Analysis of the effects of process variations on delta morphology and stratigraphy in Delft3D computational models

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**Analysis of the effects of process variations on delta morphology and stratigraphy in Delft3D computational models**

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Report

September 2014, Delft
To Father and Mother
Preface

Essentially, all models are wrong, but some are useful.

--George E.P. Box

This thesis report marks the end of my M.Sc. program in petroleum engineering and geosciences, with specialization in reservoir geology, at TU Delft. During the two years of study and stay at Delft, I have not only learnt more about geology, but also my horizon broadened. It has been a pleasant adventure.

The project presented here is a finite element analysis involving the use of Delft3D to make different process-based models. They represent what a delta would ‘look’ like under different hydraulic forcings (river discharge and tide) and with different size of the particles that build up our modelled deltas. The findings thereafter can then throw light upon the delta external morphology and further, its internal architecture. Of course, the models deviate from natural deltaic systems, but we can still gain some knowledge from the models, regarding deltas’ morphology and stratigraphy.

I am grateful to Dr. Joep Storms, who has supervised the project over the past 10 months, and provided me with all the ideas and guidance, and Ir. Dirk-Jan Wlastra, who has offered me this great opportunity to work as a trainee at Deltares and supported me with his hydraulic input, as well as encouragements. Without their help, this project would be most difficult, if not impossible to accomplish. I wish to express my gratitude to Liang Li and Helena van der Vegt, for their continuous advice and thoughtful discussions, and keeping track of my day-to-day progress. They are always so calm even when I got so panicked and they were able to calm me down to continue with the work. Their feedback has been very helpful in the revising and polishing up of the report. Constructive advice given by Bas Huisman serves as a good kick-off at the very beginning set-up phase of the project.

I am thankful that I did not travel through this all alone, but spent great time with fellow graduating students. Patricia, Jasper, Bas, Jian, Enrico, and others have shared with me their expertise or happiness, or both.

Finally, I am particularly thankful to my parents in every aspect throughout the years.

Fei Chen

September 2014, Delft

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1 A British mathematician and Professor of Statistics at the University of Wisconsin, and a pioneer in the areas of quality control, time series analysis, design of experiments and Bayesian inference.
Abstract

Deltaic reservoirs are of great significance in both exploration and production of oil & gas and they have aroused increasing interest during the recent years. Coastal engineering deals with sediment transport on a millisecond and micron scale, while geology deals with sequence stratigraphy on a millenary and 10-100 km scale. However, relatively less is known in between, and the effect of different processes cannot be separately analysed. The presented study is one way of understanding what effect would different processes, namely river discharge, tidal influence and sediment supply D50, have on the evolution, morphology and stratigraphy of a delta, on a decades and parasequence scale, by using Delft3D process-based modelling techniques.

The approach adopted in the study is to setup a reference case with Delft3D based on literature study and Deltares/TU Delft expertise, to simulate the building out process of a delta. On top of that, 36 geologically and hydrodynamic realistic models were set up by systematically varying the tidal conditions, river discharge and sediment fractions in the supply. Upon their finishing, the area, rugosity, length to width ratio, dip magnitude, dip magnitude variance and dip azimuth angular dispersion, and sand fraction distribution have been measured for each of the numerical deltas. These results are then either plotted or visualized and compared with the reference case and also between each other.

The study results suggest that (1) channel activity magnitude as indicated by the rugosity is positively related to mean river discharge and inversely proportional to the tidal influence; (2) the effect of tide and river discharge cannot be separated, since they interact with each other in a system. Higher combined strength of tidal and riverine forcing leads to larger mean foreset dip magnitudes, larger variance in dip magnitudes, and a larger dip azimuth angular dispersion. Sand body distribution is more continuous in low discharge and low tidal influenced situations; (3) The different dry bed densities of sediments supplied and their correspondent transport formula influences delta’s morphology in a significant way. With increasing D50, the deltas show: smaller area given the same mass of sediment, higher rugosity, more avulsions, lower length to width ratio, steeper foreset slopes, larger dip magnitude variance and less clean sand bodies.

Key words: Finite element analysis, Delft3D process-based modelling, tidal influence, river discharge, sediment supply, rugosity, foreset dip, sand distribution
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1. Introduction

*To achieve great things, two things are needed: a plan, and not quite enough time.*

-- Leonard Bernstein

1.1. Problem statement and objective

During the past decade, considerable efforts have been made in numerical modelling of deltas, as well as linking the delta morphology to stratigraphy of deltaic formations. There has been an urgent need to understand how different delta morphologies arise because morphology determines the stratigraphic architecture (Caldwell & Edmonds, 2013), which is of most interest to the oil-gas industry. Hence, in this study, the following research questions will be addressed:

What effects will the river discharge, tide and sediment particle size have on the morphology and stratigraphy of the delta?

The objective of the project is to generate a database including a series of models with different representative predefined input parameters from a variety of dominant and secondary processes, in order to investigate what effect will the variation in the processes impose on the whole delta system, both morphology and stratigraphy. An analysis was then carried out based on the resulting database, and comparisons were made between the models.

1.2. General framework and workflow

The study was conducted in the following stages:

I. In the beginning, literature research was done to build the basic background of the study, including the characteristics of deltas, possible processes that may have influence upon the evolution of the deltas, and workflow of Delft3D modelling tools. An understanding of previous work done on this topic was reached.

II. Afterwards, a relatively stable reference model encompassing all the process parameters was built with Delft3D, and the most sensitive parameters to stability were found, on top of which variations can be made. The base case was set to run 12 months in hydrodynamic time, which was a sufficiently long period, in order to guarantee its stability, so that less unwanted crashes can be potentially avoided.

III. Various model runs were made, including the variations on the river discharge, tidal influence, input sediment composition and the combinations between the variations. In specific, model setups of 3 river discharge scenarios, 3 magnitude levels of tidal influences and 4 compositions of sediment supplies were made, as well as combinations between each other, resulting in $3 \times 3 \times 4 = 36$ model runs.

IV. Further, the analysis started in the next stage, to dig into the models to extract their unique differences relative to others and to throw light upon the relations between the variations in input processes and the output morphological and stratigraphic results. The extraction of models’ characteristics started with the dimensions (length/width ratio, water depth) of the resulting deltas, depth-averaged velocities, the sediment volume fractions and the relation between the number of distributary channels and tidal influence. Based on those characteristics, further analysis regarding the reservoir properties were conducted, addressing features such as deltaic shoreline rugosity, foreset dips, net to gross ratio (N/G),
and facies distribution, which would potentially indicate connectivity and predict the permeability baffles.

1.3. Scope of the study

This study focuses on the morphology and stratigraphy of tidal-influenced river deltas in an ideally simplified coastal environment.

Geological modelling packages such as Petrel and RMS tend to run on a large scale in space (at least 10 km); while coastal engineers usually model deltaic hydrodynamic processes and morphodynamic responses on a small scale (millimetres and seconds). There is a gap in between the geoscientists and coastal engineers, (Figure 2) which is being bridged over the past years. This study would potentially contribute further to bridging the gap, by building models of meso-scale, i.e., kilometres and tens of years.

In the light of this, this study did not address hydrodynamic issues such as sediment transport in details but however, pushed the limits towards the geology side.
There are more controlling processes for the evolution of a delta’s morphology and stratigraphy than ones that discussed here in the present study. Waves, for example, play a vital role. In addition, deltas are usually formed in shallow marine environment, where fresh water from rivers meets the salt water in the sea or ocean. The salinity, therefore, will have certain influence on deltas, too. From a perspective of geology, the initial bathymetry and structure of the coastal area is determined by tectonics (Okiwelu & Ude, 2012). However, they are all beyond the scope of the study and were not discussed.
2. Literature Study

2.1. Deltaic system and basic environments

Deltas are discrete shoreline protuberances formed where an alluvial system (rivers, alluvial fans or braided plain) enters a basin, sea, lake or even a lagoonal bay for example, and supplies sediment more rapidly than it can be redistributed by basinal processes. (Orton & Reading, 1993) A delta can be typically $10^1$ to $10^3$ of km$^2$ in area and $10^1$ to $10^3$ meters thick. For the sake of clarity, deltas are not necessarily in a triangular shape as Nile Delta, to whom the term was first given.

Generally, a delta consists of a delta plain, a delta front, and a prodelta. Each region has its unique facies. The delta plain is the extensive lowland area which comprises active and abandoned distributaries separated by inter-distributary zones of shallow water and emergent or near emergent areas. It is characterized by interdistributary marshes and swamps, flood plains, channels and beach complex. The delta front is the steeply sloping portion of the delta where deltaic deposits slope downward from sea level to the level of the sea floor. In this part, thinly bedded turbidites, and a coarsening upward sequence can be found. The prodelta is the most distal area of the delta which progrades furthest into the basin from shore, characterized by fine-grained distal mudstones. Because delta is prograding through time, these deposition environments superimpose on top of one another (Prothero & Schwab, 2003).

Every part in the deltaic system is dynamically interrelated with each other, i.e., the whole system will respond to changes that happen in any component of the delta. Internal component such as the basin bathymetry, transportation, sedimentation and erosion of the sediments are linked by feedback loops (Harbaugh & Bonham-Carter, 1977). On the other hand, external components, which are the major concern of this study, including sediment supply, tidal influence, do not have feedback on the whole system, but their output is still stored in the stratigraphic record. (Orton & Reading, 1993) A schematic from Allen (1970) contrasts the deltaic facies with the lithofacies stored in the stratigraphic record. (Figure 3)
2.2. Delta classifications

In terms of the controlling factors of the delta morphology in map view, the spectrum of delta morphology has 3 end members: tide-dominated, wave-dominated and river-dominated. Deltas can thus be divided into the following 3 categories, (Galloway, 1975) as shown in Figure 4. However, this classification schemes developed during the 1970s did not explicitly accommodate grain size, until McPherson (1987) noted that very coarse-grained fan deltas behave differently from ‘common’ braided deltas. After a series research work done to explain this phenomenon, Orton & Reading (1993) considered fan deltas and braided deltas together and accommodated the spectrum of feeder alluvial systems within deltaic classification schemes using grain size. This is another control on the delta geometry and stratal architecture, besides waves, tides and river discharge. They also noted that most sedimentary processes on coarse-grained deltas are gravity driven. In contrast, on fine-grained deltas, deposition is more dependent upon the spatial distribution of riverine processes on the delta plains and marine processes.
Figure 4 the delta classification scheme after Galloway, 1975

Figure 5 Extended process-based classification including grain sizes (Orton & Reading, 1993)
2.2.1 River-dominated deltas
River dominated deltas are predominantly controlled by the actions of river currents in distributary channels. The ‘bird-foot’ shape present in the Mississippi Delta in the US is a typical morphology found in river dominated deltas. Constructive riverine forcings are the strongest influential factor in this case and the deposition of sediments at the river mouth exceeds the reworking and redistribution by tide and wave processes. Larger discharge of a river transports more sediments into the system and thus resulting in larger deltas. Deltas with higher ratio of highest discharge over lowest discharge also tend to prograde further basinward. The variation in discharge prevents the sediments being transported further to form a subaqueous fan but to be accumulated near the river mouth so that a delta can form and gradually build out. River dominated deltas are usually characterized by thick deposits, vast area, low sand-to-mud ratio, relatively stable channel and levee, and high progradation rate. (Scholle & Spearing, 1982, Boggs Jr., 1995)

2.2.2 Tide-dominated deltas
In tide-dominated deltas, tidal processes have strong influence over the channel flow and thus on the whole deltaic system. The Fly River delta in Papua New Guinea (Figure 6) serves as a good example in that the channel of Fly River becomes aligned with the direction of oscillation current which is perpendicular to the coastline. The sediments are reworked and redistributed by tidal currents and smaller deltas, also known as ebb deltas, are formed. The condition for tidal deltas to form is high tidal amplitude, low wave energy, minimal long-shore flow, and a bay-shaped basin. In times of flood, the tidal currents flow into the river channel or in between the multiple channels, which are funnel-like and have low sinuosity and high width/depth ratio. In this period, linear sand bodies within the channel are formed by the tidal currents. In times of ebb, however, tidal currents flow back into the basin, bringing large amount of water away with them (also known as tidal prism). In this period, ebb deltas form near the river mouth. (Scholle & Spearing, 1982, Boggs Jr., 1995)
2.2.3 Wave-dominated deltas

Although wave effects will not be considered in this study, it is included here for the sake of completion. Wave dominated deltas are deltas whose evolution is dominated by wave processes. The São Francisco Delta in Brazil, with its deflected beak shape, small and few distributary channels, and low sediment input serves as a typical case for wave-dominated deltas. Because of the high wave interference, the river mouth in a wave-dominated delta has usually shifted off its original place. Sediments from the river are significantly and constantly reworked and redistributed along the coastline, making it much sandier than other types of deltas, coarsening upward, since high wave energy is capable of mixing up more coarse grains. At the same time, finer grain sediments are being transported offshore to form the subaqueous bars in the prodelta. In this manner, the progradation of the distributary channels are restricted for the sediments are deposited as beaches and bars. (Society for Sedimentary Geology, 2014)

2.3. Process-based modelling of deltas

Numerical models have a proven track record in sedimentary geology (Syvitski & Bahr, 2001). Past decades have seen a series of modelling tools and applications designed to enable reservoir engineers to gain more ideas and insights of the behaviour of sedimentary systems when subjected to varying conditions. Process-based modelling, among other geological modelling methods, is considered to be the most suitable modelling method to represent and capture the critical moments during the evolution and built-out morphology and stratigraphy of complicated systems as deltas. Process-based models are based on the description of underlying physical processes. This type of models usually consists of several modules which describe different processes (Dastgheib, 2012). For example, in a process-based model of a delta, the model will include a hydrodynamics module for wave, tide and current, and a module to control sediment transport. The modules are not isolated from each other but interact dynamically with the defined bathymetry, and all of them will be represented in the resulting morphology.

The processes within process-based models need to be carefully selected, for there can be a number of processes occurring at the same time. Each of the relevant (contributing) processes should be modelled adequately, not only in the sense of process description, but also, the interaction between the counterparts, which forms the model as a whole. (De Vriend, 1996) Especially in this case where deltas are being modelled, as is mentioned before, a deltaic system is a system that responds to changes occurring in all parts of the whole system. Hence, it is of utmost importance to organize the input of different processes in order to get realistic modelling results.

Because of the limitations in time or computational power, model reduction methods are usually applied. There are two types of reductions in process-based models. One of them is called ‘input reduction’, in which long-term effects are modelled with schematized inputs. For example, the spring tide and neap tide features are not described in the model, and instead an ideal tide with constant amplitude is applied. Another reduction concept is ‘model reduction’, in which less important or contributing processes do not take part in the simulation, but only the most important physical processes are taken into account. An example in the modelling of tidal deltas is to neglect the wave effects from the sea, since tidal deltas only form in regions with minimal wave effect (Walstra, Ruessink, Hoekstra, & Tonnon, 2013).
Another problem encountered by previous process-based modellers of deltas is how to couple different basic module units of processes in one uniform model and to have the result with the desired accuracy in a reasonable computational time. (Dastgheib, 2012) These issues have been addressed with different techniques developed during the years and well summarized by Roelvink (2006).

Process-based models are not only used in reproducing the virtual reality, in other words, the deltas that are already there, but also they can be used as numerical labs to conduct ‘what-if’ analysis, in order to find out which physical processes will have major influence on the morphological behaviour of deltas and what the effects are. These models then serve as realistic analogues, to compare with other phenomena observed in the fields (Roelvink & Reniers, 2012).

2.4 Documented effects of processes on numerical deltas in Delft3D

In recent years, a number of studies have been conducted with long-term process-based models (longer than 10 years) to model the morphological and stratigraphic evolution of deltas, to understand what effect the forcings have upon deltas.

Caldwell & Edmonds (2013) have found that besides the differences in fluvial energy and tidal energy, grain size plays a significant role in the growth of a delta. With 33 Delft3D numerical models, the authors concluded that at low median grain size, deltas have elongate planform morphologies with sinuous shorelines characterized by shallow topset gradients. While at high median grain size, deltas transit to semi-circular planform morphologies with smooth shorelines characterized by steeper topset gradients, with more stable distributary channels.

Leonardi, Canestrelli, et al (2013) made 2 Delft3D models, one was fluvial dominated while the other tidal dominated. The simulations indicated that trifurcations form when the tidal discharge is large relative to the fluvial discharge and the tidal amplitude is small compared with the water depth.

Slingerland, Burpee, & Edmonds (2012) performed a thorough investigation on the effect of grain size. They conclude that a finer sediment feed tends to produce bird’s foot-like deltas with rugose shorelines, rough floodplains, lower range of clinoform dip direction and lower angles. The sand body connectivity was poor. With a coarser sediment, however, fan-like deltas tend to be produced, with smooth shorelines, higher range of dip direction and higher dip angles. Sand bodies are coarsening-upwards continuous sheets. In this way, by knowing the sediment properties of an ancient delta, one can predict the expected clinoform geometries.

Geleynse, et al. (2011) produced Delft3D river deltas with tidal influence. In his models, tide-induced flow reversals are limited to zones seaward of the deltas front, due to a relatively high river discharge. They drew the conclusion that deltas forming under mere riverine forcing prograded via sequences of mouth-bar induced flow bifurcation and upstream channel shifting. In contrast, river-deltas with tidal influence were found to prograde mainly via lengthening of initial and stable distributaries. Hence, the distributary channels would show a elongated planform. The (maximum) river discharge is the strongest predictor for the number of distributary channels on a delta plain.
3. Delft3D

There never was a good knife made of bad steel.

-- Benjamin Franklin

Delft3D has been developed by Deltares as a unique, fully integrated computer software suite for a multi-disciplinary approach and 3D computations for coastal, river and estuarine areas. It is capable of simulating flows, sediment transports, waves, water quality, morphological developments and ecology. The Delft3D suite is composed of several modules, grouped around a mutual interface, while being capable to interact with one another.

In this chapter of the report, relevant background and modules will be concisely introduced, to give an idea of the working mechanism behind the interface where all the parameters are tweaked. For a full description of the working mechanism of Delft3D system, the reader is referred to Delft3D-Flow user manual (Deltares, 2013).

3.1 Delft3D-Online method

An ‘Online’ approach was adopted in Delft3D to incorporate integrated flow, sediment transport and bathymetry updates are executed at each time step (Roelvink, 2006). Each of these modules use the others’ output as input of next time step.

Figure 7 shows the schematics of work-flow of Delft3D online within one full morphodynamics loop, namely, one time step. Starting from a predefined bathymetry, the current interaction is solved over one cycle, using an iterative approach. The resulting flow and wave fields are then fed into a transport model, which calculates the corresponding bed load and suspended load sediment transports over the cycle. The averaged result is applied to compute bed changes, which defines the updated bathymetry. The updated bathymetry is then looped back to the transport model through the ‘continuity correction’ or to the full hydrodynamics module for the next time step. (Roelvink, 2006)

Figure 7 Flow diagram of Delft3D-Online (Roelvink, 2006)
3.2 Delft3D-Flow

All the model runs in the present study were built with Delft3D-FLOW. It is a multi-dimensional (2D or 3D) hydrodynamic simulation program that calculates non-steady flow and transport phenomena in shallow-water. Shallow-water means shallow seas, coastal areas, estuaries, lagoons, rivers and lakes, where horizontal spatial and temporal scales are much larger than vertical scales (Lesser, Roelvink, van Kester, & Stelling, 2004). The flow and transport phenomena result from tidal and meteorological forcing on a rectilinear or a curvilinear, boundary fitted grid. The 2D-schematization averages a body of water in depth, whereas in 3D simulations, the hydrodynamic module applies the so-called ‘sigma co-ordinate transformation’ on the vertical axis, which results in a smooth representation of the bottom topography. (Deltares, 2013) In the staggered grid, which was applied in Delft3D-FLOW, not all the properties of the grid cell, such as water level, water depth, the velocity components or concentration of sediments, were defined at the same location in the numerical grid. Figure 8 shows the positions of properties defined for one grid cell. As is shown in the legend below the figure, open boundaries are define through the horizontal velocity component on either m and n direction, or the water level points depending on the boundary condition. Properties such as water level are defined in the centre of a grid cell, while the m- and n-velocity components are perpendicular to the grid cell faces.

![Staggered Grid of Delft3D-FLOW](image)

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 ξ-direction (also called u- and m-direction)
  - horizontal velocity component in η-direction (also called v- and n-direction)
  - depth below mean (still) water level (reference level)

As is mentioned before, Delft3D solves shallow water equations. The system of equations consists of horizontal momentum equations, the continuity equation, the transport equation, and a turbulence closure model. Vertically, the momentum equation is reduced to hydrostatic pressure relation. The
reason is that vertical accelerations are assumed to be small compared to gravitational acceleration, and therefore not taken into account. Under this assumption, vertical acceleration due to buoyancy effects or sudden variations in the bottom topography is not taken into account. (Lesser, Roelvink, van Kester, & Stelling, 2004) The resulting expression is:

$$\frac{\partial P}{\partial \sigma} = -\rho gh$$

Where:

- $P$ Hydrostatic pressure
- $\rho$ Density of water
- $g$ Gravitational acceleration [m/s$^2$]
- $h$ Water depth

Horizontally, the momentum equations read:

$$\frac{\partial U}{\partial t} + U \frac{\partial U}{\partial x} + v \frac{\partial U}{\partial y} + \frac{\omega}{h} \frac{\partial U}{\partial \sigma} - fV = -\frac{1}{\rho_0} P_x + F_x + M_x + \frac{1}{h^2} \frac{\partial}{\partial \sigma} (v \frac{\partial U}{\partial \sigma})$$

$$\frac{\partial V}{\partial t} + U \frac{\partial V}{\partial x} + v \frac{\partial V}{\partial y} + \frac{\omega}{h} \frac{\partial V}{\partial \sigma} - fU = -\frac{1}{\rho_0} P_y + F_y + M_y + \frac{1}{h^2} \frac{\partial}{\partial \sigma} (v \frac{\partial V}{\partial \sigma})$$

Where the pressure terms can be substituted by Boussinesq approximations:

$$\frac{1}{\rho_0} P_x = g \frac{\partial \zeta}{\partial x} + g \frac{h}{\rho_0} \int_0^\sigma (\frac{\partial \rho}{\partial x} + \frac{\partial \sigma}{\partial x} \frac{\partial \rho}{\partial \sigma}) d\sigma'$$

$$\frac{1}{\rho_0} P_y = g \frac{\partial \zeta}{\partial y} + g \frac{h}{\rho_0} \int_0^\sigma (\frac{\partial \rho}{\partial y} + \frac{\partial \sigma}{\partial y} \frac{\partial \rho}{\partial \sigma}) d\sigma'$$

The horizontal Reynold's stress, $F_x$, and $F_y$, on a large-scale simulation can be simplified as:

$$F_x = v_H (\frac{\partial^2 U}{\partial x^2} + \frac{\partial^2 U}{\partial y^2})$$

$$F_y = v_H (\frac{\partial^2 V}{\partial x^2} + \frac{\partial^2 V}{\partial y^2})$$

where:

- $\sigma$ The gradients along $\sigma$-plane
- $M$ Stress gradient due to external sources or sinks of momentum [m$^3$/s$^2$]
- $\zeta$ Water level (in accordance with the reference level) [m]
- $U$ Depth-averaged velocity in m-direction [m/s]
- $V$ Depth-averaged velocity in n-direction [m/s]
- $V_H$ Horizontal eddy viscosity [m$^2$/s]
In addition, the depth-averaged continuity equation is given by:

\[
\frac{\partial \xi}{\partial t} + \frac{\partial [h \bar{U}]}{\partial x} + \frac{\partial [h \bar{V}]}{\partial y} = S
\]

where \( S \) is the contributions per unit area due to discharge or withdrawal of water, evaporation, and precipitation. (Lesser, Roelvink, van Kester, & Stelling, 2004)

For numerical stability reasons, the Courant-Friedrichs-Lewy number (CFL) should not exceed a value of 10 (Deltares, 2013). The Courant-Friedrichs-Lewy number is given by:

\[
CFL = \frac{\Delta t \sqrt{gH}}{\{\Delta x, \Delta y\}}
\]

Where:

\( \Delta t \)         Time step [s]
\( H \)             Total water depth [m]
\( \{\Delta x, \Delta y\} \)  Characteristic value (usually the minimal value) of the grid spacing in either direction [m]

Delft3D offers various transport formulations by default, while also allowing users to define their own and call them from Delft3D-FLOW. These transport formulations include Van Rijn, Engelund-Hansen, and Ackers-White etc. Each is an empirical relation designed for different situations, such as wave conditions and sediment loads.

In the presented study, the Engelund and Hansen formulation was applied. The detailed description of the transport formulation is discussed in Section 4.6.
4. Methodology

The whole study is a Finite Element Analysis (FEA) (Strang & Fix, 1973), composing of (A) pre-processing, (B) solution and (C) post-processing. During (A) pre-processing, a suitable finite element mesh was developed and properties and boundary conditions were assigned. During (B) solution, Delft3D was applied to solve the equation and stored the primary quantities as output files. During (C) post-processing phase, an examination of the quantities was performed. Additional data was also derived from the primary quantities to allow more in depth understanding and discussion of the results.

4.1 Modelling assumptions

Models, however carefully designed, are representations of real world situations, based on pre-defined assumptions and corresponding limitations. For practical reasons, the following assumptions apply in the presented models:

1. The tide in the model is an ideal semi-diurnal tide, with the tidal signal following a cosine curve with two complete cycles each day. The tidal range variations between spring tide and neap tide were not taken into account. The resultant stratigraphic features of spring-neap cycles (double mud drapes) would have a thickness between about 0.002 mm and 0.02 m (Allen J., 1982), which is well beyond the vertical resolution of the models used in this study.

2. The water level change at the basinal boundary propagates landward instantaneously without any lag. The actual time lag in between would be in an order of seconds, well beyond the temporal resolution of the model runs.

3. The sea level change was not taken into account in the model settings, for this is a theoretical investigation on the evolution of the deltas on a relatively short time scale (around 1 year in hydrodynamic time and 30 years in morphodynamic time) compared with the global Eustatic cycle. According to the available geological data, the average global sea level rise was 0.5mm per year over the last 6,000 years and at an average rate of 0.1 to 0.2 mm per year over the last 3000 years (Houghton, Ding, & Griggs, 2001). This would give at most 0.006m of sea level rise over a morphological time of 30 years. Therefore, the model assumes stable mean relative sea level over the whole period.

4. The substrate was defined as an unerodible sediment fraction referred to in this study as ‘Sediment subsilt’, to ensure that the basin is fed only by sediments coming from the river.

5. Seasonal discharge, withdrawal of water, evaporation and precipitation were not taken into account. This means ‘S’ equals to 0 in the continuity equation (section 3.2).

6. Sea water and river are considered to be of the same density, salinity and temperature. All ecological processes are disregarded. (Flores, 2011)

4.2 Pre-processing: model setups

4.2.1. Grid

The grid was designed using RGFGRID, a program for creating, modifying and visualizing grids for Delft3D-FLOW simulations. The Cartesian coordinate system is applied with coordinates easting and northing in meters. (Deltares, 2013)
Finer grid cell size can provide a higher resolution, which can be desirable when analysing the results. However, increasing the resolution over a certain level is redundant, given the spatial scale of this specific study. Furthermore, smaller grid cells require a concurrent smaller time step to fulfil a Courant condition, and thus demand even more computational time. Decreasing grid cell size without coupling it with a smaller time step induces instability in the model (Geleynse N., 2013), because this would increase the Courant number. Hence, the grid cell size was selected to be neither too coarse to capture features such as bars, nor too fine that computational time exceeds the available timeframe of the project.

Based on the above stated considerations and as a trade-off, the whole horizontal domain is discretized by 302 and 282 grid cells in streamwise direction (m direction) and spanwise direction (n direction) respectively, and each grid cell measures 50 meter by 50 meters. The majority of the would-be land section was removed in order to save computational power. Yet, in order to keep the flow within the banks, a sufficient land area is left in the domain. (Figure 9)

4.2.2. Initial conditions
The initial bathymetry was generated with Delft3D-QUICKIN, where initial bed level can be assigned by the user for each grid cell.

This study investigates how a delta would respond to different tidal-fluvial- and sedimentary forcing. Hence the bathymetry was designed in such a way that a river channel, with a water depth of 3m, flows into a sedimentary basin sloping away from the river channel. The basin has the same slope as the channel and ends in a shelf break at the distal end, marked by a steep slope. At the end of the domain, a M2 type tide was assigned, with varying tidal amplitude and a 30 degree per hour cyclicity.
On the ‘River’ boundary (Figure 10) is the river channel which is 5 km long. The river heads towards the basin, with a width of 300m and bounded by floodplain which is dipping towards both the channel and the basin. The elevation difference between the top and bottom of the channel at the upstream boundary is 3m. Over the slope of the channel it linearly deepens and reaches an elevation difference of 5m at the river mouth. The initial water depth is 10m at the shelf break, and deepens to 15m at the continental slope. After setting these values in QUICKIN, the function ‘smoothing’ is used twice to smooth the vertical angles in the bathymetry, thus generating more curved channel shape and substrate, to mimic the natural situation. Figure 10 shows the initial condition of the bathymetry.

A layered bed stratigraphy (multiple sediment layers), which is a user-defined number of bed composition bookkeeping layers were included to keep track of sediment deposits. (Deltares, 2013)

In our model, one transport layer and 75 underlayers were assigned. The transport layer is the layer where sediments distribute. It imports sediment to the grid cell in the case of deposition and exports in the case of erosion. The transport layer replenishes itself with sediments from underlayers directly beneath it during erosion (exports sediments to the water column). When deposition happens, the transport layer mixes and redistributes the imported sediment from the water column to the underlayers. In this way, the layer maintains a constant thickness, 0.2 m in this case. The 75 underlayers of 0.3 m each are buffer for the transport layer. They store the sediments from the transport layer in the case of deposition and supply the transport layer with sediments in the case of erosion. (Moerman, 2010) The underlayers are initially set as 100% ‘Sedimentsubslit’ which has a shear stress of 100 N/m², making it unerodible under the hydrodynamic conditions in the models analysed here (Flores, 2011) (Section 4.1 (3)).
4.2.3. Boundary conditions

Boundary conditions define coordinates, flow conditions and transport conditions at the boundaries of the model domain, and are necessary for Delft3D to solve the hydrodynamic and morphodynamic equations. The types of boundary conditions which can be applied in Delft3D are water level definition, total discharge or Neumann conditions. Forcing types include harmonic, astronomic and time-series. Flow conditions define the water level change caused by tidal activities or the discharge variations from the river. Meanwhile, transport conditions specify the concentration of each type of sediment over time. Figure 11 shows an example of the parameters that can be used to define a boundary condition.
The ‘River’ boundary in the Figure 10 was defined by its total discharge over all the ‘river’ grid cells. It consisted of two components, a varying discharge (representing the discharge variation induced by tide) imposed on a mean river discharge. In nature, water level rises and the signal propagates upstream, bringing in water into the estuary (in our case the channel) in times of high tide. During the ebb period, the tidal prism retreats from the estuary. The tidal prism is represented by the discharge variation specified in the ‘river’ boundary to approximate the tidal activity. Hence the discharge variation was represented by a harmonic sine signal. The sediment concentration was also assigned to change accordingly because of the induced change in transportation capacity of the river. However, the relationship between sediment concentration and discharge is, in most cases, empirical, and calls for long-term measurements. Even with this data available, the empirical correlation curves may not work for all rivers, nor do they show directional physical relationship. The reason lies in that the discharge ‘Q’ is but a surrogate of a very complex pattern of forces including shear stress and stream power (Hickin, 2009). Therefore, a time-series triangular signal is used to mimic the positive correlation between sediment concentration and the discharge. This will be elaborated in later sections.

The ‘Basin’ boundary represents the basin and is captured by its water level. The water level was assigned to change periodically over time (30deg/h) to resemble the cyclic features of tide. The amplitude was set to vary with different modelling scenarios from 0.8m up to 1.5m.

For the ‘North’ and ‘South’ boundaries of the domain, Neumann type was selected, since it is a type to impose the alongshore water level gradient and should be applied on cross-shore boundaries in
combination with a water level boundary at the basinward side. This is necessary to make the solution of the mathematical boundary value problem well-imposed (Deltares, 2013).

4.2.4. Sediment features
Storms et al. (2007) has proved that the realisitic modelling of deltaic environment can be achieved with two classes of sediments. For this reason only 2 classes of sediment types are applied in the model runs, cohesive sediment and non-cohesive sediment. Non-cohesive ‘Sediment Sand’ represents all the non-cohesive sediments transported into the domain, while cohesive ‘Sediment Silt’ or ‘Sediment Clay’ represent all the cohesive sediments involved.

The specific density of a type of sediment was used in the transport calculation, while the dry bed density (bulk density) was used to calculate the bed level change caused by the accumulation of sediments, which takes into account the void spaces in the bed. The critical shear stress for erosion is the shear stress above which the deposition begins to be eroded.

‘Sediment Sand’ in the models has a median grain size (D50) of 150 µm, a specific density of 2650 kg/m^3, and a dry bed density of 1600 kg/m^3.

‘Sediment Clay’ was defined by its settling velocity and critical shear stress for erosion. The modelled ‘Sediment Clay’ particles were assigned to a settling velocity of 0.5mm/s, which is higher than realistic value, since it was doubled to accelerate the simulation process, and at the same time, the erosion parameter was doubled, too. The same upscaling technique was also applied to silt and sand. Sediment Clay has a specific density of 2650 kg/m^3, a dry bed density of 500 kg/m^3. The critical shear stress for erosion of sediment clay is 0.5 N/m^2. The median grain size (D50) of clay cannot be specified in Delft3D, but it can be approximated with Stokes’ Law (Lamb, 1994), which reads:

\[
V_s = \frac{2g(\rho_p - \rho)R^2}{9\mu}
\]

where:
- \( V_s \) the particle’s settling velocity (m/s);
- \( g \) the gravitational acceleration;
- \( \rho_p \) the mass density of the particle and \( \rho \) the density of the fluid;
- \( R \) the radius of the particle;
- \( \mu \) the fluid dynamic viscosity.

In order to calculate the approximate median grain size (D50), which is twice the radius, the equation can be rewritten into:

\[
V_s = \frac{g(\rho_p - \rho)D_p^2}{18\mu}
\]

where \( D_p \) is the diameter of the particle.

Therefore, the calculated diameter for clay particles is 23.58 µm. Since Delft3D uses uniform diameters, hence the D50 is approximately the calculated diameter. Note that the particle size of ‘Sediment Clay’ does not fall into the common range for natural clay particles, since the settling velocity has been doubled in order to accelerate the simulation.
‘Sediment silt’ was defined as cohesive sediment in the model, with a settling velocity of 2.4mm/s, a specific density of 2650 kg/m³, and a dry bed density of 500kg/m³. Applying the same calculation method for median grain size, the D50 for ‘Sedimentsilt’ is 51.66 µm. According to Hwang & Mehta (1989), the relationship between the critical shear stress for erosion and the wet bulk density of the bed is given by:

$$\tau^C_e = a_e (\rho_{wb} - \rho_b)^b + \rho_e,$$

where:

- $\tau^C_e$ the critical shear stress for erosion (N/m²)
- $a_e$, $b_e$, $c_e$ and $\rho_b$ the coefficients, with default values of 0.883,0.2,0.05 and 1.065,
- $\rho_{wb}$ the wet bulk density (g/cm³).

They also presented a relationship for the erosion parameter as a function of the wet bulk density of the bed (Hwang & Mehta, 1989) which reads:

$$\log_{10} M_e = 0.23 \exp\left(\frac{0.198}{\rho_{wb} - 1.0023}\right),$$

where:

- $M_e$ the surface erosion rate constant (mg/cm²/hr).

Considering that ‘Sedimentsilt’ and ‘Sedimentclay’ were assigned to an identical density, the critical bed shear stress of ‘Sedimentsilt’ was set to 0.5N/m², and the erosion parameter constant to 0.0002 kg/m³/s, same as ‘Sedimentclay’.

Table 1 summarizes the properties of the sediments.

<table>
<thead>
<tr>
<th>Type</th>
<th>Clay</th>
<th>Silt</th>
<th>Subsilt</th>
<th>Sand</th>
</tr>
</thead>
<tbody>
<tr>
<td>D50 (µm)</td>
<td>(23.58)</td>
<td>(51.66)</td>
<td>-</td>
<td>150</td>
</tr>
<tr>
<td>Critical Shear Stress for Erosion (N/m²)</td>
<td>0.5</td>
<td>0.5</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Settling Velocity (m/s)</td>
<td>0.0005</td>
<td>0.0024</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Dry Bed Density (kg/m³)</td>
<td>500</td>
<td>500</td>
<td>500</td>
<td>1600</td>
</tr>
<tr>
<td>Specific Density (kg/m³)</td>
<td>2650</td>
<td>2650</td>
<td>-</td>
<td>2650</td>
</tr>
<tr>
<td>Erosion Parameter (kg/m²/s)</td>
<td>0.0002</td>
<td>0.0002</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

### 4.2.5. Numerical parameters

Apart from the variables that have physical meanings and can be observed or measured in the field or in laboratory experiments, a numerical model consists of a series of numerical parameters that can also influence the resultant delta.
Time step is the time interval between the bathymetry updates performed by Delft3D. Here, it was given a value of 0.5 minute, which has been a common value in other similar studies. This value would keep the Courant number (discussed in section 3.2) around 7.3, below the critical stable threshold of 10.

The concept of a morphological acceleration factor (Morfac) was introduced to the modelling of deltas (Roelvink, 2006). In short, the bed level change is multiplied by Morfac after each hydrodynamic time step. This concept enables modellers to simulate morphological evolution in coastal areas at the time scales of tens of years, and substantially reduces the computational time. For a detailed discussion on Morfac, the reader is referred to Li’s thesis (2010). Taking sensitivity, stability, computational effort and time issues into account, a uniform morphological scale factor of 30 was applied in the modelling, meaning that one unit of hydrodynamic time is scaled up by a factor of 30, in terms of morphological time.

The spin-up interval before morphological changes was set to 1440 min, meaning no bed level change occurred in the first simulated hydrodynamic day. This period is sufficient to make space for a complete adaptation of the hydrodynamic simulation to the dynamic boundary conditions (Leonardi et al., 2013).

All the values assigned here fall inside the range of values used in other hydrodynamic – morphodynamic studies.

Engelund & Hansen transport formula is an empirical non-cohesive sediment transport relation that has frequently been used in rivers and estuaries (Deltares, 2013). It has a good fit with the models in our studies in that this study is mainly about river and tides. The formula reads:

\[ S = S_b + S_{s, eq} = \frac{0.05aq^5}{\sqrt{gC^3D^5q}} \]

where:
- \( q \) magnitude of flow velocity,
- \( \Delta \) the relative density \((\rho_s - \rho_w) / \rho_w\),
- \( C \) Chézy friction coefficient,
- \( \alpha \) the calibration coefficient.

A calibration coefficient (\( \alpha \)) of 2 was applied to double the sediment supply rate, to couple the doubled rate for cohesive ‘Sedimentclay’ and cohesive ‘Sedimentsilt’. The transport of the cohesive ‘Sedimentclay’ and ‘Sedimentsilt’ is computed through a depth-averaged advection-diffusion formula.

So far, all the modelling settings have been described. Table 2 summarises them for the sake of a clear view.
4.2.6. Varying parameters

In this study, tidal influence, sediment fractions, and mean river discharge were varied. The changes were coupled with each other to produce different deltas, so that the effects of these forcings can be analysed.

4.2.6.1. River discharge

The mean river discharge rates were set to 700, 900 and 1100 m$^3$/s. Higher discharge rates were not used here to ensure the stability of the modes. For in higher discharges, the basinward discharge rate would exceed 2300m$^3$/s in times of ebb tide, which is prone to model instability and ultimately causing the model to crash using the current model settings. Smaller discharge rate than those would produce a delta of comparable size over longer time, which is not feasible within the current project time constraints.

4.2.6.2. Sediment fraction within supply

An infinite number of combinations of different types of sediments can be included in Delft3D model runs. This model acts as a pilot project and as such addresses the end members (see Chapter Recommendations for more details). Hence, four types of sediment mixtures were used:

(1) 100% clay (D$_{50}$=24 µm)

(2) 50% clay and 50% sand (Sandy clay, D$_{50}$=40 µm)

(3) 50% silt and 50% sand (Silt loam, D$_{50}$=77 µm)
In order to control the sediment influx, the mean combined concentration of all sediment fractions was kept the same: 0.24 kg/m³. However, during times of high tide (flood), the total basinward discharge diminishes and this amount of sediments would exceed the river’s transport capacity. The sediments would then be deposited along the channel causing it to become blocked, and eventually causing the model to crash. Hence, a smaller sediment concentration was used during high flood tide periods. To compensate, the same amount of sediments was added during ebb periods. During both processes the concentration curve mimics the discharge curve to keep the whole system stable. In the mixed sediment definition models, each sediment fraction shared half of the assigned concentration at each time step. While in mono-fraction sediment supplies, the concentration of this single fraction was set equal to the total concentration. Figure 13 gives an example of the behaviour of discharge rate and concentration. In this way, the basin was supplied with the user-controlled amount of sediment.
The detailed behaviour of total sediment concentration is shown in Table 3. For mixed sediment scenarios, each sediment type shared half of the total sediment concentration.

Table 3 - Total Concentration behaviour

<table>
<thead>
<tr>
<th>Total Concentration</th>
<th>High Tide (flood)</th>
<th>Mean Tide</th>
<th>Low Tide (Ebb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weak Tide</td>
<td>0.12 Kg/m³</td>
<td>0.24 Kg/m³</td>
<td>0.36 Kg/m³</td>
</tr>
<tr>
<td>Medium Tide</td>
<td>0.090 Kg/m³</td>
<td>0.24 Kg/m³</td>
<td>0.39 Kg/m³</td>
</tr>
<tr>
<td>Strong Tide</td>
<td>0.006 Kg/m³</td>
<td>0.24 Kg/m³</td>
<td>0.474 Kg/m³</td>
</tr>
</tbody>
</table>

Figure 13 Discharge and concentration variation behaviour in model run 1: weak tidal influence, 700 discharge, and 50% sand & 50% clay supply. Red dots stand for initial mean state.
4.2.6.3. Tidal influence

The influence of tide was determined by recognizing the direction and magnitude of flow velocities at flood tide and ebb tide. 3 levels of tidal influence were defined in our model runs:

A. Weak tidal influence, where the flow reverses during flood period at the river mouth.
B. Medium tidal influence, where the flow reverses during flood period in the middle section along the channel.
C. Strong tidal influence, where the flow velocity is upstream everywhere within the channel during high tide period.

The influence was achieved by combined effect of both the water level change at the basinal boundary (representing tidal amplitude) and discharge variance (representing the amount of water brought in or out by tides, e.g., tidal prism).

Table 4 gives an overview of the tidal parameters used in the model settings.

Table 4 Tidal influence parameters

<table>
<thead>
<tr>
<th>Mean river discharge rate (m³/s)</th>
<th>Tidal influence</th>
<th>Discharge rate variance (m³/s)</th>
<th>Tidal amplitude (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>700</td>
<td>Weak</td>
<td>480</td>
<td>0.8</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>540</td>
<td>1.0</td>
</tr>
<tr>
<td></td>
<td>Strong</td>
<td>770</td>
<td>1.2</td>
</tr>
<tr>
<td>900</td>
<td>Weak</td>
<td>670</td>
<td>0.9</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>740</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Strong</td>
<td>990</td>
<td>1.3</td>
</tr>
<tr>
<td>1100</td>
<td>Weak</td>
<td>810</td>
<td>1.1</td>
</tr>
<tr>
<td></td>
<td>Medium</td>
<td>930</td>
<td>1.3</td>
</tr>
<tr>
<td></td>
<td>Strong</td>
<td>1210</td>
<td>1.5</td>
</tr>
</tbody>
</table>

4.3. Modelling scenarios

Based on the above discussions, 36 models were set up and the scenarios are simulated. The simulations were done with parallel computing with a partition number of 4. All the models were set to print the map output once every 2 hydrodynamic days, and save the map data (including water
level, velocity, bed level, sediment volume fractions, etc.) for each grid cell, in a NEFIS file format. This is the solution phase of the finite element analysis procedure.

Table 5 all model runs

<table>
<thead>
<tr>
<th>Model ID</th>
<th>Sediment Fraction</th>
<th>Mean Discharge Rate (m$^3$/s)</th>
<th>Tidal Influence</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>50% Sand &amp; 50% Clay</td>
<td>700</td>
<td>Weak</td>
</tr>
<tr>
<td>2</td>
<td>50% Sand &amp; 50% Clay</td>
<td>700</td>
<td>Medium</td>
</tr>
<tr>
<td>3</td>
<td>50% Sand &amp; 50% Clay</td>
<td>700</td>
<td>Strong</td>
</tr>
<tr>
<td>4</td>
<td>50% Sand &amp; 50% Clay</td>
<td>900</td>
<td>Weak</td>
</tr>
<tr>
<td>5</td>
<td>50% Sand &amp; 50% Clay</td>
<td>900</td>
<td>Medium</td>
</tr>
<tr>
<td>6</td>
<td>50% Sand &amp; 50% Clay</td>
<td>900</td>
<td>Strong</td>
</tr>
<tr>
<td>7</td>
<td>50% Sand &amp; 50% Clay</td>
<td>1100</td>
<td>Weak</td>
</tr>
<tr>
<td>8</td>
<td>50% Sand &amp; 50% Clay</td>
<td>1100</td>
<td>Medium</td>
</tr>
<tr>
<td>9</td>
<td>50% Sand &amp; 50% Clay</td>
<td>1100</td>
<td>Strong</td>
</tr>
<tr>
<td>10</td>
<td>100% Sand</td>
<td>700</td>
<td>Weak</td>
</tr>
<tr>
<td>11</td>
<td>100% Sand</td>
<td>700</td>
<td>Medium</td>
</tr>
<tr>
<td>12</td>
<td>100% Sand</td>
<td>700</td>
<td>Strong</td>
</tr>
<tr>
<td>13</td>
<td>100% Sand</td>
<td>900</td>
<td>Weak</td>
</tr>
<tr>
<td>14</td>
<td>100% Sand</td>
<td>900</td>
<td>Medium</td>
</tr>
<tr>
<td>15</td>
<td>100% Sand</td>
<td>900</td>
<td>Strong</td>
</tr>
<tr>
<td>16</td>
<td>100% Sand</td>
<td>1100</td>
<td>Weak</td>
</tr>
<tr>
<td>17</td>
<td>100% Sand</td>
<td>1100</td>
<td>Medium</td>
</tr>
<tr>
<td>18</td>
<td>100% Sand</td>
<td>1100</td>
<td>Strong</td>
</tr>
<tr>
<td>19</td>
<td>100% Clay</td>
<td>700</td>
<td>Weak</td>
</tr>
<tr>
<td>20</td>
<td>100% Clay</td>
<td>700</td>
<td>Medium</td>
</tr>
<tr>
<td>21</td>
<td>100% Clay</td>
<td>700</td>
<td>Strong</td>
</tr>
<tr>
<td>22</td>
<td>100% Clay</td>
<td>900</td>
<td>Weak</td>
</tr>
<tr>
<td>23</td>
<td>100% Clay</td>
<td>900</td>
<td>Medium</td>
</tr>
<tr>
<td>24</td>
<td>100% Clay</td>
<td>900</td>
<td>Strong</td>
</tr>
<tr>
<td>25</td>
<td>100% Clay</td>
<td>1100</td>
<td>Weak</td>
</tr>
<tr>
<td>26</td>
<td>100% Clay</td>
<td>1100</td>
<td>Medium</td>
</tr>
<tr>
<td>27</td>
<td>100% Clay</td>
<td>1100</td>
<td>Strong</td>
</tr>
<tr>
<td>28</td>
<td>50% Sand &amp; 50% Silt</td>
<td>700</td>
<td>Weak</td>
</tr>
<tr>
<td>29</td>
<td>50% Sand &amp; 50% Silt</td>
<td>700</td>
<td>Medium</td>
</tr>
<tr>
<td>30</td>
<td>50% Sand &amp; 50% Silt</td>
<td>700</td>
<td>Strong</td>
</tr>
<tr>
<td>31</td>
<td>50% Sand &amp; 50% Silt</td>
<td>900</td>
<td>Weak</td>
</tr>
<tr>
<td>32</td>
<td>50% Sand &amp; 50% Silt</td>
<td>900</td>
<td>Medium</td>
</tr>
<tr>
<td>33</td>
<td>50% Sand &amp; 50% Silt</td>
<td>900</td>
<td>Strong</td>
</tr>
<tr>
<td>34</td>
<td>50% Sand &amp; 50% Silt</td>
<td>1100</td>
<td>Weak</td>
</tr>
<tr>
<td>35</td>
<td>50% Sand &amp; 50% Silt</td>
<td>1100</td>
<td>Medium</td>
</tr>
<tr>
<td>36</td>
<td>50% Sand &amp; 50% Silt</td>
<td>1100</td>
<td>Strong</td>
</tr>
</tbody>
</table>
4.4. Post-processing: analysing the results

Upon the finishing of the simulation, the output files were completed for each model. The output file stores properties for each grid cell and for each time step recorded. These properties can be extracted with Delft3D-Quickplot and Matlab scripts. The analysed features are listed in Table 6.

Table 6 An overview of analysis performed and relevance

<table>
<thead>
<tr>
<th>Analysis name</th>
<th>Brief Description</th>
<th>Relevance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delta area</td>
<td>The area of the whole delta</td>
<td>Straightforward and sensitive to the variations</td>
</tr>
<tr>
<td>Delta fringe rugosity</td>
<td>The roughness of the delta fringe (semi-circle as a reference)</td>
<td>The rugosity is an indicator for distributary channel activity</td>
</tr>
<tr>
<td>Delta length to width ratio</td>
<td>Ratio between half the width and the length of a delta</td>
<td>Capture the influence of tide</td>
</tr>
<tr>
<td>Delta foreset dip magnitudes</td>
<td>The dipping angles measured on the delta foreset</td>
<td>Capture influence of D50</td>
</tr>
<tr>
<td>Delta foreset azimuths</td>
<td>The preferred dipping directions of delta foreset sections, quantified by angular concentration (R)</td>
<td>Reflection of distributaries on the topset</td>
</tr>
<tr>
<td>Sand fraction distribution</td>
<td>The distribution of sand, both on map and on profile</td>
<td>Understand reservoir architecture</td>
</tr>
</tbody>
</table>

4.4.1. Normalization

With the model settings given in Table 5, models with different discharge rate and tidal influence would have received different amounts of total sediment input and hence be at different evolution stages if they were compared at a uniform time step. In order to compare all the models at a same evolution stage, normalization need to be performed. The goal is to find a time step for each model so that all models have equal sediment input mass at the critical time steps. In this section, a method to pinpoint the critical time step is discussed, and the resultant time step is verified by the bed level change as observed in the models.

4.4.1.1. Quantification of sediment input mass

The mass of sediment input is given by the formula below,

\[
M = Q * C_o * t * \text{MORFAC}
\]

where
- \(M\) the total mass of the sediments,
- \(Q\) the discharge of the river in \(m^3/h\),
- \(C_o\) the sediment concentration in the flow in \(kg/m^3\),
- \(t\) the hydrodynamic time in hours,
- \(\text{MORFAC}\) the morphological acceleration factor.

Ideally, the total mass of sediment can be considered as the sediment input of one day multiplied by the hydrodynamic days concerned, assuming seasonal change of discharge can be neglected. The calculation for model 1 (700 \(m^3/s\) river discharge, a imposed variation amplitude of 480 \(m^3/s\), a tidal amplitude of 0.8m and half sand half clay sediment input) is explained in the following paragraph as an example. The method applied is identical for all the other models.
In the first 12 hours, the total sediment input is given by:

\[
M_{12h} = \int_0^3 Q(0) \cdot C_{x0} \, dt + \int_0^3 Q(0) \cdot C_{x0} \, dt + \int_0^{12} Q(0) \cdot C_{x0} \, dt + \int_9^3 Q(0) \cdot C_{m0} \, dt + \int_9^{12} Q(0) \cdot C_{m0} \, dt
\]

\[
Q = Q < r > + Q < t > = 2.52 \times 10^6 + 1.728 \times 10^6 \sin \frac{\pi}{6} t
\]

\[
C_{sand} = C_{clay} = \begin{cases} 
0.02t + 0.12, & t \in [0, 3] \\
-0.02t + 0.24, & t \in [3, 9] \\
0.02t - 0.12, & t \in [9, 12] 
\end{cases}
\]

Where \( Q < r > \) is the discharge rate of the river and \( Q < t > \) is the discharge rate variation induced by varying tide. Here, however, the discharge rate variation is defined by the user.

Solving all the equations gives \( M_{12h} = 8.264 \times 10^6 \) kg. The total sediment input influenced by semi-diurnal tide and only by this kind of tide, hence in 24 hours the sediment input is doubled, that is \( 1.6528 \times 10^7 \) kg. Since model 1 has the lowest discharge and therefore lowest sediment input, it was set to run for 424 hydrodynamic days and the total sediment input is \( 2.10 \times 10^{11} \) kg. This mass is then set as a benchmark for the other model runs in order to identify the critical time steps in other models which give the same amount of sediment. For example, the time for model 2 which has the same river discharge (700 m\(^3\)/s), a higher variance (540 m\(^3\)/s) and higher tidal amplitude of 1m to have the same amount of sediments into the domain is 404 days. Since sediment concentration and discharge does not have a linear relationship in this case, the calculation of this number is by doing the integration again.

The critical time step for each model can be obtained by applying the same method to all of them. Table 7 shows the summarized the resultant time steps.

**4.4.4.2. Validation of the time steps by calculating the bed level change**

The critical time steps calculated from the above mentioned method can be verified by the bed level change method. The bed level change is the volumetric difference between bed level at the critical time step and that at the initial stage. Sediment influx volume is given by:

\[
\Delta V = V_{ts} - V_{ini} = \Delta x \cdot \Delta y \cdot \Delta h
\]

Where:
- \( \Delta V \) the sediment influx volume [m\(^3\)],
- \( V_{ts} \) the total sediment volume in the domain at the critical time step [m\(^3\)],
- \( V_{ini} \) the total sediment volume in the domain at the initial time step [m\(^3\)],
- \( \Delta x, \Delta y \) the grid cell size on m- and n-direction [m],
- \( \Delta h \) the total bed level change over the entire domain [m].

For instance, the input sediment mass for model 1 up to the critical time step is calculated as \( 2.10 \times 10^{11} \) kg. The mass can be converted to volume using dry bed densities, which are 1600 kg/m\(^3\) for ‘Sediment Sand’ and 500 kg/m\(^3\) for ‘Sediment Clay’. Hence, the total input volume is \( 2.76 \times 10^8 \) m\(^3\). While using the bed level change method, the daily sediment input is \( 6.52 \times 10^5 \) m\(^3\). Hence, the
cumulative volume change in model 1 from initial condition to the critical time step determined by the mass method (424 days) is $2.76\times10^8 \text{m}^3$, which is approximately the same as the mass-converted volume. The negligible volume difference is caused by the sediment which has been transported outside the domain. By applying the same method for all the models, it can be concluded that the two calculations for each model produce approximately the same results regarding the total input sediment volume till the critical time step (Table 8). In addition, this result has validated that all the models have the same amount of sediment input over the entire domain at the critical time steps (Figure 15). Hence, these time steps can be safely used in further time-dependant analysis. The normalized bed level plots for the 36 models are shown in the Appendix A.

### Table 7 Critical time steps for each model given in hydrodynamic days

<table>
<thead>
<tr>
<th>Model No.</th>
<th>Critical Time Step (day)</th>
<th>Model No.</th>
<th>Critical Time Step (day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>424</td>
<td>19</td>
<td>424</td>
</tr>
<tr>
<td>2</td>
<td>405</td>
<td>20</td>
<td>405</td>
</tr>
<tr>
<td>3</td>
<td>337</td>
<td>21</td>
<td>337</td>
</tr>
<tr>
<td>4</td>
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<td>5</td>
<td>311</td>
<td>23</td>
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</tr>
<tr>
<td>6</td>
<td>262</td>
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<td>262</td>
</tr>
<tr>
<td>7</td>
<td>268</td>
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<tr>
<td>8</td>
<td>253</td>
<td>26</td>
<td>253</td>
</tr>
<tr>
<td>9</td>
<td>214</td>
<td>27</td>
<td>214</td>
</tr>
<tr>
<td>10</td>
<td>424</td>
<td>28</td>
<td>424</td>
</tr>
<tr>
<td>11</td>
<td>405</td>
<td>29</td>
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</tr>
<tr>
<td>12</td>
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<tr>
<td>18</td>
<td>214</td>
<td>36</td>
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</tbody>
</table>

### Table 8 Comparison between the values from two methods

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass-Volume Method (m$^3$)</th>
<th>Bed Level Change Method (m$^3$)</th>
<th>Error percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.7602E+08</td>
<td>2.7473E+08</td>
<td>0.469%</td>
</tr>
<tr>
<td>2</td>
<td>2.7670E+08</td>
<td>2.7640E+08</td>
<td>0.110%</td>
</tr>
<tr>
<td>3</td>
<td>2.7549E+08</td>
<td>2.7530E+08</td>
<td>0.070%</td>
</tr>
<tr>
<td>4</td>
<td>2.7654E+08</td>
<td>2.7580E+08</td>
<td>0.267%</td>
</tr>
<tr>
<td>5</td>
<td>2.7613E+08</td>
<td>2.7603E+08</td>
<td>0.036%</td>
</tr>
<tr>
<td>6</td>
<td>2.7613E+08</td>
<td>2.7573E+08</td>
<td>0.145%</td>
</tr>
<tr>
<td>7</td>
<td>2.7558E+08</td>
<td>2.7511E+08</td>
<td>0.172%</td>
</tr>
<tr>
<td>8</td>
<td>2.7588E+08</td>
<td>2.7535E+08</td>
<td>0.191%</td>
</tr>
<tr>
<td>9</td>
<td>2.7574E+08</td>
<td>2.7495E+08</td>
<td>0.288%</td>
</tr>
</tbody>
</table>
4.4.2. Delta area

The area of each delta has been calculated, because this is the most straightforward feature that can be observed and measured in modern deltas. Therefore, the effects of different processes can be easily identified regarding the area of the delta.

The fringe of a delta is defined by inspection. Since all the deltas simulated have been normalized, the difference in the definition of the fringe is kept on a relatively small scale. In other words, all the deltas can share the same definition for the water depth at the fringe. The fringe is the line that best captures the outline shape of a delta, with delta plain, delta front, and pro delta all included. The fringe was defined at 7.1m water depth, which is also the water depth at the coastline at minimal tidal amplitude.
The area is calculated by determining the number of grid cells inside the delta fringe line, and then multiplies this number by the area of one grid cell, which is 50m by 50m (2500m²).

4.4.3. Delta fringe rugosity
The rugosity is an index for the roughness of the delta fringe. The rugosity is considered to be a reflection of delta distributaries activities. Burpee (2012) defined isoperimetric quotient (IQ) to quantify the rugosity by:

\[ IQ = \frac{2\pi A}{P^2} \]

Where:
- \( IQ \) the dimensionless isoperimetric quotient;
- \( A \) the area of the delta enclosed by the fringe [m²];
- \( P \) the length of the delta fringe [m]

Thus, a perfect semi-circle has a rugosity of 1. Complex fringes that deviate from a circle (Figure 17) have low rugosity, while rugosity nearer to 1 indicates smoother fringes.

![Figure 17 Rugosity of a delta whose fringe deviates from a circle](image)

4.4.4. Delta length to width ratio
The delta length to width ratio is measured because tide is known to produce elongated channels, and this measurement may give clues on how this would influence the geometry of the delta. The length to width ratio is defined as half the ratio between the longest distance on the X-direction (length, streamwise) in a delta and that on the Y-direction (Width, spanwise) (Figure 18).

\[ \frac{L}{W} = \frac{1}{2} \frac{(\max(x) - \min(x))}{(\max(y) - \min(y))} \]
It is halved so that this ratio also reflects the symmetry of the delta. Considering a symmetric circle again, this measurement would give a length to width ratio of 1.

![Figure 18 Delta length to width ratio](image)

4.4.5. Delta foreset dips

The riverine forcing interacts with marine forcing at the delta front, causing the outflow to decelerate and disperse (Figure 26), and most of the suspended sediments to deposit. While the coarse materials are deposited at the distributary mouth, the fines are transported further offshore and are deposited in a deeper location. This differentiated distribution of sediments would therefore construct a seaward-dipping profile sloping gently into the basin, generally at an angle of less than $2^\circ$, and fines progressively into the basin (Reading, 1996). The dip magnitude and direction are hypothesized to be controlled by the grain size and discharge, and these measurements might validate the theory and explain the mechanism.

The dip angle magnitudes, dip directions and both their variances of each delta foreset slopes were measured. For preparation, the main river channel, distributary channels and topset were removed from the bed level data. In this way, the bed level map file of the model run was reduced to geometry of a foreset surface (Figure 19).
The dip magnitude is the angle between the foreset surface and the horizontal plain (Figure 19). It is calculated as an average of the all the gradient between two adjacent points along the whole slope, from the rollover to the delta toe. The rollover and the toe of the foreset are defined by cumulative erosion/sedimentation. The rollover is the point when the shape of the delta transforms from convex to concave; while the toe is the area where the cumulative sedimentation is below 0.1 m (a user defined cut-off value below which sedimentation is negligible). A mean dip magnitude is calculated, as well as the standard deviation of the dip magnitudes (Figure 20).

Foresets’ dip azimuths’ variance, or angular concentration (R), is also considered to be an indicator for distributary channel activities. In geological field work to modern deltas, one can measure the azimuths along the roll over line. This is the same idea as the method that is applied here. In Jones(2006), all the dippings (Figure 21) are considered as unit vectors, with a length of 1 and pointing at various directions.
The combined vector of n unit vectors (all the vectors shown in Figure 21) has a orientation $\vec{\theta}$, and a length R. The orientation $\vec{\theta}$ (in degrees) is given by:

$$
S = \sum_{i=1}^{n} \sin \theta_i, \quad \bar{S} = S / n
$$

$$
C = \sum_{i=1}^{n} \cos \theta_i, \quad \bar{C} = C / n
$$

$$
\vec{\theta} = \begin{cases} 
\tan^{-1}(S/C), & S > 0, C > 0 \\
\tan^{-1}(S/C) + 180, & C < 0 \\
\tan^{-1}(S/C) + 360, & S < 0, C > 0
\end{cases}
$$

Where $n$ is the number of dip angles measured.

The length R is calculated as:

$$
R = \sqrt{\bar{S}^2 + \bar{C}^2}
$$

The length R is a reflection of the variance. If all n of the unit vectors are essentially oriented in the same direction, R will be nearly equal to n; while if the n vectors point to every direction around the compass, R would be approximately 0. Therefore, a small R is analogous to a large variance and a large R means a small variance.

### 4.4.6. Sand fraction distribution

The sand fraction distribution is shown both in a plan view and as cross-sections. They provide an overview of the locations and trend of sand bodies, which are potentially reservoirs (if charged by source rock). Additionally, they can hint the connectivity between the discrete sand bodies that scatter over the whole domain, on condition that they have not been reworked by tectonic activities.

In a plan view, the sand fractions in the underlayers were integrated across all layers, resulting in one value for each horizontal grid cell. In order to find a general trend for sand distribution, the river
channels have to be averaged, for they contain values that are much lower than the neighbouring grid cells. Hence, an averaging of adjacent 8 grid cells was performed for each grid cell (Figure 22). The values less than 0.2 were then cut off, for these areas are, by any means, not connected with other sand-rich areas, and thus hinting the connectivity. This analysis was only applied to 50% sand & 50% clay and 50% sand & 50% silt models, because in other models where the sediment input was set to 100% sand or 100% clay, where the fraction became meaningless.

On a cross-section, with a vertical resolution of 0.3m, the grain size change trend can be observed within the sequence. Figure 23 shows as an example. Three cross-sections were taken in the middle of the delta, and then averaged, making one pseudo-cross section, enclosing the delta apex, delta plain, and delta front. In the same way, pseudo-cross-sections on the either side of the delta and a longshore pseudo cross-section were made. The intercalated layers with varying sand fractions can be better visualized by zooming in the profile. Red in the profile means the sand fraction at that specific spot is high; while blue means the sand fraction is low. This is analogous to a drilling core or borehole logs in the real world case.
5. Modelling results from Delft3D

*Measure what is measurable, and make measurable what is not so.*

– Galileo Galilei

In the first section of this chapter, an overview of the visualized evolution patterns of modelled deltas is provided, and the patterns with varied boundary conditions are compared against each other. The rest sections of the chapter shows the results of the proposed analysis listed in Table 6.

### 5.1. General evolution pattern of modelled deltas

Delft3D is capable of simulating the evolution of a delta, and store the map file including hydrodynamic conditions, bed levels, sedimentation and erosion at each location.

The topography of the delta can be best represented by its bed level. This section first gives a brief description of the evolution pattern of Model 5 as a reference case, and then compares it with other models that have similar settings but varied boundary condition (Figure 24). The comparison is done by comparing the delta morphology at the same evolution stage, i.e., percentage complete. In this case, 17%, 34%, 51%, 67%, 83%, and 100% complete were chosen.

Figure 25 shows the bed level of model run 5 (900m³/s discharge, medium tidal influence and 50% sand & 50% clay input) at hydrodynamic day 54, 106, 148, 208, 260, and 312.

---

**Figure 24 Comparison between the models**
The screenshots were captured at an equal time span. Generally speaking, the river carries sediments basinwards, both sand and clay in this case. At the entry of the basin, the flow velocity disperses and decreases, causing the bed load and suspended load to deposit as the mouth bar (Figure 26).
Afterwards, the flow is bifurcated by the mouth bar in the middle of the entrance. Two main channels each feed one side of the delta (Figure 25a). The delta keeps growing by avulsions and channel migrations, e.g., distributary channels switching their courses, always prone to break the levees and find the most direct course downslope, driven by hydraulic efficiency (Figure 25b). A bay shape (Figure 25c) is usually formed as a temporary feature, where the two major distributary channels carries most of the sediment supply, while the middle part fails to be filled. Yet, the distributaries eventually break the levees and spill out to the middle, in order to find a shorter course into the basin.

Usually at a later stage, when the delta become mature with a complex distributary network of channels on top of the delta plain, one of the distributary channels will become dominant. Long and deep, the major channel causes the delta to prograde further into sea. This phenomenon can be observed in Figure 25f, Figure 27e, for example.

Because the bed is sloping towards the sea, the accommodation space is increasing basinwards as well. This causes the area of the delta to increase non-linearly; first in a relatively high rate and in later phase at a lower rate. At a mature stage, for example the last two captures, e and f, the growth almost cannot be recognized visually.

5.1.1. **Analysing the effect of discharge variation**

In comparison, model run assigned with a lower mean river discharge and other identical conditions, such as model 2 (Figure 27). Despite a lower evolution rate (as shown in days), the pattern, however,
is similar to the model 5: bifurcate-feed the sides-fill the space in between-avulsion-feed the sides, etc. Therefore, the bay feature can be observed in multiple stages of the delta evolution.

With a larger discharge, namely model No.8 (Figure 28), the initial two dominant distributary channels are more pronounced. It is also evident that the channels are less stable as they tend to avulse more often. The bay shaped feature has been initiated by the two major distributary channels, as can be seen in d, e and f. With a large discharge and a medium tidal influence, the dominant riverine forcing is shaping the delta in a ‘bird foot’ shape, displaying more mouth bars fingering into ocean, as is shown in f. This can be explained by the enhanced transport capacity of

Figure 27 Bed level of model run 2 (700 m³/s discharge rate, medium tidal influence and 50%sand & 50%clay) at day 70, 136, 204, 272, 338, and 406
the channels enabling them to transport more sand to build the mouth bars at the distal end of the delta.

5.1.2. Analysing the effect of tidal variation

In order to visually describe the effect of tide, model 5 is compared against model 4 (Figure 29), whose tidal influence is weaker, and model 6 (Figure 30), whose tidal influence is stronger. The other settings of 4, 5, and 6 are identical: 900 m$^3$/s discharge rate and 50% sand & 50% clay sediment supply.
Compared with model 5, the evolution rate of model 4 (Figure 29) is lower, for the ebb-jet is smaller in this case. Because of the relatively smaller total discharge, the total size is smaller with less sediment supplied (cf. model run 8 in Figure 28). There is not a predominant distributary channel present, and the delta front progrades at a similar rate, thus making fan-like deltas (when the gaps would be eventually filled at a later stage).
Model 6 (Figure 30) has a strong tidal influence, but given the river discharge, this modelled delta has not gone into the realm of ‘tide-dominated deltas’ (see chapter 6 Discussions). The evolution pattern is more influenced by tide than model 5 in that the distributary channels have been stabilized and outstretched by the ebb-jet flows. This is the major progradation pattern of this delta model, instead of channel switching. Elongated distributary channels tend to lengthen the whole delta geometry for they are more capable of transporting the sediments further offshore for the delta to build.
5.1.3. Analysing the effect of varying D50
Model 23 (Figure 31) has similar model settings to Model 5, except that the sediment supply is 100% clay, meaning a smaller D50 (23.58 µm, while model 5 has a D50 of 40.75 µm). The evolution of the delta is, in its early stage, symmetric. As it evolves the channel breaks through the initial mouth bar and overflows directly into the bay in between the two major distributary channels. The former distributary channels then become abandoned and the middle channel becomes dominant and progrades fast to the centre of the basin. The distributaries appear to be more sinuous (meandering) than those in 50% sand and 50% clay deltas, and the delta extends to larger areas than all the previous models. Delta front area (cyan colour) grows larger in size as well.

Figure 31 Bed level of model run 23 (900 m³/s discharge rate, medium tidal influence and 100% clay) at day 9, 69,129,189,249,309

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Model 32 (Figure 32) has a sediment supply of 50% sand and 50% silt. The bay-shaped feature is more pronounced as is shown in c. The delta is also more elongated than model 5.

Figure 32 Bed level of model run 32 (900 m$^3$/s discharge rate, medium tidal influence and 50% sand & 50% silt) at day 9, 69, 129, 189, 249, 309

Figure 33 shows the model runs with 100% sand as sediment supply (therefore a D$_{50}$ of 150 µm), and again, with the rest of the settings staying the same as model 5, the reference case. For sand is more gravity-driven rather than fluid-driven (Orton & Reading, 1993), it is harder to be transported further offshore than finer materials. Thus, sand concentrates near shore with a smaller area and manifests a conservative feature, forming the fan-delta seen in Figure 33f. It is asymmetric from the very beginning and the distributaries avulse more frequently than model 5, as seen from its rugose
delta fringe. In a later stage, because of the limited accommodation space and transport capacity, the sand settles within the river channel before even entering the basin. This is a common phenomenon in sandy delta models (Appendix A).

5.2. Delta area
For the area comparison, each of the deltas is compared at the critical time step determined in the ‘post-processing’ section. As discussed in section 4.4.1, with the increased sediment supply associated with larger discharge the delta models with larger discharge will reach the critical time step sooner. However, at the critical time steps for each delta, they all have the same amount of
sediment input, and the effect of differing mean river discharge is dampened. Hence, the delta areas at the critical time steps will only be investigated with the influence of tide and sediment mixture D50.

Figure 34 shows the relationship between the delta area and the D50 of the sediment supply, and the tidal influence. The graph indicates that D50 is the major controlling factor for the area of the delta in these models, and the area decreases with increasing D50. The trend curve shows an exponential decline in area with decreasing D50. This also has been observed in the previous section 0.

Additionally, the areas of deltas whose sediment supply has a small D50 deviate from the mean area, having a large spread; while spread gradually converges with the increasing of D50. In 100% sand scenarios, all the delta models have very similar area values closing to their mean value.

One of the other observations is that the medium tidal influence seems to be more favourable for large deltas to be built.

![D50 vs. Area](image)

**Figure 34** the relationship between D50, tidal influence and delta area at their critical time steps

Since the effect of discharge has been dampened due to the normalisation in the first place, it is therefore necessary to investigate the effect of discharge at the same time step as well. An example is given in Figure 35. Both model 3 and model 9 are strongly tidal influenced and have the same sediment input fraction (50% sand & 50% clay). Model 3 has a mean river discharge rate of 700 m³/s, while model 9 has a discharge of 1100 m³/s. This figure shows that the model with a higher discharge has a larger area than the one with a smaller discharge.
5.3. Delta fringe rugosity

As explained in section 4.4.3, rugosity is an indicator for the shoreline roughness. The rugosity is quantified with the isoperimetric quotient (IQ), where a low IQ means high rugosity and vice versa. Figure 36 shows the relationship between the increasing D50 of the sediment supply, tidal influence and the IQ (representing delta fringe rugosity). This graph suggests that sandy deltas are more rugose, meaning a rough fringe; while muddy deltas and clay-dominated deltas have more smooth fringes. The mean D50 has a strong impact on the geometry of the delta.

![Figure 35](image1.png)  
**Figure 35** the area model 3 (left) and area of model 9 (right), both at hydrodynamic day 365.

![Figure 36](image2.png)  
**Figure 36** the relationship between D50, tidal influence and the isoperimetric quotient (IQ)

The combined influence of mean river discharge rate and tidal influence is shown in Figure 37, Figure 38, Figure 39, and Figure 41.

In 50% sand and 50% clay delta models (Figure 37), the tidal influence has negligible effect on the rugosity of the delta fringe when the discharge is as low as 700m$^3$/s. Then the effect is enhanced in 900m$^3$/s cases, where the IQ decreases with increasing tidal influence. In 1100m$^3$/s cases, weak tidal influence still produces highest IQ, while medium tidal influence produces the lowest.
In 100% sand scenario (Figure 38), tidal influence has no notable impact on delta fringe rugosity in the low discharge rate cases (700 m$^3$/s) either. Though model 7, which is the outlying ‘x’ marker on top of the 900 m$^3$/s discharge rate group, has a slightly higher IQ, the overall trend of the IQ is, however, decreasing with the increase of mean river discharge rate. Besides, all the IQ values are lower than the other 3 groups, below 0.3, meaning that the fringes of sandy delta models are constantly more rugose and rough than other groups of modelled deltas.

Figure 39 shows the relation between the rugosity and the discharge in 100% clay scenarios. The ‘700w’ blue dot (model 19 has a 700 m$^3$/s discharge rate and a weak tidal influence) has a higher IQ because the delta grew and reached the upper boundary of the domain, making the measured perimeter of the fringe shorter, and therefore results in a higher pseudo-IQ (Figure 40). Hence, in low discharge models, the rugosities do not differentiate much, while in medium discharge models,
the one with weak discharge has the lowest rugosity and in high discharge models, the one with weak tidal influence has highest rugosity.

### Discharge vs. IQ in 100% clay deltas

![Discharge vs. IQ in 100% clay deltas](image)

**Figure 39** Relation between discharge and IQ in 100% clay deltas

**Figure 40** Model 19, delta reaching the upper boundary, resulting in a smaller perimeter and therefore larger IQ

Figure 41 shows the relation between rugosity and discharge in 50% sand and 50% silt cases, indicating the fringe rugosity of small discharge delta models is not sensitive to tidal influence. For the tidal amplitude and tidal prism were assigned to be positively correlated with the mean discharge rate, the tidal prism and tidal amplitude were small, yielding less absolute influence upon the delta rugosity. However, in higher discharge models, the IQ responds to tidal influence in a negatively correlated way, i.e., at the same discharge level, higher tidal influence produces lower IQs. In higher discharge cases (second and third column), IQ generally decreases with higher discharge.
In order to give an overview of the joint effect of tide and river, the ratio of tidal to fluvial discharge ($P/Q_r$) is introduced (Stive & Rakhorst, 2008) and plotted on the X-axis against the IQ, where $P$ is the tidal prism (Figure 42). The figure not only suggests that delta models with higher D50s generally have lower IQs, but also that with the increasing relative influence of tide, the IQ decreases, indicating more rough delta fringes.
5.4. Delta length to width ratio

The result of length to width ratio in relation to the mean river discharge of the 36 models has been plotted in Figure 43.

![Mean discharge vs. L/W](image)

**Figure 43 Relationship between mean river discharge and length to width ratio**

Except for one outlier (model 23) and an end member (model 18), the trend appears to be converging to a length to width ratio of 1, with the increasing of mean river discharge. However, the mean river discharge is also an indicator for the dominance of fluvial forcing in the whole deltaic system.

It is hypothesised that the river dominance has a significant effect on the length to width ratio of the delta.

In order to test the hypothesis, another experiment was designed and conducted. This designed model has a 900m$^3$/s mean river discharge rate, and 50% sand & 50% clay sediment input, and no tidal fluctuation was prescribed. Therefore, it is a purely ‘river-dominated’ delta (Figure 44).
It develops to be an approximately rectangular shape, with a length to width ratio close to 1, according to the method as defined in section 4.4.4. Hence, the author hypothesizes that in an extreme case where river is absolutely dominating the development of the delta, the length to width ratio would equal to 1, in a numerical lab setup as described in the methodology chapter.

The influence of D50 on the length to width ratio of modelled deltas is shown in Figure 45. A trend that the length to width ratio decreases with the increasing of D50 in all tidal strength groups can be identified. The trend line of low tidal influence group, however, declines more gentle than the other two groups.
5.5. Delta foreset dips

5.5.1. Mean dip magnitude

The dip magnitudes for all the deltas at their critical time steps were measured, and the data is shown in Figure 46.

This graph suggests that the grain size has a strong effect on the mean dip magnitude of delta foresets. The mean dip magnitude increases significantly with the increasing fraction of sand in the supply, i.e., the increasing D50, and also the range increases at the same time.

Though the effect of discharge is dampened on a time-dependant slice, some trend can still be found. Figure 47 shows the effect of mean river discharge on the mean dip magnitude.

![D50 vs. Mean dip magnitude](image)

**Figure 46** Mean dip magnitude increases with D50

![Mean river discharge vs. Mean dip magnitude](image)

**Figure 47** Relation between mean river discharge and mean dip magnitude
The data is clearly divided into an upper group and a lower group. The lower group consists of mud-dominated deltas and mixed-supply deltas. The upper group consists of the 100% sand supply deltas. Tide and discharge do not seem to have great effect on deltas with a small D50. However, when it comes to sand-dominated deltas, those with a larger river discharge have larger mean dip magnitudes than counterparts with the same tidal influence. Vice versa, those with a stronger tidal influence have larger mean dip magnitudes than counterparts with the same mean river discharge.

5.5.2. Standard deviation of the dip magnitudes
The standard deviation of the dip magnitudes for each modelled delta is measured and shown in Figure 48 and Figure 49. For deltas with a smaller D50, the dipping angles within one delta foreset deviate less from their mean value than those with larger D50. The relation between D50 and standard deviation of dip magnitudes appears to be exponential. Variation in tide and mean river discharge do not seem to play an important role in models other than ones with 100% sand supply. In 100% sand supply cases, however, the stand deviation of dip magnitudes respond to the increasing of mean river discharge, and they are positively correlated.

![Figure 48 Standard deviation increases with increasing D50](image)
5.5.3. Delta foreset azimuths

The azimuths of a delta foreset can be quantified by its angular concentration (R). The angular concentration (R) is an indicator measuring how much dip azimuths concentrate, which is inversely proportional to angular dispersion. A large R means a small variance and a small R is analogous to a large azimuth variance. The relations between angular concentration (R) and D50 is shown in Figure 50, while the relation between angular concentration and mean river discharge is shown in Figure 51. Tide does not seem to impact the result in a significant way, while a higher discharge is believed to contribute to a higher ‘R’, meaning a smaller dispersion. When the riverine forcing becomes dominant within the system, the delta would prograde at a high rate into the basin without too many distributaries flowing sideways. Thus, the preferred angle for development would concentrate around 90°, making a large R (small angular dispersion).

As can be observed in Figure 50, the column with the largest D50, i.e., 100% sand deltas, has the most similar angular concentration values among all other groups. The non-cohesive sand has higher density and is therefore less sensitive to hydrodynamic conditions such as riverine force and tidal influence, but more gravity-driven (Orton & Reading, 1993). Therefore, sandy materials respond inactively to the variance in mean river discharge and tidal amplitude. In contrast, the column on the left, which stands for 100% clay deltas, has the largest range of angular concentration. This means that clay materials are more sensitive to the change in hydrodynamic conditions and therefore respond actively to tide and riverine forcing. The outstanding delta (No.27) on the upper left corner in Figure 50 is the same as the one on the upper right corner in Figure 51. The 100% clay delta has a strong tidal influence, a largest mean river discharge rate of 1100 m³/s. Hence, the assumption is that the angular dispersion is not controlled by merely mean river discharge rate or tidal influence, but a combined effect of those two: the total discharge rate of ebb jet flow. A high ebb jet flow can excite the whole system to a higher energy level and the flow would disperse to different directions,
causing the levee and distributary mouth to build to the sides instead of concentrating to the due basinward direction.

Figure 50 Relation between D50 and angular concentration (R)

Figure 51 Relation between mean river discharge and angular concentration (R)
5.6. Sand fraction distribution
The sand fraction distributions averaged over all underlayers (i.e. vertically) for the 50% sand & 50% clay cases and 50% sand & 50% silt cases are shown in Figure 52 and Figure 53 respectively.

Figure 52 Sand fraction distribution on a plan view; model 1-9 (50% sand & 50% clay)
Figure 53 Sand fraction distribution on a plan view; model 28-36 (50%sand & 50% silt)

In particular, the plan view of sand fraction distribution for model 5 is show in Figure 54. It can be observed from the figure that the sand concentrates most at the delta apex. However, the delta apex is at the same time the most favoured place for distributary channel activities such as bifurcation and avulsion, which erode the sediments and carry them elsewhere. Therefore, the sand body that stretches about 25 coarsened grid cells, e.g. 1km$^2$, is isolated from other sand bodies. From the apex to the edge of the delta, the sand fraction gradually diminishes.
On a cross section (Figure 55), the general trend in section A, B and C is that the sand fraction is diminishing towards the basin, and the initial mouth bar is the most sand-concentrated section over the whole domain. On cross-section D, the sand body of initial mouth bar is in an asymmetric lenticular shape, with a flat bottom and a convex top. It has a thick core and thinning towards its wings, and coarsening towards the upstream river. On cross-section A, the overall sand fraction is low, and this is in accordance with the observation of the plan view. However, on cross-section C, the sand fraction is as high as that in the middle of the delta (section B), and this is actually the sandy area that can be seen on the plan view as well. This is because cross-section C cuts right through the natural levee, which is sandy. On the longshore cross-section D, two compartmentalized sand bodies are in the middle, and the right one being the levee mentioned above. The coarsening upward sequence can be found on either side of the delta, since the clay has been deposited there first because of their lower density whereas sand is transported and deposited only later. This section has a potential to develop into a labyrinth-type reservoir.

It is worth noticing that in all the cross-sections, sand tends to concentrate in a relatively small space and do not seem to favour mingling with the clay material. In other words, it is, in most cases, either red (meaning over 80% sand) or blue that is observed on the cross-section. This is not a common phenomenon in nature for the difference in D50 between the modelled ‘SedimentSand (150 µm)’ and ‘SedimentClay’ (23.58 µm) is way larger than that in nature and the material with a D50 in between is absent.

Model 32 (Figure 56, Figure 57, Figure 58) has identical hydrodynamic conditions (medium tidal influence and 900m³/s river discharge rate) to model 5, but the clay in model 5 is replaced by silt, which has a larger D50, and is closer to sand in not only this regard, but also closer settling velocity. Hence, silt’s behaviour and favourable location for deposition is closer to sand than clay, and mingles
more with sand, causing a larger area of cyan colour to be seen on the cross-sections. Sand bodies distribute along the distributary channels in a ribbon shape.
Figure 55 Sand fraction distribution of model 5 on cross-section view. Red for high fraction and blue for low fraction.
Figure 56 Bed level of model 32 and cross sections

Figure 57 Sand fraction distribution on a plan view of model 32
Figure 58 sand fraction distribution of model 32 on cross-section view. Red for high fraction and blue for low fraction
Cyclic tidal sedimentary features such as double mud drapes are well beyond the model resolution, and therefore cannot be visible.

The effect of discharge, however, can be analysed by checking model 5 (medium tidal influence, 50% sand & 50% clay, 900 m$^3$/s discharge rate) against model 2 (medium tidal influence, 50% sand & 50% clay and 700 m$^3$/s discharge) and model 8 (medium tidal influence, 50% sand & 50% clay and 1100 m$^3$/s discharge), both on plan view and cross-sectional view.
Figure 61 sand fraction distribution of model 2 on cross-section view. Red for high fraction and blue for low fraction.
As can be observed from the plan view of sand fraction distribution of model 2 (Figure 59), the sand connectivity at the mouth bar is better than those of previous models described. On a cross-section view (Figure 61), all the sand bodies concentrate closer to the shoreline than the courter parts. This phenomenon is most visible in section D, whose sand fraction is higher and spread a wider range on this cross-section than other D-sections. The mouth bar sand body is also thicker.

In comparison, on the plan view of model 8 (Figure 62), due to a higher discharge of 1100m³/s, sand distributes along the distributary channels in a shoestring geometry. Except for the mouth bar and the natural levees along the distributary channels, the sand fraction stays relatively low.
On a cross-section (Figure 64), more channel incisions are found than those in Figure 61. This explains why the overall sand fraction is lower in model 8 than model 2, whose discharge is lower.
There are more distributary channels in model 8 due to a higher discharge, and in some cells near the distributary channels, the averaged sand fraction is lower than 0.2 and are therefore cut off. The sand concentration on the delta front on cross-section A is the distal bar. The sand fraction is high, since a high river discharge is capable of transporting sand to this distant location from the shoreline.
6. Discussions

Do not quench your inspiration and your imagination; do not become the slave of your model.

--Vincent van Gogh

The aim of this study is to understand how river discharge, tide and grain size would influence the geometry and stratigraphy of a delta, on a temporal scale of tens of years and a spatial scale of hundreds of square kilometres. The results in Chapter 5 did give insights into this question, suggesting that grain size, among others, has the strongest influence on the stratigraphy and geometry, while the interacting between the tidal and riverine forcing influences delta geometry mainly by controlling distributary channel activities and ebb jet.

6.1. Validity of Delft3D numerical models

The modelling assumptions and boundary conditions have been listed in section 4.1, and they are validated by the results shown in Chapter 5.

In the model settings, the D50 varies from 20 to 150 µm, mean river discharge varies from 700 m³/s to 1100 m³/s. The tidal amplitude varies from 0.8m to 1.5m and the tidal prism to mean discharge ratio is between 0.68 and 1.1. These boundary conditions fit in the natural settings (Figure 65 and Figure 66, Syvitski & Satio, 2007).

![D50 vs. Ln mean river discharge](image)

**Figure 65 Comparison of assigned D50 and mean river discharge with natural systems**

The resultant numerical models have flow velocity between 0.1 and 2 m/s, reasonable evolution pattern and planform. Burpee (2012) measured the isoperimetric quotient of the Goose River Delta (Canada) and Last Chance Delta (US), which respectively reads 0.28 and 0.47. The IQs measured in the present study falls around this range. However, the dip magnitudes measured in the present study is lower than the real world data, and the explanation could be that the evolution time is not long enough for the sequences to aggradate, and hence the dip magnitudes of numerical deltas are vertically under-estimated.
If the models were given longer timespan to run beyond the critical time step (as discussed in section 4.4.1), the morphological features such as rugosity and the length to width ratio continue to change (Figure 67). This suggests that the models are not yet fully in their finalised state. However, this does not affect the existing data and corresponding findings.

Figure 66 Comparison of assigned $P/Q_r$ ratio and mean river discharge with natural systems ($P/Q_r$ ratio is the ratio between tidal prism and mean river discharge)

Figure 67 Comparison between normalised morphological values and that of a later stage
6.2. The effect of mean river discharge

The mean river discharge rate has direct control on two things: (1) the mass of sediment brought in and (2) the distributary channel network.

Delta’s growth rate is an indicator for the mass of sediment input, and has been normalized at the beginning of the post-processing. However, it is evident that with the same period of time elapsed, the size of the delta scales with the river discharge rate (Figure 35), of both sediment and water, as shown in the time steps chosen for the normalisation. This agrees with the finding of Syvitski & Satio (2007), that the delta area is almost proportional to the mean river discharge.

The discharge rate influences the morphology by controlling the distributary channel network. In models with a higher discharge, the distributary channels are more active relative to those in lower discharge models, and they tend to breakthrough the levees and avulse more often, as is observed in section 495.1.1.

6.3. The effect of tide

Regardless of what kind of tidal influence is assigned in the models, all the models are river-dominated deltas, since the tidal prism to river discharge ratios \(P/Q_r\) are far less than 20 (Stive & Rakhorst, 2008).

The results have indicated that even in a river-dominated spectrum, tide still has a significant effect on the evolution, morphology of the delta.

Instead of frequent channel switching, tide-influenced models show more stable and elongated channels. This phenomenon is mainly caused by the ebb jets induced by tide. Syvitski & Satio (2007) have found that tide widens the channels, allowing the distributary channels to better accommodate the high volume and velocity of the water in times of ebb tide. Large channels are less frequent overrun and therefore less breakthrough of levees happen. This in turn prevents the forming of more distributary channels. This proposed mechanism has been indicated by Geleynse (2011) that in river dominated delta models, tide-influenced ones are found to prograde mainly via lengthening of initially-formed, and relatively stable distributary channels. This means less avulsions happen in tidal influenced deltas, resulting in less distributary channels. This, at the same time, produces smoother fringe and low rugosity.

In terms of stratigraphy, Geleynse (2011) has found that tide-influenced river deltas are characterised by cyclicity in the mouth bar and coastal plain deposits, i.e., interbedding of sands and silts. Yet, this is not clearly visible in the results of this study. The reason could be that in Geleynse’s study, the substrate actually contributes to the building sediment of a delta. On top of that, the model setting of the present study is more dynamic than that of Geleynse’s. Since the total discharge varies drastically over time because of the imposed ebb discharge, the slack water period is relatively shorter than Geleynse’s model, making it difficult for cohesive clay or silt to settle in areas of mouth bar and coastal plain. Nevertheless, what is proved in this study is that tides have influence over sediment dispersion by controlling the evolution of the distributary channels, and hence the levees.

6.4. The effects of relative strength between tidal and riverine forcing

Mean river discharge and tidal influence were two independent elements in the model settings. However, the tidal prism, as a result of interactions between the two throughout the whole spatial
and temporal domain, was imposed to the river discharge. Therefore, discharge variation is dependent upon tidal influence, and it is advisable to interpret the features observed as a combined effect of the two processes.

Delta models with a river dominance (lower P/Qr) show, in general, higher rugosity (Figure 42). As is mentioned in section 4.4.3, the rugosity measures the roughness of the delta fringe, where a fringe with more bumps and dents is rougher than a smooth one. In deltaic systems, when the distributary channels are in an active status, with high flow velocity and high sediment transport capacity (in our case, this means heavier sediment load), they tend to break the levees and take a new, steeper course to the basin. At the delta front then, the sediments are deposited and they build a new deltaic lobe. The roughness of the fringe is mainly determined by the number of lobes, which is the reflection of distributary channel activity.

This therefore infers that the distributary channel activity (migrations and avulsions) magnitude is positively related to mean river discharge and inversely proportional to the tidal influence.

The mean river discharge is major control on the spread of length to width ratios (L/W) of the modelled deltas, as is shown in Figure 43. The length to width ratio has a large spread in models with a low discharge, since other processes still have influence on it. The ratio converges to 1 in high discharge models, as riverine forcing has superimposed other processes and has become the only factor that matters the length to width ratio. The additional model (Figure 44) with no marine forcing (tide in this case) has indicated that in cases where riverine forcing is absolutely dominating that the marine forcings can be neglected, the length to width ratio would converge to one value (in this case 1, since it is a symmetrical bed level setting). It can be concluded that, the length to width ratio is most sensitive to, among other things, the mean river discharge. This is also an indication that the river is the most influential process in the situation concerned, which is backed up by the low tidal prism to river discharge ratio.

The mean dip angles and their variance (Figure 47, Figure 49 and Figure 51) are, besides controlled by D50, dependent on the combined strength of riverine forcing and tidal forcing, i.e., energy level. In high energy level cases, the dip magnitude is larger, its variance larger, and the dip towards more directions. This has inevitably led one to hypothesize that the geometry of the delta foreset is influenced by the ebb jet flow.

As is observed in Figure 52 and Figure 53, the sand bodies are more continuous in low discharge and low tidal influenced models (low energy level in general). The physics behind is that for low energy cases the sand cannot be transported further but concentrates at the initial mouth bar, or even fill in the channel. With fewer channels, the averaged sand fraction remains high, leading to a good connectivity. However, in high energy cases, the sand spread over the whole delta in a shoestring shape encased in clay (silt), on top of which the averaging over channels and sand bodies further lowers and fraction, and even below the cut-off value. Nevertheless, in these cases the distributary network manages to transport the sand to the distal bar to be deposited, which is different to that in low energy cases.

6.5. The effects of sediment fraction
Sediment fraction (average D50 of the supplied sediments) produces considerable effect in the modelled delta area, rugosity, dip magnitude and variance, and dip azimuth angular dispersion.
With the same amount of total sediment input (mass), the area of the modelled delta increases significantly with the decreasing of D50. Considering that the bed level is sloping to the basin, the effect of D50 could have been larger. The reason is that the dry bed density of clay (silt) is $500\text{kg/m}^3$, while the density of sand is $1600\text{kg/m}^3$. With the same mass, the volume of a clayish delta is bound to be larger.

Delta models with the 100% sand input (largest D50) has the roughest fringe, and the rugosity decreases with decreasing D50. The explanation is that the suspension load of fines is significantly higher than that of sand, and therefore the subaqueous levee can be built with a higher rate. The levees can confine the flow, and thereby enable the distributary channel to prograde rapidly towards the basin (Slingerland, Burpee, & Edmonds, 2012), instead of avulse to new courses. Less active distributary channels then result in rough fringe (higher rugosity).

The length to width ratio is decreasing with increasing D50, as is shown in Figure 45. This is also due to the rapid building up of natural levees and resultant high basinwards progradation rate.

The foreset geometry is strongly controlled by the D50 of the supplied sediment. Large D50 results in steeper foreset slopes and a larger range of spread of the dip angles. In mixed scenarios, the fines are easier to transport and are deposited further, at the toe of the foreset slope, while the sand stays behind the rollover. In 100% sand cases, however, all the particles are of the same size and have large D50, and they cannot be differentiated by the flow. Therefore, the foreset slope is steeper. In 100% clay cases, all the particles are easily transported to the toe and the delta models are in general flatter than other models, resulting in a gentler slope towards the basin.

In terms of stratigraphy, the sand is less clean in sand-silt mixed cases than sand-clay mixed cases. Silt has a higher D50 and resultant higher settling velocity, meaning that during the same deposition period, more silt can be settled down than clay, and hence silt amalgamates with sand more than clay does. Thus, the 50%sand &50% clay models would potentially produce more homogeneous reservoirs than 50%sand &50%silt models. This is also observed by Leuven (2014).

To summarise, D50 makes a difference because the density of the sediment is different and the transport formula applied is different. This is a qualitative change in the behaviour of sediment particles. In natural systems, however, more classes of sediments present in the system and the D50 is assumed to have less effect for it induces a gradual change in the transportation of the sediments instead of a sharp and fundamental one.

### 6.6. Relevance to reservoir geology

With the decreasing amount of easily accruable oil within currently proven reserves and the ever-increasing energy demand around the globe at the same time, the challenge is that whether more subtle oil reservoirs can be explored and whether spare oil can be extracted from existing developed oil and gas fields, in order to meet the energy supply problem before new types of energy can be widely facilitated.

Oil and gas are generated by source rock, and then migrate towards the surface and at a certain moment trapped in reservoirs. In nature, there are 2 different types of reservoirs: clastic reservoirs and carbonate reservoirs. Among clastic reservoirs, ancient deltas contain significant amount of hydrocarbon reserves worldwide, because they tend to encompass complete petroleum systems.
within themselves. The Mahakam Delta, Niger Delta and Brent Delta nurse giant oil provinces, for example. However, deltaic system can be complicated systems involving a large degree of heterogeneities and uncertainties. A detailed and reliable field development plan targeting the subtle reservoirs and remaining oil reservoirs can only be made with a flow model, which is based on the upscaling of a static reservoir model. With the large part of the complicated subsurface geology of deltaic system unknown to the geologists and petroleum engineers in spite of limited data acquired from seismic and sparse core data, an accurate static reservoir model encompassing all the significant objects cannot be built and optimized unless additional insights on heterogeneities and morphology are provided by process-based models. The insights may include but not limited to: connectivity between the sand bodies, channel geometries, channel distributions, and net to gross ratio distribution.

In each model of the present study, only two types of sediment are ascribed, non-cohesive sediment (sand), and cohesive sediment (fines, either silt or clay). Limited by the number of sediment classes defined, the porosity and permeability, both of which are a function of grain size, cannot be analysed, since perfect sorting within each kind of material is assumed in this case. Even if enough classes of sediments are included in the model, the resultant porosity and permeability are but temporary. As long as digenesis is concerned, the numerical values from a coastal environment cannot be compared with those from the subsurface. However, the distribution of sand and their connectivity indicated by it can still be of value. If reservoir geologists can get access to the paleogeography and paleohydrodynamic condition, the size, shape and location can be predicted with the knowledge brought by numerical models. One example could be, if the clinoform dip of an ancient deltaic formation can be measured, the fraction of sand can be roughly predicted by the relationship between the foreset dip magnitude and the sand fraction in sediment supply in numerical deltas.
7. Conclusions

In this project, it is verified that Delft3D is capable of producing realistic geological models at a reasonable scale in a reasonable amount of time (Geleynse, et al., 2011). The 3 varied parameters produce 36 distinctive results with the same initial settings.

This study has revealed that:

1. The mean river discharge rate influences the delta morphology by controlling the input energy level and the amount of sediment. Besides larger area in the same period of time, deltas with higher discharge tend to have more complex distributary network. Additionally, the length to width ratio (L/W) is most sensitive to the mean river discharge rate.
2. Models with a relatively higher tidal influence (P/Qr) produce less but deeper distributary channels, indicated by lower rugosity. Tide stabilises the distributaries and produce elongated channels.
3. In the present study, the effect of discharge and tide cannot be separated. They interact and influence the morphology of the delta, specifically the distributary channel network. Higher combined strength of tidal and riverine forcing leads to larger mean foreset dip magnitudes, larger variance in dip magnitudes, and a larger dip azimuth angular dispersion. Sand body distribution is more continuous in low discharge and low tidal influenced situations.
4. The sediment fraction (average D50 of the sediment supply) influences delta area, rugosity, dip magnitude and its variance, and dip azimuth angular dispersion by their differentiated density and settling velocity. With increasing D50, the deltas show: smaller area given the same mass of sediment, higher rugosity and more avulsions due to the higher density, lower length to width ratio, steeper foreset slopes, and larger dip magnitude variance. Additionally, silt tends to amalgamate with sand more than clay does because of its higher settling velocity, and therefore sand-silt models have less clean sands than sand-clay models.
8. Recommendations

The models presented in the report are by far believed to be the most realistic simulation both in terms of hydrodynamics and geology, and have covered sufficient range in the sensitive parameters to draw the conclusions. Due to limited timespan of the study, however, the following recommendations should be considered in the future research, in order to further furnish the start-up database and provide more realistic and detailed data.

1. As is discussed in section 6.1, the models are not yet fully in a finalised state. It would be interesting to investigate how the morphological features continue to evolve over even longer time period.

2. A wider range of mean river discharge can be experimented, as long as the model remains stable. The effect of mean river discharge will be more distinguishable in that case.

3. The number of underlayers can be reduced, for the no sedimentation or erosion has happened within the bottom layers. This is case-dependent and hence, it is recommended that a few testing runs being made to determine the necessary number of underlayers before making a series of model runs.

4. The sea water or ocean water are salty. The salinity and density of sea water can be taken into account to produce possible different morphologies. This option exists in Delft3D, but would mean model will be way more computationally expensive. The current models are depth-averaged models, namely 2D models. If the salinity is concerned, the homopycnal flow would be hypopycnal flow because of the higher water density in the basin. Thus, more computational power is needed to account for the vertical convection and a full 3D model is needed.

5. Spring tide/ neap tide are neglected in the light of ‘input reduction’ concept. It would be interesting to review the model results with this tidal amplitude change over time.

6. Wave processes will have remarkable effect on the model, and can be very computationally expensive at the same time. Further studies can include waves and examine its effect on morphology and stratigraphy of the delta.

7. More sediment fraction combinations can be investigated, for example, 20% sand & 80% clay, 80% sand & 20% clay, and 50% clay & 50% silt. Also, more D50 variations (e.g. fine sand, coarse sand, and fine silt, etc.) can be helpful to analyse the detailed stratigraphy.

8. The generated data can be converted into grid to be integrated into flow simulation software such as Petrel. In this way and with more detailed classification of sediment input, the reservoir physical properties such as porosity, permeability and connectivity can be systematically analysed, and flow simulation can be performed.
References


