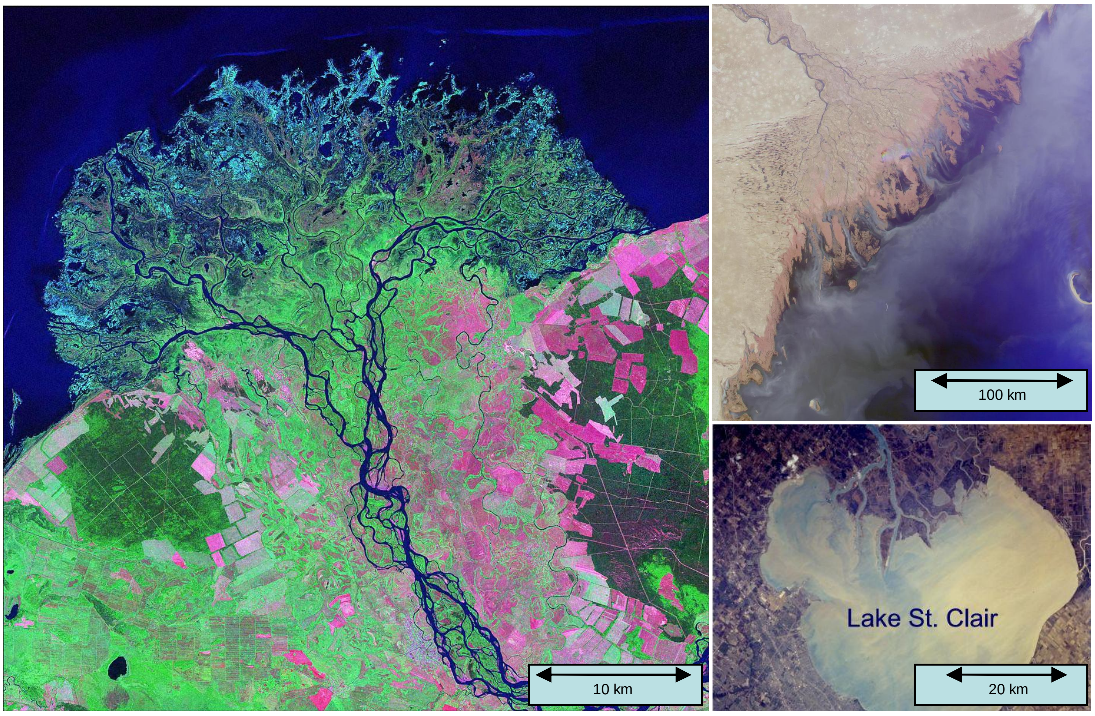

Figure 1.4 *Selenga River delta in Lake Baikal, Russia (left), Volga delta in the Caspian Sea, Russia (upper right) and the Lake St. Clair delta, Canada (lower right) (images by USGS and NASA)*

Also in non-lacustrine environments deltas with similar characteristics to Geleynses example delta can be found. The initial delta building process, as under study by Geleynse, is also comparable with the development of the Atchafalaya and Wax Lake deltas in coastal Louisiana, United States of America. These deltas are situated in the micro-tidal Gulf of Mexico, which has a gentle wave climate (Figure 1.5), but exhibit a similar process of delta building as the earlier mentioned lacustrine deltas.

Figure 1.5 Wax Lake delta (left) and Atchafalaya delta (right) in Louisiana, USA (Google Earth, March 2009)

1.3 Problem statement and objectives

Within the current research on delta building of fluvial-dominated deltas, the processes that occur in a degrading delta are not under investigation yet. In delta degradation sediment reworking by basinal processes is a major process. The major driver of sediment reworking in many deltas is the energy of waves. This study into sediment reworking by waves in the deltaic environment is conducted because relatively little is known on wave-influenced deltas, sediment reworking and the interaction of processes in the deltaic environment and wil therefor contribute to ongoing research in the field of both hydraulic engineers and geologists. This study helps to bridge the knowledge gap between morphology and stratigraphy on meso-scale. Two main research objectives were defined for this study, based on current on-going research, of which an overview is presented in the next chapter, and the problem description. The main objectives of this study are:

1 to develop a process-based morphodynamic model that properly simulates the process of meso-scale sediment reworking by free-surface waves in the deltaic environment.
2 to apply this model to investigate the effect of these waves on both the morphology and stratigraphy of a pre-defined (simulated) fluvial-dominated delta.

These study objectives are elaborated in more detail with the following specific questions, given per main objective:

1 Develop a process-based morphodynamic model that properly simulates the process of meso-scale sediment reworking by free-surface waves in the deltaic environment.

- Is it possible to model the influence of free-surface waves on the deltaic environment? Can the interaction of fluvial- and basinal processes be modelled?
- Is the process of sediment reworking realistically modelled? Are the sediment characteristics and the modelled sediment transport realistic?
- How sensitive are the model outcomes to its parameters and which parameter seems to be most effective? Is the model suitable for a case-specific approach?

2 Apply this model to investigate the effect of these waves on both the morphology and stratigraphy of a pre-defined (simulated) fluvial-dominated delta.

- What are the morphologic and stratigraphic characteristics of the simulated delta?
- Do the modelled morphology and stratigraphy correspond with classic delta classifications, known from literature?
- How does the (wave-influenced) deltaic environment react to changes in fluvial input? What are the specific effects of riverine water and sediment discharge on delta development?

1.4 Reader's guide

In this study the possibilities of a hydrodynamic and morphologic numerical process-based delta model are explored in order to acquire greater understanding in both modelling and the behaviour of the deltaic environment. The context and framework of this study have been provided in this chapter. Chapter 2 gives an overview of the current knowledge on deltas, delta classifications, stratigraphy, sediment reworking and wave influence in the deltaic environment. Chapter 3 describes the process-based numerical model Delft3D in which the model of this study is set up. The specific model set up is outlined in chapter 4 and the results of the simulations carried out for this graduation project and the model sensitivity analysis are discussed in chapter 5. Finally, the conclusions on the study objectives and recommendation and opportunities for further research are provided in chapter 6.

2 Literature study

The term delta was first introduced by the Greek historian Herodotus in the year 450 B.C. when he observed that the shape of the alluvial plain of the Nile river mouth resembled the shape of the uppercase Greek letter delta (Δ). However, the term 'delta' is not restricted to the Nile delta, but also accounts for other delta types. Research on deltas has been conducted for over centuries, mainly because hydrocarbons are found in deltaic sand bodies. Delta research is conducted in different disciplines and has focused on different processes apparent at different scales. Short-term morphologic processes in the deltaic environment, such as longshore sediment transport, have been investigated as well as long-term processes, such as facies development of a delta. In this study the knowledge of some of the major research disciplines, stratigraphy and morphology, is combined in order to gain new insight into the deltaic environment.

In this chapter an overview of relevant literature on processes in the deltaic environment is presented. First, the definition of a delta as used in this study is given, as many definitions have been developed for deltas and the deltaic environment is ordered with respect to different characteristics by zonation of the deltaic environment. Next, different classifications of deltas are reviewed in order to determine this study's framework. Subsequently, an example of the stratigraphy of deltas is discussed in which the changes of the depositional environment of the dynamic deltaic environment over time can be recognized. This evolution of a delta can be described by a cyclic pattern called the deltaic cycle, which is described next. Finally, this chapter deals with the influence of waves within the deltaic environment as degradation of deltas under wave conditions is under investigation in this study.

2.1 Introduction to deltas

2.1.1 Definition

As alluvial sediments (free-moving sediments) reach the shore, they are redistributed by basinal processes such as longshore drift, coastal current drift, waves, storms and tidal currents. In this study the redistribution of sediments is called the reworking of sediments. Combined with the basin's geometry, the interplay of fluvial input and basinal energy determines the shape of a coastline. A difference in the balance between fluvial and basinal processes can cause a coastline to migrate landwards, which is called degradation or transgression, or seawards, referred to as progradation or regression. Many different types of coasts are recognized over the world, such as estuaries, lagoons, deltas and strandplains, based on the variation of fluvial and basinal processes. Figure 2.1 gives an overview of these different coastal landforms and the varying conditions in which a delta can develop.

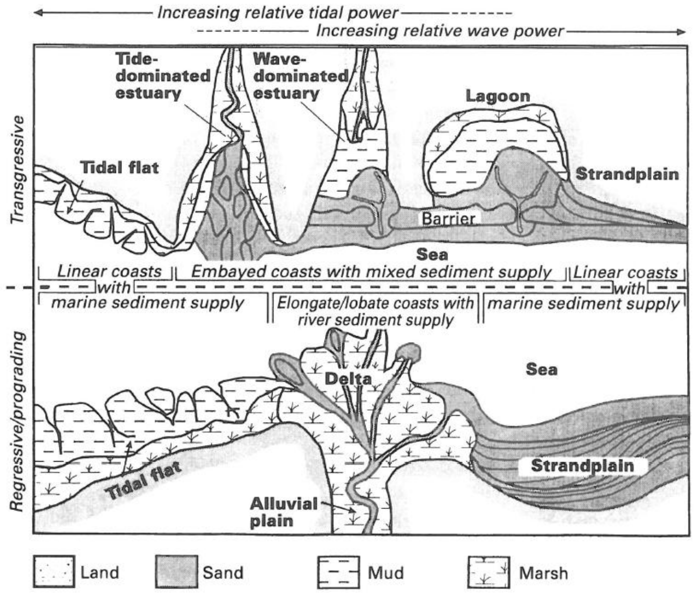

Figure 2.1 Regressive (progradational) and transgressive coasts under varying conditions (based on Boyd, Dalrymple and Zaitlin (1992) in (Reading and Collison, 1996))

The definition and hence classification of deltas is still under discussion. Some characteristics applied in most definitions are the presence of a river, large amounts of alluvial deposits and the interplay of fluvial and basinal processes. A widely accepted definition of a delta was provided as early as 1912 (Barrell, 1912 *in* Nemec, 1990). This definition, combined with comparable definitions used in later studies read: [a delta is] *'the coastal prism of land-derived sediment built by a river into a lake or sea'* (Nemec, 1990). Nemec reviewed delta terminology and rephrased this definition in a more general one: [a delta is an] *'alluvium that has prograded into or against a body of standing water'* (Nemec, 1990). This definition is considered too general for this study, since this study focuses on a river delta and the influence of basinal processes. Therefore the definition of Reading and Collison (1996) is preferred in this study, as it focuses on a river and includes the role of basinal energy. This definition reads: "where a river supplies sediment more rapidly than basinal energy can redistribute, a discrete shoreline protuberance is developed, which is called a delta" (Reading and Collison, 1996).

2.1.2 Zonation

The development of a delta takes place at the boundary between dominant influence of alluvial and basinal processes. Three zones can be distinguished in a delta, the so-called physiographic zones, which are determined by the governing processes in that area. As these zones have their own characteristics it is important to make a distinction between them; the delta plain, the delta front and the prodelta.

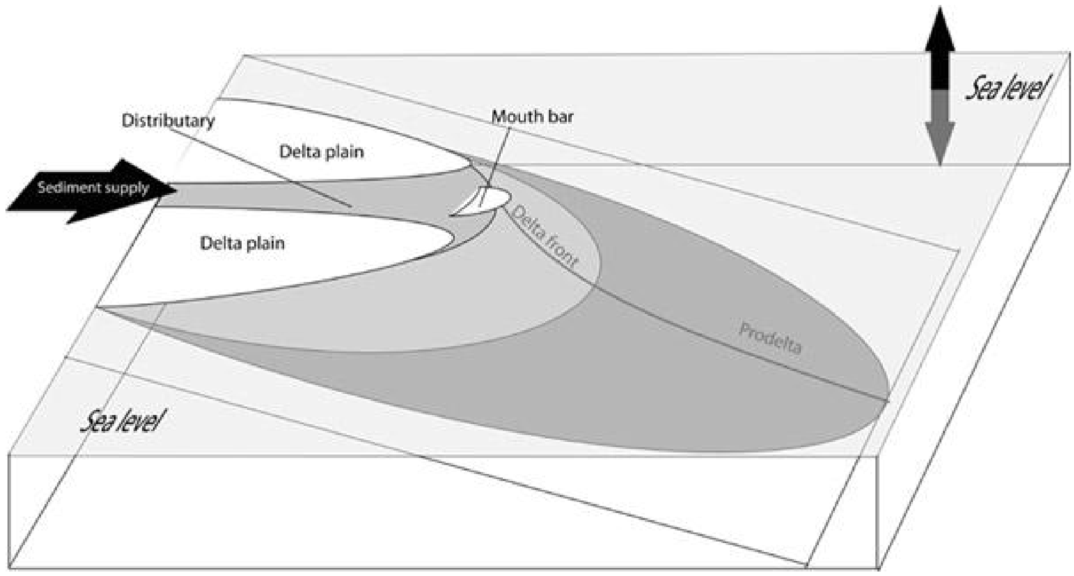

Figure 2.2 Zonation of a delta (Hoogendoorn, 2006)

Figure 2.2 shows a schematization of a delta into these three zones. The delta plain consists of extensive lowlands with active and abandoned distributary channels. In between the channels bays, lagoons, floodplains, marshes and tidal flats can be found. The delta plain is subaerial and in general not (much) affected by basinal processes. The deposits in this area are called the topsets, which are not presented in the figure. The delta front is the area where the interaction between the fluvial processes and basinal processes occurs and here the progradation (or degradation) takes place. In this area distributary mouth bars, beach ridges (if wave-influenced), tidal channels (if tide-influenced) and subaqueous levees are found. The deposits of the delta front are fine-grained, but coarser than in the prodelta, and are seen in the stratigraphy as foresets. The prodelta is the deep water area of the delta. Sediment is deposited here from suspension, so (mostly) very fine sediments (clay to silt) are found here, these deposits are called bottomsets. The prodelta is deep enough for the sediments not to be affected (after deposition) by basinal reworking processes (waves and tides).

2.2 Delta classification

Throughout the years many different classifications of deltas have been developed. Most of these classifications were developed to predict the shape and distribution of the deltaic sand bodies of both ancient and modern deltas, because of the presence of hydrocarbons deeply buried in these sand bodies. The determination of the sedimentary framework of a delta is often based on the delta's morphology, which in turn is the result of the interplay of fluvial and basinal processes. Because of this mutual dependence, delta classifications give insight in both the morphology and the stratigraphy of a delta.

As deltas can contain large hydrocarbon reservoirs in sand bodies at great depth but there is a lack of data on the delta's stratigraphy at this depth, classifications give insight in hard to study characteristics by comparison of certain aspects of a certain delta under investigation with similar delta (systems). Stive et al. (2009) discussed coastal classifications and mentioned that classifications provide an understanding of the dominant processes, which can provide qualitative insight to apply process-based concepts. Classifications can be helpful in communication, e.g. to illustrate a (general) problem. For this study classifications were applied to predict the morphology and stratigraphy of a (model) deltaic environment and thereby provided a validation of model outcomes.

The starting point of research on delta classification are the studies of Gilbert and Barrell, who both studied ancient deltas to find a hydrodynamic explanation for delta formation (Gilbert, 1885 and Barrell, 1912 *in* Miall, 1979). From the 1920s onward the presence of hydrocarbons in the deltaic environment pushed research on deltas. Therefore, untill the 1980s most of the research on deltas was conducted in the Gulf of Mexico and the Mississippi delta became the standard case study for the research on delta processes. A large role in this research was taken by the Coastal Studies Institute of the Louisiana State University and the oil- and gas industry of Houston and New Orleans. Other deltas intensively studied in that period were the Niger delta and the Rhône delta. In this paragraph two classifications of the 1975 are discussed, followed by a classification from 1993 based on a 1970s classification.

The categorization of Nemec (1990), used to review the classifications, is applied in this paragraph, but only with respect to river deltas. Nemec (1990) discussed several classification schemes and reviewed their pros and cons with respect to application by researchers. These classifications were - and still are - well accepted delta classifications. Nemec's discussion also included non-alluvial deltas, not formed by rivers. Figure 2.3 shows this broad division as suggested by Nemec (1990), which includes deltas formed by non-alluvial processes (right) and delta systems build from alluvial sediments, such as river deltas, but also deltas with a different feeder system (left). The definition used in this study, determined in paragraph 2.1.1, only refers to the river delta in Figure 2.3 (upper left).

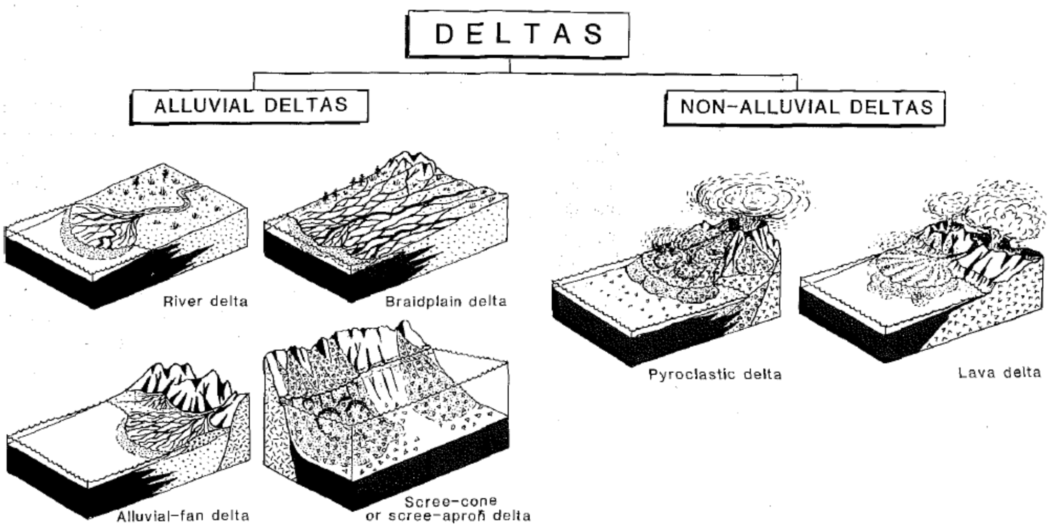

Figure 2.3 Broad division of deltas (Nemec, 1990)

Nemec reviewed the classifications of alluvial deltas on the following criteria:

- Thickness distribution
- Delta front regime
- Delta front regime and grain size
- Feeder system
- Tectono-physiographic setting

In this study only the classifications based on the thickness distribution and the delta-front regime (with and without grain size) are relevant. The classifications based on thickness distribution investigate the links between a delta's morphology and stratigraphy. Both morphology and stratigraphy are modelled in this study and give extra information when combined. The delta front regime classification is interesting since another major aspect of this study, sediment reworking, mainly takes place at the delta front.

The classifications based on thickness distribution and delta front regime show surprising similarities and are still widely applied within delta research. The classifications based on the feeder system and tectono-physiographic setting are not considered here. The classification with respect to the feeder system is left out of consideration, because the focus of this study is on sediment reworking at the delta front for a pre-defined alluvial system. The classification with respect to the tectono-physiographic setting is not assumed relevant since a large focus of these classifications is on the tectonic settings rather than on delta characteristics, which are outside the scope of this study.

Below delta classifications of Coleman and Wright (1975), Galloway (1975) and Orton and Reading (1993), which are yet the most widely applied classification schemes, are discussed. These three studies each highlight one of the criterions; thickness distribution, delta front regime, or delta front regime and grain size.

2.2.1 Coleman and Wright (1975)

In the 1970s Coleman and Wright, both researchers of the Coastal Studies Institute, published on the processes that control the variability of modern river deltas (Coleman and Wright, 1975; Wright and Coleman, 1972; Wright and Coleman, 1973; Wright et al., 1974). The control processes as described by Coleman and Wright, are often applied as a basis for, or included in, other classifications. Their studies provide a clear description of the complexity of the deltaic environment.

The focus of Coleman and Wright was mainly on the sedimentary framework of the deltaic environment. They noticed that the variability in the geometry of subsurface deltaic sand bodies had not been systematically studied, although it was recognized that interacting dynamic processes influenced the deposition of river sediments. Up to then no detailed systematic comparisons between deltas were made and it was not possible yet to predict vertical sequences of deltas. Their studies were originally based on the Mississippi delta, but were quickly set up broader. The resulting extensive study focused on 50 deltas including field studies in 16 deltas to determine the distinctive sedimentary frameworks of a delta and also provides detailed information on several of the world's major deltas (Coleman and Wright, 1975). The study mapped the processes that control (the depositionary framework of) modern river deltas and thereby gives an overview of the governing processes in a delta system.

In Figure 2.4 an overview of the delta control processes as determined by Coleman and Wright is shown. Four parts of a delta are defined, indicated in Figure 2.4 from top to bottom; (1) the basin, which determines the river (water) discharge and sediment, (2) the alluvial valley, which characteristics determine the shape and size of (3) the delta, together with the processes in the receiving basin (4). A more detailed overview of the delta control processes is given by a list of twelve processes, that illustrate the wide variability of processes in the deltaic environment and the influences they can exert on the delta. These twelve factors believed to control the delta and, thereby the distribution of their deposits, are:

1. Climate
2. Relief in drainage basin
3. Water discharge regime
4. Sediment yield
5. River mouth processes
6. Wave power
7. Tidal processes
8. Wind systems
9. Currents
10. Shelf-slope
11. Tectonics of receiving basin
12. Receiving basin geometry

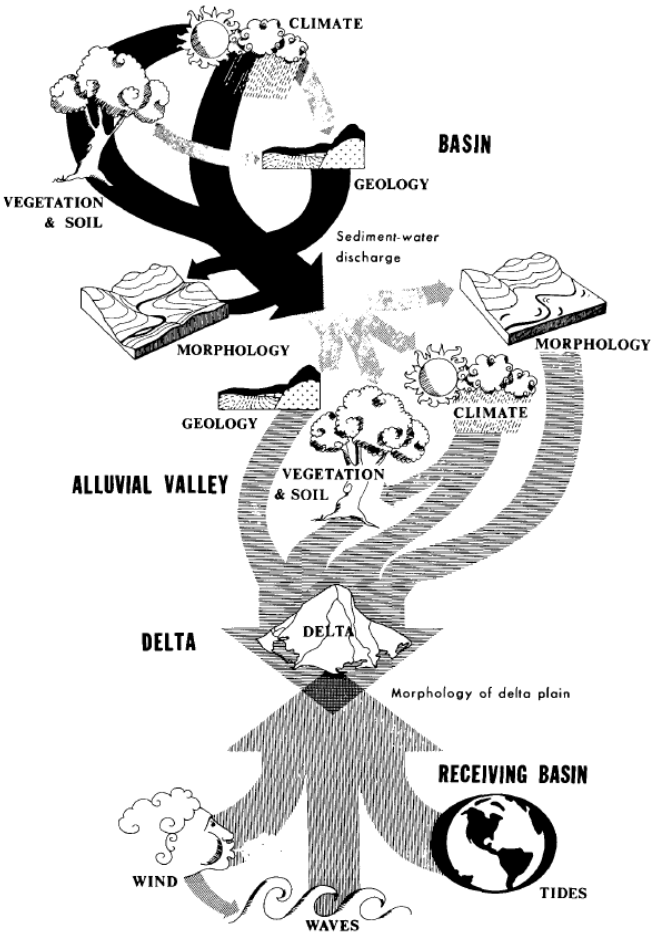

Figure 2.4 Major process controls of a river system according to Coleman and Wright (1975)

The sand distribution patterns are determined by the resulting delta type that on its turn is based on delta characteristics, which are defined by a combination of the control processes. Although one would expect a very large number of delta types, based on these twelve factors, Coleman and Wright (1975) argued that only certain combinations are common, based on the deltas they investigated and field studies they conducted. Combinations of the specific processes result in six types of sand distribution patterns; six end-member types of deltas (Figure 2.5). Type 1 shows a widespread body of sands formed by distributary mouth bar deposits in a low energy basin. Type 2 also has finger-like deposits of sand (like Type 1), but due to tidal influence isolated offshore sand bars are visible. In type 3 the waves rework these isolated sand bars into beach ridges. Beach-barriers are formed in type 4, with behind the barriers lagoonal deposits and a smaller and more landward directed finger-like deposition of sands. The wave-dominated delta type 5 has well sorted sands spread in littoral direction, whereas the sands in type 6 are poorly sorted and deposited in several large elongate bars.

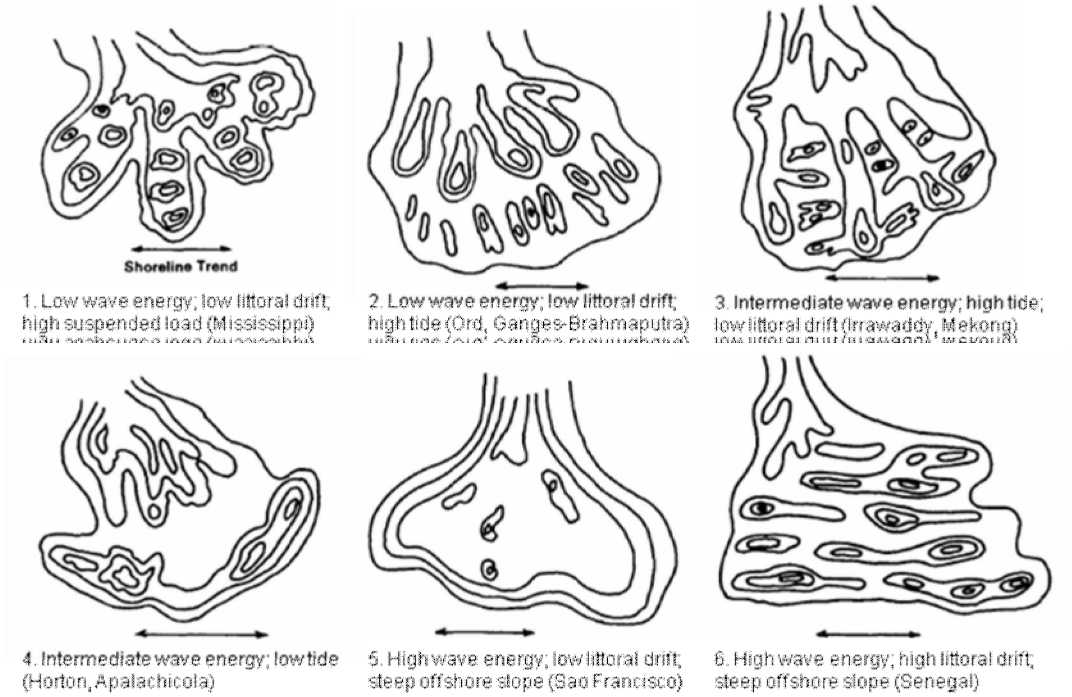

Figure 2.5 Six net sand distribution patters resulting from combinations of control processes (Coleman and Wright, 1975).

A lot of information is required to determine the sand distribution pattern of a delta by the method of Coleman and Wright (twelve distinct control variables, of which most can be (sub) divided into different parameters). Inter-relations, hence generalizations of the twelve control variables are possible (Miall, 1979), which would simplify the classification. Furthermore, when studying a delta, a dataset often already contains more information (than needed for the classification) and in that case the classification is obsolete (Nemec, 1990). The studies of Coleman and Wright came up with extensive information and data-sets on many of the world's major deltas. The listed control processes provides a clear overview of what shapes the deltaic environment. On the other hand, the generic and descriptive classification of the six end-member types gives little information compared to the detailed input required. There is a larger variation in resulting delta types based on the large number of combinations of control processes than is mentioned by Coleman and Wright. This large number of control processes gives a large number of resulting delta types, which calls for process-based modelling of the deltaic environment or a case-specific approach, to determine the depositional facies and morphology of the delta considered.

2.2.2 Galloway (1975)

The probably most well-known classification of modern deltas is provided by Galloway (1975). Galloway realized that modern deltas exhibit a continuous spectrum of morphologic types. This is interesting with respect to the stratigraphy of a delta, because this indicates that an equally broad spectrum of sedimentary facies can be produced by different delta types. Galloway stated that the morphology and stratigraphy of a delta are the product of fluvial sediment input and the reworking by basinal processes. Wave and tidal energy flux are the primary basinal processes that transport and deposit sediments, therefore the morphology suggests two end-member types which are wave or tidal energy dominated. Other basinal processes such as; oceanic currents, wind drift, density currents, and storm surge do not demonstrate forming of (volumetrically) significant framework sand facies within delta systems (Galloway, 1975).

Galloway's classification is a triangular scheme in which a delta can be plotted with respect to the influence of fluvial, wave or tidal processes (Figure 2.6). Each corner of the triangle resembles the influence exerted by fluvial, wave or tidal processes. Where (in the scheme) a particular delta is positioned with respect to these corners (processes) gives an indication of the delta type and characteristics of that delta. The scheme is a basic tool to classify a delta per end-member type and includes examples of modern day deltas per end-member type. Because the position of a delta can be plotted in the scheme by (semi-quantitative) estimation, the scheme of Galloway is a useful and popular scheme. The focus is on the basinal energy processes, which determine the degree of reworking of the delta front. The classification does however not include processes in the river system.

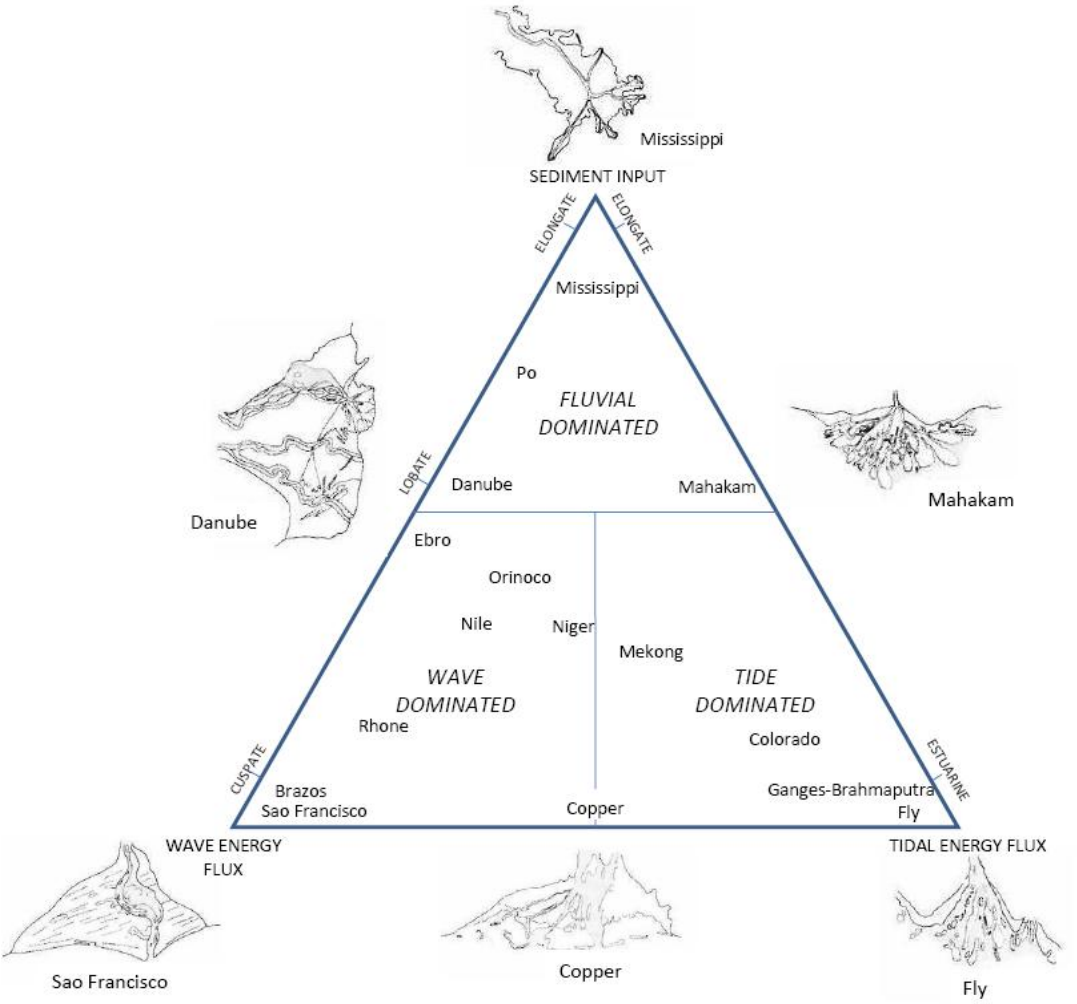

Figure 2.6 Triangular classification of Galloway (1975).

Several studies build on the scheme of Galloway, because it is quite general and can be extended (see also the next paragraph). The six delta types as determined by Coleman and Wright can also be plotted in Galloway's scheme (Figure 2.7), which shows that these six types are not conclusive.

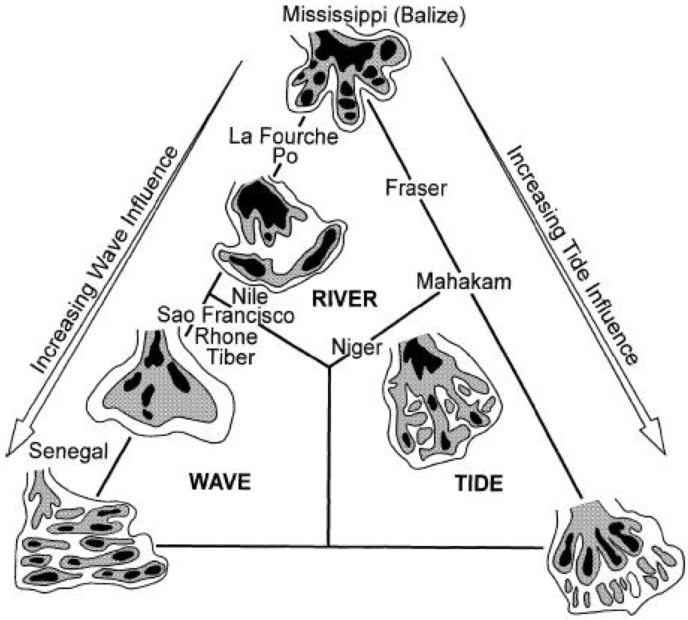

Figure 2.7 Six basic delta types (Coleman and Wright, 1975) plotted on the classification of Galloway (1975) (Bhattacharya and Giosan, 2003).

A drawback of the classification scheme of Galloway is that deltas, which are complex dynamic systems, are force fitted in one place (or part) of the scheme, based on the degree of reworking alone. Deltas with a different morphology and different characteristics can therefore be plotted in the same part of the scheme, if they experience the same degree of reworking. Nemec (1990) stressed that positions in the scheme of Galloway are subject to the researcher's ability to make correct estimates. To determine the position of a delta within the Galloway's scheme semi-quantitative estimates are needed and it is unclear how the degree of reworking should be quantified.

The scheme provides a useful tool for first estimation of an expected delta type given the balance of fluvial and basinal processes and is interesting with respect to sediment reworking because of the focus on the basinal processes. If it would be possible to quantitatively determine the position of a delta within the scheme it would be more accurate. However, many delta characteristics cannot distinctively be represented in the scheme, which obstructs a quantitative approach for Galloway's scheme.

2.2.3 Orton and Reading (1993)

Galloway (1975) paid attention to the role of sediment input and mentioned it as part of the influence of the fluvial input, but did not include it in his diagram. The effectiveness of reworking of sediments by basinal processes in the deltaic environment is however strongly related to the sediment characteristics. A coarse-grained delta responds differently to wave-reworking than a fine-grained delta. Orton and Reading (1993) did go into this and extended the diagram of Galloway with sediment supply, especially focussing on grain size. They argued that, next to river discharge, discharge variability, wave energy flux and tidal range, the deltaic facies is directly affected by the transport and grain size of sediment. Their study illustrated the sensitivity of the deltaic environment to sediment supply and gives examples of the impact of sediments on features and processes in the different zones of the deltaic environment; the distributary channels, delta plain slope and sedimentation in the delta plain, the river mouth behaviour and reworking by basinal processes of the delta front and the (shape of the) prodelta. Also the influence of sediment characteristics on the type of delta system was reviewed by Orton and Reading. Their resulting classification is the tertiary diagram of Galloway, extended with the influence of sediments from very fine to coarse (Figure 2.8). The diagram shows deltas with respect to dominant processes (input, wave or tide) in a Galloway-type triangle in four different cross-sections differentiated by grain size. Images of several deltas are shown, next to the corresponding triangular cross-section of the diagram (Figure 2.8). The dots with two letters in the diagram represent deltas (legend for abbreviations given in Appendix B). The diagram shows that for most modern deltas the dominant characteristic median sediment diameter is fine sand, that no mud/silt deltas are found in a wave-dominated basin and that coarse grained deltas are subject to little tidal influence.

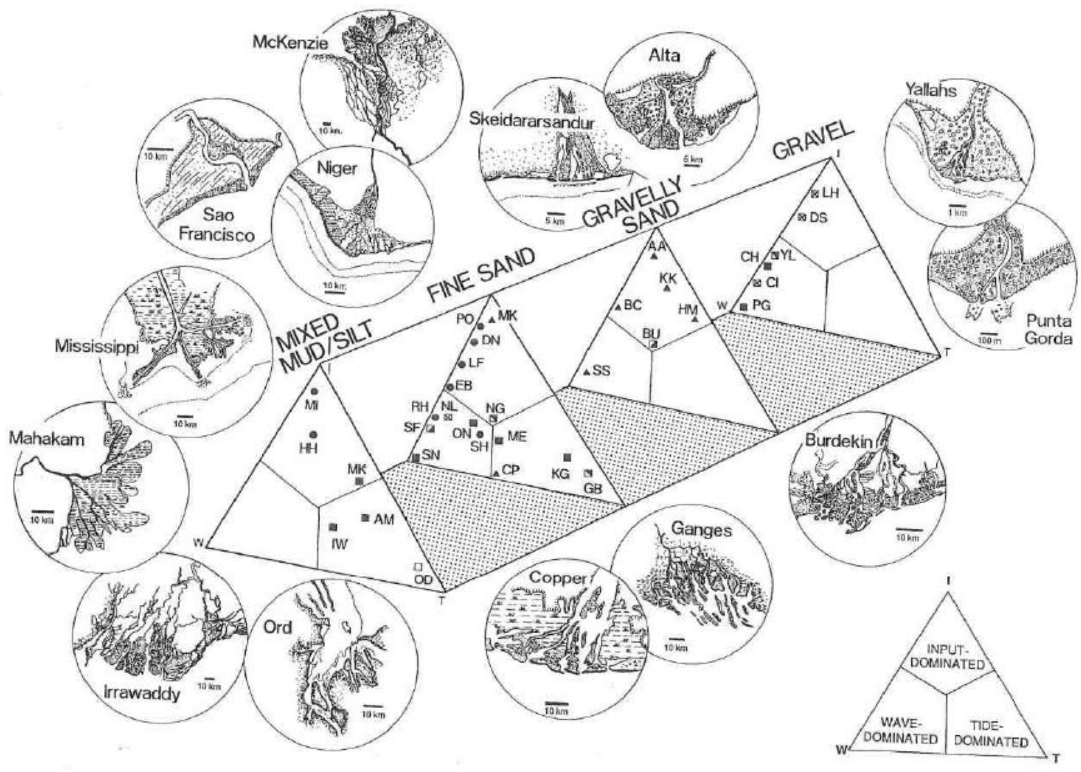

Figure 2.8 Diagram of delta classification based on dominant processes (input, wave or tide) and grain size (Orton and Reading, 1993)

The scheme of Orton and Reading is more elaborated than the diagram of Galloway. It accounts (partly) for effects of the river system by the sediment (supply) characteristics and the degree of reworking is more refined. Because sediment characteristics are relatively easy to determine the diagram helps to compare the ratio of fluvial and basinal processes of similar delta systems (with respect to grain size) and narrows the focus of investigations. However, most of the shortcomings as listed for the classification of Galloway do still apply for this diagram. Another shortcoming of this classification is that it is based on two variables which directly affect each other (degree of reworking and sediment size), which makes the classification less reliable (Nemec, 1990).[1]

1. *The work of Orton and Reading (1993) was not discussed in Nemec (1990), but the study of 1993 is an extended classification build on research of that of Orton (1988), which was reviewed in Nemec (1990). These remarks, however, still apply.*

The classification of Orton and Reading (1993) clearly underlines the importance of taking sediment characteristics into account with respect to delta classification. However, in this study density differences and cohesiveness need to be included besides the grain size because they are important for the morphology and stratigraphy of deltas as well.

2.2.4 Concluding

This paragraph gave an overview of classifications for deltas, each with an emphasis on different aspects and processes in the deltaic environment. Classifications can be applied to determine certain characteristics, determine expected stratigraphy and to categorize certain behaviour. For ancient deltas the classifications are still helpful to that respect, but for modern deltas a classification gives relatively little (new) information, especially for specific scenarios. The classification schemes under review in this paragraph are largely descriptive and generic and (almost) no quantification methods are provided for the reviewed classifications. Delta classifications are, from that perspective, mainly helpful for categorization or communication. For more detailed information, e.g. to determine a delta's specific stratigraphy or future scenarios, deltas should be investigated per case on the specific processes under investigation.

The scheme of Galloway (1975) is applied in this study to describe general delta characteristics and to illustrate changes in the deltaic environment. The control processes of Coleman and Wright (1975) that are of importance to this study are included in the model. Also the importance of sediment characteristics, as shown by Orton and Reading (1993), is taken into account. The classifications show that deltas are dynamic and complex systems and the processes in the deltaic environment interact with one another, which points out the opportunities and importance of process-based modelling. The process-based approach of this study helps to obtain information on specific (delta) cases and the classifications can be used to check the expected behaviour. However the output of the model should provide more detailed and case-specific information on the delta's morphology and stratigraphy (compared with the information provided by the classification). A similar combined approach (i.e. classifications for general information and a process-based approach for specific information) was determined for coasts by Stive et al. (2009).

2.3 Stratigraphy

Delta classifications give insight into both the morphologic and stratigraphic behaviour of a delta. The morphology of a delta determines the depositional environment and thereby influences the stratigraphy. On the other hand, the deposits in the deltaic environment do influence changes in the morphology. To effectively study sediment reworking the stratigraphy of the delta under study should be known. This paragraph gives a short and general introduction in a delta's stratigraphy by describing certain general characteristics.

As indicated by the different delta classifications, many different aspects determine the deltaic environment and due to the wide range of deltaic environments many variations in sequences are found. Still some general characteristics of the stratigraphic sequences can be recognized. For fine grained (sand-silt mixed) deltas, the most commonly observed deltas (Orton and Reading, 1993), the depositional process of a delta is in a certain order. The fine silts and clays of the bottomsets are deposited at first (prodelta) and are covered by foresets (delta front), which consist of coarser silts followed by sands. Deltaic sediments are therefore said to coarsen upwards; the sediments become coarser closer towards the surface (upward direction) over a stratigraphic section. The coarsening upwards is capped by topsets (delta plain) which is a layer of marsh deposits. In Figure 2.9 a cross-section of a delta lobe illustrates the coarsening upwards stratigraphy. The prodelta deposits (first clay, next silty clay) are deposited on the edges of the delta, which builds up the prodelta needed for delta advance. When the delta progrades further into the basin sands of the delta front are deposited on top of these layers. The numbers in Figure 2.9 show the formation in seaward direction, where at stages 3 and 4 distributaries deposit sands on top of the prodelta deposits. Figure 2.9 also shows the sandy character of the distributary channels. The thick marsh deposits on the delta plain put a lot of pressure on the earlier formed deposits (in stages 1 and 2), which causes compaction.

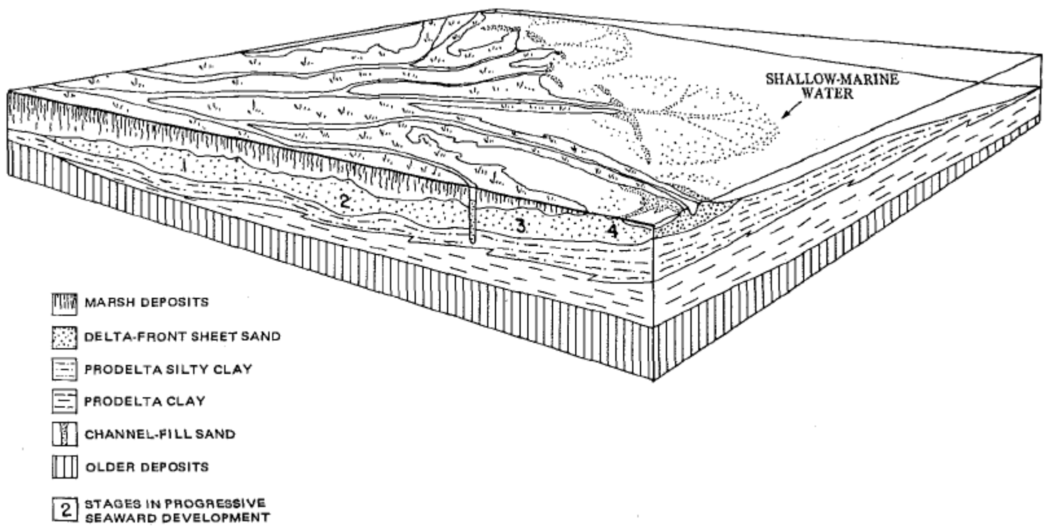

Figure 2.9 Development of a delta – based on the Mississippi delta (Gould, 1970)

Within the deltaic environment sequences of progradational and degradational sediments are found. Progradational deposits are mostly thicker compared to degradational sediments and are generally well preserved in the stratigraphy (Reading and Collison, 1996). Within degradational environments the sediments are reworked and the dominant processes continuously vary, therefore a variety of facies can be found. These sequences are described for three major deltas; Rhône, Niger and Mississippi, but do not have a very characteristic pattern (Reading and Collison, 1996).

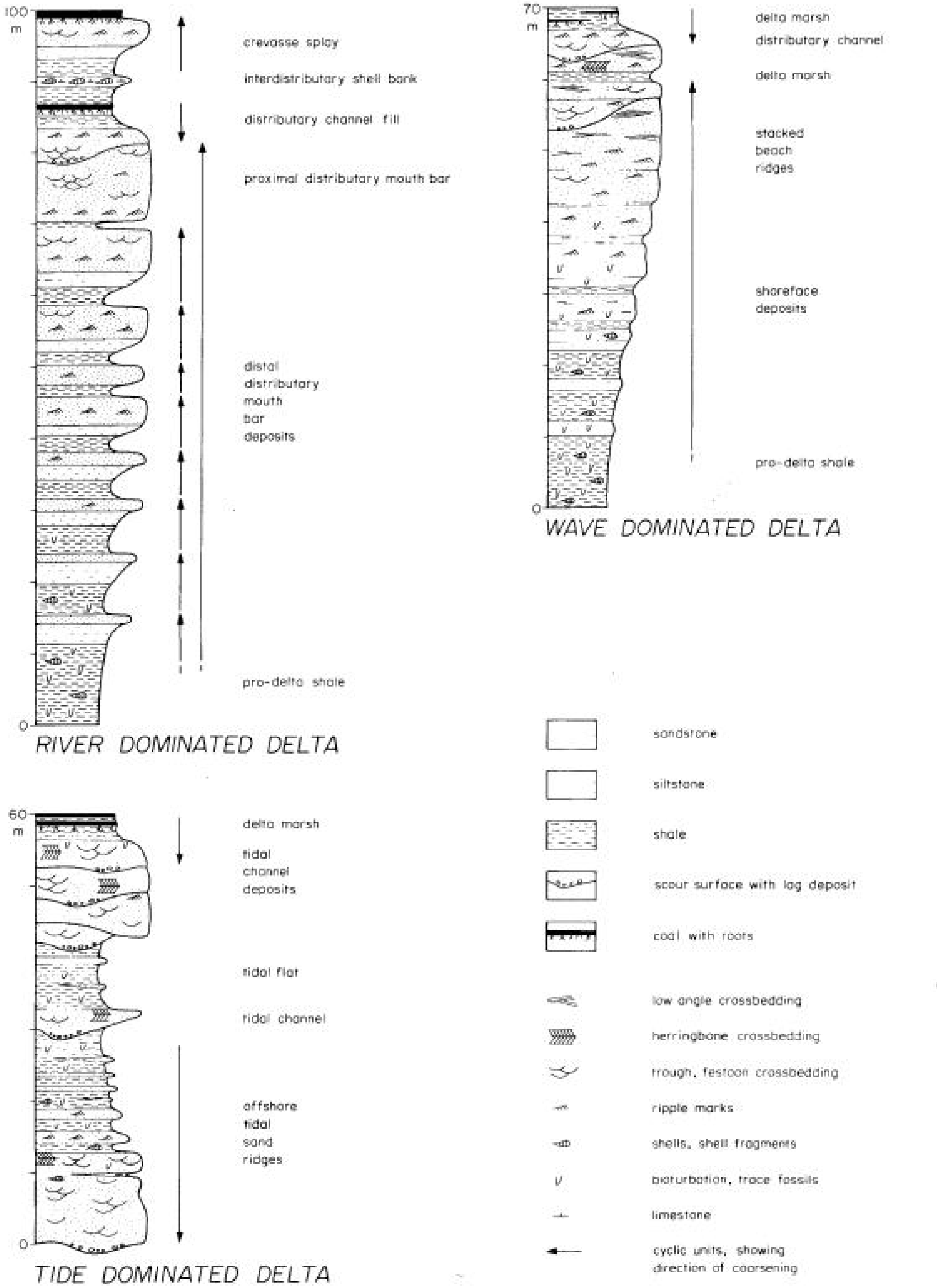

Figure 2.10 Stratigraphic sections of the principal types of deltas (Miall, 1979)

A general description of delta facies sequences can however be given (Miall, 1979; Reading and Collison, 1996), based on the classification of Galloway (1975). Examples of the stratigraphy of a fluvial, wave and tide-dominated delta are given in Figure 2.10. The figure shows stratigraphic sections of three types of deltas in which the stratigraphic order of the facies types is more or less constant (causing the coarsening upwards). The layers however have a varying thickness, due to the difference in character of the depositional environment. The fluvial-dominated sequences (upper left, Figure 2.10) have a relatively large thickness (between 50 meters and 150 meters for large-scale switching of delta lobes) and form a clear example of coarsening upwards.

The sequence starts from prodelta muds, covered by silts and bar fronts, which are laminated packages with well-sorted silts and sands. The topset contains evidence of distributary channels, where slight erosion is found. In wave dominated deltas (upper right, Figure 2.10) beach ridges are found which are deposited and reworked by the waves. In the sequences of the tide dominated delta (lower left, Figure 2.10) the presence of current ridges and tidal channels is visible, which show less well-sorted sands and due to the two-directional flow of the tides the deposits have different orientations.

This paragraph outlined some of the general characteristics of a delta's stratigraphy and explained why deposits of a degrading delta are hard to determine. This study can give greater insight in the depositional processes which determine the stratigraphy of a delta over time under conditions of a stable sea level. Also insight in the formation of degradational sediments can be acquainted, within the limitations of this study. Untill now this was only studied for specific major deltas. Especially since sediment reworking during delta degradation removes deposits from the stratigraphic sequences, studying the process of deposition and erosion on meso-scale will document the changes in the deltaic environment which are not or hardly visible in the stratigraphy.

2.4 Deltaic cycles

The deltaic environment is dynamic and due to altering delta characteristics deltas undergo a life cycle, often exhibiting a characteristic cyclic behavioural pattern; the delta cycle (Scruton, 1960). Two phases in the evolution of a delta can be distinguished, namely the constructional phase and the destructional phase (Scruton, 1960). The phase when the river supplies sediment more rapidly than it can be reworked by basinal processes, the process of delta building, is called the constructional phase. When the sediment supply decreases, often due to a shift of the river to a shorter route to the basin, the basinal processes get the overhand and the delta degrades, this is the destructional phase of the deltaic cycle. The time period of the deltaic cycle is, for major delta systems such as the Mississippi delta, in the order of thousands of years (Miall, 1979).

2.4.1 Cyclic behaviour Mississippi delta

The cyclic behaviour of deltas was discovered at first on large scale for the Mississippi delta where Russell pointed out that several abandoned deltas could be recognized in coastal Louisiana. This study was later revised in greater detail by Kolb and van Lopik (Russell, 1936 and Kolb and van Lopik, 1958 *in* Coleman and Gagliano, 1964). The many shifts of the Mississippi river and their corresponding shifts of the delta lobes make that a number of abandoned deltas in varying stages of deterioration can be found in this area (Coleman and Gagliano, 1964) which can be used to study the cyclic behaviour. Figure 2.11 shows the Mississippi deltas lobes, as identified by Kolb and van Lopik, with the corresponding periods in which they were active. The numbers indicate the different deltas over time (1 is the oldest, 6 is the current delta). The pattern of the deltaic cycle as seen for the Mississippi delta may not be applicable to each delta, but is a clear example of cyclic behaviour of a fluvial-dominated delta. Tide- and wave-dominated deltas can also be described as high-constructive and high-destructive (Miall, 1979).

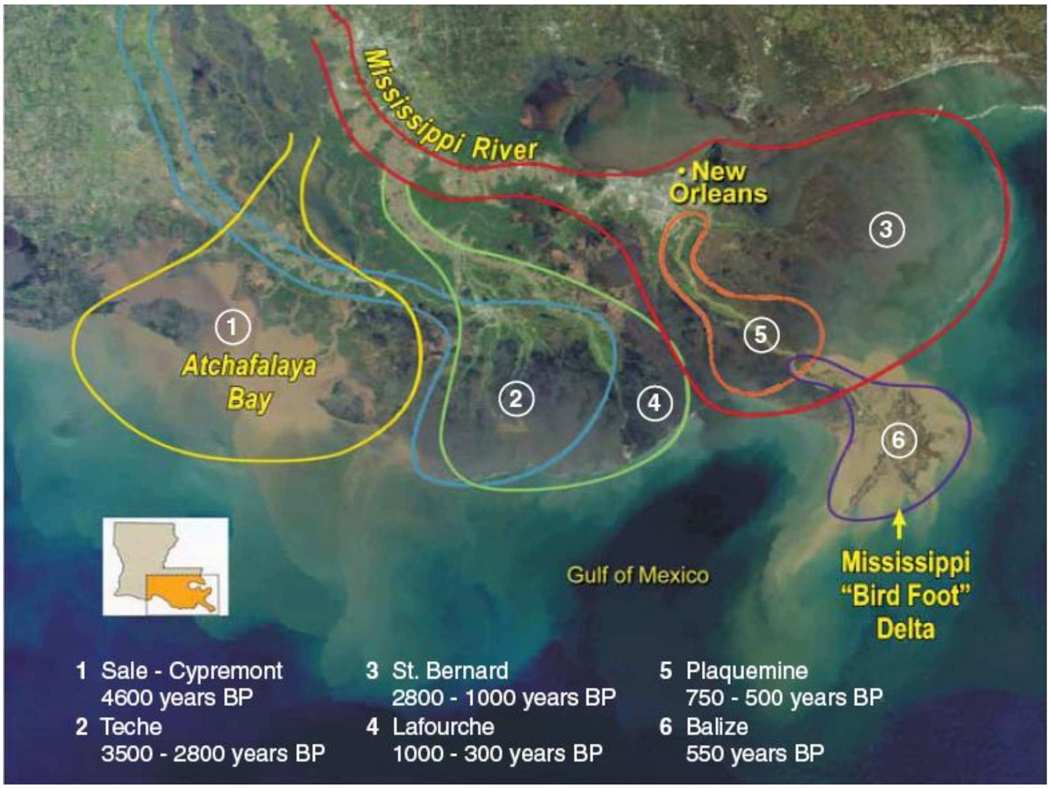

Figure 2.11 History of Mississippi delta lobes, first given by Kolb and van Lopik (Day et al., 2007)

Further research into the Mississippi delta by Coleman and Gagliano (1964) revealed that the cyclic behaviour of a delta is visible on different scales. The following hierarchy is assumed herein (from large to small scale); delta (system), delta lobe/subdelta, sublobe and crevasse. Sublobes or crevasses can be seen as scaled down versions of the major deltaic cycle. Since the lifetime of a crevasse is approximately 100 years, these systems are often well documented and studied (Coleman and Gagliano, 1964). Figure 2.12 shows several crevasses in the current active Mississippi delta, based on a study by Coleman and Gagliano (1964) who mentioned the shift in the point source of sediment as the initiation of a new deltaic cycle. This point source is the river for a (major) delta and a breach in the natural levees in case of a crevasse. A shift in the sediment supply also initiates the start of the degradation of an active delta lobe which is abandoned by its feeder system. Therefore, a switch of the sediment point source starts both a new deltaic cycle and ends an ongoing one.

The deltaic cycle is also visible for the Atchafalaya delta close to the Mississippi delta, which is located in the Atchafalaya Bay (number 1 in Figure 2.11). Due to upstream control structures, 30% of the Mississippi River water was diverted through the Atchafalaya River, which caused the formation of the Atchafalaya delta and later the Wax Lake delta. The following stages of the deltaic cycle were observed during (stages I, II and III) and are predicted for (stage IV) the development of the Atchafalaya delta (Shlemon, 1975):

I. Initial flocculation suspended sediment and deposition far from point source of sediments
II. 15 – 25 years slow subaqueous growth.
III. Rapid subaerial expansion.
IV. Subsidence and compaction, old delta lobes degrade when sediment input disappears and subsidence and waves enhance degradation.

The stages of the deltaic cycle of the Atchafalay delta are comparable with the deltaic cycles of the Mississippi delta (Shlemon, 1975).

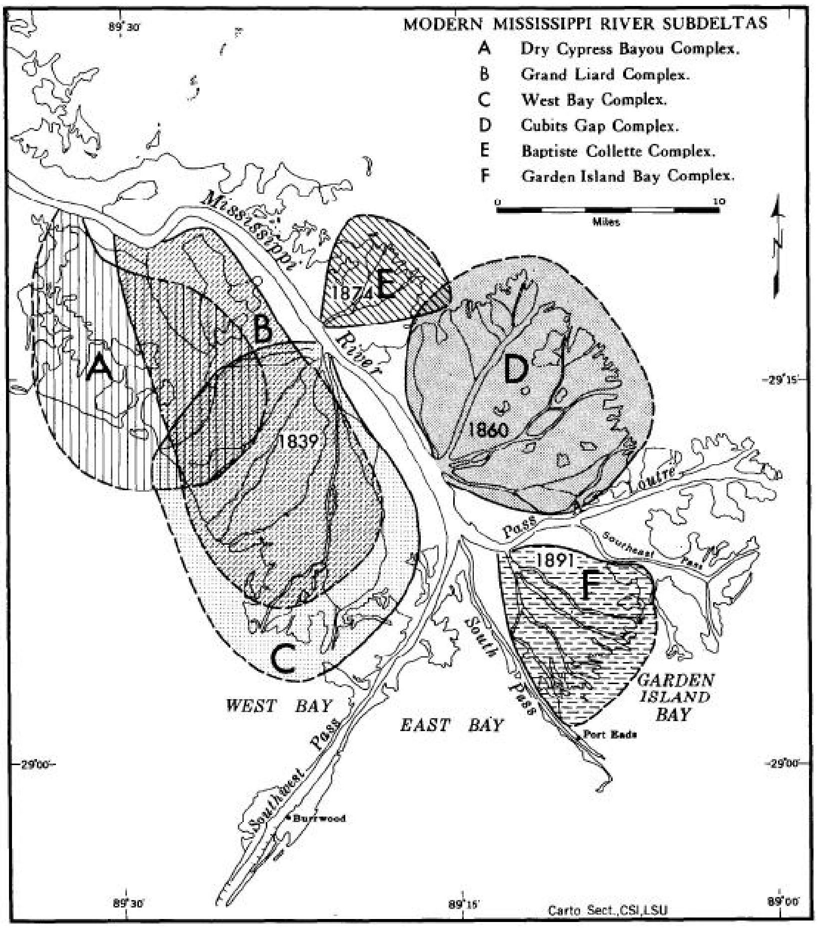

Figure 2.12 Sublobes of the current delta of the Mississippi delta (Coleman and Gagliano, 1964)

2.4.2 Stratigraphy deltaic cycle

The deltaic cycle is well recognizable in a delta's stratigraphy. During the constructional phase of the deltaic cycle the stratigraphy of the delta is formed and the bottomsets, foresets and topsets are deposited. Therefore this phase has been under the interests of geologists. Due to differences in mainly settling velocity, fluid stresses and river discharge, sands are deposited shorewards at the delta front and fine sediments in suspended load are deposited in the prodelta. This process has been studied in detail for the Mississippi delta (e.g. (Coleman and Gagliano, 1964; Fisk et al., 1954; Gould, 1970; Scruton, 1960), but is also seen in many other deltas, such as the Orinoco and Rhône deltas (Scruton, 1960). In Figure 2.13 the constructional phase of a delta is illustrated; large prodelta clays and silts are deposited first, building the delta out seawards, followed by delta front sands close to the sea level. Time lines illustrate the progress of delta building (prograding to the right).

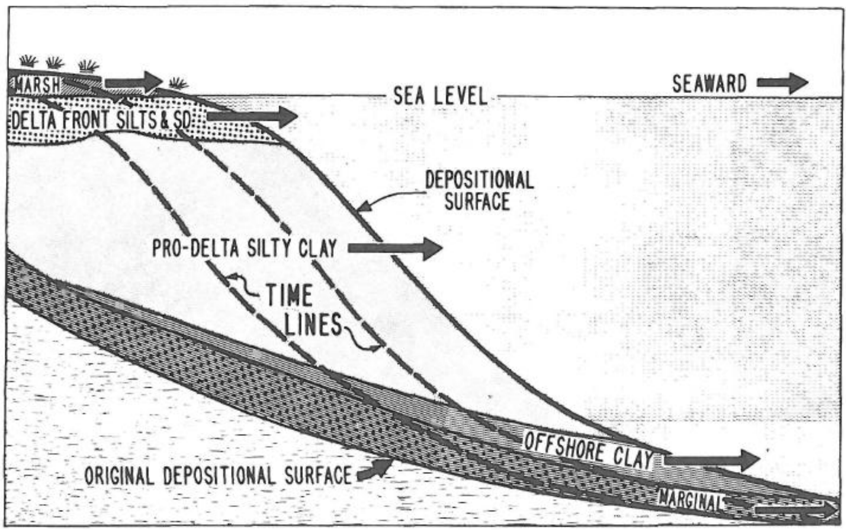

Figure 2.13 Constructional phase of a deltaic cycle (Scruton, 1960)

During the destructional phase, deposits are scoured and transported (reworked), and the facies get thinner and more laminated. Also marine deposits get the overhand and beds of shells are observed. During this period of degradation more variation in the deposits exists and these deposits are harder to interpret. Less general patterns can be recognized, although in specific studies sediment reworking of the destructional phase is recognized in the facies distribution. Curray (1964) described regression and transgression and provided a hypothetical Mississippi subdelta case study, fo which Figure 2.14 shows a section of the subdelta and several phases of deposition. During phase I no distributary is present and transgressive deposits were deposited, phase II and IIIa show the constructional phase of the subdelta and when the subdelta is abandoned (phase IIIb) again transgressive (or degradational) deposits are found. During phase III a stable sea level is assumed.

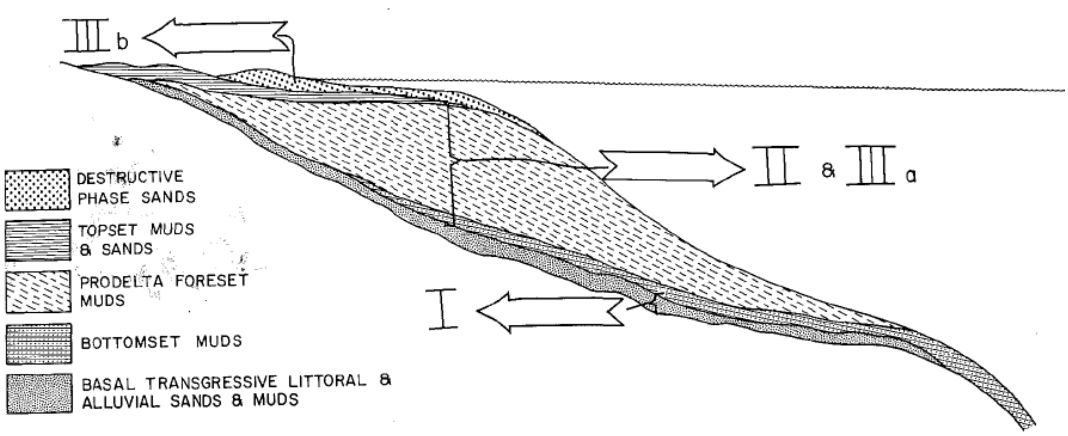

Figure 2.14 Constructional and destructional phase of delta (Curray, 1964)

Also in a delta's stratigraphy a succession of environmental events can be recognized (Coleman and Gagliano, 1964). Figure 2.15 shows a core of about 70 meters (220 feet) drilled near the current Mississippi river mouth. Three deltaic cycles can be distiguished from this stratigraphic section. Each deltaic cycle exhibits the same succession of depositional events: the prodelta clays, which are the subaqueous stage of the delta formation, followed by coarser sediments of the delta front, next the interdistributary bay deposits are found combined with natural levees. Due to continuous sedimentation in the deltaic environment the different delta cycles can be identified in cores by bounding sediments. These bouding sediments are deposited in between delta cycles and are layers of marsh deposits or marine clays and shells. Because of the drilling location (at the prodelta of the St. Bernard delta) no crevasse or inter-distributary bay deposits are found in Cycle B.

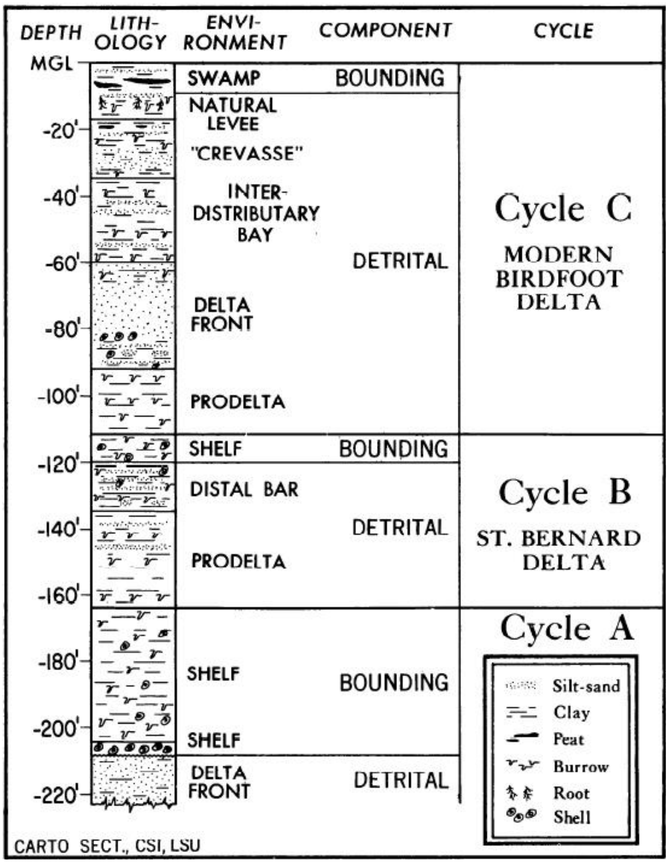

Figure 2.15 Stratigraphic section from a Fort Jackson boring in the modern Mississippi birdfoot delta (Coleman and Gagliano, 1964)

2.4.3 Wave influence on the deltaic cycle

As described in the previous paragraphs, sediment reworking is one of the causes of delta degradation during the destructional phase of the deltaic cycle. For deltas situated in an environment with wave influence (from fluvial-dominated to wave-dominated deltas) waves are the major energy source for sediment reworking in a degrading delta. As a delta progrades in offshore direction the amount of wave energy that is absorbed by the delta (mainly at the delta front) increases. Also, the sediment supply delivered by the river is distributed over a larger area. At some point the delta is prograded into the basin where the basinal processes get the overhand. In the destructional phase, often initiated by a decrease in sediment supply, the sediment supply is not sufficient to sustain the deltaic environment. Deepening by sediment reworking of the foreshore enhances the reworking process, because consequently higher wave energy arrives at the delta front. This way the degradational conditions of the destructional phase start and continue. A decrease in sediment supply of a fluvial-dominated delta in a modest wave climate will therefore make this delta shift from fluvial-dominated via wave-influenced to wave-dominated.

Galloway (1975) described this delta evolution as a switch from a fluvial-dominated delta to a wave dominated delta. Figure 2.16 shows a stratigraphic section of the evolution of a delta resulting from a decrease in sediment input he developed as an illustration of this phenomenon. The delta changes from a fluvial-dominated (F) prograding delta into a fluvial-dominated lobate influenced by waves (F/W) and finally to a fluvial-influence delta dominated by waves (W/F). In the next paragraph the influence of waves on the deltaic environment is discussed in more detail.

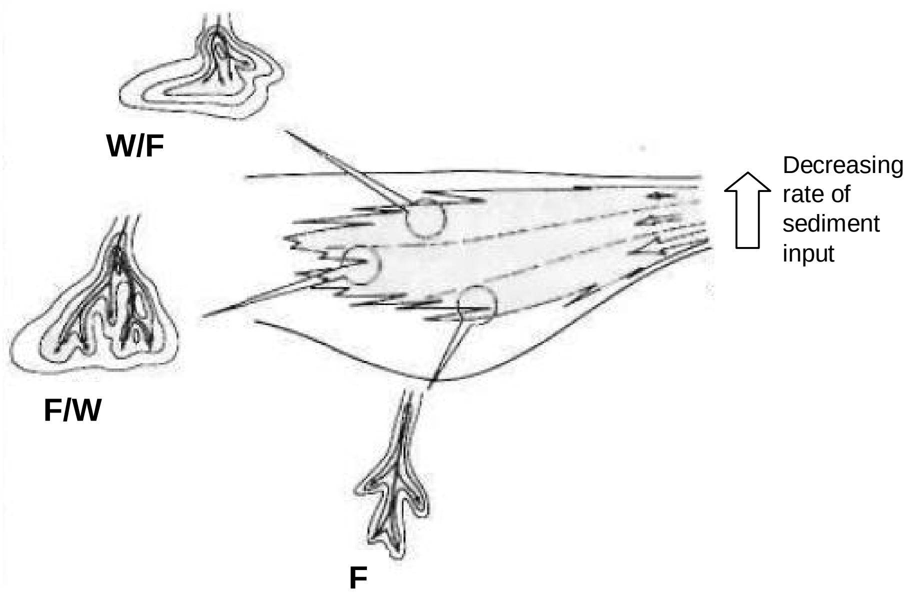

Figure 2.16 Stratigraphic section illustrating the evolution of a delta (Galloway, 1975)

2.4.4 Concluding

Within this study the deltaic cycle is of interest since it provides a framework in which a degrading delta can be regarded as a delta in the destructional phase. Because progradational sediments are clearly visible in stratigraphic sequences of a delta, this phase is relatively well studied. However, little is known about the destructional phase of the deltaic cycle. Influence of sediment reworking causes the destructional phase and is often determined by waves that become the dominant process. To study sediment reworking and delta degradation, the focus of this study is on the destructional phase. Also, sediment supply is of major importance in the process of the deltaic cycle. The shift in point source of sediment supply, induced by delta switching, can start the destructional phase in which sediment reworking gradually takes over. Therefore a change in the river characteristics (and thus sediment supply to the delta) may change the delta's behaviour significantly. In this study, to investigate sediment reworking, the sediment supply to the modelled delta is stopped in order to get the sediment reworking to take over and get the delta in the destructional phase of the deltaic cycle. In addition, the impact of waves on the deltaic environment is investigated to study sediment reworking.

2.5 Wave influence on deltas

Waves are considered the governing marine process in coastline development (Reading and Collison, 1996; Wright and Coleman, 1973) and wave influence is one of the main influences in the deltaic environment. Degrading or abandoned deltas are subject to reworking by waves. This is valid for environments where the influence of tides is negligible or much smaller compared to the fluvial and wave processes. As determined in paragraph 2.4.3 waves have a major role in sediment reworking in the deltaic environment. Wave influence on deltas causes sorting of sediments due to the different responses of (the difference in) coarse and fine sediments on the reworking processes. The influence of waves largely shapes the deltaic environment. Combined with the variability in sediment supply different features develop. In a delta under wave conditions with a high sediment supply beach-ridges and a gentle well-sorted slope are found. A lower sediment supply gives barriers with spits of which the spits disappear if the sediment supply is even lower.

2.5.1 Sediment reworking by waves

Sediment reworking in the deltaic environment by waves can be divided into two steps. The first step is initiation of motion of sediment in the bed by the stirring up sediments by the oscillating motion of the waves and the energy of breaking waves. Next, the sediment particles are stirred up and transported by currents.

Sediment characteristics have a major impact on the process of sediment reworking. The difference in the response to sediment reworking by waves of the coarse and fine sediments is of interest for the deltaic environment since it causes sediment sorting and is responsible for the formation of features as beach-ridges, barriers and spits. The initiation of motion and transport of sediment particles depends on the sediment characteristics. Fine sediments can be easily stirred up and transported, where sands require more energy to be mobilized. This explains the presence of sands in wave-influenced environments.

Coarse sediments are transported by bed- and suspended load transport and fine sediments mainly by suspended load transport. Wave induced transport can be directed both onshore and offshore; near the surface the sediment transport is generally directed landwards (onshore) and near the bottom a return current is formed which transports sediments seawards (offshore). Wave asymmetry results in onshore sediment transport. If waves approach the shoreline under a certain angle a net longshore transport is present.

In general an environment with high wave power has concave well-sorted shores and a low wave environment has convex offshore profiles with poorly sorted sands (Coleman, 1976). General stratigraphic environments associated with waves are beach-ridges, sand facies and degradational elements. With respect to the morphology, wave reworking may cause landward degradation and form barriers, beach or dune complexes (Coleman, 1976). These elements are considered part of the destructional phase of the deltaic cycle that is under study.

2.5.2 Characteristics wave-influenced deltas

Wave-influenced deltas are relatively complex to represent in a model because the variation and interaction of fluvial and basinal factors complicates modelling of the deltaic environment and facies. The delta classifications discussed in paragraph 2.2 give only general information for wave-influenced deltas and their facies. Also the scarcity of data on wave-influenced deltas has so far caused a lack of quantitative models. Recently more advanced models have been developed to investigate the distribution of sand bodies in the deltaic environment (Bhattacharya and Giosan, 2003) and investigate the medium-term development of a wave-influenced delta (van Maren, 2004), but sound predictions are still hard to make.

Wright and Coleman (1973) reviewed the influence of waves on 7 major river deltas subject to varying wave climates. These deltas covered the spectrum from fluvial-dominated to wave-dominated on the triangular scheme of Galloway (1975). The morphology, the ratio between river discharge and wave force (discharge effectiveness index) and the role of the subaqueous slope were compared and general characteristics of the facies sequences were determined. The possibility of waves to influence the deltas morphology was determined by the ratio between river discharge and wave force and the role of the subaqueous slope (Wright and Coleman, 1972; Wright and Coleman, 1973). A relative high wave force and a steep subaqueous slope were found to be favourable conditions for wave impact. The determined characteristics and the resulting typical deltaic sequences description however remained general and are therefore not always applicable to other wave-influenced deltas due to the large variation in resulting delta morphologies.

Symmetric wave-influenced deltas (with little longshore drift) quite accurately match the classifications of Wright and Coleman (1973), Coleman and Wright (1975) and Galloway (1975). In these deltas deposits of sand-ridges are found on both sides of the river mouth. This behaviour has already been modelled with a relatively simple computer model by Komar (1973), who found quite accurate results for perpendicular incoming waves, but was not able to correctly model oblique incoming waves. When Wright (1977) studied river mouth behaviour, he determined the distribution patterns of deposits near the river mouth behaviour in detail, of which Figure 2.17 shows examples of:

a. a typically wave dominated delta front (left) with perpendicular incoming waves; sand-ridges are found on both sides of the river mouths and a symmetric equilibrium profile is visible with a decreasing angle, with respect to the incoming waves, further away from the river mouth,
b. a delta front (right) where oblique incoming waves shift the river mouth and irregular sand-ridges and a longshore current are formed.

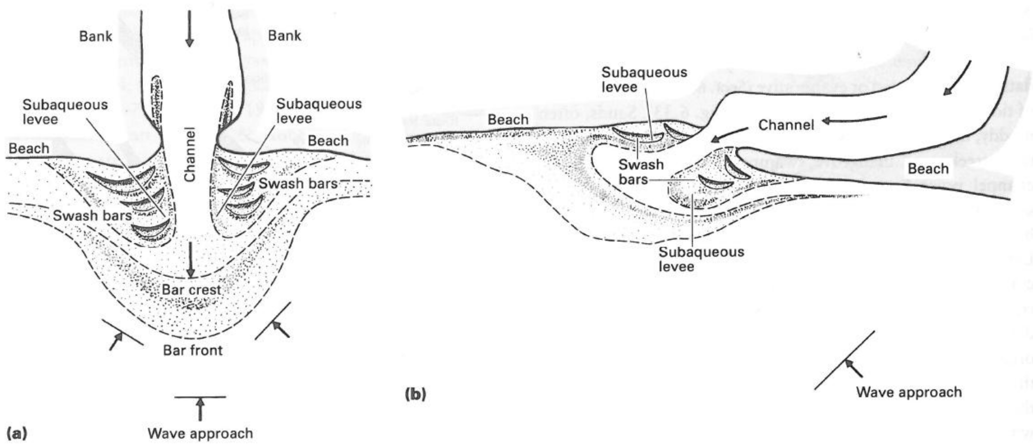

Figure 2.17 Wave-dominated river mouth settings (Wright, 1977)

The facies in situation (a) of Figure 2.17 are easier to predict than in situation (b) where there is a larger complexity of processes which in turn can cause a wide range of (changing) morphologies and a wide range of resulting facies distribution. Figure 2.18 (Reading and Collison, 1996) shows the possible influence of waves on the river mouth processes. The figure shows that bed load transports generated by the outflowing river water (indicated by the thick black arrows) are deflected due to incoming waves. During flood stages the fluvial related currents are dominant (smaller black arrows in Figure 2.18). The information on symmetric wave-influenced deltas that is visualized is relatively accurate, but as several conditions can exist, specific information on wave-influenced deltas with a higher complexity was not presented in Wright (1977) or Reading and Collison (1996).

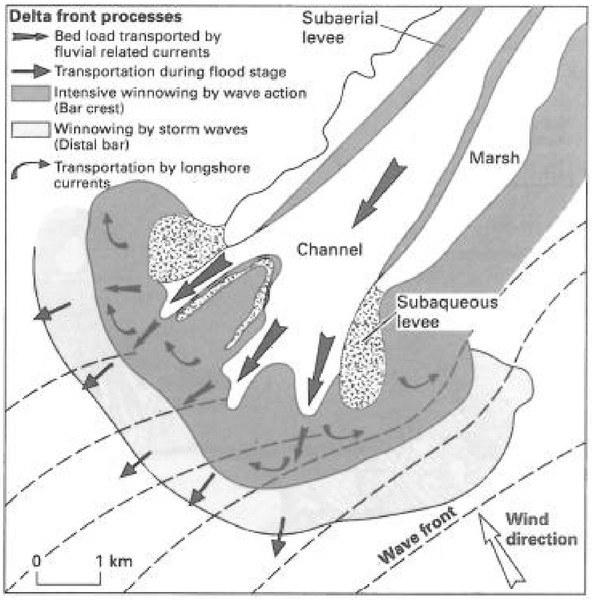

Figure 2.18 Delta front processes (Coleman and Gagliano, 1965 adjusted by (Reading and Collison, 1996))

To identify the distribution of (sand) facies in wave-influenced deltas, Bhattacharya and Giosan (2003) developed a model to predict the facies distribution of wave-influence deltas. They developed a conceptual model, based on several case studies, which addressed the influence of waves. This model divides the development of a wave-influenced delta into three phases (Figure 2.19); (A) the development of a subaqueous delta (prodelta), (B) the development of a middle-ground bar phase and (C) the formation of a barrier island at the downdrift side of the river mouth. Within this process sands are deposited on the updrift side of the river mouth and fine and less sorted deposits are found at the downdrift side, where sandy barrier islands form elongate lakes which act as sediment traps for fine sediments (silt). Important in Bhattacharya and Giosan's model is the asymmetry of wave-influenced deltas, which gives an asymmetric morphology and facies distribution, and which is assessed via an asymmetry index (ratio river discharge and longshore drift).

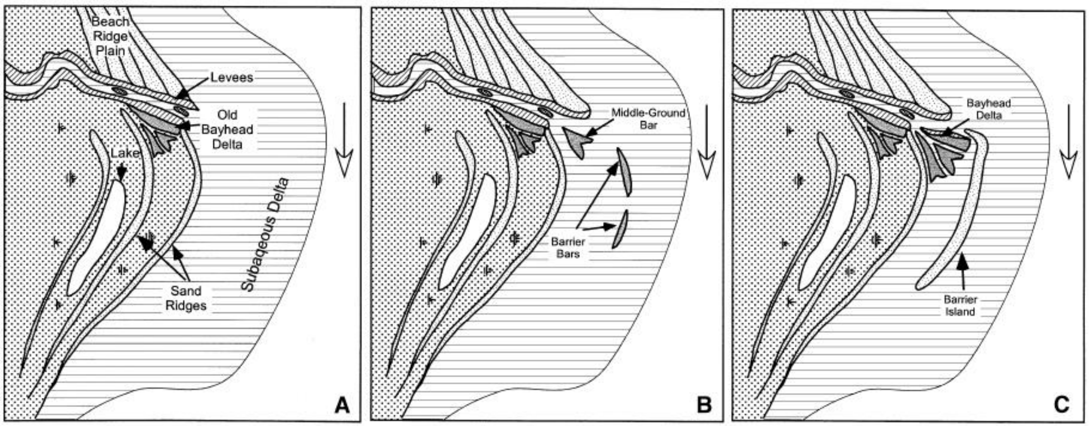

Figure 2.19 Wave-influenced delta evolution model, with subaqueous phase (A), middle-ground bar phase (B) and barrier island phase (C) (Bhattacharya and Giosan, 2003).

The model of Bhattacharya and Giosan (2003) also determined that facies of wave-influenced deltas may contain facies elements which are normally associated with non deltaic or destructional phase deposits. Another general characteristic of wave-influenced deltas is that the sediment supply is partly river-derived sand and partly (old) river-derived sand that is reworked from abandoned delta lobes and transported via longshore drift. A lot of the sediment in wave-influenced deltas can therefore be longshore derived rather than supplied by the river.

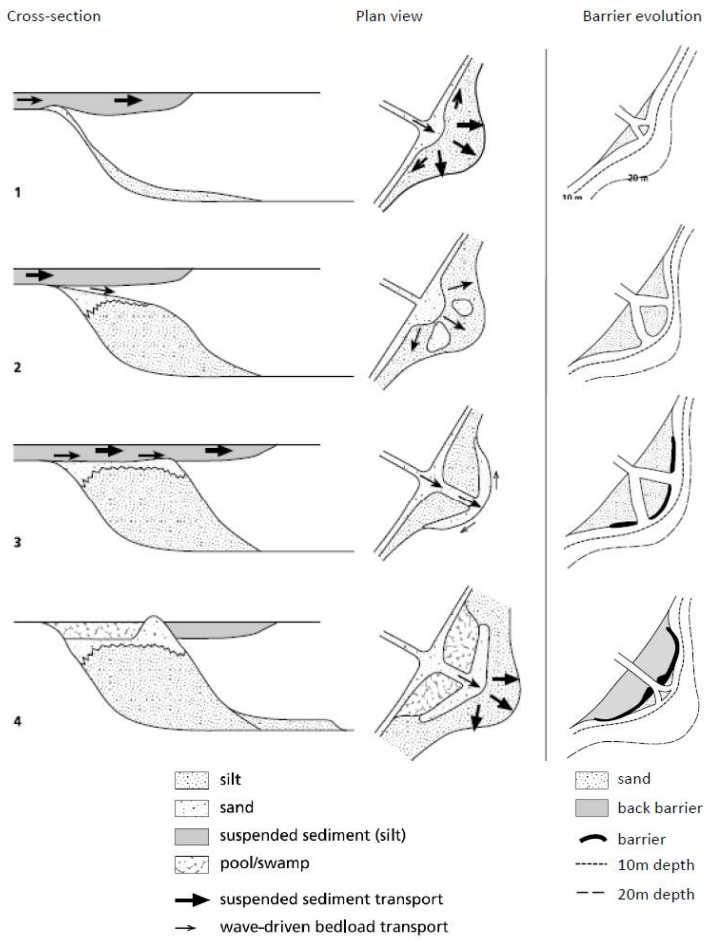

Figure 2.20 Cyclic delta growth (lef) and barrier evolution (right) of the Ba Lat delta (van Maren, 2004)

Van Maren (2004) investigated the Ba Lat delta, a delta at one of the distributaries of the Red River in Vietnam. Van Maren (2004) stressed the high complexity of a wave-influenced delta and the processes of sediment sorting under waves and the formation of sand barriers. The study focused on the cyclic progradation of this wave-influenced delta. The formation of this delta exhibits a cyclic behaviour, in which both fluvial-dominated and wave-dominated stages exists. Important in the prograding cycle of this delta is the sand barrier formed at the delta front due to wave reworking. The process is shown in Figure 2.20 in which the cyclic delta growth is indicated on the left and the barrier evolution on the right. First, the sediments at the river mouth build a subaqueous delta which effectively reduces wave energy (stage 1). When the delta progrades further (stage 2) a point is reached where onshore sediment transport by waves take over and a barrier is formed (stage 3). Finally, a wave-dominated situation exists where the area behind the barrier is filled with fine sediments and a new river mouth is formed in front of this barrier (stage 4). The duration of the cycle is approximately 100 years in which the Ba Lat delta progrades 5 kilometres (van Maren, 2004).

2.5.3 Concluding

Waves play a major role in sediment reworking in the deltaic environment. Sorting of sediments occurs and sand-ridges are expected in a wave-influenced environment and especially the processes around the river mouth at the delta front have a major influence on the deltaic environment. However, the variation and interaction of fluvial and wave processes make the morphology and stratigraphy of a wave-influenced-delta hard to predict. Situations with perpendicular incoming waves, called symmetric wave-influenced deltas, can be relatively well predicted. A larger variation occurs in the morphology and facies of an asymmetric wave-influenced delta and the prediction thereof. The approach of Bhattacharya and Giosan (2003) gives more insight in the expected stratigraphy than the classic delta classifications, but only in a qualitative way. The large variability of processes in cases in which waves are involved makes a case-specific process-based approach desirable.

3 Delft3D

In this study a model is set up in Delft3D. To understand the model set up an explanation of Delft3D is presented. The process-based numerical model Delft3D is a software package under continuous development by Deltares. It offers a multi-disciplinary approach and 1D, 2D and 3D computations for coastal, river and estuarine areas. Delft3D consists of several modules, which interact with each other and each focus on a specific process; flows, sediment transports, water quality, ecology, morphological behaviour and waves.

This chapter describes Delft3D, its mathematical background and the modules used in this study, to give insight in the principles underlying the software package. The numerical aspects as well as the application and use of the morphological module of Delft3D have been extensively described by Lesser et al. (2004) and for a depth-averaged approach by van der Wegen and Roelvink (2008). For practical use is referred to the Delft3D manuals, especially the Delft3D-Flow User Manual (Deltares, 2007a).

3.1 Delft3D-Online

This study used the hydrodynamic simulation module Delft3D-Flow, which includes the morphological simulation, in combination with the Delft3D-Wave module. The 'online' approach (Roelvink, 2006) was applied, in which flow, sediment transport and bottom updating are all executed at each time step.

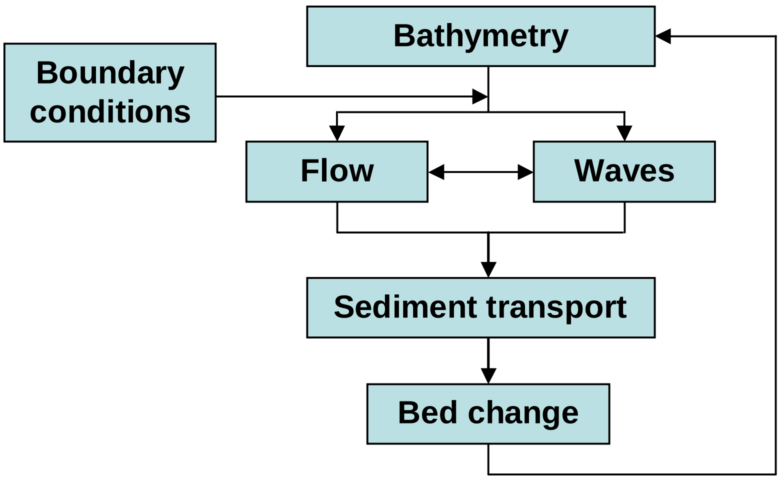

Figure 3.1 Schematic overview Delft3D-Online (adjusted after Roelvink (2006))

Figure 3.1 gives a schematic overview of the processes during a time step with Delft3D-Online. The model runs from a grid on which the bathymetry is represented. The bathymetry can be defined by the user, loaded from datasets, or can be output of previous model runs. Together with the initial conditions the bathymetry provides the starting conditions of the model runs. For the bathymetry, given the boundary conditions, the flows are calculated. Different modules can be active during the same time step. For this study a wave field was calculated frequently, which is coupled with the Flow module and directly affects the flows (and vice versa). After the flow field is defined, the corresponding sediment transports are calculated with help of the selected sediment transport formulation. Bed level changes are determined based on divergence of the sediment transports and define the morphologic behaviour. At every time step the bathymetry is updated and next a new set of computations, like described above, is executed for the following time step.

3.2 Flow

The Delft3D-Flow module, which defines the hydrodynamic part of Delft3D, describes non-steady flow and transport phenomena. This concerns situations where the flow phenomena have a horizontal scale (both length and time) which is significantly larger than the verticale scale (depth). These are situations such as shallow seas, coastal areas, estuaries, lagoons, rivers and lakes. The flows result from external forcing, which in case of this study were waves and river discharge (the latter not present in all computational runs). In a morphological model, the Flow module is the main component, because it is the first step in modelling activities since every problem in coastal, river and estuarine engineering concerns flows.

In Delft3D-Flow two-dimensional (2D) or three-dimensional (3D) flow and transport phenomena can be simulated. If the simulated flows are, or approach a situation where they are, vertically homogeneous, a two-dimensional depth-averaged approach (2DH) can be applied. This is the case for this project. In a 2DH approach the Flow module solves the unsteady shallow water equations in two dimensions.

Delft3D-Flow is based on a large number of assumptions. The main assumptions and approximations, relevant for this study, are:

- The depth is assumed to be much smaller than the horizontal length scale. The shallow water assumption is assumed to be valid and the hydrostatic pressure relation is applied. Vertical accelerations are assumed to be small compared to the gravitational acceleration and are therefore not taken into account.
- Dynamic online coupling of flow and morphological changes is conducted by the Delft3D-Online method.
- Drying and flooding of a velocity point is determined by the water depth. When the water depth is below half of a user-specified threshold, the point is set dry. The point becomes wet again when the threshold value is reached.
- There is no flux through the bed (flux is zero).
- The enhanced bed shear-stress due to the combination of waves and currents is based on a 2D flow field. The velocity near the bed is generated by a logarithmic approximation.

A detailed description and complete overview of the assumptions of Delft3D-Flow are provided in the Delft3D-Flow User Manual (Deltares, 2007a).

3.2.1 Shallow water equations

Delft3D-Flow solves the Navier Stokes equations for an incompressible fluid, under shallow water and Boussinesq assumptions. In the equations below the influence of density differences and the wind is neglected.

The depth-averaged continuity equation in two dimensions is:

$$\frac{\partial \zeta}{\partial t} + \frac{\partial [hU]}{\partial x} + \frac{\partial [hV]}{\partial y} = 0 \qquad (3.1)$$

The depth-averaged momentum equations in two dimensions (in respectively x- and y-direction) are:

$$\frac{\partial U}{\partial t}+U\frac{\partial U}{\partial x}+V\frac{\partial U}{\partial y}=-g\frac{\partial \zeta}{\partial x}+fV+\nu_H\left[\frac{\partial^2 U}{\partial x^2}+\frac{\partial^2 U}{\partial y^2}\right]-\frac{gU\sqrt{U^2+V^2}}{hC^2}+F_x \quad (3.2)$$

$$\frac{\partial V}{\partial t}+U\frac{\partial V}{\partial x}+V\frac{\partial V}{\partial y}=-g\frac{\partial \zeta}{\partial y}-fU+\nu_H\left[\frac{\partial^2 V}{\partial x^2}+\frac{\partial^2 V}{\partial y^2}\right]-\frac{gV\sqrt{U^2+V^2}}{hC^2}+F_y \quad (3.3)$$

Where:

ζ	Water level according to reference level, [m];
d	Depth towards reference level, [m];
h	Total water depth ($h = d + \zeta$), [m];
U, V	Depth-averaged velocity in respectively x- and y-direction, [m/s];
g	Gravitational acceleration, [m^2/s];
f	Coriolis parameter, [1/s];
ν_H	Horizontal eddy viscosity, [m^2/s];
C	Chézy-coefficient, [$m^{1/2}$/s];
F_x, F_y	Radiation stress gradient in respectively x- and y-direction, [m/s^2].

The terms on the right hand side of the momentum equations represent respectively: the horizontal pressure, the Coriolis force, the horizontal Reynold's stresses, the friction term and the contribution to the momentum by waves.

3.2.2 Numerical aspects

Delft3D-Flow is a numerical model based on finite differences. Therefore the shallow water equations have to be discretized. The shallow water equations are discretized via the staggered grid approach (paragraph 3.2.3), where the water level points are defined in the cell centers and the velocity components perpendicular on the middle of the grid cell faces. An alternating direction implicit (ADI) method is used to solve the continuity and horizontal momentum equations (Leendertse, 1987). With the ADI method one time step is split into two stages in which all terms of the equations are solved with (at least) second-order accuracy in space. This method was extended by Stelling (1984) with a special approach for the horizontal terms and resulted in a scheme denoted as a 'cyclic method' (Stelling and Leendertse, 1991). The 'cyclic method' is a computationally efficient method, which is at least second-order accurate and stable at Courant numbers up to 10. The numerical methods are described more thourougly and in greater detail by Lesser et al. (2004) and in the Delft3D-Flow User Manual (Deltares, 2007a).

Of every model built within the Delft3D-Flow environment the numerical stability can be checked with the Courant number. The Courant number gives an indication of numerical stability and accuracy of a model. To obtain sufficient accuracy the Courant number has to be below a set threshold value.The Courant number can be set by adjusting the time step. Although a smaller time step gives a lower Courant number, it increases the computation time of the model. For two-dimensional models the Courant number is defined as (Stelling, 1984):

$$C_r = 2\Delta t\sqrt{gh\left(\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}\right)} \quad (3.4)$$

Where:

C_r	Courant number;
Δt	Time step, [s];
g	Gravitational acceleration, [m/s^2];
h	Local water depth, [m];
Δx, Δy	Grid mesh size in x- and y-direction, [m].

3.2.3 Grid

Models constructed in Delft3D work from a rectilinear or curvilinear boundary fitted grid. Delft3D uses a staggered grid approach, which means that different quantities are defined at different locations in a numerical grid cell (Figure 3.2). Therefore the staggered grid approach gives a different number of numerical grid cells than one would expect based on the size of the modelled area. One of the advantages of the staggered grid approach is that boundary conditions can be implemented on the grid in a rather simple way. Boundaries are defined on different locations. Closed boundaries are defined through u- or v-points, as are velocities, but water levels are defined at water level points (+, or ζ-points).

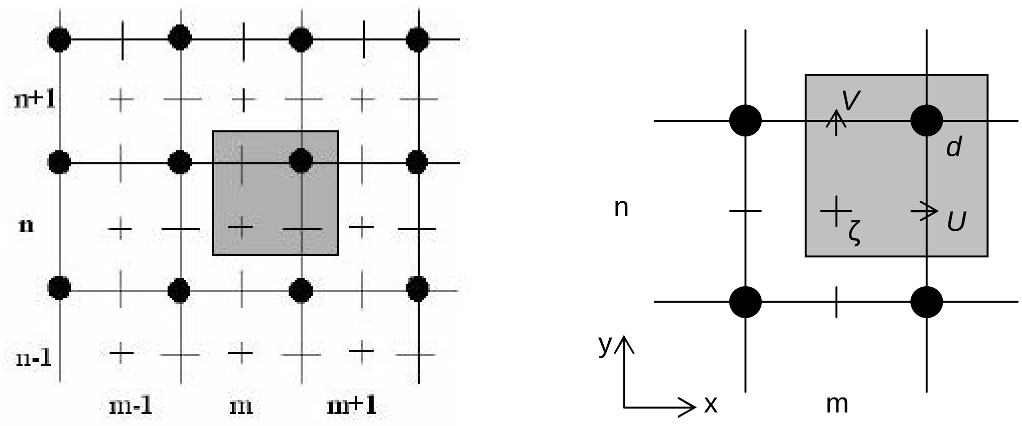

Figure 3.2 Staggered grid of Delft3D (Deltares, 2007a) (left) and staggered grid as used in this project (right)

The staggered grid has the following legend:

full lines	The numerical grid;
grey area	Items with the same grid indices (m, n);
+	Water level, concentration of constituents, salinity, temperature;
-	Horizontal velocity component in u- or x-direction (m-direction);
|	Horizontal velocity component in v- or y-direction (n-direction);
●	Depth below mean (still) water level (reference level).

The Delft3D user can select several different grid coordinates. Cartesian rectangular coordinates (for a rectilinear grid), othogonal curvilinear coordinates (for a curvilinear grid) and spherical coordinates (in case a spherical grid is used).

3.3 Sediment Transport

The description of sediment transport in this paragraph is given with respect to the model set up and sediment transport formulations applied in this study. The overview of sediment transport in Delft3D-Flow is therefore by no means complete. For a general and more detailed description is referred to Lesser et al. (2004), and the Delft3D-Flow User Manual (2007a).

The total sediment transport in Delft3D-Flow is determined by the sum of the sediment transport of multiple sediment fractions consisting of cohesive and non-cohesive sediments. Each sediment fraction must be classified as 'mud' (cohesive suspended load transport), 'sand' (non-cohesive bed-load and suspended load transport), or 'bed-load' (non-cohesive bed-load only), since a distinction is made for schematization purposes. Different formulations can be assigned to these different types of sediment. In Delft3D-Flow also a distinction is made between bed load and suspended load transport (Figure 3.3).

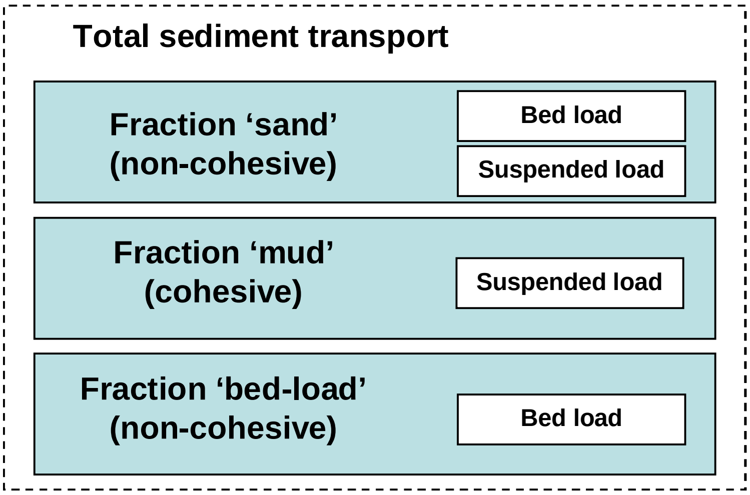

Figure 3.3 Schematic overview of sediment transport via different sediment fractions in Delft3D-Flow

Within this project only non-cohesive sediment fractions ('sand' fractions) are defined due to the use of the sediment transport formulation of van Rijn (2007a; 2007b); TRANSPOR2004 (TR2004 in short). Therefore no information on cohesive sediments is provided in this paragraph. A motivation for the use of TR2004 is given in paragraph 4.4.

The depth-integrated sediment transport in this project consists of bed load transport and suspended load transport. Bed load transport is defined as the transport of sediment particles close to the bed. This is the transport of particles which roll, slide and saltate in a thin layer (with an order of magnitude 0.01m) along the bed. Transport of sediment above this bed load layer is considered suspended load transport and is subject to influences of the water column. In Delft3D-Flow the height of the bed load layer is determined by the reference height (a) as determined by van Rijn (1993) based on the bed roughness. Bed load transport is calculated following a transport formulation that can be selected per model and suspended load transport is calculated with the advection-diffusion equation.

Both the suspended load transport and the bed load transport account for current-related transport and wave-related transport. The formulation of the bed load transport includes the current-related bed load transport ($q_{b,c}$ in current direction) and the wave-related bed load transport ($q_{b,w}$ in wave direction, following or opposing), but also the wave-related suspended load transport ($q_{s,w}$ in wave direction, always onshore). The wave-related suspended load transport is calculated with the bed load transport because this transport is considered to respond instantaneously to the hydrodynamics.

This gives the following bed load transport formulations in *x*- and in *y*-direction (Brière and Walstra, 2006):

$$q_{b,x} = fbed \frac{u_{b,x}}{\left|\bar{u}_b\right|} q_{b,c} + (fbedw \cdot q_{b,w} + fsusw \cdot q_{s,w}) \cos\varphi \tag{3.5}$$

$$q_{b,y} = fbed \frac{u_{b,y}}{\left|\bar{u}_b\right|} q_{b,c} + (fbedw \cdot q_{b,w} + fsusw \cdot q_{s,w}) \cos\varphi \tag{3.6}$$

Where:

$q_{b,x}$, $q_{b,y}$	Bed load transport in *x*- and in *y*-direction [kg/m/s];
fbed	Used-defined calibration factor;
$u_{b,x}$, $u_{b,y}$	Velocities in *x*- and in *y*-direction, [m/s];
u_b	Velocity in bottom computational layer, [m/s];
fbedw	Used-defined calibration factor;
fsusw	Used-defined calibration factor;
φ	Angle between direction of wave propagation and computational grid, [˚].

The suspended load transport is defined by the time-averaged current velocities and includes stirring up by waves. Within Delft3D this concerns only the current-related suspended load transport, which is defined by (Brière and Walstra, 2006):

$$q_{s,c} = fsus \int_{z_a}^{h} cudz \tag{3.7}$$

Where:

$q_{s,c}$	Current-related suspended load transport, [kg/m/s];
fsus	Used-defined calibration factor;
h	Water depth, [m];
z_a	Reference level, [m];
c	Concentration profile (see Figure 3.6), [kg/m^3];
u	Velocity profile (see Figure 3.5), [m/s].

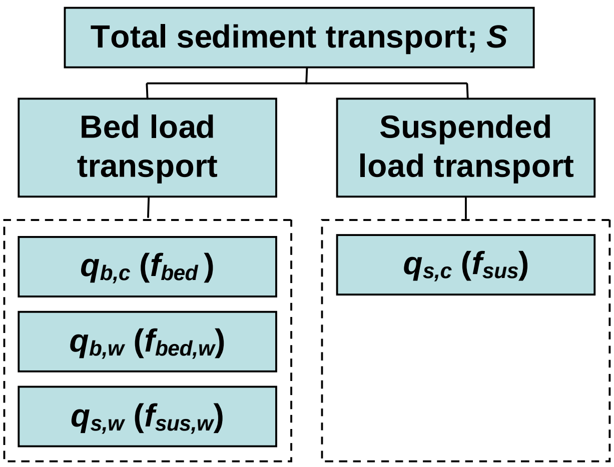

Figure 3.4 Schematic overview sediment transport and sediment transport coefficients

Figure 3.4 presents a schematic overview of sediment transport for TR2004. The current-related and wave-related transports are shown, with their corresponding user-defined calibration factors (*fbed, fsus*, *fbedw* and *fsusw*).

3.3.1 Bed load sediment transport

The bed load transport in Delft3D-Flow consists of sediment transport in the bed load layer (defined by the reference height *a*) of the non-cohesive sediment fractions and the fractions marked as 'sand' and 'bed-load'. The calculation of bed load transport is conducted in two steps. First, the magnitude and direction of the transport are computed with one or two formulations (the latter in case of waves). These formulations are defined by the user. In this study these formulation were given by TR2004 (van Rijn, 2007a). Next, the sediment transport vectors are relocated from the water level points (grid cell center) to the velocity points (grid cell faces) by means of an 'upwind' (i.e. in the direction of movement) computational scheme. Finally, these vectors are adjusted for bed-slope effects and sediment availability (details in van Rijn et al. (2004) and Lesser et al. (2004)).

The bed load transport in the TR2004 model is described by intra-wave transport generated by intra-wave velocity (according to Isobe and Horikawa,1982 *in* van Rijn, 2007a). The bed load transport formula of TR2004, for a situation with or without waves, as applied in this project, reads (van Rijn, 2007a):

$$q_b = 0.015 \rho_s u h \left(\frac{d_{50}}{h} \right)^{1.2} M_e^{1.5} \tag{3.8}$$

Where:

q_b	Depth-integrated bed load transport, [kg/m/s];
ρ_s	Sediment density, [kg/m^3];
u	Depth-averaged velocity, [m/s];
	$u = \sqrt{U^2 + V^2}$;
h	Local water depth, [m];
d_{50}	Median particle size, [m];
M_e	Mobility parameter (Appendix A.1).

The full formulation of this bed load formula is given in van Rijn (2007a) and Appendix A.1.

The sediment formulation of TR2004 presents a unified framework for sediment transport of fine silts to coarse sand and accounts for the effects of different particle sizes on sediment transport. With respect to the bed load attention is given to the initiation of motion and the bed roughness (van Rijn, 2007a; van Rijn et al., 2004). The formulation of the initiation of motion, the moment when a sediment particle starts moving, accounts for particle-particle interaction. Another important aspect of the TR2004 formulation is the bed roughness predictor. Sediment transport strongly depends on the bed roughness and vice versa. The van Rijn roughness predictor is the sum of four types of roughness and depends on the flow conditions. The bed roughness is considered an integral part of the sediment transport model. The roughness predictor can be used to predict the bed roughness of silt and sand in the range from 8 to 2,000 µm and has among others been validated with Mississippi River data (van Rijn, 2007a).

3.3.2 Suspended sediment transport

For suspended sediment transport, the advection-diffusion equation is solved in Delft3D-Flow. In this study the depth-averaged advection-diffusion equation is applied (Elias, 2006):

$$\frac{\partial[h\bar{c}]}{\partial t} + U\frac{\partial[h\bar{c}]}{\partial x} + V\frac{\partial[h\bar{c}]}{\partial y} = D_H\frac{\partial^2[h\bar{c}]}{\partial x^2} + D_H\frac{\partial^2[h\bar{c}]}{\partial y^2} + h\frac{\bar{c}_{eq} - \bar{c}}{T_s} \tag{3.9}$$

Where:

h	Local water depth, [m];
$\bar{c}$	Depth-averaged sediment concentration, [kg/m^3];
U, V	Depth-averaged velocity in respectively x- and y-direction, [m/s];
D_H	Horizontal dispersion coefficient, [m^2/s];
$\bar{c}_{eq}$	Depth-averaged equilibrium concentration, [kg/m^3]; $\bar{c}_{eq} = \frac{\lvert S_{sus,eq} \rvert}{\lvert U \rvert h}$
$S_{sus,eq}$	Depth-integrated suspended sediment transport for steady and uniform conditions, [kg/m/s];
T_s	Adaptation time-scale, [s].

The depth-averaged advection-diffusion equation is an approximation in vertical direction, in which the downward transport by gravity (settling of the sediment particles) and the upward transport by turbulent processes (sediment mixing) determine the concentrations. The settling velocities of the sediment particles, which cause the downward transport, depend on the particle size and the relative density of the particles. The sediment mixing coefficients are a combination of the current-related mixing coefficients and the wave-related mixing coefficients. The distribution of mixing coefficients over the water depth used in TR2004 is shown in Figure 3.5.

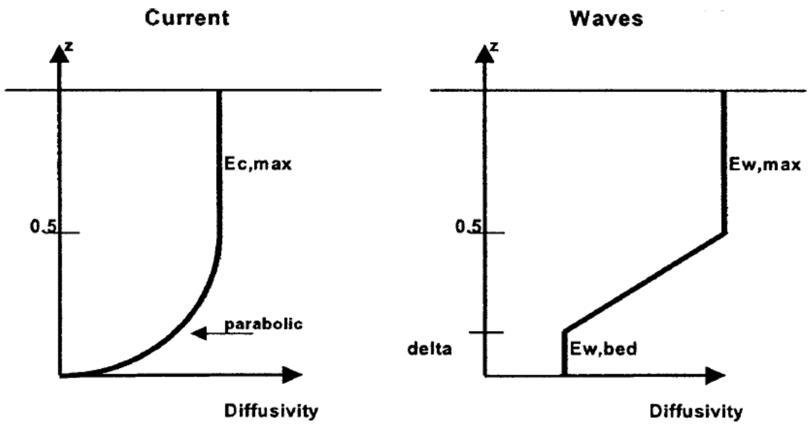

Figure 3.5 Vertical distribution of sediment mixing coefficients (van Rijn, 2007b)

The resulting sediment concentration profile over the water depth is a Rouse-type profile. By integrating this profile the mass concentration of sediment in the depth-averaged advection-diffusion equation is determined.

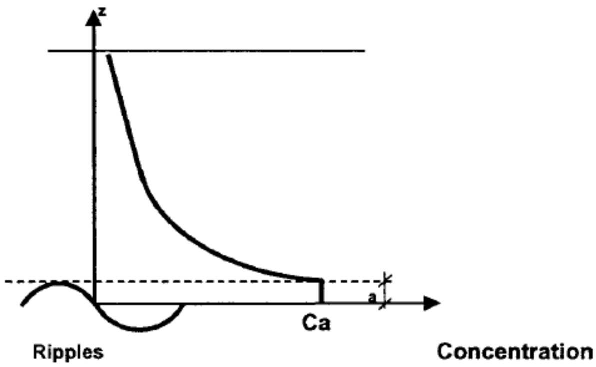

Figure 3.6 Rouse-type profile and reference concentration (van Rijn, 2007b)

The Rouse-type sediment concentration profile is defined by the reference concentration. This reference concentration (c_a) is given by (van Rijn, 2007b):

$$c_a = 0.015\left(1 - p_{clay}\right) f_{silt}\rho_s \frac{d_{50}}{a}\frac{T^{1.5}}{D_*^{0.3}} \tag{3.10}$$

(with c_a maximum is 150 kg/m^3).

Where:

c_a	Reference concentration, [kg/m^3];
f_{silt}	Silt factor $f_{silt} = d_{sand}/d_{50}$ (f_{silt} = 1 for $d_{50}>d_{sand}$=62μm);
ρ_s	Density of solid sediment particles, [kg/m^3];
d_{50}	Median particle size, [m];
a	Reference level, [m];
T	Dimensionless bed-shear stress parameter (Appendix A.2);
D_*	Dimensionless particle parameter (Appendix A.2).

In Appendix A.2 equation (3.10) is given in detail.

When multiple sediment fractions are used equation (3.10) in Delft3D-Flow becomes (van Rijn et al., 2004):

$$c_a^{(l)} = f_{sus}\eta^{(l)} 0.015\left(1 - p_{clay}\right) f_{silt}\rho_s^{(l)} \frac{d_{50}^{(l)}}{a}\frac{\left(T^{(l)}\right)^{1.5}}{\left(D_*^{(l)}\right)^{0.3}} \tag{3.11}$$

Where:

$c_a^{(l)}$	Reference concentration of sediment fraction *(l)*, [kg/m^3];
f_{sus}	Multiplication factor suspended sediment (specified in the morphological input file);
$\eta^{(l)}$	Relative availability of sediment fraction *(l)*:

$$\eta^{(l)} = \frac{\text{mass of fraction } (l) \text{ in mixing layer}}{\text{total mass of sediment in mixing layer}}.$$

The method presented with TR2004 for suspended sediment transport is applicable for sediments in the range of 8 to 2,000 μm. Special attention was given to the modelling of sediment concentration and transport in the silt and sand range. Flocculation, hindered settling and turbulence damping effects are taken into account in determining the suspended sediment transport. Other adjustments made for TR2004 with respect to previous methods using the advection-diffusion equation are that the bed-shear stress is based on a bed roughness predictor and that wave-related mixing processes are included.

3.3.3 Morphodynamics

The exchange of sediment of the water column with the bed in Delft3D-Flow is implemented via sediment sources and sinks located near the bottom of the flow. The sediment source and sink terms are located directly above the reference height (Figure 3.7).

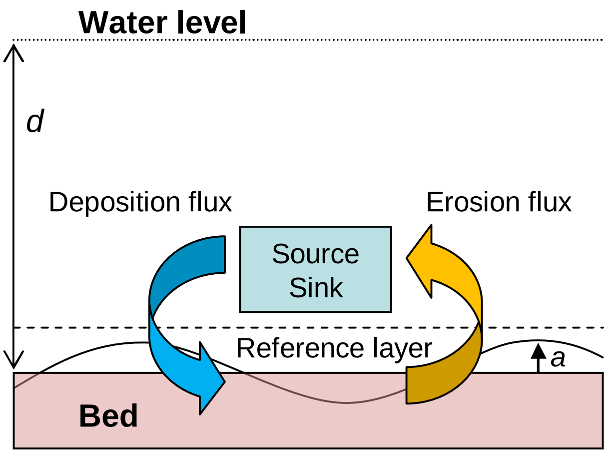

Figure 3.7 Schematic representation of the flux bottom boundary condition (adjusted after (Deltares, 2007a))

With the reference concentration (equation (3.11)) in the reference layer and the deposition (sediment settling) and erosion fluxes (upward diffusion) calculated each time step, the source and sink terms are determined. This defines the transfer of sediment between the bed and flow and gives the corresponding sedimentation and erosion with which the bed level changes are determined.

Morphological changes often take place over a much longer time period as compared to hydrodynamic changes. Furthermore, morphological changes due to changes in the hydrodynamics are often very small and do not affect the hydrodynamics and sediment transport pattern much. Therefore, for long-term morphological simulations, as conducted in this project, a morphological acceleration factor can be applied in Delft3D-Flow (Lesser et al., 2004; Roelvink, 2006). The morphological acceleration factor deals with the difference in time-scales of hydrodynamic and morphological changes. By simply multiplying changes in the bed sediment with the morphological acceleration factor, the morphological time step is extended (equation (3.12) and Figure 3.8).

$$\Delta t_{morphology} = f_{MOR} \Delta t_{hydrodynamic} \tag{3.12}$$

Where:

$\Delta t_{morphology}$ Morphological time step, [s];
f_{MOR} Morphological acceleration factor;
$\Delta t_{hydrodynamic}$ Hydrodynamic time step, [s].

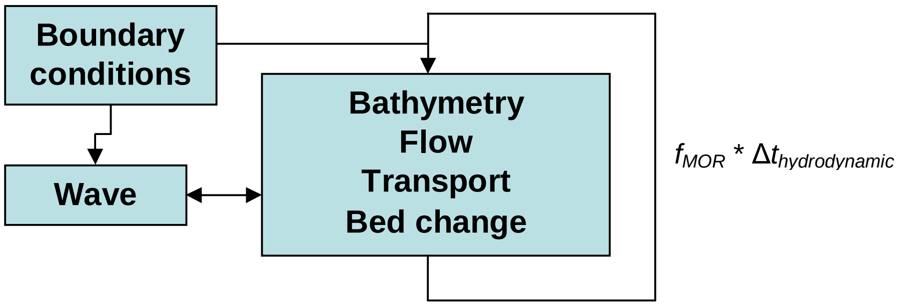

Figure 3.8 Schematic overview Delft3D-Online with morphological acceleration factor (Roelvink, 2006)

However, there are limits to the morphological acceleration factor. Small bed changes due to short-term changes by varying hydrodynamic conditions are exaggerated by this method and the results can be unrealistic. Therefore expert judgement and sensitivity testing before applying the morphological factor are required.

To prevent unrealistic morphological behaviour at the start of a computation a spin-up (time) interval should be applied. During this time interval no morphological changes are made to allow the hydrodynamics to adjust to the initial bathymetry.

3.3.4 Stratigraphy

The stratigraphy within Delft3D is defined by the bed composition of a user-defined number of bookkeeping layers (underlayers) as shown in Figure 3.9. The bed composition of an underlayer is given in percentages of the sediment fractions present in the underlayer. On top of the underlayers the transport layer is present, which represents the bed load transport. The lower-most underlayer is the base layer, which is always present and stores information that does not fit in the other layers.

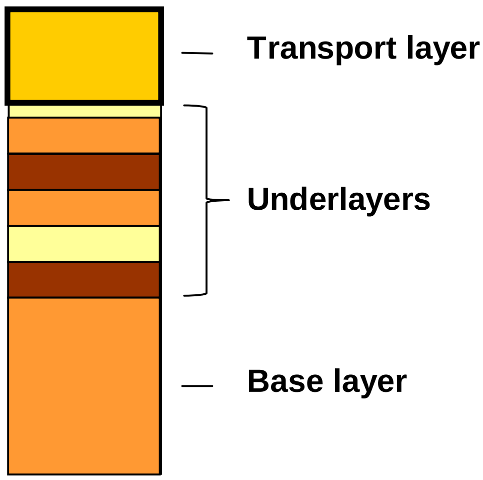

Figure 3.9 Transport layer and bookkeeping layers (underlayers) in Delft3D

The bed composition may be changed during a model run by the sedimentation and erosion processes (paragraph 3.3.3). Figure 3.10 represents the process of deposition. When sediments are deposited, they are initially added to the top-most (transport) layer (1 in Figure 3.10). After mixing in the top layer, the sediments are stored in the underlayers beneath it (2 in Figure 3.10). The underlayers have a maximum thickness which is user-defined. They are filled with sediments up to this thickness and if this threshold is exceeded a new underlayer is created (3 in Figure 3.10), up to the maximum number of layers. If this maximum would be reached, the lower-most underlayers are merged (4 in Figure 3.10).

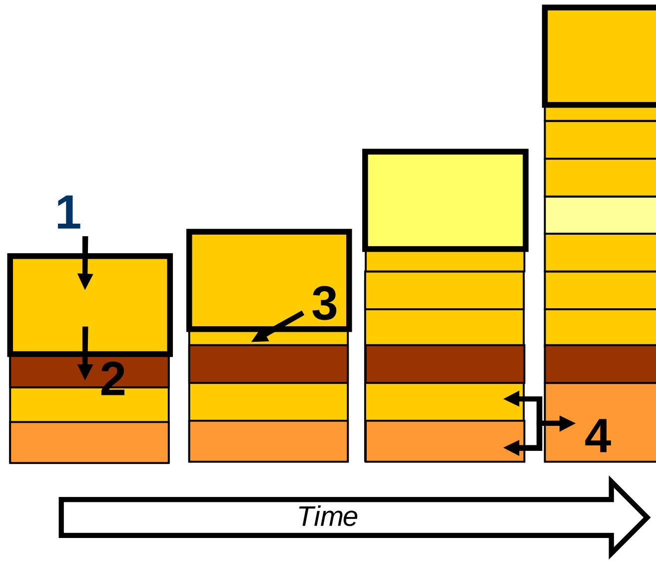

Figure 3.10 Process of deposition over time

Only sediment in the transport layer is available for erosion. It is assumed that the erosion rate is proportional to the availability of the sediment fraction considered in the transport layer. Figure 3.11 represents the process of erosion. After erosion (1 in Figure 3.11), the transport layer is replenished from below (2 in Figure 3.11).

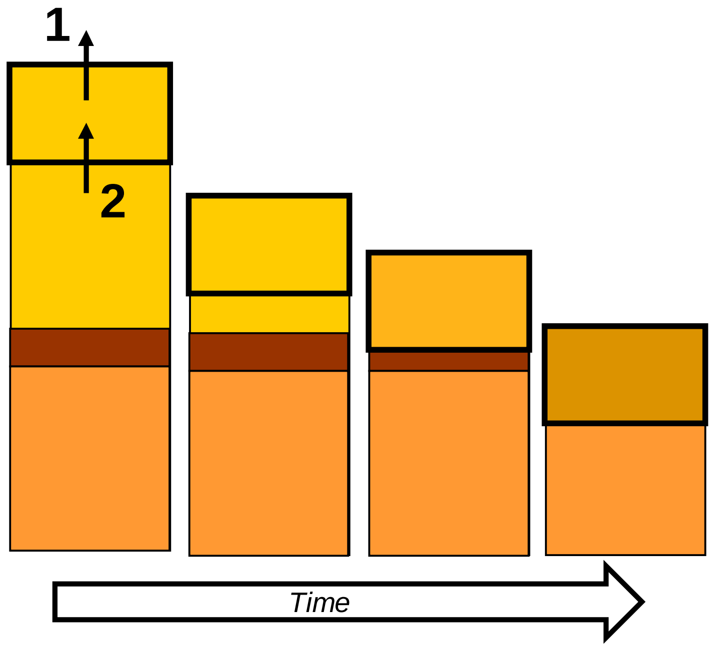

Figure 3.11 Process of erosion over time

The stratigraphy can be defined as an initial condition. In case no initial stratigraphy is provided the starting condition is a uniformly mixed bed (representing one sediment layer).

3.4 Waves

Wave simulations in Delft3D are conducted with the Delft3D-Wave module. The simulations of Delft3D-Wave are performed by the 3rd generation SWAN model (Booij et al., 1999). The SWAN (**S**imulating **WA**ves **N**earshore) model computes the evolution of short waves in coastal regions. SWAN is based on the discrete spectral balance of action density and driven by boundary conditions and winds. Random wave fields propagating from different directions can be simulated simultaneously. The model accounts for various physical processes (Deltares, 2007b), namely:

- Wave refraction over a bottom of variable depth and/or a spatially varying ambient current
- Depth and current-induced shoaling
- Wave generation by wind
- Dissipation by whitecapping
- Dissipation by depth-induced breaking
- Dissipation due to bottom friction
- Non-linear wave-wave interactions
- Wave blocking by flow
- Transmission through, blockage by or reflection against obstacles
- Diffraction

More information about SWAN can be found in Booij et al. (1999) and the Delft3D-Wave User Manual (Deltares, 2007b).

3.4.1 Action balance equation

The waves are described with the two-dimensional wave action density spectrum rather than the energy density spectrum, because in the presence of currents the action density is preserved whereas energy density is not. The action density is equal to the energy density divided by the relative frequency:

$$N(\sigma,\theta) = \frac{E(\sigma,\theta)}{\sigma} \tag{3.13}$$

Where:

$N(\sigma,\theta)$	Action density, $[m^2/Hz^2]$;
$E(\sigma,\theta)$	Energy density, $[m^2/Hz]$;
σ	Relative frequency, [Hz];
θ	Wave direction, [˚].

The evolution of the wave spectrum is in SWAN described by the spectral action balance equation. In case of Cartesian coordinates, such as in this study, the spectral action balance equation is:

$$\frac{\partial N(\sigma,\theta)}{\partial t} + \frac{\partial c_x N(\sigma,\theta)}{\partial x} + \frac{\partial c_y N(\sigma,\theta)}{\partial y} + \frac{\partial c_\sigma N(\sigma,\theta)}{\partial \sigma} + \frac{\partial c_\theta N(\sigma,\theta)}{\partial \theta} = \frac{S(\sigma,\theta)}{\sigma} \tag{3.14}$$

Where:

c_x, c_y	Wave propagation speed in respectively x- and y-direction, [m/s];
c_σ, c_θ	Propagation speed for respectively σ and θ, [Hz/s], [˚/s];
$S(\sigma,\theta)$	Energy density source or sink term, $[m^2/Hz]$.

The terms on the left hand side of the action balance equation represent respectively: the local rate of change of action density in time, the propagation of action density by wave groups in respectively x- and y-direction, the shifting of the relative frequency due to variations in depth and currents and the depth-induced and current-induced refraction. The source or sink term at the right hand side of the action balance equation represents the effects of generation by wind, dissipation and non-linear wave-wave interaction.

3.4.2 Coupling with Delft3D-Flow

The wave simulations of Delft3D-Wave can be included in the Delft3D-Flow simulation via different coupling methods. The 'online' method is applied in this study, in which the simulations of both modules influence each other by computations at each time step. With this coupling a dynamic two way wave-current interaction is established. The communication interval of the Flow and Wave modules should be carefully considered since changes in the water level, bathymetry and flow field do affect the waves and vice versa.

4 Model set up

To investigate sediment reworking under wave conditions in the deltaic environment, this study is set up using a process-based morphodynamic model of a schematic deltaic environment in Delft3D. The degradation process of a pre-defined fluvial-dominated delta formed in a gentle sloped basin on meso-scale is schematized and investigated. This study was conducted following two scenarios. In the first scenario the modelled deltaic environment was subjected to a gentle perpendicular wave climate with no river discharge to study sediment reworking under waves in a degrading delta (in this report referred to as the base case). In the second scenario an upstream part of the river was included in the model domain and a varying riverine water and sediment discharge was added to investigate this influence (in this report referred to as the fluvial input case).

The model of Geleynse et al. (2009) is used to investigate the morphology and stratigraphy of a degrading delta. Geleynse models delta building of a fluvial-dominated delta. This model is referred to as the reference model, whereas the model developed and applied in this study is referred to as ‘the model’, or ‘this (study’s) model’. The model set up of the reference model was continued where possible, to minimize inconsistencies of the research and ease comparison. Therefore most assumptions and conditions are kept similar. But certain alterations had to be made because of the specific focus on the representation of waves and sediment reworking in this study. The reference model set up was only changed if necessary for this specific focus and these changes are assumed not to cause major inconsistencies that would influence the model results.

To model the deltaic environment and investigate the study objectives several choices are made to find a balance between the level of detail, the number of processes included, and (time-) efficient computations. The similarities and differences between the reference model and this study’s model regarding these choices are discussed in this chapter. In paragraph 4.1 the assumptions and limitations with respect to the model, modelled processes and model environment are outlined. The focus on certain processes follows directly from the study objectives. Next, the model set up is shown in more detail by explaining the numerical set up of the initial condition and main model parameters, grid, boundary conditions, wave climate, sediment transport formulation, sediment characteristics and stratigraphy.

4.1 Assumptions and limitations

The objectives of this study focus on sediment reworking by waves and the influence of the river discharge and sediment supply during the destructional phase of the deltaic cycle. The most accurate way this can be studied would be to include and model all of the processes involved and subsequently calibrate and validate the model with field data. However, that is not feasible in the given time frame as it would make the model unnecessary complex and take a very long computational time. Besides, for this study no datasets on sediment reworking are available for calibration and validation of the model. Therefore a schematic set up is applied which has a number of advantages. The main advantage is that the focus is on the dominant processes, which can be studied in a fully controlled environment. Certain assumptions are required to simplify the model environment of which the four main assumptions are discussed in this section.

To efficiently study the process of sediment reworking under wave conditions, no other basinal processes than waves are included in this model. Other processes will further complicate the model because of extra varying parameters and a higher interaction with the processes in the deltaic environment. To study the influence of waves on the deltaic environment, the influence of tides is not included. The model therefore resembles a lacustrine delta, a delta in an enclosed fresh water basin, or a sheltered delta in semi-enclosed bays in an area with micro-tidal conditions.

Density differences which can affect hydrodynamics and sediment behaviour, but also have an impact on the water quality and ecology, are also not included. Although density effects can influence the morphology and stratigraphy, other parameters have more influence on the sediment characteristics. Therefore the effects of density differences are considered to be outside this study’s scope (homopycnal conditions).

a. The deltaic environment under study is not subject to the influence of tides and density effects are not included.

Compaction of deposits in the deltaic environment can be an important factor in the degradation process of alluvial deltas. In the Mississippi delta, in the United States of America, a high subsidence rate is one of the main reasons of delta degradation. Especially subsidence combined with eustatic sea level rise, called relative sea level rise accounts for degradation of the deltaic environment and is a threat to deltas (Day et al., 2007). Due to the investigation of sediment reworking under waves, other degradational processes as relative sea level rise are not taken into account.

b. In this study delta degradation is caused by sediment reworking by waves in the deltaic environment and changes in riverine water and sediment discharge. Relative sea level rise is not included in the model.

Due to a stop of, or changes in, the fluvial input and because of the addition of waves, the model resembles an abandoned delta. This may indicate that there is a new delta (lobe) forming nearby. The sediments of this new delta (lobe) and other deltaic deposits can influence the sediment reworking of the modelled delta (Bhattacharya and Giosan, 2003). For simplification, this is neglected and the assumption is made that other sediment sources does not influence the degradation process.

c. In this study, nearby deltas, or delta lobes, and other sediment sources are not included in the model area and therefore have no influence in the area under study.

The model time scale represents 44 months and is distorted. It probably does not represent the actual time the processes of sediment reworking in the deltaic environment. It can however by considered an accelerated time scale and it is assumed that the dominant processes are unaffected.

d. During the chosen run time the dominant processes of sediment reworking by waves are represented by the model environment.

4.2 Initial condition

The initial condition of the model is a fluvial-dominated delta with the resulting morphology and stratigraphy of the reference model. The grid characteristics, basin configuration, set up of the stratigraphy (number of underlayers) and the number of sediment fractions are similar to the reference model. The input is however adjusted with respect to the sediment characteristics, sediment transport formula and the introduction of waves. Figure 4.1 (plan view) and Figure 4.2 (three-dimensional representation) show the resulting morphology of a fluvial-dominated delta simulation of which the basinal part is applied as initial condition of the model.

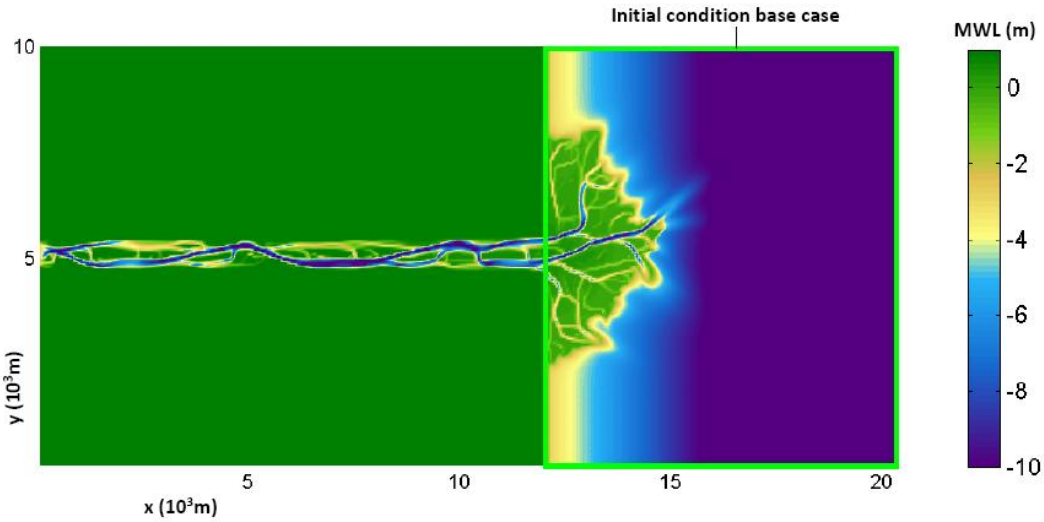

Figure 4.1 Plan view morphology of reference model including river system with the initial condition of the base case highlighted

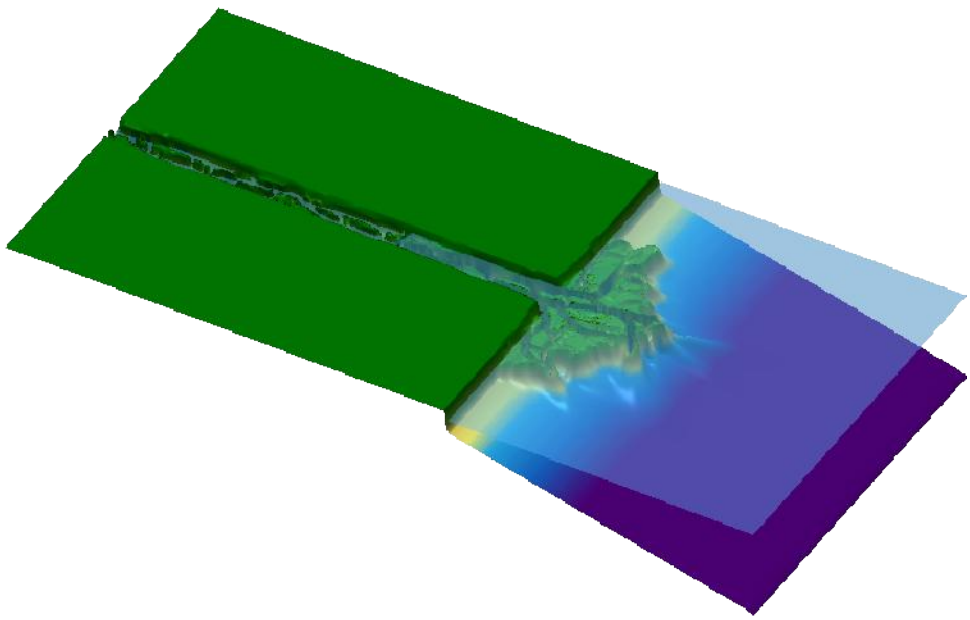

Figure 4.2 3D representation of reference model morphology

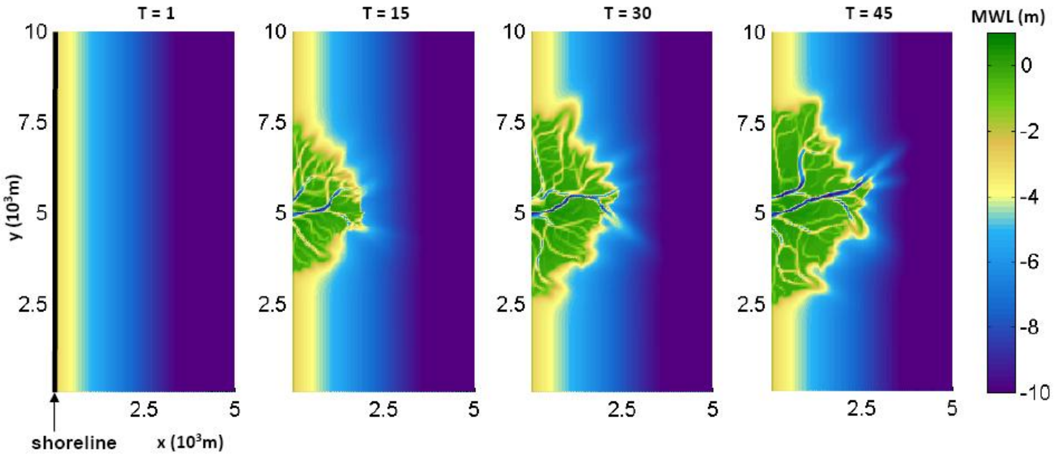

Figure 4.3 *Plan view morphology of the reference model over time*

The Delft3D simulations of the reference model show delta development of river deposits in an empty basin (Figure 4.3). The left side boundary of the plan view images of the morphology in Figure 4.3 represents the shoreline, this is the case for all plan view images of the morphology in this report. The initial delta building of a fluvial-dominated delta was conducted by sediment present as an erodible layer in the river bed, which is scoured and transported to the basin by the river. Waves were not included in the reference model. The boundary conditions were a constant discharge of 2000 m^3/s, an equilibrium sediment load determined by the hydrodynamic conditions (around 0.035 kg/m^3) for the sand sediment fraction, a constant sediment concentration (0.035 kg/m^3) for the cohesive sediment fraction and a fixed water level on the basin side. The delta which provides the initial morphology and stratigraphy is assumed to enter a phase where degradation processes get the overhand. Table 4.1 gives an overview of the model set up by the main model parameters of this study's model compared with the reference model.

Model parameters		Model values	
Parameter	Symbol	Reference model	This study
Runtime	T_{run}	44 months	44 months
Timestep	*dt*	15 – 30 s	30 s
Morphologic acceleration factor	*MorFac*	60	60
Grid resolution	-	50 m x 50 m	50 m x 50 m
Flow grid size	-	408 x 200	167 x 200
Wave grid size	-	-	170 x 382
Morphological characteristics			
Sediment transport formula	-	Engelund-Hansen for sand-faction; Partheniades-Krone for clay-fraction	TRANSPOR2004 for both sediment fractions
Specific density (both fractions)	ρ	2,650 kg/m^3	2,650 kg/m^3
Type of sediment (fraction 1)	*SedTyp (1)*	(non-cohesive) sand	(non-cohesive) sand
Median grain size (sediment fraction 1)	d_{50} *(1)*	125 μm	125 μm

Dry bed density (sediment fraction 1)	ρ_s (1)	1,600 kg/m^3	1,600 kg/m^3
Type of sediment (sediment fraction 2)	*SedTyp (2)*	(cohesive) clay	(non-cohesive) sand
Median grain size (sediment fraction 2)	d_{50} (2)	-	50 µm
Fall velocity (sediment fraction 2)	w_s	1.5 mm/s	-
Dry bed density (sediment fraction 2)	ρ_s (2)	500 kg/m^3	500 kg/m^3
Number of underlayers		75	75
Thickness of transport layer	*ThTrLyr*	0.2 m	0.2 m
Maximum thickness bookkeeping layer	*ThLyr*	0.1 m	0.1 m
Suspended transport factor	*fsus*	1.0	1.0
Bed load transport factor	*fbed*	1.0	1.0
Wave-related suspended transport factor	*fsusw*	-	0.3
Wave-related bed load transport factor	*fbedw*	-	0.3
Spin-up interval before morphological changes	*MorStt*	60 min	60 min
Boundary conditions			
Waves	-	-	perpendicular, H_s = 1 m, T_p = 5 s
River discharge	*Q*	2,000 m^3/s	Base case: no discharge; Fluvial input: varying discharge (Table 5.1)
River sediment concentration (sediment fraction 1)	*S(1)*	Equilibrium concentration	Equilibrium concentration; or constant concentration (Table 5.1)
River sediment concentration (sediment fraction 2)	*S(2)*	Constant concentration; 0.04 kg/m^3	Equilibrium concentration; or constant concentration (Table 5.1)

Table 4.1 Model set up reference model and this study's model

4.3 Grid

An equidistant grid with a grid cell resolution of 50 meters is applied in both crossshore and longshore direction to simulate the deltaic processes on a spatial scale of kilometers. The grid cell resolution is proven practical in earlier computations (personal communication Storms and Walstra, 2008). For the hydrodynamic grid of the base case a grid size of 167 by 200 numerical cells is chosen, with an open boundary at the basin side and Neumann boundaries on both lateral sides. For simulations which include fluvial input this grid is extended with 66 cells (representing 3,300 meters) in upstream (landward) direction, to include part of the river system to prevent new channel formation. The river discharge is imposed directly at the existing channel so not many changes in the river system will occur. This is to keep the focus on the delta under investigation. For this scenario a total grid size of 233 by 200 numerical cells is applied. The reference model is created on a grid with the same grid resolution. The representation of the river channels and distributaries can be inaccurate if the channel width approaches the grid cell resolution of 50 meters. The model lacks the level of resolution to represent these distributaries in detail, but still represents the processes of channel switching and channel infill accurately.

For the wave component a grid size of 170 by 382 numerical cells is chosen. This grid is extended in longshore direction to eliminate boundary effects and create a constant perpendicular wave climate (see right part of Figure 4.4). In the left part of Figure 4.4 the grids of the base case are shown and in the middle part of Figure 4.4 the grids of the fluvial input case. The wave grids are indicated in red and the flow grids in respectively green and blue. The part of the wave grid that coincides with the flow grid has the same grid cell resolution as the flow grid (50 m x 50 m). Outside the flow domain the grid cell resolution is uniform (50 m) in crossshore direction, but grid cell resolution increases in the longshore direction over the 182 cells on both lateral sides (50 m, 100 m to 200 m). Wave fields generated on this grid show comparable results with an equidistant wave grid with constant resolution of 50 m, but this causes a significant decrease in computational time.

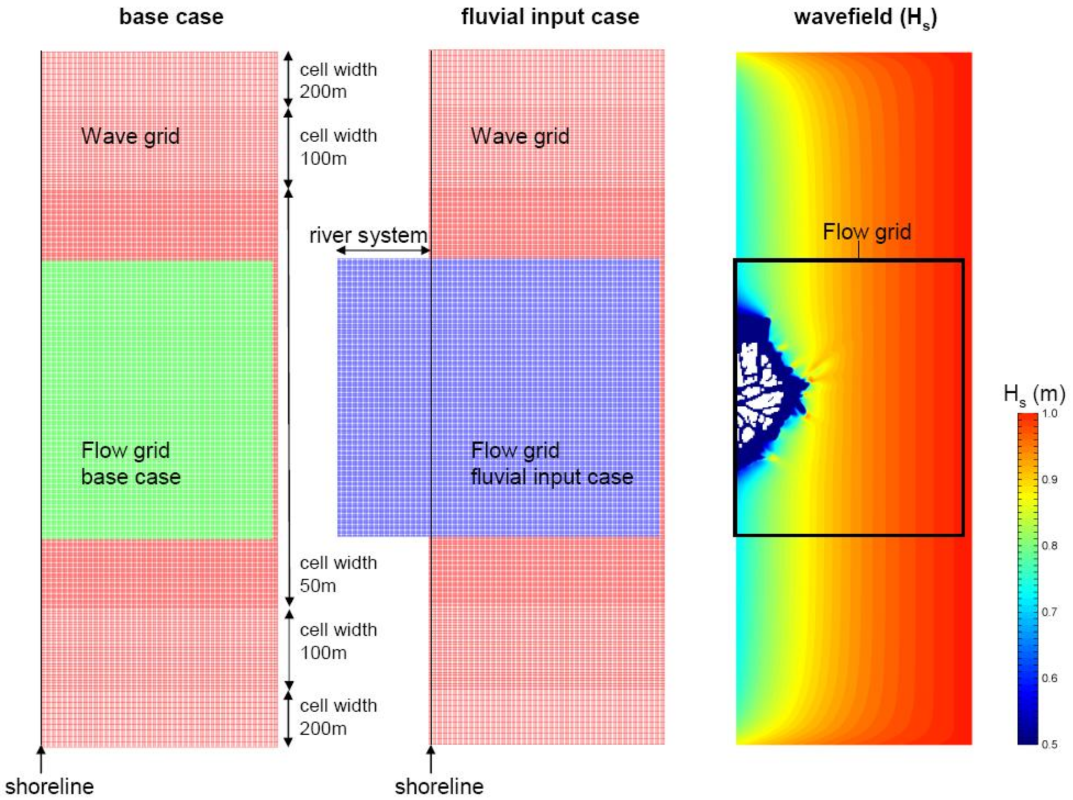

Figure 4.4 *Wave and Flow grids of the base case and fluvial input case and significant wave height of wave field*

4.4 Boundary conditions

Initial and boundary conditions are required in Delft3D to solve the hydrodynamic and morphologic equations. The initial conditions are given by the initial morphology and stratigraphy, initial water level and sediment concentrations of the model. A spin-up time of 60 minutes is applied to allow the hydrodynamics to adjust to the initial bathymetry before changes in the morphology are allowed, to prevent the occurrence of unrealistic erosion and sedimentation.

The following boundary conditions are imposed at the model boundaries:

- The basin boundaries in crossshore direction are defined as Neumann boundaries. The Neumann condition imposes a longshore water level gradient as an open boundary condition, which allows waves to propagate and be correctly represented (Roelvink and Walstra, 2004 *in* Deltares, 2007a).
- The ocean side of the basin (longshore direction) is an open water level boundary, which defines the water level.
- The river discharge and river sediment load is defined as an upstream boundary condition (flux). For the scenario with varying discharge the discharge is spread over 6 grid cells, which determine the river bed. The sediment supply is also determined at this boundary. The sediment supply is defined as a constant concentration, or as an equilibrium concentration which depends on the hydrodynamics of the first cells next to the boundary.
- The wave climate is imposed on the boundaries of the basin and is discussed in the next paragraph. The Wave module communicates every hydrodynamic hour with the Flow module.

The model schematization with the boundary conditions shown at the corresponding boundaries is presented in Figure 4.5 for the base case and in Figure 4.6 for the fluvial input case. The morphology shown in the figures is the initial condition. The main difference between the two simulations is the extension of the fluvial input case with the river system on the flow grid and the fluxes of the riverine water and sediment discharge at the upstream boundary. The sediment supply flux has varying characteristics since it is imposed as an equilibrium concentration depending on the hydrodynamics ($dS/dt \neq 0$) or a constant supply ($dS/dt = 0$). This is described in paragraph 5.2.

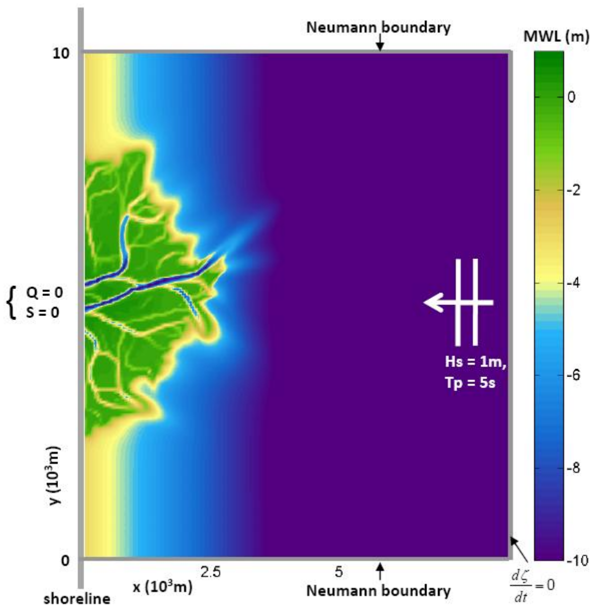

Figure 4.5 Model schematization base case

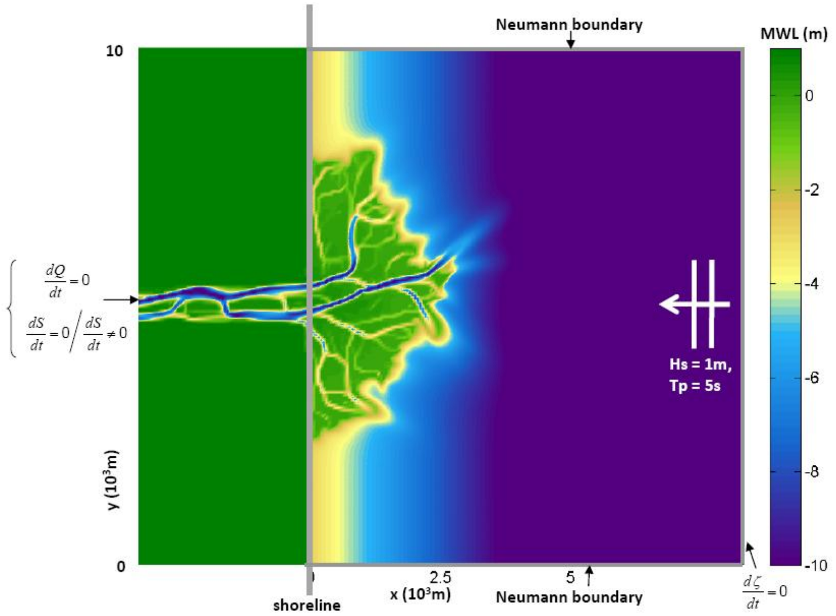

Figure 4.6 Model schematization fluvial input case

4.5 Wave climate

The wave climate applied in this study is a constant wave field. Although the influence of waves is a major component of this study, one constant wave field is applied to keep the interpretation of the effects of sediment reworking as unambiguous as possible. In all simulations perpendicular waves with a significant wave height (H_s) of 1 meter and a wave period (T_p) of 5 seconds are imposed at the basin boundaries. This wave field applied in this model represents a gentle low energy wave climate, which is comparable to the wave climate (without storms) in the Gulf of Mexico around the Louisiana coast (where the Mississippi, Wax Lake and Atchafalaya deltas are situated).

4.6 Sediment transport formulation

Sediment transport formulations are empirical formulations designed for specific conditions. The sediment transport formulations applied in the reference model are chosen with respect to river morphodynamics in a situation without waves and therefore not applicable in this model. The sediment transport formulation TRANSPOR2004 (van Rijn, 2007a; van Rijn, 2007b) is applied in this study. This sediment formulation provides one unified framework in which both the suspended and bed load sediment transport of the two sediment fractions are modelled. The formulation is applicable for a broad range of sediment sizes (fine silt to coarse sand) subject to varying conditions. The sediment fractions have to be defined as sand fractions, but TR2004 does account for cohesive effects of very fine sediments. The formulation also accounts for the combined effects of waves, currents and river dynamics, and also for particle-particle interaction, bed slope effects, flocculation and hindered settling. Combined with the van Rijn roughness predictor the sediment transport in the deltaic environment under influence of waves is realistically represented. Scaling of the sediment transport parameters and specific parameters concerning TR2004 is conducted in the sensitivity analysis (paragraph 5.3)

4.7 Sediment characteristics

The sediment characteristics influence the morphology directly and the stratigraphy indirectly, since they have an impact on the bed roughness, initiation of motion, sediment transport and the processes of sedimentation and erosion. An accurate representation of the sediments in the deltaic environment is required. It is not feasible to represent the continuous range of sediments present in the deltaic environment since every sediment fraction significantly increases the computational time of the model. In the deltaic environment of this study fine-grained sediments are represented, this is comparable to the alluvial deltas as determined by Orton and Reading (1993) which shows comparable deltas in the range with fine sands and silts. Storms et al. (2007) illustrated that the sediments of the deltaic environment can be realistically represented with two sediment fractions. In this study two sediment fractions are present, each fraction represents a range of sediments that behaves approximately similar. The two fractions thereby illustrate the difference between the fine (clay and silt) and coarser (sand) sediments in the deltaic environment. The first sediment fraction represents fine sand with non-cohesive characteristics. The other fraction represents very fine sands, which have a low density and approaches the behaviour of cohesive silt. In the reference model also two sediment fractions were used; a non-cohesive fine sand fraction and a cohesive clay fraction. The sediment fractions in this model have approximately the same characteristics, but are both modelled as non-cohesive sand fractions. This is due to the use of the sediment transport formulation TR2004, which account for a broad spectrum of sediments, but models only non-cohesive sediments. TR2004 does take into account the cohesive characteristics of very fine sediments.

The sediment fractions are defined by specific and dry bed density and the median grain diameter (d_{50}). The very fine silt-like sediment fraction has a d_{50} of 50 μm, a specific density of 2,650 kg/m^3 and a dry bed density of 1,600 kg/m^3. The fine sand sediment fraction has a d_{50} of 125 μm, a specific density of 2,650 kg/m^3 and a dry bed density of 500 kg/m^3. These characteristics are determined by the model sensitivity analysis (paragraph 5.3.2).

4.8 Stratigraphy

The stratigraphy is represented according to the bookkeeping layer approach of Delft3D as described in paragraph 3.3.4. Similar to the reference model the maximum number of underlayers in the model is defined as 75, with a maximum thickness of 0.1 meter. The varying thickness created a more detailed representation around the channels and distributaries and other dynamic parts of the deltaic environment. The substrate of the model is an erodible 20 meters thick layer (base layer) consisting of 50% of each of the sediment fractions, also similar to the initial stratigraphy of the reference model.

5 Results simulations

This study uses the model environment that was set up in Delft 3D, as described in the previous chapter, to simulate and investigate two types of simulations. The first simulation is the base case, and the second is a more elaborated case in which fluvial input was included, the fluvial input simulation. The base case simulates a simplified process of sediment reworking of a destructional deltaic environment. For the fluvial input simulation, in which the influence of a river was included, a varying river discharge and sediment supply are added to the base case. This chapter discusses the results of the numerical simulations conducted for these investigations.

The results of these numerical simulations are described by the processes that contribute or are related to delta degradation. The processes observed in the base case are discussed in paragraph 5.1, the interpretation of these results is provided and certain processes are checked with available literature. Also uncertainties of the base case model are discussed and suggestions for a more accurate investigation are provided. Paragraph 5.2 discusses the processes for the base case extended with fluvial input; riverine water and sediment discharge. For this situation the results of multiple simulations are described and compared in similar fashion.

5.1 Base case

The base case is a simulation in which the number of processes is limited to investigate sediment reworking in a degrading deltaic environment. The fluvial input of a fluvial-dominated delta is stopped and the delta is subjected to a gentle wave climate. The degradation is by sediment reworking under waves only, because compaction of the deposits is not modelled and no other sediment reworking processes are present. Due to absence of riverine water and sediment discharge the fluvial-dominated delta radically changes to a wave dominated coast. In this study this is regarded a simplified representation of a degrading delta.

The results of the base case show that the fluvial-dominated delta quickly adjusts to the incoming waves. Sediment reworking under waves causes the retreat of the delta front and sorting of the sediments. The base case illustrates that simulation of a deltaic environment in the destructional phase of the deltaic cycle is possible and that including waves in the process-based model gives realistic results. In the next paragraphs the details of this simulation are described in more detail.

5.1.1 Setting

The base case is a simplified representation of a deltaic environment, but represents the dominant processes of a change in the deltaic environment which occur in reality. Although in reality a fluvial-dominated delta formed in a basin without waves is never suddenly subjected to wave reworking, the switch of dominant processes can be regarded to changes as observed in deltaic environments. The schematic model has an extreme switch, where in nature this would occur gradually, but this helps to study the dominant processes. The base case is comparable to a situation where changes in the deltaic environment start the process of delta degradation. These changes can have a fluvial or a basinal origin.

With respect to changes within fluvial input, the base case can be considered as an abandoned delta, or abandoned delta lobe, initiated by delta switching. With delta switching the river of the delta ceases to deliver sediment to the deltaic environment. A decrease in sediment supply is experienced as a delta enters the destructional phase of the deltaic cycle (Coleman and Gagliano, 1964; Scruton, 1960). Next to natural delta switching, human adjustment in the river system, may also cause a sudden change in sediment supply (McManus, 2002; Syvitski, 2008).

The base case can resemble a situation in which wave energy becomes increasingly influential with respect to the fluvial input. The increasing wave influence might be climate change induced (Nicholls et al., 2008), but can also be caused by increased exposure of the deltaic environment to incoming waves. The increased exposure can also be caused by the loss of a shielding environment, such as the loss of barrier islands or the deterioration of the wetlands surrounding the deltaic environment.

Figure 5.1 shows the change of the dominant processes in the deltaic environment, as they occur in the simulations, by means of a classification scheme. Since the river influence in the base case is stopped, the deltaic environment becomes a wave dominated coast; a strandplain. Figure 5.1 is based on the classification of Dalrymple et al. (1992), which is an extended scheme based on the triangular scheme of Galloway (1975) and includes coastal landforms such as estuaries, tidal flats and strandplains. The original classification of Dalrymple et al. is shown on the right side of Figure 5.1. Following their classification, the absence of river input and the influence of waves change the environment of the fluvial-dominated delta into an environment which is comparable to that of a strandplain. This indicates that the deltaic environement will be reworked to have some of the chacaracteristics of a strandplain. The arrow in the left figure represents the change induced by the stop of river discharge and the introduction of waves.

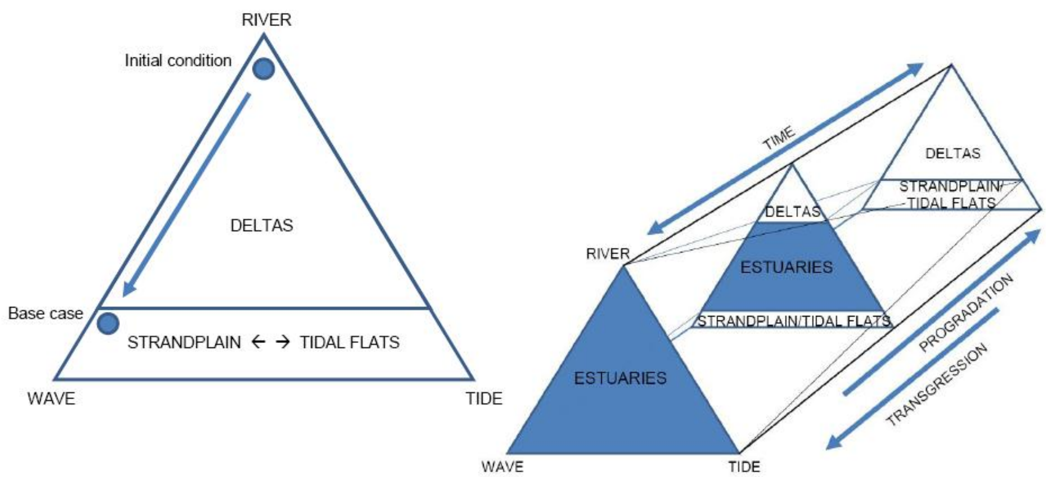

Figure 5.1 Change of dominant processes in deltaic environment (left) based on the classification of Dalrymple et al. (1992) (right)

5.1.2 Initial condition

Before the results of the base case are discussed, the initial condition is reviewed. The morphology and stratigraphy of the initial condition are the result of simulations of delta building of a fluvial-dominated delta. The initial condition is already described in paragraph 4.2, but here some specific features of the morphology and stratigraphy are highlighted, which help interpretation of the results of the base case.

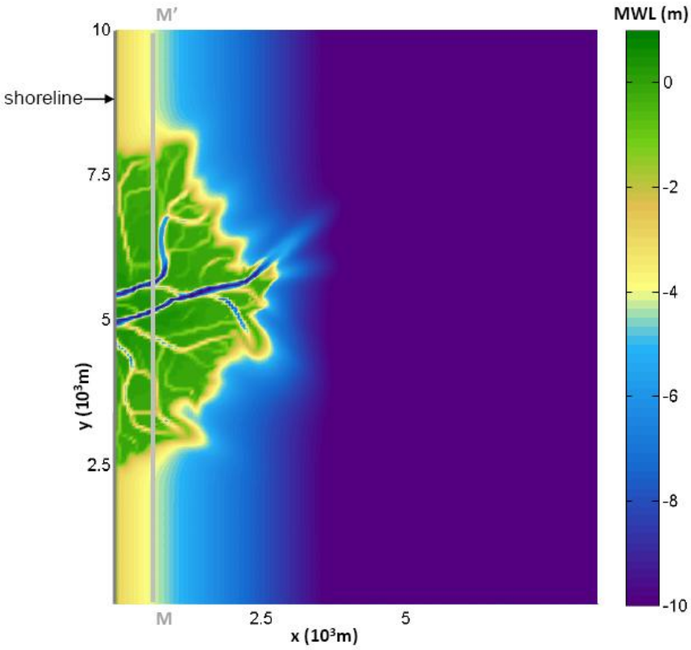

Figure 5.2 Plan view morphology initial condition

Figure 5.2 shows the plan view of the morphology of the initial condition. Two main channels can be distinguished, next to a high number of distributaries. Channel switching caused the formation of this delta's morphology. Bed load (in this case mostly non-cohesive sand) and suspended load (in this case mostly cohesive silt) sediments were transported through these channels and distributaries. Due the flow conditions the channels have a sandy character. The silts were deposited on the edges of the delta front and in the prodelta. A fining of sediments in lateral direction as well as in basinward direction is observed.

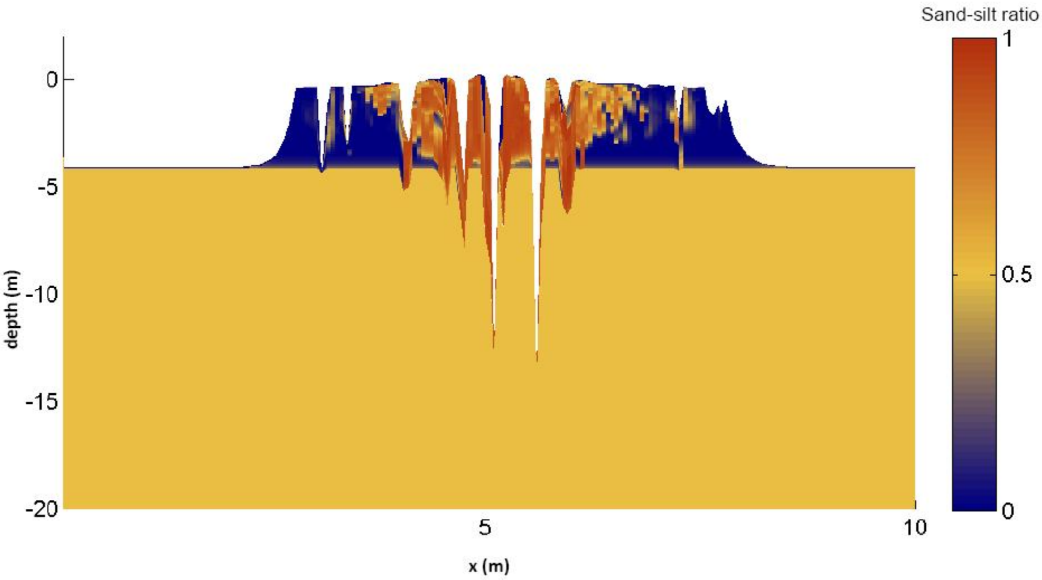

Figure 5.3 Stratigraphy (ratio sand – silt) initial condition of longshore cross-section M-M'

A longshore cross-section (M-M’, location indicated in Figure 5.2) of the deltaic environment is shown in Figure 5.3. The colours indicate the presence of sand with respect to silt (ratio sand-silt). The substrate is the unaffected bottom in which no deposits can be recognized and which is not considered here. Because the substrate can function as an erodable layer a 50-50% mixture of both sediment fractions is present in this layer. Along and in the channels and distributaries sand deposits are observed. Fine sediments (silt) are deposited at both lateral sides. This also holds for the edges of the delta front, which is surrounded by silt deposits. In Figure 5.3 also coarsening of the deposits in upward direction can be observed. First, silt is deposited, which is later covered by coarser sediments due to the progradation of the delta and finally sands, deposited by the distributaries, is placed on top. In the base case no discharge flows through the channels and distributaries, and sediments in the deltaic environment are distributed under the influence of waves.

5.1.3 Morphology

The changes in morphology of the deltaic environment can be quickly observed for the process of delta degradation. With the disappearance of the fluvial input the fluvial character of the system of channels and distributaries is lost. The small distributaries are filled in from the basin side and reworked sediments get deposited in the distributaries. Over time the morphology changed and sediment reworking caused a smoothing of the delta front. A gently curved shoreline profile is developed as the delta front orientation changed with respect to the incoming waves.

In Figure 5.4 these changes of the morphology over time are shown. The deltaic morphology is shown at four stages of the degradation of the deltaic environment. In the initial condition the deltaic environment resembles a fluvial-dominated delta, with many distributaries and two main channels. The distributaries near the delta front quickly disappear and the deposits near the distributary mouths are reworked in the first time steps (see T=5 in Figure 5.4). Over time the deltaic environment looses the deltaic characteristics and transforms to a delta with characteristics of a wave-influenced coast.

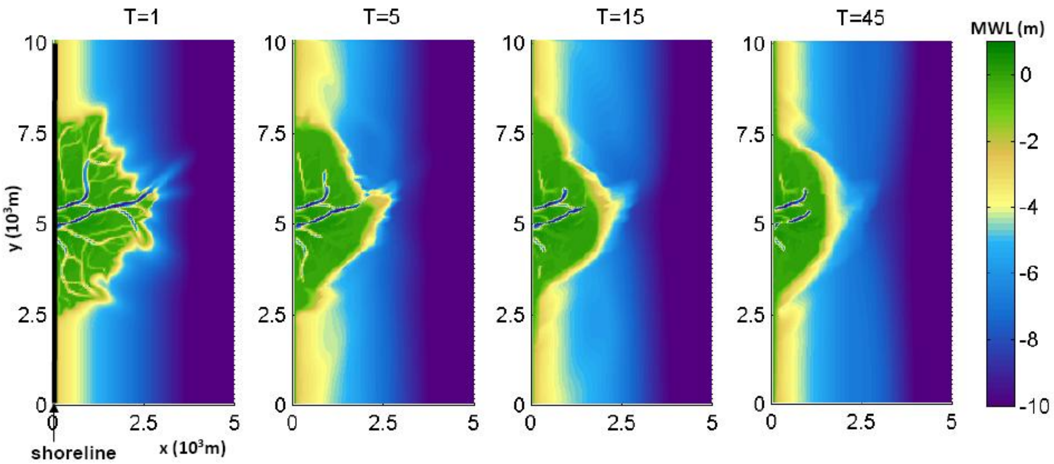

Figure 5.4 Plan view of morphology of deltaic environment of base case over time

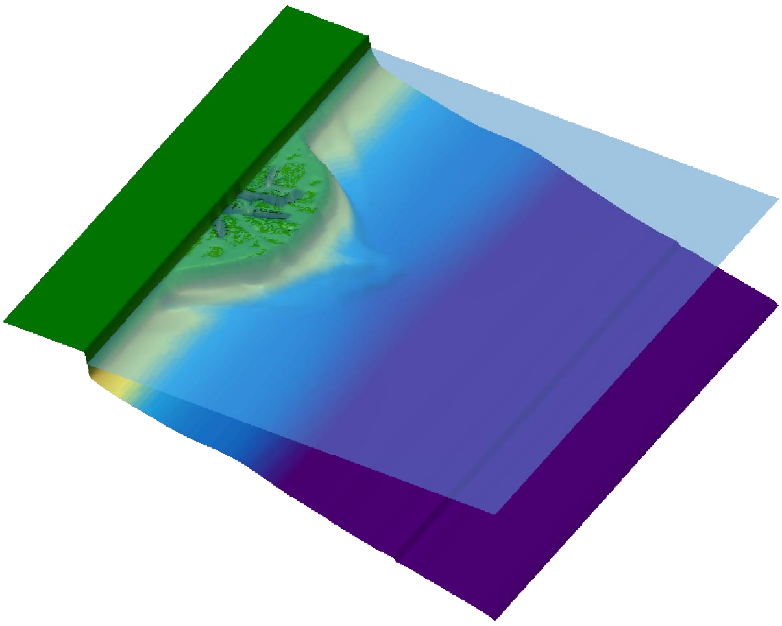

Figure 5.5 3D representation of the resulting morphology of the base case

In Figure 5.5 a three-dimensional representation of the resulting morphology of the base case is shown. The shoreline and land area are not modelled in the base case, but are added to the figure to illustrate the settings of the base case.

5.1.4 Erosion of the delta front

The continuous impact of waves on the edge of the delta front causes the delta front to retreat, creating a degradational delta. The wave energy transports eroded sediments of the delta front in landward direction. Waves cause stirring up of the sediments and the wave-induced currents transport the sediments. Along the delta front, fine sediments, the silt sediment fraction, are brought into suspension and transported and the sand particles are transported both by bed and suspended load. Most of the erosion of the delta front occurs in the first timesteps, because the sudden change of processes cause erosion of fine sediments deposited along the delta front and just deposited sediments are almost directly stirred up and transported. The erosion of the delta front is illustrated by two crossshore cross-sections (N1-N1’ and N2-N2’) and one longshore cross-section (M-M’) in Figure 5.6. In this figure the positions of the cross-sections are indicated on plan views of the initial and final morphology of the base case.

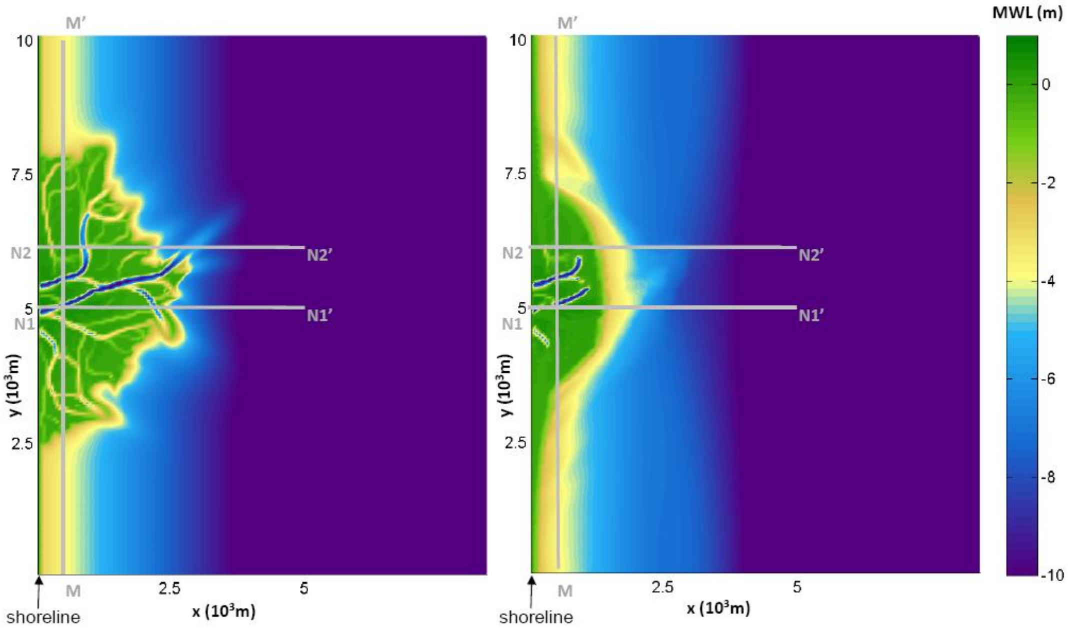

Figure 5.6 *Plan view plan views of initial morphology (right) and final morphology (left) with crosssections M-M', N1-N1' and N2-N2' indicated*

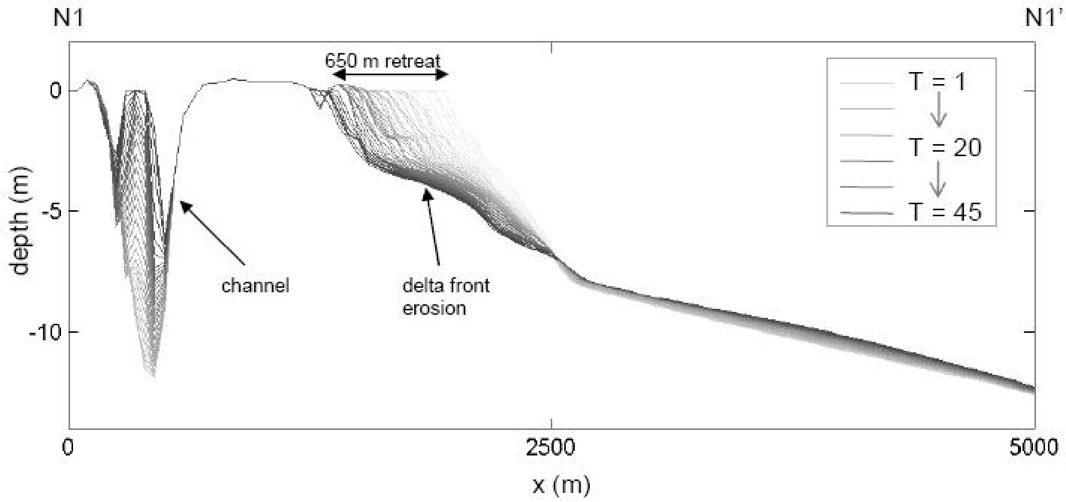

Figure 5.7 *Bed profiles of crossshore cross-section N1-N1' over time*

Figure 5.7 illustrates the erosion of the delta front over time in the crossshore cross-section N1-N1'. Light grey lines indicate crossshore profiles of the delta during the first time steps of the simulation and black lines represent the profile at the end of the simulation. The fast adjustment of the delta front to the incoming waves can be observed from the distance between the light grey lines. The distance between the profiles decreases over time as the profile is displaced in landward direction.

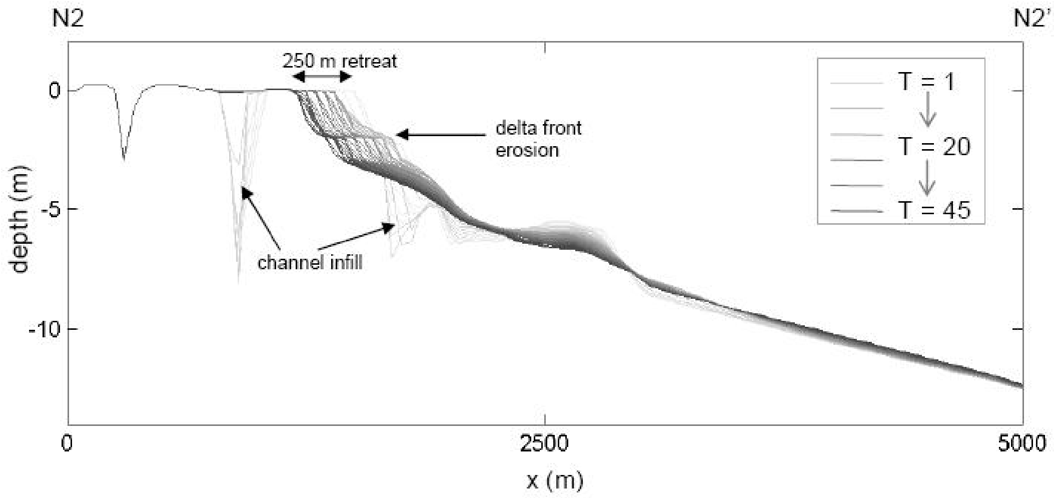

Figure 5.8 Bed profiles of crossshore cross-section N2-N2' over time

The development over time of the crossshore profile of cross-section N2-N2' is shown in Figure 5.8. This cross-section is located one kilometer in lateral direction from cross-section N1-N1' and at this location less erosion of the delta front can be observed. However, the smoothing of the profile over time is more prominent in this cross-section. The irregular profile and offshore bars in the shallow zone in front of the delta are smoothened over time and a gentler beach profile is the result. The light grey lines with a depth of several meters indicate small distributaries which are quickly filled by reworked sediments and the more inland located channel is also quickly filled in.

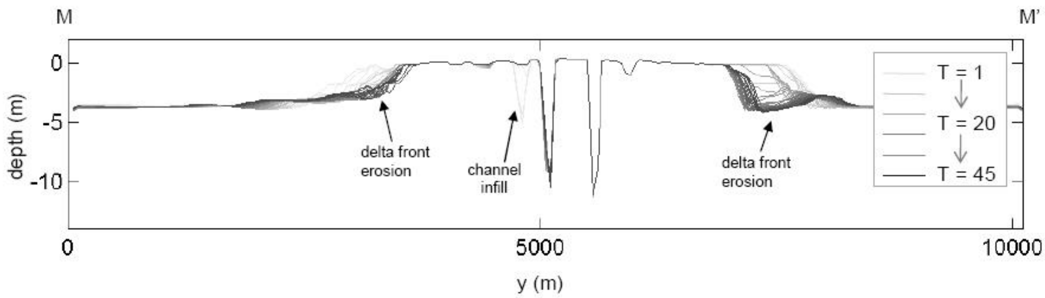

Figure 5.9 Bed profiles of longshore cross-section M-M' over time

The erosion of the delta front can also be observed in longshore cross-sections of the delta. In Figure 5.9 the profiles of the longshore cross-section M-M' are shown. Here the erosion of the delta front is present at the lateral sides of the delta. Cross-section M-M' is located in the basin at a distance of 500 meters from the coast. The two main channels in the middle of the cross-sections are well shielded by the delta front and are not filled in. The smaller distributary as seen next (thin light grey line) to the left of the left channel is however quickly filled in.

5.1.5 Channel infill

The abandoned distributaries of the fluvial-dominated delta of the initial condition are quickly filled in by the silt sediment fraction. Due to the absence of river discharge, flow through the distributaries is not continued and the distributaries become obsolete. Waves that break on the delta front deposit silt in the distributaries. The relatively large depth of these channels causes sedimentation of the stirred up silt. Parts of the channels remain open since these parts are well-shielded and no sediment is transported to these more inland located channels. These abandoned channels form enclosed lakes in the deltaic environment.

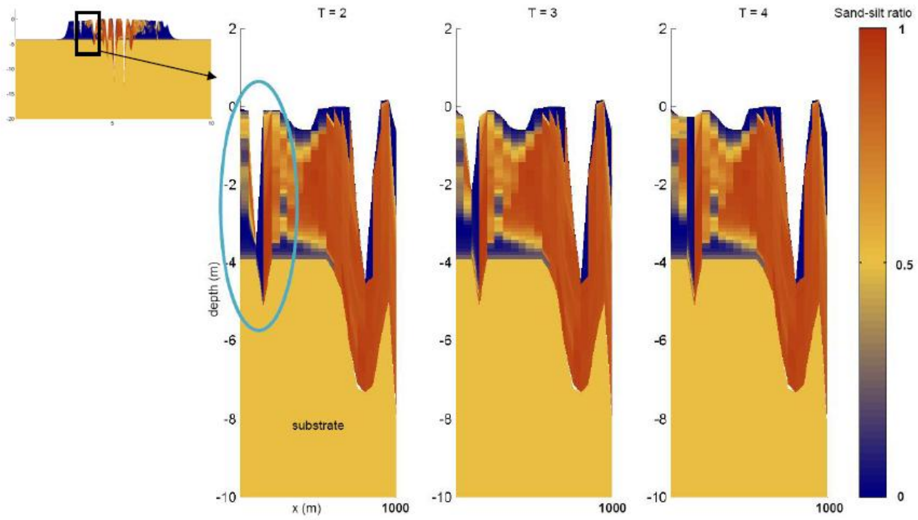

Figure 5.10 Process of distributary infill by fine silt, detail of cross-section M-M'

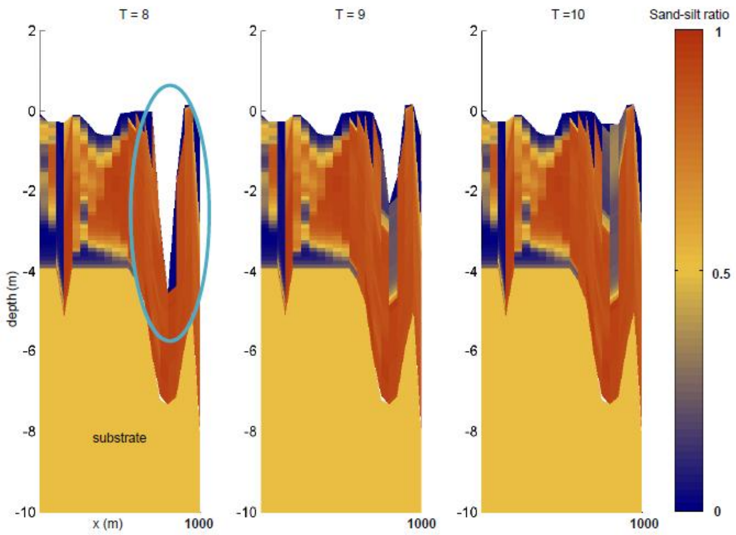

Figure 5.11 Process of distributary infill by fine silt, detail of cross-section M-M'

An example to illustrate the process of distributary infill is provided in Figure 5.10 and Figure 5.11 with two timeseries of the stratigraphy of a detail of cross-section M-M'. Here a distributary closer to the delta front is filled in first and later on channel infill of a more inland situated channel occurs. Along the channels and distributaries sandy deposits can be observed. The sediments that get transported in shoreward direction over the delta front are suspended sediments, mostly silts, which cause channel infill that can clearly be observed. First, a small distributary channel, highlighted in Figure 5.10, is filled in by silt. This infill occurs just after the simulation is started and happens in two timesteps. About five timesteps later the larger distributary channel is filled in which is located more inland, this is highlighted in Figure 5.11. With the infill of this distributary channel sediments show a fining upwards pattern, which is similar to river systems. Contrary to the distribution of deltaic sediments, the distributaries exhibit the process of fining upwards. The coarser sediment is transported less easily and is deposited at first (at the distributary bed), followed by the finer grained sediments afterwards. This phenomenon is well visible in the middle figure of Figure 5.11 (T=9).

5.1.6 Sediment transport

The erosion of the delta front and the process of channel and distributary infill have a strong relation with the sediment transport. Longshore currents and thereby longshore sediment transport are caused by the angle between the shoreline and the incoming waves. The highest currents are observed where the delta front orientation has the highest angle with respect to the incoming waves.

Figure 5.12 illustrates the mean bed load transport for both sediment fractions. The colorbar in the left image indicates the transport rates for both images (in m^3/s/m). The figure illustrates that the bed load transport consists almost entirely of sand. Bed load transport only exists along the delta front where the transport is in landward direction. Details of the mean bed load transport along the delta front are shown in Figure 5.13.

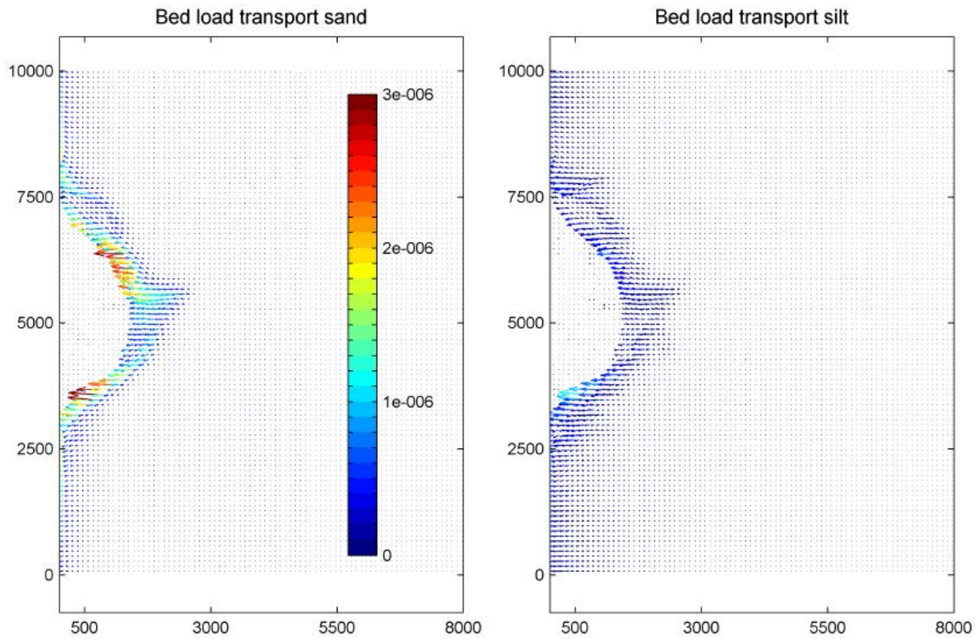

Figure 5.12 Mean bed load transport of sand fraction (left) and silt fraction (right)

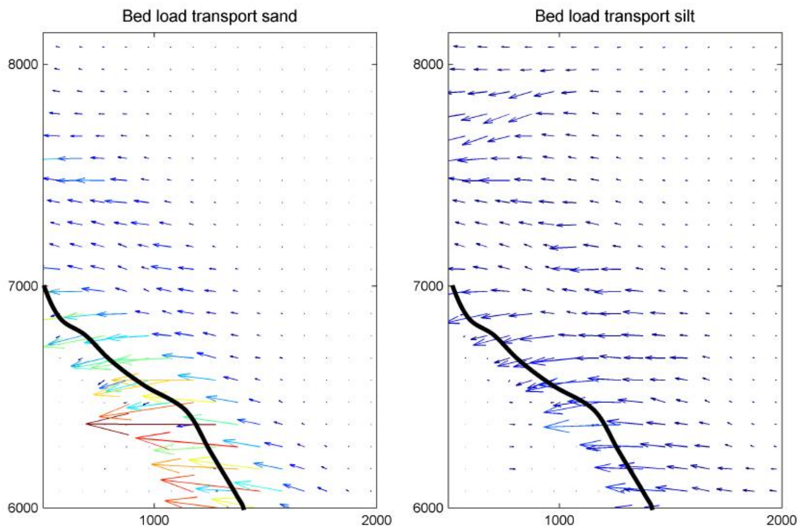

Figure 5.13 Details of mean bed load transport of sand fraction (left) and silt fraction (right)

From Figure 5.14 it can be observed that most of the sediment is transported by suspended load transport and that for the sand sediment fraction this is almost twice the amount of the bed load transport. However, most of the suspended load transport is transport of the silt sediment fraction. This is as expected since fine sediments require less energy to be brought in suspension. The highest bed load rates are observed along the delta front, but suspended load transport occurred over a broader area. On both lateral sides of the delta, offshore directed suspended load transport cause circulation patterns due to the waves that bend these transports. Figure 5.15 shows a deltailled overview of the mean suspended load transport along the delta front.

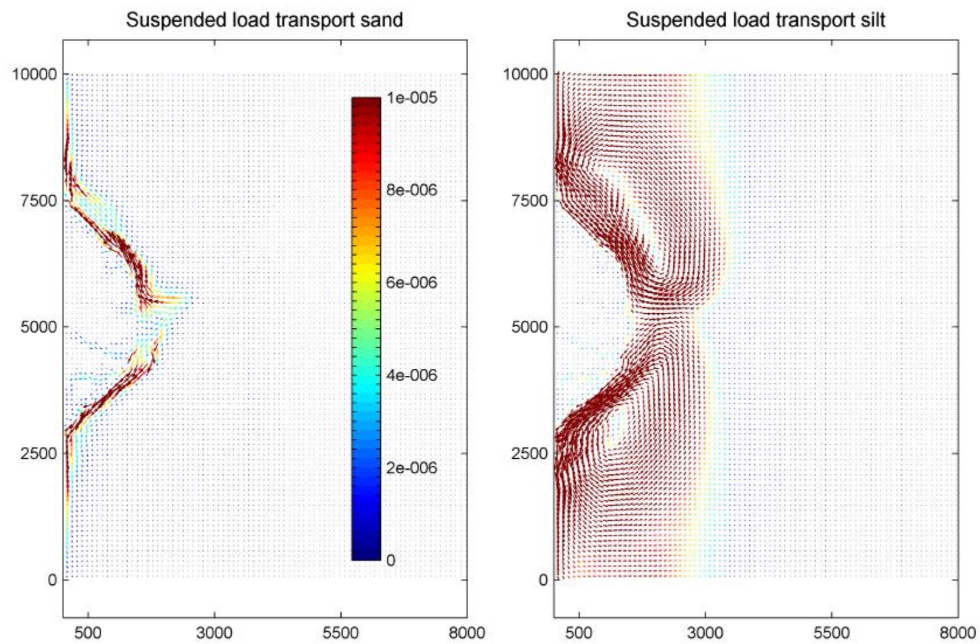

Figure 5.14 Mean suspended load transport of sand fraction (left) and silt fraction (right)

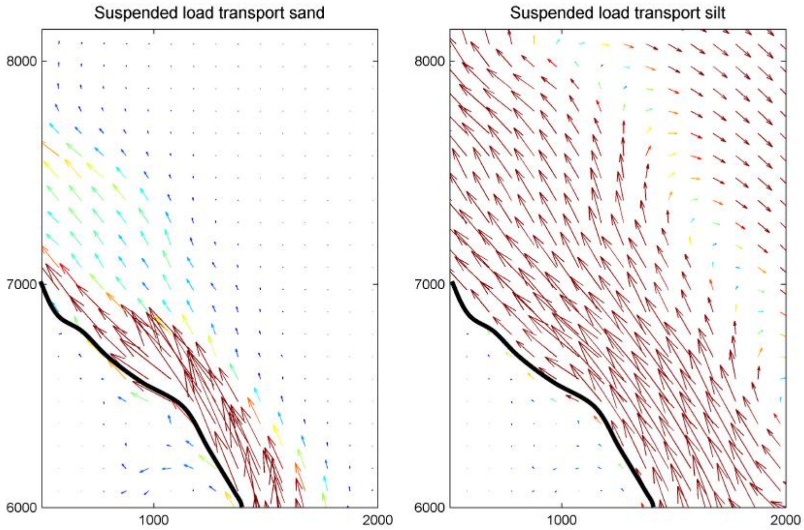

Figure 5.15 Details of mean suspended load transport of sand fraction (left) and silt fraction (right)

5.1.7 Sediment sorting

The influence of the waves on the deltaic environment in the base case accounts for erosion of the delta front and channel infill but also for sorting of the sediments. Because silt requires little energy to be stirred up and transported as suspended load transport, these sediments are transported from the delta front. With increasing exposure to the waves also the sand sediments are brought into motion, both in suspension and in the bed load layer. These sediment dynamics are similar to what has is observed in the Atchafalaya Bay, Louisiana, where the sandy Wax and Atchafalaya deltas have been prograding under a modest wave climate and where suspended sediments are transported offshore (Roberts et al., 2005). Robert et al. (2005) determined that modest waves erode the delta front and cause sediment resuspension and that mostly sand deposits remain in the delta.

Figure 5.16 illustrates the cumulative sedimentation and erosion over the run time of the base case. The process of channel infill and delta front erosion are observed, as is deposition of banks offshore, that are 2 meters thick, on both lateral sides of the deltaic environment. These banks are silt banks which are deposited by the circular suspended transport patterns, the silt deposited here comes from the delta front. On both lateral sides of the delta, directly adjacent to the shoreline, thin strips of sand deposits are observed, which are transported here by bed and suspended load transport along the delta front and deposited when the flow velocity of these transports decreases.

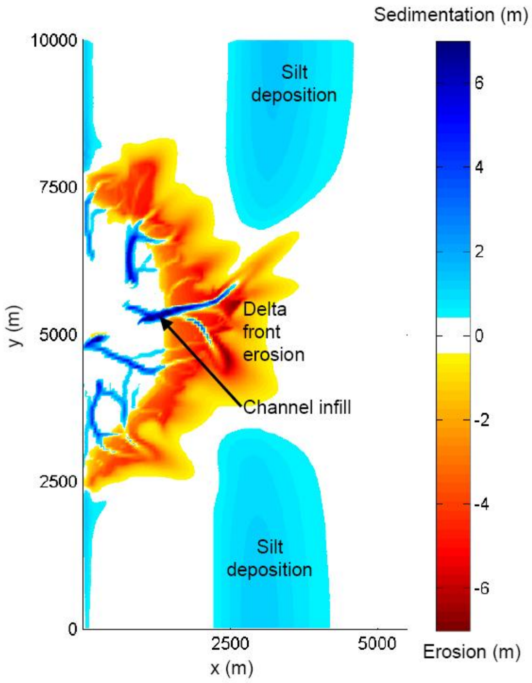

Figure 5.16 Plan view of cumulative sedimentation and erosion of the base case

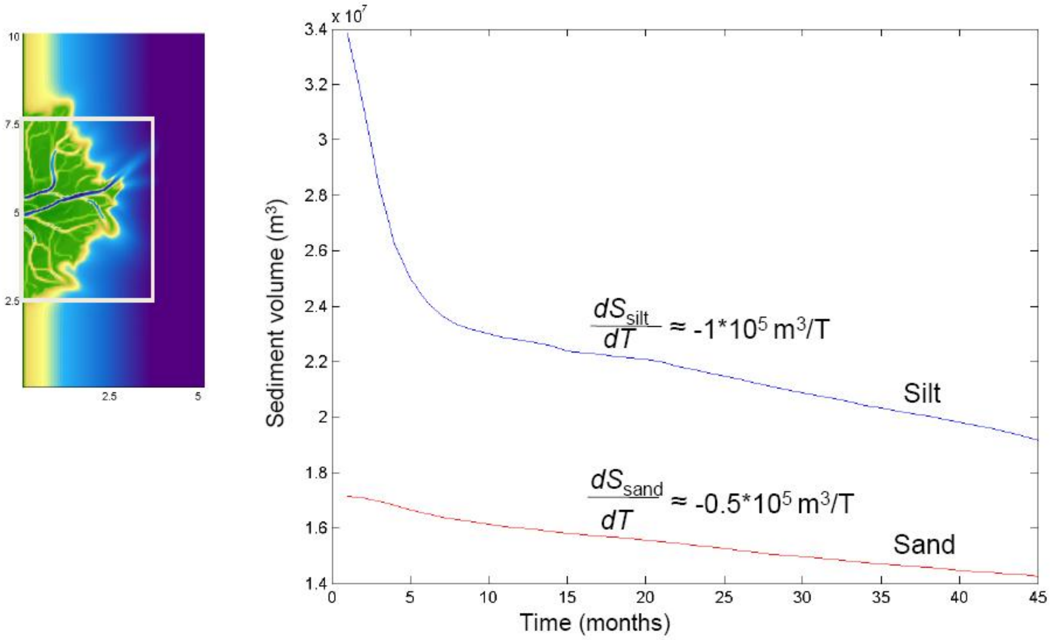

Figure 5.17 Sediment budget of deltaic environment, as indicated in the insert, showing the decrease of sediments over time

Wave conditions transport silt out of the the deltaic environment and leave a framework of sandy deposits. In Figure 5.17 the rapid adjustment of the deltaic environment to the incoming waves is seen as a rapid decrease in the amount of silt in the deltaic environment. At the start of the simulation silt are transported out of the deltaic environment at a high rate. These amounts of silt were deposited along the delta front in a fluvial-dominated environment with no waves and are unshielded and therefore directly exposed to the waves. Due to the constant forcing of the waves and the absence of depositional processes the silt sediments are easily stirred up and transported. This indicates the vulnerability of the deltaic environment to changes.

During the following timesteps the steady decrease in silt continues at a rate of $1*10^{-5}$ m^3 per month (Figure 5.17). The decrease of the amount of sand in the deltaic environment is about half the rate of decrease of silt. During the simulation sand deposits arre formed at the edges of the delta front. These are believed to shield the underlying silts from erosion. However, still a decrease of sediments could be observed. This is because sand deposits are reworked and consequently the underlying silt deposits are exposed to the waves and transported.

Similar sediment reworking behaviour was also observed at the Isles Dernieres, barrier islands in the Mississippi delta (Dingler and Reiss, 1990). Dingler and Reiss (1990) found that the degradation of these islands occurred when sand of the beach-face was reworked and a volume of the exposed underlying mud deposits, in direct proportion with the loss of beach-face, was transported. Part of the reworked sand was deposited on the backshore, but the mud deposits were lost.

This behaviour is illustrated in Figure 5.18. In the model at the edges of the delta front sand deposits are formed (indicated in red), but as these erode (process not represented in figure) a large portion of the deltaic environment is quickly transported and a new layer of sand deposits is deposited on the new edge of the delta. Figure 5.18 shows the initial cross-section with silt deposits at the delta front (left, in blue) which are eroded and sands are deposited on top over time (right, in red).

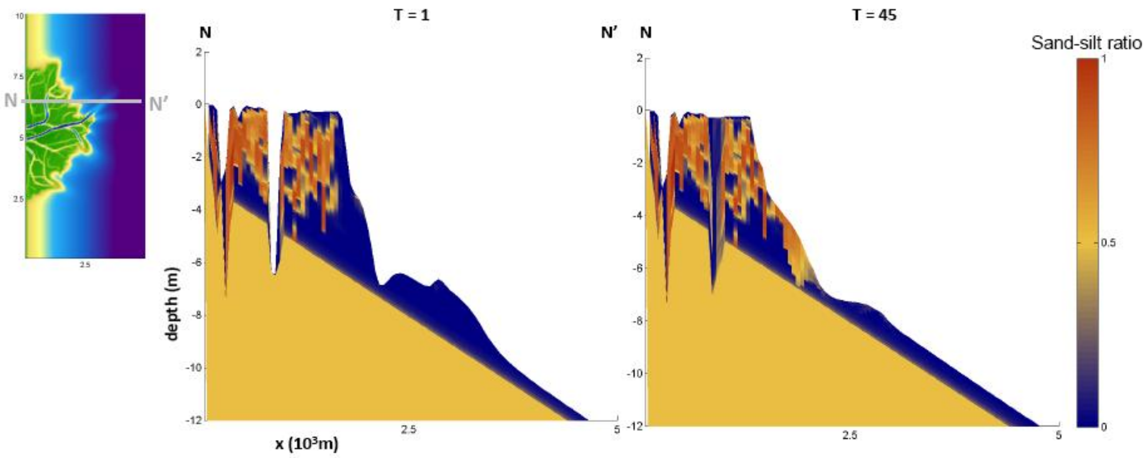

Figure 5.18 Crossshore stratigraphic sections (N = 125) of initial and resulting condition to illustrate sediment sorting and shielding

5.1.8 Conclusion

The base case shows that the processes of sediment reworking and changes in the deltaic environment can be realistically represented with the model and give interesting results for changes in the morphology and stratigraphy on meso-scale. Sediment reworking under waves causes the retreat of the delta front and sorting of the sediments. The sediment transport processes under wave conditions transport (mainly fine) sediments along the delta front to the lateral sides of the delta and offshore. Due to the sudden switch of dominant processes the delta adjusts rapidly to the wave conditions. Next, scenarios with a higher complexity, but a more natural representation, are investigated by including fluvial input in the base case. Several simulations with different riverine water and sediment discharges are investigated in the next paragraph.

5.2 Fluvial input case

The base case concerns a situation without fluvial input. However, the interaction of fluvial input and basinal reworking is what shapes a typical deltaic environment. In reality changes in the fluvial input which change the deltaic environment are more likely to occur and can cause the delta to enter the destructional phase of the deltaic cycle. Therefore the base case is elaborated with fluvial input; varying river discharges and a changing sediment supply to investigate the influence of (changes in) fluvial input.

The base case is extended with an upstream boundary condition where a water- and sediment flux are determined. The river discharge is determined as a constant over the run time. The sediment supply is indicated as an equilibrium concentration depending on the hydrodynamics and as a constant value. Part of the river system of the reference model is included in the model environment. The grid of the base case is extended with 66 cells (3,300 meters) in landward direction to prevent adjustments in the deltaic environment due to changes in the flow pathways. Therefore the discharge is imposed directly at an already present (main) channel.

The simulations of the fluvial input case illustrate the high variability of outcomes due to the interaction of fluvial- and basinal (wave) processes. The large number of distributaries of the initial condition is quickly abandoned and one main channel remains. Depending on the river discharge and sediment supply the fluvial input can help sustain the deltaic environment by creating sand-ridges near the river mouth. On the other hand, the river outflow often creates a jet which also transports part of the existing environment into the basin.

5.2.1 Setting

Changes with respect to the deltaic environment are mostly induced by a change in the balance between fluvial- and basinal processes. This balance changes when one of the three controlling factors (fluvial input, wave flux or tidal flux) is changed. Of these factors the fluvial input is most likely to change due to human involvement (McManus, 2002; Syvitski, 2008; Syvitski and Saito, 2007). Over time human engineering changed water flux, sediment flux, flow patterns and land use in the deltaic environment (Syvitski and Saito, 2007). These changes disturb the balance in the deltaic environment which may lead to a decrease in delta building and a larger influence of the basinal processes, since the basinal processes often remain unchanged.

Fluvial input consists of riverine water and sediment discharge. To investigate the influence of both parameters these are varied separately. In Table 5.1 an overview of the simulations of the fluvial input case is provided. Simulations # 1 to 4 investigate the influence of river discharge in combination with gentle waves on the deltaic environment. The discharge applied for delta building in the reference model is 2,000 m^3/s, so the discharges of the fluvial input case are scaled to that situation. However, in the fluvial input case a smaller river system is used and the discharge is imposed at one (main channel). Next, simulations # 5 to 8 investigate the influence of the sediment supply on the destructional phase of a delta.

#	Simulation description	River discharge [m^3/s]	River sediment discharge (both sediment fraction)
1	Low river discharge, equilibrium sediment concentration	500	Equilibrium condition (almost no sediment load)
2	Median river discharge, equilibrium sediment concentration	1,000	Equilibrium condition (mean sediment load approximately 0.002 kg/m^3)
3	Median river discharge, equilibrium sediment concentration	1,500	Equilibrium condition (mean sediment load approximately 0.013 kg/m^3)
4	High river discharge, equilibrium sediment concentration	2,000	Equilibrium condition (mean sediment load approximately 0.035 kg/m^3)
5	Median river discharge, constant (mean of equilibrium) sediment concentration	1,000	Constant sediment concentration of 0.002 kg/m^3
6	Median river discharge, high constant sediment concentration	1,000	Constant sediment concentration of 0.02 kg/m^3
7	High river discharge, constant (mean of equilibrium) sediment concentration	2,000	Constant sediment concentration of 0.035 kg/m^3
8	High river discharge, high constant sediment concentration	2,000	Constant sediment concentration of 0.1 kg/m^3

Table 5.1 Overview of characteristics simulations of fluvial input case

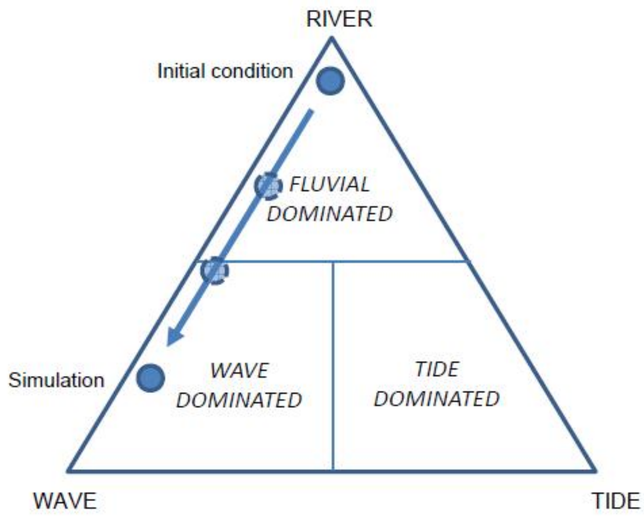

Figure 5.19 Change of dominant processes in the simulated deltaic environment based on the classification of Galloway (1975)

The changes in the deltaic environment are illustrated with the classification scheme of Galloway (1975). The arrow in Figure 5.19 indicates the change of dominant process for the simulations in which fluvial input is included. The simulations can be placed on several positions along the arrow, depending on the fluvial input (since wave power is kept constant).

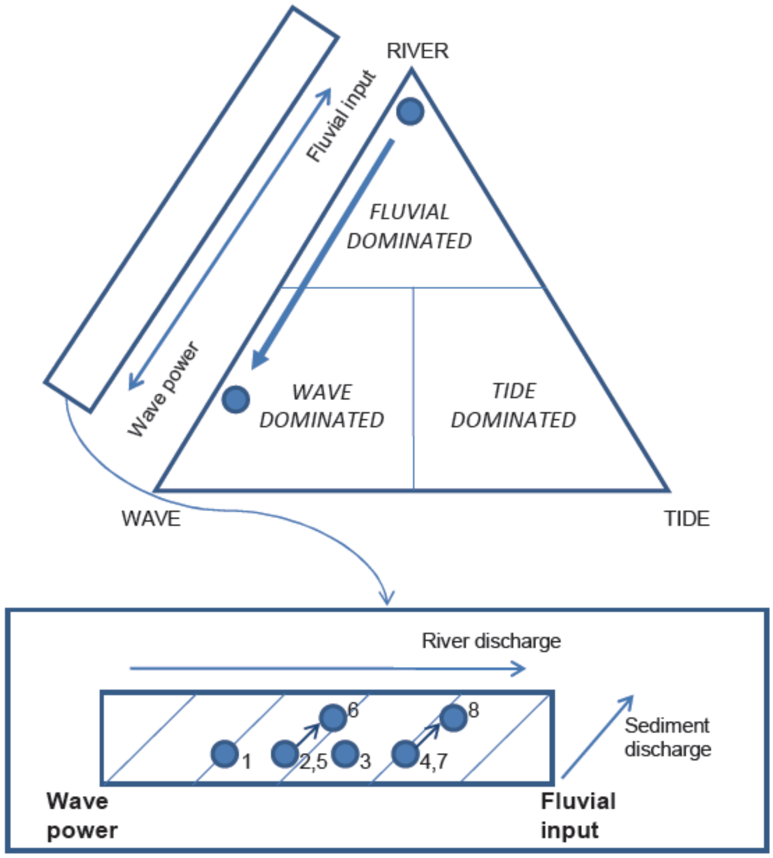

Figure 5.20 Change of dominant processes in the simulated deltaic environment based on the classification of Galloway (1975) elaborated with respect to riverine water and sediment discharge

Due to the variability of both the riverine water and sediment discharge the relative change of the dominant processes is hard to indicate in the classification scheme of Galloway. Therefore this scheme is extended with the ratio wave power to fluvial input. Since the wave power is kept constant, this is of no influence on the scheme and the change in processes of the simulation is determined entirely by the change in fluvial input. The fluvial input itself was split into (the influences of) river discharge and sediment supply. A partly similar model is defined by McManus (2002), to illustrate the influence of changes in the river on the deltaic environment. Figure 5.20 shows this model in which the effects of varying fluvial input are highlighted. The dots represent the simulations with the corresponding numbers following Table 5.1. Although a qualitative indication, the model indicates the differences in influence of riverine water and sediment discharge. Following this model, the change of river discharge and sediment supply combined with the influence of waves will change the fluvial-dominated delta to a wave-influenced delta.

5.2.2 Morphology

The changes in the resulting morphology for the fluvial input simulations are partly similar to the base case. The small distributaries are quickly filled in by silt, but the main channel(s) which discharge(s) the river discharge and sediment supply remain(s) open. At higher discharges (simulations #3 and #4; discharge 1,500 m^3/s and 2,000 m^3/s) some of the smaller channels remain open for a few timesteps, but the river discharge quickly flows through the main channel. At the river mouth of the channel the river outflow is comparable to a jet debouching into the basin. Here the formation of river mouth bars can be observed and deposition of the sand sediment fraction takes place. The resulting morphology approaches a plan view as predicted by the main classification schemes for symmetric wave-influenced deltas; one main channel that discharges in the middle of a symmetric deltaic environment, a shoreline with decreasing angle towards the incoming waves and the formation of a river mouth bar and sand-ridges on the lateral sides of the river mouth.

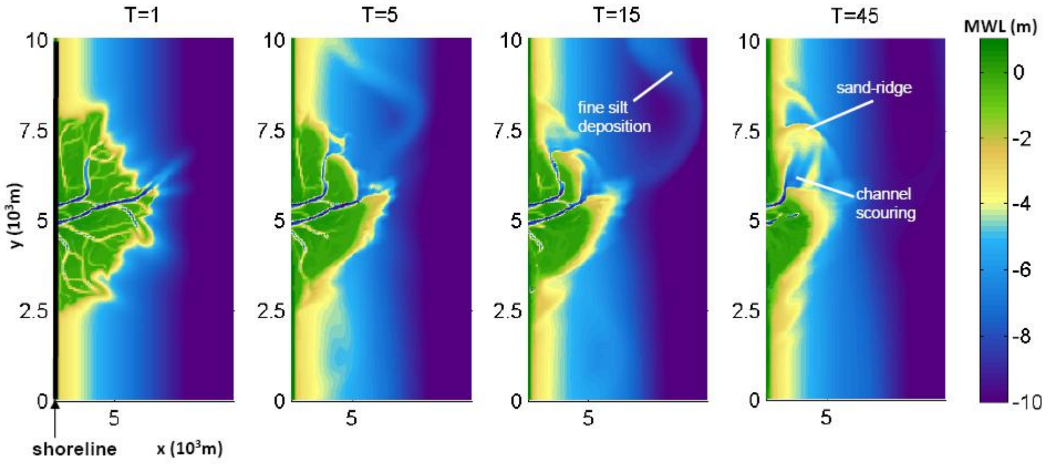

Figure 5.21 Plan view morphology for fluvial input simulation #1 (discharge 500 m^3/s, equilibrium sediment supply) over time

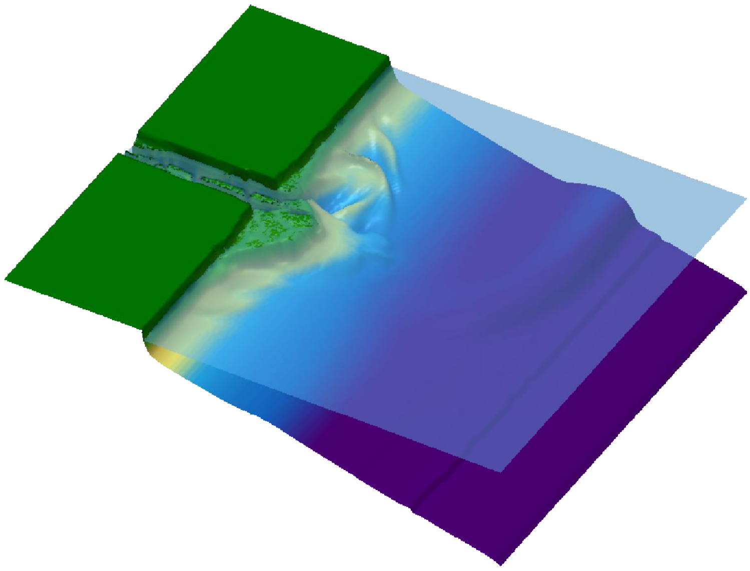

Figure 5.22 3D representation of the resulting morphology of fluvial input simulation #1

In Figure 5.21 the plan view morphology for simulation #1 (discharge 500 m^3/s, equilibrium sediment concentration) is shown. Figure 5.22 gives a three-dimensional representation of the resulting morphology. The channel debouches under an angle into the basin due to the initial morphology and the deposits in front of the river mouth which block the shortest route towards the basin. At the river mouth the scouring of the main channel is observed as are the deposits in the direction of the jet outflow of the river. These deposits are san-ridges. The river mouth behaviour causes an irregular morphology. The silt at the edges of the delta front is transported offshore by suspended sediment transport or by the river-induced currents (see T=5 and T=15 in Figure 5.21). At the lateral side of the delta which is not influenced by the fluvial input, the morphology resembles the base case.

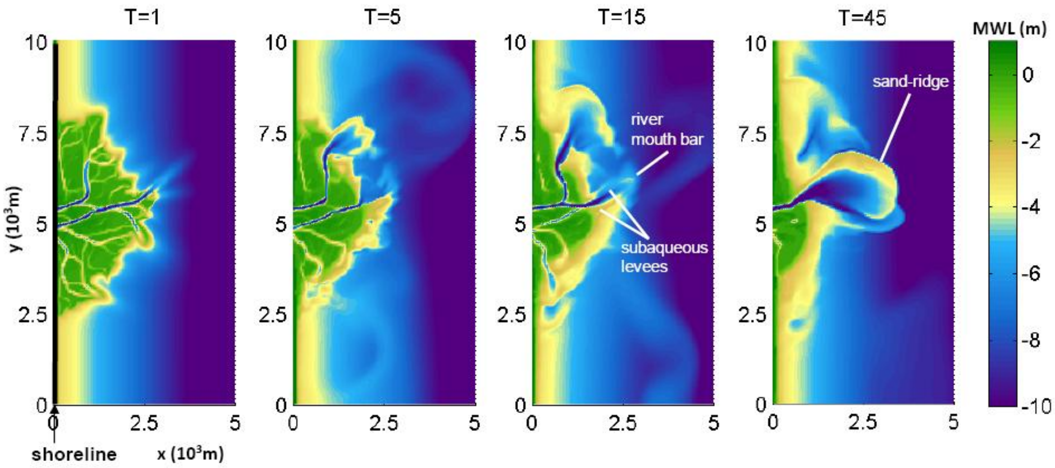

Figure 5.23 Plan view morphology for fluvial input simulation #4 (discharge 2,000 m^3/s, equilibrium sediment supply) over time

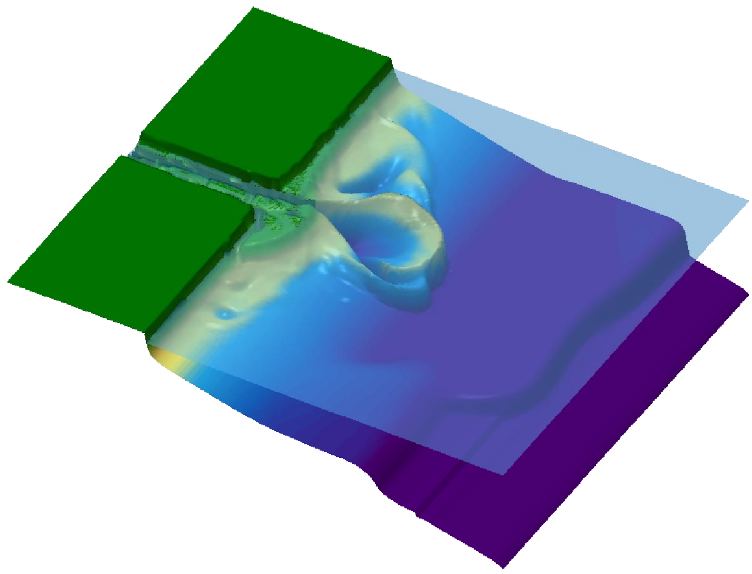

Figure 5.24 3D representation of the resulting morphology of fluvial input simulation #4

The plan view morphology of simulation #4 in Figure 5.23 shows the situation for high river discharge (discharge 2,000 m^3/s, equilibrium sediment concentration) and Figure 5.24 gives a three-dimensional representation of the resulting morphology. It can be stated that the amount of river discharge determines the rate of change of the morphology. The high river discharge causes channel switching by the high fluvial input. In the resulting morphology (T=45, right in Figure 5.23) the river mouth switches towards the middle of the deltaic environment. At both sides of the river mouth, the jet outflow deposit sand banks, resembling subaqueous levees. When the river determines its route to the basin it erodes sediments of the deltaic environment. At locations where the flow velocities decrease sand is deposited; directly next to the channel as subaqueous levees or as sand-ridges. These sand-ridges are an irregular pattern, which results from the interaction of constand river discharge and a constant wave climate. A higher variability of these processes would give more natural depositions patterns.

The erosion of the delta front is higher where the river flow scours its path through the deltaic environment, which is observed at the simulations #3 and #4 (discharge 1,500 m^3/s and 2,000 m^3/s). The scouring brings a larger amount of sediments into suspension, which quickly changes the morphology of the deltaic environment. Where in the base case the waves create a stable delta front with sand deposited at the edges of the delta front, the higher dynamics with the addition of fluvial input induce more erosion of the deltaic environment. The river flow helps to transport the silts offshore and the offshore silt banks are formed at a larger distance from the shoreline.

5.2.3 Sediment sorting

In the simulations of the fluvial input case the process of sediment sorting is observed more distinctively compared to the base case. The interaction of fluvial and wave processes causes even more stirring up of the fine sediments and the resulting currents transport these sediments ofshore. Sand is deposited where the flow velocities decrease and is therefore deposited at the delta front and sand-ridges near the river mouth. The findings of Robert et al. (2005) are applicable to the fluvial input case simulations since the simulations that include the influence of sediment discharge give comparable deposition processes to the deltas in the Atchafalaya basin.

The bed load transport gives an indication of the distribution of sand over the model environment. Figure 5.25 and Figure 5.26 illustrate the relative presence of sand (by the sand to silt ratio) in the model transport layer. Figure 5.25 shows the increased presence of sand over time for simulation #2 (1,000 m^3/s, equilibrium sand concentration). The influence of the riverine sediment discharge is visible since there is more sand presence in the transport layer in the direction of the river outflow (upper part figure). Figure 5.26 shows the larger presence of sand in the transport layer when a higher discharge is applied (simulation #4; 2,000 m^3/s, equilibrium sand concentration). At T=5 the location of the channels can be recognized by the bed load transport patterns.

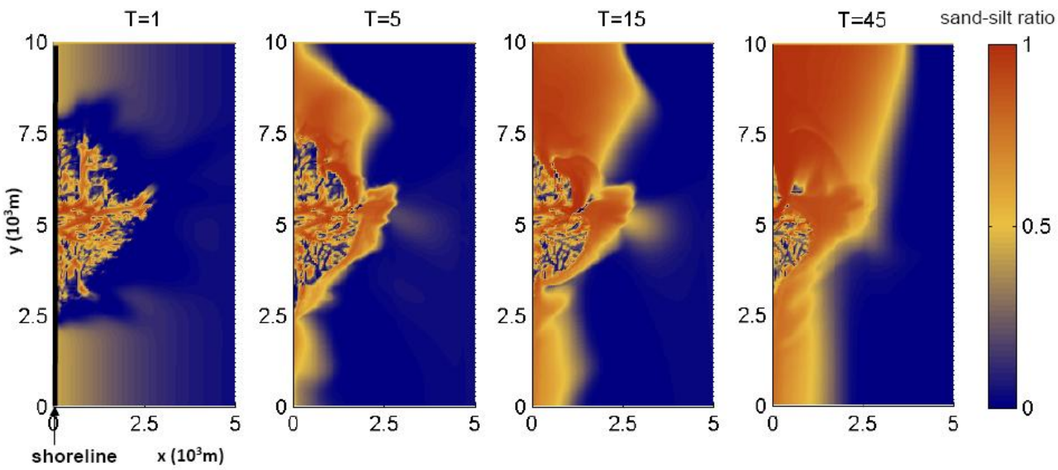

Figure 5.25 Plan view of the grain size distribution in the transport layer of fluvial input case simulation #2

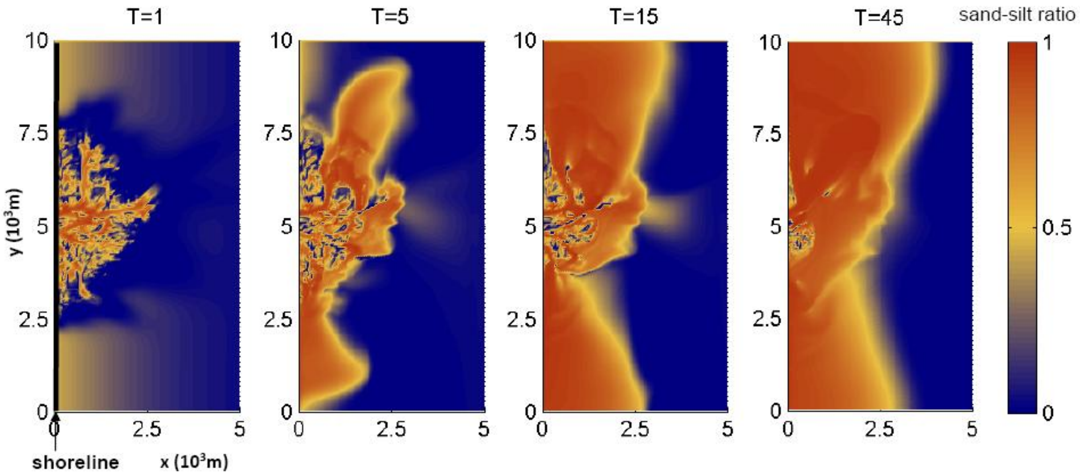

Figure 5.26 Plan view of the grain size distribution in the transport layer of fluvial input case simulation #4

Figure 5.27 gives an overview of the cumulative sedimentation and erosion of the first four simulations of the fluvial input case. Comparable with the base case the process of channel infill and delta front erosion are observed. Interesting is the position of the offshore deposition of silts. Due to the river outflow and the interaction of fluvial and wave processes, the fine sediments are deposited in a more chaotic pattern and are also found in front of the delta. For simulations with a higher discharge (bottom two pictures in Figure 5.27) the silt is deposited further offshore. Also the effect of channel switching can be observed in Figure 5.27 as the silt deposition depends on the orientation of the river mouth. For the simulations with higher discharge also the formation of (relatively large) sand-ridges is observed.

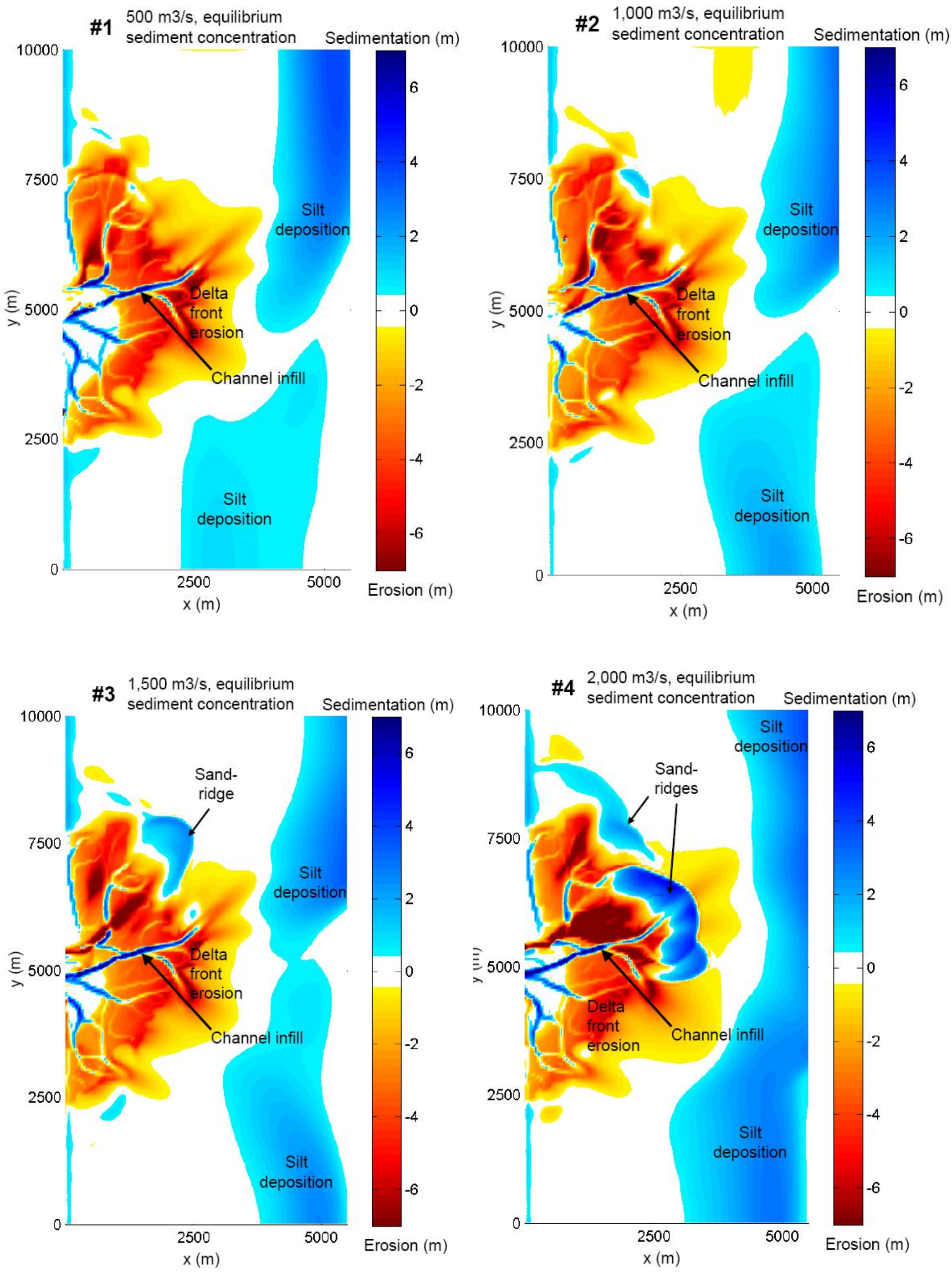

Figure 5.27 Cumulative sedimentation and erosion patterns simulations (#1, 2, 3 and 4) of fluvial input case

The deposition of sand, given a sediment discharge which is sufficiently high for the sand sediments to reach the river mouth, can be observed with the sediment budget of the delta front over time. In Figure 5.28 and Figure 5.29 the sediment budget of simulation #2 (1,000 m^3/s, equilibrium sediment concentration) and #4 (2,000 m^3/s, equilibrium sediment concentration) are shown. Where in simulation #2 the silt fraction rapidly decreases and a lot of sediments are transported out of the deltaic environment, in simulation #4 the amount of sand in the area considered increases steadily. The fines are for simulation #4 still reworked and transported out of the system, but the sand deposits remain (and grow due to continuous sediment rich discharge). For both simulations the rapid adjustment of the silt to the new forcing is observed (as in the base case).

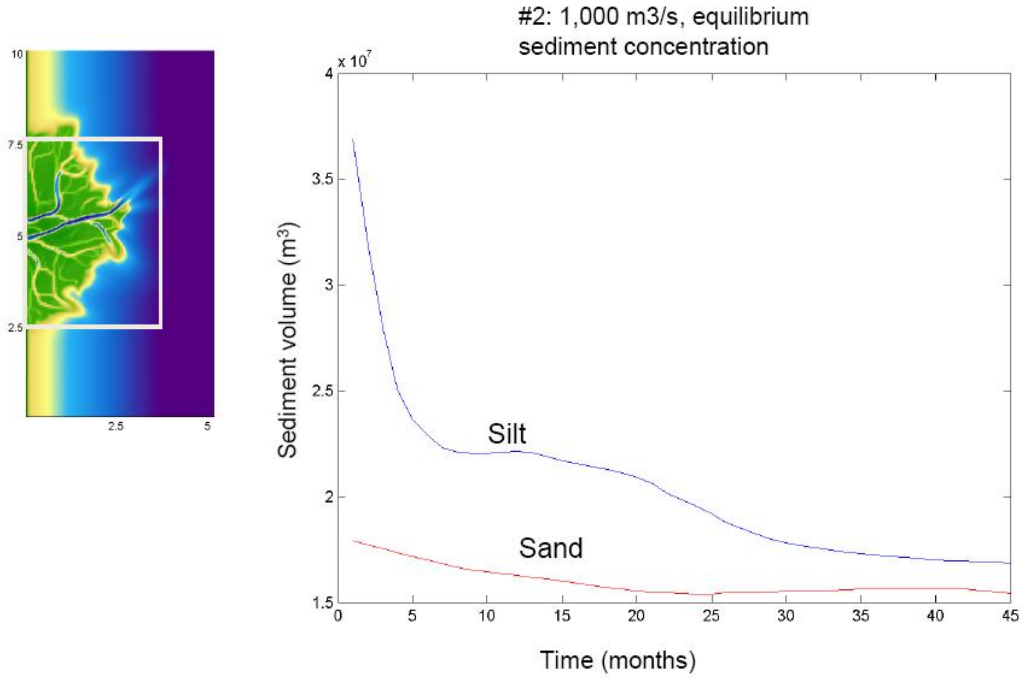

Figure 5.28 Sediment budget of deltaic environment, as indicated in the insert, showing the decrease of sediments over time for simulation #2 of the fluvial input case

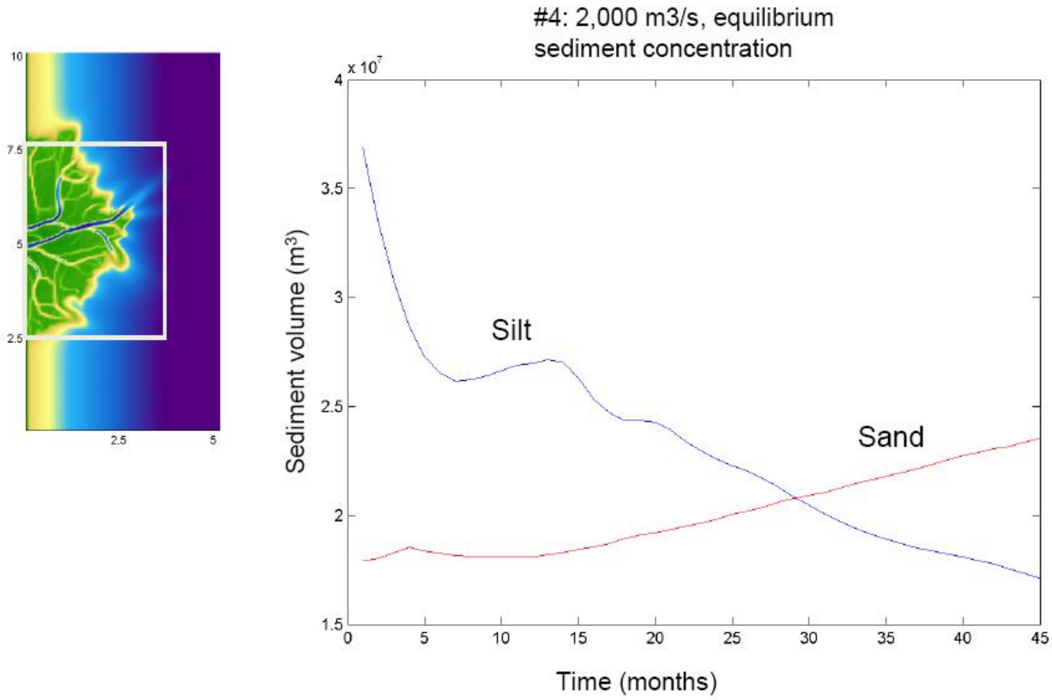

Figure 5.29 Sediment budget of deltaic environment, as indicated in the insert, showing the decrease of sediments over time for simulation #4 of the fluvial input case

Most of the deposits of the deltaic environment are reworked, but as shown in Figure 5.29 there is deposition of sands (in simulation #4). This is also observed in the stratigraphy. Figure 5.30 represents a longshore cross-section of simulation #4 over time. At the left side of the first the fine sediments are eroded. Next, sand-ridges are formed due to the discharge of a distributary. These sand-ridges are reworked and more sand is deposited. The last figure shows that the originally fine deposits are replaced by sand deposits.

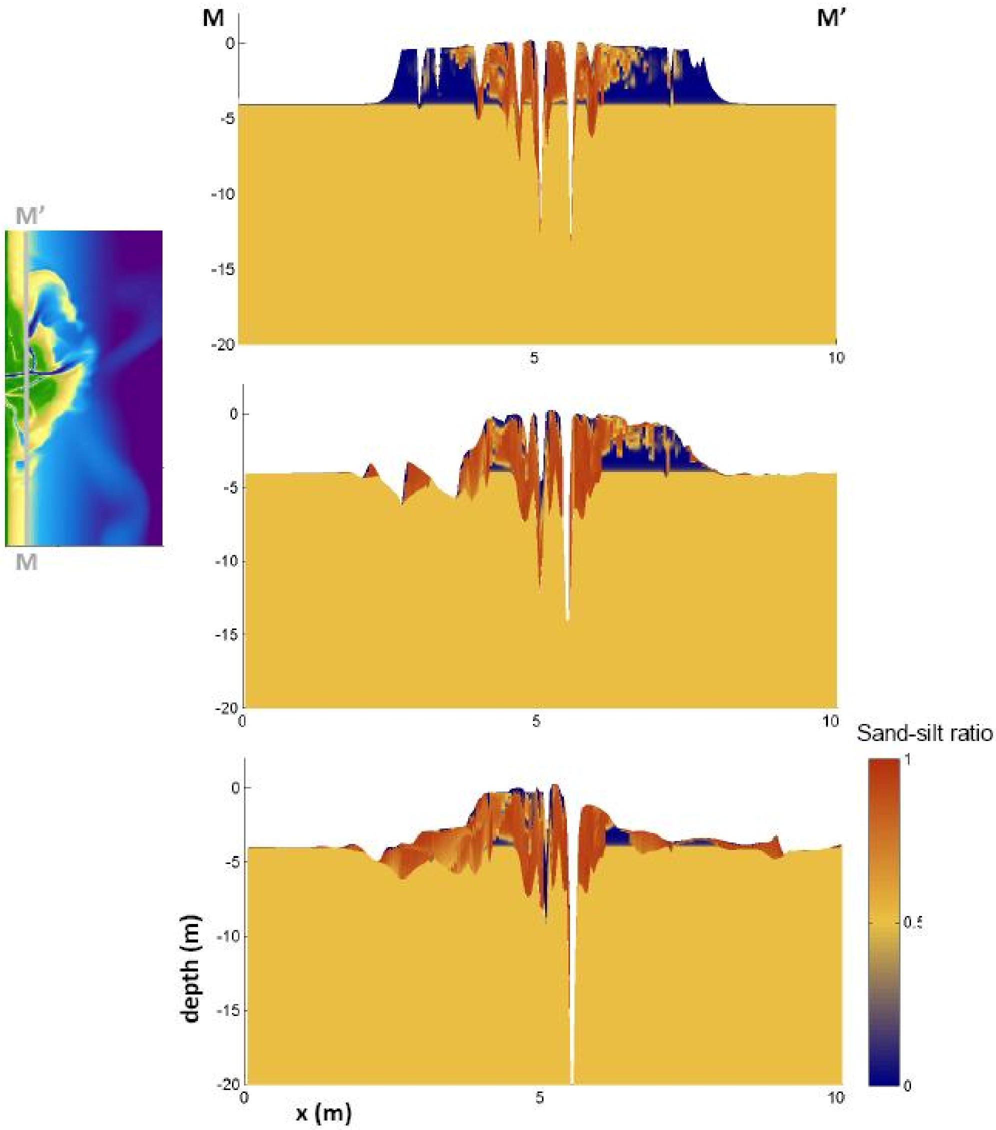

Figure 5.30 Stratigraphic longshore cross-section of simulation #4 over time

The increase of the amount sand in the deltaic environment is observed in the deposition of sand-ridges at the river mouth. Due to the rapid deposition of sand sometimes fine sediments along the delta front are topped by sand deposits and this way these are preserved. An example is shown in Figure 5.31. Here a crossshore cross-section of fluvial input case simulation #4 (2,000 m^3/s, equilibrium sediment concentration) illustrates sand deposits covering earlier deposited silts.

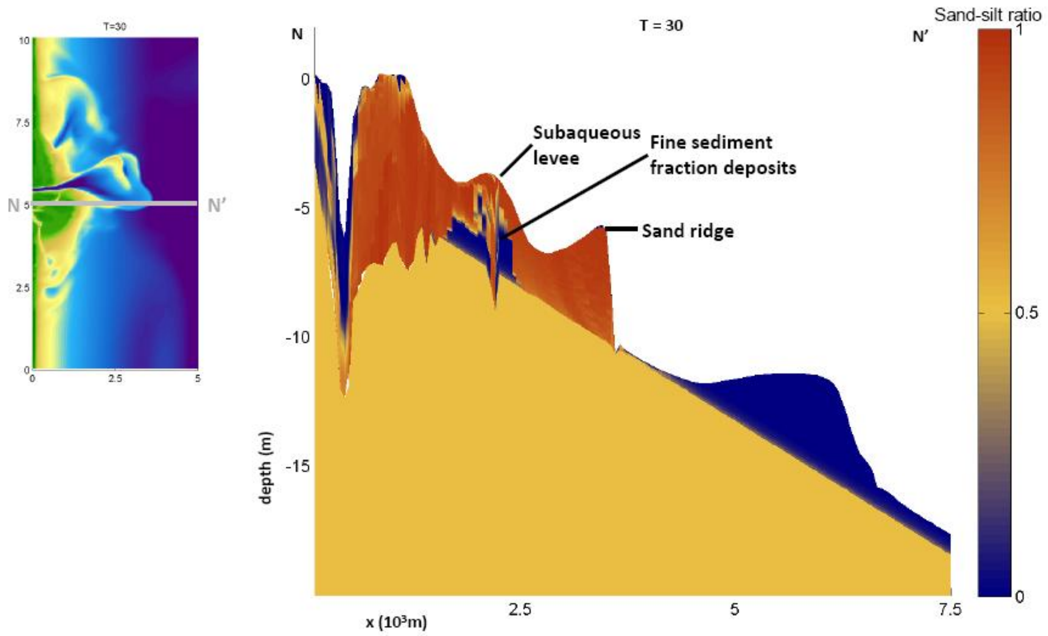

Figure 5.31 Crossshore stratigraphic cross-section illustrating partial preservation of fine sediments topped by sand deposition

5.2.4 Influence sediment discharge

The sediment supply to the deltaic environment determines the shape of the delta and influences the river mouth processes which determine the resulting morphology. The influence of the sediment discharge on the delta's morphology and stratigraphy is dominant over the influence of water discharge, although these two parameters are closely related. At high discharge, a higher sediment supply is often found, due to the higher transport capacity and the higher scouring capacity of the river.

To investigate the influence of sediment discharge on the deltaic environment, the mean sediment concentrations of simulations #2 (1,000 m^3/s, equilibrium sediment concentration) and # 4 (2,000 m^3/s, equilibrium sediment concentration) are determined. Next, these mean sediment concentrations are applied as constant sediment concentrations (boundary condition) for simulations #5 (1,000 m^3/s, constant sediment concentration 0.002 kg/m^3) and # 7 (2,000 m^3/s, constant sediment concentration, 0.035 kg/m^3). These simulations are compared with the simulations in which an equilibrium sediment concentration is applied. Figure 5.32 and Figure 5.33 illustrate that these simulations are comparable, however for the higher discharge simulations (#4, #7) irregularities around the process of channel switching occur, but the overall morphology is considered comparable

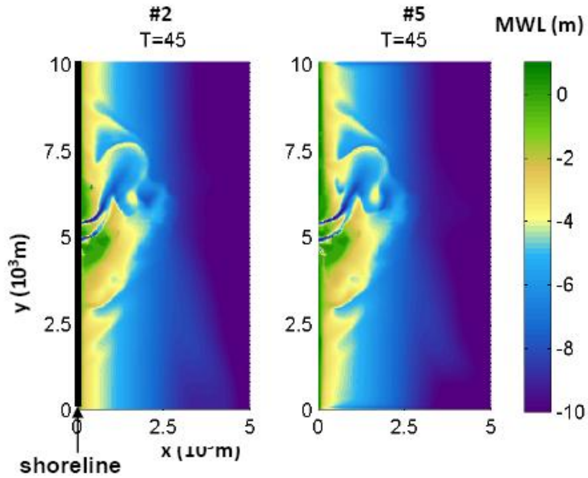

Figure 5.32 Resulting morphology of fluvial input simulations #2 and #5 with the same water discharge, with a different (but comparable) sediment boundary condition

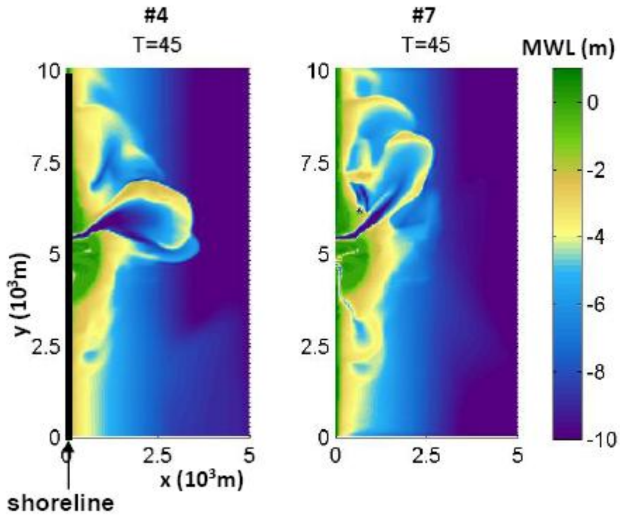

Figure 5.33 Resulting morphology of fluvial input simulations #4 and #7 with the same water discharge, with a different (but comparable) sediment boundary condition

Because the resulting morphologies are similar for a situation with an equilibrium sediment concentration and a comparable constant sediment concentration, the constant sediment concentrations are scaled to higher values to investigate the influence of sediment discharge. However, the constant sediment concentration of simulation #6 (1,000 m^3/s, constant sediment concentration 0.02 kg/m^3) is not that high and most of the sediment remains in the river system, because its profile was formed with a higher discharge (2,000 m^3/s). Therefore simulation # 8 (2,000 m^3/s, constant sediment concentration 0.1 kg/m^3) is investigated to study the influence of a high sediment discharge.

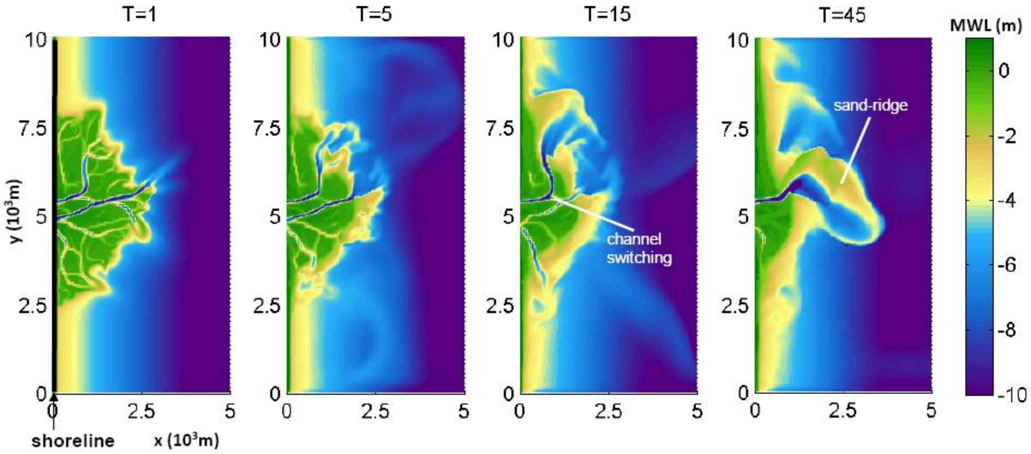

Figure 5.34 Plan view morphology of fluvial input simulation #8 over time

Figure 5.34 illustrates the morphology of simulation #8 (2,000 m^3/s, constant sediment concentration 0.1 kg/m^3) over time. The resulting morphology shows large quantities of sand deposited at the river mouth. Also channel switching occurred early during the simulation. The higher sediment discharge causes higher sand deposition at the river mouth, thereby obstructing the river mouth and enforcing switching of the channel.

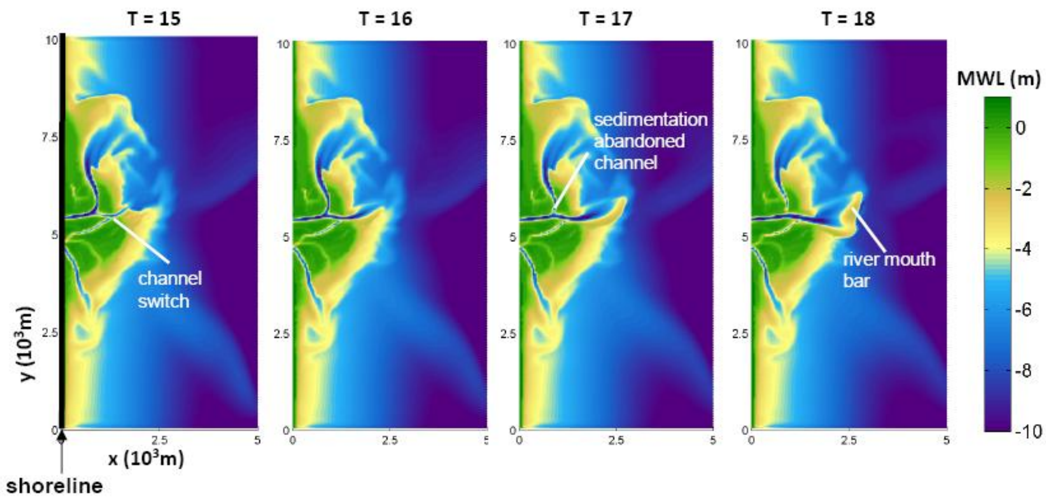

Figure 5.35 Process of channel switching and sedimentation of abandoned channel for fluvial input simulation #8

In Figure 5.35 the process of channel switching for simulation #8 is shown. Channel switching occurs over three month and also the process of sedimentation of the abandoned channel takes place. When water and sediment discharge enter the basin under an angle sands are deposited at the location where the velocity of the river outflow decrease. This hinders the outflow of the river and a shorter route to the basin is enforced. This process occurs more rapidly when sand is quickly deposited, which is in the case of high sediment discharge (simulation #8).

For a situation with high sediment discharge the river mouth rapidly makes a right angle with the incoming waves, comparable to the classic delta classification (Galloway, 1975)and literature. Sand-ridges are formed at the sides of the river mouth (Wright, 1977) form a protective barrier with respect to the incoming waves (Bhattacharya and

Giosan, 2003). Due to the constant forcing of both the fluvial input and the waves the sand-ridges are less reworked. In reality the sand-ridges are expected to be reworked in landward direction by the waves and this process is already partly visible at the lateral sides of the deltaic environment. However, the model forcings are constant and due to the high dynamics of the deltaic environment and the high sediment discharge the wave conditions are considered too gentle to rework the sand-ridges.

5.2.5 River mouth processes

The morphology of the wave-influenced deltas with varying fluvial input of this study is determined for a large part by the processes at the river mouth. The sand deposits are influential for the orientation of the river mouth, sand-ridges at the river mouth can cause channel switching and the jet outflow can cause scouring and offshore deposition of silt and sand sediments.

Around the river mouth the velocities decrease when the outflow enters the basin. The interaction with waves and the decrease of the outflowing current cause the deposition of the sediment transported by the flow (Figure 5.36). Due to the decreased flow velocity, sands get deposited first and the silt in suspension is transported by the resulting currents. The sand is deposited around the river mouth, sometimes as a river mouth bar, but often as a sand-ridge which gradually blocks the outflow current thereby causing enhanced deposition. The deposited sand determines the orientation of the river mouth since it may block the outflowing current, forcing the river to take another path with less resistance.

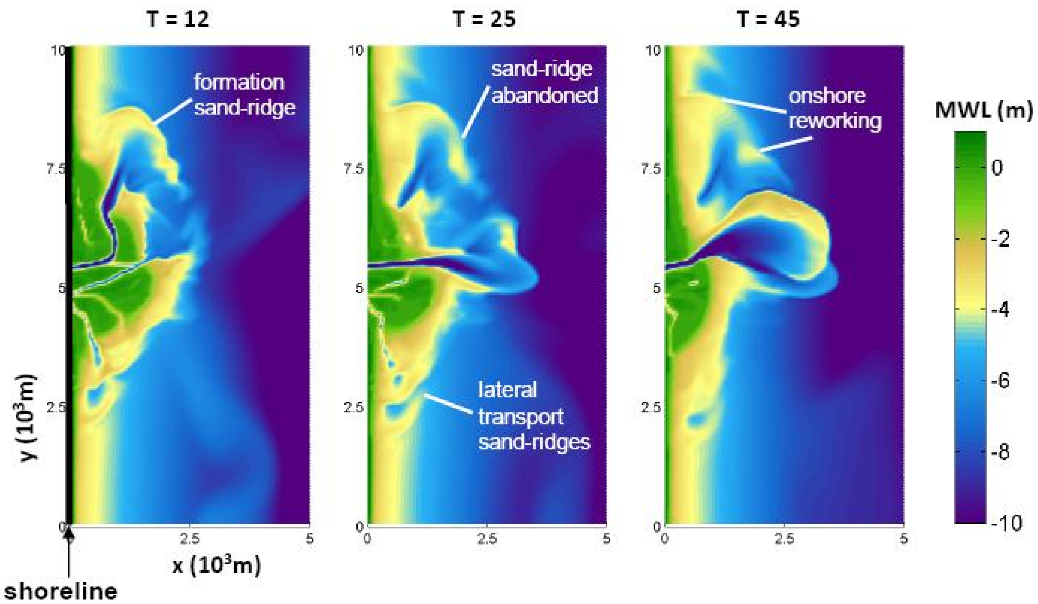

Figure 5.36 Formation and reworking of sand-ridges in fluvial input simulation #4

If the river discharge is not high enough to scour a new path through the existing delta environment, the sand-ridges increasingly block the outflow of the river, forcing the channel to switch as illustrated in the previous paragraph. New sand-ridges are formed at the by channel switching newly formed river mouth. The sand-ridges at the abandoned river mouth are not fed by the sediment supply from the river anymore and are subject to reworking by waves, this is illustrated in the middle and right part of Figure 5.36. These 'abandoned' sand- ridges are gradually transport in landward and lateral direction by waves or wave-induced currents, where the sand-ridges are expected to join the deltaic environment. This process is assumed to be better represented when sediment reworking under a changing wave climate is investigated instead of a constant forcing (as in the fluvial input case).

5.2.6 Conclusion

The simulations of the fluvial input case show continuous dynamics in the deltaic environment due to the interaction of fluvial and wave processes. This higher complexity is however realistically represented in the model, even with constant forcing of both the fluvial input and wave conditions. The processes of delta front erosion, channel infill and sediment sorting are observed and are comparable to the base case. However, the amount of erosion and sediment reworking depends on the ability of the river outflow to transport sediments from the deltaic environment. The sediment discharge accounts for deposition of sands and the formation of sand-ridges along the river mouth. Also the process of channel switching is observed, which is influenced by sediment discharge. The deltaic environment is clearly vulnerable to changes as the dynamic interaction continously reshapes the morphology and stratigraphy.

5.3 Model sensitivity analysis

The robustness of the model and the influence of certain model parameters were tested with a sensitivity analysis. The sensitivity analysis illustrates the model's response to different model settings and provides insight in the application of the model for comparable cases in the deltaic environment. The settings of the base case are used as the reference case. To test the influence of the change for each parameter of the sensitivity analysis, only one parameter varies while all others remain constant. In Table 5.2 an overview of the parameters tested in the sensitivity analysis is shown. The scaling of these parameters is based on a similar sensitivity analysis of the implementation of TR2004 in Delft3D (Brière and Walstra, 2006) and based on expert judgement. The scaling of the parameters is discussed in the following paragraphs.

	Sensitivity analysis scaling		
Parameters	Symbol	Scaling values	Unit
Current-related transport factors	*fsus, fbed*	[0 1]	-
Wave-related bed load factor	*fbedw*	[0 0.1 0.2 0.3 0.4 0.5 0.7 1]	-
Wave-related suspended load factor	*fsusw*	[0 0.3 1]	-
Dry bed density	ρ_s	[500 1,000 1,600]	kg/m^3
Median grain diameter	d_{50}	[8 16 25 50 125]	μm
Bed roughness formulation	*C, n*	[Chézy, Manning, predictor]	m^{½}/s, m$^{-1/3}$s
Relaxation time roughness predictor	T_{ks}	[0 30 60]	min
Roughness predictor bed form factor	F_{ks}	[0.5 1.0 1.5]	-
Morphological factor	*MorFac*	[30 60]	-
Time step	*dt*	[0.25 0.5]	min

Table 5.2 Overview scaling of parameters in sensitivity analysis

5.3.1 Sediment transport

Both sediment fractions in the model are transported by suspended load transport and bed load transport. Both transport types account for current-related and wave-related transport. Sediment transport directly influences major processes of this study, sediment reworking and sediment sorting, and is therefore investigated. As shown in paragraph 3.3 each type of transport can be scaled by a user-defined calibration factor; *fbed* (current-related bed load transport), *fsus* (current-related suspended load transport), *fbedw* (wave-related bed load transport) and *fsusw* (wave-related suspended load transport).

In this paragraph the model's response to changes in both current-related and wave-related transport is investigated by scaling the following coefficients:

- Current-related transport factors; *fsus*, *fbed* [0 1]
- Wave-related suspended load transport factor; *fsusw* [0 0.3]
- Wave-related bed load transport factor; *fbedw* [0 0.1 0.2 0.3 0.4 0.5 0.7 1]

Current-related transport factors

The current-related calibrations factors (*fbed* and *fsus*) are kept 1.0 and were not adjusted. This is based on an extensive sensitivity analysis after the implementation of TR2004 in Delft3D by Brière and Walstra (2006) and based on sensitivity tests to explore the behaviour of the current-related transport. The influence of the current-related sediment transport was investigated by setting the wave-related transport factors to 0. This resulted in a gentle sloped crossshore profile, with deposition of sand next to the shoreline on the lateral sides of the delta (Figure 5.37). The current-related transports cause a smoothing of the slope of the deltaic environment.

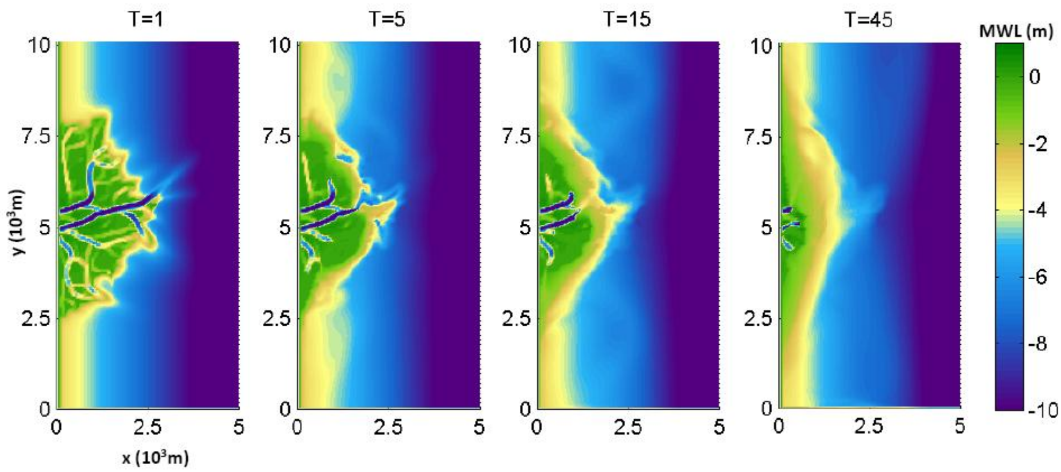

Figure 5.37 Plan view morphology over time of sensitivity run with no wave-related transports

Another sensitivity test was run with only current-related suspended load transport (the wave-related transport factors and the current-related bed load factor were set to 0). The results of this model run showed a gentle sloped profile with sand deposition comparable to the test which included (only) both current-related transports. In conclusion; the current-related transport cause lateral spreading of the reworked sediments, a smoothing of the delta (front) slope and the (current-related) suspended load transport is most influential.

Wave-related transport factors

The wave-related sediment transport was scaled in detail, since sediment reworking by waves is under investigation and earlier sensitivity analysis concluded that scaling of this type of transport is influential on the total sediment transport in shallow water

(Brière and Walstra, 2006). The wave-related transports mainly cause onshore directed transport due to wave asymmetry.

Based on similar sensitivity tests (Brière and Walstra, 2006) the wave-related suspended transport factor (*fsusw*) was scaled at low values [0 0.3] to obtain realistic results. Also van Maren (2004) applied a high value for *fsusw* (1.0) to investigate barrier formation in the Ba Lat delta and argued that the wave-related suspended transport factor should be at least scaled half that value.In Table 5.3 an overview of the wave-related transport factors in several sensitivity tests is provided. During these tests both current-related transport (*fbed* and *fsus*) factors were set to 1.0.

	Sensitivity tests for scaling wave-related transport factors							
Transport factor	a	b	c	d	e	f	g	h
fsusw	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3
fbedw	0.3	0.1	0.2	0.3	0.4	0.5	0.7	1.0

Table 5.3 Scaling of wave-related transport factors

The value of the wave-related suspended transport factor was determined rather quickly (0.3). The wave-related suspended transport factor causes a strong onshore transport, which is present under wave conditions, but is overestimated at values above 0.3.

The wave-related bed load transport factor was scaled in detail, because of the contribution to sand transport and since this value is not adjusted in most models (and remains 1.0). Low values of *fbedw* [0.1 0.2] gave a smooth gentle sloped delta front with sand deposition on both lateral sides of the delta front (Figure 5.38, left). High values of *fbedw* [0.7 1.0] gave a relatively steep delta front with local erosion along the edges of the delta front (Figure 5.38, right). The onshore transport reworks sand onto the delta front and creates a steeper, harder to erode, delta front. Due to the orientation of the delta front with respect to the perpendicular incoming waves, scouring along the delta front occurs by wave-induced currents. An overview of the resulting crossshore profiles with different wave-related bed load transport factor is given in Figure 5.39.

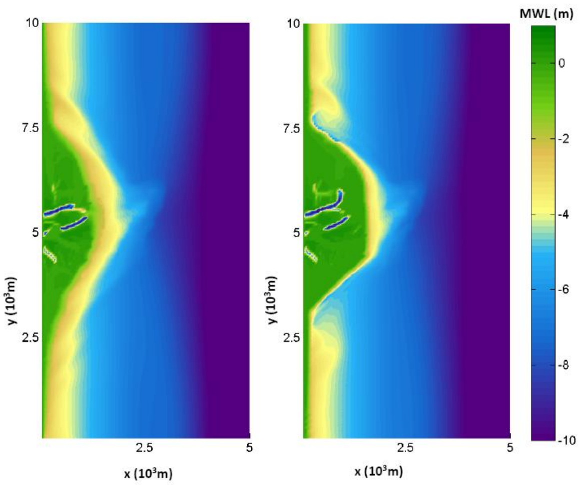

Figure 5.38 Plan view of resulting morphology of sensitivity runs with different wave-related bed load transport factors

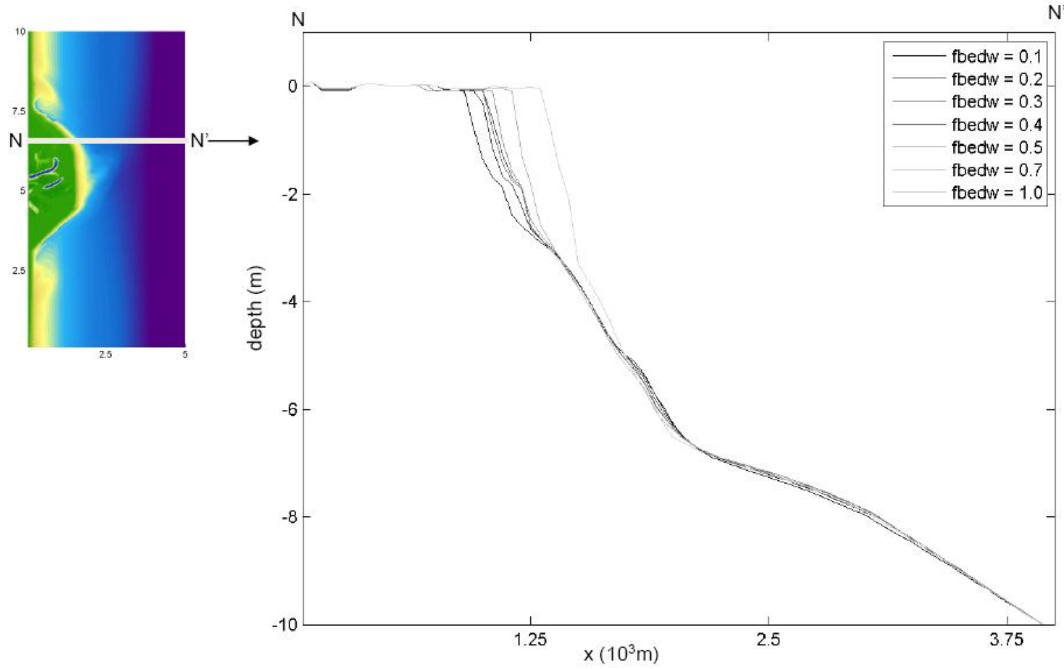

Figure 5.39 An overview of the resulting crossshore profiles (N=130) with different wave-related bed load transport factors

As shown in Figure 5.39 the sensitivity runs with moderate values of *fbedw* [0.3 0.4 0.5] gave comparable results. With respect to the expected profile of the deltaic environment in a gentle sloped basin under the influence of waves, the resulting morphology of *fbedw* = 0.3 gave the most realistic results. The model will still perform well for other moderate values for the wave-related bed load transport.

5.3.2 Sediment characteristics

The sediment characteristics of the sand fraction are the same as in the reference model. The characteristics of the fine sediment fraction (silt) are different compared to the reference model. The silt sediment fraction is defined as a non-cohesive sand fraction due to the application of the sediment transport formulation of TR2004. To give this sediment fraction comparable characteristics as in the reference model, the dry bed density is kept low (comparable to cohesive sediments) and the sediment grain size (relatively) small. To model this sediment fraction realistically and to test the influence of dry bed density (ρ_s) and the median grain diameter (d_{50}) several model runs were conducted to test the sensitivity of these parameters.

The following values of the dry bed density and the media grain diameter were investigated for the fine sediment fraction:

- Median grain diameter; d_{50} [8 16 25 50 125] µm
- Dry bed density; ρ_s [500 1,000 1,600] kg/m^3

Median grain diameter

TR2004 is capable of determining the sediment transport for sediments with a grain size as small as 8 µm. According to the sediment classes of American Geophysical Union for sediments the following subclasses are distinguished for fine sediments (van Rijn, 2007a):

- Fine sand (non-cohesive) 62 – 500 µm

- Coarse silt (sometimes cohesive) 32 – 62 μm
- Fine silt (weakly cohesive) 8 – 32 μm

To approach the silt behaviour as modelled in the reference model the median grain size varied from fine silt to fine sand: [8 16 25 50 125] μm. For the small median grain sizes [8 16 25] μm relatively similar results were obtained. Delta front erosion continued until a small layer of sand was deposited on the delta front. The fine sediments were transported in onshore direction and less transport to the lateral sides of the delta or offshore took place compared to situations where the fine sediment fraction had a larger d_{50}. Channel infill occurred more rapidly with smaller grain sizes, but the differences are negligible. An example of the morphology over time for a sensitivity test with a small d_{50} (8 μm) for the fine sediment fraction is given in Figure 5.40.

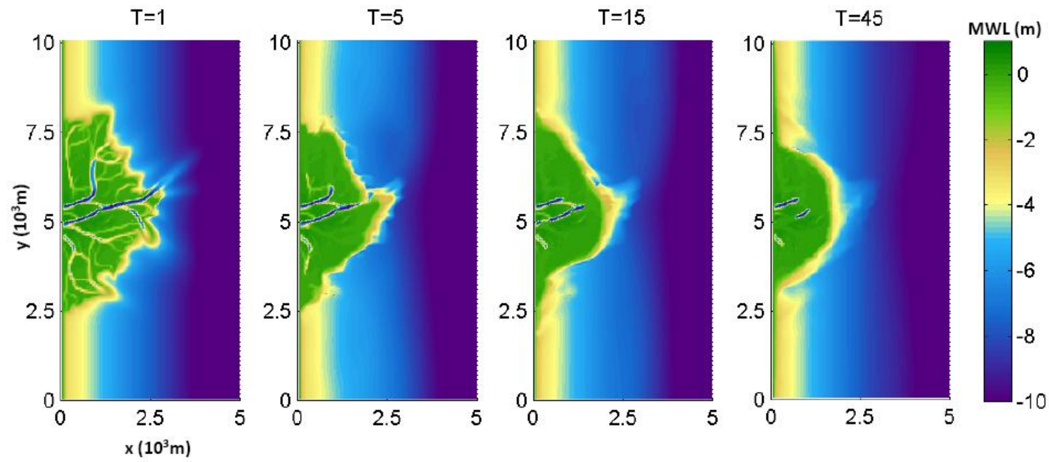

Figure 5.40 Plan view morphology over time of sensitivity run with d_{50} of the fine sediment fraction = 8 μm

When the median grain size was the same as the median grain size of the sand fraction (125 μm), the behaviour of the sediments is similar to the behaviour of the sand fraction. Less channel infill and sediments are transported along the delta front to the lateral sides of the delta where deposition takes place.

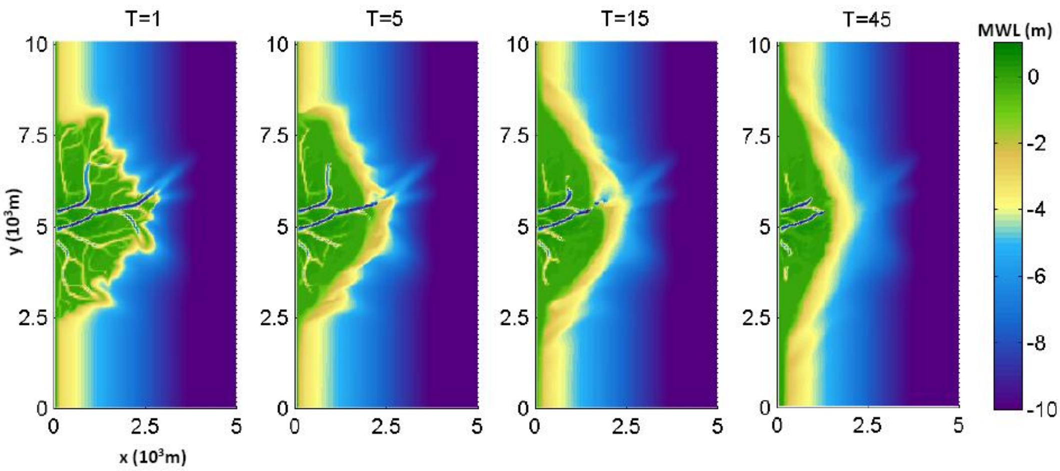

Figure 5.41 Plan view morphology over time of sensitivity run with d_{50} of the fine sediment fraction = 125 μm

A median grain size of 50 μm was selected for the fine sediment fraction, because this sediment size show silt behaviour as expected in the deltaic model. With this median grain size lateral and offshore transport of fines is visible as well as onshore directed transport (which causes channel infill).

Dry bed density

A low bed density indicates higher porosity and is observed for (weakly) cohesive materials such as clay and fine silt. In the sensitivity runs a higher dry bed density results in less transport of the fine sediments offshore. The erosion of the delta front remains the same as is the amount of sediment reworked by waves. Figure 5.42 shows the resulting crossshore profiles for dry bed densities of 500 kg/m^3 (red), 1,000 kg/m^3 (blue) and 1,600 kg/m^3 (green). The initial crossshore profile is indicated in black. The fine sediment fraction requires more energy to be brought into suspension when a higher dry bed density is applied and is therefore less easily transported offshore (Figure 5.42). With respect to continuity and to approach the behaviour of cohesive sediments a dry bed density of 500 kg/m^3 was determined. With this density the fine sediment fraction does approach the expected behaviour of fines in the deltaic environment more realistically and the expected sediment sorting occurs. It can be concluded that the sediment transport of fine sediments is determinative for the deltaic environment.

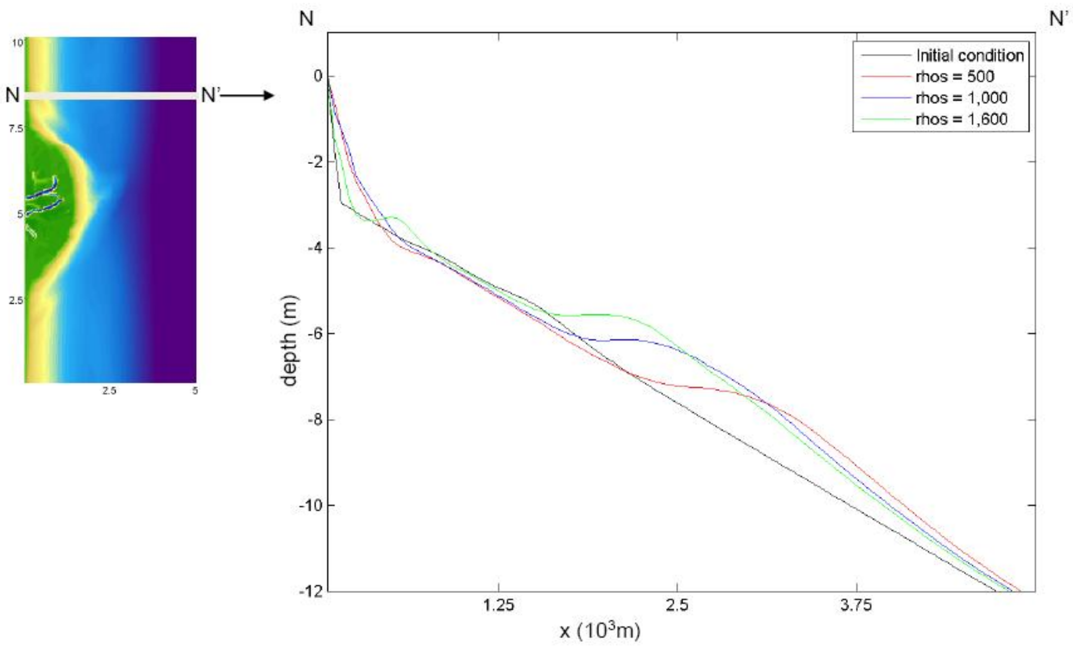

Figure 5.42 An overview of the resulting crossshore profiles (N=170) with different dry bed densities of the fine sediment fraction

Importance fine sediment fraction

To test the influence of fine sediments under wave reworking, a sensitivity test was carried out in which both sediment fractions had the same characteristics, a dry bed density of 1,600 kg/m^3 and a median grain size of 50 μm. The results are shown in Figure 5.43. Less channel infill and delta front erosion are observed. The morphology shows a smoothing of the delta front over time, but it remains largely intact. There is almost no offshore transport of sediments. The behaviour of sediment reworking in the deltaic environment is dominated by the difference of sediment characteristics (fine sediments and sands).

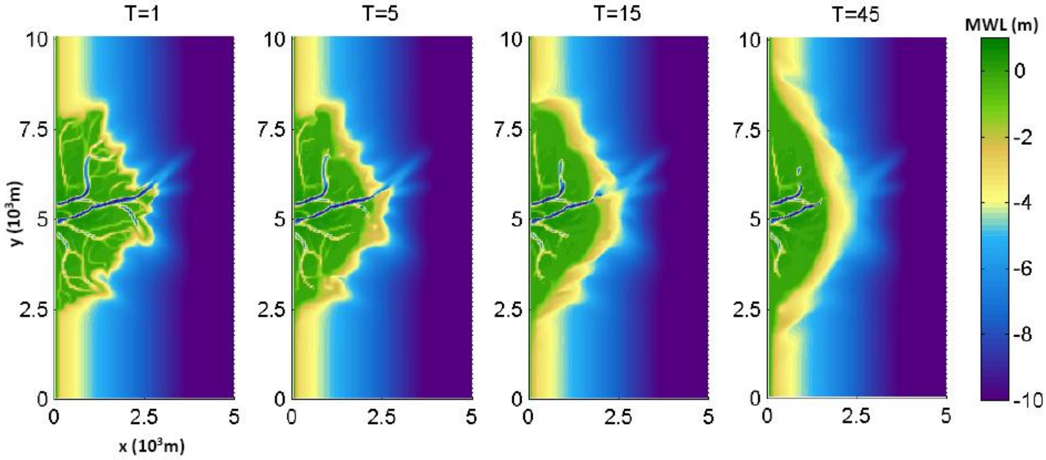

Figure 5.43 Plan view morphology over time of sensitivity run with both sediment fractions with the same characteristics

5.3.3 Bed roughness

The friction of the bed with the flow is determined in this study by the bed roughness. The bed roughness is mainly determined by bed forms which are formed by the hydrodynamics. The hydrodynamics on their turn are influenced by the bed roughness. Due to this causal relationship the bed roughness is hard to predict. In this study the van Rijn bed roughness predictor was applied (van Rijn, 2007a) to determine the bed roughness and thereby the friction. The van Rijn bed roughness predictor is based on four types of roughness; grain size roughness, wave-related bed form roughness, current-related bed form roughness and the apparent roughness. The apparent roughness is the bed roughness resulting from wave-current interaction processes when free-surface waves are superimposed on steady flow conditions.

The friction parameters of the Chézy and Manning formulations determine friction losses based on empirical based parameters. These formulations are not based on the roughness of elements on the bed, such as grain size or bed forms. The parameters are determined with respect to the situation in which they are applied. This means they can be scaled with respect to a certain situation. The van Rijn bed roughness predictor gives a roughness that changes in space and time and is based on the actual roughness of the bed at the moment of computation. However, to test the applicability of the van Rijn bed roughness predictor it was compared with situations where the friction was determined by Chézy and Manning. Comparable constant values for the Chézy coefficient and the Manning coefficient were applied to test the different formulations:

- Chézy; C [60] $m^{½}/s$
- Manning; n [0.03] $m^{-1/3}/s$

Next the scaling parameters of the van Rijn roughness predictor were investigated:

- Relaxation times; T_{ks} [0 30 60] min
- Bed form factors (for ripples and mega-ripples); F_{ks} [0.5 1.0 1.5]

Chézy

The Chézy coefficient can be regarded as a smoothing coefficient, since higher values of the Chézy coefficient indicate less friction; a smoother situation:

$$u = C\sqrt{Ri} \tag{5.1}$$

Where:

u Velocity, [m/s];
C Chézy coefficient, [$m^{½}/s$];
R Hydraulic radius, [m];
i Bottom slope, [m/m].

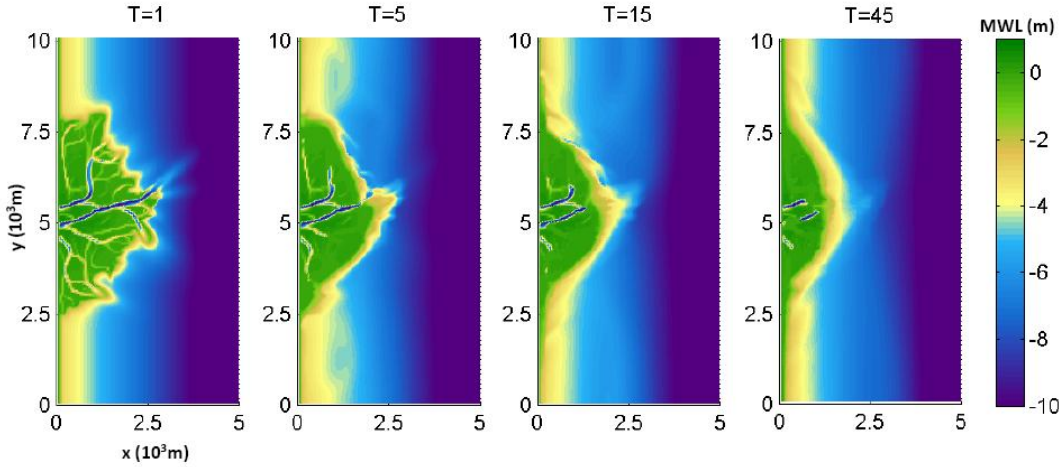

Figure 5.44 Plan view morphology over time of sensitivity run with friction determined with Chézy (C= 60 $m^{½}/s$)

When friction is determined according to Chézy a higher smoothening of the the slope of the delta front takes place. Slightly more sand is deposited on the lateral sides of the delta, but the resulting coast profile has characteristics similar to the base case. The process of channel infill is well represented. Friction determined with Chézy provides good results and is well applicable for the base case where the forcing of the model is constant. For a situation with a higher complexity, the van Rijn roughness predictor is expected to give better results because of the more location- and time-specific predictions.

Manning

The friction coefficient of Manning is comparable to the formulation of Chézy and gives a Chézy coefficient which depends on the water depth (equation (5.2)). This means for example that for lower water depth the Chézy coefficient decreases and thus the friction increases:

$$C = \frac{h^{1/6}}{n} \tag{5.2}$$

Where:

h Water depth, [m];
C Chézy coefficient, [$m^{½}/s$];
n Manning coefficient, [$m^{-1/3}s$].

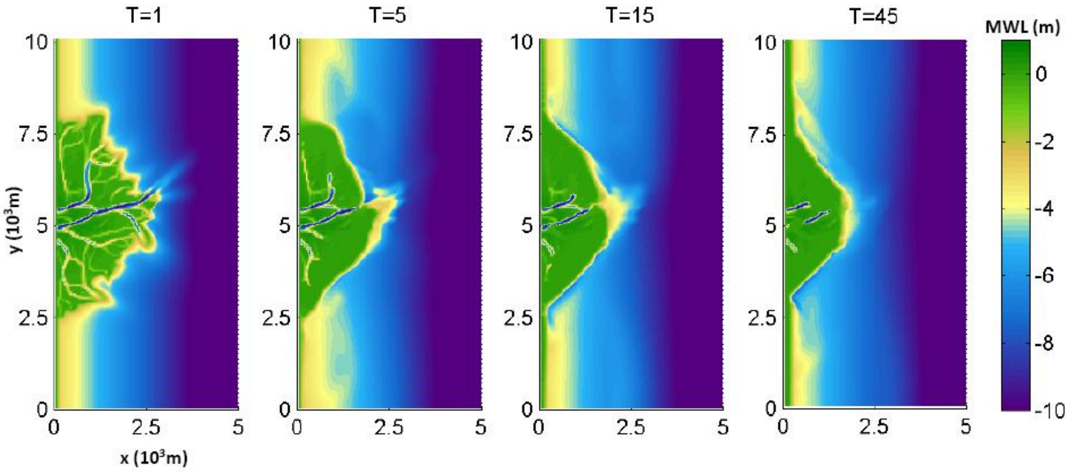

Figure 5.45 Plan view morphology over time of sensitivity run with friction determined with Manning (n = 0.03 $m^{-1/3}$/s)

Figure 5.45 shows relatively strong erosion along the delta front. The increased friction in areas with lower depth creates significant erosion along the delta front and a steep delta front results. The depth-depending Manning coefficient strengthens the formation of steep slopes. The erosion of the delta front is less compared to the base case, because once a steep delta front is formed the degradation becomes significantly less. The resulting morphology is not considered realistic.

Scaling parameters van Rijn roughness predictor

In Delft3D scaling parameters were provided for the van Rijn roughness predictor (Brière and Walstra, 2006; van Rijn et al., 2004). In this study these scaling parameters are tested.

With the implementation of TR2004 and the van Rijn roughness predictor in Delft3D, relaxation times were implemented to prevent instability of the model due to sudden changes in the hydrodynamics. The influence of the relaxation times is little in general (personal communication van Ormondt, 2008), but was not expected to be of influence for this study since in this study no sudden changes in the hydrodynamics occur due to the constant forcing and the gentle wave climate. Different relaxation times [0 30 60] (minutes) were tested, but no real differences were found.

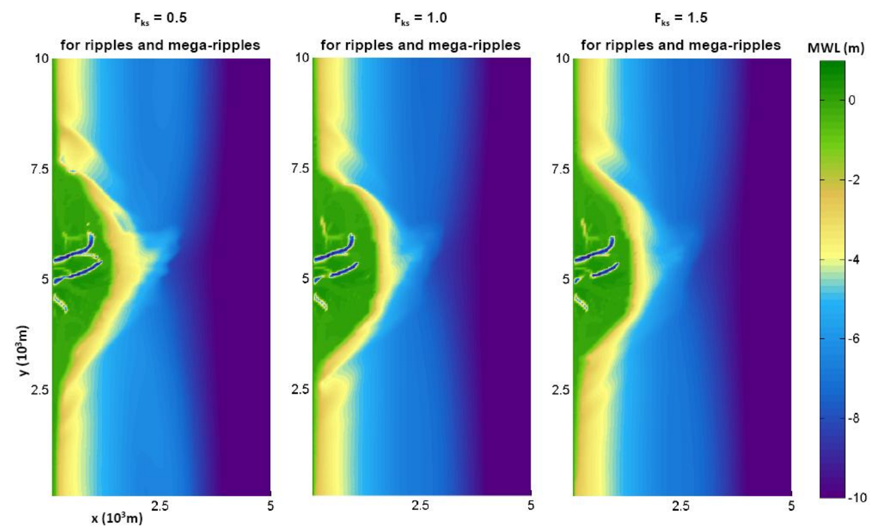

Figure 5.46 Overview of resulting morphology of the sensitivity tests with different bed form factors

The influence of small-ripples and mega-ripples can be adjusted to scale the roughness of bed forms. Both parameters were adjusted (and set to the same value) and show a decrease in roughness for F_{ks} = 0.5, or an increase in roughness for F_{ks} = 1.5, just as expected. The parameter for dunes was set to 0, since dunes are relatively large bed forms and only present in major rivers. Figure 5.46 shows the resulting morphology of sensitivity tests with different values for the bed form (scaling) factors.

5.3.4 Morphological acceleration

In order to study the stability of the model with respect to the numerical stability and the morphologic stability due to upscaling effects, the time step and morphological acceleration factor were investigated.

- Time step, *d*t [0.25] min.
- Morphological acceleration factor, *MorFac* [30]

Time step

To investigate the numerical stability of the model, the Courant number was checked. Since this is no guarantee for stability, a sensitivity test with a time step of half of the model time step was carried out. The results are almost identical to the base case and therefore it is concluded that the applied time step of 0.5 minutes is sufficient.

Morphological acceleration factor

Based on the reference model a morphological acceleration factor of 60 was applied. This is a relatively high factor and to investigate if instabilities due to the morphologic upscaling occurred a sensitivity test with a morphological acceleration factor of 30 was conducted. The results of this sensitivity test are almost identical to the outcome of the base case and a morphological acceleration factor of 60 is assumed to be applicable.

5.3.5 Conclusion

The sensitivity analysis showed that the model is robust and not very sensitive to changes in the set up. The complex processes in the deltaic environment are realistically represented within the model is therefore assumed to be applicable for case-specific approaches in the deltaic environment when waves rework the sediments.

With respect to sediment transport the sensitivity analysis confirmed that current-related transports cause lateral spreading of sediments and smoothing of the slope of the deltaic environment and that wave-related transports are influential with respect to onshore sediment transport. The model reacts significantly for high wave-related transports factors. The wave-related transports have a major influence on the process of channel infill and determine the slope of the delta front. Within Delft3D the wave-related transports are overestimated for the deltaic environment if no scaling is applied.

The characteristic process of sediment sorting in the deltaic environment is caused by the presence of different types of sediment; coarse and fine sediments. The resulting morphology and stratigraphy can be attributed to the erosion and transportation of fine sediments. The fine sediment fraction, in the deltaic environment often weakly cohesive clay, can be represented as a sand fraction, but requires a d_{50} of silt to give the most realistic results.

The van Rijn roughness predictor and friction determined by Chézy give comparable results. However, the van Rijn roughness predictor is assumed to be consistent with TR2004 and predicts the bed roughness in higher detail (process-based) which is expected to be more realistic in case of higher complexity.

6 Conclusions and recommendations

This study investigates wave reworking in the deltaic environment by the development of a process-based model to conduct multidisciplinary research on the process of sediment reworking by free-surface waves. The two main objectives are (1) to develop this model and (2) consequently apply it to study the effects of wave reworking on the morphology and stratigraphy of a delta.

This chapter discusses the development of the model and the results of the base case and fluvial input case in relation to the objectives. The conclusions of this study are provided in paragraph 6.1. In paragraph 6.2 recommendations with respect to the study outcomes are given and opportunities for further research are identified.

6.1 Conclusions

This first main objective was to develop a process-based morphodynamic model to simulate the process of meso-scale sediment reworking by free-surface waves in the deltaic environment. The simulations show that the model realistically represents the dominant processes to study meso-scale wave reworking in the deltaic environment. Furthermore, the findings of the sensitivity analysis illustrate that the developed model is robust and not sensitive to changes in the model set up and can therefore be applied for case-specific approaches.

The effects of wave conditions on the deltaic environment are successfully included in the model. Also the interaction of fluvial- and wave processes is realistically represented. With the schematic model the dominant processes of riverine water and sediment discharge combined with waves simulate the dynamic behaviour of deltas according to literature.

For the applied model set up the Delft3D-Online method is capable of modelling the process of sediment reworking in the deltaic environment. The application of one unified framework for sediment transport, TRANSPOR2004, for multiple sediment fractions and sediment characteristics gives realistic results with respect to the process of reworking, erosion and sedimentation and current- and wave-related transport. The difference in coarse (sand) and fine (silt) sediments in the deltaic environment is approached realistically, even though fine cohesive sediments are not included.

The findings of the sensitivity analysis show that the sediment characteristics must be scaled carefully, especially the fine sediment fraction, to obtain realistic results. Wave-related transport is also a dominant parameter in the model and is overestimated in Delft3D.

The model provides a good method to map relative short-term sedimentologic and morphologic changes (channel infill, erosion and deposition) and investigate long-term changes (long-term morphology and stratigraphy). With research on meso-scale phenomena of the stratigraphy can be checked with the development of the morphology over time. This gives extra insight in the construction of the sedimentary framework and in formation of degradational sediments.

The complexity of the deltaic environment underlines the need of a numerical process-based approach to study deltas with respect to different disciplines. Classic delta classifications provide general insight in the expected morphology and stratigraphy of deltas and case-specific numerical process-based approaches are required to study a specific unique deltaic environment. The model can be applied for such a case-specific approach and provides insight into both the morphology and stratigraphy of a delta.

It can be concluded that process-based modelling provides promising results with respect to simulating the effects of sediment reworking by waves on the morphology and stratigraphy of the deltaic environment.

The second main objective was to apply the model to investigate the effects of wave-influence on the morphology and stratigraphy of a pre-defined fluvial-dominated delta. Both the morphology and stratigraphy adjust rapidly to the sudden change in forcing. Sediment reworking causes erosion of the delta front, channel infill and sediment sorting. The deltaic environment adapts itself to the wave conditions in which the difference of sand and silt sediments is dominant with respect to the resulting morphology.

The model gives insight in sediment behaviour of a wave-influenced delta. Fine sediments are stirred up by waves and removed from the deltaic environment; transported to the lateral sides of the delta and offshore. Sand is also reworked, but the sandy framework of a delta remains largely intact. Sand is deposited on the lateral sides of the delta and on the edges of the delta front, forming a protective layer; the sand sediments prevent erosion of the underlying fine sediments. Waves combined with fluvial input cause the deposition and sand-ridges, which provide a shielding function for the more landward located deltaic environment. Similar sediment behaviour is observed in literature and described by classic delta classifications.

Model simulations in which fluvial input is included remain highly dynamic due to the (continuous) interaction of processes. After sorting of the sediments occurs, the shape of a symmetric wave-influenced delta (according to the classical classification) is observed. One main channel remains open and tries to find the shortest way to the basin. Riverine sediment discharge has a major influence on channel switching. A high sediment load causes rapid channel switching and can provide sufficient sediment for the deltaic environment to keep up with the basinal sediment reworking.

6.2 Recommendations

This study of a multidisciplinary research approach for the deltaic environment shows promising results. However it is recommended that a case study is conducted to validate the model. A full model study with validation on an existing wave-influenced delta should be set up to provide greater insight in the (local) processes of sediment reworking and make comparisons with the observed delta behaviour. Such a study can be started in collaboration with different departments of Deltares, the U.S. Geological Survey, or the Coastal Studies Institute of the Louisiana State University.

To obtain better understanding of deltas and their behaviour, continued research is required. It is recommended to continue research with the developed model but also to elaborate and extend it. The following extensions of the model are recommended, based on the findings of this study:

- The model deltaic environment should be subjected to a combination of several wave climates with varying significant wave heights and under varying angles. Also varying of the fluvial input should be applied. This will better simulate the dynamic deltaic environment, account for seasonal shift and investigate asymmetric wave-influenced deltas. A higher interaction of processes will be observed, which will result in the simulation of a more natural situation.

- A realistic model time-scale should be determined in which the processes in the deltaic environment under investigation are represented. Due to the schematized model environment, but mainly due to the sudden change in forcing and the application of constant forcing (both a constant wave climate and a constant fluvial input) the delta under investigation rapidly adjusted to the new situation, which is probably an accelerated time-scale. With insight in the time-scale, effects such as compaction and sea level rise can be included, as they can be scaled according to their timespan.

- A larger area of the deltaic environment with extra sediment sources should be modelled, or alternative sediment sources should be included in the model, to account for the contribution of reworked sediments of the surroundings of the delta under investigation. Especially when modelling abandoned deltas, other sediment sources are expected to be present and influence the study.

- The impact of storm fronts should be included in the simulations. Storms can have a devastating impact on the deltaic environment and can play a major role in sediment reworking. This allows for comparing high-frequency low amplitude waves with low frequency high amplitude events and can determine the dominant process. The effect storm events can have on the deltaic environment is still under discussion and is therefore an interesting extension.

- The effects of compaction of the deltaic deposits should be accounted for to study delta degradation. Especially with respect to the investigation of the deltaic cycle and for situations with deltas with large delta plains and marsh areas compaction has a major role. Compaction influences the sediment reworking directly and makes it possible to study barrier island formation and the influence of flooding of the delta plain. However, this should be initiated after a realistic model time-scale is determined.

- Sea level rise should be added to the model, because of the high vulnerability of the low-lying deltaic environments to sea level rise. There is already a great deal of research on the effects of sea level rise to low-lying coastal areas, but deltas are likely to respond non-linear due to the complexity of processes. Therefore, a numerical process-based investigation could be required. With compaction included in the model relative sea level rise can also be investigated. Again, this should be initiated after a realistic model time-scale is determined.

- A (locally) more refined grid should be applied to study processes concerning distributaries in higher detail. Also on smaller scale some effects, such as channel switching or sediment transport close to the delta front, should be investigated with a 3D approach.

- Biological effects should be included in the model. The deltaic environment has a unique ecology in which marshes and vegetation influence the hydrodynamics and morphodynamics. The effects of biological influences are not yet included in (most) delta models.

- Effects of human modification should be included in the model to test the response of the deltaic environment. This could be water- and hydrocarbon extraction, adjustments to the river and waterways (dredging, fixing channels), decreased sediment supply and adjustments of the shoreline.

A next step in application of the model could be to investigate delta building in a wave-influenced environment. This is a complex investigation due to the high complexity caused by the variation and interaction of different processes (channel formation and meandering (in the river-domain), sediment reworking and sediment transport (river- and basin), waves, seasonal influences, storm events and other processes).

A lot of research on deltas, their behaviour and the changes of their environment can be conducted. Data sets of deltas and research approaches should therefore be shared to encourage cooperation and research between researchers of different disciplines. With deltas under increasing pressure this research is of increasing importance.

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A TRANSPOR2004

In this appendix the bed load and suspended load transport formulations as described in TRANSPOR2004 are given. For more detailed elaborations and a complete background of these formulations is referred to van Rijn (2007a; 2007b). The implementation of TRANSPOR2004 in Delft3D is described by van Rijn et al. (2004).

A.1 Bed load transport formula

$$q_b = 0.015 \rho_s u h \left(\frac{d_{50}}{h} \right)^{1.2} M_e^{1.5}$$

Where:

q_b depth integrated bed load transport, [kg/m/s];
ρ_s sediment density, [kg/m^3];
u depth-averaged velocity, [m/s];
h water depth, [m];
d_{50} Median particle size, [m];
M_e mobility parameter.

$$M_e = \frac{(u_e - u_{cr})}{\left[(s-1) g d_{50} \right]^{0.5}}$$

u_e effective velocity, m/s.

$$u_e = u + \gamma U_w$$

u depth-averaged flow velocity, [m/s];
γ 0.4 for irregular waves and 0.8 for regular waves;
U_w peak orbital velocity, [m/s];

$$U_w = \frac{\pi H_s}{\left[T_p \sinh(kh) \right]}$$

H_s Significant wave height, [m];
T_p Peak wave period, [s];
k Wave number, [1/m].

u_{cr} critical velocity, [m/s].

$$u_{cr} = \beta u_{cr,c} + (1-\beta) u_{cr,w}$$

$$\beta = \frac{u}{(u + U_w)}$$

$u_{cr,c}$ critical velocity for currents based on Shields (initiation of motion), [m/s];
$u_{cr,w}$ critical velocity for waves based on Komar and Miller (1975), [m/s].

- $u_{cr,c} = 0.19(d_{50})^{0.1}\log\left(\frac{12h}{3d_{90}}\right)$ for 0.00005 < d_{50} < 0.0005 m;
- $u_{cr,c} = 8.5(d_{50})^{0.6}\log\left(\frac{12h}{3d_{90}}\right)$ for 0.0005 < d_{50} < 0.002 m;
- $u_{cr,w} = 0.24\left[(s-1)g\right]^{0.66} d_{50}{}^{0.33}\left(T_p\right)^{0.33}$ for 0.00005 < d_{50} < 0.0005 m;
- $u_{cr,w} = 0.95\left[(s-1)g\right]^{0.57} d_{50}{}^{0.43}\left(T_p\right)^{0.14}$ for 0.0005 < d_{50} < 0.002 m.

A.2 Reference concentration for suspended load transport

The reference concentration (c_a) defines the Rouse-type sediment concentration profile.

$$c_a = 0.015\left(1-p_{clay}\right) f_{silt}\,\frac{d_{50}}{a}\,\frac{T^{1.5}}{D_*^{0.3}}$$

with $c_a \le 0.05$

Where:

c_a Reference concentration, [m^3/m$^{3]}$];
f_{silt} Silt factor $f_{silt} = d_{sand}/d_{50}$ (f_{silt} = 1 for d_{50}>d_{sand}=62μm)
d_{50} Median particle size, [m];
a Reference level, [m];
D_* Dimensionless particle parameter;

$$D_* = d_{50}\left[(s-1)\frac{g}{\upsilon^2}\right]^{\frac{1}{3}}$$

T Dimensionless bed-shear stress parameter;

$$T = \frac{\tau'_{b,cw} - \tau_{b,cr}}{\tau_{b,cr}}$$

$\tau_{b,cr}$ Time-averaged critical bed-shear stress according to Shields, [N/m^2];
$\tau'_{b,cw}$ Time-averaged effective bed-shear stress, [N/m^2];

$$\tau'_{b,cw} = \tau'_{b,c} + \tau'_{b,w}$$

$\tau'_{b,c}$ Effective current-related bed-shear stress, [N/m^2];

$$\tau'_{b,c} = \mu_c \alpha_{cw} \tau_{b,c}$$

μ_c Current-related efficiency factor;

$$\mu_c = \frac{f'_c}{f_c}$$

f'_c Grain-related friction coefficient based on $1d_{90}$;
f_c Current-related friction coefficient based on predicted bed roughness values
α_{cw} Wave-current interaction factor (van Rijn 1993);

$\tau'_{b,w}$ Effective wave-related bed-shear stress, [N/m^2];

$$\tau'_{b,w} = \mu_w \tau_{b,w}$$

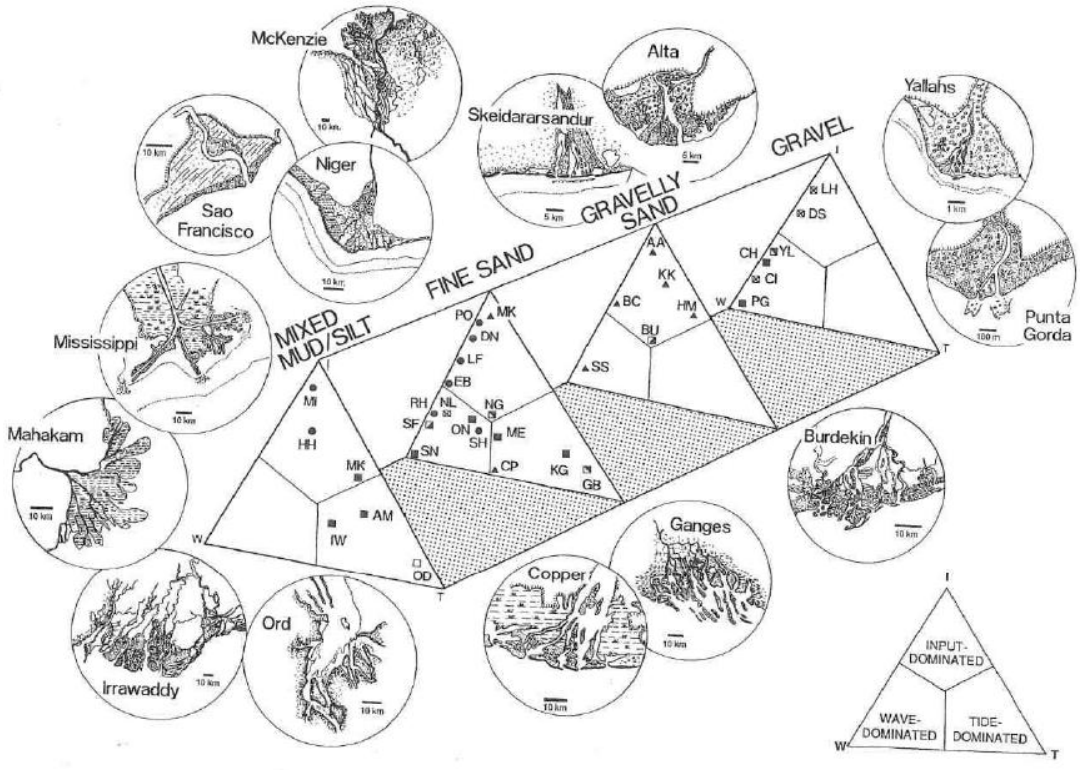
μ_w Wave-related efficiency factor;

$$\mu_w = \frac{0.7}{D_*}$$

with $\mu_{w,\min}$=0.14 for $D_* \geq 5$
and $\mu_{w,\max}$=0.35 for $D_* \leq 5$

B Abbreviations in Orton and Reading (1993)

This appendix shows the diagram of Orton and Reading (1993) with legend of the abbreviations of the delta systems.



AA: Aalta, AM: Amazon, BC: Bella Coola, BU: Burdekin, CH: Chao Pharya, CL: Colorado, CP: Copper, DN: Danube, DS: Dead sea, EB: Ebro, GB: Ganges/Brahmaputra, HH: Huanghe, HM: Homathko, IW: Irrawaddy, KG: Klang, KK: Klinaklini, LF: Lafourche, LH: Liaohe, ME: Mekong, MI: Mississippi, MK: MacKenzie, NG: Niger, NL: Nile, ON: Orinoco, PG: Punta Gorda, PO: Po, RH: Rhone, SH: Shoalhaven, SF: Sao Francisco, SN: Senegal, SS: Skeidararsandur and YL: Yallahs.