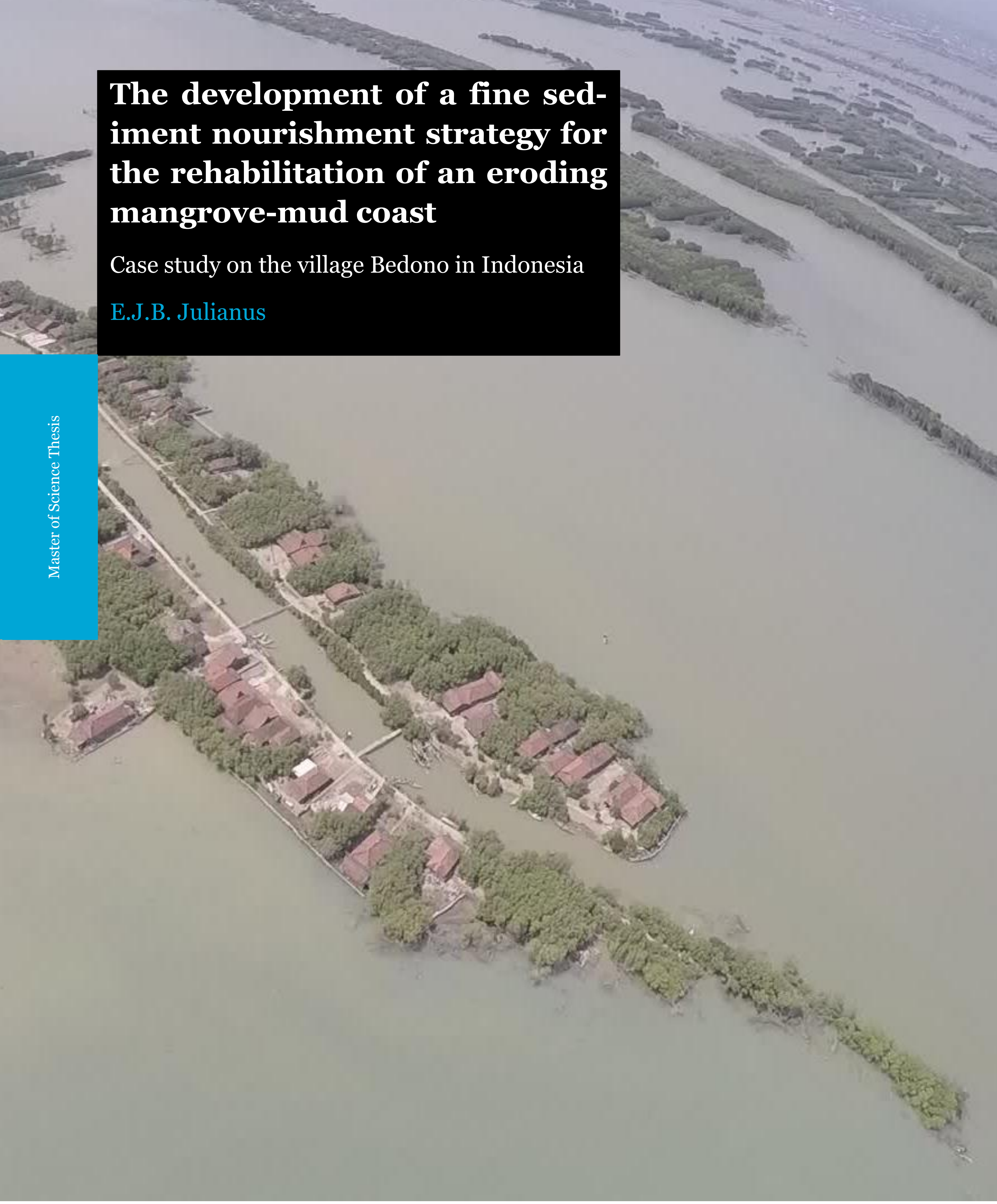
The development of a fine sediment nourishment strategy for the rehabilitation of an eroding mangrove-mud coast

Case study on the village Bedono in Indonesia

E.J.B. Julianus

Master of Science Thesis



Cover image : the village Bedono in Indonesia from drone observations by the project team of Ecoshape.

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by

E.J.B. Julianus

in partial fulfilment of the requirements for the degree of

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"Things work out best for those who make the best of how things work out."

-*Titus Livius*

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This document forms the final thesis report to obtain the Master of Science degree in Hydraulic Engineering at the Delft University of Technology. The thesis comprehends the development of a fine sediment nourishment strategy to enhance sediment deposits and increase the coastal resilience near the Indonesian village Bedono. The study is carried out at Boskalis and Deltares under the supervision of my committee composed of Han Winterwerp, Marcel Stive, Jaap van Thiel de Vries, Fokko van der Goot and Mick van der Wegen.

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Eric Julianus

Delft, November 2016

Abstract

Mangrove coasts are under pressure due to mangrove removal and the disturbance of the fine sediment balance. An example is the coast of Demak in Indonesia which suffers from severe coastal erosion and frequent floods. In order to restore the coast and establish mangrove recruitment it should be restored to a suitable state in terms of ecological, physical and chemical properties.

One of the possible solutions is the application of semi-permeable dams. This method is developed to hold the erosion process, increase the coastal resilience and induce coastal accretion. It reduces erosive wave energy while it still allows the sediment to enter a low-energy zone behind and stimulates sedimentation.

The semi-permeable dams are based on the concept Building with Nature which uses the dynamics of the nature and are climate-adaptive. Furthermore, it uses natural material, ecological and physical processes in achieving effective and sustainable hydraulic designs. It changes the conventional single purpose design to a multi-purpose design that combines ecology and engineering while stimulating a sustainable land use practice. Moreover, the local stakeholders are involved in the design, construction and the maintenance.

The semi-permeable dams made of brushwood are applied in the pilot project Demak and the result is that sedimentation raised the bottom level and enhanced the growth of flora.

The second possible solution is to restore the original configuration of the chenier through a sand nourishment. Cheniers are long, shallow beach ridges composed of sand and shelves which originally rests on the mud flat in front of the mangrove forest. The sandy sediment originates from rivers and is distributed by longshore transport along the coast and thrown back to form a sand lens by the waves. Due to coastal erosion the cheniers are now located in the open water. The exposure to a more dynamic environment and the decrease of coarse sediment supply deteriorate the chenier. The role of cheniers on the coastal dynamics is important because the configuration determines the attenuation of waves. The reduction of wave forcing on the coast is favourable for the direct erosion of the coast. However, by reducing the wave forcing also the mobilization of fine sediments from the bed is reduced which is unfavourable on the supply side of fine sediments. The chenier restoration is intended to reduce the wave attack on the coast and create a low-energy zone for natural deposition.

The third possible solution is to increase the fine sediment flux to the shore by the use of a fine sediment nourishment. The increase in sediment availability is intended to stimulate deposition near the coast.

There is not much knowledge and experience on the second and third measurement. Therefore, these alternatives are investigated to diversify the options for the restoration of former mangrove coasts.

This MSc thesis developed the most suitable fine sediment nourishment strategy taking into account technical, executable and social aspects to induce sediment deposition near the village of Bedono. Next to that, it revealed which role chenier restoration can have on the rehabilitation of eroding mangrove-mud coasts.

The conclusions in this report are based on fundamental research consisting of literature study, monitoring results, practice and numerical modeling. A site-specific 2DH hydrodynamic model was set-up in Delft3D Flexible Mesh to simulate the water movement. Subsequently, the hydrodynamics were used in DELWAQ to assess the sediment transport direction. The model was difficult to validate since the Demak coastal zone is a remote and data poor environment. Therefore, the validation is largely based on qualitative observations and expert judgement.

The sediment balance for mangrove-mud coasts is governed by erosion and sedimentation. It is stated that the majority of sediment transport takes place during day to day conditions. The daily interaction of waves that stir-up sediment and subsequently transported by the tide is considered as the largest sediment transport contributor.

It is stated that short high energy events like storms first induce erosion and erode the coastline. However, the net effect is positive because large quantities of sediments on the foreshore are brought in suspension, transported towards the coast and deposited during the calmer conditions afterwards.

The proposed execution period for the fine sediment nourishment is near the end of the South-East monsoon. It is recognized that in this period net erosion takes place because short wind-waves erode the coast and high sediment concentrations are transported via the undertow in offshore direction. However, in the dry season the change on hinder from strong wave activities and storms are minimalized. This benefits the workability and it provides conditions in which the nourishment can establish itself.

The most favourable distribution of sediment towards the coast is in the North-West monsoon. In this period net accretion takes place because the wave activity is able to stir-up a surplus of sediment in the foreshore and the tide transports it to the coast. Next to that, the undertow with high sediment concentration is onshore directed.

Therefore, the nourishment is proposed to execute near the end of the South-East monsoon and subsequently let the North-West monsoon transport the sediment.

The advised location for the nourishment is on the coast. In this scenario the nourishment is already in the intended area and step-by-step builds out into the sea. The nourishment configuration along the full coastline is preferred over the nourishment peninsula because it provides directly larger areas of soil for potential mangrove recruitment.

Nourishment locations in front of the coast are not in this case advised. The nourishment first need to be brought into suspension, subsequently transported to the intended area and deposited. Nourishment locations beyond 200 m in cross-shore direction from the coast are mainly transported in offshore direction while nourishments within 200 m demonstrate predominantly transport towards the coast. Though, this process needs more time to reach the coast and create the intended coastline stabilization for the rehabilitation of the eroding mangrove-mud coast.

The calculated nourishment volume is 200.00 m^3 and the particle sizes are fine mud particles in the order of 63 micrometre.

Furthermore, it is stated that the presence of a chenier in front of the coast or chenier restoration improves the conditions for the rehabilitation of eroding mangrove-mud coasts. The chenier reduces the direct wave attack on the coast and create a low energy zone behind the chenier. Thereby, erosion is reduced and sedimentation enhanced.

The recommendation for the project is in the philosophy of 'learning by doing'. It is important to take into account that the project in Demak is a demonstration project. The latter means it functions as an area in which substantiated solutions are tested and to show the world how new techniques contribute to the rehabilitation possibilities of eroding mangrove-mud coasts.

For instance, the testing of different semi-permeable dam configurations provided information which is of great value and hardly to obtain from modelling. Therefore, the advice is to try a substantiated fine sediment nourishment in an enclosed research area and deduce the effect. Even if the proposed engineering solution exceeds the project scale, this is the place where it is intended and allowed to test new engineering techniques.

Note, the solutions are site specific. This implicates it does not automatically works on other places with different circumstances but it is extremely useful for the development of measurements.

Deducing generic recommendations is also difficult due to the site specific research. The reaction of the local system and distribution of sediment depends on factors which are variable per location. Though, based on my research I advise to carefully keep in mind the status of the coast, coastline configuration, bathymetry and local wave height.

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Nomenclature

ABBREVIATIONS

BwN	Building with Nature
CD	Chart Datum
CSD	Cutter Suction Dredger
DDB	Delft Dashboard
DELWAQ	Engine of the D-Water Quality and D-Ecology programs in the Delft3D suite
DFM	Delft3D Flexible Mesh
D-WAVE FM	Delft3D Wave module in Flexible Mesh
D-FLOW FM	Delft3D Flow module in Flexible Mesh
MSL	Mean Sea Level
NW	North-West monsoon often referred as the ‘wet season’ from October to March
SE	South-East monsoon often referred as the ‘dry season’ from March to October
SPM	Suspended Particle Matter
SWAN	Simulating Waves Near-shore
TSHD	Trailing Suction Hopper Dredger

S1	First bed layer in DELWAQ often referred as the ‘fluffy bed layer’
S2	Second bed layer in DELWAQ often referred as the ‘consolidated bed layer’
IM1	Inorganic Matter 1 in DELWAQ indicates the first sediment particle with specific properties
IM2	Inorganic Matter 1 in DELWAQ indicates the second sediment particle with specific properties
IM3	Inorganic Matter 1 in DELWAQ indicates the third sediment particle with specific properties

K1	Main tidal constituent ‘Lunar diurnal’
01	Main tidal constituent ‘Lunar diurnal’
M2	Main tidal constituent ‘Principal lunar semidiurnal’
S2	Main tidal constituent ‘Principal lunar semidiurnal’

SYMBOLS

C	Roughness coefficient of Chezy	$[m^{1/2}\ s^{-1}]$
c	Concentration	$[g\ m^{-3}]$
D_{50}	Median grain size	[m]
H_b	Breaking wave height	[m]
H_s	Significant wave height	[m]
n	Roughness coefficient of Manning	$[s\ m^{-1/3}]$
M	Erosion parameter	$[g\ m^{-2}\ s^{-1}]$
k_s	Roughness coefficient Nikuradse	[m]
u	Flow velocity	$[m\ s^{-1}]$
T_m	Mean period	[s]
T_p	Peak period	[s]
Pa	SI-unit Pascal	$[kg\ m^{-1}\ s^{-2}]$
ρ	Density	$[kg\ m^{-3}]$
ρ_s	Sediment density	$[kg\ m^{-3}]$
ρ_w	Water density	$[kg\ m^{-3}]$
τ	Shear stress	$[N\ m^{-2}]$
τ_b	Ambient bottom shear stress	$[N\ m^{-2}]$
τ_c	Critical shear stress for erosion	$[N\ m^{-2}]$
ω_s	Settling velocity	$[mm\ s^{-1}]$

Chapter 1 Introduction

Mangrove coasts are under pressure and an example is the coast of Demak (Indonesia) where the coastal resilience has decreased drastically. Reasons are linked to economic growth, urbanization, intensive agriculture and aquaculture. Examples are interventions in the coastal configuration, reduction of sediment supply to the coast due to mining in rivers, land subsidence due to water extraction and large deforestation of mangroves (Van Wesenbeeck et al., 2015).

Mangroves are the ecological term referring to a classification of a diverse assemblage of trees and shrubs that form the dominant plant communities in tidal, saline wetlands along sheltered (sub) tropical coasts (Blasco et al., 1996). Mangroves play an important role in coastal protection and ecological services. First of all, mangroves reduce wave height and flow velocities (Schiereck & Booij, 1995). The reduction is attributed to the trunk, roots and branches of the mangroves and causes sedimentation (Schiereck & Booij, 1995). Subsequently, mangroves can rapidly colonise stable intertidal sediments, help to consolidate new sediment and may induce further sedimentation (Blasco et al., 1996). Secondly, mangrove forests are productive ecosystems for the environment and human societies (Healy et al., 2002).

In a healthy mangrove coastal system, there is an abundance of sediment due to input from rivers, land runoff but most of all due to the stirring up of sediment by large waves on the foreshore. The sediment is transported by the tide on the higher parts of the mud flat and into the mangrove forest where it settles. The deposition is larger than the erosion and this result in net accretion (Winterwerp et al., 2013). Furthermore, the coast is convex shaped and contains wide mudflats with mild slopes. The mudflat functions over longer time scales as an important source of sediment for the coast (Bearman et al., 2010). Another feature, that is only present in systems with sand inflow from rivers, is a chenier. Cheniers are long, shallow beach ridges composed of sand and shelves which rest on the mud flat in front of the mangrove forest. The sandy sediment originates from rivers and is distributed by longshore transport along the coast and thrown back to form a sand lens by the waves. The role of cheniers on the coastal dynamics is important because the configuration determines the attenuation of waves (McBride et al., 2002). The reduction of wave forcing on the coast is favourable for the direct erosion of the coast. However, by reducing the wave forcing also the mobilization of fine sediments from the bed is reduced which is unfavourable on the supply side of fine sediments (Winterwerp et al., 2013).

Deforestation and reduction in sediment availability have de-stabilized the equilibrium state of the coast in Demak. The barren coast is vulnerable because it is fully exposed to erosive wave forces and it is not able to capture sediment. This causes that the coastline regresses and the bottom profile changes from convex to concave. The new bottom profile destabilizes mangroves on the new edge of the coast (if these are not cut) and prevents the natural establishment of new mangroves. Moreover, wave loads become larger on the concave foreshore and may deteriorate the height of the chenier (Friedrichs, 2011). Thereby it reduces the wave attenuation and enhances the direct erosion of the coast. Furthermore, the whole area is subjected to subsidence. The result is a destabilized coast with continuous erosion that cannot return to a stable equilibrium by itself, see Figure 1-1 (Winterwerp et al., 2005).

Figure 1-1 Eroding coast (left) and flooded village (right) in Demak area

Hard structures and replanting mangroves are methods applied in the past and nowadays (Winterwerp et al., 2005). The construction of solid dams on the soft mud soil is intended to stop the erosion and protect the hinterland. In reality the opposite happens. The impermeable dams reflect the incoming wave height which causes local scour in front of the dam, enhances the concave shape and finally undermines the dam (Winterwerp et al., 2005). Moreover, the impermeable dam blocks the sediment flux to the shore by the tide. If more sediment is eroded by the waves, and less sediment is deposited by the tide, the misbalance strengthens the coastal retreat (Winterwerp et al., 2013). The replanting of young mangroves is intended to restore the coastal state and stabilize the coast with its former vegetation. No natural suitable conditions are present in the area of replanting and that makes it extremely difficult for the young mangroves to survive (Primavera & Augustinus, 2008). The exposure to high wave forces and long tidal inundation causes high mortality rates after replanting of young mangroves (Primavera & Augustinus, 2008).

Recently semi-permeable dams made of local brushwood are applied in Demak in order to hold the erosion process, increase the coastal resilience and induce coastal accretion. The semi-permeable dams are constructed perpendicular to the dominant wave direction. Stretches are left open in order to let sediment pass since the dams are semi-permeable for water but not for sediment, see Figure 1-2. The semi-permeable dams are based on the concept Building with Nature and derived from the Dutch reclamation works (Dijkema et al., 2013). This concept uses natural material, ecological and physical processes in achieving effective and sustainable hydraulic designs. It changes the conventional single purpose design to a multi-purpose design that combines ecology and engineering while stimulating a sustainable land use practice. Building with Nature solutions use the dynamics of the nature and are climate-adaptive. Moreover, the local stakeholders are involved in the design, construction and the maintenance (Tonneijck et al., 2015). On the Northern coast of the Netherlands this approach has been successful (Dijkema et al., 2013). The semi-permeable dams interfere in the dynamics between the sea and the land. It reduces erosive wave energy while it still allows the sediment to enter a low-energy zone behind and stimulates sedimentation (Tonneijck et al., 2015). The sedimentation raised the bottom level and enhanced the growth of flora (Dijkema et al., 2013).

The application of semi-permeable dams in a small scale pilot in Demak show improvements in the sedimentation rates but it also encounters challenges. First of all, it is unknown if the current sedimentation rates lead to the required bottom profile and stimulate the natural mangrove re-establishment. Besides, sedimentation takes place irregular in front and behind the semi-permeable dams. This shows that the application of semi-permeable dams and their influence depends on local settings. Secondly, the technical lifetime of the semi-permeable dams is limited due to the material, construction quality and degrading circumstances like woodworms and wave action. Thirdly, the sedimentation process is irregular due to varying hydraulic conditions through the year (Tonneijck et al., 2015). Fourthly, the application of semi-permeable dams and the recolonization of mangroves need to be incorporated in the local socio-economic setting. For instance, the local population should not make the same mistake by cutting the mangroves when they return. Therefore their awareness has to be raised and proper alternatives provided.

This MSc thesis assumes that the sediment availability is restricting the sedimentation. The quality and configuration of the current semi-permeable dams are not investigated. The focus is on the understanding of the hydro- and sediment dynamics in the coastal system of Demak. The system understanding comprises ecological, hydrological and morphodynamic elements in order improve the coastal resilience. The result is a fine sediment nourishment strategy to rehabilitate the mangrove-mud coast near the village Bedono.

Figure 1-2 Semi-permeable dams in Demak area

1.1 Problem description

The main problem is that large parts of former mangrove coast are eroding because of mangrove removal and the disturbance of the fine sediment balance. In order to restore the coast and establish mangrove recruitment it should be restored to a suitable state in terms of ecological, physical and chemical properties. In this MSc thesis the focus is on the coast near the village Bedono in Indonesia which suffers from frequently flooding and an eroding coastline, see Figure 1-3.

Figure 1-3 The area of interest and the village Bedono (red dashed line) (Google Earth, 2016)

Three measurements are proposed to stop coastal erosion and restore the equilibrium system.

The first solution is the application of semi-permeable dams. Monitoring results demonstrate that the semi-permeable dams induce sedimentation rates but these are irregular in location, time and magnitude. First, sedimentation takes place in front of the semi-permeable dams while it is intended to occur only within the created basin where it should spread evenly and builds out towards the sea. Secondly, the sedimentation process is irregular in time due to varying hydraulic conditions through the year. The North-West monsoon period induces large sediment deposits while in the South-East monsoon there is less sedimentation or even erosion (Tonneijck et al., 2015). Thirdly, the magnitude of sedimentation differs per location which does not create the intended bottom profile for mangrove re-establishment. Another problem is the limited technical lifetime of the semi-permeable dams due to the material, construction quality and degrading circumstances like woodworms and wave action.

The second solution is to restore the original configuration of the chenier through a sand nourishment. The chenier reduces wave attack on the coast and creates a low-energy zone where natural deposition is intended.

The third solution is to increase the fine sediment flux to the shore by the use of a fine sediment nourishment. The increase in sediment availability is intended to stimulate deposition near the coast.

There is not much knowledge and experience on the second and third measurement. To diversify the options for the restoration of former mangrove coast it is needed to investigate and explorer these alternatives.

1.2 Objective

This MSc thesis aims to develop the most suitable fine sediment nourishment strategy taking into account technical, executable and social aspects to induce sediment deposition near the village of Bedono. Therefore it is needed to increase the system knowledge, determine the driving processes and assess sediment transport patterns in the Demak coastal area.

1.3 Research question

The problem definition and the objective have led to one main research question:

What is the most suitable fine sediment nourishment strategy taking into account technical, executable and social aspects to induce sediment deposition near the village of Bedono?

1.4 Reader's manual

The report is divided into chapters and each chapter is subdivided into sections.

The next chapter, Chapter 2, describes the research methodology and how the research objectives are reached through a systematic sequence of research. Chapter 3 provides theoretical background information on fine sediment and mangrove coasts. Subsequently, all the relevant information concerning the research area in Demak is provided including general theoretical background information in Chapter 4. The method and information is translated into Chapter 5: Model set-up. This chapter provides information on the important modelling related aspects. Chapter 6 Model results, provides the most relevant and summarized results of all hydrodynamic and sediment dynamics results. Chapter 7 Execution, elaborates on suitable execution methods of the fine sediment nourishment. Chapter 8 Discussion forms the base for the interpretation and implications of the results and the theory. Chapter 9 Summary and conclusion, wraps-up all things done and how this finally leads to the conclusion of the research. Finally, the recommendations for further research are found in Chapter 10.

Appendices function as storage for background knowledge, figures, detailed calculations and model results.

Furthermore, I would like to emphasize the work I did together with Bob Smits for the development of Delft3D Flexible Mesh. We both have extensively tested the FLOW-, WAVE and SED/MOR modules in Delft3D Flexible Mesh. In this process we closely cooperated with the developers of the software to reveal bugs and improve the latest software versions. This work and effort was unexpected but played an important part in my graduation process. Through this paragraph I would like to describe briefly this important notification while the summary of all the work is described in 5.2 Development Delft3D Flexible Mesh.

Chapter 2 Research methodology

This chapter outlines the sequence of research steps, the intended methods and for which goal. This is presented in Table 2-1. The research questions are answered through literature research, monitoring results, a model applied on the case study in Demak and this finally lead to a conclusion and recommendation about the effect and strategy for a fine sediment nourishment. The following paragraphs elaborate more extensively on each subject.

2.1 Target coastal habitat

The first part of the research is done on the identification of requirements concerning the target coastal habitat. The method used in this part is literature from articles, reports and monitoring results. The intended natural recolonization of mangroves determines the content and layout of the bottom profile. Mangrove species require different slopes, elevation levels, soil properties, hydrological conditions and nutrient availability. Besides, it is important to know which period of the year mangroves propagate and mangroves make the most development. If the bottom profile is suitable for mangrove establishment but there are no propagules or the development is low this is unfavourable for the rehabilitation process.

The requirements of the target coastal habitat determine the intended end situation and have a large influence on the execution plan of the fine sediment nourishment.

2.2 System analysis

The second part of the research focusses on the analysis of the present system in Demak. The methods used in this part are data analysis, monitoring results and modelling of the research area in Demak. The model approach is depth-averaged (2DH) in order to understand and quantify the spatial distribution of currents and sediment in the present system. The specific system in Demak cannot be represented in a 1D ray due to irregularities and long-shore interactions. A 3D approach describes also the behaviour in the vertical and is in this stage not necessary.

The spatial movement of water is determined by the combination of the wave, wind and tidal climate, the hydraulic forcing. The key aspects of the wave climate are the dominant wave-direction, wave-period and wave height. The tidal propagation and the flow velocity induced by tide are the main tide aspects. The wind climate also influences the water movement due to its energy transfer. Important components are the direction and wind speed. The bottom profile and the location of the semi-permeable dams are necessary to create an accurate representation of the bathymetry in the research area. The type of sediment and the suspended sediment concentration determine the sediment behaviour and the availability.

The system analysis creates an initial position and behaviour of the present system, the benchmark. The creation of a model of the Demak area is done in Delft3D Flexible Mesh for the hydrodynamics.

2.3 Fine sediment nourishment

The third part of the research investigates the impact of different fine sediment nourishment strategies on the sediment distribution and deposition locations. The method used in this part is modelling. The different fine sediment nourishment strategies are compared with each other. The behaviour of the fine sediment nourishment depends on the type of material, location of application and the hydraulic forcing. The type of sediment is based on common soil properties in this region.

Most important is to find an optimum between the location and period of the year to apply the fine sediment nourishment. Furthermore, a sensitivity analysis on model input parameters like sediment and wave properties is executed. This provides insight in the dependencies of the coastal rehabilitation. The Delft3D Water Quality module (DELWAQ) is used for sediment transport.

2.4 Execution

The last part of the research investigates strategies for the execution of the fine sediment nourishment. The methods used in this part are literature research combined with information from practice. In the target coastal habitat section is determined how the end configuration and content must be to create suitable conditions for the natural recolonization of the mangrove greenbelt. The system analysis and fine sediment nourishment sections determine how the system works and how the optimum location and time of the year to execute the fine sediment nourishment is found. This chapter investigates and compares different methods for executing the fine sediment nourishment.

The execution research provides insight in the feasibility of proposed fine sediment nourishment strategies.

Subject	How	Goal
1. Target coastal habitat	Literature Monitoring results	Identify the requirements for the natural recolonization of mangroves.
2. System Analysis • Wave climate ○ Direction ○ Period ○ Height • Wind climate ○ Direction ○ Speed • Tidal climate ○ Elevation level ○ Tidal propagation • Bathymetry • Sediment ○ Sediment characteristics ○ Suspended sediment concentration ○ Critical shear stress for erosion ○ Critical shear stress for deposition ○ Settling velocity ○ Re-suspension capacity	Data analysis Monitoring results Model	Identify and quantify the current hydro- and sediment dynamic interaction: creation of the benchmark. Spatial analysis of currents and sediment. Indicator analysis for erosion and sedimentation Determination of chenier location and configuration
3. Fine sediment nourishment • Where to place the fine sediment nourishment? • Which period of the year is the most favourable for the distribution?	Model	Determine the sediment transport patterns of different fine sediment nourishment strategies Sedimentation and erosion locations
4. Execution • What is the most suitable and applicable execution strategy for this specific area?	Literature Practice	Feasibility nourishment solutions

Table 2-1 Schematic overview research process

Chapter 3 Theoretical background

This section provides theoretical information on typical features for mud coasts. Subsequently, it elaborates on fine sediment properties, erosion and transport. All information and figures are based on the lectures of the course Sediment Dynamics (CIE4308) at the Delft University of Technology and the book 'Introduction to the Physics of Cohesive Sediment Dynamics in the Marine Environment' from Winterwerp and van Kesteren (2004).

Detailed information on mangroves and general hydrodynamic processes is in Appendix A Mangroves, Appendix B Wind, Appendix C Wave and Appendix D Tide.

3.1 Fine sediment

Mud is defined as the mixture of fine particles (silt and clay below 63 micrometre), organic matter and water. The clay content in the mud mixture has cohesive properties which mean they attract to each other, coherence. Important implication is that sand or silt particles can no longer settle when they are in suspension and surrounded by sufficient large clay content.

The attraction of cohesive particles can form flocs. This process, flocculation, is a dynamic process and depends among other things on space, time and the organic composition (seasonal effects). Furthermore flocs are loose structures that contain a large water content (>95%) and have typical sizes of hundreds of micrometres. The layering of small particles leads to a small permeability and can induce liquefaction because when the water pressure increases rapidly the effective soil strength reduces. With the result that the soil loses bearing capacity because the soil turns into a 'liquid'.

The settling velocity and settling behaviour for fine cohesive sediment (clay and silt) is different than for coarse non-cohesive sediment (sand). Stokes' classic settling law is applicable on sand (Euclidean particles) but is not applicable to mud flocs (non-Euclidean). In mixtures of fine and coarse sediment occurs sorting of sediment due to the different settling velocity, see Figure 3-1. The coarse sediment settles faster while the settling velocity for fine sediment is smaller and comprehends different processes.

The flocculation process attracts several small particles and increases the 'combined' settling velocity. Increasing the suspended sediment matter concentration enhances flocculation but this increase has its limitation. After a certain concentration the settling velocity decreases as the results of sediment blockage, hindered settling (Dankers & Winterwerp, 2007). The highest volumetric concentrations are near the bottom since the sediment is stirred-up from the fluffy bed layer. The exceedance of the critical concentration induces blockage of sediment near the bottom and hinders further settlement from sediment above this layer. The blockage forms a shockwave which is known as the lutocline see Figure 3-2. The dynamic interaction of fine sediment, flocculation and hindered settling make the settling velocity complex and not constant.

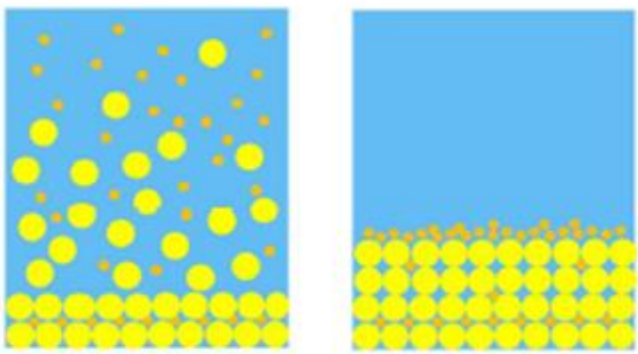


Figure 3-1 Turbulent mixing (left) and sediment segregation (right)

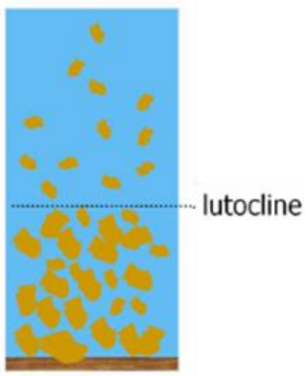


Figure 3-2 Lutocline formation

As a result of the sediment sorting the bed composition follows the sequence of the settling velocity. The particles with the smallest settling velocity form the upper layer. This fine and erodible layer is called the 'fluffy layer'. The particles with larger settling velocity are formed beneath the upper layer and are concerned as the 'consolidated layer'. The difference between these layers is that the fluffy layer has a constant interaction with the water column while the more consolidated layer only erodes during more extreme forcing.

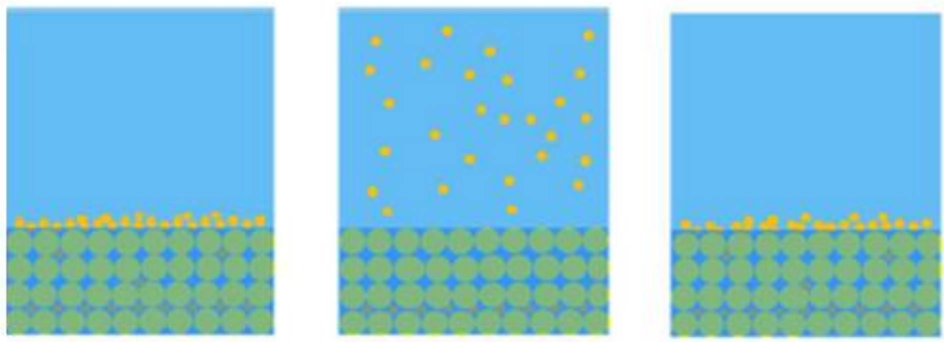


Figure 3-3 Settling and deposition sequence over a tidal cycle

The exchange of fine sediment between the bed and the water column depends on the hydrodynamic forcing, settling velocities and the state of the bed.

The magnitude of energy to erode cohesive fine sediments from the bed is much larger than the energy to keep the fine sediment in suspension. In other words, fine sediments erode above a certain forcing threshold and stay in the water column under even very small forcings.

Waves play an important role in the erosion of fine sediment and the dynamics of the mud coast. Firstly, wave forcing stirs-up fine sediment from the bed. Secondly, waves strengthen flow-induced mixing and waves reduce the strength of the soil by oscillatory stresses. Transport induced by waves is not relevant since if it would occur, fine sediment cannot accumulate. The theory states that waves mobilize sediment while currents mix and transport the sediment. The vertical mixing depends on the thickening of the flow boundary by the waves. In the highly turbulent breaker zone the behaviour is different and long-shore transport is dominated by radiation shear stresses.

The state of the bed comprises cohesive, non-cohesive sediment and consolidated, fluffy bed layer. Starved bed conditions, where the availability of sediment is limited, may occur for fine sediment. For this condition the entrainment functions is applicable and not the transport formulae for alluvial bed conditions (unlimited availability of sediment). The entrainment is a pick-up function and is only valid for grain sizes of 0.1 to 1.0 millimetre.

Four erosion modes can be distinguished for muddy beds: entrainment, floc erosion, surface erosion and mass erosion. Entrainment is bringing particles into re-suspension from the bed through turbulent vertical mixing. Floc erosion is the rupture of individual sediment flocs from the bed when the flow induced shears stresses exceed the drained strength of unconsolidated flocs. Surface erosion occurs when horizontal layers of flocs are withdrawn from the consolidating bed, drained failure. Larger flow induced shear stresses that exceed the undrained bed strength, may erode large pieces of material from the over-consolidated bed. The mass erosion is caused by failure within the bed through crack formation, see Figure 3-4.

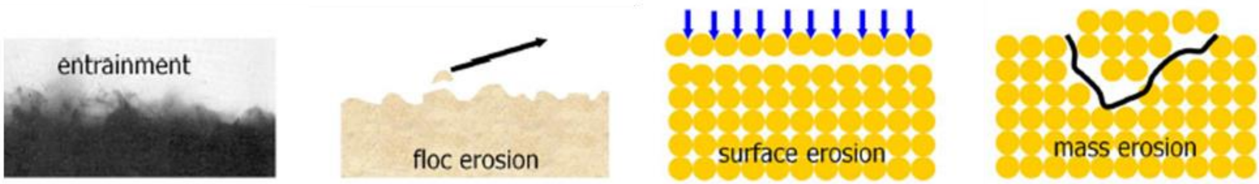


Figure 3-4 Erosion modes for muddy beds

The erosion and deposition formulation of Partheniades-Krone is widely used. The difference between the erosion and deposition equals the increase in suspended sediment concentration (Partheniades, 1965). The erosion models for fine sediment is named after Partheniades and inspired by the work of Kandiah (1974) and Ariathurai (1978). This surface erosion model is applicable on consolidated and homogenous beds. It states that erosion depends on the erosion parameter (M), the ambient shear stress (τ_b) and the critical shear stress for erosion (τ_c). Requirement for erosion is that the ambient shear stress exceeds the critical shear stress for erosion.

$$E = M(\frac{\tau_b}{\tau_c} - 1) \quad (3.1)$$

The deposition model for fine sediment is developed by Krone and depends on the fall velocity (w_s), the concentration (c), the ambient shear stress (τ_b) and the critical shear stress for erosion (τ_c). The magnitude of the deposition depends on the magnitude of concentration, fall velocity and the magnitude of the ambient shear stress.

$$D = w_s c(1 - \frac{\tau_b}{\tau_c}) \quad (3.2)$$

One of the limitations of the Partheniades-Krone model is that the single layer model cannot represent steady or slowly varying flow since the critical shear stress for erosion is fixed, see Figure 3-5. This implicates that if the threshold is not exceeded (unlimited deposition) or exceeded (unlimited erosion) occurs.

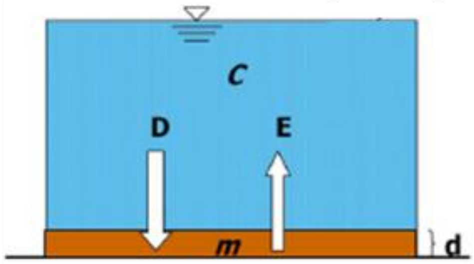


Figure 3-5 Single layer model

Another model is developed by Van Kessel et al (2011) which comprise a two layer system, see Figure 3-6. The upper layer and the layer underneath function separately depending on physical and biological processes. The upper layer is active on short time scales while the lower layer is active on long time scales. This enables to model spatial and temporal variability reasonably well.

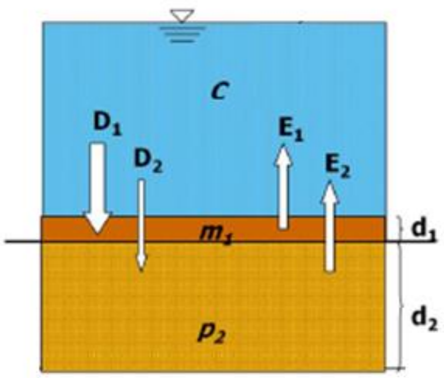


Figure 3-6 Two layer model

3.2 Mud coast dynamics

Accumulation of fine sediment has led to a mildly sloping foreshore with slopes in the order of 1:1000 – 1:1500. In a healthy and equilibrium mangrove-mud coast the shape is convex. While a degrading mangrove-mud coast changes to a concave shape on which eroding wave forces become larger and enhances erosion, see Figure 4-5.

Waves approach the coast perpendicular due to refraction on the mild cross-shore slope of the foreshore. During the propagation to the coast the wave loses energy due to dissipation and only a small amount due to wave-breaking. The result is that long-shore currents are small and sediment transport follows the movement of the tide perpendicular to the coast, see Figure 3-7. Furthermore, fine sediments are also dispersed in the foreshore by local wind-driven currents and locally generated waves.

The interaction of stirring-up sediment in the foreshore by waves and the transport by the tide are the driving factors of the sediment availability of the coast. The transport is towards the coast during rising tide and is called 'tidal filling', see Figure 3-7 and Figure D- 1. During falling tide the transport is offshore directed.

Large and small waves are both able to stir-up sediment in the foreshore. Though, they vary in stir-up magnitude. For smaller waves the eroding forces on the coast are larger than the sediment availability it creates. Larger waves are considered to create a positive net effect since the sediment availability exceeds the erosion of the coast. The result is that small waves are considered as the reason for coastal retreat.

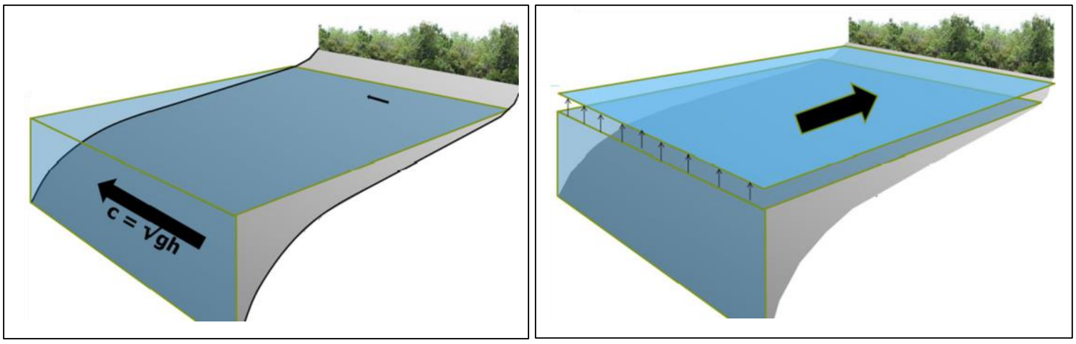


Figure 3-7 Small long-shore current nearshore (left) and tidal filling (right)

The undertow plays an important role in the transport of sediment. In the wet-season fresh water is discharged into the sea and the wind pushes the water against the coast. The baroclinic pressure gradient induces saline water to move under the fresh water layer towards the coast. The surface current is offshore directed while the undertow contains high sediment concentrations and is towards the coast, see Figure 3-8.

In the dry-season the fresh water decreases and the wind blows still from the sea to the land. The wind induces a set-up against the coast with an onshore surface current and an offshore undertow. This time the high sediment concentrations are offshore transported through the undertow, see Figure 3-8.

Coastal accretion or retreat (small net effect) is the balance between the sedimentation and erosion (two large gross effects). Small variations in the sedimentation or erosion results in a direct large net effect of accretion or retreat.

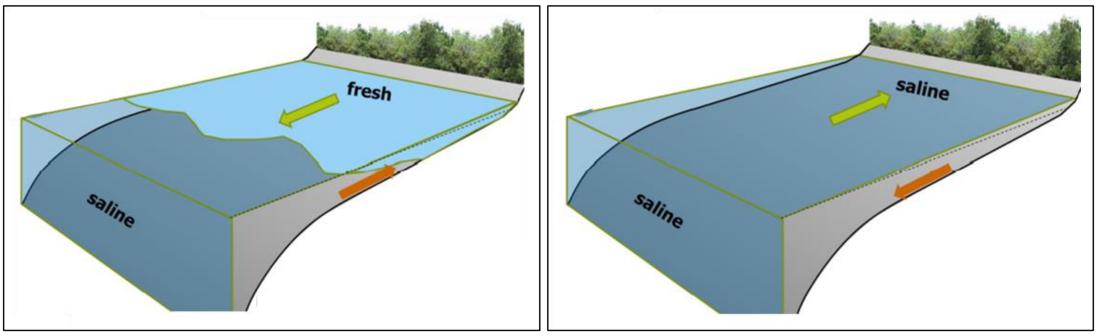


Figure 3-8 Surface current and undertow in wet season (left) and dry-season (right)

3.3 Mangroves

Mangrove is an ecological term referring to a classification of a diverse assemblage of trees and shrubs that form the dominant plant communities in intertidal areas, saline wetlands along sheltered (sub) tropical coasts (Blasco et al., 1996). Plants of the mangrove community belong to many different genera and families. There characteristics are morphological, physiological and reproductive adaptations that enable them to grow in a particular dynamic and salty environment (Blasco et al., 1996). Their root system is developed to maintain stability in the anaerobic mud subsoil and retrieve oxygen from the atmosphere (Lewis III, 2005).

MANGROVE FOREST SERVICES

Mangrove forests are productive ecosystems for the environment and human societies, see Figure 3-9. Mangroves regulate the water quality by filtering suspended material and assimilating nutrients from various natural and human sources. Mangroves cope with nutrients in different ways. They are able to absorb nitrogen, phosphate and heavy metals and store them in their roots, stems and leaves. Furthermore, they induce sedimentation of suspended material with phosphate and heavy metal. Next, they provide habitat for organism that decompose waste (Barbie et al., 2011).

They produce organic matter that forms the start of the food chain. They offer protective areas, nursery and feeding grounds for land and marine based animals, for example birds, fish, crab and shrimps (Hutchison et al., 2014). On the other hand, people live from the flora and fauna attracted by the mangroves (Healy et al., 2002).

Mangroves reduce wave height and lower flow velocities. The magnitude of wave damping and flow reduction depends on the wave period, water depth, mangrove characteristics (species, size of trunk, roots and branches), the density of the forest and the forest width (Schiereck & Booij, 1995).

Transmission decreases with decreasing wave period because the orbital motion of the wave near the bottom becomes less. This implicates that shorter waves (wind waves) penetrate less into the mangrove forest than longer waves (tsunamis, cyclones and swell). The transmission increases with increasing water depth because there is less dissipation of waves on the bottom slope and the influence of the mangrove roots decrease (Schiereck & Booij, 1995). The configuration and size of the mangrove trunk, roots and branches contribute to the reduction in transmission. The configuration depends on the specie while more mature mangroves increase in size and form a larger obstacle. Next to that, densely spaced mangroves are more effective reducers than widely spaced mangroves (McIvor et al., 2012).

Reductions of wave height in the order of 13-66% can occur within the first 100 m and reductions of 50-99% occur within 500 m of the mangrove forest (McIvor et al., 2012). A minimal width of 100 m reduces the wave height and allows a revetment to be designed less conservative (Quartel et al., 2007). However, mangroves are not effective as a single breakwater and cannot be used as a fully protective measure for the hinterland (McIvor et al., 2012). Moreover, mangroves cannot withstand wave heights above a certain level, for example tsunami or cyclone levels (Nippon Koei, 2005). These forces are too large, destabilize the mangroves and vanish the forest.

Flooding impacts induced by storm surges, cyclones, typhoons or hurricanes are only reduced by kilometres of mangroves (McIvor et al., 2012). The mangrove forest forms an obstruction and induces a set up in front of the coast (Tonneijck et al., 2015).

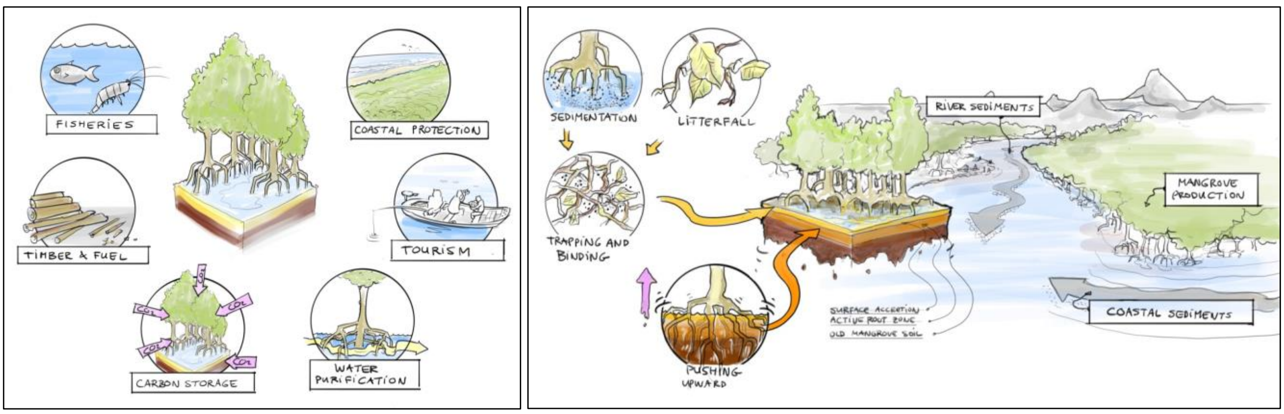


Figure 3-9 Mangrove forest services (left) and coastal overview situation (right)

Furthermore, a mangrove forest is able to reduce the wind speed depending on its height and density. The horizontal sheltered area distance is 20-30 times the height of the mangrove forest. Though, mangroves cannot reduce the wind velocities of cyclones and typhoons (Marchand, 2008).

Mangroves induce sedimentation due to their ability to reduce orbital velocity of waves and current velocities, see Figure 3-10. The sedimentation rates depend on the local conditions and sediment availability. The sediment material might be endogenic (leaf litter and chemical processes by flora and fauna) or exogenic (entrapped sediment from rivers, land run off or the sea). The magnitude is on average in the order of 1-10 millimetres per year. Furthermore, mature mangroves consolidate and increase the compaction of the soil (Tonneijck et al., 2015).

A deficit in sediment supply cause the net sediment balance to become negative (sedimentation – erosion < 0). This changes the equilibrium from a net accreting coast to a net eroding coast. The erosion process changes the coastal foreshore shape from convex to concave. This causes that the wave height does not shoal (reduce) on the foreshore and increases the load on the mangroves. Moreover, the shape of the profile undermines the mangroves so they lose their stability and collapse (Winterwerp et al., 2013).

Figure 3-10 Transmission through mangrove forest and sedimentation (University of Waikato, 2016)

MANGROVE REHABILITATION LESSONS FROM THE PAST

Mangrove rehabilitation is often been unsuccessful because not all crucial and boundary conditions for mangrove establishment were taken into account (Balke et al., 2011). For example, constructing solid sea defences and large scale mangrove replanting has been unsuccessful in the past. The solid sea defence blocks the sediment flux to the coast behind. Besides, reflection of incoming waves erodes the bottom in front of the construction and induces collapsing, see Figure 3-11 (Winterwerp et al., 2013). Replanting of mangroves is often been unsuccessful because the young mangroves are exposed to a dynamic environment. Long tidal inundation and strong wave activities cause stresses with resulting high mortality rates (Lewis III, 2005).

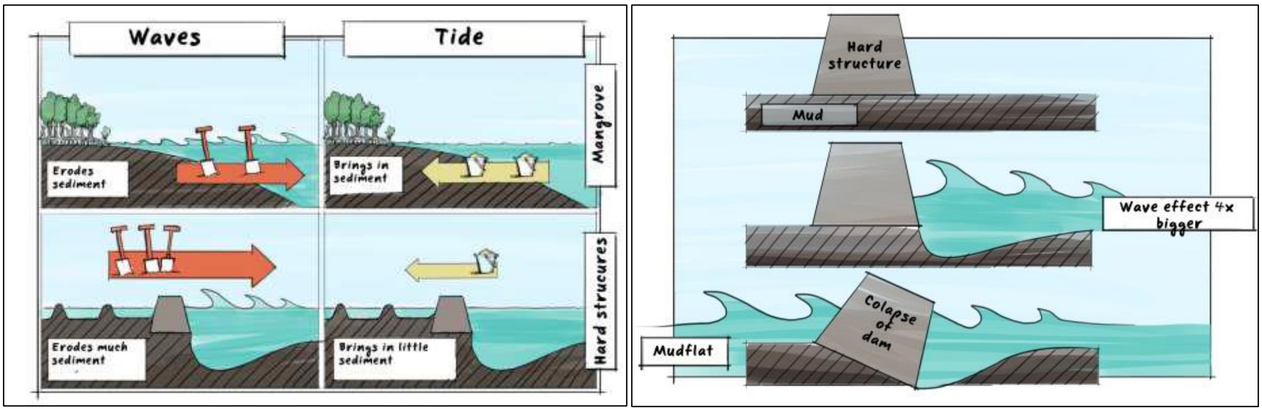


Figure 3-11 Processes on healthy mangrove coast and degraded mangrove coast

MANGROVE REHABILITATION IMPROVEMENTS

Winterwerp et al., (2013) proposes a strategy that comprises social, hydrological, morphodynamic and ecological aspects for rehabilitating eroding mangrove-mud coasts.

SOCIAL

The social aspect focusses on the cooperation, raising awareness and teaching of the local communities. The awareness should be raised by the local people how essential mangroves are in coastal protection. Next to that, new solutions should be consulted and developed with the local community. Their knowledge and cooperation is crucial for the success of the rehabilitation process.

HYDROLOGY

Hydrological aspects are important for natural mangrove re-establishment. The natural exchange of water by the tidal in- and outflow allows fresh water, sea water, sediment and propagules to enter the system (Lewis III, 2005). The propagation of mangroves relies on the dispersal of fleeting seedlings and propagules. Seedlings are small and have little capacity to settle in highly dynamic conditions thus have less chance to survive. Propagules are more developed and are able to deal with the environment. The propagule is buoyant and travels in the water before rooting itself on the subsoil (Balke et al., 2011). The propagule must establish itself before the next inundation period enters because waves and currents can loosen the propagule. This period of low or absent disturbances is called 'the window of opportunity' (Balke et al., 2011). Longer inundation periods or excessive sediment deposits can bury and kill the propagule (Ellison J. C., 1998). Others stresses are caused by the salinity, anoxic soils, predators, competition with young mangroves and other vegetation (Quartel et al., 2007). Once the propagule is established and adapted to the environment it is able to develop a young mangrove. The further development depends on site specific geomorphology, hydrology and climate conditions (Marchand, 2008).

The hydrological conditions can be improved by the restoration of rivers and tidal creeks. The restoration of rivers with fresh water reduces the salinity and increase sediment inflow from the hinterland. The restoration of tidal creeks reconnects the sea with the hinterland and allows propagules exchange. The removal of obstructions like fish ponds is also beneficial for the dispersal of propagules by tidal streams (Lewis III, 2005).

MORPHODYNAMIC

Morphodynamic aspects are important to stop coastal erosion and facilitate conditions for mangrove establishment. Mangrove coast are highly dynamic and subjected to coastal progradation and coastal retreat. In a healthy mangrove ecosystem there is a balance between the sedimentation and erosion. Sediment is brought into the coastal system by rivers and distributed by the current along the coast. On the other hand, sediment in the foreshore is stirred-up by waves and transported by the tide through the water column to the coast. Large waves erode less sediment than they stir-up and induce net accretion. Small waves erode more sediment at the coast than they stir-up and therefore lead to net erosion.

The morphodynamic conditions can be improved by the restoration of the sediment balance. The magnitude of sediment supply should be larger than the magnitude of erosion to stabilize the coast. For example, the restoration of rivers and stop river mining increases the sediment supply. Next to that, to increase the onshore sediment flux all obstacles need to be removed in cross-shore direction. Fine sediment need to be trapped in a natural way on the mud flat to induce accretion. On the other hand, erosive wave forces near the coastline need to be reduced and longshore currents need to be reduced to prevent sediment loss from the system.

ECOLOGY

The restoration of the sediment balance and hydrology enhances the natural restoration of the ecosystem. Mangroves, if available in the system, start to colonize the accreted foreshore when it is suitable through spreading of propagules. The quantity of propagules depends on the amount of nearby mangroves. Removal of mangroves decreases the amount of propagules and the ability to naturally induce establishment of autochthonous mangrove species. Autochthones mangrove propagules make more growth progress rather than allochthonous planted mangrove species. So it is advised to a restore the natural habitat, not to plant allochthonous mangrove species but first enhance the autochthonous mangrove seedlings disperse.

Chapter 4 Case Demak

The information in this chapter is retrieved from monitoring results, expert interviews and literature. The sub-paragraphs elaborate on the current features and status of the coastal system of Demak.

4.1 Area of interest

The area of interest is in Indonesia on the northern part of the island Java, see Figure 4-1. It is in the Central Java province, in the Demak district and has the adjacent city of Semarang on his left side, Figure 4-2. Its coordinates are -6 degrees latitude and 110 degrees longitude on the southern hemisphere.

Figure 4-1 Java (Indonesia) (Google Earth, 2016)

Figure 4-2 Area of interest Semarang city and Demak coastal area (Google Earth, 2016)

4.2 Historical development coast Demak

4.2.1 Coastal erosion

The Demak shoreline suffers from severe erosion and noticeable measurements are done since 1972. The reason for this is linked to interventions in the coastal configuration, blockage of sediment in land runoff, reduction of sediment supply to the coast due to mining in rivers, land subsidence due to water extraction and large deforestation of mangroves. The erosion rates are in the order of hundreds of meters up to a few kilometres, see Figure 4-3 and Figure 4-4 (Tonneijck et al., 2015).

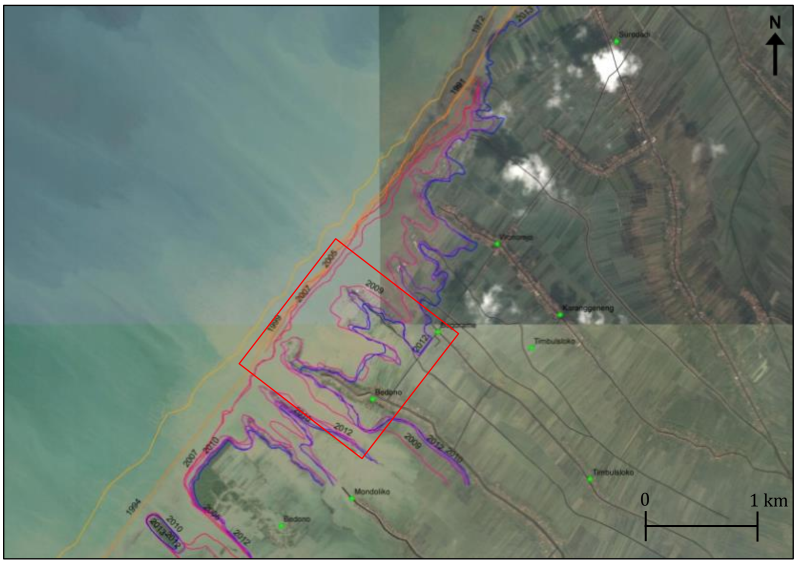


Figure 4-3 Overview coastal erosion Demak between 1972-2013 (Tonneijck et al., 2015)

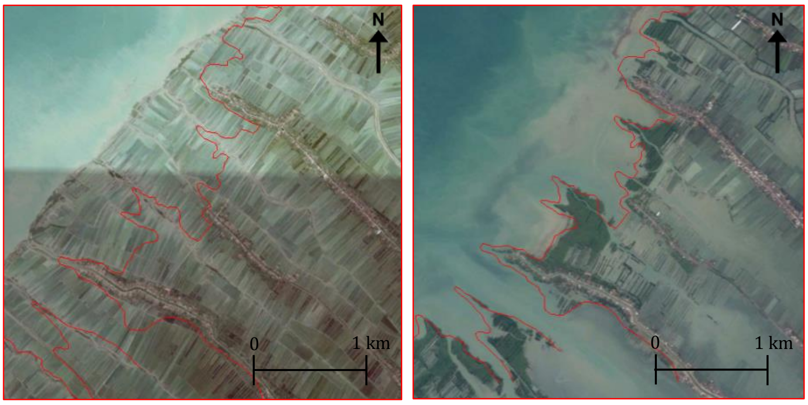


Figure 4-4 Overview coastal erosion near the village Bedono between 2003-2015 (Google Earth, 2016)

4.2.2 Cross-shore slope of the foreshore

The original cross-shore slope of the foreshore was between 1:1000 and 1:1500 and had a convex profile. This slope and profile changed after human interventions and the disturbance of the sediment balance. The current cross-shore slope is around 1:600 with a concave profile, see Figure 4-5 (Winterwerp et al., 2013) (Tonneijck et al., 2015).

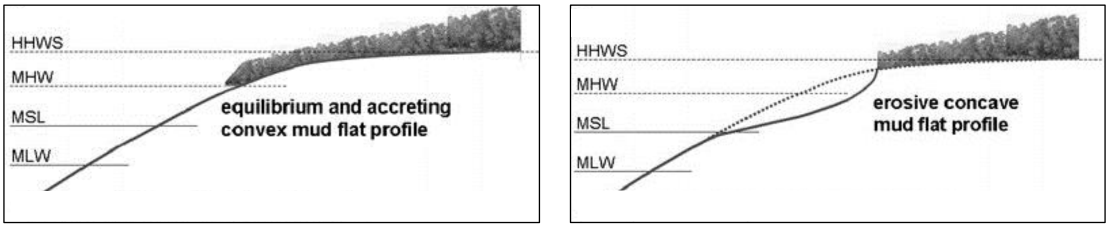


Figure 4-5 Convex and concave cross-shore slope of the foreshore (Winterwerp et al., 2013)

4.2.3 Subsidence

Land subsidence is induced by natural consolidation, loads of construction and extraction of large volumes of ground water, see Figure 4-6. In the Demak area ground water is extracted by the local population on a small scale for their household. The largest contribution to the subsidence comes from ground water extraction for industrial and aquaculture purposes (Tonneijck et al., 2015). The resulting magnitude of subsidence in the coastal area exceeds 8 centimetres per year with measured maximums of 15 centimetres per year (Abidin et al., 2010).

Figure 4-6 Land subsidence Demak (red colours indicate larger subsidence) (Tonneijck et al., 2015)

4.3 Meteorological processes

4.3.1 Monsoon

Two monsoons can be distinguished through the year, the North-West monsoon and the South-East monsoon, see Table 4-1. Below is elaborated on the characteristics and additional consequences on the sediment transport.

NORTH-WEST MONSOON
The North-West monsoon is from October up to and including April. The months December – February, the wet season, are characterized by rainfall, increase in wind speed and wave height. The fresh water discharge from rivers is distributed along the coastline in eastward direction. The density difference between the fresh water and the salt sea water induces a gravitational circulation along the coast and keeps fine sediments close to the shore. The conditions in these months induce more erosion but this is counteracted since the wave climate mobilizes more sediment for coastal accretion (Tonneijck et al., 2015).

SOUTH-EAST MONSOON
The South-East monsoon is from May up to and including September. This period, dry season, is characterized by draught and a mild wind and wave climate. The fresh water discharge including fine sediment from rivers is transported directly into the Java Sea. The effect of gravitational circulation is more localized and there is no large scale transport of sediment in the coastal system. The decrease in sediment availability and with this milder wave climate induces coastal erosion (Tonneijck et al., 2015).

March	April	May	June	July	August	September	October	November	December	January	February
South-East monsoon							North-West monsoon				
Transition		Dry season					Transition		Wet season		

Table 4-1 Indication meteorological periods in one year

4.3.2 Wind

The direction and the magnitude of the wind depend on the monsoon. In the North-West monsoon the prevailing wind direction is west to northwest while the magnitude varies between 5-15 m/s. In the South-East monsoon the prevailing wind direction is east to southeast with a magnitude in the order of 0-10 m/s, see Figure 4-7.

Detailed information and figures are in Appendix B Wind.

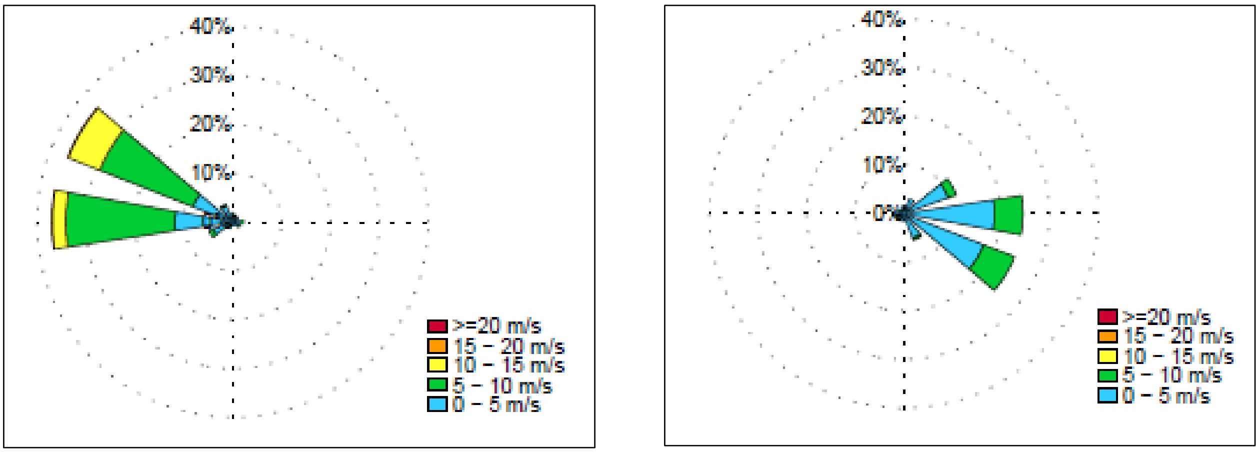


Figure 4-7 Typical wind rose North-West monsoon (left) and South-East monsoon (right)

4.3.3 Rainfall

The rainfall magnitude varies over the year and is strongly correlated with the monsoon periods. The rainfall feeds the fresh water discharges into the coastal system where it mixes with the denser and saline sea water.

In the North-West monsoon the monthly rainfall is between 200-450 cm and this is the so called wet season. In the South-East monsoon the monthly rainfall is between 100-250 cm and this is the dry season, see Figure 4-8 (Bayong Tjasyono et al., 2008).

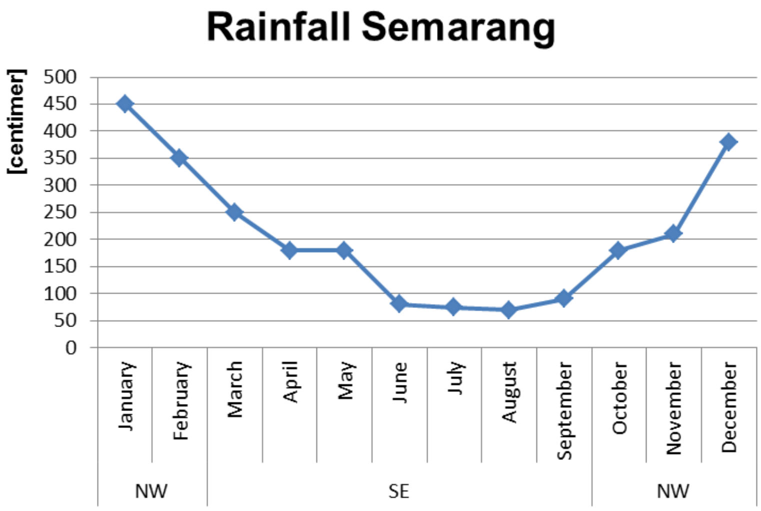


Figure 4-8 Average rainfall distribution Semarang (Bayong Tjasyono et al., 2008).

4.4 Hydrodynamic processes

4.4.1 Tide

TIDAL CHARACTER

The tide in the coastal system of Demak is a mainly large diurnal signal and small semi-diurnal components, see Figure 4-9. The tide does not follow the 14 day spring-neap cycle and leads to a variation in tidal water levels over time. The neap-tidal range is 0.4 m and the spring-tidal range is 0.6 m. These magnitudes can be larger when the semi-diurnal components synchronise with the diurnal components. Tidal currents are perpendicular to the coast and in the order of 0.15 m/s (Tonneijck et al., 2015).

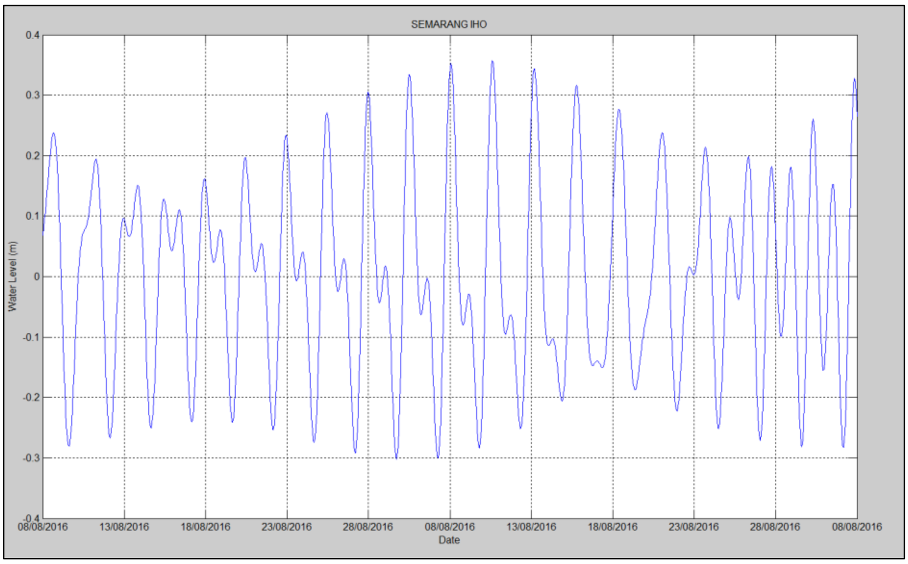


Figure 4-9 Tidal elevation August at Semarang station (Delft Dashboard)

TIDAL WAVE PROPAGATION

The tidal wave in the Java Sea propagates from east to west and its main contributors are the tidal constituents K1 and M2. The origin of the K1 tidal wave differs since it comes from the Pacific Ocean and the M2 tidal wave is from the Indian Ocean. The K1 enters from the north via the Makassar Strait and deviates to the west into the Java Sea. The M2 component enters from the east via the Flores Sea and large parts deviate to the north into the strait of Makassar while a smaller part continues in westward direction (Hatayama et al., 1996). The K1 constituent phase propagation is clockwise and corresponds with the propagation behaviour in the southern hemisphere. The M2 constituent phase propagation deviates from the latter and demonstrates a counter clockwise pattern. This deviation is caused by the larger amplitude of the incoming wave through the Makassar Strait which propagates along the southern coast of Kalimantan Island (Yusuf & Yanagi, 2013).

Furthermore, the tidal wave propagation in western direction within the Java Sea can be separated in two parts. In the southern part it propagates faster with a relatively smaller tidal amplitude. In the northern part it propagates slower with a larger tidal amplitude. This deviation is caused by the deeper bathymetry in the southern part of the Java sea (Yusuf & Yanagi, 2013).

TIDAL ENERGY PROPAGATION

The K1 tidal energy propagation is through the Makassar Strait in southern direction. The M2 tidal energy propagation is to the west in the Flores Sea and to the north after the entrance in the Java Sea (Ray et al., 2005) (Zu et al., 2008). So the merging tidal energy fluxes enters at the eastern part of the Java Sea, propagates to the west where it leaves through the Sunda Strait, Karimata, Gaspar and Bangka (Yusuf & Yanagi, 2013).

TIDAL RESIDUAL CURRENT

The flow pattern of the residual current within the Java Sea is very complex and is separated in two separate components K1 and M2. The K1 tidal residual current enters from the Makassar Strait follows the coast of Kalimantan to the west where it encounters Sumatra, bends down to the south and propagates along the northern coast of Java back to the Makassar Strait, see Figure 4-10.This counter clockwise propagation is induced by geometrical boundary effects and bottom topography. The M2 tidal residual current enters from the Flores Sea in the eastern part of the Java Sea. Subsequently, it follows the northern part of the Java Sea along the coast of Kalimantan to the west where it remains, see Figure 4-11 .In this area it makes a clock-wise rotation and does not fully return along the northern part of Java to its entrance location.

The velocity magnitude of the tidal-residual current is smaller than the tidal current. Though, the tidal-residual current forms an important role in the long-term sediment transport (Yusuf & Yanagi, 2013).

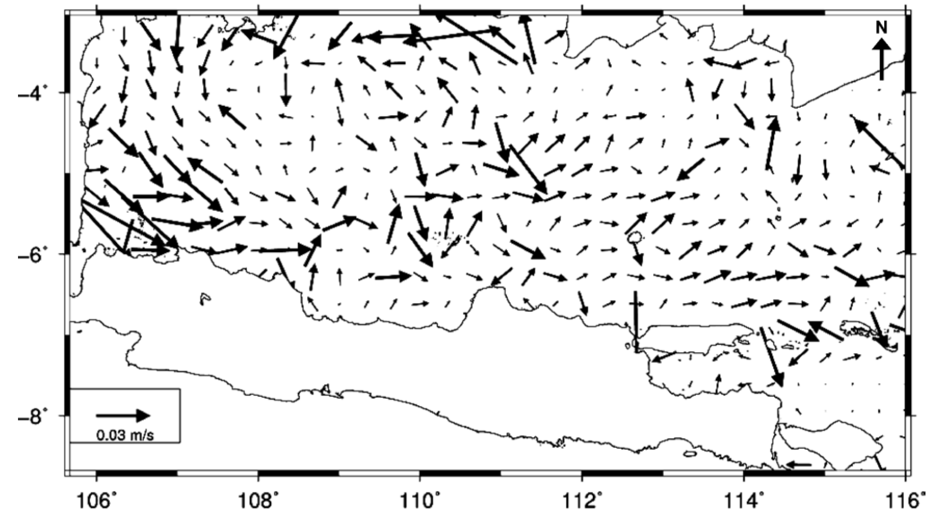


Figure 4-10 K1 tidal residual current (Yusuf & Yanagi, 2013)

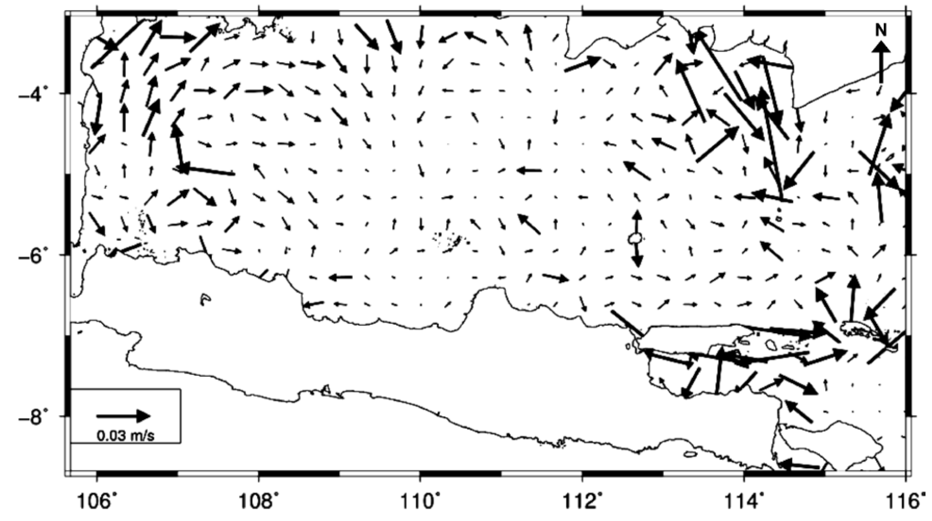


Figure 4-11M2 tidal residual current (Yusuf & Yanagi, 2013)

4.4.2 Residual current

Residual currents close to the coast are small in magnitude and the result of wind-driven circulations induced by the monsoons. The directions are very complex and are influenced by the local bathymetry and coastal configuration. On a larger scale, within the Java Sea, the residual current during the South-East monsoon is towards the west while during the North-West monsoon to the east, Figure B- 4 (Tonneijck et al., 2015) (Beccario, 2016).

Detailed information and figures are in Appendix D Tide.

4.4.3 Wave

The offshore wave height is derived from multiple global data sets (no measured buoy data) with information on the coordinates 6.0 ° S and 110 ° E. The Java Sea is an enclosed sea and does not allow swell waves to enter. The waves present in the Java Sea are considered as locally generated wind waves. The offshore wave transforms during its propagation towards the coast. The angle of approach changes over the very shallow foreshore due to refraction and ends up with a perpendicular approach at the coast. The wave height decreases due to energy dissipation on the gentle soft mud slope. The data show distinctive differences in height and direction during the North-West monsoon and South-East monsoon, see Table 4-2, Table 4-3 and Figure 4-12.

Detailed information and figures are in Appendix C Wave.

	Max. significant wave height	Mean wave period	Wave direction	Wave direction
	[m]	[s]	[from which point]	[° from the north]
	1.5	5.5	North-West	310

Table 4-2 Properties maximum significant wave – offshore (Winterwerp et al., 2014)

Period	Mean wave height	Mean wave period	Wave direction	Wave direction
[-]	[m]	[s]	[from which point]	[° from the north]
North-West monsoon	0.6	4.7	North-West	310
South-East monsoon	0.4	4.5	East-South-East	110

Table 4-3 Properties mean significant wave - Semarang station (Tonneijck et al., 2015)

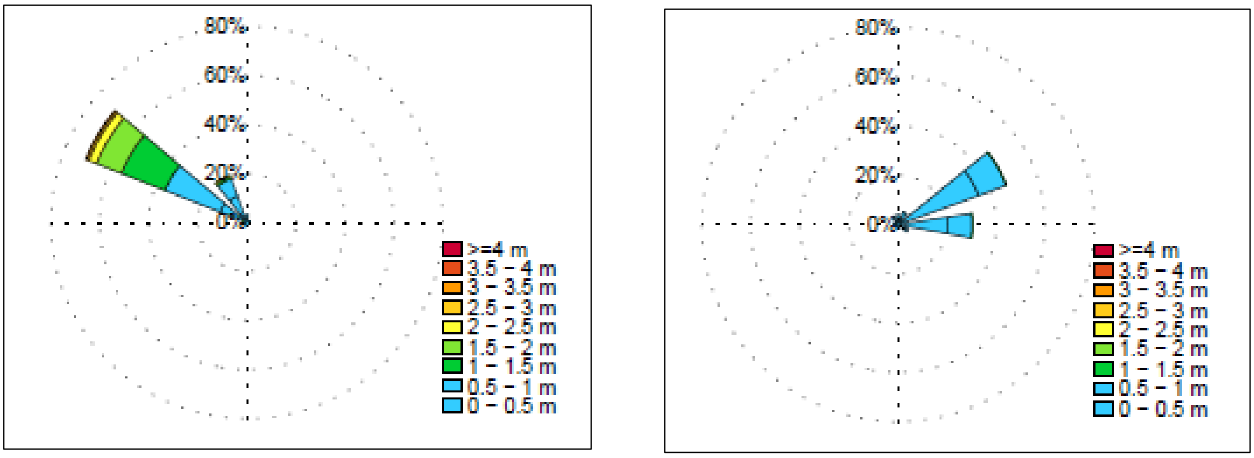


Figure 4-12 Typical wave rose North-West monsoon (left) and South-East monsoon (right)

4.5 Morphological processes

4.5.1 Sediment characteristics

Mud and sand particles are present in the Demak coastal system. The majority is silt in the range of 1 -30 micron while there is a small amount of fine sand between 100 – 300 micron, see Figure 4-13.

The sediment in the coastal system has a terrestrial origin. Numerous rivers have transported and weathered abundance of sediment into the coastal system. The silt particles were distributed along the coast and fed the mangroves to slowly expand their territory. This is a sensitive cross-shore transport balance of silt particles between the coast and the foreshore.

Also the larger fine sand particles were distributed along the coast but the wave forcing kept them close to the edge of the coast. This created the so called 'cheniers', see Figure 4-14. Cheniers attenuate incoming waves from offshore and their evolution is strongly associated with the specific coastal status (McBride et al., 2002).

The stratigraphy of the soil is mud but the exact thickness of consolidated and less consolidated mud layers is not known.

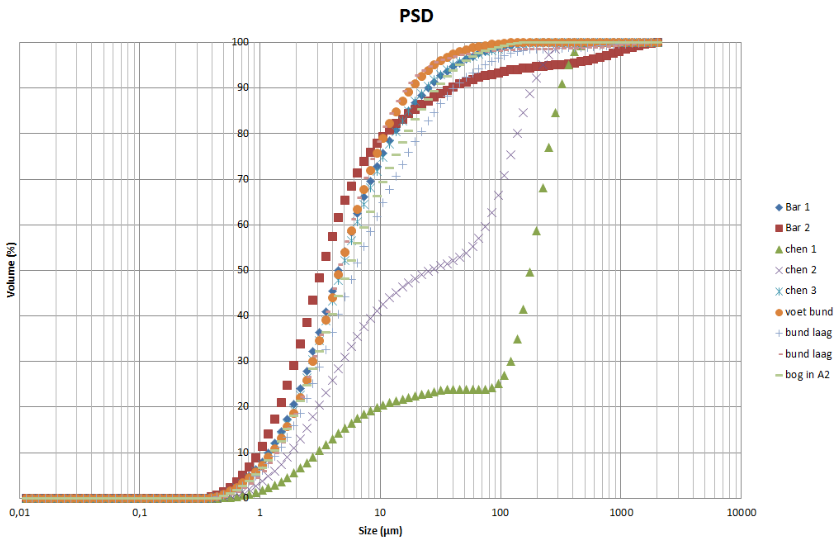


Figure 4-13 Example particle size distribution Demak

Figure 4-14 Chenier near the village Wonorejo in 2012 (Google Earth, 2016)

4.6 Vegetation

Along the north coast of Java the majority of mangroves appear in the fringe community located above the Mean High Tide. The flora zonation in the Demak coastal system is characterized by a variety of plant species. On the landward side, the vegetation is dominated by grasses and a relatively small amount of Lamtoro (*Leucaena Leucocephala*), Turi (*Sesbania grandiflora*) and planted banana trees (*Musa acuminata)*. In the intermediate zone are halophilic herbs which can tolerate a salt rich environment (*Euphorbia curassavicus* and *Sesuvium portulacastrum*). On the seaward zone are halophilic sedges (*Cyperaceae*), six mangrove species (*Rhizophora, Sonneratia, Avicennia, Ceriops, Bruguiera* and *Xylocarpus)* from which are two dominant (*Avicennia marina* and *Rhizophora mucronata*) (Tonneijck et al., 2015).

Detailed information and figures are in Appendix A Mangroves.

Figure 4-15 Vegetation Demak coast Avicennia marina (left) and Rhizophora mucronata (right)

4.7 Project goal

It is important to take into account that the project in Demak is a demonstration project. The latter means it functions as an area in which substantiated solutions are tested and to show how new techniques contribute to the rehabilitation possibilities of eroding mangrove-mud coasts. Note, the solutions are site specific which implicates it does not automatically works on other places with different circumstances. The project goal for Ecoshape is formulated as follows:

"It is our goal to support the development of resilient and sustainable livelihoods in the destroyed or threatened coastal zone of Demak district, such that these livelihoods benefit from mangroves, and that the depending populations consider mangrove maintenance as a condition for the survival of themselves and future generations".

The Indonesian government is aware of the problems in the coastal region of Demak and developed four requirements for the pilot project of Ecoshape:

1. To protect the people and their houses
2. To protect the infrastructure along the coast
3. To protect existing mangrove fringes
4. To stimulate re-establishment of mangroves

4.8 Research area Bedono

The most urgent goal of the current pilot project in Demak is to protect the people and their villages. In order to do so there is chosen in this report for one coastal village that suffered and still suffers from flooding and erosion. For research purposes it is stated to investigate a distinct research area which is not too large, that contains no irregular coastline shape and other effects which can influence the hydrodynamics.

The research area is the western part of the village Bedono, see Figure 4-16 and Figure 4-17.

Figure 4-16 Coastal region Demak (Google Earth, 2016)

Figure 4-17 Research area nourishment near the village Bedono (Google Earth, 2016)

Chapter 5 Model set-up

The aim of the modelling work is to understand and quantify the spatial distribution of currents and sediment in the coastal system of Demak. This chapter starts with the explanation of the used model software, Delft3D Flexible Mesh and DELWAQ. Subsequently, the used input data, research area Demak, boundaries, physical parameters, numerical parameters, calibration and validation are presented. Finally, the model considerations are discussed which provide insight in the capabilities of the model.

5.1 Delft3D Flexible Mesh Suite

The Delft3D Flexible Mesh Suite is developed as the successor of the structured Delft3D. It is able to simulate detailed flow, water levels, waves, sediment transport and morphology, water quality and ecology. Delft3D Flexible Mesh uses different modules which are linked and integrated to each other. The used modules, FLOW and WAVE, are explained through information derived from the user manual for Delft3D Flexible Mesh (Deltares, 2016).

D-FLOW

This module provides the option to build structured grids but also unstructured like triangles, quads, pentagons and hexagons. The access to different grid configurations improves the modelling flexibility. It is easier to construct a new grid, it enables modifying of existing grids and it is possible to locally increase of the resolution. Furthermore, in Delft3D Flexible Mesh either the Cartesian or the Spherical co-ordinates can be chosen.

The D-FLOW module uses a finite volume solver on a staggered grid. Since, there is no grid with rows and columns there is also no ADI-solver possible. The continuity equation is solved implicitly for all points in the system. Time integration is done explicitly for part of the advection term and the resulting dynamic time-step limitation automatically changes based on the Courant criterion. The latter depends also on the grid size and might require refining or coarsening of the grid at locations.

The equations used in the model are the shallow water equations. The latter are derived from the Navier-Stokes equations for incompressible fluid under the shallow water and the Boussinesq assumption. In the vertical momentum equation the vertical acceleration is neglected, which leads to the hydrostatic pressure equation.

The input file for the D-FLOW module is in E.9 MDU-file.

D-WAVES

This module computes the non-steady propagation of short-crested waves over an uneven bottom, considering wind action, energy dissipation due to bottom friction, wave breaking, refraction, shoaling and directional spreading. This module is based on the spectral model SWAN.

SWAN is the numerical model that is used for wave transformation from offshore to nearshore. Input parameters are the bathymetry, initial water level, wind direction, wind speed and an offshore wave spectrum. The model does not simulate individual waves but does the transformation on basis of the wave spectrum. The offshore wave spectrum is translated to a nearshore wave spectrum with a spectral shape, wave height, wave period and frequency. Physical processes that are incorporated are wave generation by wind, quadruplet- wave-wave interaction, triad wave-wave interaction, white capping, depth-induced breaking, friction and wave set-up.

The interaction between the D-FLOW and D-WAVE modules is done through offline or online running. The coupling method depends on the required output precision and available computation time. Offline means that first the entire hydrodynamic simulation is done and thereafter the wave simulation is done separately. Finally this is used to do the hydrodynamic simulation again. This sequence does not provide interaction and continues feedback between the hydrodynamic and wave simulation. Therefore, online running is used in this report which allows continues feedback from the hydrodynamic simulation of the wave simulation. For instance, the influence of the water depth is crucial for the actual wave height and the location of wave breaking. On each time step it is important to know the actual water depth to make a correct wave simulation.

The input file for the D-WAVE module is in E.10 MDW-file.

5.2 Development Delft3D Flexible Mesh

Unintentionally the development and testing of Delft3D Flexible Mesh became an important part of my research and also required large parts of my time. This paragraph is the summary of the development and testing of Delft3D Flexible Mesh.

The intention was to make a model with tide, waves, fine sediment and morphological bed update. During the development of the model it became clear that the cohesive sediment transport and morphological updating of the bed level in Delft3D Flexible Mesh was not working correctly. Therefore it was needed to investigate in which part the error occurred. Together with Bob Smits we investigated a small simplified case to test the behaviour of cohesive sediment transport and morphological updating of the bed level. The case was tested in a D-Flow FM standalone run and in a D-Flow and D-Wave FM coupled run. These results were compared to the same case in a validated Delft3D model to assess the correctness of the outcome.

The development was an iterative process of adapting the model, analysing the results and arranging meetings with the model developers and my committee. The intermediate steps are not presented in this report but only the set-up and the final result. The improvements and progress in the software came too late for me and I decided to switch to the software DELWAQ. I decided to use the hydrodynamics modelled in Delft3D Flexible Mesh and use this for modelling sediment transport without morphological bed update.

MODEL DESCRIPTION

The simplified case consisted of a 3x3 km depth averaged model. The rectangular grid is 30 by 30 cells of each 100 m. The bottom has a constant slope from -1 m in the North to 0.3 m in the South, see Figure 5-1. These identical cases are constructed in Delft3D Flexible Mesh and Delft3D.

The West, South and East side of the model are closed boundaries while the North side is the only open boundary. From this side a tidal boundary with an amplitude of 0.3 m was applied and a wave boundary was applied with waves coming from the North with a wave height of 0.3 m and a peak period of 4.4 s. The constant wind condition of 10 m/s was also applied from northern direction. Important parameters were a breaker parameter of 0.78 and a Manning roughness coefficient of 0.015.

The fine sediment transport is computed by the Krone-Partheniades formulation. Cohesive sediment with a settling velocity of 0.1 mm/s was applied and a critical shear stress for erosion of 0.25 N/m^2 was used. The critical shear stress for sedimentation was 1000 N/m^2 to induce sedimentation all the time. The initial fine sediment concentration and boundary sediment concentration was 1 g/l. To strengthen the morphological bed updating an upscaling factor of 15 was used.

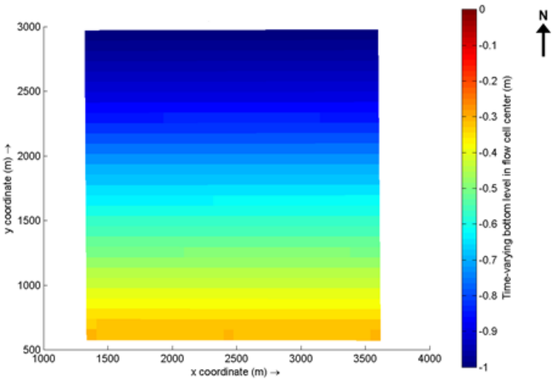


Figure 5-1 Model configuration with bathymetry for Delft3D Flexible Mesh and Delft3D

MODEL RESULTS FINAL

The bed level and sediment thickness are used to compare the Delft3D Flexible Mesh and Delft3D model. First the results with only tidal forcing are analysed. The results demonstrate the same general pattern of no erosion (due to too low shear stress) and sedimentation in the same order of magnitude (5-10 cm), see Figure 5-2.

Subsequently, the coupled flow and wave run are analysed. The most important observation is that the largest erosion in Delft3D Flexible Mesh occurs near the northern boundary. While in Delft3D the erosion is smaller and equally spread over the domain, see Figure 5-3.

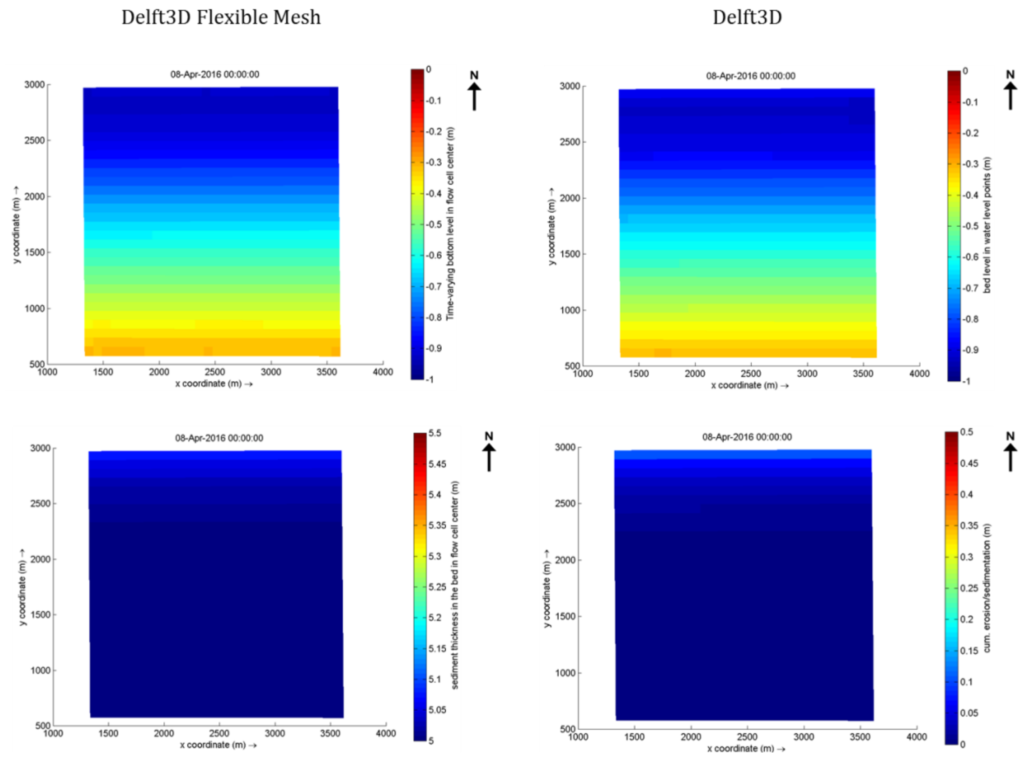


Figure 5-2 Bed level (upper) and sediment thickness (below) after 7 days– D-Flow FM and Delft3D standalone

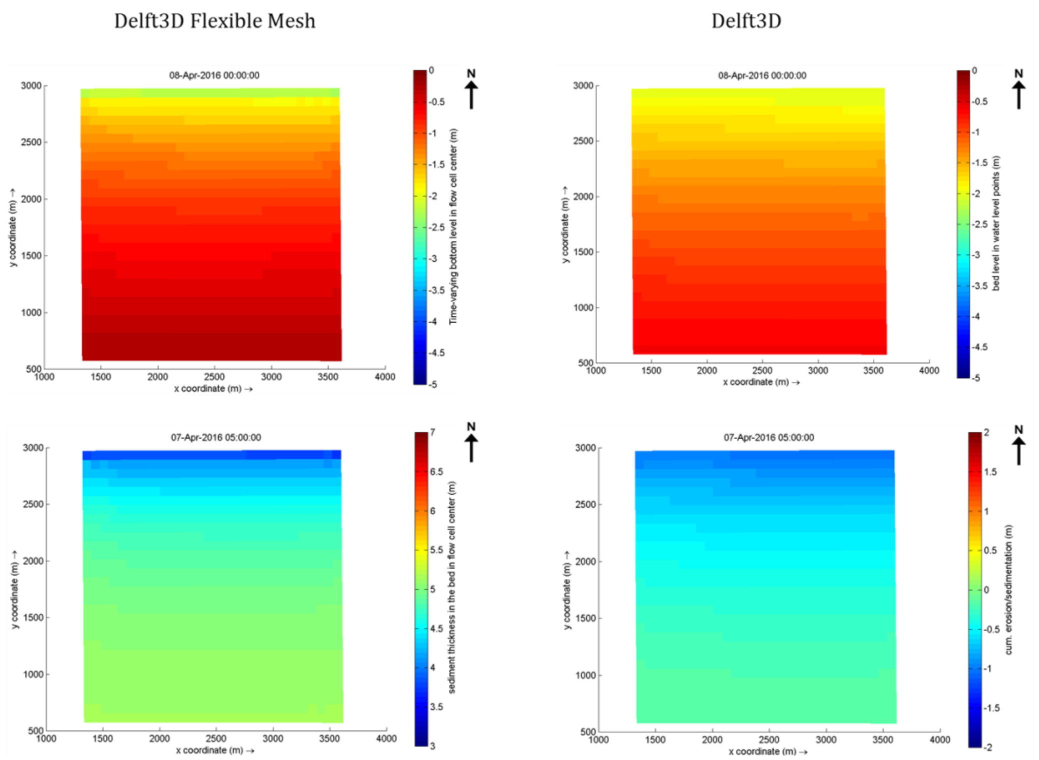


Figure 5-3 Bed level (upper) and sediment thickness (below) after 7 days – D-Flow FM and D-Wave FM coupled

5.3 DELWAQ

This section is based on information from the user manual for DELWAQ.

The D-Water Quality module (DELWAQ) is a mathematical model for water quality and ecology. It solves the equations for advective and diffusive transport of substances in water and it models the water quality kinetics of chemistry, biology and physics that influence of the behaviour of substances and organism in the water. DELWAQ does not compute the flow itself but it contains the mass conserving finite volume principle and can therefore be connected to a Delft3D Flexible Mesh water flow model that is mass conserving. The water balance is checked for two types of control volumes: grid cells and for nodes with a water volume.

The user can select the numerical scheme it will use to solve the advection-diffusion equation. The different models require different time steps to fulfil the stability of the model.

The settling and deposition formulation of Partheniades-Krone (1962) is used. Multiple sediment particles, Inorganic Matter, can be created with their own values. The most influential parameters are the critical shear stress for erosion, first order re-suspension rate and settling velocity per fraction. The erosion rates are zero until the shear stress exceeds a certain critical value. The total bed shear stress is composed of the shear stress from flow and wave. The settling velocity is calculated from a pre-defined settling velocity and the flocculation effect. The latter depends on the salinity, total suspended sediment concentration and the water temperature. All the processes related to re-suspension and deposition is represented in two bed layers, S1 and S2. The first bed layer, S1, is defined as the 'fluffy' bed layer from which erosion is more easily. The second bed layer, S2, the represents the more 'consolidated' bed layer. Each bed layer has its own parameters and there is exchange with the water column and between the two bed layers. The sediment deposits are stored in the bed but there is no morphological bed update. Therefore the hydrodynamics are not affected by sediment deposits or erosion. (Deltares, 2016).

The use of multiple sediment fractions and the pre-defined hydraulic forcing leads to a quick assessment tool for the transport of sediment. Once the hydraulic forcing is computed this can be used and repeated in separate DELWAQ runs.

The input file for DELWAQ is in F.9 DELWAQ-file.

5.4 Data

5.4.1 Data collection

WIND

Wind data is retrieved from the global model database of Fugro. This is a global database with wind and wave time series data. The data are derived from the European Centre for Medium-range Weather Forecasts' (ECMWF) operational and hind cast models. The data are calibrated by Fugro OCEANOR against satellite data, and where available in-situ buoy data. The data are available as parameter data or directional spectra. The used data for the model are wind speed, wind direction and frequency of occurrence.

Detailed information can be found in Appendix B Wind.

WAVES

Also the wave data is retrieved from the global model database of Fugro. The used data for the model are the offshore wave height, wave direction and frequency of occurrence for wind and swell waves.

Detailed information can be found in Appendix C Wave.

TIDE

Tidal information is retrieved from TOPEX/POSEIDON global tide model in Delft Dashboard. This database provides information for the tidal boundary condition on the flow grid and information of the nearshore tidal station of Semarang.

Detailed information can be found in Appendix D Tide.

BATHYMETRY

For the creation of the bathymetry are three resources used. First of all, GEBCO data is used for the determination of the offshore bathymetry. This database contains depth points per every square kilometre offshore. The bathymetry nearshore is determined by the use of local gathered data from Pak Sugeng and Stefan Verschure. They collected high resolution depth points nearshore. The depth points are assumed to be representative for the whole coastal stretch and therefore copied along the coast. The combination of the offshore and nearshore data created the total bathymetry, see Figure 5-7.

The configuration and location of the chenier is based on the configuration of nearby cheniers and Google Earth images.

5.4.2 Data processing

The data is processed through Matlab to obtain specific information for the model. The processing is intended to distillate representative conditions for the two large meteorological periods, North-West monsoon and South-East monsoon

WIND

The information on wind direction is displayed in a histogram with the wind direction on the x-axis and the frequency on the y-axis. This distribution provides insight in which direction occurs the most frequent during the North-West and South-East monsoon. Subsequently, the wind direction is chosen near the highest peak of frequency.

The information on wind speed is processed in a histogram with the wind speed on the x-axis and the frequency on the y-axis. Not the mean wind speed but the median wind speed is chosen. The mean is assumed to be too largely affected by the relatively few very high wind speed samples on the right of the histogram, outliers. The median is chosen to derive the central tendency of the skewed histogram.

Detailed information can be found in Appendix B Wind.

WAVES

The dominant wave direction in the North-West and South-East monsoon is very constant and is therefore retrieved from the wave roses. Also for the wave height and wave period is chosen to determine the representative value by calculating the median value for the data set.

Detailed information can be found in Appendix C Wave.

5.5 Research area Demak

The research area used in the modelling concentrates on the coastal region of Demak, see Figure 5-4. There is a separate larger grid for the wave module and a smaller grid for the flow module, see Figure 5-5. The next paragraph elaborates on each grid and the bathymetry. Note, the scale and colour indication in the D-wave grid and D-Flow grid is different.

Figure 5-4 Research area Demak (Google Earth, 2016)

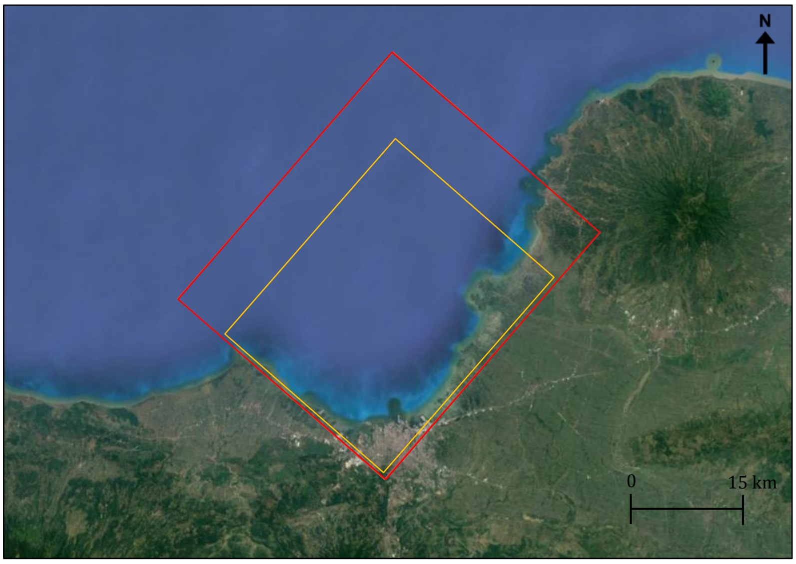


Figure 5-5 Research area Demak (red = wave grid and orange = flow grid) (Google Earth, 2016)

5.5.1 D-Wave grid

The wave grid is generated in Delft Dashboard and loaded into the D-Wave module. The grid contains grid cells of 40 m^2 and the total size of the grid is larger than the flow grid. This allows the wind to generate wind waves within the grid. On the other hand, the shadow zone inherent to SWAN is not affecting wave computations in the area of interest close to the shore. Note, the grid is too fine to be displayed correctly on this scale, see Figure 5-6.

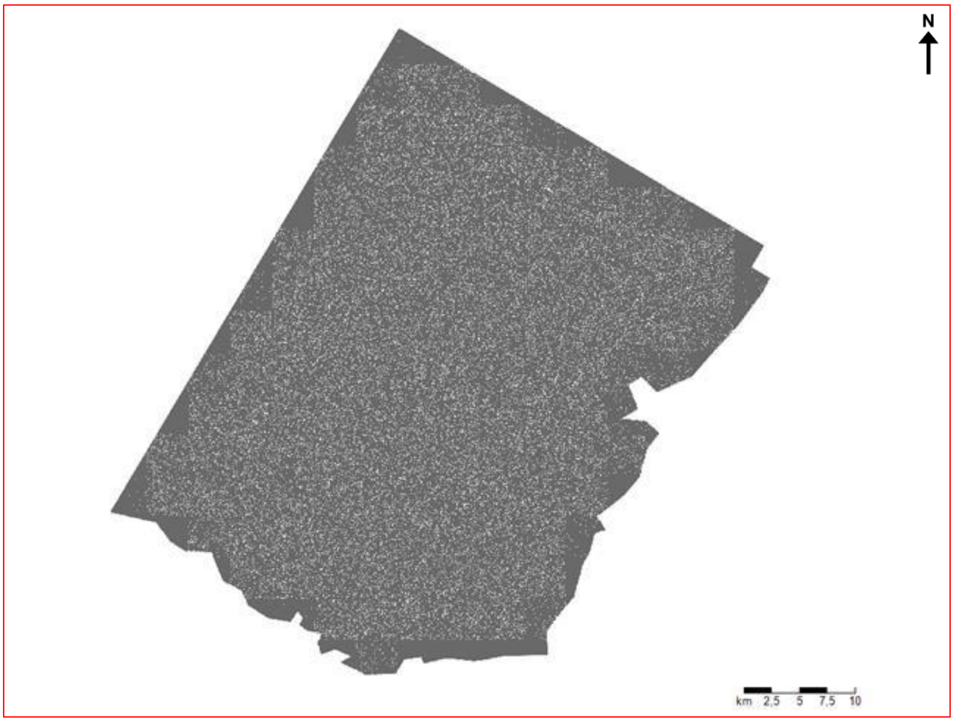


Figure 5-6 Grid D-WAVE FM Demak

5.5.2 D-Wave bathymetry

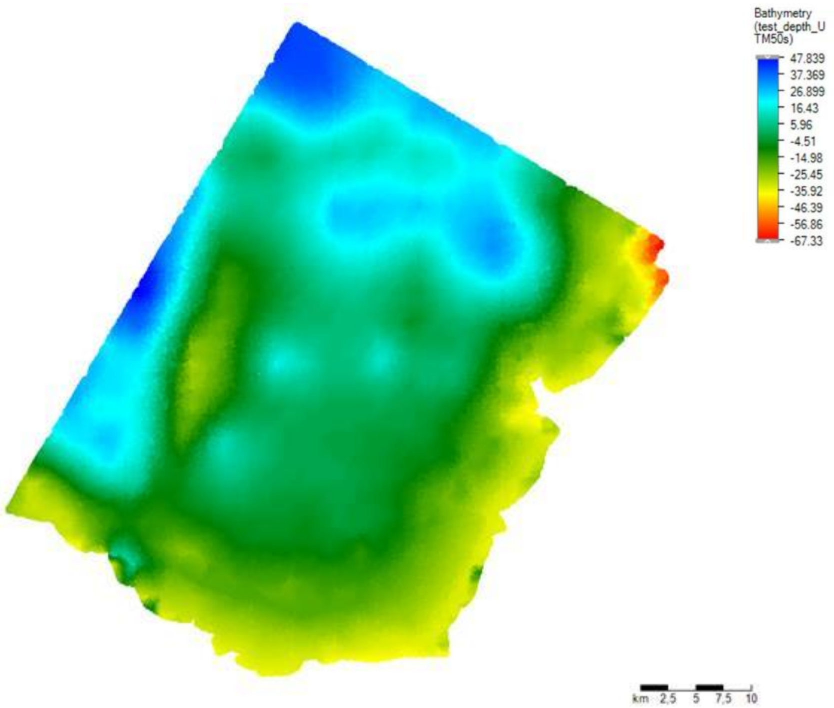


Figure 5-7 Bathymetry D-WAVE FM Demak

5.5.3 D-Flow grid

The rectangular shape is chosen to keep the boundaries sufficient far away from the area of interest, nearshore. The shape also prevents strange interactions between the western and northern boundary. The rectangular flow grid refines stepwise towards the coast and the area of interest. The offshore grid size refines from 1000 to 500, 250, 125, 62.5, 31.75 and 15.875 m nearshore.

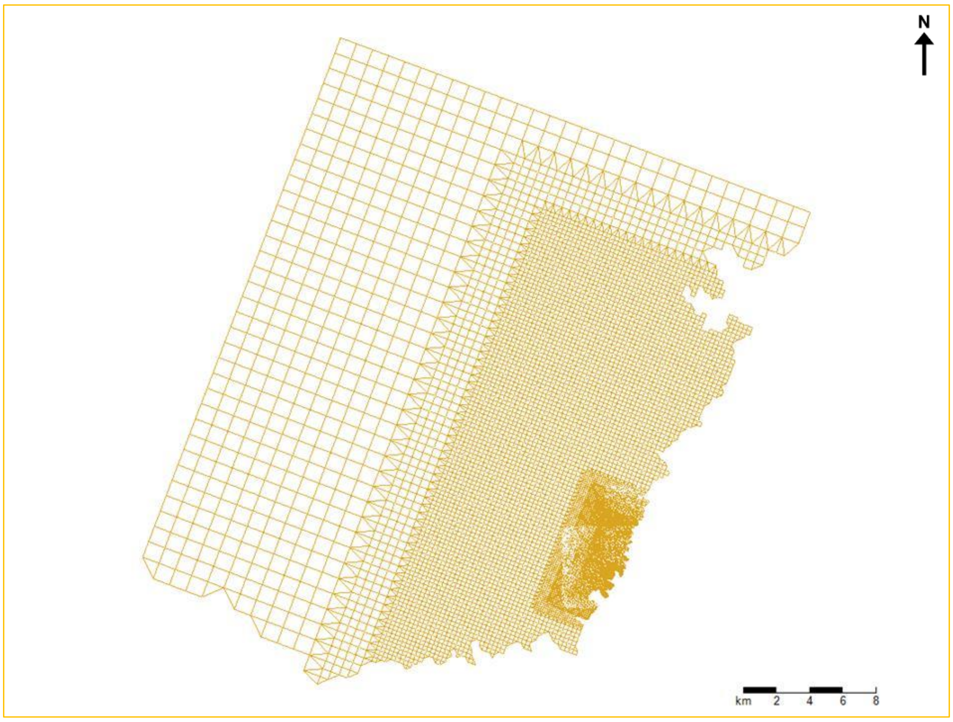


Figure 5-8 Grid D-FLOW FM Demak

5.5.4 D-Flow bathymetry

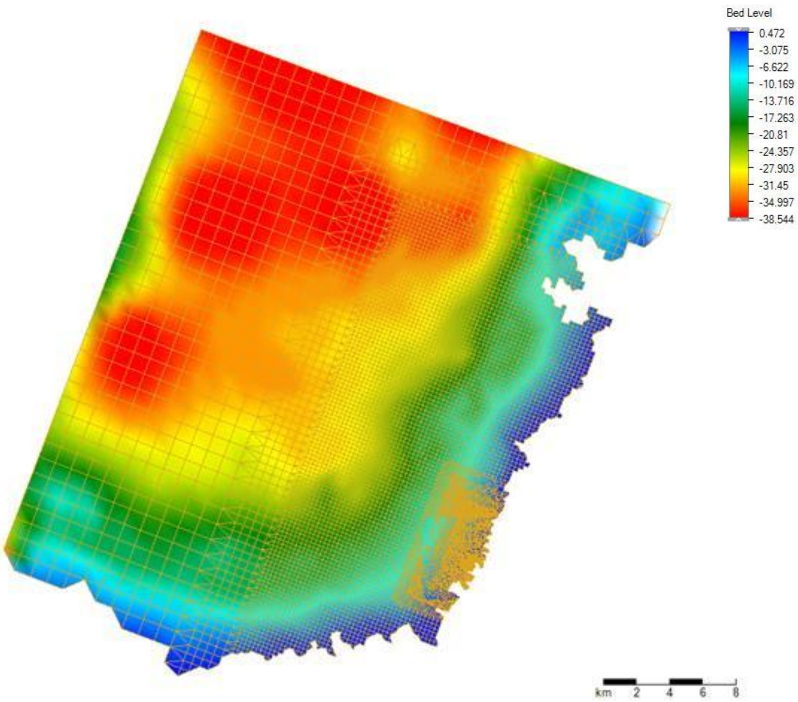


Figure 5-9 Bathymetry D-FLOW FM Demak

5.6 Boundaries

The tidal boundary on the flow grid consists of water levels imposed by astronomical components. The information is retrieved from the global tide model TOPEX/POSEIDON in Delft Dashboard.

The wave and wind boundaries are determined for the North-West and South-East monsoon; see Table 5-1 and Table 5-2. For all wave information is a JONSWAP spectrum (young sea state) chosen. The wave and wind information are no variable time series but constant in time.

	North-West monsoon	
Wave height (significant)	0.6	[m]
Wave period (mean)	4.7	[s]
Wave direction	310	[°]
Wind speed	4.4	[m s^{-1}]
Wind direction	280	[°]

Table 5-1 Wave and wind parameters North-West monsoon

	South-East monsoon	
Wave height (significant)	0.4	[m]
Wave period (mean)	4.5	[s]
Wave direction	110	[°]
Wind speed	3.0	[m s^{-1}]
Wind direction	110	[°]

Table 5-2 Wave and wind parameters South-East monsoon

5.7 Physical processes and parameters

This section describes first the physical processes that are present in the used FLOW-module and WAVE-module in Delft3D Flexible Mesh and in DELWAQ. Thereafter, the most important physical parameters are discussed.

The FLOW-module takes wave set-up, wind growth and diffraction into account. The WAVE-module includes bed friction, refraction, wind growth, depth-induced breaking, quadruplet wave-wave interaction, white capping and frequency shifting. Both modules do not account for triad wave-wave interactions. Furthermore, effects of temperature or salinity are neglected since the approach is depth-averaged.

DELWAQ used the hydrodynamics of the Delft3D Flexible Mesh and is used as assessment tool for diffusive sediment transport without morphological bed updating.

The water density is constant over the whole domain and set to 1025 kg/m^3 for salt water. The viscosity and diffusivity are 1 kg/m s. The roughness coefficient of Manning for flow is 0.012 s/m$^{1/3}$ and the roughness coefficient of Nikuradse for waves is 0.01 m. The breaker parameter is 0.78.

The settling velocity is defined for three particles. The first particle has a fall velocity of 1, the second particle of 0.5 and the third particle of 0.25 mm/s. The critical shear stress for erosion is for all three particles 0.5 N/m^2 and the critical shear stress for sedimentation is 1000 N/m^2. The erosion parameter is also the same for all three particles since in reality the particles form one nourishment unit. The magnitude is set to 1 g/m^2 s. Note, this research is not about absolute values and exact numbers but about the net sediment transport direction ('tracer study'). More reasonable values for the erosion parameter are in the order of 10^{-5} 1 g/m^2 s. The initial- and boundary concentration in the water are 0 g/l. The only sediment in the system originates from the nourishment in the bed. The parameters are summarized in Table 5-3.

The full numerical parameter overview is in E.9 MDU-file, E.10 MDW-file and F.9 DELWAQ-file.

	Parameters	
Water density	1025	[kg m^{-3}]
Viscosity	1	[kg m^{-1} s^{-1}]
Diffusivity	1	[kg m^{-1} s^{-1}]
Manning	0.012	[s m$^{-1/3}$]
Nikuradse	0.01	[m]
Breaker parameter	0.78	[-]
Settling velocity particle 1	1	[mm s^{-1}]
Settling velocity particle 2	0.5	[mm s^{-1}]
Settling velocity particle 3	0.25	[mm s^{-1}]
Critical shear stress for erosion	0.5	[N m^{-2}]
Critical shear stress for sedimentation	1000	[N m^{-2}]
Erosion parameter	1	[g m^{-2} s^{-1}]
Initial sediment concentration	0	[g m^{-3}]
Boundary sediment concentration	0	[g m^{-3}]

Table 5-3 General parameters used in Delft3D Flexible Mesh and DELWAQ

5.8 Numerical parameters

This section contains a reduced overview of the numerical parameters used in the computation of the hydrodynamics in Delft3D Flexible Mesh and the sediment dynamics in DELWAQ; see Table 5-4, Table 5-5 and Table 5-6.

The full numerical parameter overview is in E.9 MDU-file, E.10 MDW-file and F.9 DELWAQ-file.

Numerical parameters D-FLOW Flexible Mesh		
[Abbreviation in MDU-file]	[Value]	[Explanation]
CFL	0.7	Maximum Courant number
AdvecType	33	Default
Limtyphu	0	No limiter type for water depth in continuity
Limtypmom	4	Monotone limiter type for cell center advection velocity
Icgsolver	4	SobekGS and Saadilud solver type for the Poisson equation
Turbulencemodel	3	K-eps turbulence model
Turbulenceadvection	0	No turbulence advection
Epshu	0.0001	Threshold water depth for wet and dry cells
Maxwaterleveldiff	0	No limiter for the water depth in the continuity equation

Table 5-4 Numerical settings D-FLOW Flexible Mesh

Numerical parameters D-WAVE Flexible Mesh		
[Abbreviation in MDW-file]	[Value]	[Explanation]
DirSpaceCDD	0.5	Discretisation in directional space
FreqSpaceCSS	0.5	Discretisation in frequency space
RChHSTM01	0.02	Relative change of wave height or mean wave period with respect to local value
RCHMeanHs	0.02	Relative change of wave height with respect to model-wide average wave height
RChNMeanTm01	0.02	Relative change of mean wave period with respect to model wide average mean wave period
PercWet	98	Percentage of points included in simulation at which convergence criteria must be satisfied
MaxIter	15	Maximum number of iterations for convergence.

Table 5-5 Numerical settings D-WAVE Flexible Mesh

Numerical parameters DELWAQ	
[Numerical options]	[Explanation]
Integration method	Numerical scheme to solve the advection-dispersion equation is local flux-corrected transport (Boris-Book)
Dispersion	No dispersion if flow rate is zero No dispersion over open boundaries
Transport over boundaries	Use first order scheme (certain high-order methods only)

Table 5-6 Numerical settings DELWAQ

5.9 Calibration and validation

This MSc thesis' focus is on the comparison of alternatives and therefore it is assumed valid to use this 'best approached' model in the data poor environment. The calibration and validation are done in consultation with the assessment committee, expert judgement.

CALIBRATION
In the iterative process of calibration several parameters are calibrated towards their final value. In this section a few parameters are described.

The roughness coefficient of Manning for flow is tested for values with the range of 0.012 and 0.023. The roughness coefficient of Nikuradse for wave is tested for values between 0.1 and 0.001. The decision is made on basis of reasonable resulting total shear stresses. The roughness coefficient of Manning is used of 0.012 and the roughness coefficient of Nikuradse is set to 0.01.

The diffusivity and viscosity are both varied between 0.1 and 1. The effects on the total bed shear stress and the hydrodynamics have led to set these values on 1.

The critical shear stress for erosion and the erosion parameter are both extensively tested for different values. These values are extremely important and sensitive for fine sediment dynamics. The critical shear stress for erosion is set on 0.5 N/m^2 and the erosion parameter on 1 g/m^2 s.

VALIDATION
The research area is in a data poor environment and therefore it was not possible to validate the model. The only possible validation is done on the water level since the port of Semarang contains a tidal station. The modelled and measured water level are similar, Figure 5-10. Though, it is recognized that this does imply that the model is correct. The wave height is validated on expert judgement based on site visits.

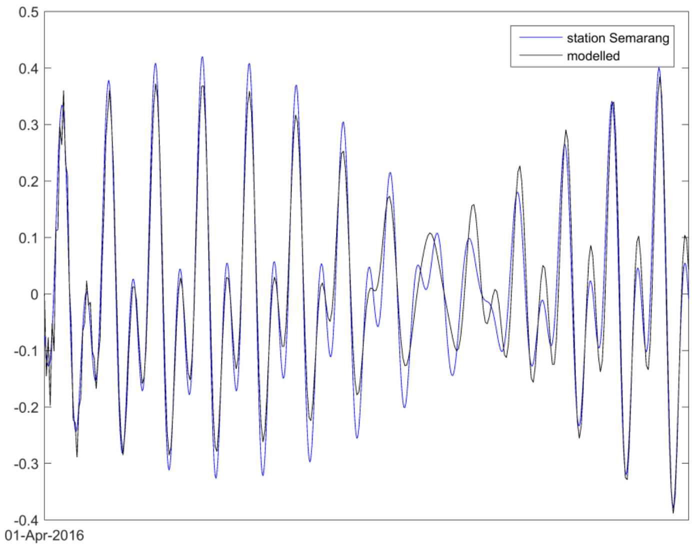


Figure 5-10 Water level measured tidal station Semarang (blue) and modelled (black)

5.10 Scenarios

This paragraph elaborates on the combination of three scenarios: coastal configuration, hydrodynamic and the nourishment location.

The coastal configuration exists of the original bathymetry without chenier and with a chenier. In reality cheniers are present along the coastline of Demak but not continuous. This distinction is also made in the model to assess the influence of the chenier on the hydrodynamics and sediment transport. It is intended to investigate the involvement of cheniers in the coastal protection and in the determination of the nourishment location. Subsequently, three representable hydrodynamic scenarios for this area are described. The two dominant monsoons, North-West and South-East, and a storm are used to assess their impact on the coastal system of Demak. Finally, different nourishment locations are investigated to find out the most strategic location. The nourishment locations are carefully chosen based on the prior work done in the hydrodynamic analysis.

The scenarios are summarized and presented in Figure 5-11 and Figure 5-12.

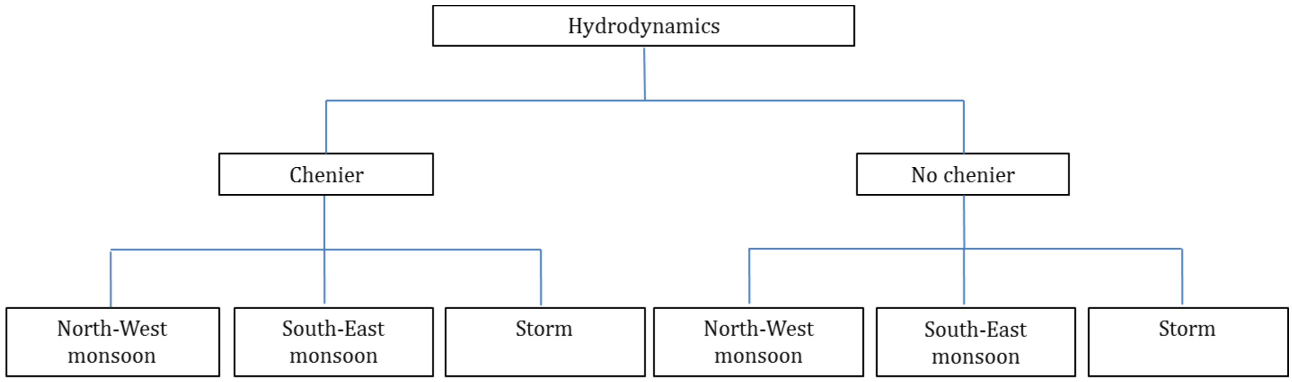


Figure 5-11 Overview coastal configuration and hydrodynamic scenarios

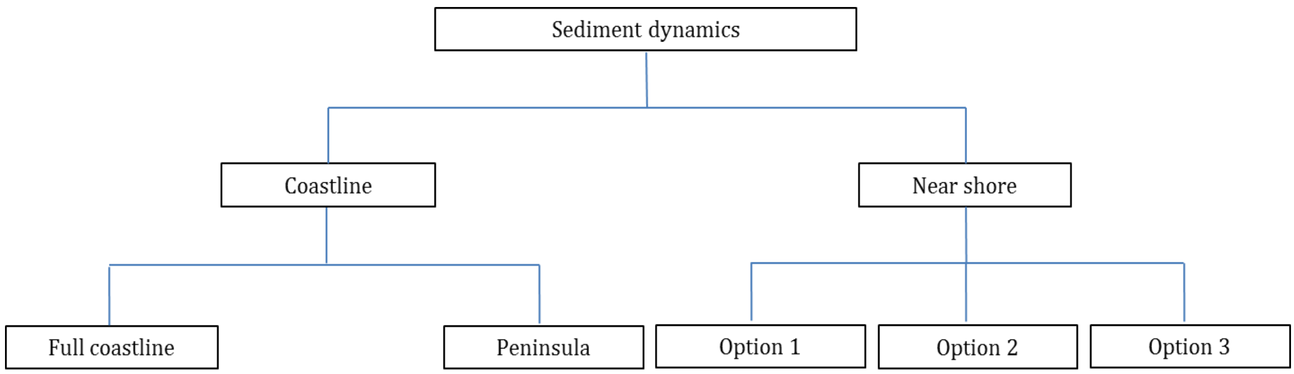


Figure 5-12 Overview nourishment locations

5.10.1 Coastal configuration scenarios

The coast in Demak is characterised as a creek system with bays formed between outflowing rivers. In front of the coast are irregular cheniers present. Cheniers are long, shallow beach ridges composed of sand and shelves which rest on the mud flat in front of the mangrove forest. The sandy sediment originates from rivers and is distributed by longshore transport along the coast and thrown back to form a sand lens by the waves. Their evolution is very dynamic and strongly associated often with eroding coastlines (McBride et al., 2002). In areas where the coast is eroded the cheniers may disappear because the coarse sediment supply from rivers is reduced and the erosive forces remain. However, on certain places the cheniers are still in place and only partially eroded. These cheniers attenuate incoming waves from offshore and have a special role in the system. The remaining cheniers reduce the erosive wave forces on the coast but on the other hand they reduce the stir-up capacity of waves behind the chenier. This is the dynamics between unfavourable coastal erosion forces and favourable activation of sediments in the bed.

CHENIER LOCATION

Adjacent cheniers are located in front of outflowing rivers along the coast. These outflows contain coarse sediment that nourishes the chenier. The location of the 'fictive' chenier in the area of interest is determined after analysing the adjacent cheniers and extrapolating this location along the coast. The width of the chenier is 30 m while the length is assumed in here on 500 m, see Figure 5-13 and Figure 5-17. All features are obtained through field observations, satellite images and expert judgement.

Figure 5-13 Determination position chenier through extrapolation along the coast

Figure 5-14 Emerging chenier during low water

The research area is divided into two different configurations with their own features.

1. No dams and no chenier

The first configuration is the original coast without dams and without chenier, see Figure 5-15. This is the coastal configuration with the least features to counteract the eroding forces. However, this is the most common coastal feature and therefore crucial to investigate the sediment transport and sediment storage development.

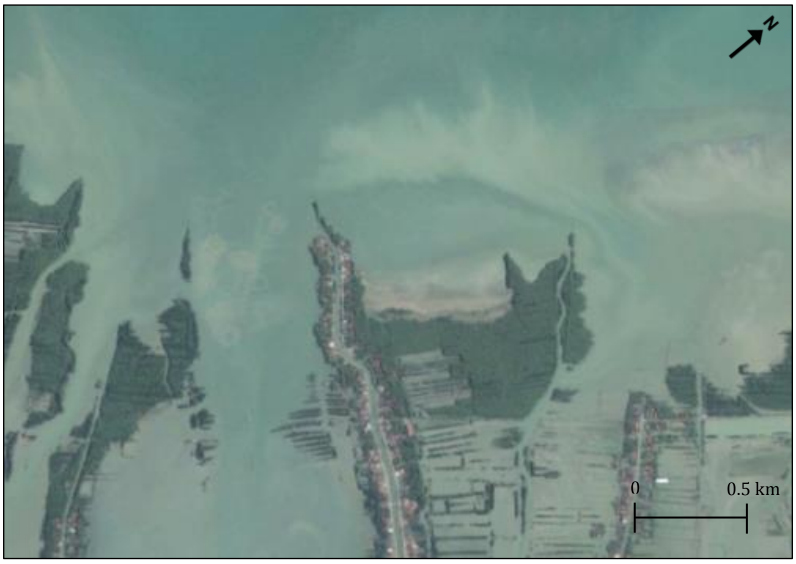


Figure 5-15 Coastal configuration no dams and no chenier scenario (Google Earth, 2016)

2. No dams and with chenier

The second coastal configuration is without dams but with an artificial chenier, see Figure 5-16. As stated earlier, there are cheniers present in the coastal system of Demak but not over the full coast length. From historical satellite images can be obtained that in this particular area was not a clear chenier present. Though, there is one chenier assumed to simulate the behaviour of the system with this shallow sand bank in front of the coast.

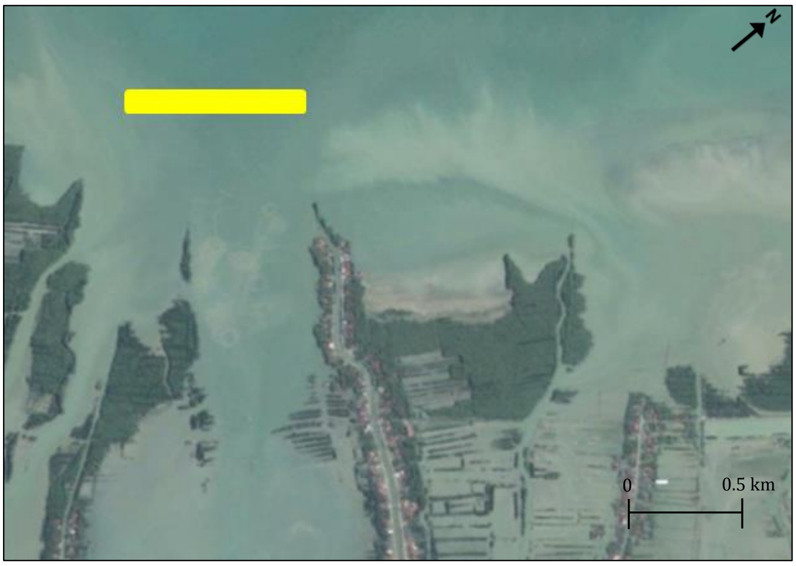


Figure 5-16 Coastal configuration no dams and with chenier scenario (Google Earth, 2016)

GOAL CHENIER

The goal of the chenier is to create a low energy area behind it, lower the shear stress and deviate the original current direction. To simulate these influences the location and height of the chenier are the most important variables.

CHENIER HEIGHT

The raise of the bed level, height of the chenier, is the most important property that influences the hydrodynamics. Field observations, aerial photos and satellite images demonstrate that adjacent cheniers emerges above the water line during low water, see Figure 5-14. In the latter situation the chenier functions as an emerged breakwater while during high water it is a submerged breakwater. To mimic these situations the bed level is raised to a level of 0.40 m below the water level (tidal amplitude fluctuates around 0.10 -0.40 m), see Figure 5-17 and Figure 5-18.

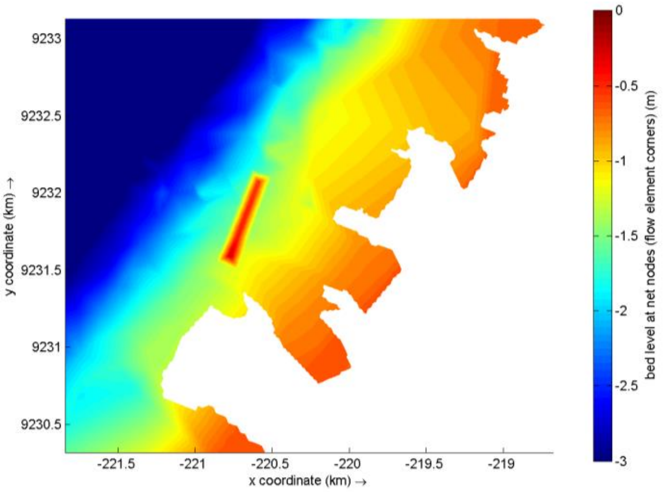


Figure 5-17 Bed level - chenier in hydrodynamic model Delft3D Flexible Mesh

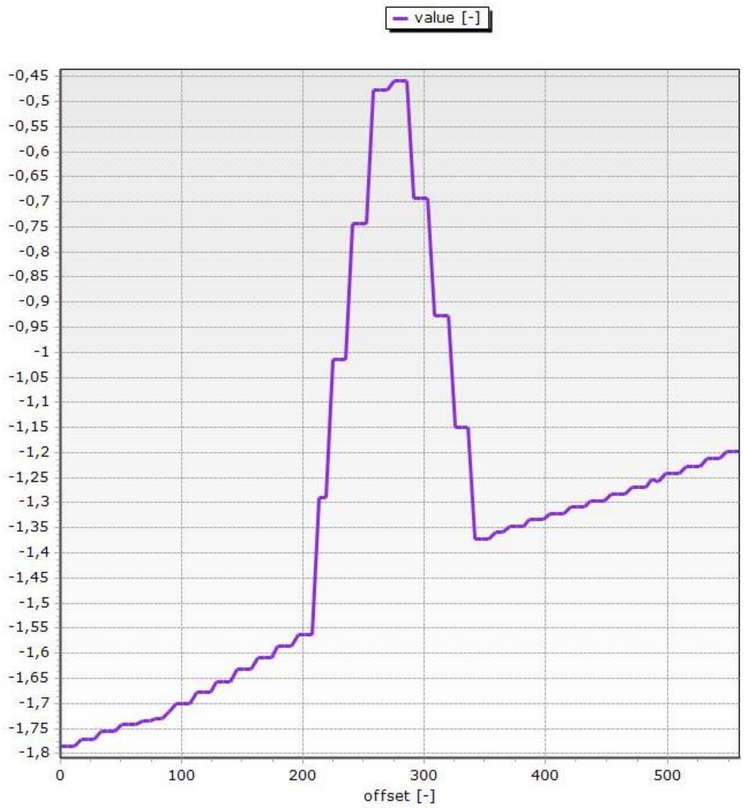


Figure 5-18 Bed level - cross section chenier - note vertical scale and horizontal scale are different

5.10.2 Hydrodynamic scenarios

The goal of applying different hydrodynamic scenarios is to investigate the impact of occurring conditions throughout the year on the coastal system in Demak. This provides insight in which conditions are dominant for the coastal system in Demak. By mimicking three hydrodynamic conditions that occur in the year it gives a realistic representation. It also provides insight in the flow pattern and shear stresses which can be used in the determination of the location for the fine sediment nourishment. It is recognized that flow patterns do not represent net sediment transport; it is only used as a first indicator.

Detailed information on the hydrodynamic scenarios can be found in Appendix E Hydrodynamics.

1. NORTH-WEST MONSOON

The North-West monsoon starts in December and ends in February. This scenario investigates the behaviour of the system over a long period by relatively high wave forcing, Table 5-7.

Time	**3 (December – February)**	**[months]**
Wave height (significant)	0.6	[m]
Wave period (mean)	4.7	[s]
Wave direction	310	[°]
Wind speed	4.4	[m s^{-1}]
Wind direction	280	[°]

Table 5-7 Hydrodynamic parameters in the North-West monsoon

2. SOUTH-EAST MONSOON

The South-East monsoon starts in May and ends in September. This scenario investigates the behaviour of the system over a long period by relatively low wave forcing, Table 5-8. Though, it is recognized that in the South-East monsoon there is a strong day-night breeze at the end of the day. When the land warms up during the day it attracts strong wind from the sea perpendicular to the coast. This increases the wave attack on the coast but this phenomenon is not included in this research.

Time	**5 (May – September)**	**[months]**
Wave height (significant)	0.4	[m]
Wave period (mean)	4.5	[s]
Wave direction	110	[°]
Wind speed	3.0	[m s^{-1}]
Wind direction	110	[°]

Table 5-8 Hydrodynamic parameters in the South-East monsoon

3. STORM

This scenario investigates the behaviour of the system over a very short period by extreme wave forcing in the North-West monsoon, Table 5-9.

Time	**3**	**[days]**
Wave height (significant)	2.1	[m]
Wave period (mean)	5.9	[s]
Wave direction	300	[°]
Wind speed	11	[m s^{-1}]
Wind direction	290	[°]

Table 5-9 Hydrodynamic parameters in a storm

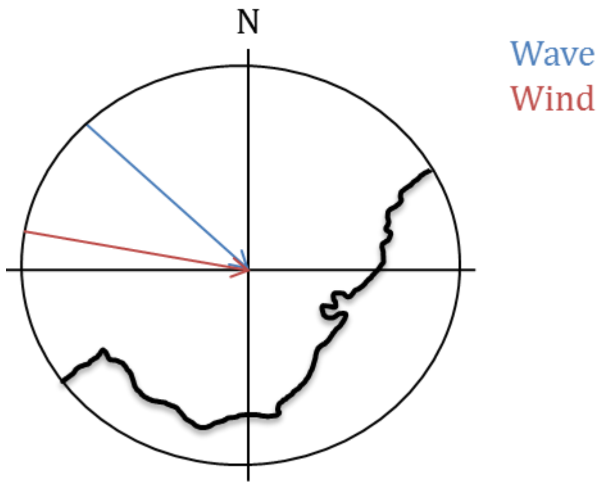


Figure 5-19 Wave (blue) and wind (red) direction in North-West monsoon

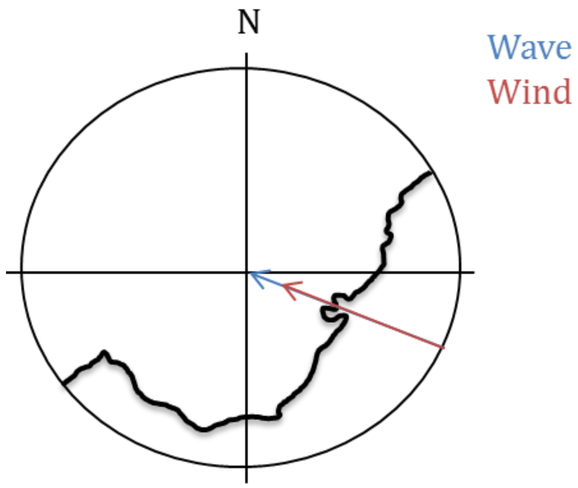


Figure 5-20 Wave (blue) and wind (red) direction in South-East monsoon

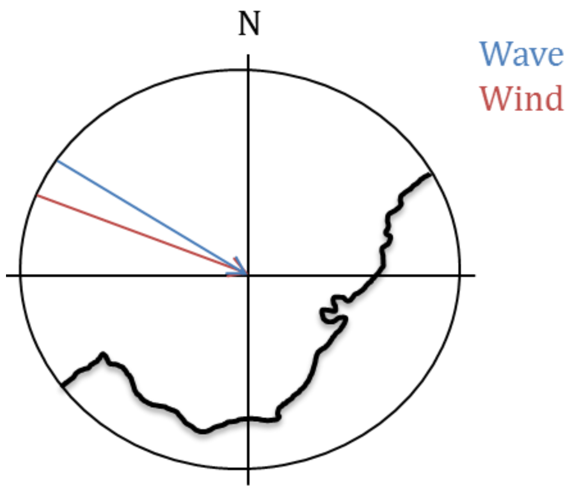


Figure 5-21 Wave (blue) and wind (red) direction in a storm

5.10.3 Nourishment location scenarios

Note, the nourishment locations are determined on the basis of system understanding and interpretation of the hydrodynamics in the coastal system of Demak.

GOAL OF THE NOURISHMENT

The project goal is to stabilize and strengthen the western side of Bedono through active sediment management. The supply of extra sediment is done by the use of a fine sediment nourishment and intended to lead to accretion near the coast. The transport and distribution of sediment should all be done by natural processes. The stimulation of coastal accretion through sediment supply is under development to form an alternative for the traditional approach with semi-permeable dams.

Two nourishment location options are discussed in this chapter: at the coast and nearshore. The goal of the nourishment at the coast is to stay in place and only smoothly spread out in the nearby surroundings. While the nourishment in front of the coast first needs to transport in the correct direction and subsequently settle.

NOURISHMENT COMPOSITION

The properties of the nourishment material are an important feature for the strategy. It influences the way of transport, settling behaviour and the way of execution. In the model, the nourishment material is represented by three different particles which are defined according their fall velocity. This provides insight in the influence of the material on the distribution. The composition of the sediment is based on expert judgement and the data available of sediment characteristics in the Demak coastal system, Figure 5-22. Three particle sizes (Inorganic Matter) can be retrieved from practical measurements, Figure 5-22. The fall velocity and critical shear stress for erosion are obtained from expert judgement, Table 5-10.

The value for the critical shear stress for erosion can be influenced by the way of execution and the time between the execution and exposure to the hydrodynamic forcing. For instance, recently nourished material is less dense and easy erodible. While more consolidated material lead to higher critical shears stresses for erosion.

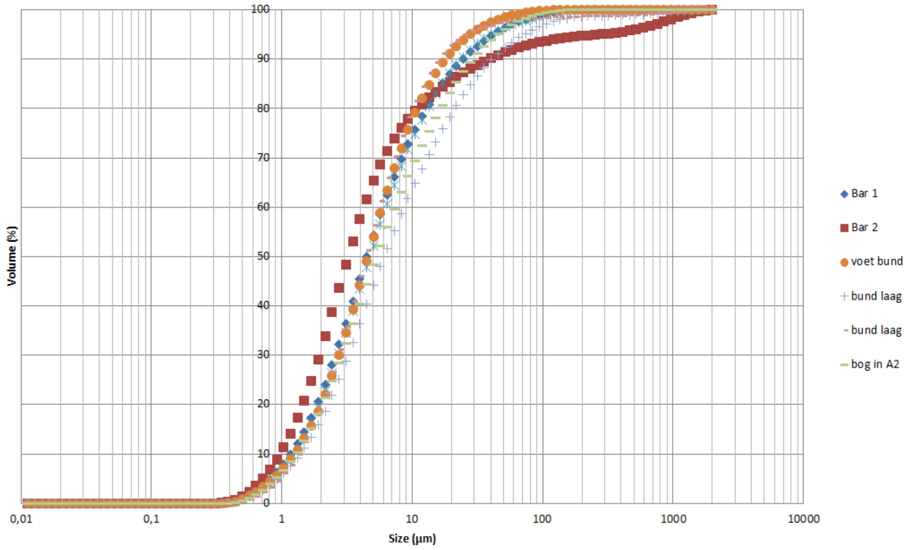


Figure 5-22 Example particle size distribution of autochthonous sediment Demak

Inorganic Matter 1 (IM1)	Particle size	20	[μm]
[85% volume is smaller]	Fall velocity	1	[mm s^{-1}]
	Critical shear stress for erosion	0.50	[N m^{-2}]
Inorganic Matter 2 (IM2)	Particle size	4.5	[μm]
[50% volume is smaller]	Fall velocity	0.5	[mm s^{-1}]
	Critical shear stress for erosion	0.5	[N m^{-2}]
Inorganic Matter 3 (IM3)	Particle size	3	[μm]
[25% volume is smaller]	Fall velocity	0.25	[mm s^{-1}]
	Critical shear stress for erosion	0.5	[N m^{-2}]

Table 5-10 Composition nourishment material autochthonous sediment

EXECUTION METHOD

In practice the nourishment is realised through discharging the mixture of fine sediments and water into the intended location. The exact placement method depends on the available equipment and local circumstances while the consolidation time is crucial for the erodibility of the nourishment. Detailed elaboration concerning the execution method is provided in Chapter 7 Execution.

In the model the active sediment management is executed through making sediment available in the bed. Not the process of the actual nourishment through the water column is simulated but it is assumed that the sediment is already in place. The reason for this is that not the actual nourishment placement is the research goal but the net transport of the fine sediment nourishment.

In the model the sediment remains in place if the hydrodynamic forcing is below the critical shear stress for erosion. If the hydrodynamic forcing is larger than the critical shear stress for erosion the sediment is brought into suspension and subsequently transported over a horizontal distance.

The software for the simulating the sediment dynamics is DELWAQ. The nourishment is added to the bed before the start of the hydrodynamic forcing and the magnitude is specified in g/m^2. DELWAQ does not include updating of the bed and therefore the nourishment is not affected by the hydrodynamics. It is only a sediment source in the bed. The magnitude is derived from the density of in-situ material, 1200 kg/m^3 which is translated to an initial sediment availability in DELWAQ of 1,200,000 g/m^2. Note, this research is not about absolute values and exact numbers but about the net sediment transport direction ('tracer study'). The initial sediment availability is the same for all nourishment locations and it does not represent the actual configuration of the nourishment in practice. It is used to determine the sediment transport from that location.

NOURISHMENT LOCATION

The location of the nourishment is crucial for the distribution of the sediment. The location of the nourishment is based on system understanding. For instance, in the North-West monsoon the dominant current direction is to the north while in the South-East monsoon the current direction is southwest. These features are taken into account for the proposition of the start position of the nourishment.

The start locations of the nourishment can be divided into two main sections: at the coast and in front of the coast. The nourishment options at the coast are intended to stay in place and smoothly build out along the coast. While the nourishment options nearshore first need to be brought into re-suspension and subsequently transported to the coast, see Figure 5-23, Figure 5-24, Figure 5-25 and Figure 5-26.

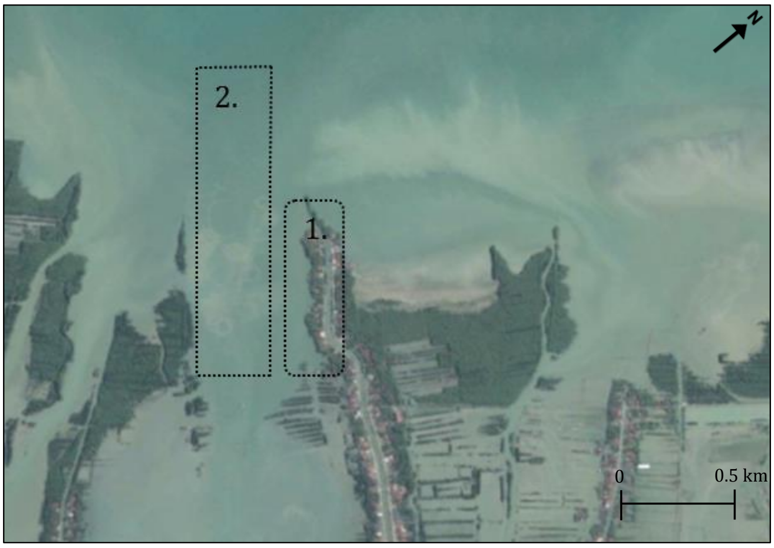


Figure 5-23 Indication possible nourishment locations (Google Earth, 2016)

Figure 5-24 Nourishment option coast - full coastline

Figure 5-25 Nourishment option coast - peninsula

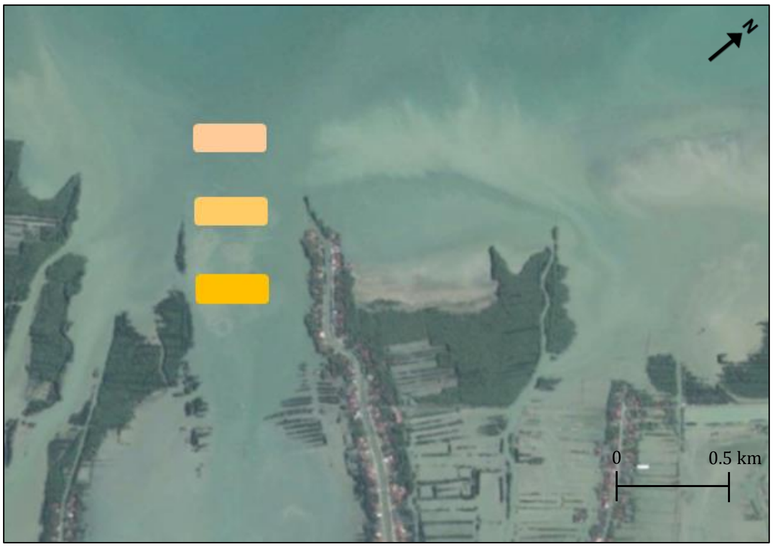


Figure 5-26 Nourishment option nearshore - three options in front of the coast

5.11 Model considerations

Before presenting the model results it is important to keep in mind that the model is used as a tool to assist the theories about the processes in the Demak coastal system. The model represents schematic situations and is used for comparing the various scenarios mutually. This paragraph briefly elaborates on the assumptions and important considerations made during the translation process from reality and theory to the model.

FM

The software Delft3D Flexible Mesh is used for the simulation of the hydrodynamics. The hydrodynamic boundaries consist of tidal constituents, constant wave height and constant wind speed. The constant wave height and wind speed are an overestimation and do not represent the real situation. In reality higher waves alternate smaller waves and the wind speed also varies during day and night.

The hydrodynamics are assembled in the FLOW and WAVE modules. The FLOW module includes the tidal components and the wind within the FLOW grid while the WAVE module includes the wave and wind input over the WAVE grid. The interaction and communication between these modules is the so called coupling time. The latter is put on one hour which means every one hour "model time" these files exchange their information. This process is called 'online' running. The exchange of information between the FLOW and WAVE module is of great importance for the wave height because the propagation of waves and the location of wave breaking depend on the actual water depth. Wave breaking is the largest contributor to the total bottom shear stress which is essential for this research. The magnitude and location of the total bottom shear stress varies due to the dynamic coupling between the water level and the wave propagation. This is in accordance with the theory which states that waves stir-up sediment in the nearshore and subsequently the tide transports the sediment over a horizontal distance.

The hydrodynamic computation time is reduced due to the creation of an 'artificial tide'. The original spring-tidal cycle with all intermediate cycles is replaced by one full spring tidal cycle composed of one high tide and one low tide that is repeated. To support this assumption extensive research is done on the total bottom shear stress, water movement and sediment transport for two extremes in the original spring-neap tidal cycle, see E.2 Spring tide and neap tide comparison.

Subsidence plays an important role in the coastal erosion of Demak but this is not considered in the model.

DELWAQ

The sediment dynamics are simulated in DELWAQ based on the hydrodynamics from Delft3D Flexible Mesh. There is no background sediment in the system and the only sediment origins from the nourishment. The sediment from the nourishment is placed in the first bed-layer as a source and does not changes the bottom topography. Subsequently the hydrodynamic forcing brings the sediment in re-suspension and transports it over a horizontal distance. Once the sediment is settled it is stored in the first bed-layer and again this does not change the bottom topography. The nourishment and sediment deposits do not influence the hydrodynamics. This forms the most important consideration of the approach.

It is recognized that normally the placement of a nourishment would largely changes the local hydrodynamics. The sequence and effect of a submerged nourishment on the bottom level is explained towards two directions. Firstly, the nourishment increases the bed level and thereby induces higher shear stresses due to wave breaking and the shallower water depth. On the other hand, the reversed behaviour is used in this research and is described as follows: (1) the nourishment reduces the total bottom shear stress at its own location (2) sediment erodes from the nourishment, deposits in the nearby environment and reduces the total bottom shear stress in this area (3) the total bottom shear stress on the original nourishment location is further reduced due to the deposits in the surroundings. The effect is that the total bottom shear stresses in the environment decrease due to the changes in bottom topography.

The total bottom shear stresses are continuous overestimated in the model and thereby the erosion rate. This is not a research on exact numbers and the model is suitable for the intended 'tracer study' goal. Though, it is important to take this important limitation into account for the understanding of the nourishment.

The nourishment in the bed represents a stable in place nourishment and does not take into account the nourishment process. The sediment is added to cells in the grid and does not incorporate realistic execution steps to maintain the nourishment in place. How this can be done is explained in Chapter 7 Execution.

Chapter 6 Model results

The model results start with the hydrodynamics results. The bottom shear stress and flow pattern are the two most important observed features. This is done for a bathymetry without chenier and with chenier during the North-West monsoon, South-East monsoon and a storm. Subsequently, sediment displacements are summarized in the sediment dynamic analysis. Each chapter contains a summary of the results and the implications are described in Chapter 8 Discussion.

The hydrodynamics and sediment dynamics are schematized in an overview, see Figure 6-1.

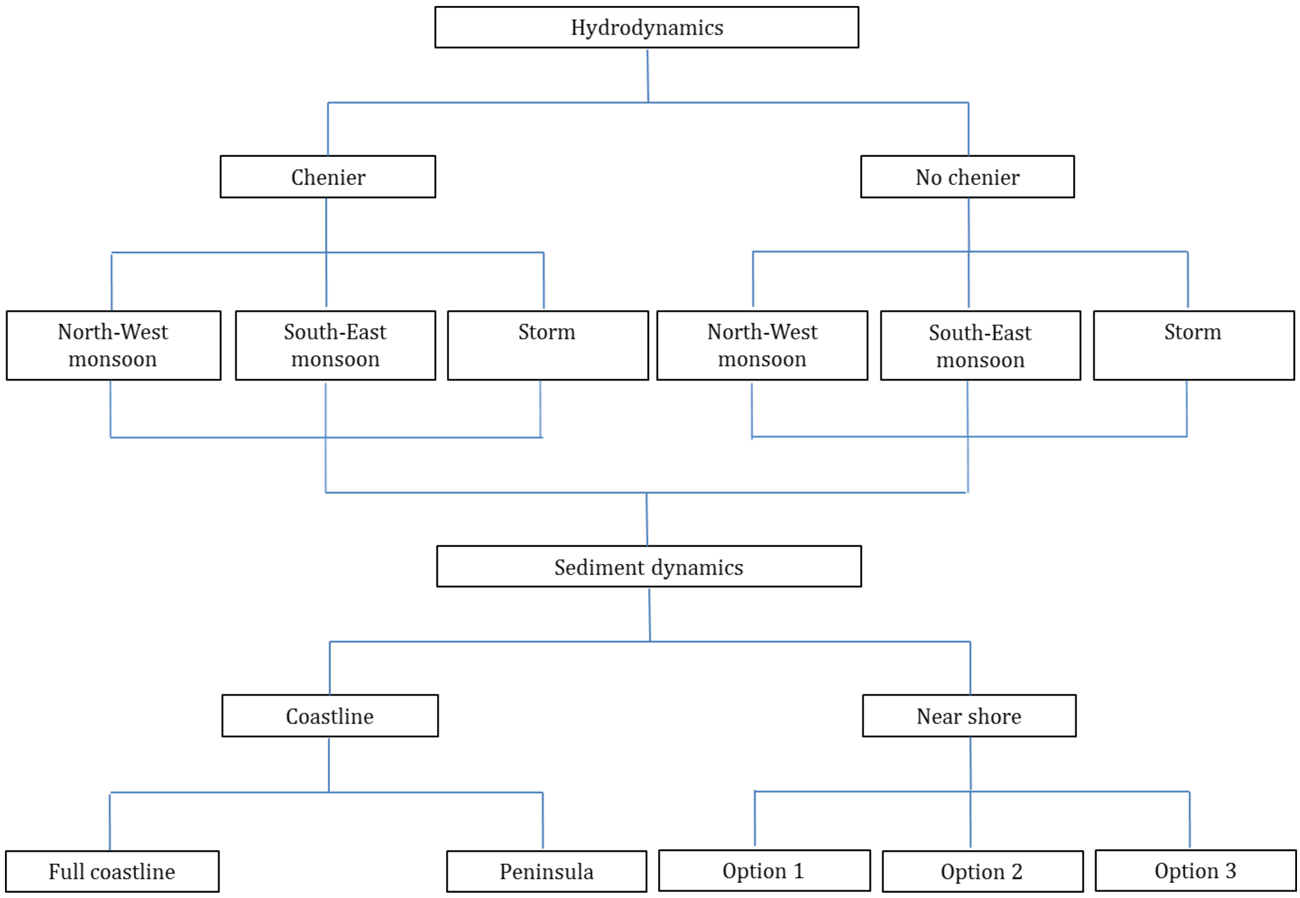


Figure 6-1 Overview scheme hydrodynamics and sediment dynamics

6.1 Hydrodynamic results

The most important hydrodynamic features, flow direction and shear stress, in the coastal system of Demak form the pre-study for the nourishment execution. The flow direction can predict the direction of the sediment transport while the shear stress indicates areas for erosion and deposition. Note, the flow direction is not the same as the net sediment transport direction. Sediment transport only takes place when sediment is stirred up and subsequently transported through the water column in the water movement. The flow direction in combination with the stirring capacity determines the sediment transport direction. The water movement in this analysis is only used as a pre-assessment tool for the sediment transport direction.

Firstly, the influence of the tide, wave and wind are assessed because this provides insight in which process is dominant in the area of interest. Two coastal configuration scenarios and three hydrodynamic scenarios are analysed through a sequence of adding each separate component and analyse the changes. The assessment is done on the dominant flow direction and the resulting shear stress.

All results on flow direction, shear stress and wave height are in Appendix E Hydrodynamics.

The sequence of information in the next paragraph is as follows:

6.1.1 Bottom topography

- Bottom topography no chenier
- Bottom topography chenier

6.1.2 Summary hydrodynamics – no chenier

- Summarized shear stress and flow direction in the North-West monsoon, South-East monsoon and Storm scenario

6.1.3 Summary hydrodynamics – chenier

- Summarized shear stress and flow direction in the North-West monsoon, South-East monsoon and Storm scenario

6.1.1 Bottom topography

Two different bottom profiles are used. The first is the original bottom profile without chenier and the second is the original bottom profile with chenier. The bed level gradually increases in the area of interest from -1.5 m to -1 m, see Figure 6-2. The chenier is 30 m wide and raises the bed level to 0.5 m below the water level, see Figure 6-3.

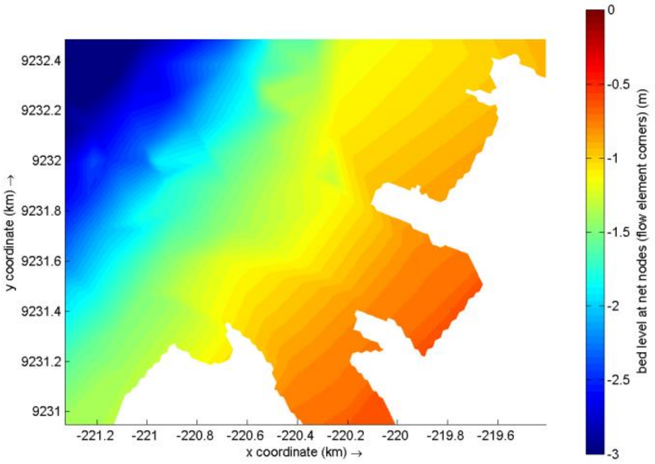


Figure 6-2 Bathymetry without chenier

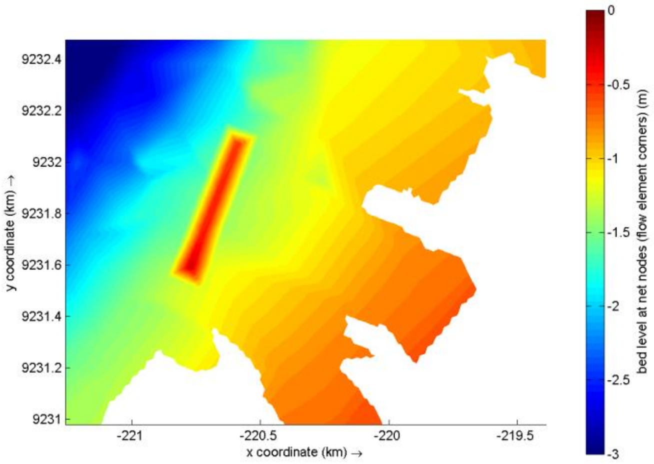


Figure 6-3 Bathymetry including chenier

6.1.2 Summary hydrodynamics – no chenier

The hydrodynamics composed of tide, wave and wind for the three hydrodynamic scenarios are summarized in Figure 6-4, Figure 6-5 and Figure 6-6. The influence of each separate component is investigated in E.7.1 North-West monsoon, E.7.2 South-East monsoon and E.7.3 Storm. This research confirmed that the wave component is dominant for the shear stress and also influences the flow direction.

The focus in this section is on the shear stress and velocity vector flow pattern. The shear stress and velocity vectors are considered as the two most important features that can assist in the assessment for the location and effect of a nourishment. The critical shear stress for erosion is 0.5 N/m^2 and the velocities are in the order of decimetres per second. Note, the shear stress figures show a snapshot while the velocity vector pattern shows a snapshot with an over layer with thicker vectors which are the summarized pattern over time.

In the North-West monsoon the shear stresses vary above and below the critical shear stress for erosion. During low tide the waves break in the area of interest due to the decrease in water depth and induce larger shear stresses. While during high tide the larger water depth allows further propagation of waves till the moment of breaking is reached. This is the ratio between the wave height and the water depth. The shear stresses are dominated by wave breaking and the very shallow water depth. The water movement in the area of interest is alongshore in northern direction but there is also water movement observed in cross-shore direction due to ebb and flood tidal influence, see Figure 6-4.

In the South-East monsoon the shear stress stay below the critical shear stress for erosion and water movement is in southern direction. The reason for the small shear stresses is that the waves in this hydrodynamic scenario do not reach the coast. The waves are from southeast direction and do not refract into the sheltered Bedono coast. These hydrodynamic circumstances do not induce sediment transport because the ambient shear stress stays below the critical shear stress for erosion, see Figure 6-5.

In the storm scenario the shear stresses fluctuate above and below the critical shear stress for erosion. The higher waves break earlier on the foreshore and therefore the highest shear stresses occur in this area. The incoming waves have a significant wave height of 2.1 m while the water depth at the edge of the observed area fluctuates around 2 m. The ratio of the wave height and the water depth is 0.95 which implicate waves are breaking there. The dominant water movement is alongshore in northern direction, see Figure 6-6.

Detailed elaboration on wave height, water depth, shear stress and velocity vectors are in E.7 Results without chenier.

Note, the shear stress figures show a snapshot while the velocity vector pattern figures show a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The shear stress range is 0 – 2 N/m^2 while the flow velocity range is 0 – 0.2 m/s

SHEAR STRESS VELOCITY VECTOR

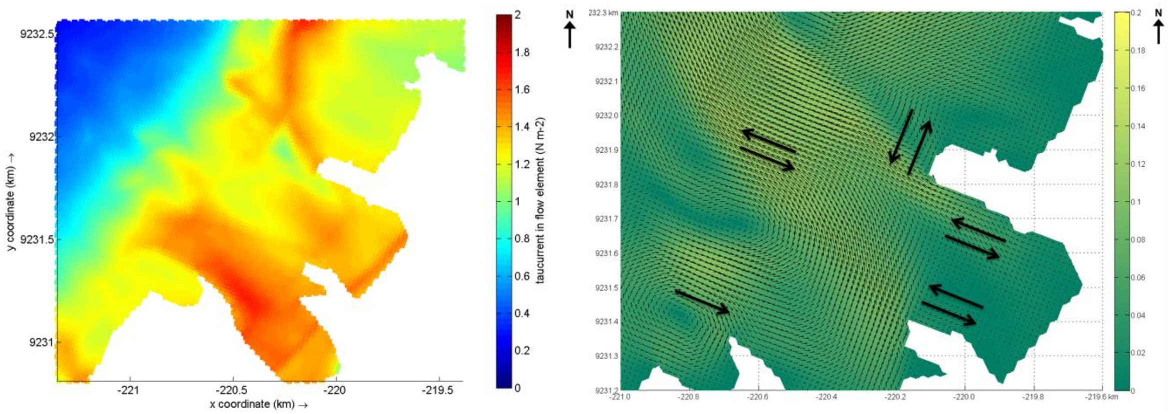


Figure 6-4 Shear stress (left) and flow pattern (right) – North-West monsoon

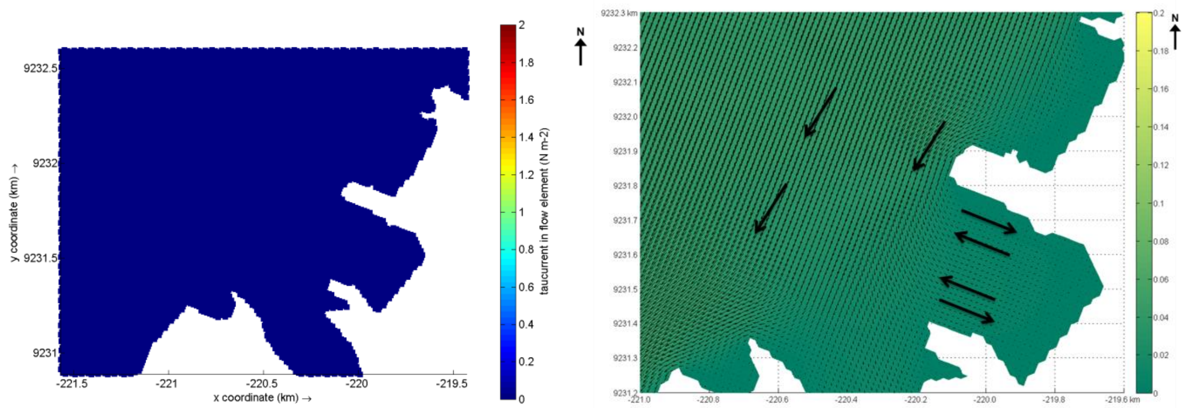


Figure 6-5 Shear stress (left) and flow pattern (right) – South-East monsoon

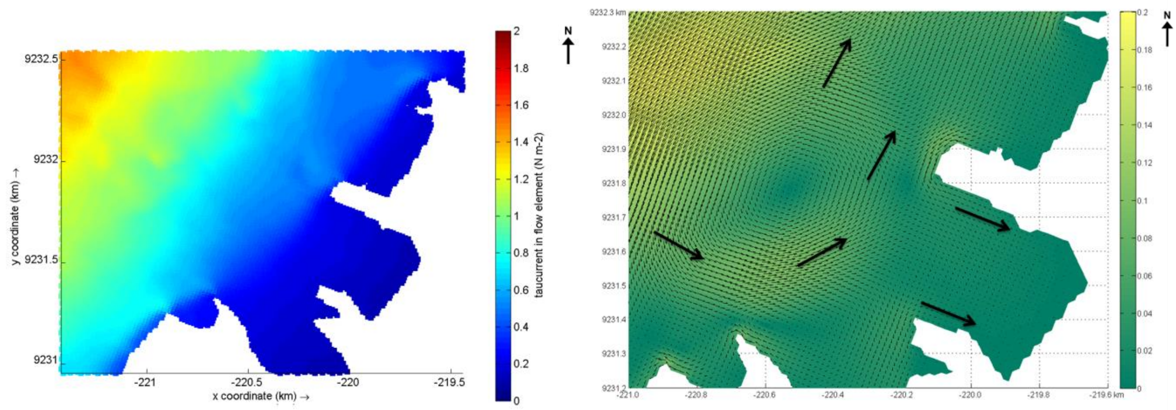


Figure 6-6 Shear stress (left) and flow pattern (right) – storm

6.1.3 Summary hydrodynamics – chenier

The hydrodynamics composed of tide, wave and wind for the three hydrodynamic scenarios are summarized in Figure 6-7, Figure 6-8 and Figure 6-9. The influence of each separate component is investigated in E.8.1 North-West monsoon, E.8.2 South-East monsoon and E.8.3 Storm. The critical shear stress for erosion is 0.5 $N/m^2$and the velocities are in the order of decimetres per second. Note, the shear stress figures show a snapshot while the velocity vector pattern shows a snapshot with an over layer with thicker vectors which are the summarized pattern over time.

In the North-West monsoon the shear stresses are high on the chenier because the local raise in bed level induces wave breaking. Direct between the chenier and the coast the shear stress is reduced while after one kilometre the shear stresses increase again. This is contributed to the small water depth and possibly to the regeneration of waves in shallow water. The dominant flow direction remains in the area of interest alongshore in northern direction while the water movement observed in cross-shore direction is less visible, see Figure 6-7.

In the South-East monsoon the shear stress stay below the critical shear stress for erosion and water movement is in southern direction. The chenier slightly effects the hydrodynamics but this does not have consequence for the water movement, sediment re-suspension and sediment transport, see Figure 6-8.

In the storm scenario the shear stresses increase on the foreshore and have the same high stresses on the chenier. The incoming waves have a significant wave height of 2.1 m while the water depth at the edge of the observed area fluctuates around 2 m. The ratio of the wave height and the water depth is 0.95 which implicate waves are breaking there. Again after the chenier the shear stresses reduce and increase after one kilometre. The dominant water movement stays alongshore in northern direction, see Figure 6-9.

The most important conclusion on the hydrodynamics analysis with cheniers is that it does have effect on the shear stresses and flow direction. The effect on the shear stress is in the first kilometre behind the chenier. The flow directions are slightly different than without cheniers but still in the same general direction.

Detailed elaboration on wave height, water depth, shear stress and velocity vectors are in E.8 Results with chenier. While the effect on the sediment transport is assessed in 6.2 Sediment dynamics results.

Note, the shear stress figures show a snapshot while the velocity vector pattern figures show a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The shear stress range is 0 – 2 N/m² while the flow velocity range is 0 – 0.2 m/s

SHEAR STRESS

VELOCITY VECTOR

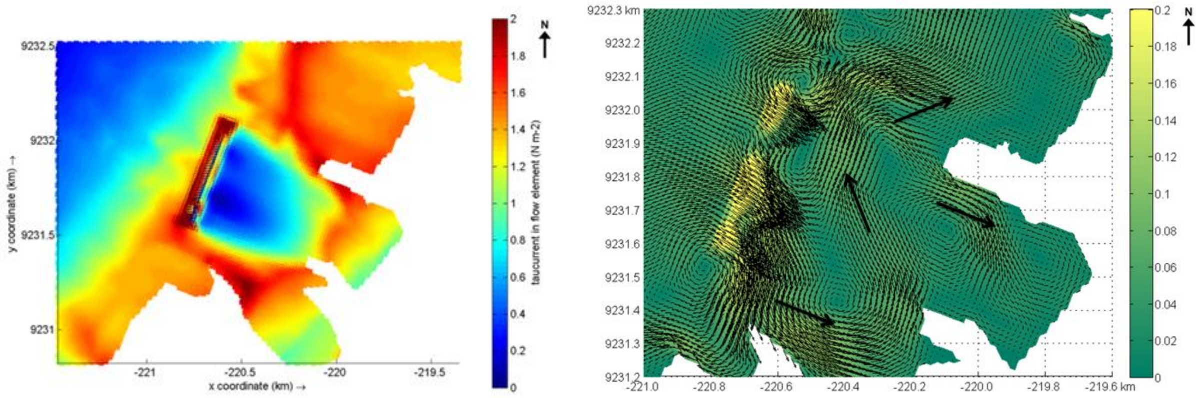


Figure 6-7 Shear stress (left) and flow pattern (right) – North-West monsoon

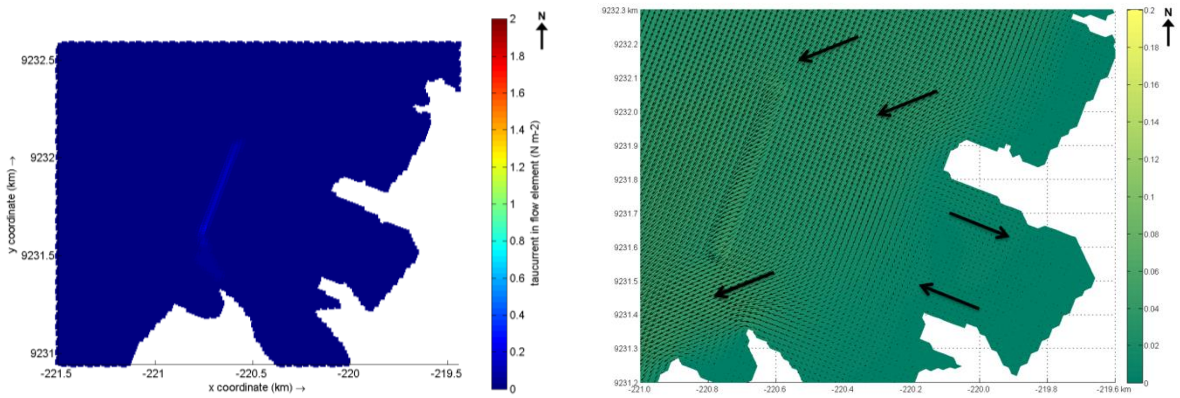


Figure 6-8 Shear stress (left) and flow pattern (right) – South-East monsoon

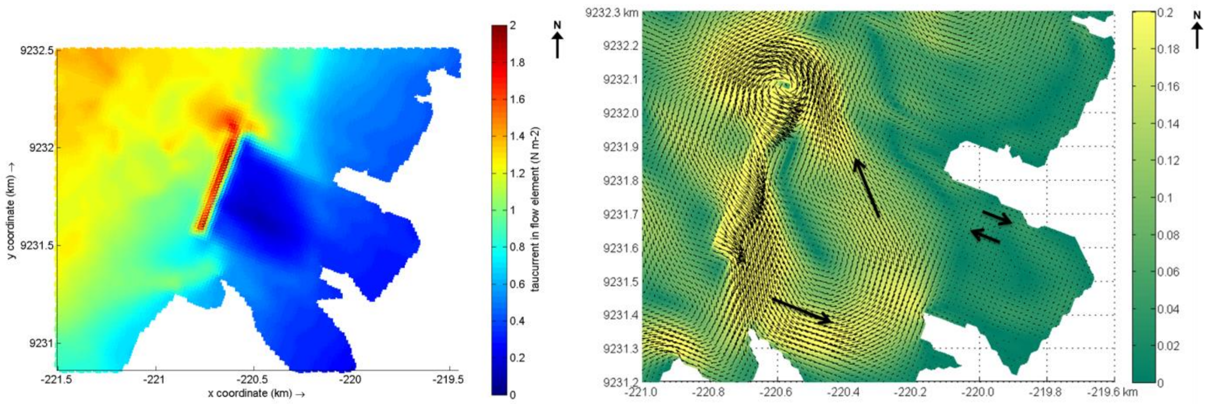


Figure 6-9 Shear stress (left) and flow pattern (right) – storm

6.2 Sediment dynamics results

Three nourishment configurations are investigated to assess the distribution of sediment. Location 1 is a nourishment along the full coastline of Bedono while location 2 is a nourishment perpendicular to the coast. Location 3 is a nourishment near-shore and is subdivided in three locations with different distances to the coast.

Each grid cell has an area of 361 m^2 (19 x 19 m) and starts with 1200 kg/m^2. The same fixed volume of initial sediment is used in each nourishment configuration. Note, this research is not about absolute values and exact numbers but about the net sediment transport direction ('tracer study'). To make the comparison of alternatives equal there is chosen for a fixed volume of sediment. This volume does not represent the actual configuration of the nourishment in practice. It is used to determine the sediment transport from that location.

To identify the behaviour of different sediment particles (in reality the nourishment exists of different sizes) and to identify the sensitivity of these parameters - three sediment particles from the 'coarsest fine sediment' to 'very fine sediment' are investigated. Particle 1 (IM1) is the coarsest fine sediment particle with a fall velocity of 1 mm/s. Particle 2 (IM2) and particle 3 (IM3) have a fall velocity of 0.5 and 0.25 mm/s. The critical shear stress for erosion is set on 0.5 N/m^2 for all three particles. The conclusion is that particles with a smaller fall velocity are transported further. Their settling time to the bottom is longer and in this extra time the particles are transported over a larger horizontal distance. There is no difference in transport pattern because all particles are subjected to the same hydrodynamic forcing. The comparison and behaviour of the other particles is demonstrated in F.2 Interpretation behaviour IM1, IM2 and IM3.

The most important assessment tools are map overviews with the sediment concentration and the sediment storage in bed layer S1. The latter is the only active bed layer which is often referred to as the 'fluffy erodible' layer. Furthermore, in this section the results are based on one sediment particle, IM1.

All results on sediment concentration and sediment storage are in Appendix F Sediment dynamics.

The sequence of information in the next paragraph is as follows:

6.2.1 Start position nourishment

6.2.2 Summary sediment dynamics – no chenier

- End situation sediment storage in bed layer S1 for all nourishment configurations after the North-West monsoon.

6.2.3 Summary sediment dynamics – chenier

- End situation sediment storage in bed layer S1 for all nourishment configurations after the North-West monsoon.

6.2.1 Start position nourishment

Note, the figures demonstrate the initial sediment storage in the first bed layer S1. The storage in the bed is expressed in a range of 0 – 12 10^5 g/m^2 which is equal to the nourishment in-situ density of 1200 kg/m^2.

SEDIMENT STORAGE IN FIRST BED LAYER S1 – INITIAL

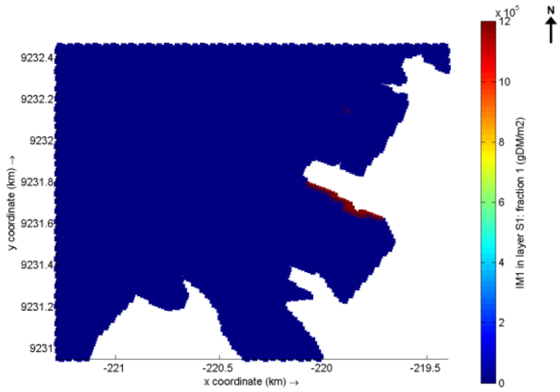


Figure 5-10 Initial position nourishment option full coastline

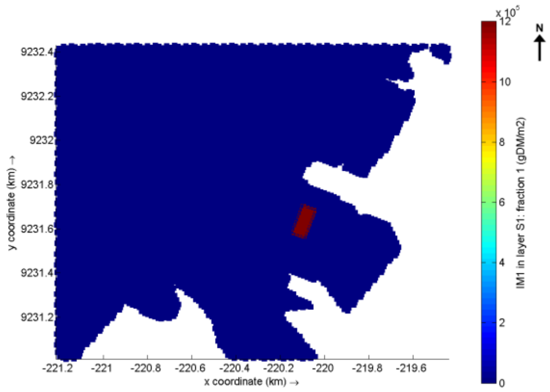


Figure 5-12 Initial position nourishment option 1 nearshore

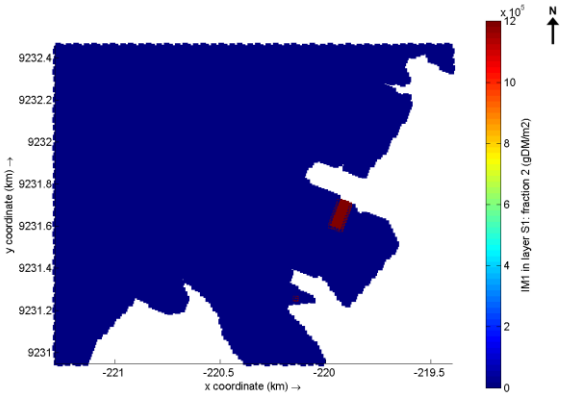


Figure 5-11 Initial position nourishment option peninsula

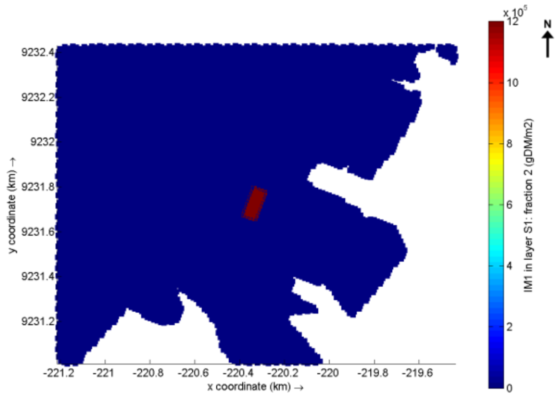


Figure 5-13 Initial position nourishment option 2 nearshore

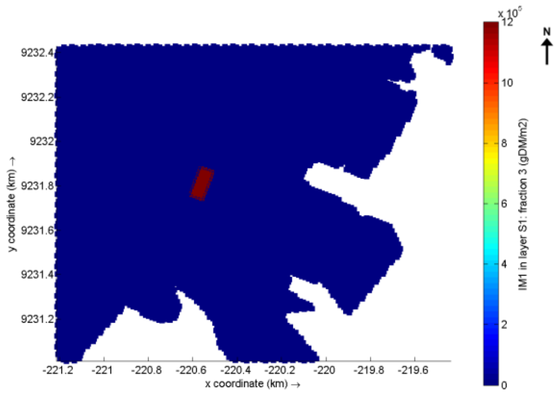


Figure 5-14 Initial position nourishment option 3 nearshore

6.2.2 Summary sediment dynamics – no chenier

This section elaborates on the displacement of sediment from five nourishment configurations after the North-West monsoon and for the bottom topography without chenier.

The reduction in the amount of results in this section is made by the interpretation of the three hydrodynamic scenarios. The North-West monsoon induces sediment transport and changes the nourishment configuration. In the South-East monsoon there is no sediment transport as predicted on the total bottom shear stress in the previous section. The storm scenario has a small impact although the conditions are more extreme. The relative short time period of three days induces sediment transport but not in the same order of magnitude of the full North-West monsoon period of three months. The shorter time period is taken into account in the interpretation. The most important observation is that the nourishment does not vanishes under the storm scenario.

Subsequently, the most favourable nourishment configuration within the North-West monsoon is shown in here. The nourishment is intended to create a bottom profile from the coast where mangrove re-esthablishment can occur. The bottom profile is not possible to reproduce in the model. The results provide insight in the distribution of fine sediment from different nourishment locations and the storage in bed layer S1 after three months of North-West monsoon forcing.

The most important assessment tools are the map overviews with the sediment concentration and the sediment storage in bed layer S1.

The color axis for the sediment storage in bed layer S1 is from 0 to 100,000 g/m^2 Dry Matter (DM). Dry Matter is the synonym for the used particle Inorganic Matter 1 (IM1). As an indication, the red areas are 100 kg/m^2 Dry Matter. With an estimated in-situ sediment density of 1200 kg/m^3 the red areas form a sediment deposit of 8 cm. It is not about the absolute value but this gives an indication to which area the largest part of the nourishement sediment is transported.

The color axis for the sediment concentration is from 0 to 500 g/m^3 Dry Matter (DM). The red areas are equivalent to 0.5 g/l concentration induced by the forcing and the only available sediment from the nourishment.

The sediment concentration and the sediment storage in the bed layer S1 have the same distribution pattern. This follows from the interaction between the erosion and the increase in the sediment concentration and between the deposition and the decrease in sediment concentration. Therefore in this section only the sediment storage in bed layer S1 is demonstrated.

The nourishment along the full coastine of Bedono is distributed perpendicular to the coast but also in cross-shore direction, see Figure 5-15.

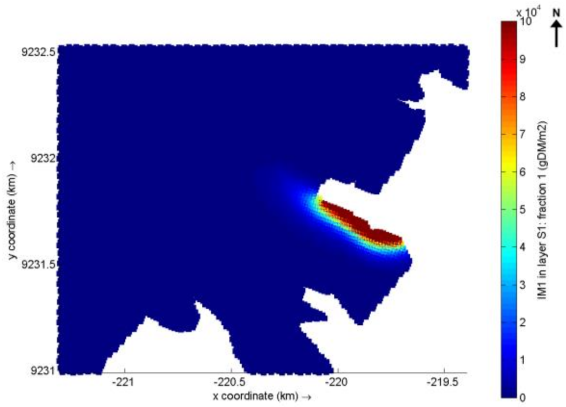
The nourishment with the peninsula shape follows the same distrubution behaviour as the full coastline nourishment because of the same hydrodynamics on that location, see Figure 5-16.

The nourishment in front of the coast demonstrate different behaviour. Option 1 nearshore, is the closest to the coastline of Bedono and spreads towards the coast in multiple directions but also in offshore direction, see Figure 5-17. Option 2, is located further offshore and shows a more elongated distribution pattern. The sediment from the nourishment does not reach the coastline of Bedono and is transported more in offshore direction, see Figure 5-18. Option 3 nearshore, is the nourishment the with the largest distance to the coast. The spreading of sediment is dominant offshore directed and does not reach the intended coastline of Bedono, see Figure 5-19.

All results on sediment concentration and sediment storage are in F.4 Option full coastline, F.5 Option peninsula, F.6 Option 1, F.7 Option 2 and F.8 Option 3.

Note, the figures demonstrate sediment storage in the first bed layer S1 after 3 months in the North-West monsoon. The storage in the bed is expressed in a range of 0 – 10^5 g/m^2.

SEDIMENT STORAGE IN FIRST BED LAYER S1 – AFTER 3 MONTHS NORTH-WEST MONSOON



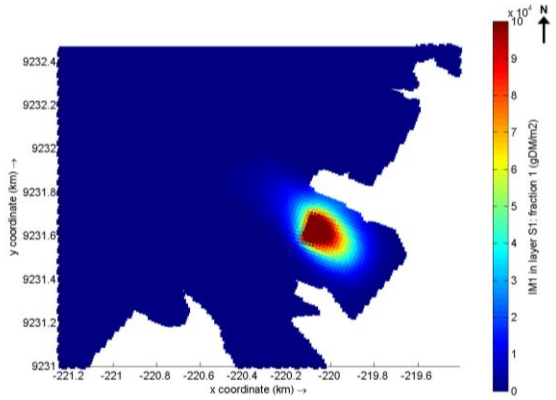
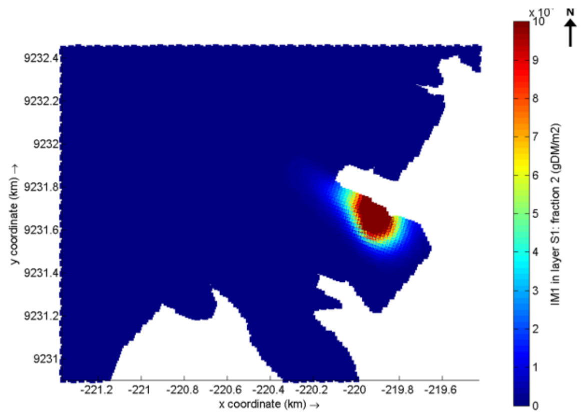


Figure 5-15 Position nourishment option full coastline after 3 months   Figure 5-17 Position nourishment option 1 nearshore after 3 months



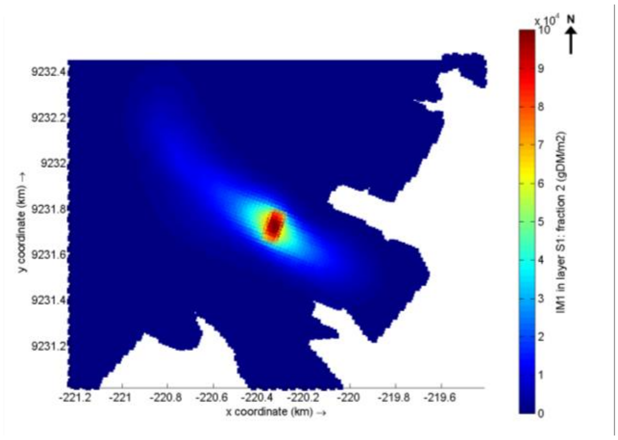


Figure 5-16 Position nourishment option peninsula after 3 months   Figure 5-18 Position nourishment option 2 nearshore after 3 months

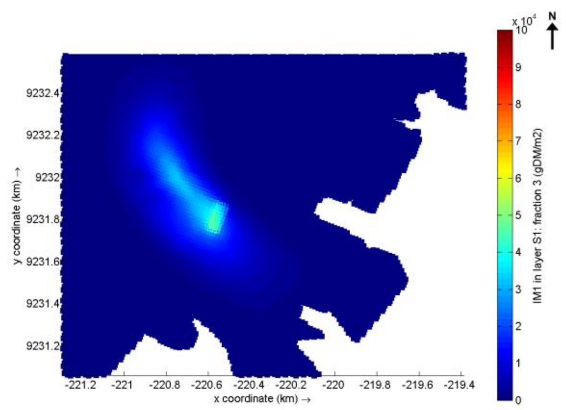


Figure 5-19 Position nourishment option 3 nearshore after 3 months

6.2.3 Summary sediment dynamics – chenier

This section elaborates on the displacement of sediment from nourishment configurations after the North-West monsoon and with the bottom topography including chener.

The most important assessment tools are the map overviews with the sediment concentration and the sediment storage in bed layer S1.

The color axis for the sediment storage in bed layer S1 is from 0 to 100,000 g/m^2 Dry Matter (DM). Dry Matter is the synonym for the used particle Inorganic Matter 1 (IM1). As an indication, the red areas are 100 kg/m^2 Dry Matter. With an estimated in situ sediment density of 1200 kg/m^3 the red areas form a sediment deposit of 8 cm.

The color axis for the sediment concentration is from 0 to 500 g/m^3 Dry Matter (DM). The red areas are equivalent to 0.5 g/l concentration induced by the forcing and the only available sediment from the nourishment.

The sediment concentration and the sediment storage in the bed layer S1 have the same distribution pattern. This follows from the interaction between the erosion and the increase in the sediment concentration and between the deposition and the decrease in sediment concentration. Therefore in this section only the sediment storage in bed layer S1 is demonstrated.

The nourishment along the full coastline is distributed perpendicular to the coast and slightly in offshore direction, see Figure 5-20. The transport in offshore direction is less than without chenier. The magnitude of displacement in perpendicular direction is similar. Reason for this is the identical ambient shear stresses in this part of the researc area.

The peninsula nourishment is equally distrubuted along the coast and in cross-shore direction, see Figure 5-21. The transport in offshore direction is more restricted compared to the peninsula nourishment without chenier. The magnitude of sediment transport is in the same order due to identical ambient shear stresses.

Nourishment option 1 nearshore is located between the chenier and the coast with the shortest distance to the coast. It shows dominant sediment displacement towards the coastline in multiple directions, see Figure 5-22. The sediment transport in cross-shore direction is reduced by the chenier.

Nourishment option 2 nearshore is located with equal distance between the chenier and the coast. The shear stresses are mainly below the critical shear stress for erosion due to the chenier. Therefore the sediment transport is very small, see Figure 5-23.

Nourishment option 3 nearshore is located direct behind the chenier. The shear stresses remain all the time below the critical shears tress for erosion and lead to no sediment transport, see Figure 5-24.

In general can be concluded that the introduction of the chenier to the bottom topography leads to smaller shear stresses behind the chenier up to 1 km. On the side of the chenier and after 1 km the shear stress increases due to the generation of wind waves in very shallow water and the shallow water depth. The consequence is that nourishment within 1 km behind the chenier are not brought into re-suspension and transported to the coastline of Bedono. The nourishments along the coast are exposed to the same magnitude of shear stresses in the scenario without and with chenier. Therefore, the general sediment distrubution is the same. The chenier does have an influence on the cross-shore sediment transport. In all cases is the sediment transport in offshore direction reduced.

All results on sediment concentration and sediment storage are in F.4 Option full coastline, F.5 Option peninsula, F.6 Option 1, F.7 Option 2 and F.8 Option 3.

Note, the figures demonstrate sediment storage in the first bed layer S1 after 3 months in the North-West monsoon. The storage in the bed is expressed in a range of 0 – 10^5 g/m^2.

SEDIMENT STORAGE IN FIRST BED LAYER S1 – AFTER 3 MONTHS NORTH-WEST MONSOON

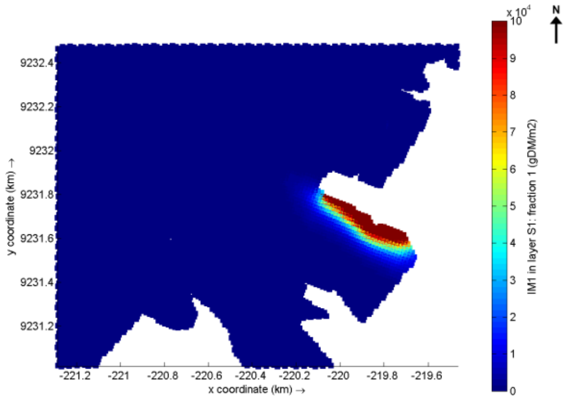


Figure 5-20 Position nourishment option full coastline after 3 months

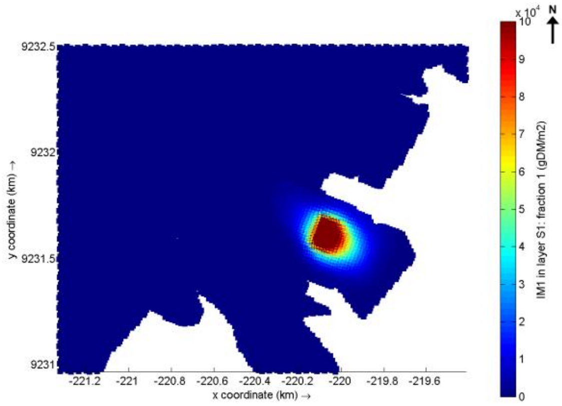


Figure 5-22 Position nourishment option 1 nearshore after 3 months

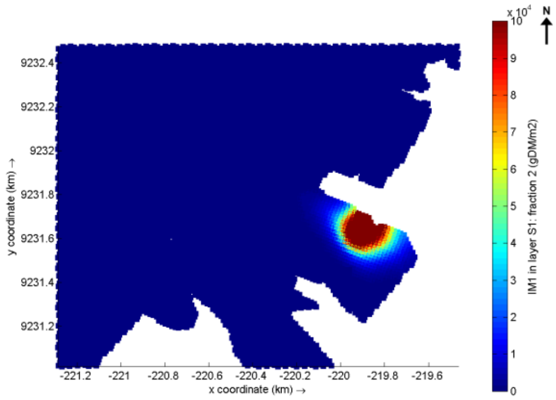


Figure 5-21 Position nourishment option peninsula after 3 months

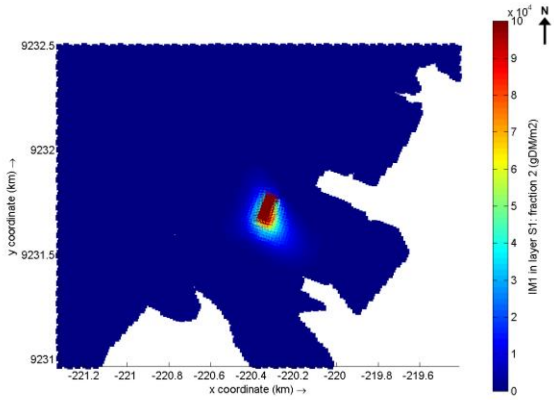


Figure 5-23 Position nourishment option 2 nearshore after 3 months

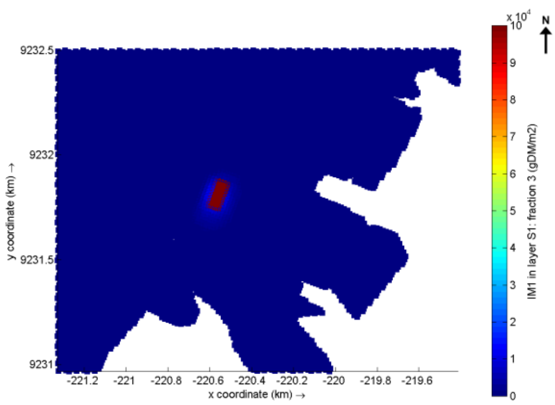


Figure 5-24 Position nourishment option 3 nearshore after 3 months

Chapter 7 Execution

This chapter elaborates on the execution of the different fine sediment nourishment locations. The information and strategies in this section are based on practical experience of Boskalis and literature from the lecture notes of Dredging Technology (CIE5300). It starts with measurements and considerations to be done before starting the actual nourishment. Subsequently, it elaborates on the technical execution of the nourishment and measurements after the nourishment.

7.1 Nourishment preparation

The first section discusses all aspects that are important in the process from dredging to transporting the material and placement. The nourishment location is fixed and functions as an important boundary condition for the process.

NOURISHMENT LOCATION AND VOLUME

The nourishment is intended to create a suitable slope for the rehabilitation of the eroding mangrove-mud coast on the west side of the village Bedono. The nourishment locations are separated in two sections on the coast and three nearshore, see Figure 7-1.

Figure 7-1 Nourishment options on the coast (left and middle) and nearshore (right)

The nourishment volume is estimated to verify if it is a reasonable volume in line with the project size. Furthermore, it is used to verify if the available equipment is suitable and the execution time is realistic. Current cross-shore slope of the foreshore in degraded status is estimated on 1:600. The intendend slope for mangrove establishment is at least 1:1000. The bed level in the area of interest is assumed to be uniformely 0.6 m. The actual situation and the desired situation are simplified in an area top view and a cross-section, see Figure 7-2 .The shape of the overview area is schematic and it is recognized that in reality the bathymetry is more complex. The bathymetry is more irregular and follows the land contours. For practical reasons and the estimation of the required volume this is assumed a good approximation. The grey area is the current bottom and the yellow area is the idealised bottom. The mangrove establishment occurs within the range of Mean Sea Level and High Water Spring, see Figure 7-2. The total volume for the nourishment according the cross-section and the top view is 165.000 m^3. The application of a factor for sediment loss in the order of 20% makes the estimated nourishment volume: 200.000 m^3.

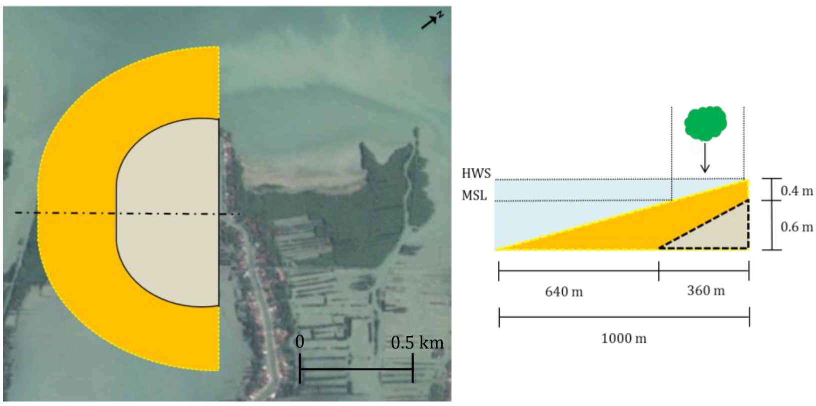


Figure 7-2 Top view area (left) and cross-section of bottom profile with mangrove re-growth area (right)

DREDGING LOCATION

The borrow pit location on mud coasts deviates from a borrow pit location for sandy coasts due to substantial different processes. For sandy coasts there is an active profile until the depth of closure. The latter is the transition between the shelf and the shoreface where waves start to feel the bottom and are capable to transport sediments. In this case sediments beyond the depth of closure are not considered as part of the active sediment buffer and are therefore suitable for dredging activities.

The dredging location on mud coasts is approached differently because there is no active profile or depth of closure. How the system reacts on a borrow pit in the mud foreshore is still unexplained in literature and practice. This paragraph elaborates and puts the different possibilities for mud coasts in perspective. It is stated that the borrow pit location is site specific and system understanding is essential.

Taking into account the mud foreshore contains an abundance of fine sediments the borrow pit can also be considered as a relocation of fine sediments. The assistance in sediment displacement to the coast reduces the original time the sediment needed to be transported to the coast.

Next, the borrow pit can be filled up by cross-shore sediment transport and then it negatively influences the sediment household of the coast. The borrow pit is then advised to move further offshore. However, the borrow pit can also be filled up by longshore sediment transport and thereby minimal influence the sediment household of the coast. This allows the borrow pit to be closer to the coast.

Besides, the fine sediment needs to be dredged by local available equipment and transported to the nourishment area. The borrow pit and the nourishment area are advised to be within the range of 4 km. This is the distance that transport is ensured and the bottom depth is reachable for the local available dredging equipment.

Furthermore, the trade-off between the borrow pit location and influence on the sediment household is also largely influenced by the cost-benefit ratio. The latter has to be in proportion to avoid unfavourable high costs.

Finally, the properties of the dredged materials in the borrow area should be similar to the autochthonous sediment properties nearshore (fine silt in the order of <63 micrometre).

DREDGING EQUIPMENT

The volume of the nourishment and the dredging location determine the dredging equipment. The work cannot be done with high capacity vessels due to the size of the project and the shallow water depth. A local contractor has been contacted and proposed to execute the work with a small Cutter Suction Dredger (CSD). The available Cutter Suction Dredger has a cutter ladder of 13.5 m. The maximum angle of the cutter ladder with the bottom is 40 degrees. This gives a maximum cutting depth of around 7 m. Next to that a certain face height is needed to smoothly cut the soil. For this specific case the face height is chosen at 2 m. The result is that the vessel can dredge up to water depths of 5 m. In the coastal system of Demak is the dredging depth limited to area between the coast and the red line, see Figure 7-3.

The second option is the use of a small Trailing Suction Hopper Dredger (TSHD). The maximum dredging depth for a small Trailing Suction Hopper Dredger is larger and is estimated at 10 m. Note, vessels with larger dredging capacities reduce the draught of the vessel and thereby their area of operation in this project area. The disadvantage is that the execution time increases drastically which is explained in the next paragraph.

The use of a Backhoe Dredger or Grab dredger is not proposed to use because this equipment functions on sediment supply from other vessels or barges which are not able to reach these shallow waters.

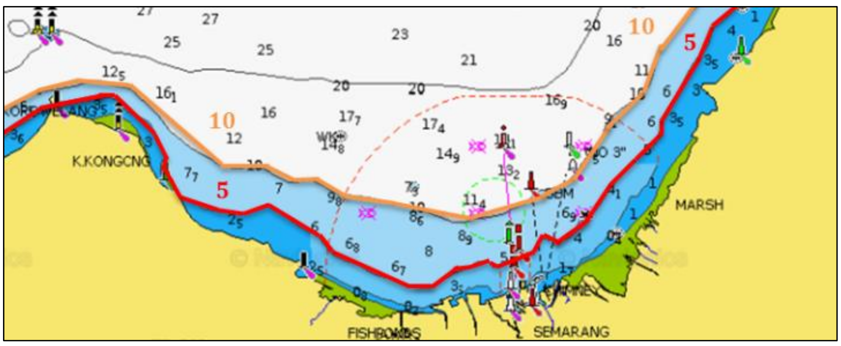


Figure 7-3 Bathymetry in coastal area Demak (Navionics, 2016)

TRANSPORT DREDGED MATERIAL

The dredging location is important but the other important aspect is the transport of the material to the nourishment location. The determining features for the transport method are the volume of the nourishment and the distance between the dredging- and nourishment location.

A transport method with barges is not proposed to use in this case. The water depth limits the use of the fill barges and during the filling fine sediment overflow losses are large. This leads to low loading capacities and fine sediment contamination in the borrow area. Moreover, the barge capacity is too small and not realistic relative to the proposed nourishment volume.

The proposed transport method is to use floating pipe- and sinker lines. The CSD or TSHD connects to the pipe line and discharges the sediment to the land. The transport distance is limited by the pump capacity but can be enlarged by adding booster stations between the floating pipe lines. The original pump capacity distance is 2 kilometre and is enhanced for 2 kilometres per each booster station in theory. In reality the pump distance is preferably kept smaller than 4 km. The downside of the extension is that in terms of operational issues the maintenance becomes more extensive and time-consuming. The pump engine of the vessel and boosters need regular fuel supply and by increasing the distance it takes more time.

There is an important difference between the TSHD and CSD during the transport of dredged material. The TSHD fills its hopper till the maximum capacity is reached and subsequently sails back to closest allowable point near the nourishment area. The vessel connects to a pipeline and discharges the sediment to the nourishment location. The disadvantage of this method is that it is more time consuming due to the sailing time between the borrow area and the pump installation. Moreover, the delivery of dredged material is not continuously. The latter is solved by the use of the CSD which is connected to the pipe lines during its dredging activity.

It is assumed that the pipe line with a diameter of 0.45 m is able to discharge a mixture of fine silts and water with a velocity of 3 m/s. This provides a mixture discharge of 1717 m^3/h. The fine sediment concentration is assumed on 30% and provides 515 m^3 fine sediment per hour. In the case the pipe line is connected to a CSD this amount is reduced by a factor 0.6 due to efficiency losses like movement of the spud poles, cut pattern and human incapability. The net fine sediment discharge capacity becomes 300 m^3/h. The net fine sediment discharge capacity for a TSHD is even less due to the periods without sediment supply during its dredging activity.

Another aspect to consider is the transport concentration. Preferably the material is placed slowly in dense high concentrations from pipe lines on the coast. This is more difficult to do with a TSHD due to its transport rates and variable discharge.

WORKABILITY

The workability is separated into the operational- and safety workability. The operational workability is the ability to perform the activities while maintaining all the necessary functionality of the plant (van der Schrieck, 2014). The interaction between the environmental aspects as wind, waves and currents with the size of the equipment used and the proposed working method determine the operational workability. Other factors as capacities of people and soil type are not taken into account for this research. It is assumed that only wind-generated waves are present in the coastal area of Demak. Swell waves are not taken into account for the operational workability since they are not present in sheltered Java Sea. The wave height, frequency and the wave direction on the Cutter Suction Dredger are the factors to determine. The permissble wave height for short (wind) waves on a small vessel with a floating pipe line is between 0.2 and 0.5 m (van der Schrieck, 2014). The orientation of the vessel to the incoming waves is important because the vessel's response varies on the angle of approach. The optimum orientation of a vessel depend on the veseel type and anchoring method. In an area like this the heading of the vessel towards waves is free to choose and optimized to the operation conditions. The permissble current for a small Cutter Suction Dredger is between 0.5 and 0.7 m/s.

The safety workability comprises the ability to shelter during extreme weather conditions. The latter is difficult in this project because there are no nearby shelter areas. The closest shelter areas are in the port of Semarang and Morodemak which are respectively 7 and 10 kilometres from the area of interest. The distance from the borrow area to a sheltered place once unpredicted circumstances cause danger is even further.

The total workability rate for this project area is estimated on 70%.

EXECUTION TIME

The net fine sediment discharge capacity of 300 m^3/h and the estimated nourishment volume of 200.000 m^3 lead to a net execution time of 700 hours. The gross execution is larger due to the workability rate of 70% and becomes 910 hours. With working weeks of 80 hours the real execution time becomes 11 weeks for the CSD.

CONCLUSION

The discussion above describes the trade-off between the CSD and the TSHD. The CSD provides a reasonable execution time and can produce constant discharges with high sediment concentrations. For the TSHD the execution time is larger and there is no constant sediment discharge. However, the TSHD can dredge up to larger water depths and thereby may reduce the impact of the nourishment on the sediment household of the coast. The execution time and continuous production of the CSD are more preferred in this project and therefore advised to use a small CSD.

The most suitable transport method to the nourishment site is via pipe- and sinker lines. The latter secures transport over a large distance and suits the shallow coastal waters near the area of interest.

The provided numbers concerning the nourishment volume, production capacity and execution time serve as an estimate at this moment. Once it is decided to execute the fine sediment nourishment it is advised to reconsider the assumptions and features with the new situation. The next paragraph provides an overview of how to execute the nourishment once the dredged material reaches the nourishment location.

7.2 Nourishment execution

DESIGN CONSIDERATIONS

In this research the loss of sediment is defined as the sediment that is transported in offshore direction and is not able to be brought back into the area of interest. Sediment that is transported in offshore direction but is still able to be brought into-re-suspension and transported to the coast is considered as a 'temporary' loss of sediment. It is temporarily stored in the fine sediment buffer in the foreshore. It is recognized that the amount of these 'temporary' losses should be kept small since the nourishment and intended increase in sediment flux should take place within a small time scale. The more sediment of the nourishment is lost to temporary storage in the foreshore or further distance from the area of interest, the more time it takes to bring it back to the area of interest.

Sediment that is transported in longshore direction and is not able to return to the area of interest is also considered as sediment loss. It is lost for this research area but it is extra sediment for the adjacent coasts. Therefore this type of sediment loss is considered less negative.

NOURISHMENT CONSTRUCTION

The nourishment option full coastline and peninsula are proposed to construct from the landside. The dredged material is transported from the vessel through floating pipe lines and sinker lines to the land. Subsequently the pipe line is constructed to the coastline where it can distribute the mixture of fine sediment and water. The dredged material spreads over the slope and accumalte in front of the coast. Once the bottom is raised in front of the pipe outlet, the pipe line is extended with pipe lines, see Figure 7-4. An alternative is the use of a pontoon in front of the coast which sprays the sediment in the water.

The nourishment starts above the water level while erosion and spreading create automatically a natural slope.

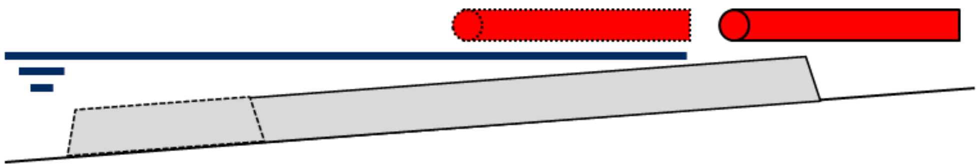


Figure 7-4 Schematisation construction method from coast

The nourishment option 1,2 and 3 nearshore are in front of the coast and require a different construction method. The construction starts with the creation of boundary dikes around the reclamation area. This can be done with sand but it is recognized that not plenty of sand is available in the nearby area. Alternative types of bund construction are geo-bags or permeable dams of local brushwood. The latter is vulnerable to higher hydrodynamic forcings and has a limited technical lifetime due to putrefacation of the wood. The encircling is needed to avoid the fine sediment to transport along the bottom over the gentle slope in offshore direction. The created basin functions as the temporary storage of dredged fine sediment subsequently the sediment is stirred-up by waves and transported by the tide towards the coast.

If the encircling is done with sand, extra equipment is needed in the form of a backhoe on a pontoon and a pontoon with sand. The backhoe can grab the sand from the pontoon and place it under water on the correct place. Geo-bags and permeable dams can be constructed and placed by smaller equipment and craftsmen. Subsequently, the dredged fine sediment can be transported through floating pipe lines from the CSD or TSHD vessel to the location nearshore. Hereafter, the dredge material is sprayed into the encircled area with a spreader pontoon. In this process the very fine sediments are brought in a dynamic environment and hindered settling prevents direct settlement in the encircled area. Parts of the sediment remains in the water column and may be transported by the tide in other direction. The sediment is estimated to settle in the nearby area and is not fully considered as 'losses', see Figure 7-5.

The nourishment is created below the water level so the hydrodynamic forcing is able to stir-up sediment and transport it to the coast.

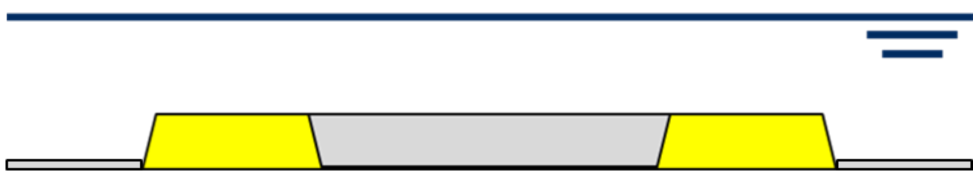


Figure 7-5 Schematisation construction method in front of coast

PIPE LINE CONFIGURATION

It is important to mention that no mangroves or existing vegetation are removed in all the different pipe line configurations. Furthermore, only small equipment can be used due to the limited infrastructure towards and in the village.The pipe lines are preferably guided over the water and not over land to avoid hinder for the stakeholders. The size of the pipe line is small and in the order of 40 cm in diameter, see Figure 7-6 and Figure 7-7.

The first option is to guide the pipe lines through the canal in the village and from there extend it to the coast on the Westside of the village. The second option is to work from a pontoon on the water in front of the coast. This prevents construction through the village but it is not preferred in terms of nourishment distribution. The most favourable distribution of sediment is when the high concentrations of fine sediment are slowly discharged from the land into the sea and not vice versa.

The approach of the pipe line to the nourishment area depends on the location of the dredging area. The the dash dot line is used to indicate the possible direction of the pipe line and the dot line is used as an example floating pipe line for the method that uses construction from the landside, see Figure 7-8, Figure 7-9 and Figure 7-10. The configuration for the floating pipe line and the pontoon is different because it is positioned on the sea side of the the coast.

The nourishment along the full coastline requires small parts of the pipe line to emerge and constructed over land. From the open water it first enters the canal in the village and from there it is partly constructed through the village to the coast, see Figure 7-8.

The nourishment peninsula needs also partly to be constructued over land. However, it only uses one passage through the village towards the sea, see Figure 7-9.

The nourishment option in front of the coast can be constructed and supplied from the sea side, see Figure 7-10.

Figure 7-6 Small floating pipe line (⌀ 40 cm) in practice

Figure 7-7 Cutter Suction Dredger connected with floating pipe line (⌀ 40 cm) towards the coast

7.3 Nourishment finishing

It is intended to have minimal post-nourishment measures and let the natural processes (waves and tide) re-distribute the sediment to a natural equilibrium. Control measures like underwater dams or bunds can be created to maintain the nourishment at its position and avoid further sliding to deeper parts.

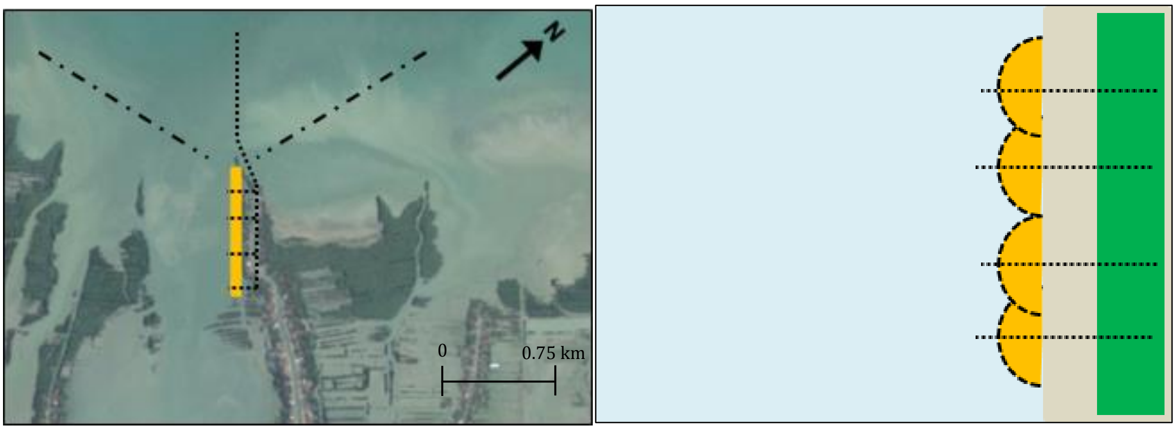


Figure 7-8 Possible pipe line approach and discharge configuration from land (top view) – full coastline

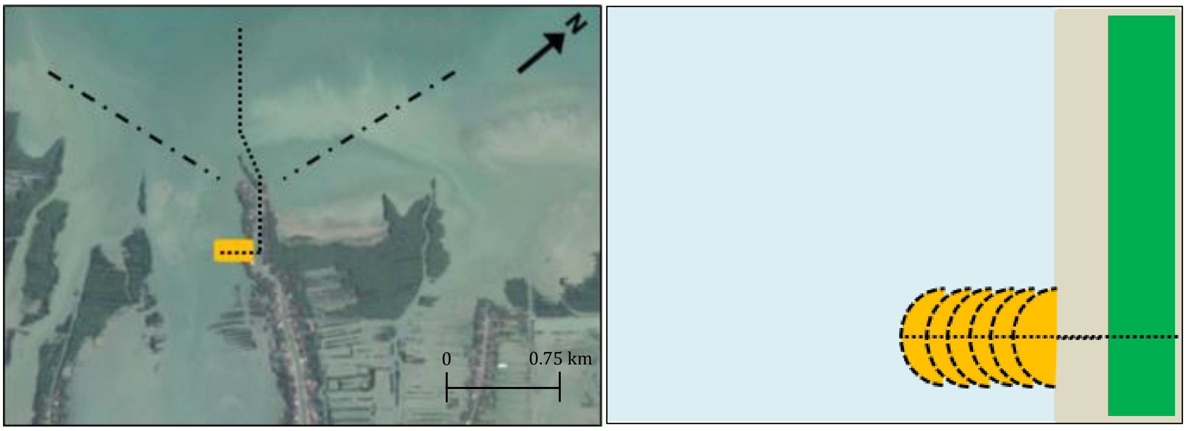


Figure 7-9 Possible pipe line approach and discharge configuration from land (top view) – peninsula

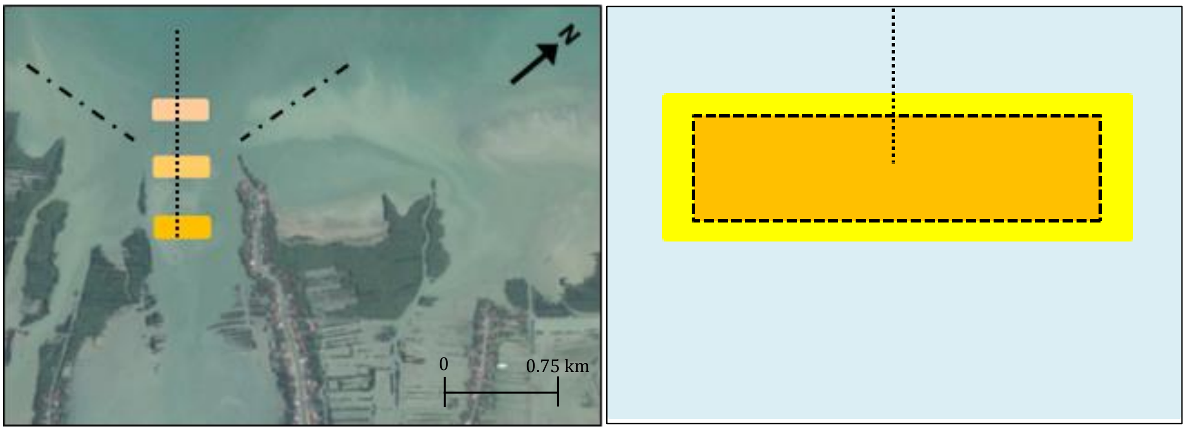


Figure 7-10 Possible pipe line approach and discharge configuration (top view) – option 1,2,3 nearshore

Chapter 8 Discussion

This chapter puts the theory (Chapter 3 Theoretical background), practice (Chapter 4 Case Demak) and model results (Chapter 6 Model results) in a common framework. The focus is on the effect of three features that serve the research objective: (1) bathymetry without chenier and with chenier, (2) three realistic hydrodynamic scenarios and (3) two nourishment locations. Hereafter, the results and limitations of the model are discussed. Finally, the principal implications are summarized and it is explained how these contribute to the research objective.

1. Bathymetry

The bottom topography with chenier creates a protected and low energy area in the direct environment behind the chenier, see Figure 8-1. In this area is the total bottom shear stresses are lower, less sediment is eroded and brought into suspension while sedimentation is enhanced. The increase in total bottom shear stress after one kilometre and close to the shore is contributed to the shallow water depth, generation of wind waves and contraction of currents. The increase in general of the total bottom shear stress near the coast is still unidentified. The general observed behaviour is in line with the theory which states that cheniers induce wave breaking, reduce wave energy and create calmer conditions behind it. The latter reduces erosion and enhances sedimentation.

Field observations confirm the crucial role cheniers have in the protection of the coastline because coastal sections with cheniers in front of the coast are less degraded than sections without chenier. They emerge above the water level during falling tide and function as an emerged breakwater. During rising tide they get flooded and function as a submerged break water.

This research confirms that cheniers form a key feature in the coastal dynamics of mangrove-mud coasts and it is stated that chenier restoration contributes to the protection of the coastline.

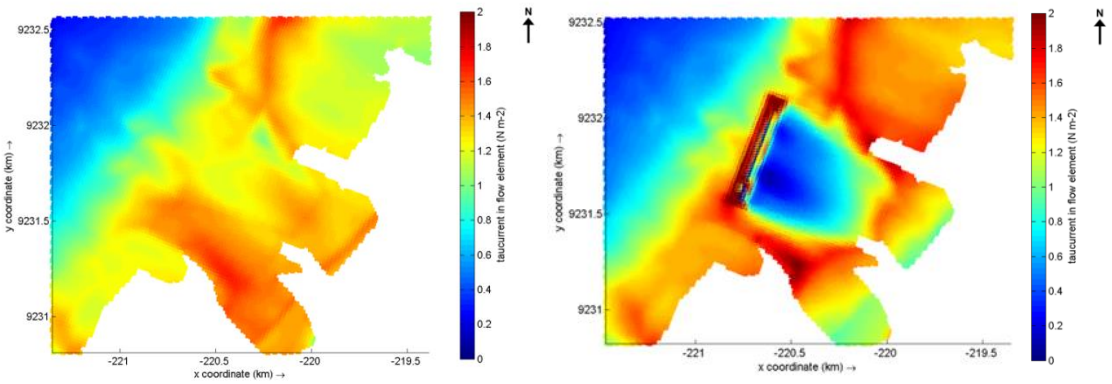


Figure 8-1 Shear stress snapshot without chenier (left) and with chenier (right) - North-West monsoon

2. Hydrodynamic scenarios

2.1 North-west monsoon

The North-West monsoon leads to water movement in cross-shore direction and in longshore direction towards the north. The total bottom shear stresses vary below and above the critical shear stress for erosion mainly due to wave breaking. Thereby periods of sediment re-suspension and no sediment re-suspension alternate each other.

The prevailing transport direction of re-suspended sediment and storage of sediment in the bed layer depend on the location of the sediment source (nourishment). Model results show that nourishments beyond 200 m from the coast in cross-shore direction move in ebb direction while they move less towards the coast. One of the nourishments in front of the coast demonstrates ebb dominancy because it is more displaced in offshore direction than to the coast, see Figure 8-2.

The observed behaviour is in line with the theory which states that sediment is stirred-up by waves and subsequently transported by the tide. Transport is towards the coast during rising tide while during falling tide the transport is offshore directed. Also the undertow may play an important role in the transport of sediment according Winterwerp & van Prooijen but this is not incorporated in the model. This theory is assumed valid and applicable in this case because the measurements are taken in mangrove-mud coasts with similar properties and circumstances. In the North-West monsoon (wet season) fresh water is discharged into the sea and the wind pushes the water against the coast. The fresh water area reaches up to 1 km out of the coast and the baroclinic pressure gradient induces saline water to move under the fresh water layer towards the coast. The surface current is offshore directed while the undertow contains high sediment concentrations and is towards the coast.

Field observations demonstrate that the conditions in the North-West monsoon induce more erosion at the coast. However, this is counteracted by the larger sediment stir-up capacity of waves in the foreshore which mobilize more sediment. The net effect in the North-West monsoon is accretion.

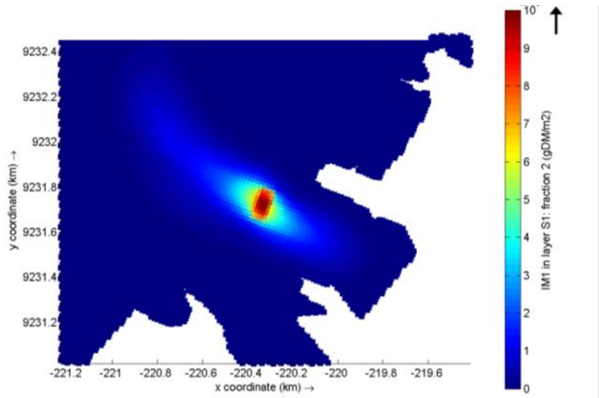


Figure 8-2 Nourishment position after 3 months in North-West monsoon for nearshore option 2

2.2 South-east monsoon

The South-East monsoon demonstrates water movement in cross-shore direction and in longshore direction towards the South. The total bottom shear stresses do not exceed the critical shear stress for erosion. The reason for this is that the waves from south-eastern direction do not refract enough in the model to influence the relative sheltered research area. Without sufficient wave activity there is no sediment re-suspension and thus no sediment to transport by the tide.

These model observations are not corresponding with the theory which states that the same interaction between the stirring-capacity of waves and transport by the tide is applicable. According the theory, the smaller waves in the South-East monsoon induce net erosion because the small waves do not stir-up a surplus of sediment in the foreshore while they do erode the coast.

The undertow may play an important role but this is not incorporated in the model. In the South-East monsoon (dry-season) the fresh water decreases and the wind blows still from the sea to the land. The wind induces a set-up against the coast with an onshore surface current and an offshore undertow. This time the high sediment concentrations are offshore transported through the undertow (Winterwerp & van Prooijen, 2015).

Field observations demonstrate that the conditions in the South-East monsoon induce less sediment re-suspension in the foreshore while they do erode the coast. The misbalance in sediment supply and sediment erosion leads to coastal erosion.

2.3 Storm

The storm scenario comprehends five days of storm conditions and the water movement is pre-dominantly to the coast and in northern direction. The total bottom shear stresses are larger, remain above the critical shear stress of erosion and occur further from the coast. Through this the sediment stir-up capacity is larger and also takes place on a larger area in the foreshore. The transport direction is towards the coast but this is not direct observable since the observation ends after five days and the horizontal transport velocity is small.

The observed behaviour is in line with the theory which states that larger waves have larger stir-up capacity and bring more sediment in suspension off the coast at a deeper location than prevailing conditions. Larger waves reach their point of wave breaking earlier on the foreshore and thereby also induce re-suspension of sediment in this area.

Field observations show erosion of the coastline due to the intense and large wave forcing. The effect on the long term is different because large quantities of sediments are brought in suspension and transported towards the coast. So the net effect of a storm is positive.

2.4 Overall discussion regarding the hydrodynamic scenarios

The water movement direction and sediment transport direction is not necessarily equal to each other. Wave activity is responsible for bringing sediment into suspension while the tide and water movement transport the suspended sediment. The cooperation between the stirring-up of sediment by waves and the tidal flow direction lead to the actual sediment transport direction.

The North-West monsoon comprehends the interaction of the sediment stir-up capacity waves and sediment transport of the tide well. There is a pre-dominantly sediment transport to the coast when the nourishment location is within 200 m from the coastline. Beyond the 200 m from the coast the transport directions changes to offshore.

The South-East monsoon is not simulated correctly according the theory and practice. The interaction of the waves and the tide is not working correctly because waves do not reach the research area.

The storm scenario which always occurs in the North-West monsoon incorporates the shear stresses and the short-term effect well. Though, the long term net effect is not obtained through this model.

The implication on the overall research objective is elaborated in the last paragraph: 5. Principal implications and contribution to research.

3. IN FRONT OF THE COAST AND ON THE COAST

The behaviour per nourishment configuration is simulated for the North-West monsoon, South-East monsoon and storm scenario. The North-West monsoon is discussed in this section and the South-East monsoon and storm scenario are further not considered. The reason for this is that the performance in the South-East monsoon is not correct and the behaviour in the storm scenario is limited due to the short simulation period. Though, it is recognized that the storm scenario lead to erosion and transport of sediment. The two general nourishment locations are evaluated on their performance according expectations from theory and system knowledge.

The nourishment in front of the coast is intended to bring sediment into re-suspension and subsequently transport to the coast to enhance the rehabilitation of the eroding mangrove-mud coast.

The model results depend on the location of the nourishment in front of the coast. The nourishment located further offshore is more eroded than closer to the coast. Next to that this location shows that more sediment is transported in offshore direction than towards the coast, see Figure 8-3. The latter is induced by the ebb dominance. The suspended sediment transport through the water column is larger in magnitude during falling tide than during rising tide. In the falling period more sediment is settled and slowly transported offshore. The larger erosion of the nourishment further offshore is induced by the turbulent and more exposed environment. Less energy is dissipated further from the coast and enhances the erosion magnitude. The nourishment location closer to the coast experiences another local environment in which the dominant sediment transport direction is to the coast.

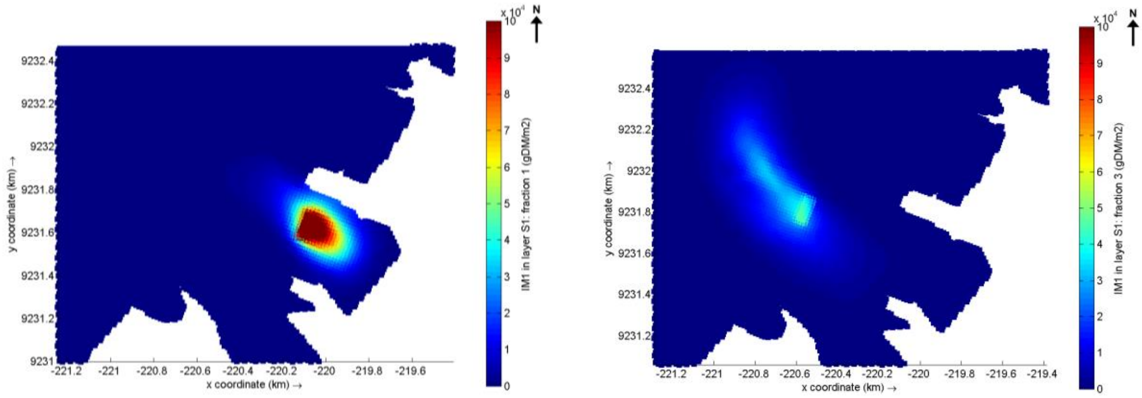


Figure 8-3 Nourishment position after 3 months in North-West monsoon for nearshore option 1 and 3

The nourishment on the coast is intended to remain in place and slowly be redistributed along the coastline to expand.

The model results demonstrate that the nourishment spreads perpendicular to the coast and also slightly in offshore direction. Close to the shore the remaining wave activity brings sediment in re-suspension and transports it by the tide to the nearby environment. The behaviour is as expected and confirms that sediment is transported step-by-step from the coast.

The implications and applicability of the two major nourishment locations is discussed in the last paragraph: 5. Principal implications and contribution to research.

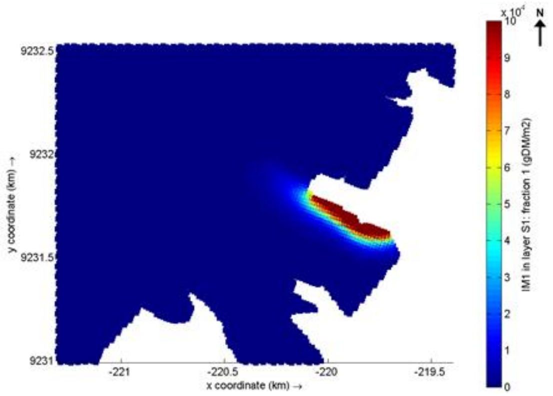


Figure 8-4 Nourishment position after 3 months in North-West monsoon for option full coastline

4. CONFLICTING RESULTS AND LIMITATIONS OF THE MODEL

The general increase of the total bottom shear stress near the coast in the scenario with chenier is still unexplained. The wave input, wind input and water depth are the same as the runs without chenier. The flow pattern and velocity are different due to the chenier but are not considered to cause an increase with this magnitude.

The first limitation of the model is that it does not include morphological bed update. This means that the nourishment itself or depositions induced by sediment of the nourishment are not incorporated and do not influence the hydrodynamics.

The sequence and effect of a submerged nourishment on the bottom level is explained towards two directions. Firstly, the nourishment increases the bed level and thereby induces higher shear stresses due to wave breaking and the shallower water depth. On the other hand, the reversed behaviour is used in this research and is described as follows: (1) the nourishment reduces the total bottom shear stress at its own location (2) sediment erodes from the nourishment, deposits in the nearby environment and reduces the total bottom shear stress in this area (3) the total bottom shear stress on the original nourishment location is further reduced due to the deposits in the surroundings. The effect is that the total bottom shear stresses in the environment decrease due to the changes in bottom topography.

The total bottom shear stresses are continuous overestimated in the model and thereby the erosion rate. It is important to take the purpose and capabilities of the model into account for the understanding of the nourishment. The model is suitable for the intended 'tracer study' while it is not intended to use for a research on exact numbers. Next to that, the nourishment size in the model does not correspond with the size of the real nourishment in practice. In reality the nourishment area is larger than the nourishment areas in the model. The impact of this is that it extremely influences the local hydrodynamics and sediment transport direction. Therefore, the outcome of the model serves as an indication for the behaviour of the system and sediment transport direction.

The second limitation is that the model is depth-averaged and does not include the undertow. The undertow may play an important role in the transport of sediment (Winterwerp & van Prooijen, 2015). This theory is assumed valid and applicable in this case because the measurements are taken in mangrove-mud coasts with similar properties and circumstances. As explained earlier, in the North-West monsoon fresh water is discharged into the sea and the wind pushes the water against the coast. The fresh water area reaches up to 1 km out of the coast and the baroclinic pressure gradient induces saline water to move under the fresh water layer towards the coast. The surface current is offshore directed while the undertow contains high sediment concentrations and is towards the coast. In the South-East monsoon the surface current is onshore directed and the undertow offshore directed.

The third limitation is concerning important time varying features of the system in Demak. The model uses a constant wave height and wind speed. In reality higher waves alternate smaller waves and the wind speed also varies during day and night. Especially, in the South-East monsoon (dry season) strong convection winds occur at the end of the day. The earth heats up during the day and in the afternoon it attracts strong winds from the sea. The effect is that these winds induce short wind waves perpendicular to the coast and induce erosion. These features are not incorporated in the model but may play an important role in the coastal dynamics.

5. Principal implications and contribution to research

This section elaborates on the principal implications while taking into account the limitations of the model. This model focusses on the displacement of sediment from an in place nourishment ('tracer study'). The objective of this research is to develop a realistic and executable fine sediment nourishment strategy for the degraded mangrove-mud coast of Bedono in Indonesia. Therefore, the execution period and nourishment location are deduced from theory, practice and supported by the model results. It starts with the influence of an important but not always present feature: chenier.

Chenier restoration improves the conditions for the rehabilitation of eroding mangrove-mud coasts. The reduction of direct wave attack on the coast and the creation of calmer conditions reduce the erosion and enhance sedimentation.

The execution period of the nourishment is different from the period which is the most favourable for the distribution. The execution is proposed to take place in the South-West monsoon to reduce hinder from strong wave activities during execution. Besides, storms rarely occur in the South-East monsoon which is favourable for the execution. Next to that, the sediment transport is small and provides the nourishment to establish itself. The most favourable distribution of sediment occurs in the North-West monsoon in which the wave activity is able to stir-up sediment and the tide transports it to the coast. Therefore, the nourishment is proposed to execute near the end of the South-East monsoon and subsequently let the North-West monsoon transports the sediment.

The sediment balance for mangrove-mud coasts is governed by erosion and sedimentation. It is stated that the majority of sediment transport takes place during day to day conditions. The daily interaction of waves that stir-up sediment and subsequently transport by the tide are considered as the largest sediment transport contributors. Though, it is recognized that short storms bring large quantities of fine sediment into suspension with a net positive effect on coastal accretion.

The tendency of sediment transport is in cross-shore direction with a slight deviation in longshore direction to the north. Nourishments on the coast are considered as the most effective because they step-by-step build out into the sea on the intended location. Nourishments in front of the coast are less effective since they need to be brought into re-suspension, transported to the coast and deposited. The transport and deposition near the coast is the most difficult part. Nourishments beyond 200 m in cross-shore direction from the coast are ebb dominant and transported in offshore direction. Nourishments in front of the coast within 200 m demonstrate pre-dominantly transport towards the coast. Though, this process needs more time to reach the coast and create the intended coastline stabilization for the rehabilitation of the eroding mangrove-mud coast.

The advice on the full nourishment strategy is given in Chapter 9 Summary & conclusion. This advice is the merge of the best technical engineering solution, feasible execution method and social acceptable solution.

Chapter 9 Summary & conclusions

In this MSc thesis a fine sediment nourishment strategy is developed that comprises technical, executable and social aspects to induce sediment deposition near the village of Bedono in Indonesia. Firstly, the motivation for the research is briefly provided as guidance to the final conclusions.

Mangrove-mud coasts are under pressure and the coastal resilience has decreased drastically. Reasons are linked to economic growth, urbanization, intensive agriculture and aquaculture. These reasons have induced human interventions in the coastal configuration, blockage of sediment in land runoff, reduction of sediment supply to the coast due to mining in rivers, land subsidence due to water extraction and large deforestation of mangroves (Van Wesenbeeck et al., 2015).

In order to restore former mangrove-mud coasts and establish mangrove recruitment it is stated to restore the system to a suitable state in terms of ecological, physical and chemical properties. Three measurements are proposed to stop coastal erosion and assist the restoration to a dynamic equilibrium system. The measurements are inspired by the 'Building with Nature' philosophy. This concept uses natural material, ecological and physical processes in achieving effective and sustainable hydraulic designs. It changes the conventional single purpose design to a multi-purpose design that combines ecology and engineering while stimulating a sustainable land use practice. Building with Nature solutions use the dynamics of the nature and are climate-adaptive. Moreover, the local stakeholders are involved in the design, construction and the maintenance (Tonneijck et al., 2015). The first solution is the application of semi-permeable dams and the second solution is to restore the original configuration of the chenier through a sand nourishment. The third solution is to increase the fine sediment flux to the shore by the use of a fine sediment nourishment, active sediment management. There is not much knowledge and experience on the second and third measurement. To diversify the options for the rehabilitation of former mangrove-mud coasts the third option is investigated.

The research comprises a case study on the village Bedono in Indonesia which suffers from coastal erosion and frequently flooding. The conclusions are based on fundamental research consisting of literature study, monitoring results, numerical modeling and practice. It starts with the role of the chenier in the rehabilitation of eroding mangrove-mud coasts. Hereafter, the conclusion regarding the technical engineering solution is given. Subsequently, concluding remarks are made concerning the feasibility of the execution and how to incorporate a social acceptable solution. Finally, the research question is answered: 'what is the most suitable fine sediment nourishment strategy taking into account technical, executable and social aspects to induce sediment deposition near the village of Bedono?'.

INFLUENCE CHENIER

It is stated that the presence of cheniers leads to the reduction of direct wave attack on the coast and create a low energy zone behind the chenier. Thereby, erosion is reduced and sedimentation enhanced. Coastline observations confirm the crucial role cheniers have in the protection of the coastline. Coastal sections with cheniers in front of the coast are less degraded than sections without chenier. Therefore, the first conclusion is that the presence of a chenier in front of the coast or chenier restoration improves the conditions for the rehabilitation of eroding mangrove-mud coasts.

TECHNICAL ENGINEERING SOLUTION

The sediment balance for mangrove-mud coasts is governed by erosion and sedimentation. It is stated that the majority of sediment transport takes place during day to day conditions. The daily interaction of waves that stir-up sediment and subsequently transported by the tide is considered as the largest sediment transport contributor.

It is stated that short high energy events like storms first induce erosion and erode the coastline. However, the net effect is positive because large quantities of sediments on the foreshore are brought in suspension, transported towards the coast and deposited during the calmer conditions afterwards.

The proposed execution period is near the end of the South-East monsoon. It is recognized that in this period net erosion takes place because short wind-waves erode the coast and high sediment concentrations are transported via the undertow in offshore direction. However, in the dry season the change on hinder from strong wave activities and storms are minimalized. This benefits the workability and it provides conditions in which the nourishment can establish itself.

The most favourable distribution of sediment towards the coast is in the North-West monsoon. In this period net accretion takes place because the wave activity is able to stir-up a surplus of sediment in the foreshore and the tide transports it to the coast. Next to that, the undertow with high sediment concentration is onshore directed.

Therefore, the nourishment is proposed to execute near the end of the South-East monsoon and subsequently let the North-West monsoon transport the sediment.

The advised location for the nourishment is on the coast. In this scenario the nourishment is in the intended area and step-by-step builds out into the sea. The nourishment configuration along the full coastline is preferred over the nourishment peninsula because it provides directly larger areas of soil for potential mangrove recruitment.

The nourishment in front of the coast needs first to be brought into suspension, subsequently transported to the intended area and deposited. Nourishment locations beyond 200 m in cross-shore direction from the coast are mainly transported in offshore direction while nourishments within 200 m demonstrate pre-dominantly transport towards the coast. Though, this process needs more time to reach the coast and create the intended coastline stabilization for the rehabilitation of the eroding mangrove-mud coast.

FEASIBILITY EXECUTION

This section provides an overview of the dredging equipment, transport method and how to execute the nourishment.

The dredging equipment that suits the project scale is a small Cutter Suction Dredger (CSD) or a small Trailing Suction Hopper Dredger (THSD). The advantage of the CSD is that its production process is continuous while the TSHD follows a cycle. It starts with the dredging cycle, followed by sailing to the discharge area, discharging and sailing back to the dredging area. The consequence is that the execution with the TSHD is longer than with the CSD. The trade-off between the CSD and TSHD is the interaction of the nourishment scale, available vessel from local contractor and resulting execution time. For this case the CSD is preferred over the TSHD due to the smaller execution time and continuous high concentrations fine sediments production.

The transport to the nourishment location is proposed to do with floating pipe lines because neither the CSD nor the TSHD is able to access the nourishment area due to the shallow water depth. The CSD is continuously connected to floating pipe lines which transport the fine sediment and water mixture to the nourishment area. The TSHD connects to a pump station on the maximum reachable water depth from which floating pipe lines discharge the fine sediment and water mixture to the nourishment area. The discharge distance through floating pipe lines depend on the pump capacity on the vessel and can be enhanced by booster stations between the floating pipe lines. In reality the pump distance is preferably kept smaller than 4 km.

A transport method with barges is not proposed to use in this case because the water depth limits the use of the fill barges and during the filling fine sediment overflow losses are large. This leads to small loading capacities and fine sediment contamination in the borrow area.

The nourishment in front of the coast requires encircling by bunds to maintain the fine sediment nourishment in place. This can be done with sand but it is recognized that not plenty of sand is available in the nearby area. Alternative types of bund construction are geo-bags or permeable dams of local brushwood. The latter is vulnerable to higher hydrodynamic forcings and has a limited technical lifetime due to putrefacation of the wood. If the encircling is done with sand, extra equipment is needed in the form of a backhoe on a pontoon and a pontoon with sand. The backhoe can grab the sand from the pontoon and place it under water on the correct place. Geo-bags and permeable dams can be constructed and placed by smaller equipment and craftsmen.

From a spray pontoon the fine sediment mixture is discharged into the encircling. The nourishment is built under the water level and in a loose way to enhance the stirring-up and transport of sediment.

The nourishment on the coast is discharged from the coastline into the sea. The erodibility of the nourishment is minimized because the nourishment is intended to remain in place and subsequently naturally build out into the sea. The nourishment is built above the water level on the coastline. However, it has the natural tendency to incline and spread out on the slope under the water.

SOCIAL ACCEPTABLE SOLUTION

The nourishment on the coast is preferred over the nourishment in front of the coast from technical engineering perspective. From the feasibility execution followed that both the nourishment locations have advantages and encounter difficulties. Next to these facets the solution needs social acceptance of the stakeholders to improve the sustainability and success. However, the social acceptance is not leading in the process of rehabilitating eroding mangrove-mud coasts. If there is a better technical solution this should be explained to the local community. Transfer of knowledge and teaching is also part of the Building with Nature philosophy.

Firstly, the social perception is discussed of the current applied semi-permeable dams versus the investigated fine sediment nourishment. Note, in practice this is not a decision between the semi-permeable dams or the fine sediment nourishment. They both serve the same goal, can be applied and have a positive influence. The interaction between the semi-permeable dams and the fine sediment nourishment is beyond the scope of this research. Though, it is estimated that the combination of a fine sediment nourishment and the semi-permeable dams can speed up the sedimentation and thereby enhance the restoration of the coast.

The local community is involved in the construction and maintenance of the semi-permeable dams. The fine sediment nourishment is executed through external parties which reduce the local stakeholder involvement. The latter is estimated to be crucial for the social acceptance. Besides, physical constructions contribute to the direct safety feeling while non-visible solutions, for instance nourishment under the water level, are perceived less safe.

The nourishment on the coast is estimated to be perceived differently than the nourishment in front of the coast. The human perception of the nourishment on the coast is positive because the changes are instantly visible and stimulate the safety feeling. The human perception of the nourishment in front of the coast is less positive because it does not contribute to the direct safety feeling. The nourishment in front of the coast has the advantage to be constructed without interfering in the living environment of the stakeholders. The construction of the nourishment on the coast is hindered by the existing houses and small capacity infrastructure in the village. Preferably the nourishment is constructed from the waterside and as less as possible from the landside.

From social acceptance perspective the preferred nourishment location is estimated to be on the coast.

SUITABLE FINE SEDIMENT NOURISHMENT STRATEGY

This research confirms that the rehabilitation of the eroding mangrove-mud coast through active sediment is reachable near the village of Bedono. From economic and social perspective a small nourishment suits the project scale. However, from engineering perspective the rehabilitation of the mangrove-mud coasts requires a large scale nourishment. This contradiction is difficult but in line with the Building with Nature philosophy it is advised to create the dialog between stakeholders and the project team. The involvement of the stakeholders and explaining why another solution is more suitable is an important part of the realisation of the fine sediment nourishment.

Moreover, it is important to take into account that the project in Demak is a demonstration project. The latter means it functions as an area in which substantiated solutions are tested and to show the world how new techniques contribute to the rehabilitation possibilities of eroding mangrove-mud coasts. This is the place where it is intended and allowed to test new engineering techniques even if these normally would exceed the project scale. Note, the solutions are site specific which implicates it does not automatically works on other places with different circumstances.

The large scale fine sediment nourishment is advised and summarized as follows:

- Execution near the end of the South-East monsoon.
- Borrow pit within 4 km of the nourishment area.
- Composition nourishment material in line with the autochthonous sediment (<63 micrometre fine silts).
- Dredging equipment is a Cutter Suction Dredger to minimalize the execution time and to ensure high concentrated discharges of fine sediment.
- Transportation through floating pipe lines due to shallow water depth and to secure continuous discharge.
- Nourishment volume of 200.000 m^3 fine sediment.
- Nourishment along the full coastline.
- High concentrations fine sediment slowly placed from landside to create layers on the bed level.
- Nourishment above the water line and erodibility minimalized.

Chapter 10 Recommendations

The application of a fine sediment nourishment depends on the interaction of complex factors which are explained in Chapter 9 Summary & conclusion. The recommendation is based on my research, experience and interpretation of the system. The advices for the nourishment strategy are intended for the project team and contractor once the execution is on schedule. The recommendation for further research is intended for the follow-up of this research.

1. NOURISHMENT STRATEGY

The first recommendation is in the philosophy of 'learning by doing'. The pilot project in Demak is in development and progresses from the lessons learned by doing and testing. For instance, the testing of different semi-permeable dam configurations provided information which is of great value and hardly to obtain from modelling. Therefore, the advice is to try a substantiated fine sediment nourishment in an enclosed research area and deduce the effect. It is recognized that testing with different semi-permeable dam configurations is less expensive and easier to do than to experiment with multiple nourishments.

Deducing generic recommendations is difficult because the proposed solution in this research is site specific. The reaction of the local system and distribution of sediment depends on factors which are variable per location. Important variable factors to keep in mind are the status of the coast, coastline configuration, bathymetry and local wave height. Furthermore, based on my research I advise to carefully take into account the following aspects:

1. *Borrow area of sediment*. Investigate the reaction of the system on the sediment extraction in the borrow pit.

2. *Transportation of sediment*. Make a plan for how to protect and maintain the floating pipe lines and booster stations in the exposed open sea. Do not or minimalize land based pipe lines and construction equipment through existing mangrove fringes and the village.

3. *Nourishment*. Keep in mind that the nourishment volume should fit the project scale, available equipment and transport method. Long nourishment processes and mega nourishments are not desired or feasible.

4. *Suspended sediment concentration.* The spreading of the nourishment and the concentrations in the water column may not burry and kill nearby mangroves.

5. *Monitoring.* It is advised to increase the monitoring frequency to provide insight in the magnitude of changes and during which periods these occur. Next to that, the monitoring areas are advised to enlarge to obtain insight in local spatial differences.

2. Further research

The recommendation for further research is as follows:

1. *Conceptual model.* The reality is hard to approach accurate by a model and validation is often not possible in remote-areas with degraded mangrove-mud coasts. Therefore it is not advised to increase the complexity of the model but to create a new simplified model. An interesting option from academic perspective and contractor perspective to investigate is the trade-off between the dredging- and nourishment location.

Firstly, it is important to formulate the correct questions before the step towards the recommendation. This is very complicated and beyond the scope of this research but the following information serves as an indication.

What happens on larger time scales with the borrow pit? For fine sediments the soil mechanic behaviour is very important. The creation of a borrow pit attracts sediments to fill it up but what is the origin of the sediment? Is this from cross-shore or longshore sediment transport? The borrow pit depth and fill up speed influence the borrow pit distance to the coast.

The latter is translated to a possible research: (1) the maximum distance the borrow pit can be from the coast before it becomes economical unfeasible. (2) The maximum distance the nourishment can be placed from the coast but still is transported to the coast. This combines the most favourable engineering solution with the reality which is largely governed by costs.

It is recommended to set-up a conceptual model with a straight coastline, same sediment size, same wave climate, same gentle slope and shallow bathymetry as in Demak. It is recognized this coastline configuration does not induce the site specific currents in Demak but only provides conceptual useful information. Subsequently, test different scenarios of the dredging- and nourishment locations relative to the coast which can be used to deduce generic insight in the distances, see Figure 10-1.

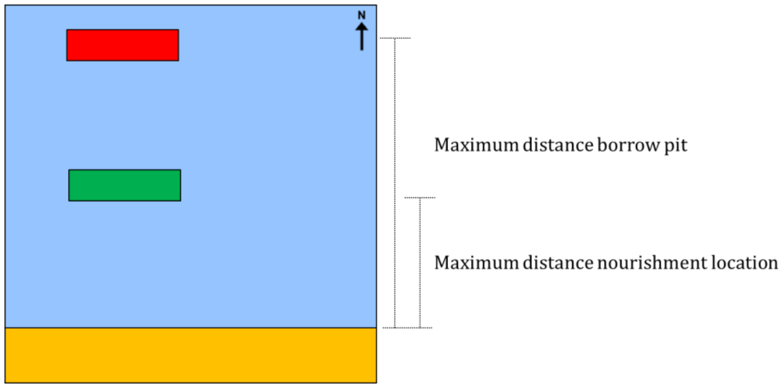


Figure 10-1 Example of a simplified conceptual model

2. *Chenier research*. The role of cheniers on the coastal dynamics is important because the configuration determines the attenuation of waves. The reduction of wave forcing on the coast is favourable for the direct erosion of the coast. However, by reducing the wave forcing also the 'build-up' capacity is reduced. The reduced wave forcing is not capable of mobilizing sediments from the bed and thereby reduces the supply of fine sediment.

It is recommended for further research to investigate by which chenier configuration the erosive wave forcing on the coast is minimalized and the stir-up capacity of fine sediments is maximized. In other words, by which configuration is the net sediment balance positive? The optimisation of the chenier height and width are considered as the most important features.

Appendix A Mangroves

This chapter presents background information on the mangrove forest, a well-functioning mangrove coast, a degraded mangrove coast and the current mangrove rehabilitation knowledge.

A.1 Definition mangrove

Mangrove is an ecological term referring to a classification of a diverse assemblage of trees and shrubs that form the dominant plant communities in intertidal areas, saline wetlands along sheltered (sub)tropical coasts. Plants of the mangrove community belong to many different genera and families. There characteristics are morphological, physiological and reproductive adaptations that enable them to grow in a particular dynamic and salty environment (Blasco et al., 1996).

The term ‘mangrove’ is used in different ways. It may refer to a plant (Macnae, 1968), community of plants (Blasco, 1975; Hamilton & Snedaker, 1984) or the full ecosystem. In this MSc thesis mangrove is used to refer to the singular form of the plant and mangrove forest is used to refer to the community of mangroves (MacNae, 1968).

A.2 Mangrove services

Coastal areas are dynamic systems where sea and land meet each other. The land may accrete and build out towards the sea. On the other hand the sea may erode the coastline and take the land. The process of erosion or accretion can be continuously or due to storm events which cause an abrupt chance. Mangroves grow in the transition zone between the sea and the land. In this area they have services in coastal dynamics and in the ecological system.

COASTAL DYNAMICS – REDUCTION HYDRAULIC FORCES

Mangroves reduce wave height and lower flow velocities. The magnitude of wave damping and flow reduction depends on the density of the forest and the forest width. Densely spaced mangroves are more effective reducers than widely spaced mangroves.

The reduction is contributed to the trunk, roots and branches of mangroves. The transmission due to the trunk does not depend on the water depth since the trunk acts over the full water depth. The transmission decreases with decreasing wave period. Shorter waves (wind waves) penetrate less into the mangrove forest than longer waves (tsunamis, cyclones and swell). The root system influences the transmission in another way. The transmission increases with increasing water depth because the roots have less influence on the orbital motion at the bottom with larger water depths. Again, the transmission increases slightly with decreasing wave period. The influence of roots dominates over the influence of the trunk in terms of transmission (Schiereck & Booij, 1995). Damping is the most effective in small water depths since the reducing effect of the roots decreases with increasing water depth.

Reductions of wave height in the order of 13-66% can occur within the first 100 m and reductions of 50-99% occur within 500 m of the mangrove forest (McIvor et al., 2012). A minimal width of 100 m reduces the wave height and allows a revetment to be designed less conservative (Quartel et al., 2007). However, mangroves are not effective as a single breakwater and cannot be used as a fully protective measure for the hinterland (McIvor et al., 2012). Moreover, mangroves cannot withstand wave heights above a certain level, for example tsunami or cyclone levels (Nippon Koei, 2005). These forces are too large, destabilize the mangroves and vanish the forest.

Flooding impacts induced by storm surges, cyclones, typhoons or hurricanes are only reduced by thousands of meters of mangroves, Figure A- 1 (Tonneijck et al., 2015).

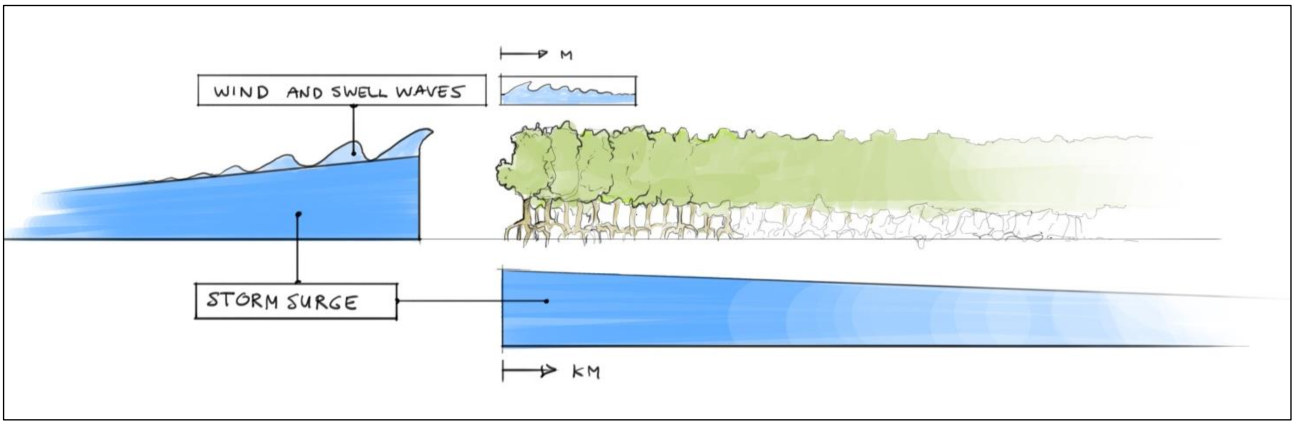


Figure A- 1 Flooding impact and reduction storm surge by mangrove forest (Tonneijck et al., 2015)

Coastal dynamics - shoreline stabilization
Mangroves induce sedimentation due to their ability to reduce orbital velocity of waves and current velocities. The sedimentation rates depend on the local conditions and sediment availability. The sediment material might be endogenic (leaf litter and chemical processes by flora and fauna) or exogenic (entrapped sediment from rivers, land run off or the sea). The magnitude is on average in the order of 1-10 millimetres per year (Tonneijck et al., 2015).

Mangroves cannot slow down coastal erosion once this process is started. A deficit in sediment supply cause the net sediment balance to become negative (sedimentation – erosion < 0). This changes the equilibrium from a net accreting coast to a net eroding coast. The erosion process changes the coastal foreshore shape from convex to concave. This causes that the wave height does not shoal (reduce) on the foreshore and increases the load on the mangroves. Moreover, the shape of the profile undermines the mangroves so they lose their stability and collapse (Winterwerp et al., 2013).

Furthermore, mature mangroves consolidate and increase the compaction of the soil (Tonneijck et al., 2015).

Coastal dynamics - wind break
A mangrove forest is able to reduce the wind speed depending on its height and density. The horizontal sheltered area distance is 20-30 times the height of the mangrove forest. Though, mangroves cannot reduce the wind velocities of cyclones and typhoons (Marchand, 2008).

Ecological
Mangrove forests are productive ecosystems for the environment and human societies. Mangroves regulate the water quality by filtering suspended material and assimilating nutrients from various natural and human sources. Mangroves cope with nutrients in different ways. They are able to absorb nitrogen, phosphate and heavy metals and store them in their roots, stems and leaves. Furthermore, they induce sedimentation of suspended material with phosphate and heavy metal. Next, they provide habitat for organism that decompose waste (Barbie et al., 2011).

They produce organic matter that forms the start of the food chain. They offer protective areas, nursery and feeding grounds for land and marine based animals, for example birds, fish, crab and shrimps. On the other hand, people live from the flora and fauna attracted by the mangroves (Healy et al., 2002).

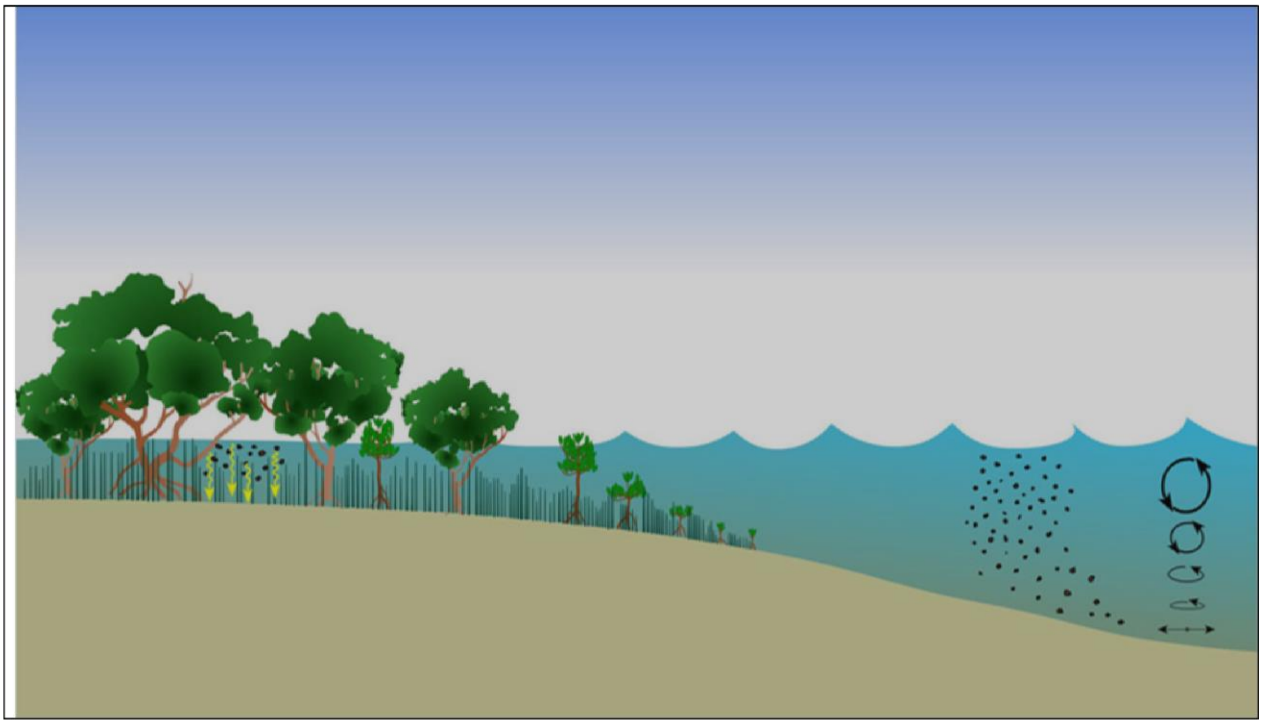


Figure A- 2 Transmission through mangrove forest and sedimentation (University of Waikato, 2016)

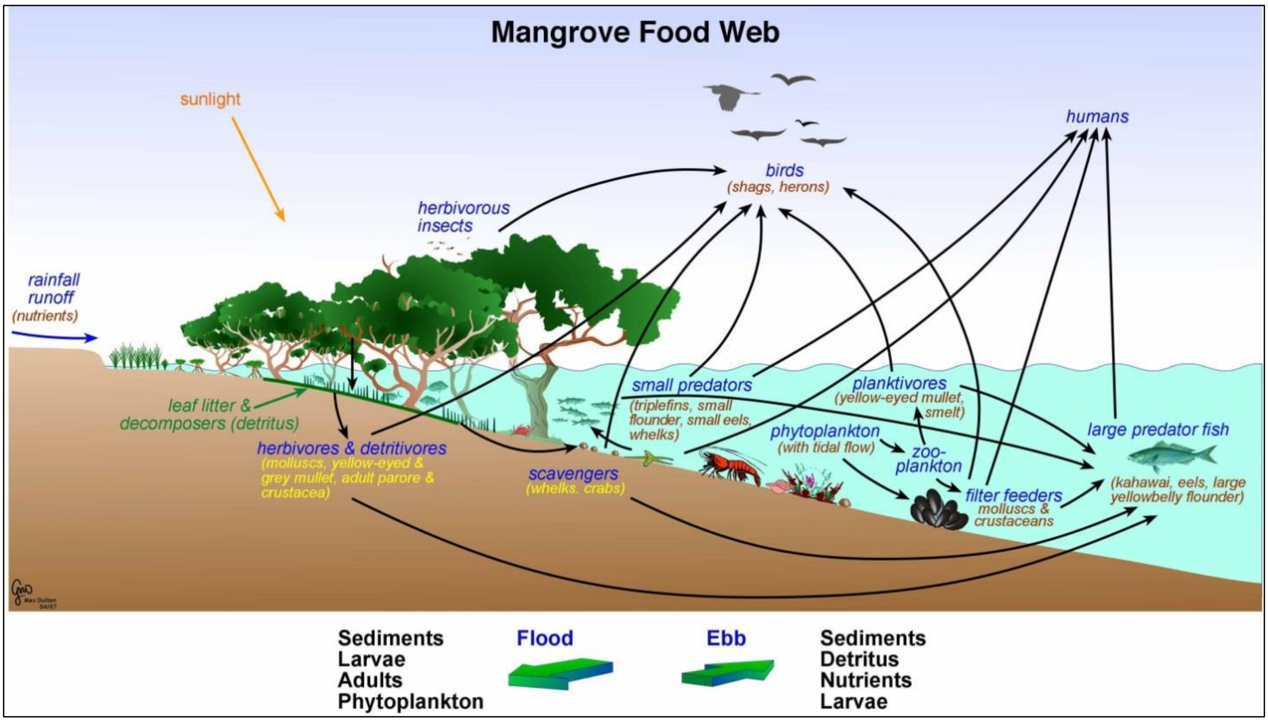


Figure A- 3 Mangrove ecosystem services (University of Waikato, 2016)

A.3 Mangrove worldwide

Mangrove distribution on the world varies in longitudinal and latitudinal direction, Figure A- 4. In latitudinal direction the appearance is enclosed between 30° on the Northern Hemisphere and 30° Southern Hemisphere. A large difference can be observed in the distribution of mangrove species in longitudinal direction. The largest variety in mangrove species is found in Asia while in America and Africa the variety is less (Balke et al., 2011). What causes this difference in appearance in latitudinal direction? The occurrence of mangrove species is linked to the combination of climate, hydrological and geomorphological settings.

First of all, mangroves are strongly correlated with the seawater temperature. The lower limit of the water temperature is 20 °C. Warm ocean currents enhance the appearance of mangroves while cold ocean currents hinder mangrove appearance. Secondly, the air temperature has a large influence on the survivability of mangroves since they cannot tolerate (long-lasting) frost (Mitsch et al., 2009).

Thirdly, mangroves prefer areas with large tidal ranges. Mangroves are able to deal with temporarily inundation which gives them a large advantage on freshwater trees in the intertidal zone. In areas with small tidal ranges mangroves experience strong competition, and in the end lose, from better adapted vegetation. On the other hand the propagation of mangroves, propagules that can float, depends on the tidal range (movement). Next, the appearance of mangrove systems is influenced by wave exposure. Strong wave activities hinder the anchoring of propagules. It also causes forces (stresses) on young mangrove trees which lower the survivability. Mature mangroves can withstand wave exposure till a certain level. Mangroves occur in low-energy hydraulic circumstances, for instance wide mud-flats on which wave energy is dissipated. Further, mangroves are found in salt water. They develop well in salt water but do not require it. They are highly adapted to salt water (halophyte) which gives them an advantage on non-adapted species. Mangroves require a periodically flooding by fresh water from rainfall, rivers and groundwater to reduce the salinity and supply nutrients. Mangroves can also grow in fresh water but they lose the competition with dominant autochthonous fresh water vegetation. These circumstances create that mangrove development is the largest in the coastal intertidal area with a combination of salt water and fresh water supply.

The appearance of mangroves depends also on the soil properties. Mangroves are able to grow on different soil types. Their preference is on muddy or silty substrates but they are also found at rocky soils. The substrate should contain sufficient nutrients and has to fulfil enough space for root attachment and drainage. Otherwise the mangrove is not stable, cannot collect enough nutrients or it gets aeration problems (Balke et al., 2011) (Kjerfve, 1990).

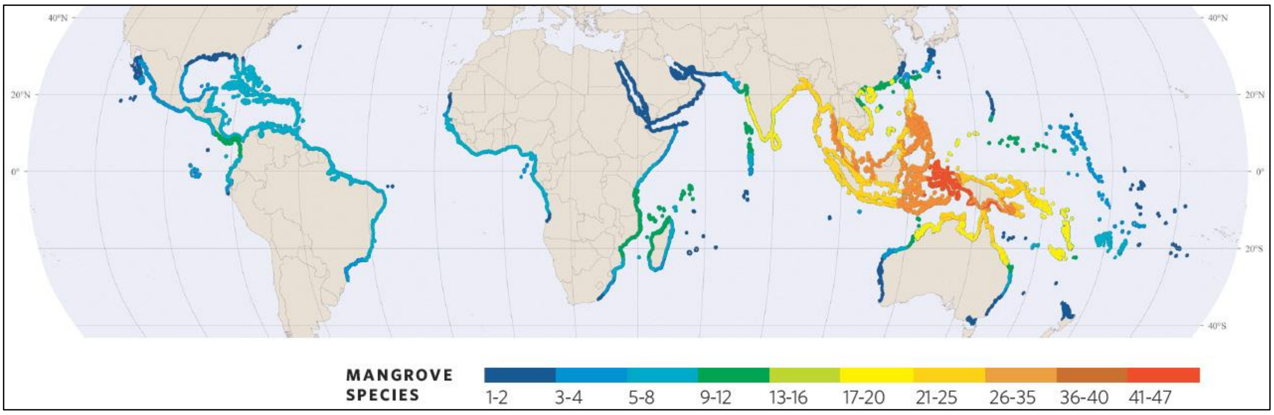


Figure A- 4 Mangrove distribution over the world (Deltares)

A.4 Mangrove settings

Mangroves develop within five different terrigenous and three different carbonate settings, Figure A- 5. Each terrigenous setting contains a different generative process and geomorphic characteristic. The generative difference is the dominant coastal process in the system, for example wave, river, tide or mix. The second difference is the origin of the sediment. Sediments are allochthonous in river, wave and tidal dominated settings and autochthonous in carbonate settings (Thom, 1984).

I. *River-dominated*
Continuously deposition of fluvial sediments from upstream rivers into the distributaries, shallow bays and lagoons of the delta. Temporal changes occur rapidly and the morphological composition is diverse due to the dependency on the upstream activities. Abandoned areas in the delta are open for salt water intrusion and allow the settlement and establishment of mangroves.

II. *Tide-dominated*
The main river is connected with multiple tidal creeks and tidal flats. The flat and low-lying estuary is subjected to strong tidal currents into land and sea direction. The wave action is low due to the energy dissipation over the intertidal flats.

III. *Wave-dominated*
The coastline is subjected to high wave energy. Barrier islands protect the lagoon and create a suitable environment for mangrove establishment.

IV. *High wave energy and high river discharge.*
Waves and currents act on sands brought by rivers or derived from the shelf to form a coastal plain dominated by beach ridges and dunes. The river mouth or the protected area in the lagoon offer natural establishment of mangroves.

V. *Drowned river valley*
Marine or fluvial deposition has not been sufficient to fill the estuary. The river discharge, wave action and tidal range are low. Mangroves are able to grow at the head of the valley or behind the bay barrier.

VI. *Carbonate platforms*

VII. *Coral reefs*

VIII. *Carbonate banks*

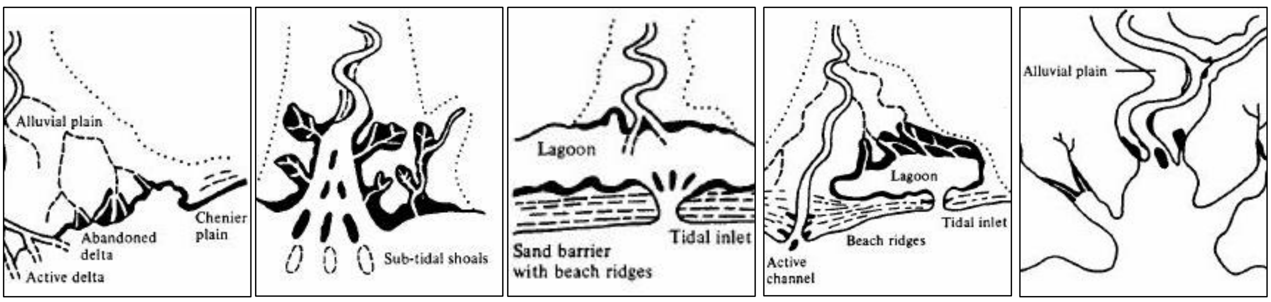


Figure A- 5 Mangrove setting (I, II, III, IV and V) (Thom, 1984))

A.5 Mangrove root system

Mangroves appear in coastal areas on muddy or silty substrates, are subjected to wave action and flooding during tidal inundation. The first important property of the root system is anchorage. Mangrove roots are situated in the first 0.5 m of the substrate (Tomlinson, 1986) and derive most of their anchorage capacity by expansion in horizontal direction. This development depends on the specie, soil type and the size of the tree. The roots have to withstand forces from waves and tidal currents on their branches with leaves, trunk and roots above the soil (Quartel et al., 2007).

The second important property of the root system is the absorption of nutrients and the gas exchange in oxygen poor sediments. Roots for absorption of nutrients are located in the muddy subsurface. Roots for aeration grow above the bottom and are developed to avoid suffocation in the anaerobe soil. These roots have on their surface, special pores to take in air (lenticels) and block intrusion of water and salt. Besides aerial roots contain large air spaces (aerenchyma) to transport air and provide a reservoir of air during high tide when all aerial roots are inundated. The root system of mangroves can be divided according to their configuration in five main types: stilt, pneumatophore, plank, buttress and knee roots.

The protrusion of the root system above the substrate in combination with the trunk of the tree has influence on the damping of waves and local currents. More detailed elaboration is in section A.2.

Figure A- 6 Mangrove root types (stilt, pneumatophore, plank, buttress and knee (Mangroves, 2016))

A.6 Mangrove propagation

Mangroves are well developed and adapted to live in harsh conditions. Their propagation has to deal the combination of hydrodynamic forces, sediment dynamics and external factors:

- Frequent inundation
- Wave attack
- Tidal currents
- Access to fresh water to lower the salinity
- Sediment burial
- Anoxic soils
- Nutrients
- Competition
- Predation

The propagation of mangroves relies on the dispersal of fleeting seedlings and propagules. Seedlings are small and have little capacity to settle in highly dynamic conditions thus have less chance to survive. Propagules are more developed and are able to deal with the environment. The propagule is buoyant and travels in the water before rooting itself on the subsoil. The root length must be sufficient to withstand waves and currents. Moreover, the propagule must establish itself before the next inundation period enters because waves and currents can loosen the propagule. This period is called the window of opportunity (Balke et al., 2011). The inundation period or excessive sediment deposits can bury and kill the propagule (Ellison J. C., 1998). Others stresses are caused by the salinity, anoxic soils, predators, competition with young mangroves and other vegetation (Quartel et al., 2007).

Once the propagule is established and adapted to the environment it is able to develop a young mangrove. The further development depends on site specific geomorphology, hydrology and climatic conditions (Marchand, 2008). The appearance of mangrove species in perpendicular direction to the coast in the intertidal zone is correlated with the elevation level, frequency of inundation and the inundation period.

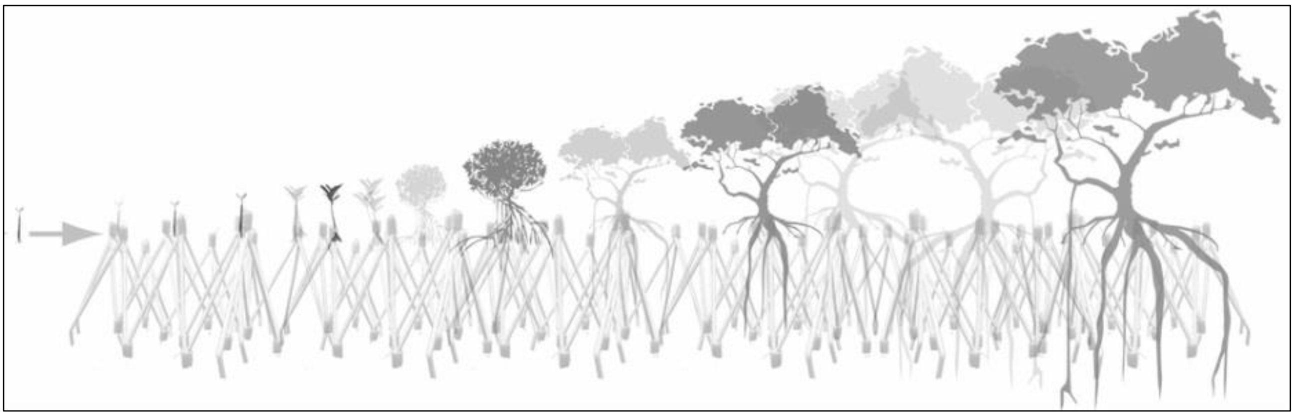


Figure A- 7 Mangrove propagation: from propagule to mature tree (van de Riet, 2016)

A.7 Mangrove forest type

Mangrove forests appear in different configuration depending on the geological and hydrological processes. Six types are classified by Lugo and Snedaker (1974) according to their soil type, depth, soil salinity range and flushing rates, Figure A- 8.

I. *Overwash mangrove forests*
Mangrove group on an island which is frequently inundated and overwashed by the tide.

II. *Fringe mangrove forests*
Dense mangrove group along shorelines with an elevation higher than high tide.

III. *Dwarf mangrove forests*
Widely spaced mangrove group along shorelines with an elevation higher than high tide.

IV. *Basin mangrove forests*
Mangrove group inside a basin where the inundation depends on the influence of the tide at their location.

V. *Hammock mangrove forests*
Mangrove group similar to the basin mangrove group. Only difference is their elevation to their surroundings.

VI. *Riverine mangrove forests*
Mangrove group along a tidal river or creek influenced by frequently flushing.

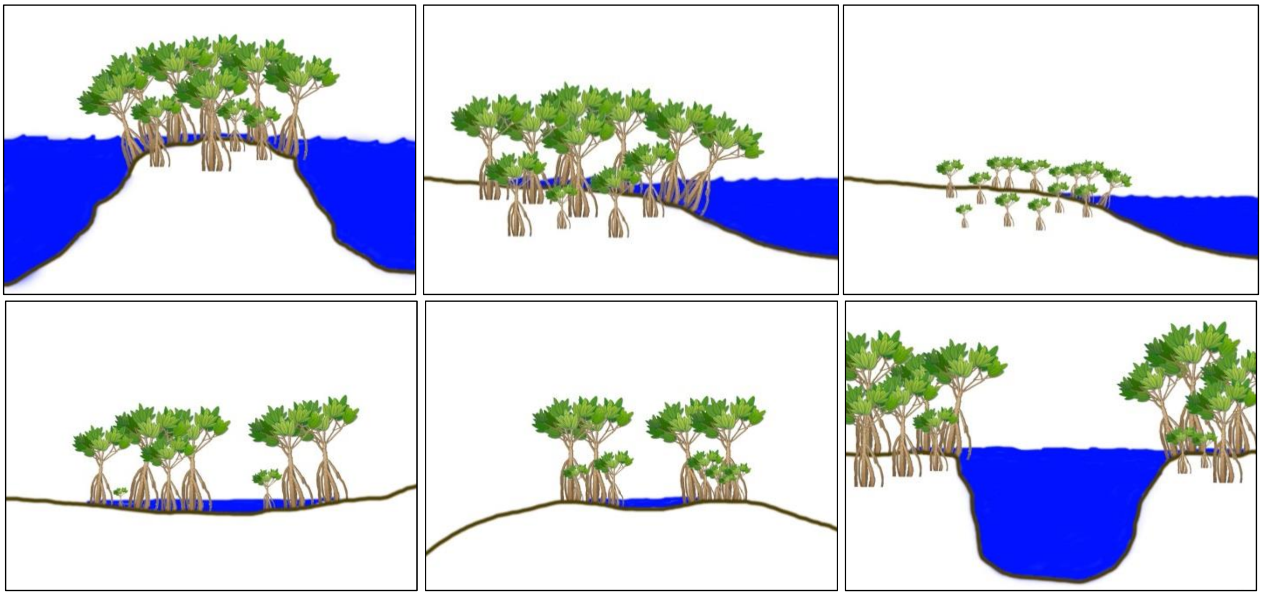


Figure A- 8 Mangrove forest types (left to right I, II, III and IV, V, VI) (Mangroves, 2016))

A.8 Mangrove intertidal coastal zonation

Zonation is the graphic representation of mangroves on the relative position from sea to land. Mangroves have been classified into seaward, mid, landward zones according to their tidal position, Figure A- 9.In these zones different mangrove species grow due to different settings like soil composition, frequency and length of inundation, salinity and access to fresh water (Snedaker, 1982).

The seaward zone consists of the mangroves is the most frequent exposed to the tide and regular inundated. The soil in this zone is normally mud and from sedimentary origin. The mangroves in this zone have pneumatophore roots for anchorage and gas exchange during inundation.

The mid zone is on higher elevation and less subjected to the tide and inundation. The soil consists of compacted mud and sedimentary deposits. The mangroves on this elevation level have stilt and knee roots.

The landward zone forms the transition to the terrestrial forest and is on an elevation level that is only inundated during the spring high water. The mangroves have buttress roots (Bell et al., 2011).

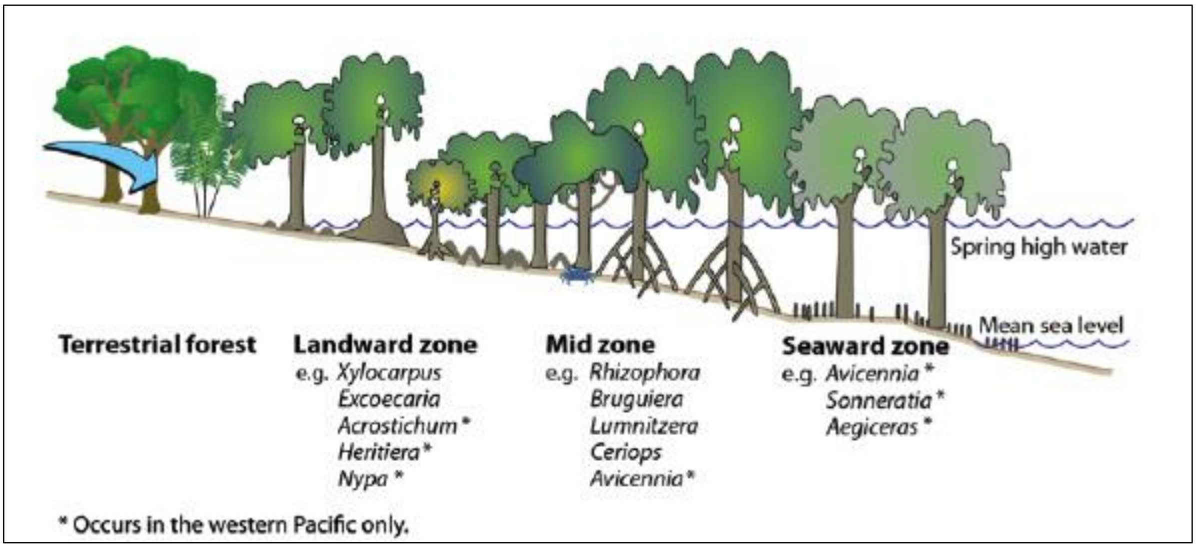


Figure A- 9 Zonation mangroves in intertidal zone (Bell et al., 2011)

A.9 Mangrove-mud coastline development

The coast is a dynamic system which varies in morphological form, pattern and configuration at all scales. The sedimentation and erosion process of a muddy mangrove coast is complex and depends on a large number of uncontrolled independent and interdependent processes (Winterwerp et al., 2005). The basis of accretional and erosional tendencies can be described by a qualitative description of the coastline development. This is the balance between the sedimentation rate and the erosion rate, equation A.1

$$\frac{dcl}{dt} = \text{sedimentation rate - erosion rate} \tag{A.1}$$

The underlying reasons are deducted from changes in source of the sediment and changes in dominant processes. It may occur that the same process has a favourable and an adverse effect. The end result depends on the magnitude and site specific conditions. The detailed process behind the sedimentation rate and erosion rate is explained below (Winterwerp et al., 2005).

Sedimentation rate

I. *Sediment supply by river*
Rivers play an important role in the sediment supply. They collect upstream sediments via rain run-off on the land and transport them into the coastal system. The timescale and impact of a change in river supply depends on the magnitude and share of the river input on the whole sediment balance.

II. *Sediment mobilization and supply by larger waves*
Large waves mobilize sediments from the bottom offshore and the tide transport this high concentrated suspension flux to the shore.

III. *Onshore sediment transport by tidal filling*
During high tide the flood transports suspended sediment on the shore into the mangroves where it can settle around slack water. The water during ebb contains less sediment and this creates a net positive accretion.

Erosion rate

I. *Subsidence*
Subsidence may occur due to natural consolidation or water withdrawal from deeper soil layers. For example subsidence of 0.01 m y^{-1} on a slope of 1:1000 gives a retreat of 10 m.

II. *Erosion by large waves*
Large waves cause erosion because they destabilize the mud deposits on the bottom of the foreshore, shoreline and mangrove trees.

III. *Erosion by small waves*
Small waves cause erosion because they destabilize the sediment near the shoreline and mangrove trees.

IV. *Longshore current transport*
Tide and wind induced longshore currents withdraw sediment and negatively influence the availability of the sediment in the system.

V. *Storm events*
The conditions during storm events damage or destroy mangroves and reduce their positive influence on the sedimentation.

A.10 Current solutions for degraded mangrove system

Interventions in the coastal configuration reduce the intertidal area and supply of sediment to mangrove coasts. The relation between the mudflat profile, onshore sediment transport and hydrodynamics conditions may cause an on-going loss of mangrove coasts. This chapter provides insight in the terminology and current lessons learned from mangrove restoration projects.

Terminology

In current plans for mangrove coast protection three words are widely used: restoration, rehabilitation and afforestation. They have different meanings depending on the prior function of the area and the type of human intervention. In order to avoid confusion they are explained and properly used in further research (Ellison A. M., 2000).

Rehabilitation: partial or full replacement of the ecosystems structural and functional characteristics

Restoration: returning an ecosystem back to its original condition (restoration can the successful end stage of rehabilitation)

Afforestation: the establishment of a forest in an area where there was no forest

Restoration

RESTORATION OF SEDIMENT BALANCE
The first step is to restore the sediment balance. The net transport of fine sediment must be positive and towards the coast

Semi-permeable dams made of local brushwood can be applied in order to hold the erosion process, increase the coastal resilience and induce coastal accretion. The semi-permeable dams are constructed perpendicular to the dominant wave direction. They imitate the function of the former present mangroves. They reduce the erosive wave energy while it still allows the sediment to enter a low-energy zone behind it and stimulates sedimentation. Sediment pass the dams through open since the construction is semi-permeable for water but not for sediment. The location of the semi-permeable dams should be chosen carefully. It is proposed to start close to the shore and build out step by step into the sea. The coast should gradually accrete and it should be prevented to create water logging between the original coast and the semi-permeable dams.

Once the shoreline has accreted to the required elevation, mangroves start to recolonize the new area. The accretion process can take 2-5 years and the natural growth of mangroves to an independent mature tree is in the order of 3-5 years. In front of the recolonized area semi-permeable structures are required to reduce wave energy until the foreshore is restored to dissipate wave energy naturally.

An additional mud nourishment can be applied to increase the sediment availability in the system. The wave energy brings the sediment in suspension while the tide transports it to the coast. The semi-permeable dams trap the sediment and stimulate the sedimentation (Tonneijck et al., 2015).

RESTORATION OF HYDROLOGY
The hydrological connection in the system and the natural exchange of water by the tidal in- and outflow must be restored. The removal of created bunds for fish ponds allows freshwater, sea water and sediment to enter the system. The restoration of the tidal creek reconnects the sea and the hinterland. The restoration of rivers enhances freshwater and sediment inflow from the hinterland. The result is a decrease in salinity, an increase in sediment supply and the natural distribution of propagules (Lewis III, 2005).

RESTORATION OF ECOSYSTEM
The restoration of the sediment balance and hydrology enhances the natural restoration of the ecosystem. Mangroves, if available in the system, start to colonize the accreted foreshore when it is suitable. Autochthones mangrove seedlings make more growth progress rather than allochthonous planted mangrove species. So it is advised to a restore the natural habitat, not to plant allochthonous species but first enhance the autochthonous mangrove seedlings disperse.

Restoration five step

Guidelines for successful mangrove restoration focus on identifying and addressing the factors that are limiting mangrove recovery (Brown & Lewis, 2006):

1. UNDERSTAND ECOLOGY OF ALLOCHTHONOUS MANGROVE SPECIES IN THE RESEARCH AREA
    1. Patterns of reproduction
    2. Propagule distribution
    3. Successful seedling establishment

    Mangroves propagate due to the distribution of seeds called propagules. The propagule enables the seed to float and survive for a certain period in the water till it can successful settle and grow. The ability to float and survival time depends on the different mangrove species. The propagation period differs per mangrove specie. The distribution of mangroves in perpendicular direction to the coast depends on the depth, duration, tidal inundation, frequency inundation, soil salinity and fresh water supply.

2. UNDERSTAND THE HYDROLOGY IN THE RESEARCH AREA
    - Depth
    - Duration
    - Frequency of tidal inundation

    Mangrove species differ in tolerance to bottom elevation level, soil composition, exposure to wave energy and tidal inundation.

3. ASSESS REASONS WHY THE ORIGINAL MANGROVE ENVIRONMENT CURRENTLY DOES NOT RECOVER
    - Blocked tidal inundation (parallel breakwater block the water)
    - Human intervention
        - Shrimp ponds
        - Clear-cut mangrove for charcoal production
        - Drying out due to change in hydrology (construction of dikes, levees, roads and upland)
    - Groundwater extraction causing subsidence
    - Hypersaline or acid sulphate soils
    - Overgrazing

    Assess stresses in the system and why there is no natural growth of mangroves

4. RESTORE THE HYDROLOGY AND ENVIRONMENTAL CONDITIONS
    - Create the natural slope and substrate height which supports normal tidal flow, natural re-establishment and growth of mangrove seedlings.
    - If needed create strategic breaches for exchange of tidal water
    - Tidal streams

5. ONLY UTILIZE ACTUAL PLANTING OF PROPAGULES, COLLECTED SEEDLINGS AND CULTIVATED SEEDLING WHEN NATURAL RECRUITMENT DOES NOT PROVIDE THE QUANTITY OF SUCCESSFULLY ESTABLISHED SEEDLINGS.

Lessons from previous projects

1. Do not build (impermeable) sea defences between the waterline and the mangrove forest. This reduces the onshore sediment transport flux, enhance the misbalance of sediment.
2. DO NOT APPLY HARD REVETMENTS SINCE HARD STRUCTURES LEAD TO REFLECTION AND ENHANCE THE EROSIVE FORCES. On the other hand, it enhances the unstable concave profile which prevents natural re-establishment of mangroves.
3. Do not build breakwater parallel to the coast because this reduces the stir up of fine sediments from the seabed by large waves.
4. DO NOT PLANT THE WRONG MANGROVE SPECIES (Primavera and Esteban, 2008) AND DO NOT PLANT AT INAPPROPRIATE LOCATIONS (too wet, too low, wrong soil, wrong hydrology, wrong hydrodynamics) or wrong conditions (eroding mudflat) (Lewis, 2005).

Appendix B Wind

The information in this section is based on the lecture notes of Coastal Dynamics I (CIE4305) by Bosboom and Stive (2013). The wind data are retrieved from the database of Boskalis and analysed through Matlab.

WIND ENERGY TRANSFER

Waves are generated through energy transfer of the wind to the water surface. The wave height, period and direction depend on the duration, speed, direction of the wind, local water depth and the fetch. The latter is the length over which the wind is effective in generating waves. In general, persistent wind duration and wind speeds induce larger wave heights and period.

The significant wave height and wave period can be estimated through the empirical equation developed by Sverdrup-Munk-Brettschneider (1984) and which is improved by Young and Verhagen (1996). Another method is to use nomograms developed by Groen and Dorrestein (1976). In the case Demak it is assumed to use the nomogram for shallow water (d/L < 0.1), see Figure B- 1.

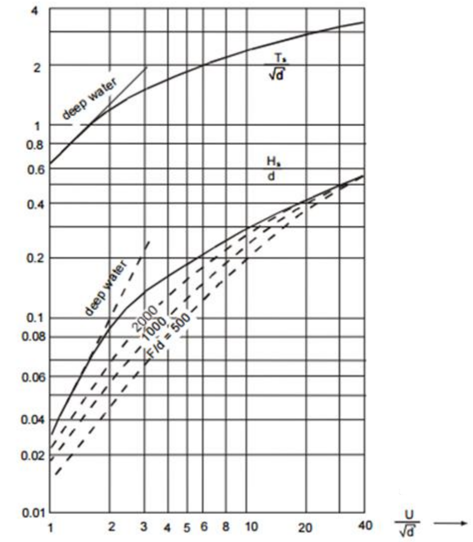


Figure B- 1 Nomogram valid for shallow water (d/L <0.1) (Groen & Dorrestein, 1976)

For waves that are not fully developed due to the wind (restricted by fetch or duration) a JONSWAP spectrum is defined. For fully developed wind waves the Pierson-Moskowits spectrum is valid, see Figure B- 2. In the case Demak a JONSWAP spectrum is assumed due to the limited fetch in the Java Sea.

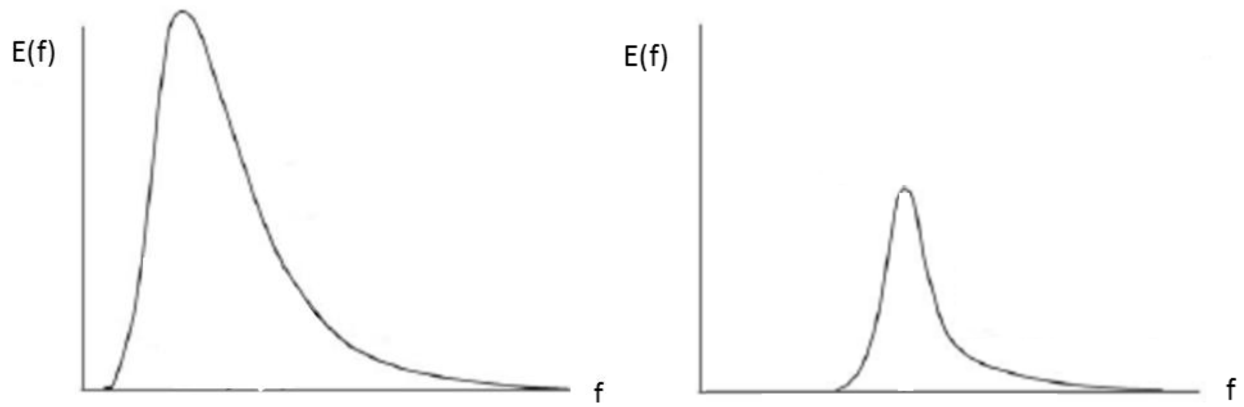
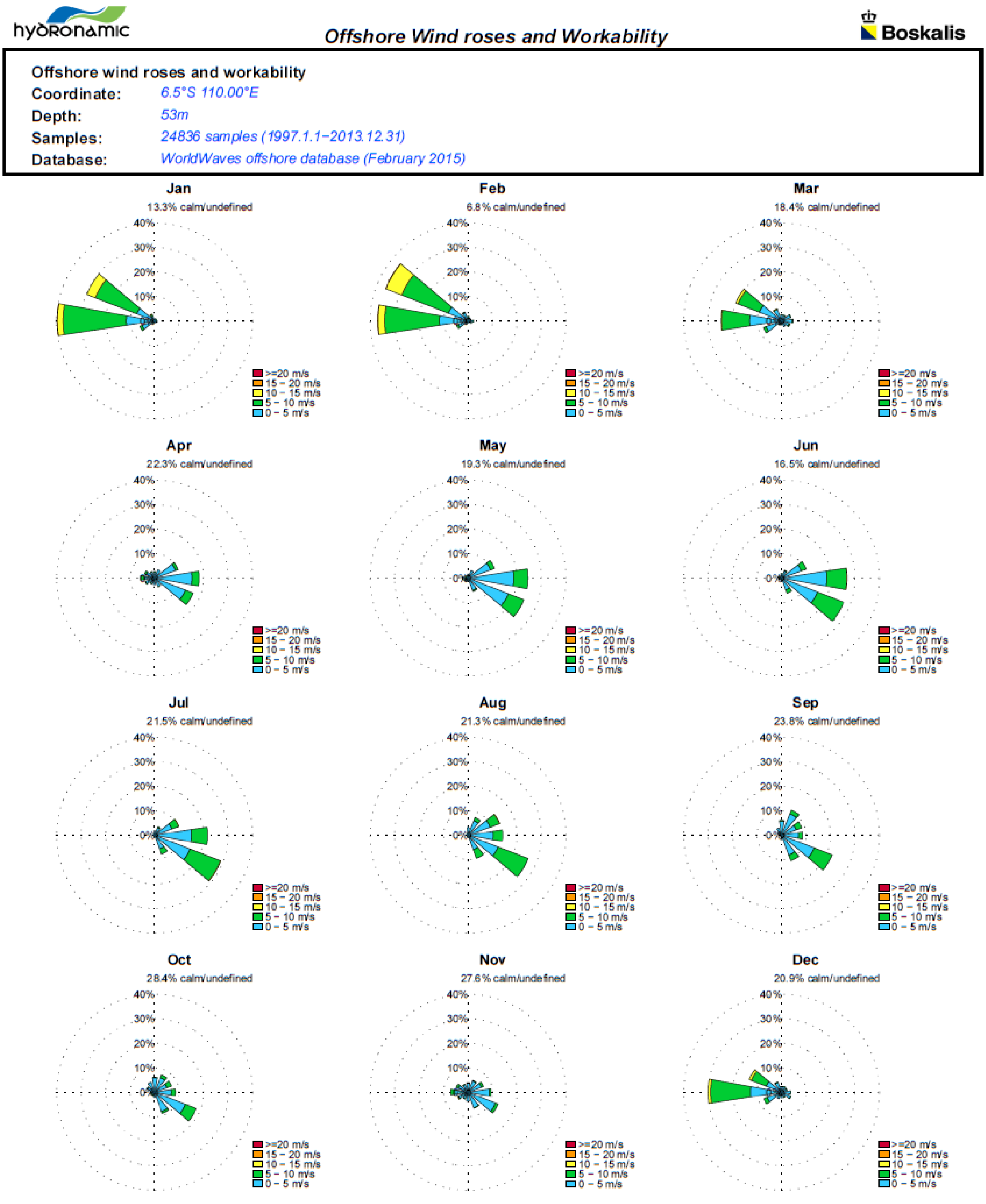


Figure B- 2 Pierson-Moskowitz (left) and JONSWAP (right)



Workability [%]

	Jan	Feb	Mar	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	year
U<1.6m/s (<=Bft.1)	20	16	34	40	33	26	28	29	33	41	48	37	32
U<3.4m/s (<=Bft.2)	31	31	59	70	60	51	49	49	59	70	79	57	55
U<5.5m/s (<=Bft.3)	53	51	80	93	89	84	80	81	90	93	96	78	81
U<8.0m/s (<=Bft.4)	80	75	94	100	99	99	98	98	100	100	99	92	95
U<10.8m/s (<=Bft.5)	97	95	99	100	100	100	100	100	100	100	100	99	99
U<13.9m/s (<=Bft.6)	100	100	100	100	100	100	100	100	100	100	100	100	100
U<17.2m/s (<=Bft.7)	100	100	100	100	100	100	100	100	100	100	100	100	100
U<20.8m/s (<=Bft.8)	100	100	100	100	100	100	100	100	100	100	100	100	100

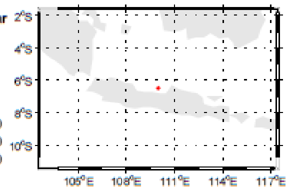


Figure B- 3 Offshore wind roses (courtesy of Boskalis)

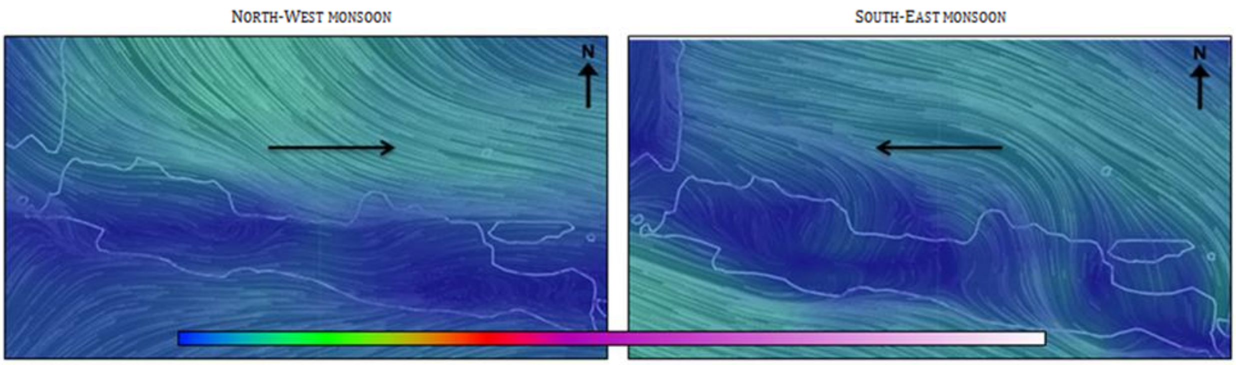


Figure B- 4 Wind direction near sea water level (Beccario, 2016)

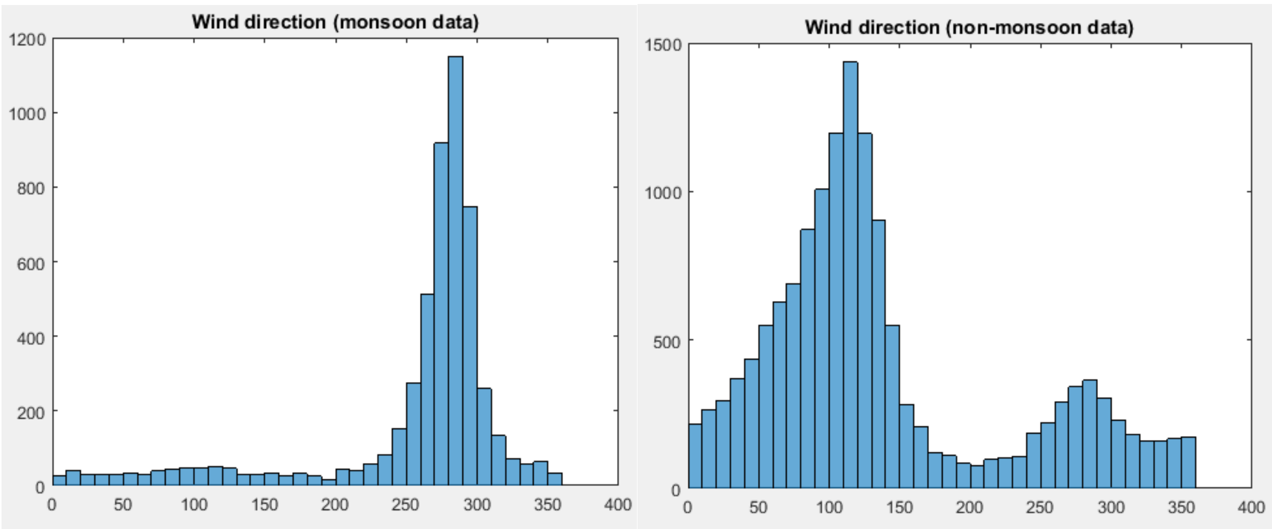


Figure B- 5 Wind direction North-West monsoon (monsoon) and South-East monsoon (non-monsoon)

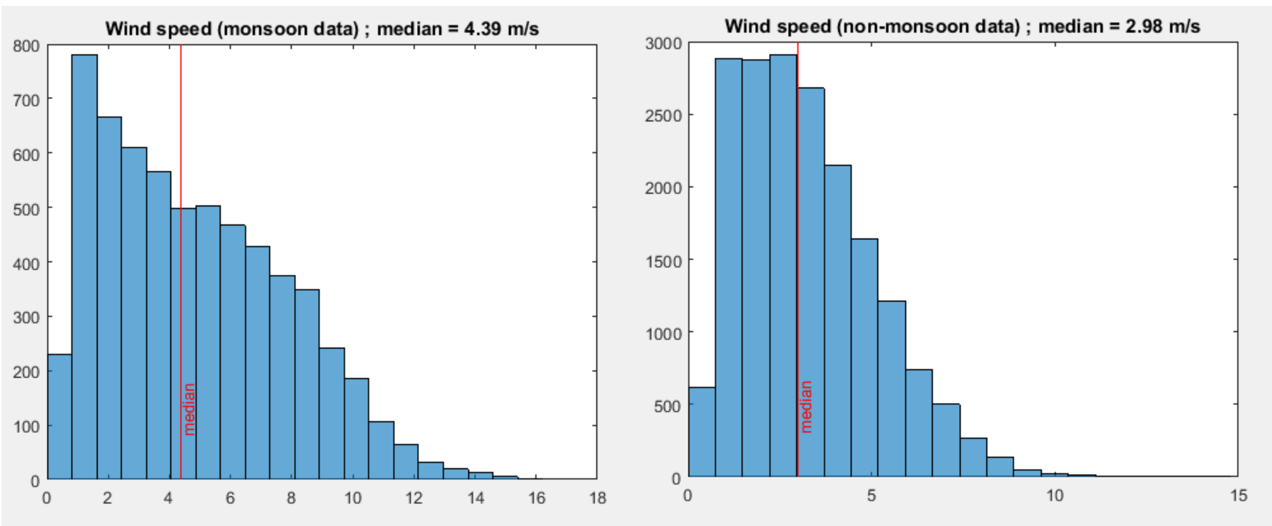


Figure B- 6 Wind speed North-West monsoon (monsoon) and South-East monsoon (non-monsoon)

Appendix C Wave

The information in this section is based on the lecture notes of Coastal Dynamics I (CIE4305) by Bosboom and Stive (2013). The wave data are retrieved from the database of Boskalis and analysed through Matlab.

WAVE PROPAGATION AND TRANSFORMATION

The wave celerity is equal to the square root of the water depth and the gravitation constant. During the propagation of waves they transform due to the bottom topography. The influence of the bottom starts to slow down waves when the water depth becomes less than half of the wave length. The wave at front notices the shallow water depth first and the propagation speeds reduces. Subsequently, the wave behind the front wave is not (yet) influenced by the shallow water depth and tends to overtake the front wave with its higher speed. The concentration of energy accumulates and the wave height increases, this phenomenon is called shoaling, see Figure C- 2. Waves cannot increase endless in wave height due to shoaling. Wave-breaking occurs when the ratio of the (breaker) wave height and the water depth exceeds the limit of 0.78. This value is based on the solitary wave theory which is a non-linear wave theory valid for shallow water. To feel the influence of horizontal motions near the bottom, bottom friction, the water depth needs to be less than half of the wave length. The wave energy is first converted into turbulent kinetic energy and later dissipated due to turbulence.

Another process is refraction where waves under influence of the increasing bottom level bend towards the shallower part. This causes that the angle of incidence at the coast is around 90 degrees and waves approach the coast perpendicular, see Figure C- 1.

Diffraction is wave transformation because of the blockage by obstructions like breakwater or islands. After the wave front hits the obstruction it continues behind it under an angle, see Figure C- 1.

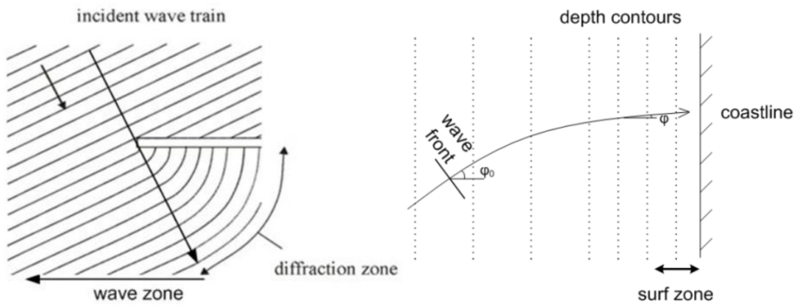


Figure C- 1 Diffraction (left) and refraction (right)

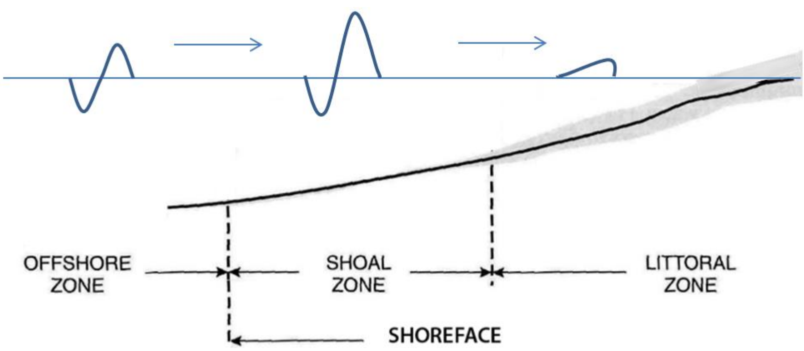


Figure C- 2 Shoaling process

RADIATION STRESS

In the previous section is described how energy is transferred within waves and to the environment. The transfer of momentum is referred as the radiation stress. This is the depth-integrated and wave-averaged flow of momentum due to waves (Longuet-Higgins & Stewart, 1962). The wave induced momentum flux changes per location in the cross-shore and this lead to forces on the water. The radiation stress increases in the shoaling zone which leads to a decrease in the water level, set-down, to level the original force balance. The radiation stress decreases in the surf zone which leads to an increase in the water level. To compensate this loss the water level rises in a set-up against the coast, see Figure C- 3.

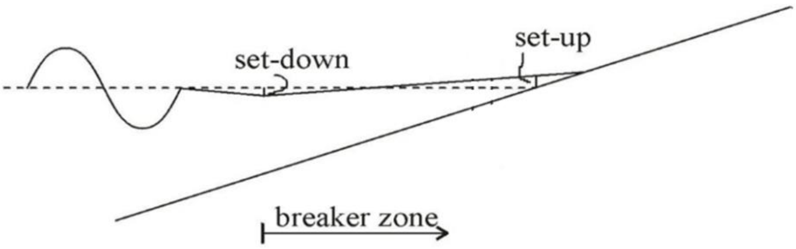


Figure C- 3 Set-down and set-up

Waves that approach the coast under an angle induce a longshore current due to the horizontal non-uniformity of the radiation stress in the surf zone, see Figure C- 4.

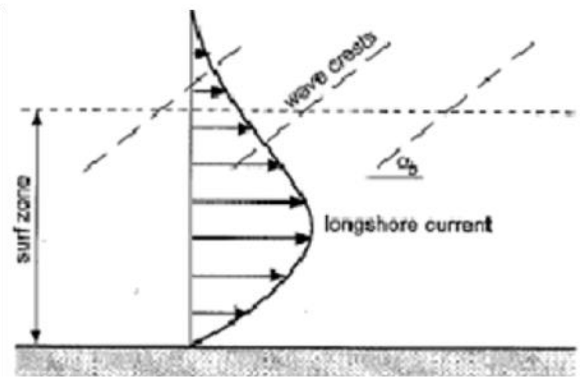


Figure C- 4 Plan view of longshore current induces by waves

Vertical non-uniformity of driving forces in the breaker zone induces secondary currents, see Figure C- 5. The pressure gradient due to the set-up is the same at all water levels but the radiation stress in the cross-shore is not evenly distributed. In the top of the water column the breaking waves induces strong pressure en velocity variations towards the coast, the surface current Continuity requires in the lower parts of the water column an offshore directed current, the undertow.

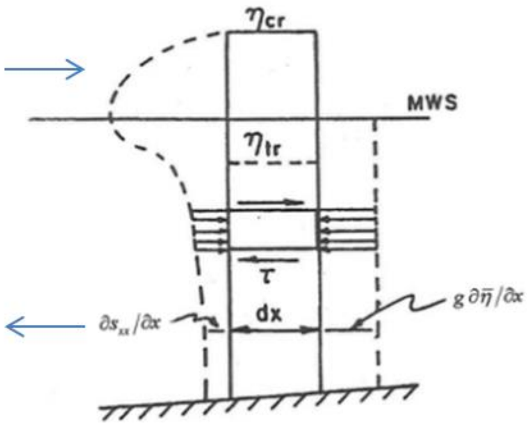
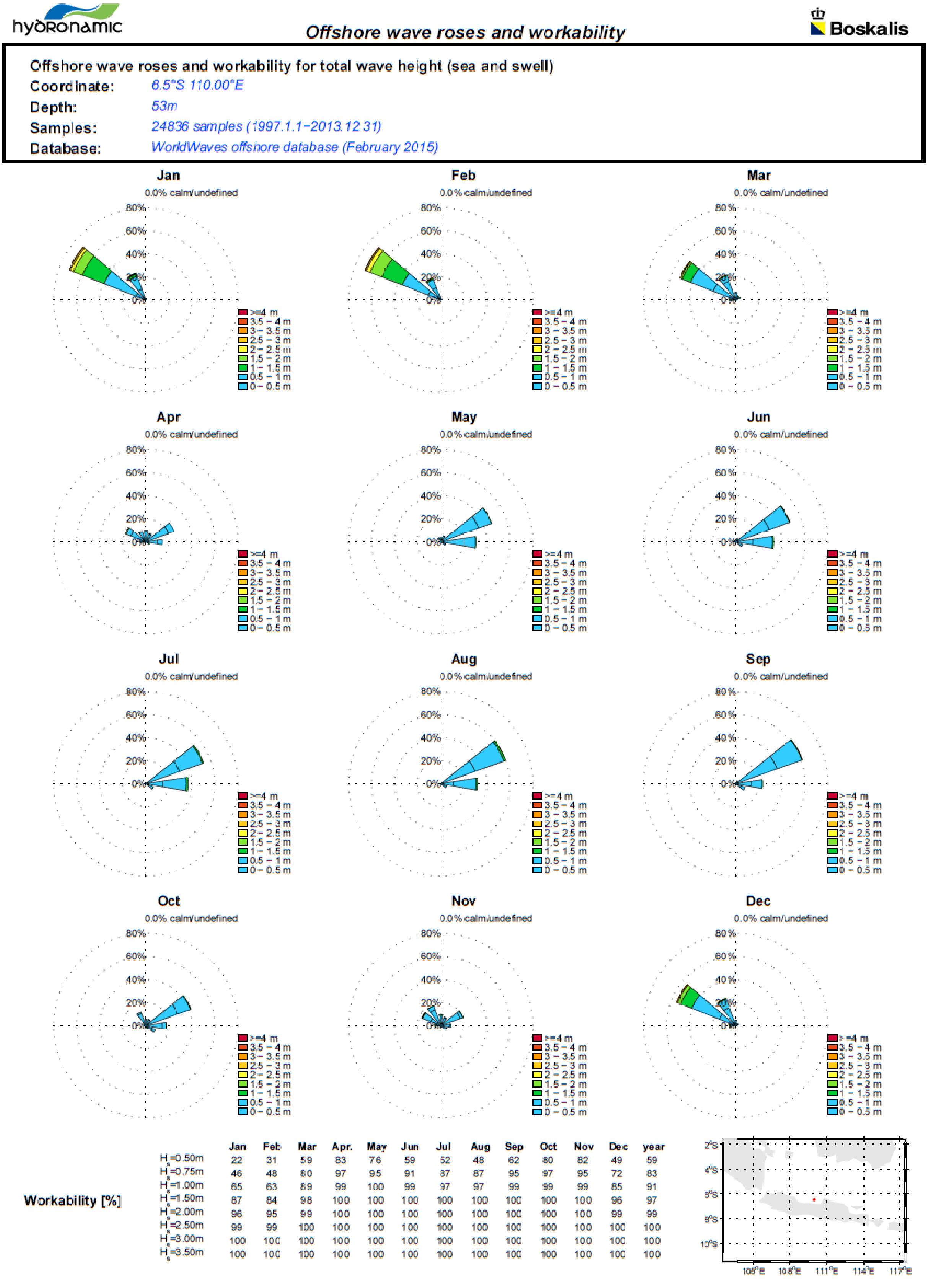


Figure C- 5 Undertow



	Jan	Feb	Mar	Apr.	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	year
H_s=0.50m	22	31	59	83	76	59	52	48	62	80	82	49	59
H_s=0.75m	46	48	80	97	95	91	87	87	95	97	95	72	83
H_s=1.00m	65	63	89	99	100	99	97	97	99	99	99	85	91
H_s=1.50m	87	84	98	100	100	100	100	100	100	100	100	96	97
H_s=2.00m	96	95	99	100	100	100	100	100	100	100	100	99	99
H_s=2.50m	99	99	100	100	100	100	100	100	100	100	100	100	100
H_s=3.00m	100	100	100	100	100	100	100	100	100	100	100	100	100
H_s=3.50m	100	100	100	100	100	100	100	100	100	100	100	100	100

Figure C- 6 Offshore wave roses (courtesy of Boskalis)

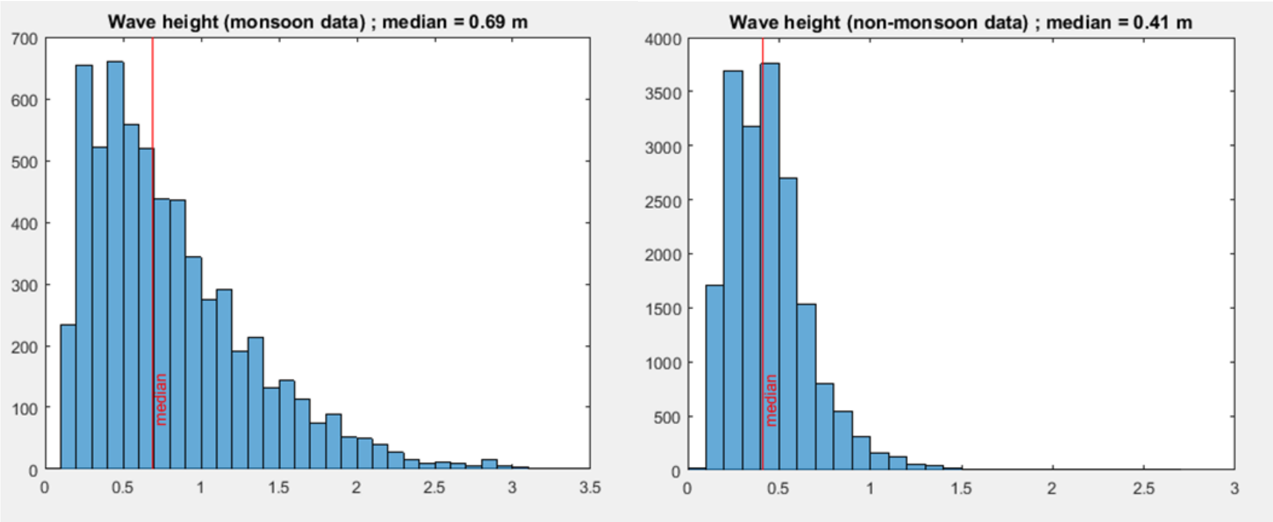


Figure C- 7 Significant wave height NW monsoon (monsoon) and SE monsoon (non-monsoon)

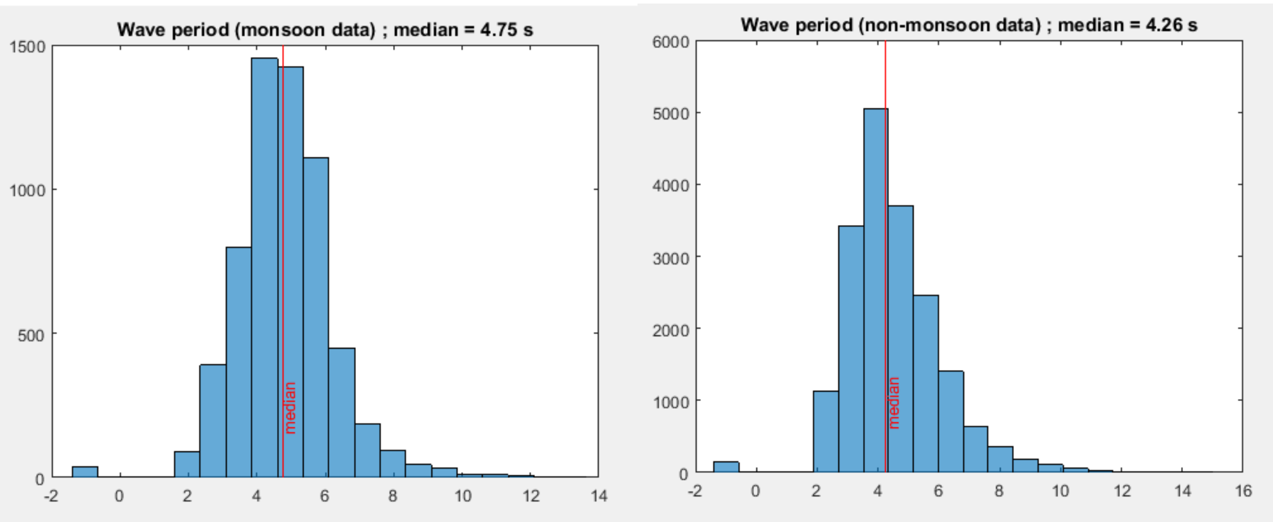


Figure C- 8 Mean wave period NW monsoon (monsoon) and SE monsoon (non-monsoon)

Appendix D Tide

The information in this section is based on the lecture notes of Coastal Dynamics I (CIE4305) by Bosboom and Stive (2013) and Yusuf and Yanagi (2013).

Vertical and horizontal tide

The vertical rise and fall of the water level is referred as the tide. The highest water level is called high tide while the lowest water is called low tide. The period from the highest tidal elevation to the lowest tidal elevation is called falling tide. The other way around, from the lowest tidal elevation to the highest tidal elevation is rising tide. The actual period of the falling tide and rising tide do not necessarily match each other and is referred as tidal asymmetry (Bosboom & Stive, 2013), see Figure D- 1.

The turning point from rising tide to falling tide is called high water slack. The flow reversal from falling tide to rising tide is referred as low water slack. The duration of slack water plays an important role in the transport of fine sediment. Fine sediment need a certain time span to settle and this happens in the relative low energy flow reversal period. Larger slack water periods enhance more fine sediment deposits. (Bosboom & Stive, 2013).

The horizontal movement of water back and forward is the horizontal tide or tidal current. If the current velocity and the tidal wave propagation are in the same direction it is flood. If the current velocity is in the opposite direction of the tidal wave propagation it is referred as ebb. The horizontal movement of water, flood and ebb, do not necessarily coincide with the vertical water movement, rising tide and falling tide. This is caused by the complex phase relation between the horizontal and the vertical tide (Bosboom & Stive, 2013).

The phase difference changes the influence of the flood or the ebb and shifts the dominance to one of them. Ebb-dominance means that the ebb has higher maximum velocities and a shorter duration. Flood-dominance means that the flood has higher maximum velocities and a shorter duration. For instance, flood-dominance can be induced by a large tidal amplitude. The tidal wave propagation is faster during flood because it is defined by the square root of the water depth. The larger flood velocity implicates that the rising period is smaller than the falling period. Ebb-dominance can be caused by large intertidal storage volume which enhances larger ebb velocities. Furthermore, ebb- and flood-dominance depends on the basin geometry. Enclosed basins are often ebb-dominance and open coasts are flood-dominance (Bosboom & Stive, 2013).

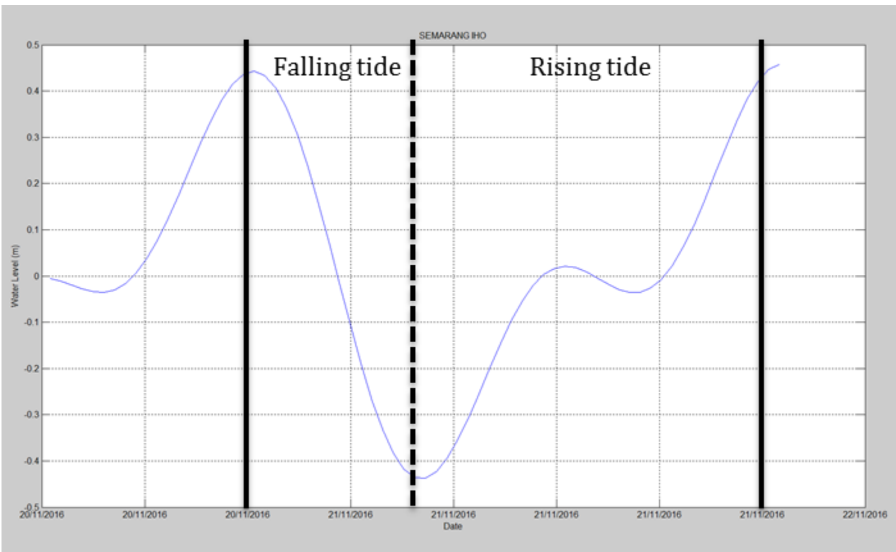


Figure D- 1 Falling tide and rising tide (Delft Dashboard)

TIDAL CHARACTER

The tidal character is determined by the use of tidal constituents and the form factor formula. Tidal constituents develop from the interaction of the moon, sun and irregularities in the movement of the Earth (Bosboom & Stive, 2013). The tidal constituents that are used for the case in Demak are shown in Table D- 1.

The form factor is the relative amplitude of the main diurnal components (K1 and O1) compared with the amplitude of the main semi-diurnal components (M2 + S2), see equation D.1 (Bosboom & Stive, 2013). The ratio between the diurnal and semi-diurnal components determines the character, see Table D- 2.

The form factor is 2.40 and according to this approach the tidal character in Demak is mixed tidal signal with mainly diurnal characteristics and small semi-diurnal components (Bosboom & Stive, 2013).

Tidal constituent	**Amplitude**	**Phase**
[-]	[cm]	[deg]
S0	95.4	-
M2	7.57	541
S2	5.93	124
N2	2.03	440
K2	1.36	124
K1	21.4	-32
O1	11.1	852
P1	7.07	-32
M4	0.61	760
MS4	1.40	321

Table D- 1 Tidal constituents Demak (Delft Dashboard)

Tidal constituent	**Amplitude**	**Phase**
[-]	[cm]	[deg]
K1	21.4	-32
O1	11.1	852
M2	7.57	541
S2	5.93	124

Table D- 2 Tidal constituents form factor Demak (Delft Dashboard)

$$F = \frac{K1 + O1}{M2 + S2} \tag{D.1}$$

Category	**F**
[-]	[-]
Semi-diurnal	0 – 0.25
Mixed with mainly semi-diurnal	0.25 – 1.5
Mixed with mainly diurnal	1.5 – 3
Diurnal	> 3

Table D- 3 Tidal character according form factor (Bosboom & Stive, 2013)

TIDAL PROPAGATION

The tide propagates as a tidal wave and is characterised by relative large wave length compared to the amplitude. The propagation velocity is defined by the square root of the water depth times the fall velocity. During its propagation the tidal wave experiences local water depth differences due to the bathymetry and reflection due to land boundaries. Furthermore, if the tidal wave enters shallow water the celerity decreases while the energy concentration remains the same (friction and dissipation effects are small) and the tidal wave amplitude increases (Bosboom & Stive, 2013). Examples of tidal wave propagation including the tidal wave amplitude, tidal phase and tidal energy are in Figure D- 2, Figure D- 3, Figure D- 4, Figure D- 5, Figure D- 6 and Figure D- 7.

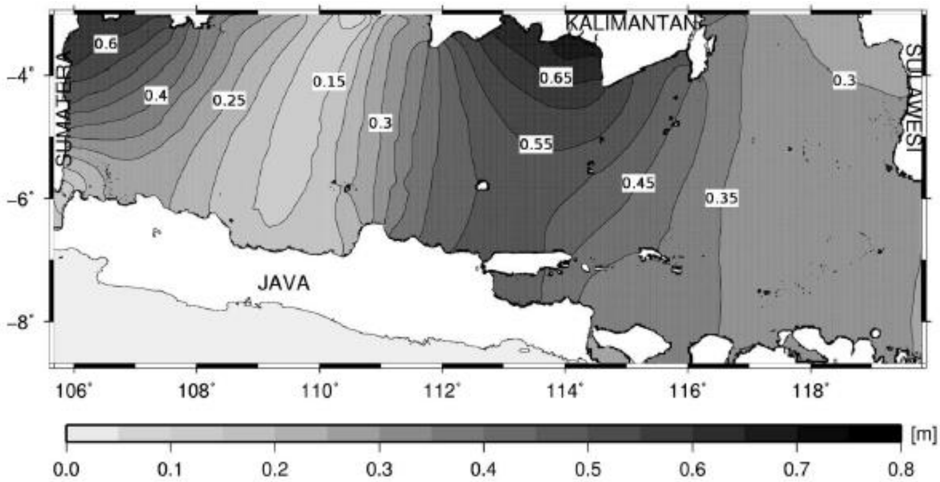


Figure D- 2 K1 tidal amplitude (Yusuf & Yanagi, 2013)

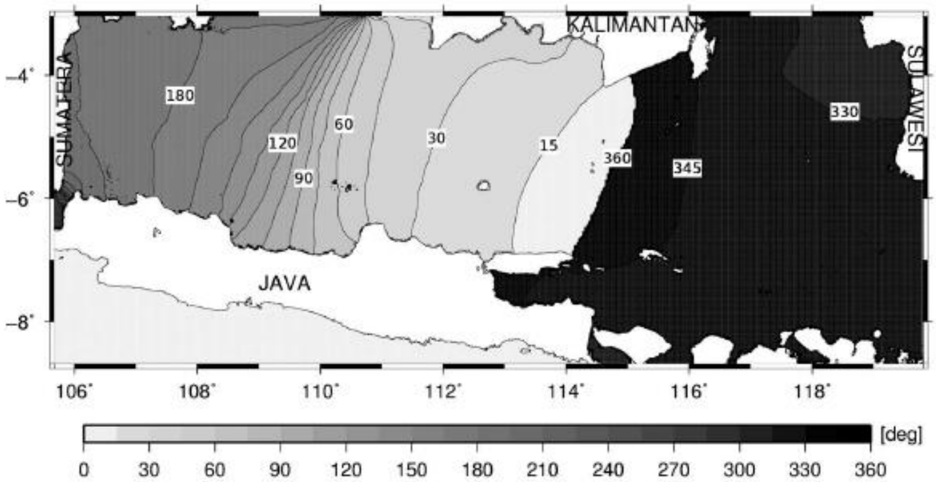


Figure D- 3 K1 tidal phase (Yusuf & Yanagi, 2013)

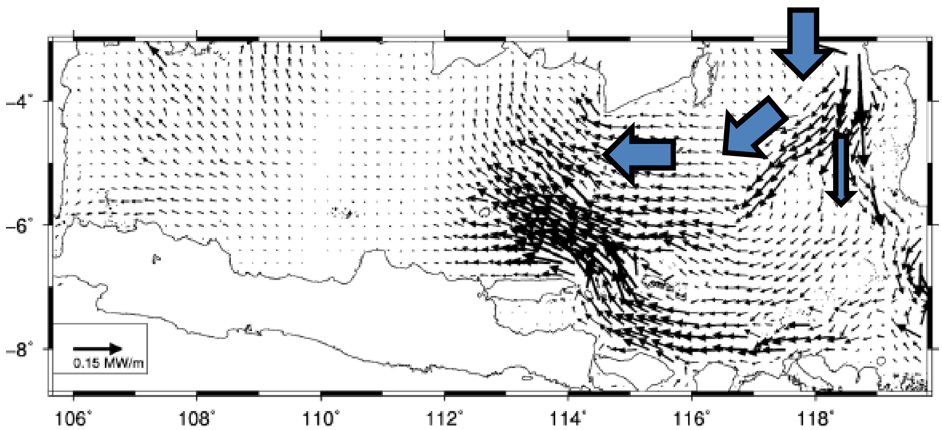


Figure D- 4 K1 tidal energy flux (Yusuf & Yanagi, 2013)

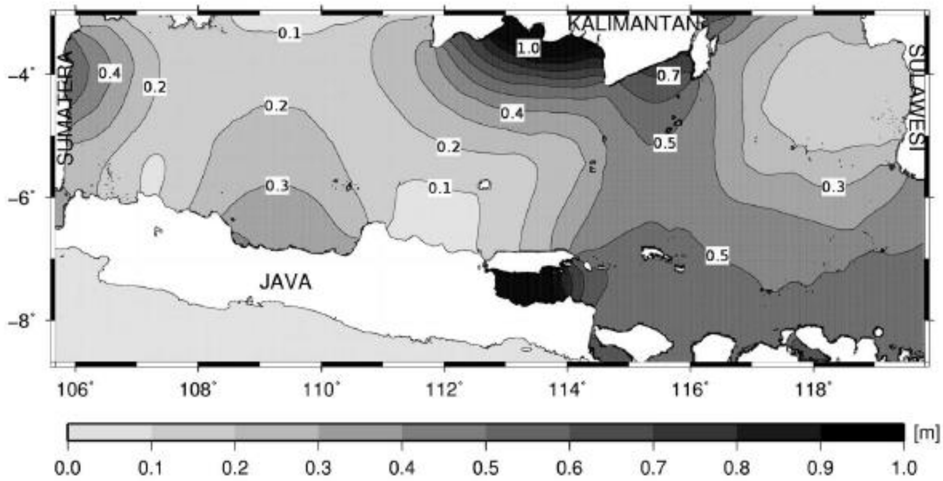


Figure D- 5 M2 tidal amplitude (Yusuf & Yanagi, 2013)

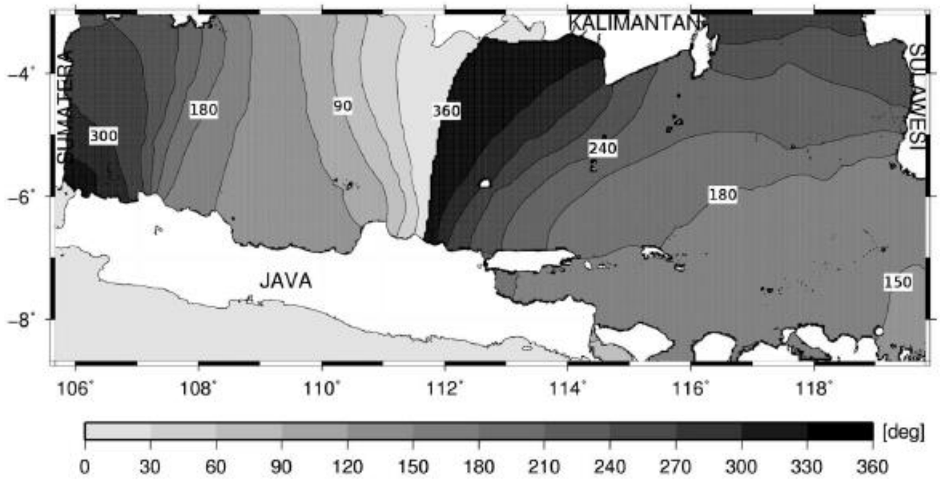


Figure D- 6 M2 tidal phase (Yusuf & Yanagi, 2013)

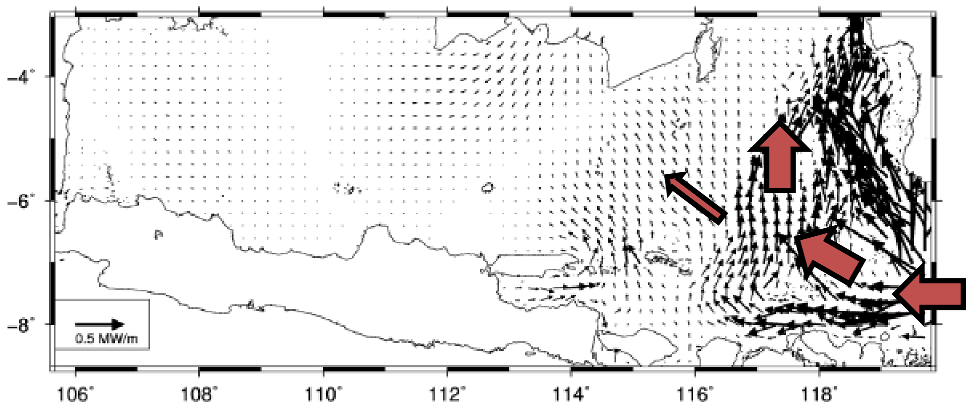


Figure D- 7 M2 tidal energy flux (Yusuf & Yanagi, 2013)

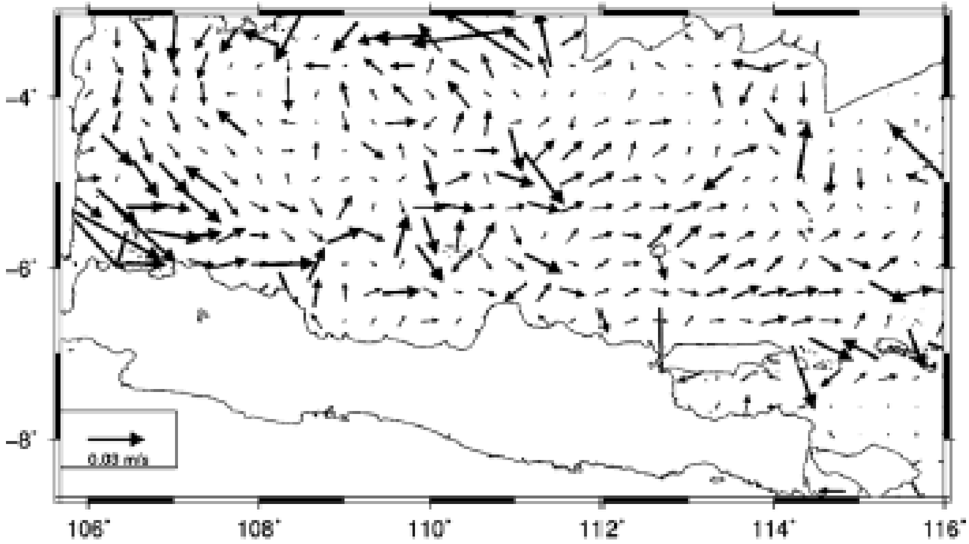


Figure D- 8 Tidal residual current K1 in Java Sea (Yusuf & Yanagi, 2013)

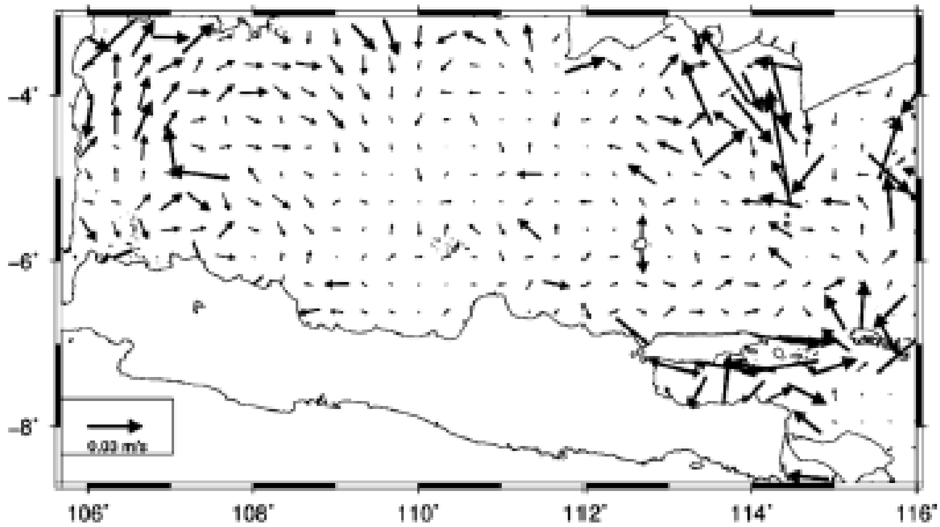


Figure D- 9 Tidal residual current M2 in Java Sea (Yusuf & Yanagi, 2013)

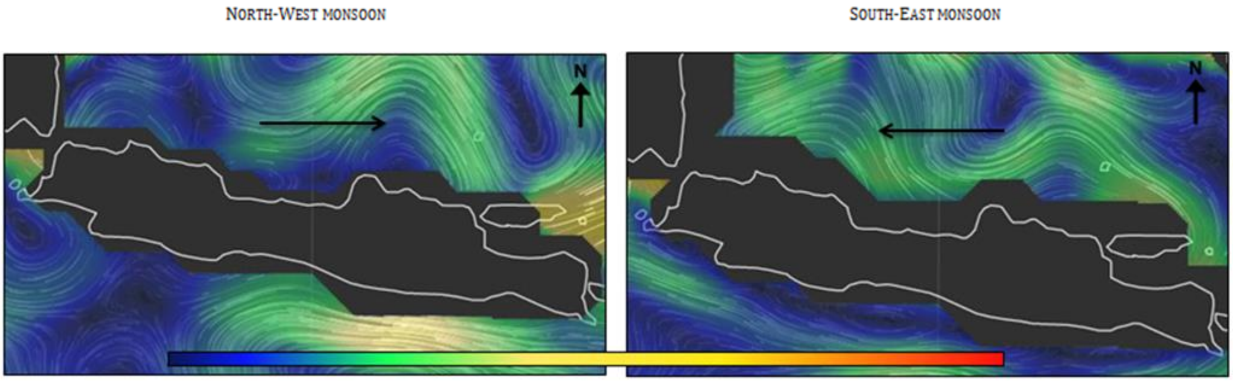


Figure C- 9 Surface current (Beccario, 2016)

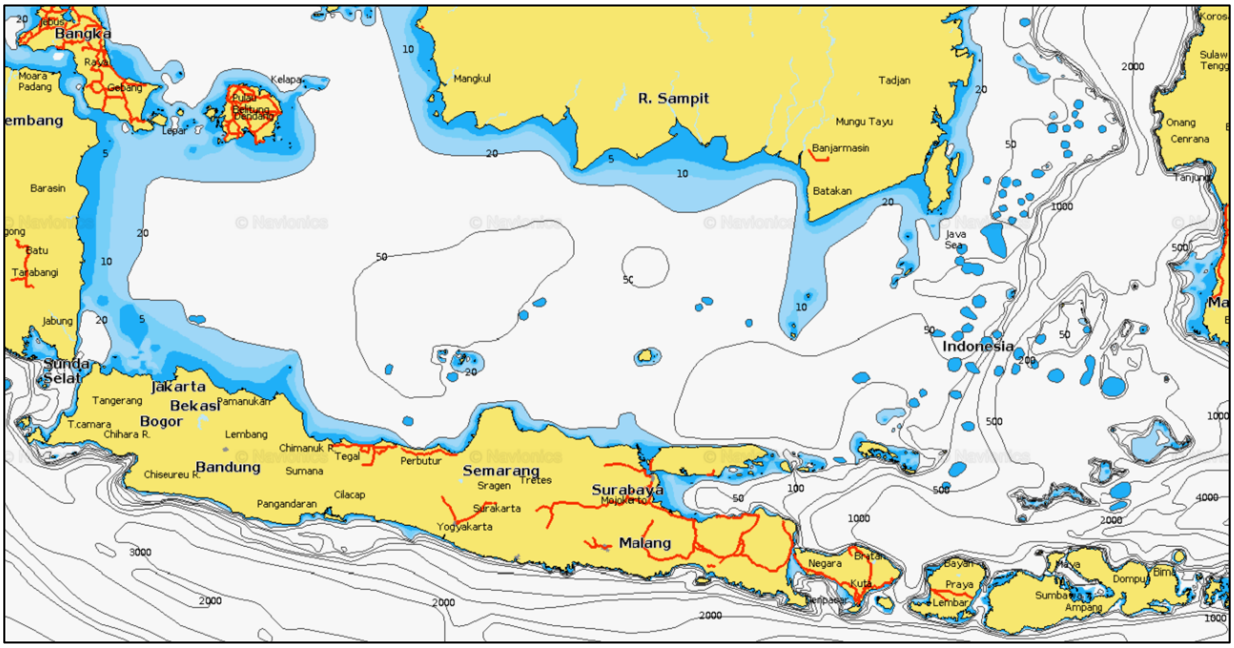


Figure D- 10 Bathymetry Java Sea and inlet Strait of Makassar and Flores Sea (Amnautical, 2016)

Appendix E Hydrodynamics

This chapter is the heart of the hydrodynamic analysis. It starts with the comparison between an online and offline run. Also the hydrodynamic difference between a spring tide and neap tide is investigated. Subsequently, the general settings and the bottom topography. Thereafter, the hydrodynamic analysis is separated into a part without chenier and a part with chenier. Per bottom topography are three hydrodynamic scenarios investigated, see Figure E- 1. Each paragraph demonstrates step by step the observed period, tidal forcing, wave forcing, flow direction and resulting shear stresses.

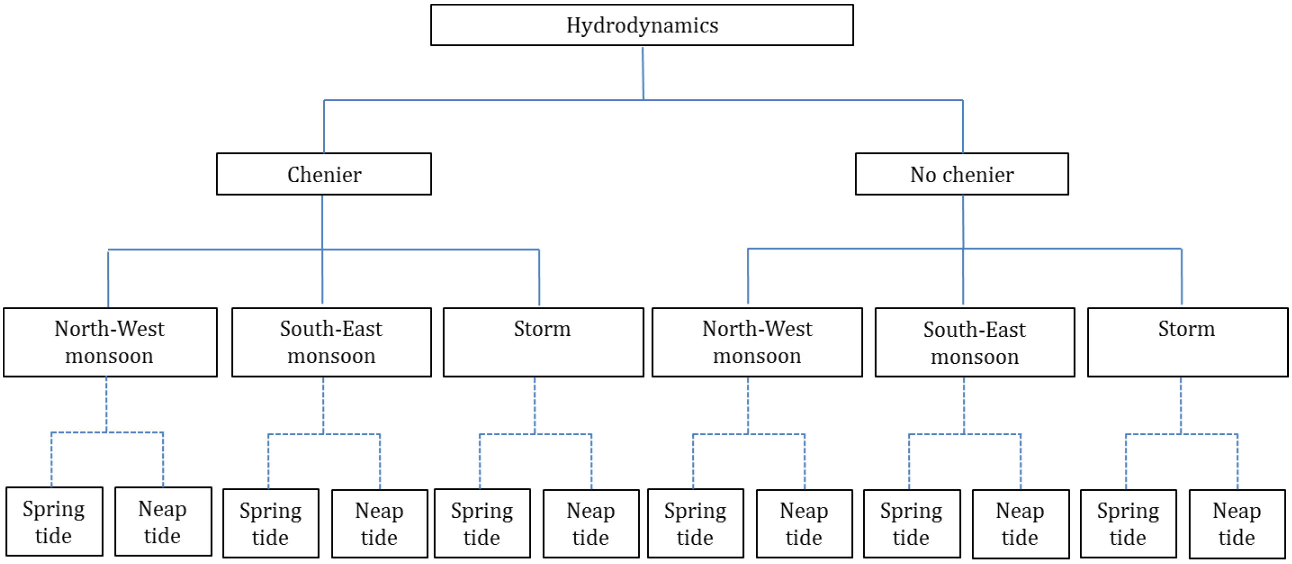


Figure E- 1 Overview scheme hydrodynamics

E.1 Online and offline run comparison

In this section it is summarized what the difference is between a full online and offline run.

In the full online run the wave information (WAVE-module) and tidal information (FLOW-module) communicate every hour and compose the final water movement and shear stress. The wave information has small influence on the water level. The water level is dominated by the tide and has a large influence on the wave information. The wave height, wave breaking and bottom shear stresses depend on the bottom topography and the instant water elevation. In an online run the water elevation and wave information cooperate and calculate every time step the results of these two.

In an offline run the tidal information communicates with a small fixed wave information file. The wave information is calculated in the first 2 hours with the according water level and results. The small fixed wave information is copied and applied over the full calculation period. For instance, this means that the wave information obtained over 2 hours with low tide is applied on the high tide period. The wave information does not match with the actual water level elevation. The consequence is that the water movement, flow velocity and shear stress is substantial different than in a full online run. This is illustrated in Figure E- 2 and Figure E- 3. Note, the shear stress figures show a snapshot while the velocity vector pattern figures show a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The shear stress range is 0 – 2 N/m^2 while the flow velocity range is 0 – 0.2 m/s

In this MSc thesis it is important to simulate the behaviour of the sediment transport in Demak. It is hypothesized that the shear stress needs to stir up the sediment and subsequently transport through the water movement composed of tide and wave. This shear stress varies due to the water elevation and the wave forcing. Therefore online runs are the most suitable approach.

All the runs in the rest of this report are done online.

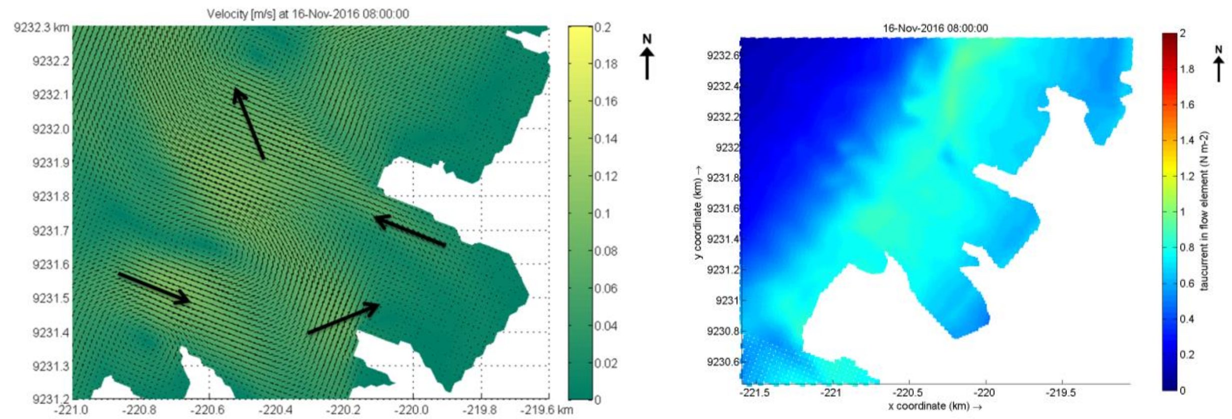


Figure E- 2 Flow direction and magnitude and shear stress –North-West monsoon – online run

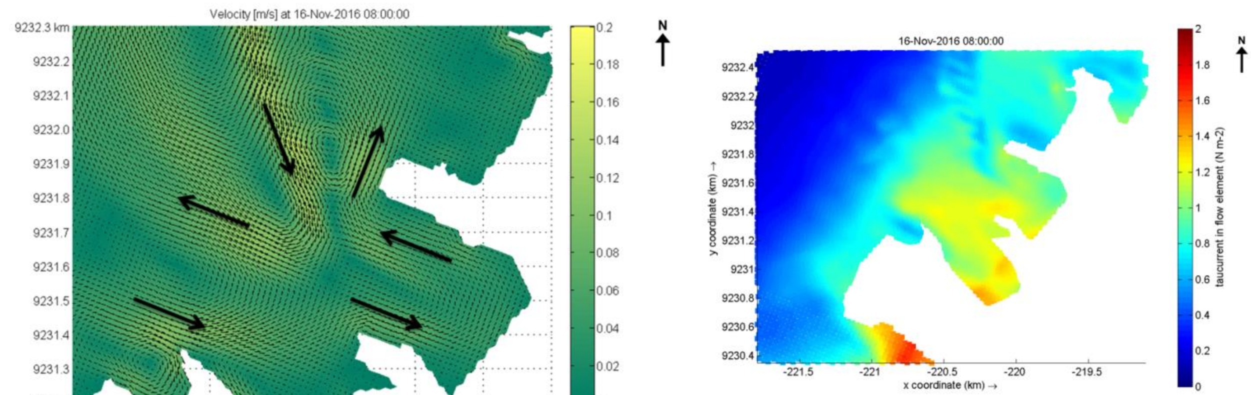


Figure E- 3 Flow direction and magnitude and shear stress –North-West monsoon – offline run

E.2 Spring tide and neap tide comparison

It is recognised that there is not a distinct 28 days spring-neap cycle in Demak. Though there are two extremes observed in 28 days and further on referred as: spring tide and neap tide. During spring tide the tidal range is at its maximum and during neap tide the tidal range is at its minimum. In spring tide and neap tide are 24 hours observed with one low water and one high water, see Figure E- 4.

To assess the impact of the two tidal ranges there is chosen to stepwise build up the information. It starts with the water depth which varies due to the tidal influence. During spring tide the lowest water is lower than during neap tide and the highest water is higher than during neap tide. The water depth influences the propagation of waves and the moment of wave breaking. The moment of wave breaking depends on the ratio of the wave height (H_b) and the actual water depth (h). This relation is expressed in the breaker index:

$$\frac{H_b}{h} = 0.78 \tag{E.1}$$

The impact of the hydrodynamic forcing is assessed through the bed shear stress. The total bottom shear stress is composed of shear stress from hydrodynamic forcing due to the tide (τ_{flow}) and wave breaking (τ_{wave}).

$$\tau = \tau_{flow} + \tau_{wave} \tag{E.2}$$

To assess the impact of the spring tide cycle and the neap tide cycle of 24 hours there is chosen to compare the high water and the low water of both, see Figure E- 4.

LOW WATER

During low water the water depth becomes smaller but the cells do not dry up. The incoming waves reach their critical water depth for wave breaking earlier due to the decrease in water level. The wave height decreases drastically and indicates wave breaking, see Figure E- 6. Subsequently, they propagate further as dissipative waves and the wind transfers energy to the water in this shallow area. Since the water depth is smaller in the spring tide, the highest shear stresses occur in this period, see Figure E- 7. The velocity vectors of the spring tidal and neap tidal cycle demonstrate the same general flow pattern during low water, see Figure E- 11.

HIGH WATER

During high water the water depth increases both for the spring tide and neap tide. The incoming waves reach their critical water depth for wave breaking closer to the coast, see Figure E- 9 . Since wave breaking does not occur the shear stress is also significantly smaller, see Figure E- 10. The velocity vectors of the spring tidal and neap tidal cycle demonstrate the same general flow pattern during high water, see Figure E- 13.

All the runs in the rest of this report are done with an artificial tidal cycle composed of only spring tides.

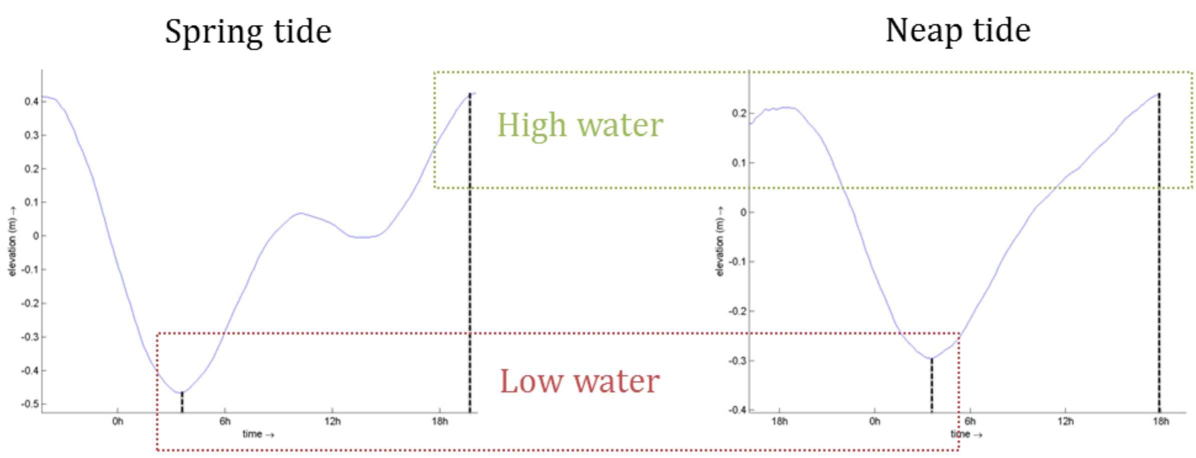


Figure E- 4 Water elevation spring tidal cycle (left) and neap tidal cycle (right)

LOW WATER

WATER DEPTH

SPRING TIDE | NEAP TIDE

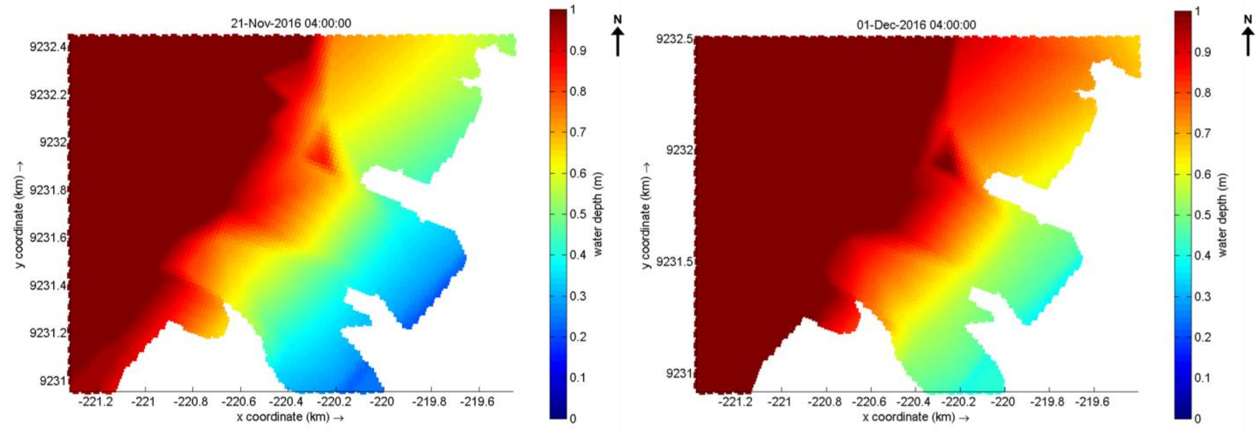


Figure E- 5 Water depth spring tide and neap tide cycle in North-West monsoon during low water

WAVE HEIGHT

SPRING TIDE | NEAP TIDE

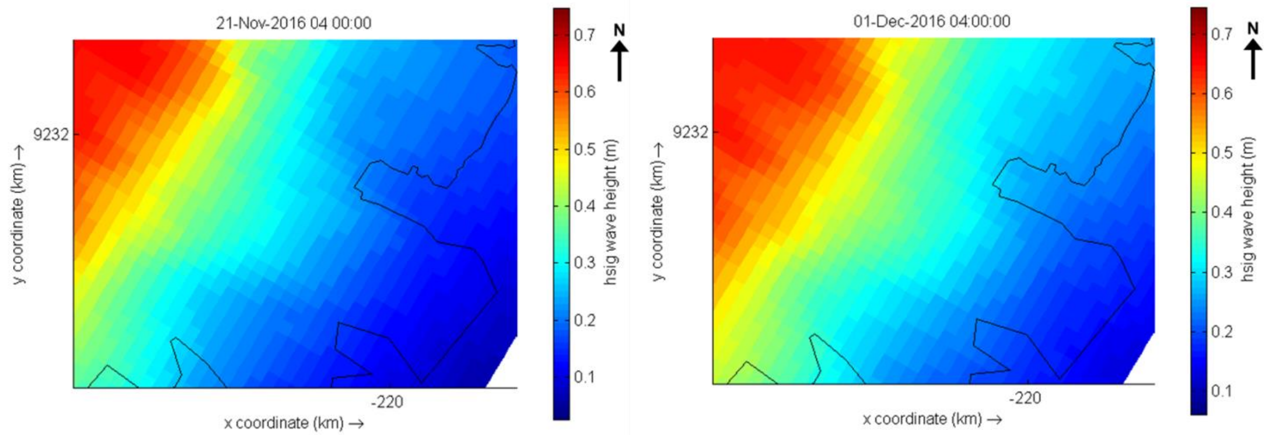


Figure E- 6 Wave height spring tide and neap tide cycle in North-West monsoon during low water

TOTAL BOTTOM SHEAR STRESS

SPRING TIDE | NEAP TIDE

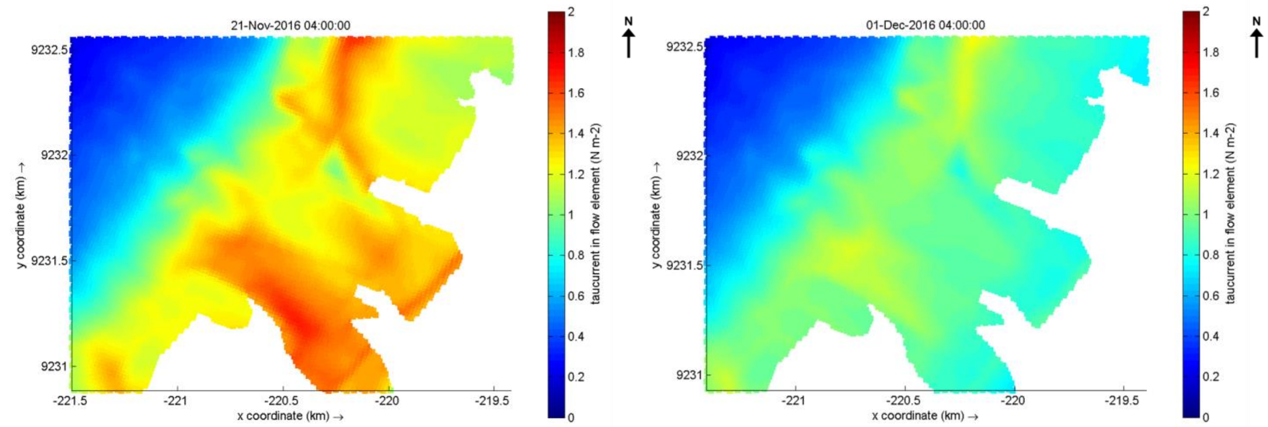


Figure E- 7 Shear stress spring tide and neap tide cycle in North-West monsoon during low water

High water

Water depth

Spring tide | Neap tide

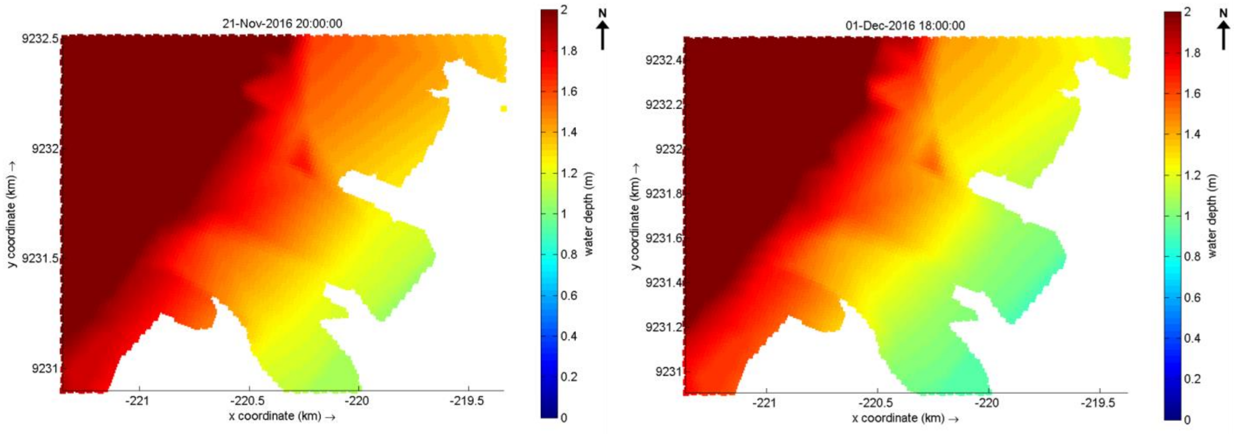


Figure E- 8 Water depth spring tide and neap tide cycle in North-West monsoon during high water

Wave height

Spring tide | Neap tide

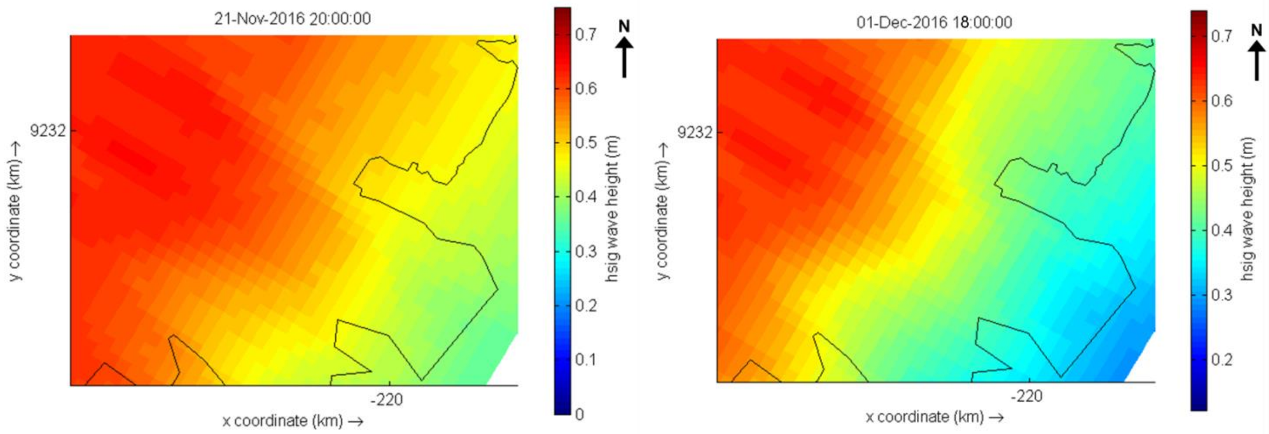


Figure E- 9 Wave height spring tide and neap tide cycle in North-West monsoon during high water

Total bottom shear stress

Spring tide | Neap tide

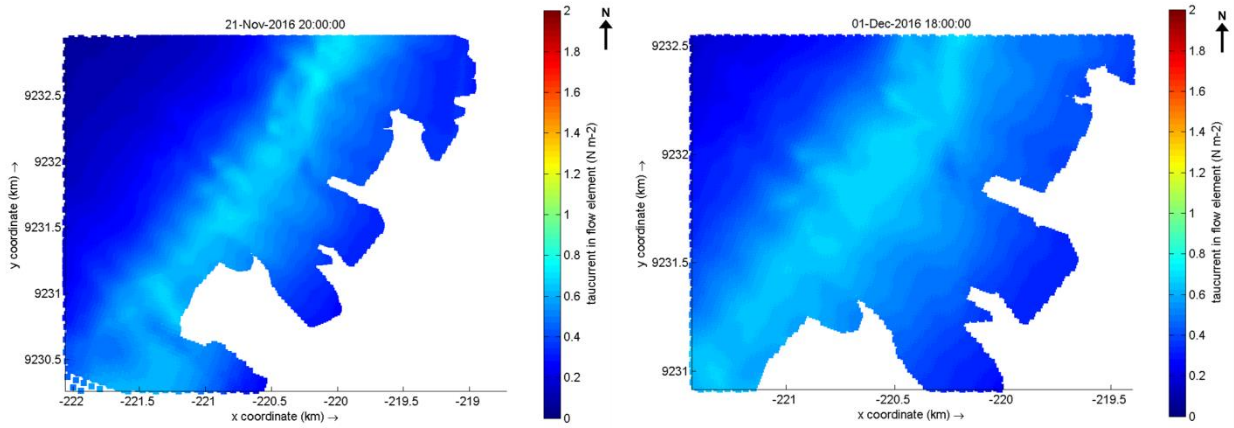


Figure E- 10 Shear stress spring tide and neap tide cycle in North-West monsoon during high water

VELOCITY VECTORS

NEAP TIDE

SPRING TIDE

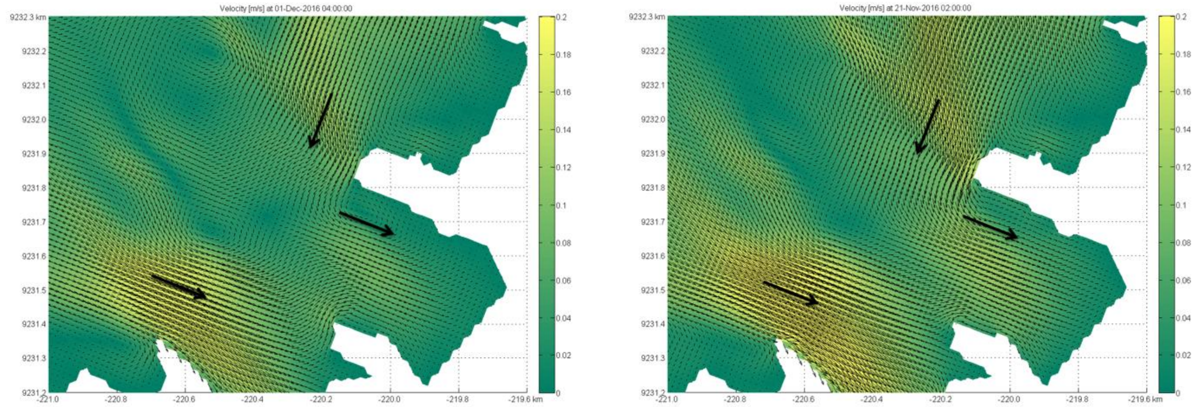


Figure E- 11 Velocity vector neap tide and spring tide at similar moment in the cycle – low water

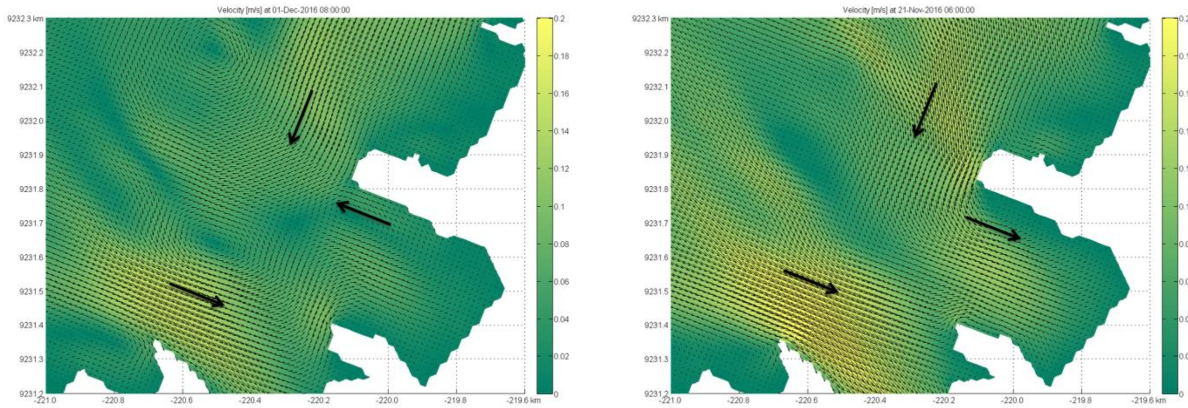


Figure E- 12 Velocity vector neap tide and spring tide at similar moment in the cycle – rising water

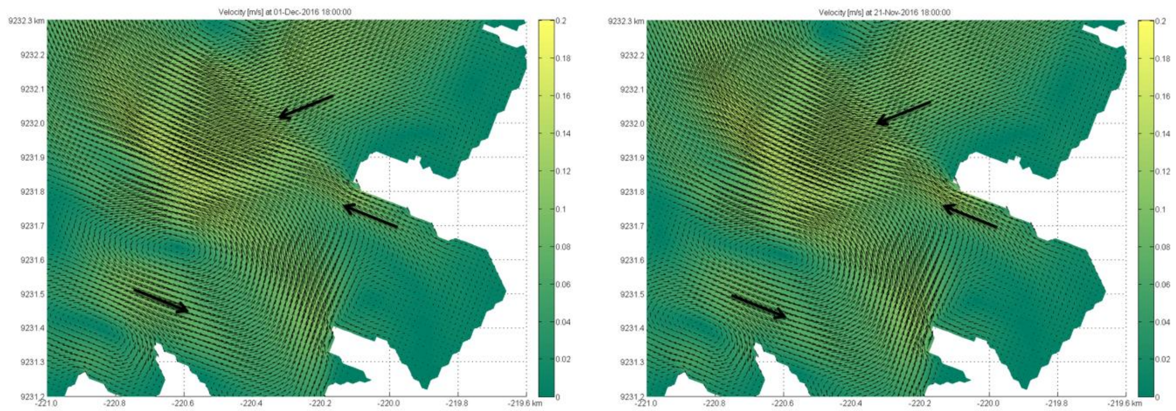


Figure E- 13 Velocity vector neap tide and spring tide at similar moment in the cycle - high water

E.3 Bottom topography

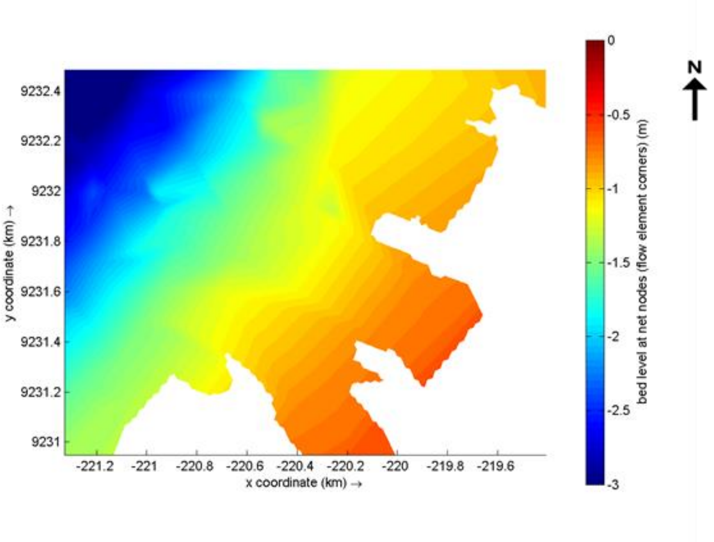


Figure E- 14 Bottom topography without chenier

The orientation of the chenier depends on the orientation of the grid. Therefore the chenier is displayed slightly different than it would be in reality. The effect of the different chenier orientation on the resulting hydrodynamics and sediment dynamics is negligible.

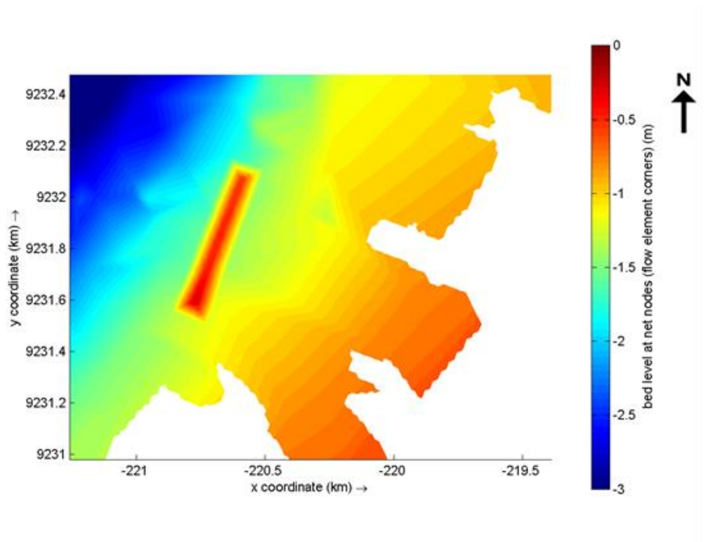


Figure E- 15 Bottom topography with chenier

E.4 Input North-West monsoon

GENERAL INPUT PARAMETERS

Manning coefficient	0.012	[$m^{-1/3}$ s]
Wave Nikuradse	0.01	[m]
Breaker parameter	0.78	[-]
Viscosity	1	[kg m^{-1} s^{-1}]
Diffusivity	1	[kg m^{-1} s^{-1}]
Water density	1025	[kg m^{-3}]
Initial temperature	25	[°C]
Background water temperature	25	[°C]

Table E- 1 General input parameters

TIDAL INPUT

The tidal input is provided by tidal components which automatically relate to the date and according water level. The tidal signal of the Semarang tidal station shows a semi-diurnal signal, see Figure E- 17 In the hydrodynamic analysis is chosen to observe one springtide and one neap tide cycle of 24 hours. This assumption is done to avoid computation time of the hydrodynamics. All the intermediate tidal cycles are covered in this range and it provides insight in the influence of the two extreme water levels. The cycles start at high water and ends at high water. To avoid influence of spin-up in the selected cycle there is chosen to start the computation eight to twelve hours earlier, see Figure E- 18 and Figure E- 19.

WIND INPUT PARAMETERS

Wind speed	4.4	[m s^{-1}]
Wind direction	280	[°]

Table E- 2 Wind input parameters North-West monsoon

WAVE INPUT PARAMETERS

Wave height (significant)	0.6	[m]
Mean wave period	4.7	[s]
Wave direction	310	[°]

Table E- 3 Wave input parameters North-West monsoon

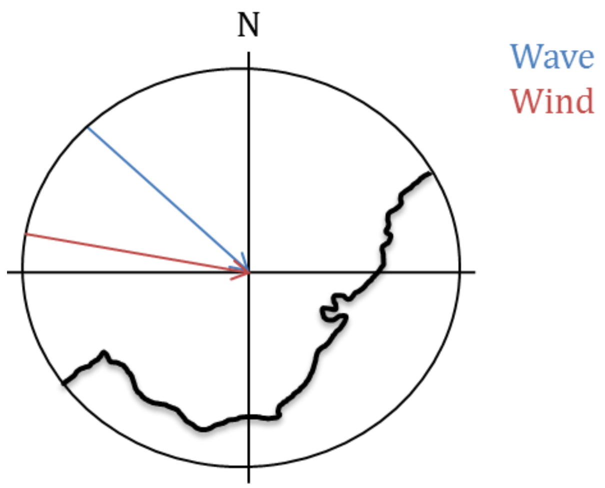


Figure E- 16 Wave and wind direction North-West monsoon

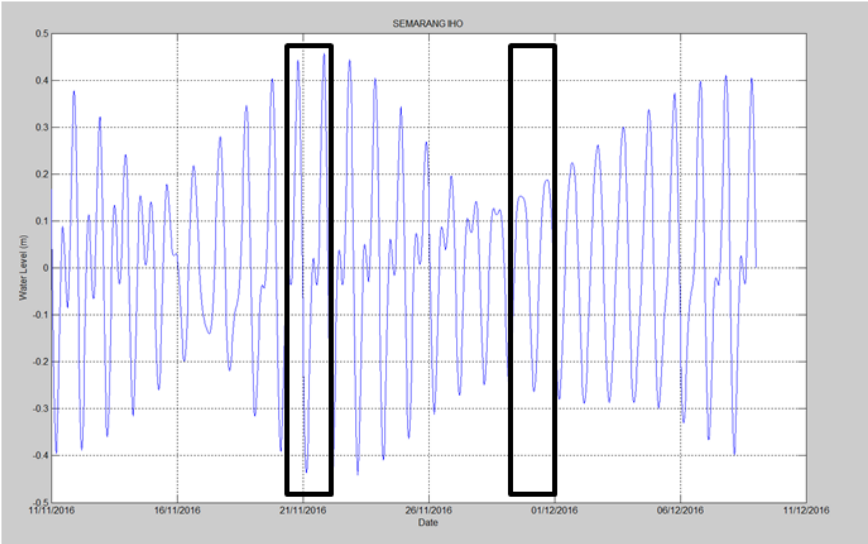


Figure E- 17 Tidal elevation Semarang station North-West monsoon – November (Delft Dashboard)

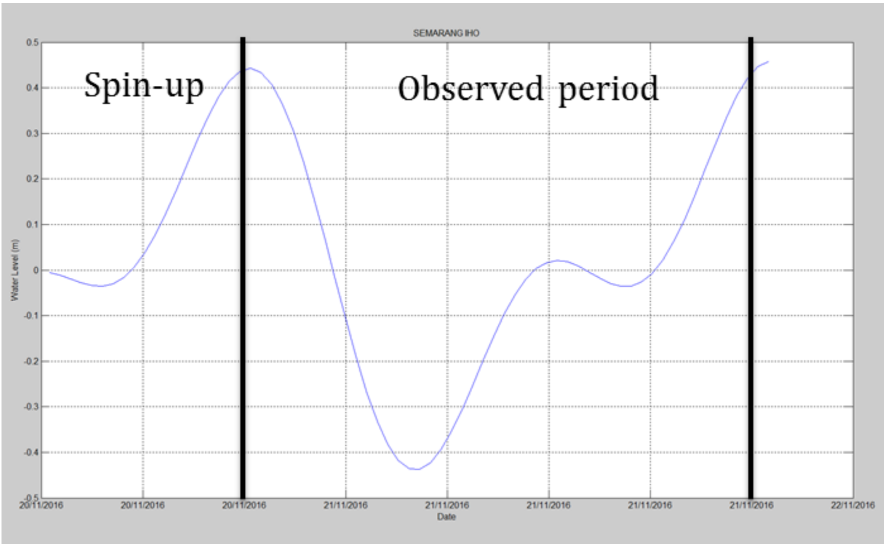


Figure E- 18 Tidal elevation Semarang station North-West monsoon – springtide (Delft Dashboard)

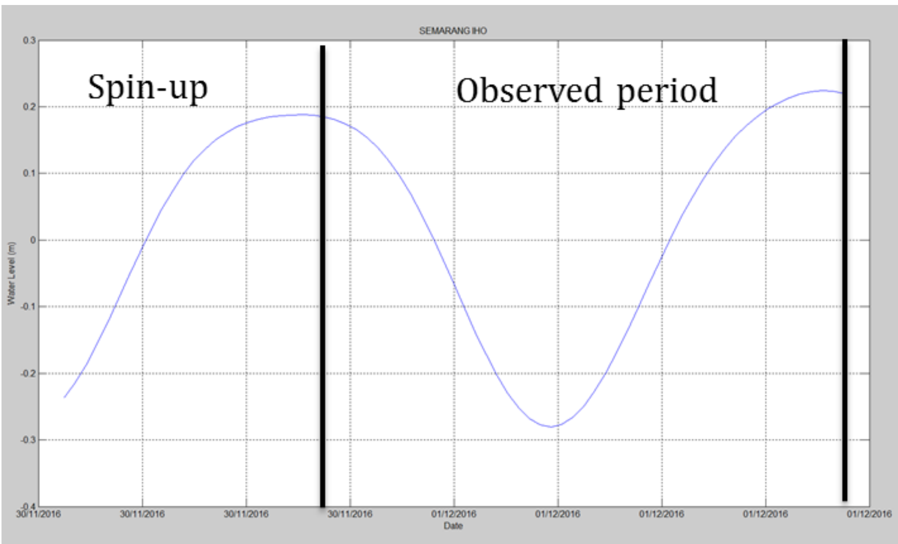


Figure E- 19 Tidal elevation Semarang station North-West monsoon – neap tide (Delft Dashboard)

E.5 Input South-East monsoon

GENERAL INPUT PARAMETERS

Manning coefficient	0.012	[$m^{-1/3}$ s]
Wave Nikuradse	0.01	[m]
Breaker parameter	0.78	[-]
Viscosity	1	[kg m^{-1} s^{-1}]
Diffusivity	1	[kg m^{-1} s^{-1}]
Water density	1025	[kg m^{-3}]
Initial temperature	25	[°C]
Background water temperature	25	[°C]

Table E- 4 General input parameters

TIDAL INPUT

The tidal input is provided by tidal components which automatically relate to the date and according water level. The tidal signal of the Semarang tidal station shows a semi-diurnal signal, see Figure E- 21. In the hydrodynamic analysis is chosen to observe one springtide and one neap tide cycle of 24 hours. This assumption is done to avoid computation time of the hydrodynamics. All the intermediate tidal cycles are covered in this range and it provides insight in the influence of the two extreme water levels. The cycles start at high water and ends at high water. To avoid influence of spin-up in the selected cycle there is chosen to start the computation eight to twelve hours earlier, see Figure E- 22 and Figure E- 23.

WIND INPUT PARAMETERS

Wind speed	3	[m s^{-1}]
Wind direction	110	[°]

Table E- 5 Wind input parameters South-East monsoon

WAVE INPUT PARAMETERS

Wave height (significant)	0.4	[m]
Mean wave period	4.5	[s]
Wave direction	110	[°]

Table E- 6 Wave input parameters South-East monsoon

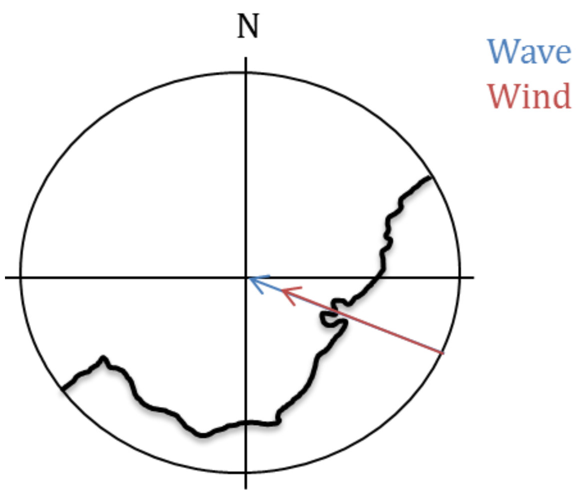


Figure E- 20 Wave and wind direction South-East monsoon

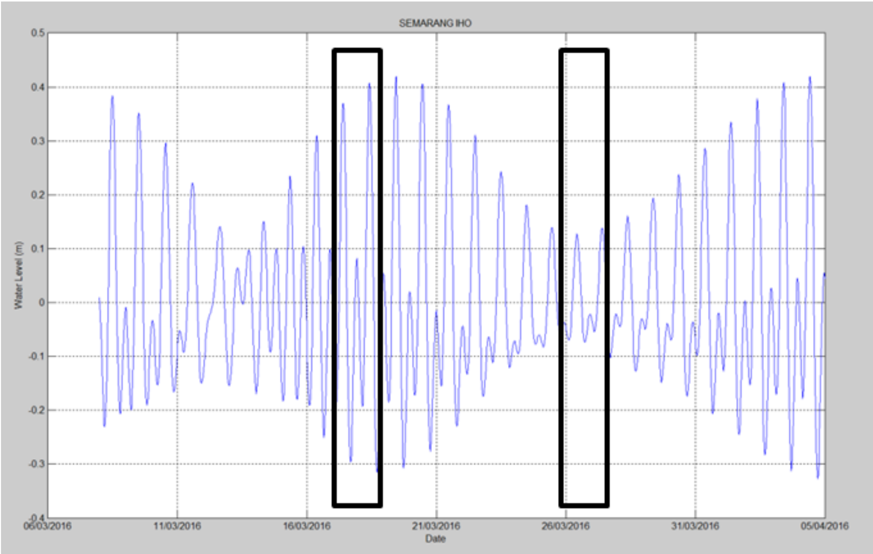


Figure E- 21 Tidal elevation Semarang station South-East monsoon (Delft Dashboard)

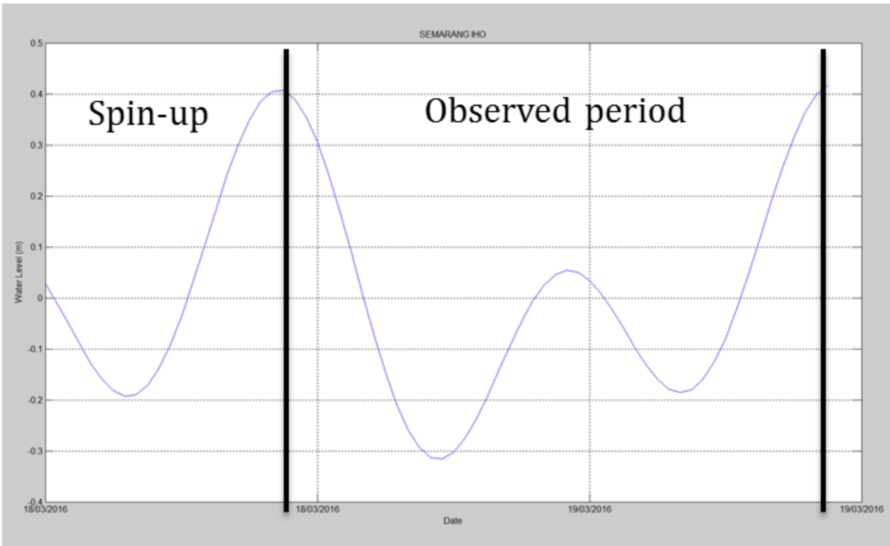


Figure E- 22 Tidal elevation Semarang station South-East monsoon – springtide (Delft Dashboard)

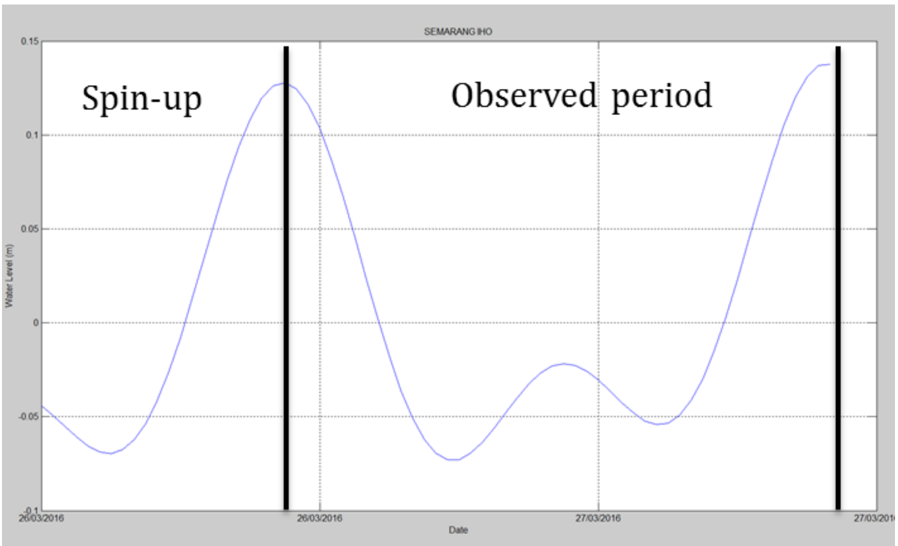


Figure E- 23 Tidal elevation Semarang station South-East monsoon – neap tide (Delft Dashboard)

E.6 Input Storm

GENERAL INPUT PARAMETERS

Manning coefficient	0.012	[$m^{-1/3}$ s]
Wave Nikuradse	0.01	[m]
Breaker parameter	0.78	[-]
Viscosity	1	[kg m^{-1} s^{-1}]
Diffusivity	1	[kg m^{-1} s^{-1}]
Water density	1025	[kg m^{-3}]
Initial temperature	25	[°C]
Background water temperature	25	[°C]

Table E- 7 General input parameters

TIDAL INPUT

The tidal input is provided by tidal components which automatically relate to the date and according water level. The tidal signal of the Semarang tidal station shows a semi-diurnal signal, see Figure E- 25. In the hydrodynamic analysis is chosen to observe one springtide and one neap tide cycle of 24 hours. This assumption is done to avoid computation time of the hydrodynamics. All the intermediate tidal cycles are covered in this range and it provides insight in the influence of the two extreme water levels. The cycles start at high water and ends at high water. To avoid influence of spin-up in the selected cycle there is chosen to start the computation eight to twelve hours earlier, see Figure E- 26 and Figure E- 27.

WIND INPUT PARAMETERS

Wind speed	11	[m s^{-1}]
Wind direction	290	[°]

Table E- 8 Wind input parameters storm

WAVE INPUT PARAMETERS

Wave height (significant)	2.1	[m]
Mean wave period	5.9	[s]
Wave direction	300	[°]

Table E- 9 Wave input parameters storm

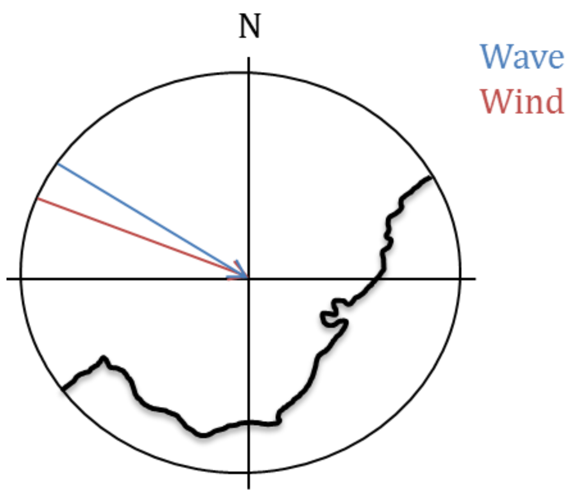


Figure E- 24 Wave and wind direction storm

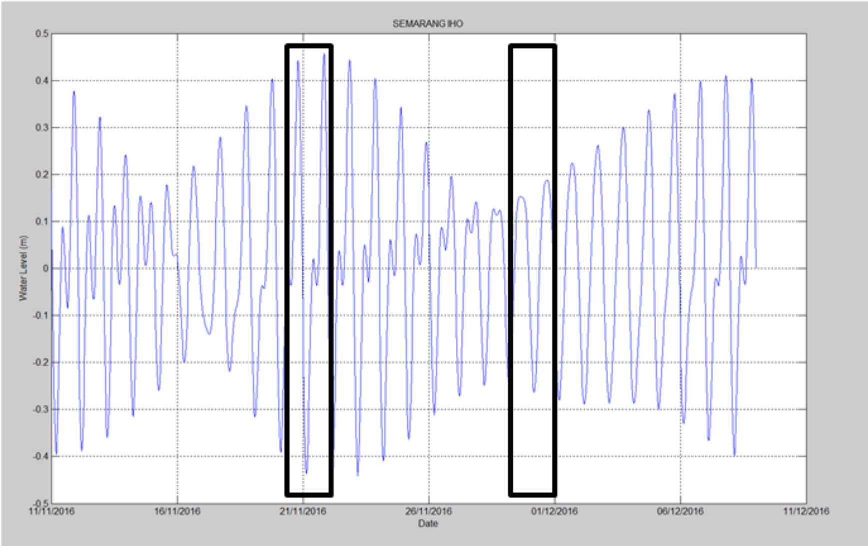


Figure E- 25 Tidal elevation Semarang station Storm – November (Delft Dashboard)

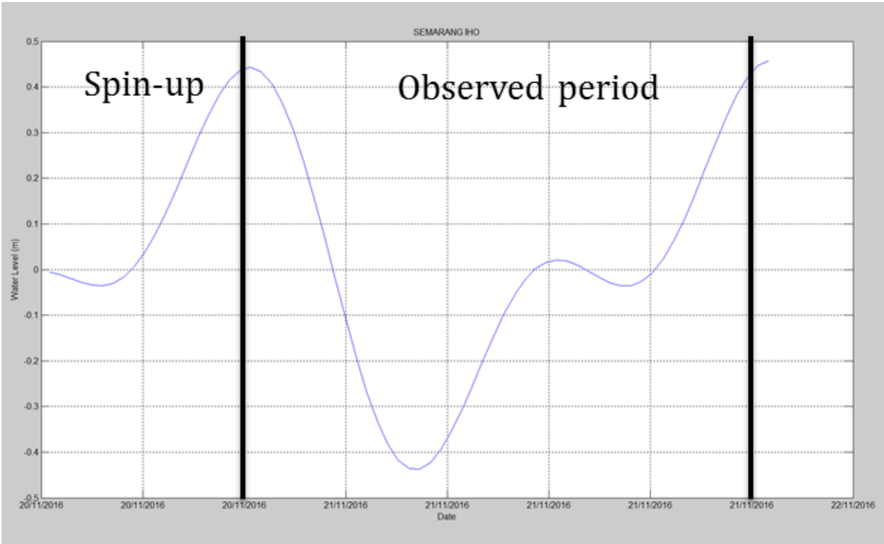


Figure E- 26 Tidal elevation Semarang station Storm – springtide (Delft Dashboard)

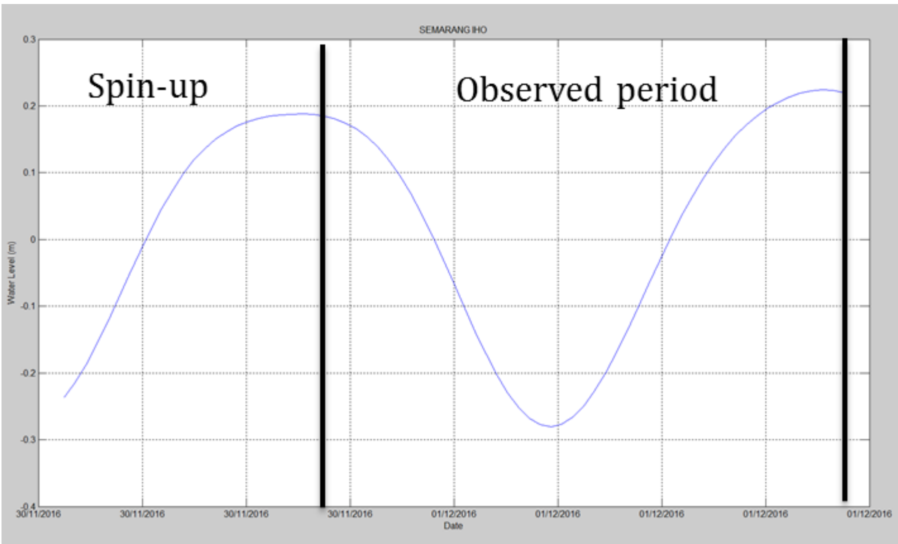


Figure E- 27 Tidal elevation Semarang station Storm – neap tide (Delft Dashboard)

E.7 Results without chenier

E.7.1 North-West monsoon

This section is used to assess the influence of the tide, wind and wave on the hydrodynamics in the area of interest near Bedono. Therefore the bottom shear stress and velocity vector are systematically observed. These factors are observed during two maximum water levels, high water and low water. Note that the figures represent a snapshot of the shears stress during low water since this induces the largest shears stress. The water movement is a snapshot with an over layer with the summarized water movement observed every hour during one day.

TIDE

The first step is to assess the water movement and shear stresses induced by only tide. The velocity vectors show a regular pattern that follows the rising and falling water level, see Figure E- 31. The flow velocity is in the order of centimetres per second. The forcing also results in small shear stresses in the order of 0.002 N/m^2, see Figure E- 34.

TIDE AND WIND

The second step is to assess the influence of the wind on the water movement. The persistent wind from North-Western direction adds energy to the water surface and strongly influences the water movement. The result is that the direction of the velocity vectors turns towards the South-East and North, see Figure E- 32. The shear stress stays in the order of 0.002 N/m^2, see Figure E- 35.

TIDE, WIND AND WAVE

The third step is to add waves to the model. The wave forcing makes the velocity vector pattern irregular due to refraction and wave breaking. Waves break on different locations because of the water depth and the local bottom level. Waves propagating to the coast shoal in shallower water and finally reach the point of breaking. The breaker index is the ratio between the wave height and the water depth, once this ratio is exceeded waves break and dissipative waves are formed. The influence of the water depth on the location of wave breaking is demonstrated in Figure E- 29 and Figure E- 30.

Furthermore, the velocity magnitude increases to decimetres per second because of the energy added by waves, see Figure E- 33. The shear stresses increase to 0.4 N/m^2 during high water and 2 N/m^2 during low water, see Figure E- 36. Higher shear stresses occur on places of wave breaking and in small water depths. The cells do not dry up with low tide and therefore wave energy stays in the water.

The summarized direction of the velocity vector and shear stress are stated in Table E- 10 and Table E- 11.

Feature	**Direction**
[Tide/wave/wind]	[To which direction]
Tide	West and north // east and south
Tide and wind	To the north and little bit to the west
Tide, wave and wind	West and north // east and south

Table E- 10 Summarized velocity vector direction

Feature	**Shear stress**
[Tide/wave/wind]	[Pa]
Tide	~ 0.002
Tide and wind	~ 0.002 – 0.01
Tide, wave and wind	~ 0.4 – 2.0

Table E- 11 Summarized shear stress

WAVE BREAKING

Note, the wave height figures show a snapshot and the range is 0 – 0.7 m.

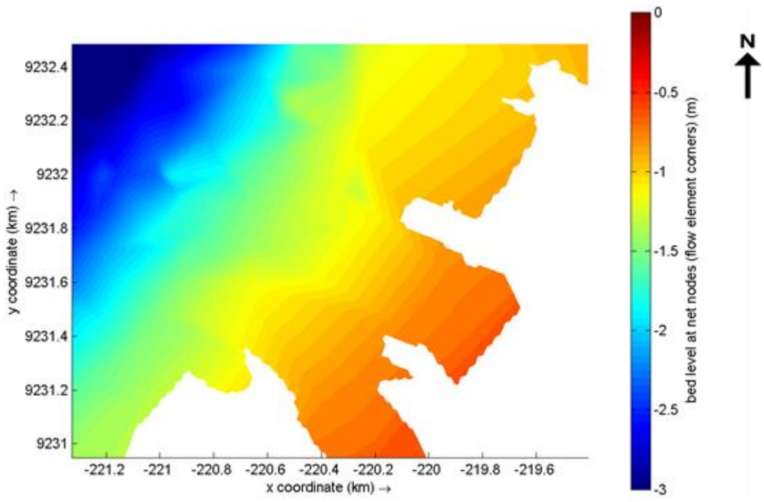


Figure E- 28 Bottom topography

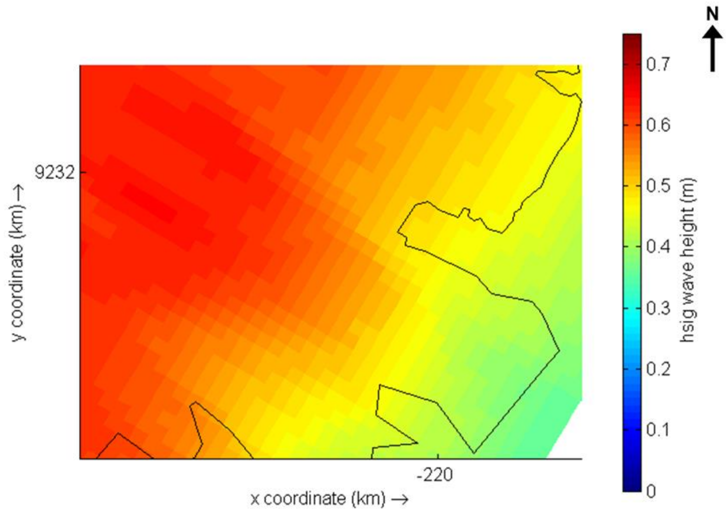


Figure E- 29 Significant wave height during high water

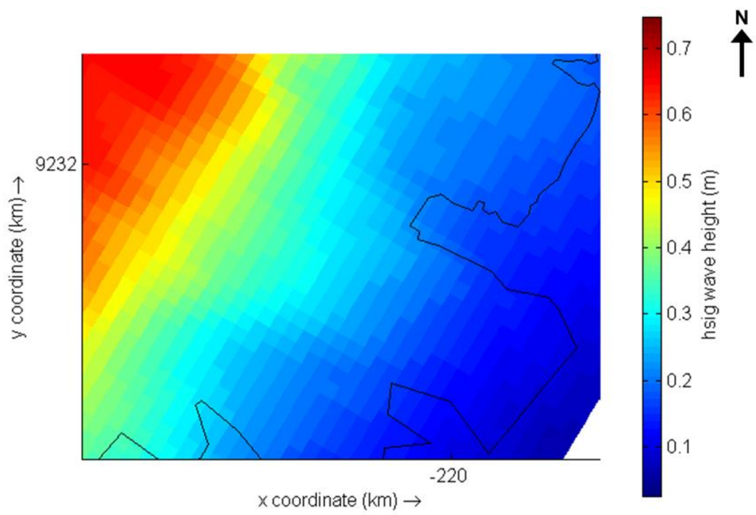


Figure E- 30 Significant wave height during low water

VELOCITY VECTOR

Note, the velocity vector pattern figures shows a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The flow velocity range is 0 – 0.2 m/s

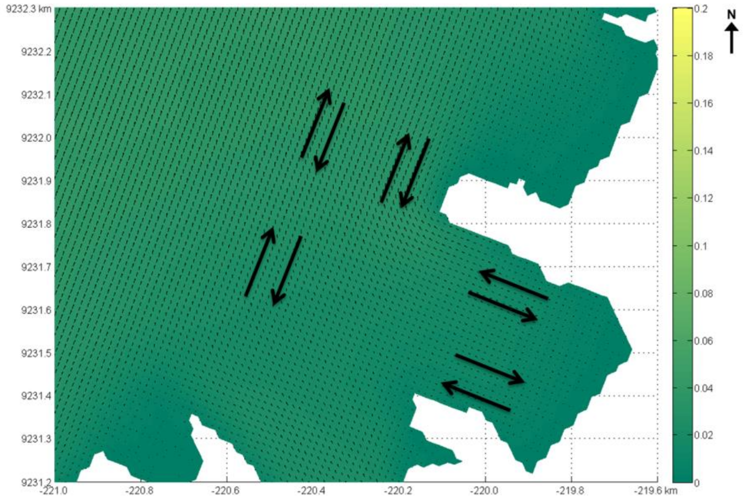


Figure E- 31 Flow direction and magnitude – induced by tide – North-West monsoon

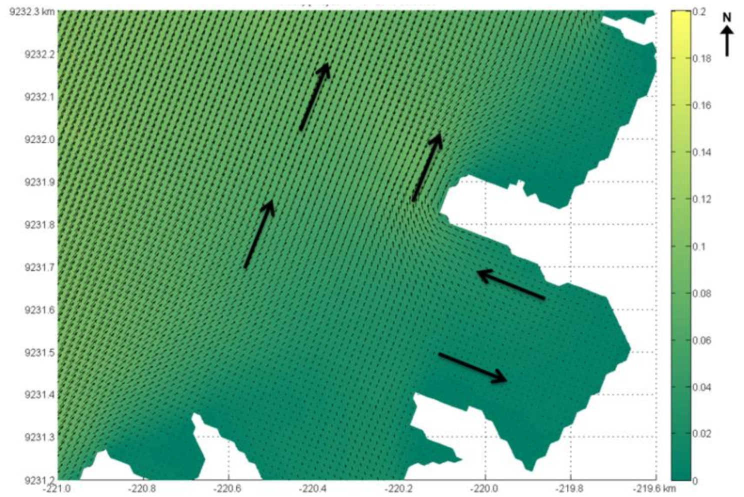


Figure E- 32 Flow direction and magnitude – induced by tide and wind - North-West monsoon

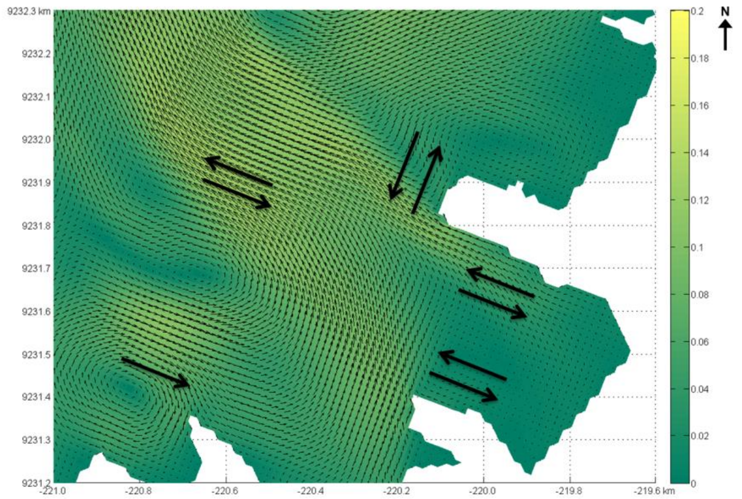


Figure E- 33 Flow direction and magnitude - induced by tide, wave and wind – North-West monsoon

SHEAR STRESS

Note, the shear stress figures show a snapshot and the shear stress range is 0 – 2 N/m².

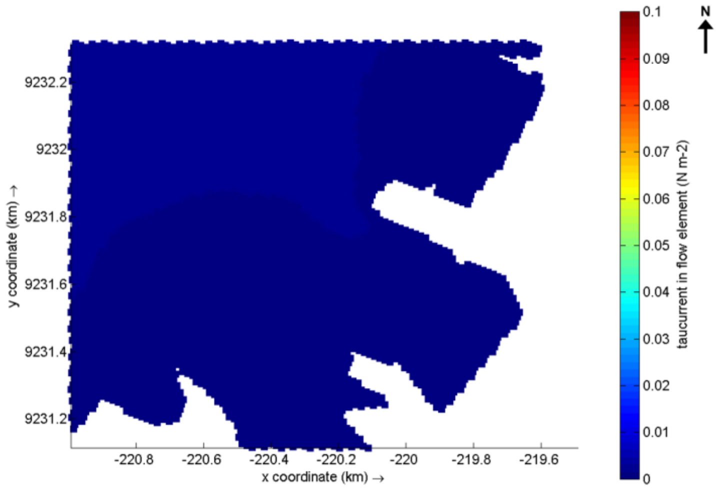


Figure E- 34 Shear stress- induced by tide – North-West monsoon

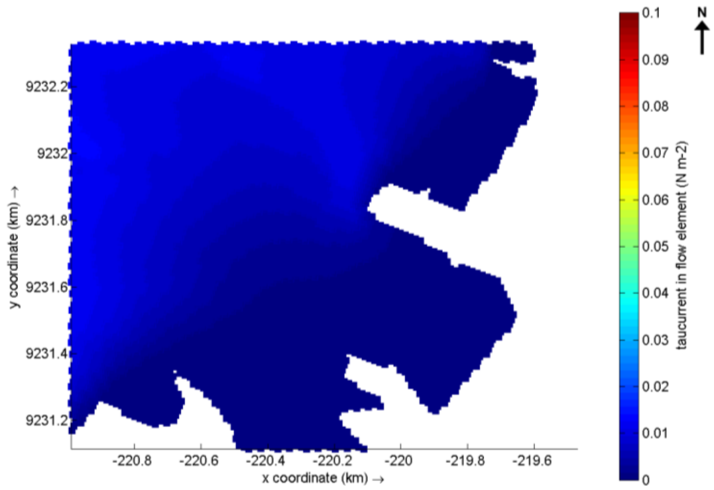


Figure E- 35 Shear stress - induced by tide and wind – North-West monsoon

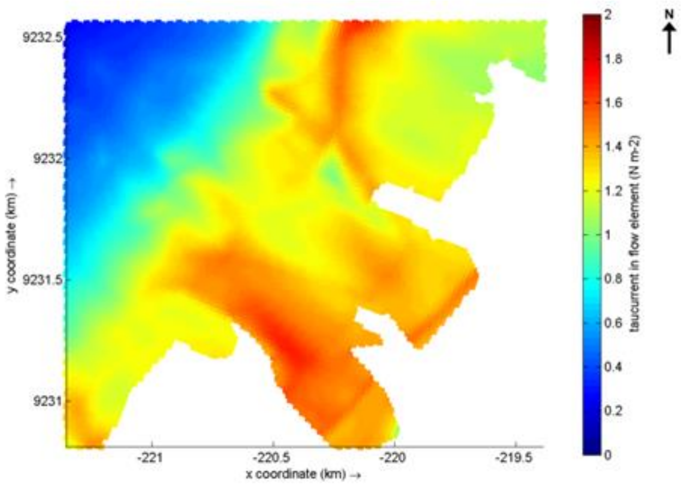


Figure E- 36 Shear stress – induced by tide, wave and wind –North-West monsoon

E.7.2 South-East monsoon

This section is used to assess the influence of the tide, wind and wave on the hydrodynamics in the area of interest near Bedono. Therefore the bottom shear stress and velocity vector are systematically observed. These factors are observed during two maximum water levels, high water and low water. Note that the figures represent a snapshot of the shears stress during low water since this induces the largest shears stress. The water movement is a snapshot with an over layer with the summarized water movement observed every hour during one day.

TIDE

The first step is to assess the water movement and shear stresses induced by only tide. The velocity vectors show a regular pattern that follows the rising and falling water level, see Figure E- 40. The flow velocity is in the order of centimetres per second. The forcing also results in small shear stresses in the order of 0.002 N/m^2, see Figure E- 43.

TIDE AND WIND

The second step is to assess the influence of the wind on the water movement. The persistent wind from South-Eastern direction adds energy to the water surface and strongly influences the water movement. The result is that the direction of the velocity vectors turns towards the South-West, see Figure E- 41. The shear stress stays in the order of 0.002 N/m^2, see Figure E- 44.

TIDE, WIND AND WAVE

The third step is to add waves to the model. In this scenario the waves approach from South-Eastern direction. The Demak coastline has a sheltered position for waves from this direction. The waves need to refract around the head land in the north of the model. Subsequently it needs to make another large refraction towards the area of interest near Bedono. These circumstances have led to no observable wave activities in the area of interest, see Figure E- 47 and Figure E- 48. Therefore no influence of the water movement and shear stress is observed, see Figure E- 45.

The summarized direction of the velocity vector and shear stress are stated in Table E- 12 and Table E- 13.

Feature	**Direction**
[Tide/wave/wind]	[To which direction]
Tide	South and southwest
Tide and wind	South and southwest
Tide, wave and wind	South and southwest

Table E- 12 Summarized velocity vector direction

Feature	**Shear stress**
[Tide/wave/wind]	[Pa]
Tide	0.002
Tide and wind	0.002
Tide, wave and wind	0.004

Table E- 13 Summarized shear stress

WAVE HEIGHT

Note, the wave height figures show a snapshot and the range is 0 – 0.7 m.

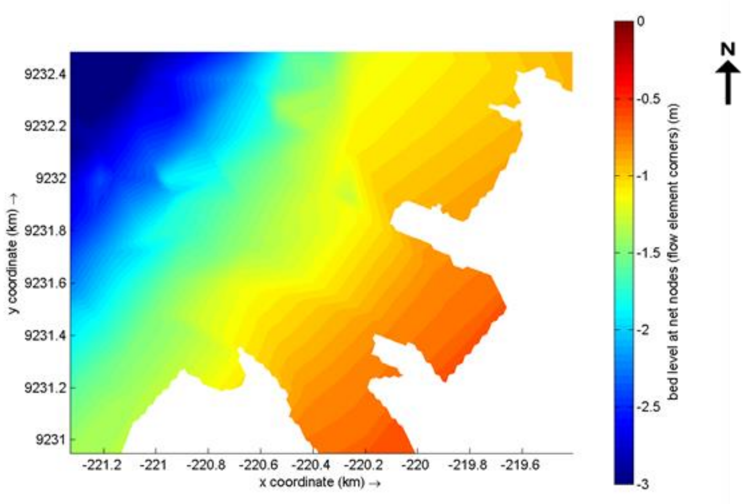


Figure E- 37 Bathymetry without chenier

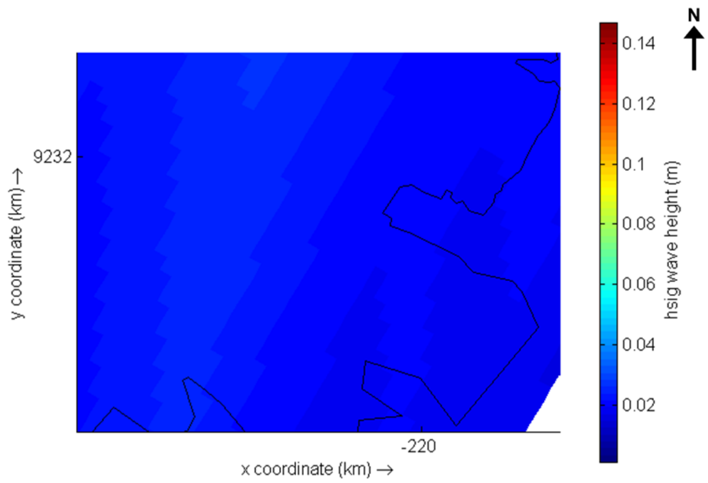


Figure E- 38 Significant wave height during high water

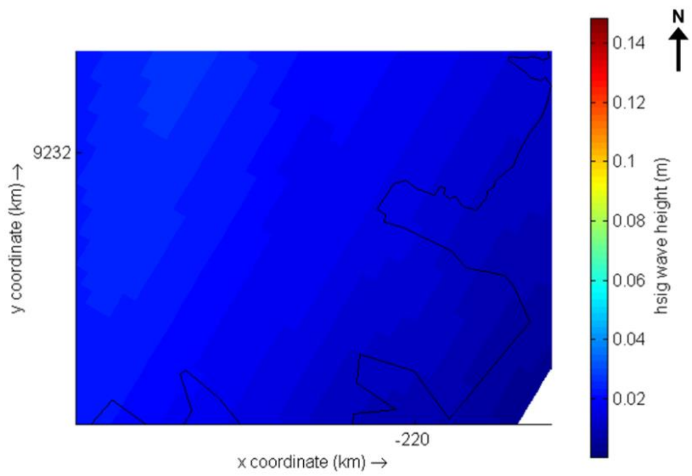


Figure E- 39 Significant wave height during low water

VELOCITY VECTOR

Note, the velocity vector pattern figures shows a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The flow velocity range is 0 – 0.2 m/s

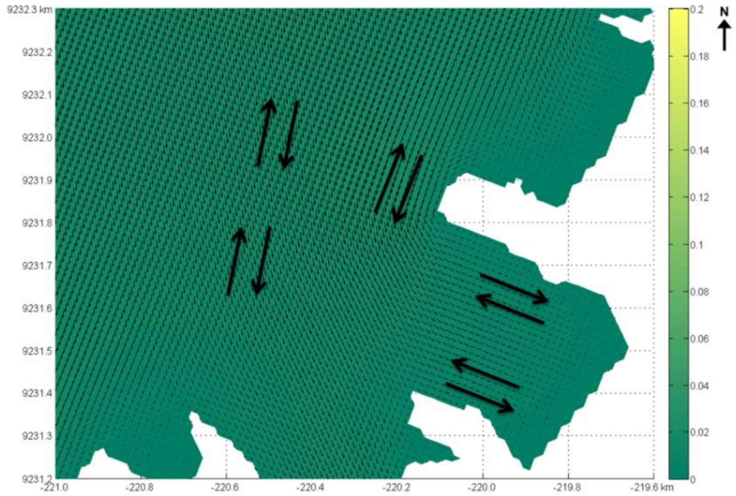


Figure E- 40 Flow direction and magnitude – induced by tide - South-East monsoon

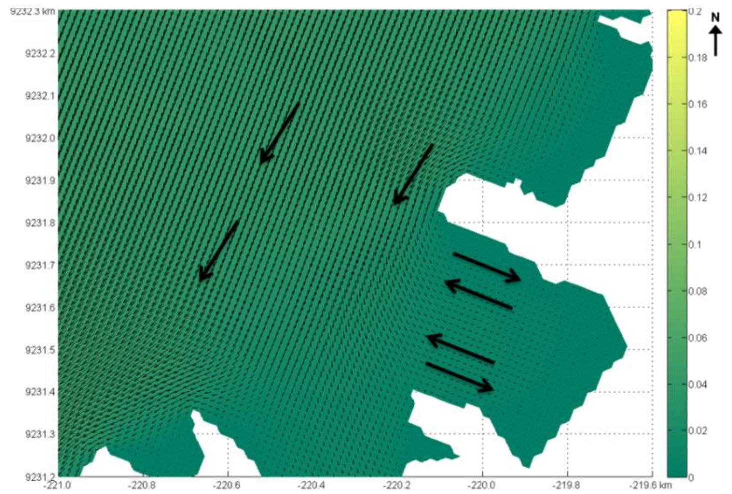


Figure E- 41 Flow direction and magnitude - induced by tide and wind - South-East monsoon

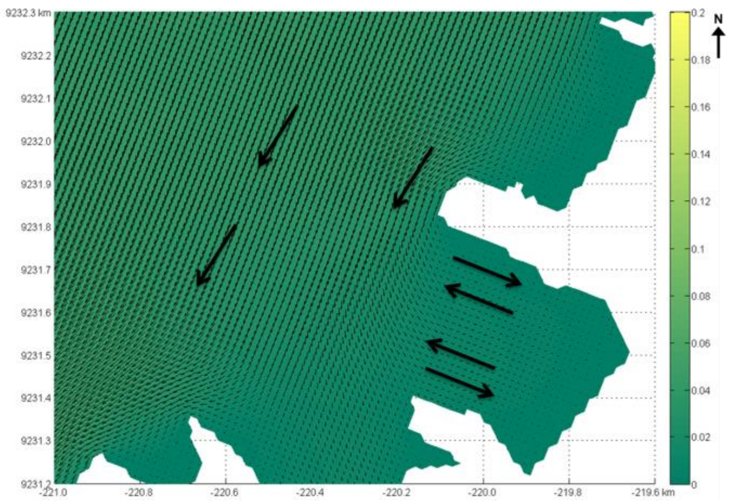


Figure E- 42 Flow direction and magnitude - induced by tide, wave and wind – South-East monsoon

SHEAR STRESS

Note, the shear stress figures show a snapshot and the shear stress range is 0 – 2 N/m².

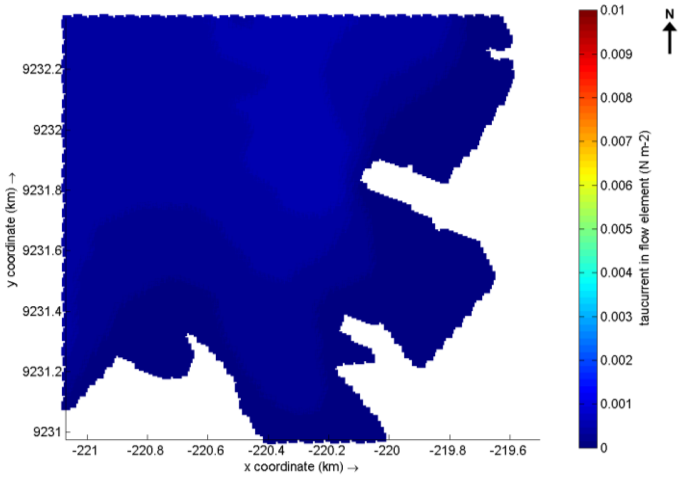


Figure E- 43 Shear stress – induced by tide - South-East monsoon

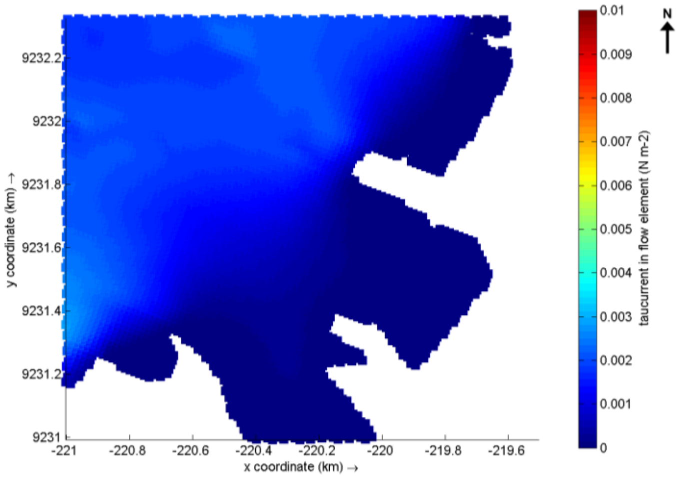


Figure E- 44 Shear stress - induced by tide and wind - South-East monsoon

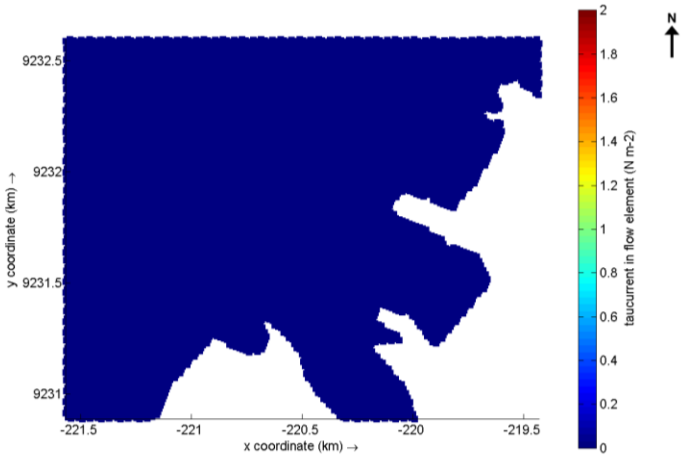


Figure E- 45 Shear stress - induced by tide, wave and wind – South-East monsoon

E.7.3 Storm

This section is used to assess the influence of the tide, wind and wave on the hydrodynamics in the area of interest near Bedono. Therefore the bottom shear stress and velocity vector are systematically observed. These factors are observed during two maximum water levels, high water and low water. Note that the figures represent a snapshot of the shears stress during low water since this induces the largest shears stress. The water movement is a snapshot with an over layer with the summarized water movement observed every hour during one day.

TIDE

The first step is to assess the water movement and shear stresses induced by only tide. The velocity vectors show a regular pattern that follows the rising and falling water level, see Figure E- 49. The flow velocity is in the order of centimetres per second. The forcing also results in small shear stresses in the order of 0.002 N/m^2, see Figure E- 52.

TIDE AND WIND

The second step is to assess the influence of the wind on the water movement. The persistent wind from North-Western direction adds energy to the water surface and strongly influences the water movement. The result is that the direction of the velocity vectors turns towards the South-East and North, see Figure E- 50. The shear stress stays in the order of 0.002 N/m^2, see Figure E- 53.

TIDE, WIND AND WAVE

The third step is to add waves to the model. The wave forcing makes the velocity vector pattern irregular due to refraction and wave breaking. Waves propagating to the coast shoal in shallower water and finally reach the point of breaking. Waves break on different locations because of the water depth and the local bottom level. The breaker index is the ratio between the wave height and the water depth, once this ratio is exceeded waves break and dissipative waves are formed. In this scenario the entering wave height is nearly 2 m and therefore reaches further from the coast the moment of breaking. The wave height starts to rapidly decrease in the northwest corner before it propagates further to the coast, see Figure E- 47 and Figure E- 48.

Furthermore, the velocity magnitude increases to decimetres per second because of the energy added by waves, see Figure E-51.The shear stresses varies between 0.5 and 2 N/m^2, see Figure E- 54. The largest shear stresses occur further from the coast since in this scenario waves break there. The ambient shear stress nearshore also exceeds the critical shear stress for erosion of 0.5 N/m^2. The reason for higher shear stresses nearshore is caused by the shallow water depth.

The summarized direction of the velocity vector and shear stress are stated in Table E- 14 and Table E- 15.

Feature	**Direction**
[Tide/wave/wind]	[To which direction]
Tide	West and north
Tide and wind	West and north / east and south
Tide, wave and wind	North and east

Table E- 14 Summarized velocity vector direction

Feature	**Shear stress**
[Tide/wave/wind]	[N m^{-2}]
Tide	~ 0.002
Tide and wind	~ 0.002 – 0.01
Tide, wave and wind	~ 0.5 – 2.0

Table E- 15 Summarized shear stress

Wave height

Note, the wave height figures show a snapshot and the range is 0 – 0.7 m.

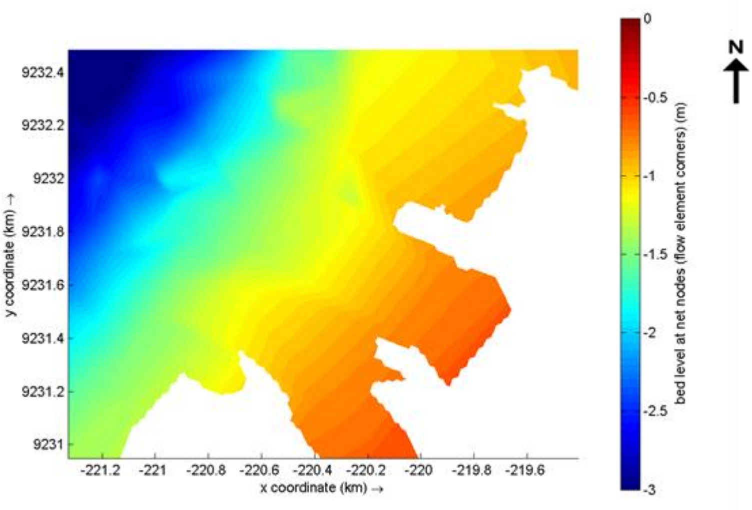


Figure E- 46 Bathymetry without chenier

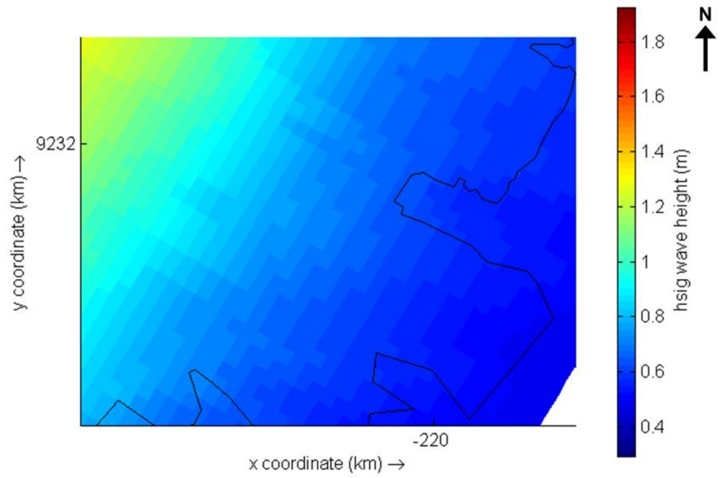


Figure E- 47 Significant wave height during high water

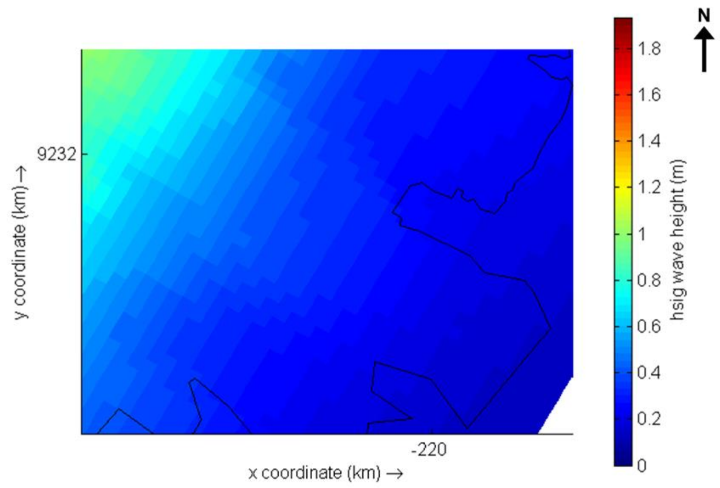


Figure E- 48 Significant wave height during low water

VELOCITY VECTOR

Note, the velocity vector pattern figures shows a snapshot with an over layer with thicker vectors which are the summarized pattern in that particular period. The flow velocity range is 0 – 0.2 m/s

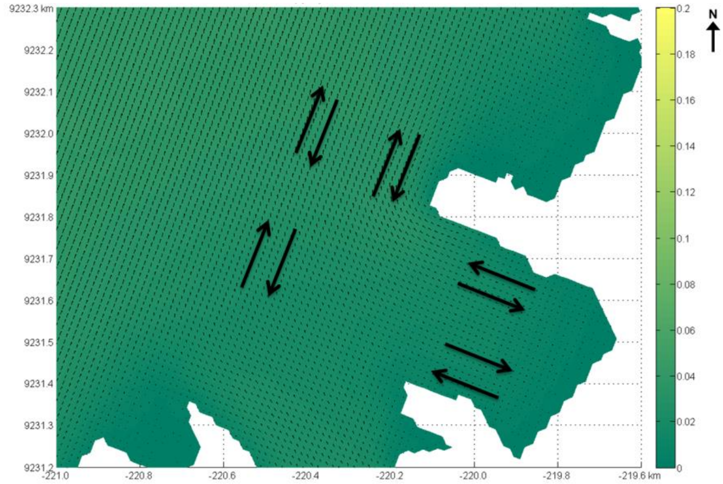


Figure E- 49 Flow direction and magnitude - induced by tide -storm

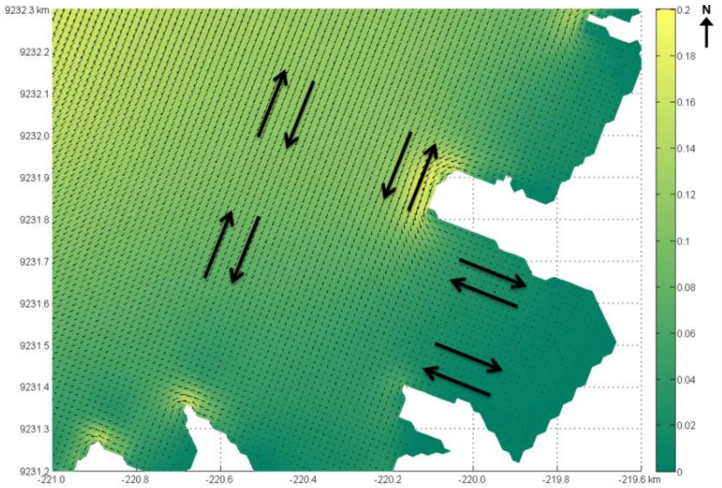


Figure E- 50 Flow direction and magnitude – induced by tide and wind - storm

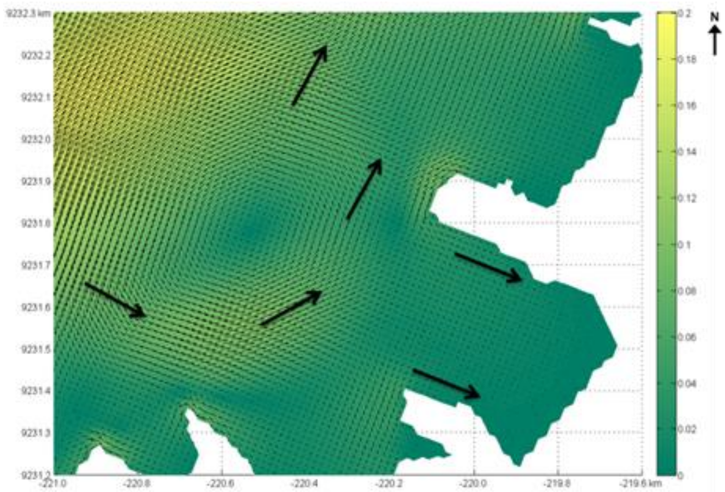


Figure E- 51 Flow direction and magnitude - induced by tide, wave and wind – storm

SHEAR STRESS

Note, the shear stress figures show a snapshot and the shear stress range is 0 – 2 N/m².

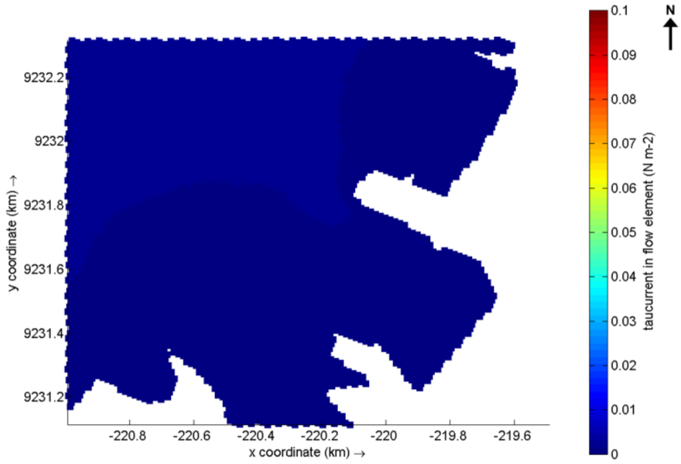


Figure E- 52 Shear stress - induced by tide - storm

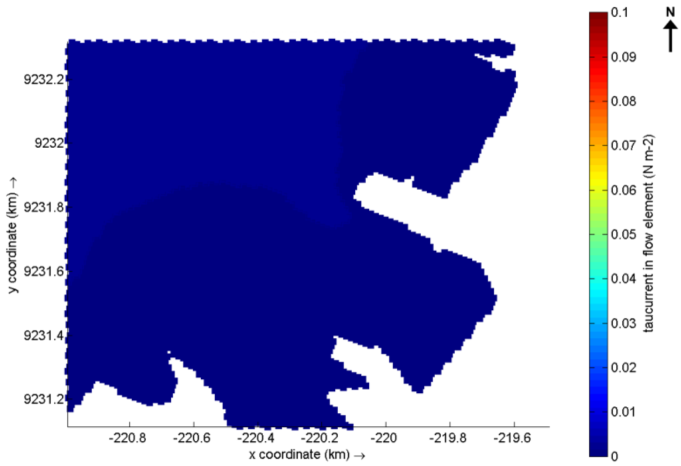


Figure E- 53 Shear stress - induced by tide and wind - storm

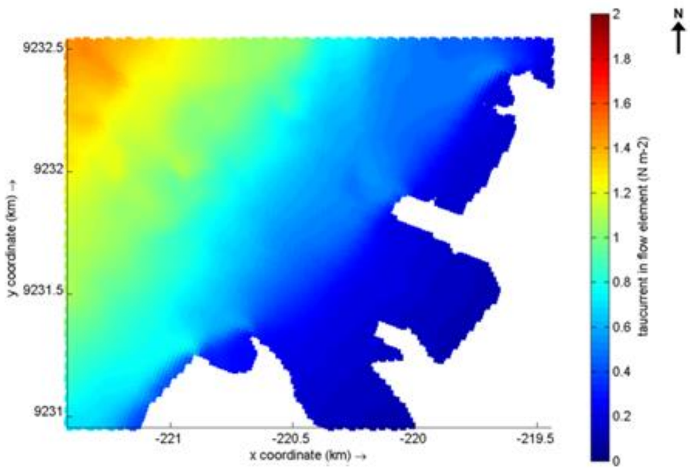


Figure E- 54 Shear stress - induced by tide wave and wind – storm

E.8 Results with chenier

E.8.1 North-West monsoon

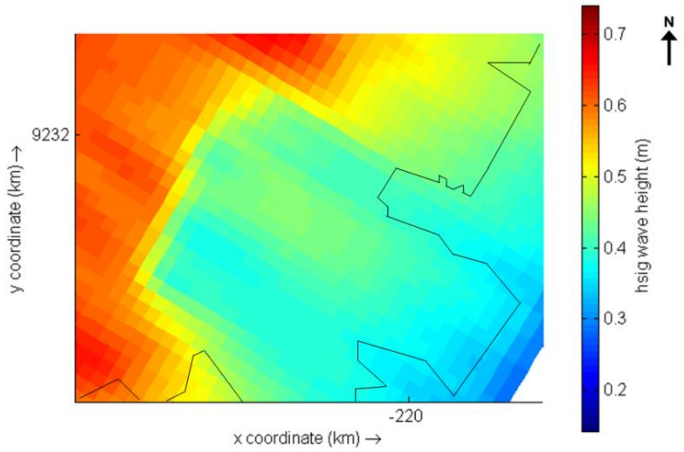


Figure E- 55 Significant wave height during high water

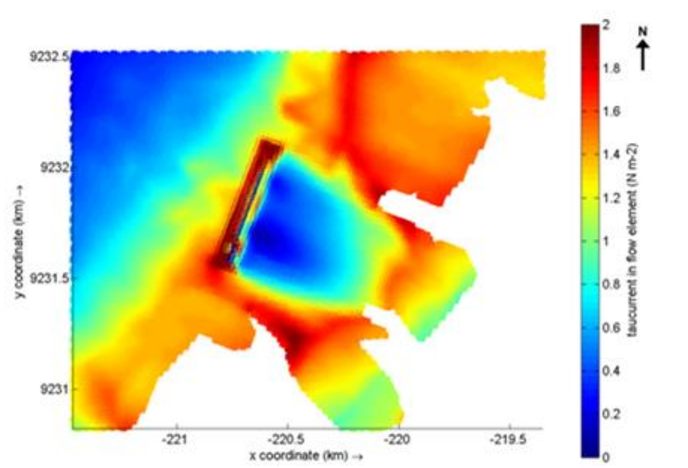


Figure E- 56 Shear stress – induced by tide, wave and wind – North-West monsoon

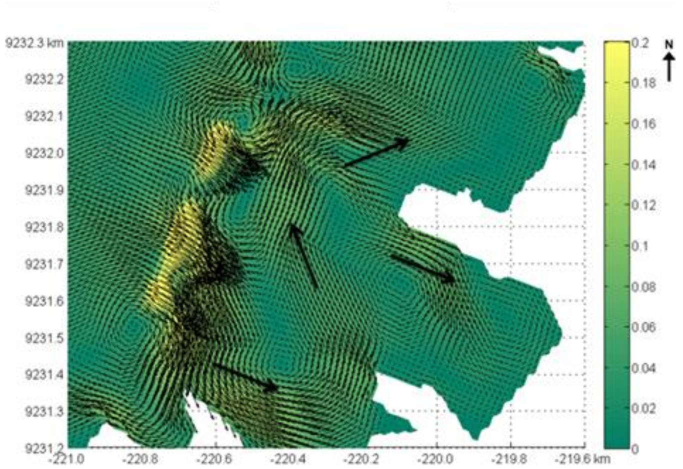


Figure E- 57 Flow direction and magnitude - induced by tide, wave and wind – North-West monsoon

E.8.2 South-East monsoon

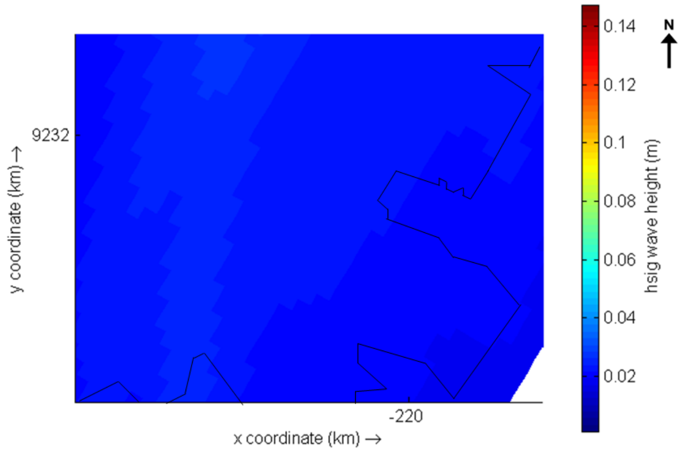


Figure E- 58 Significant wave height during high water

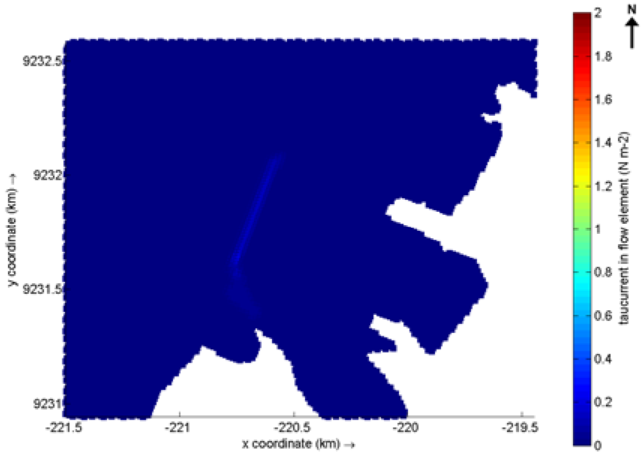


Figure E- 59 Shear stress – induced by tide, wave and wind – North-West monsoon

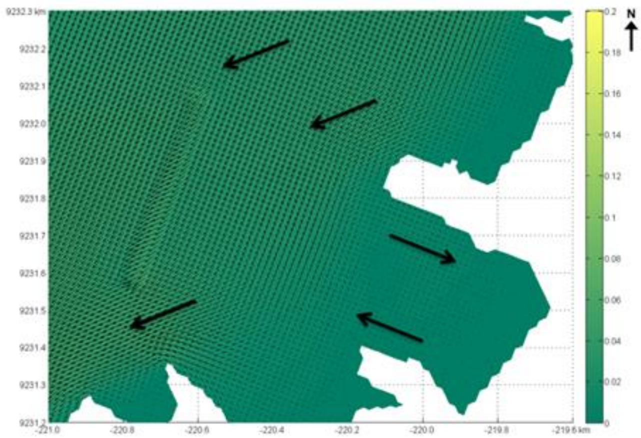


Figure E- 60 Flow direction and magnitude - induced by tide, wave and wind – North-West monsoon

E.8.3 Storm

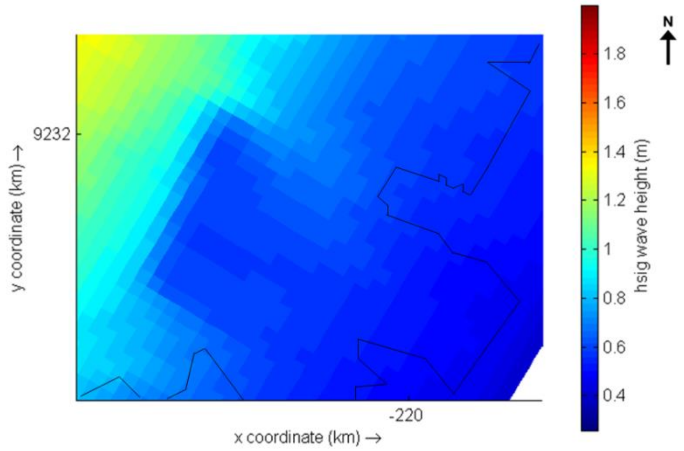


Figure E- 61 Significant wave height during high water

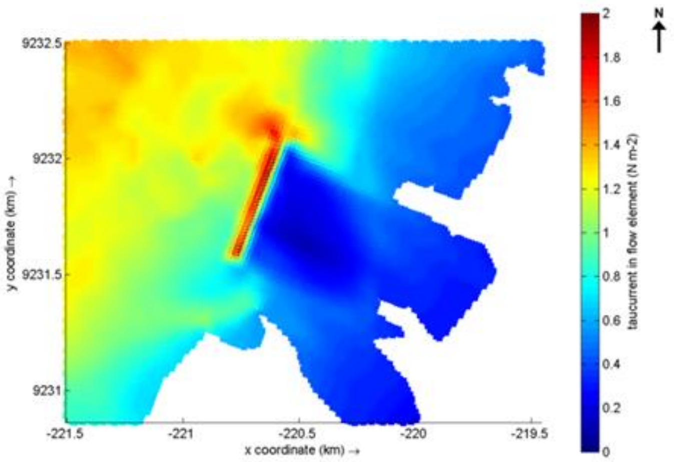


Figure E- 62 Shear stress – induced by tide, wave and wind – North-West monsoon

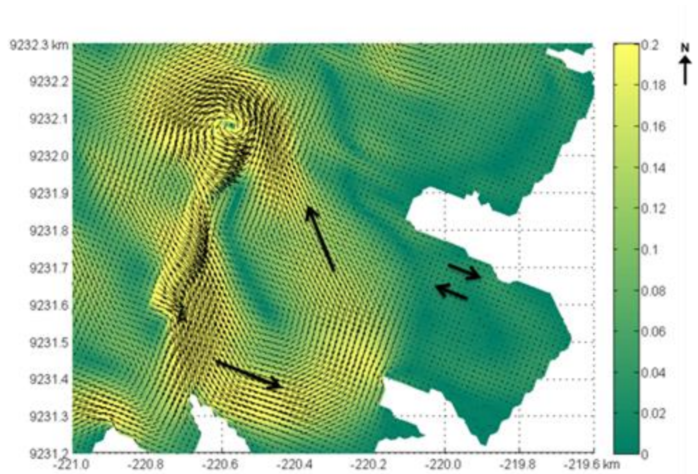


Figure E- 63 Flow direction and magnitude - induced by tide, wave and wind – North-West monsoon

E.9 MDU-file

```
# Generated on 04/21/2016 13:34:25
# Deltares, FM-Suite DFlowFM Model Version 1.0.1.32933, DFlow FM Version 1.1.154.42806

[model]
Program                  = D-Flow FM
Version                   = 1.1.154.42806
MDUFormatVersion         = 1.02
GuiVersion               = 1.0.1.32933
AutoStart                = 0

[geometry]
NetFile                  = demak_20160713_16m_net.nc
BathymetryFile           = bathy_20160713.xyz
DryPointsFile            =
WaterLevIniFile          =
LandBoundaryFile         = demak_coastline.ldb
ThinDamFile              =
FixedWeirFile            =
StructureFile            =
VertplizFile             =
ProflocFile              =
ProfdefFile              =
ProfdefxyzFile           =
Uniformwidth1D           = 2
ManholeFile              =
WaterLevIni              = 0
Bedlevuni                = -5
Bedslope                 = 0
BedlevType               = 3
Blmeanbelow              = -999
Blminabove               = -999
PartitionFile            =
AngLat                   = -6.9
AngLon                   = 0
Conveyance2D             = 1
Nonlin2D                 = 0
Sillheightmin            = 0.5
Makeorthocenters         = 0
Dcenterinside            = 1
Bamin                    = 1E-06
OpenBoundaryTolerance    = 3
RenumberFlowNodes        = 1
Kmx                      = 0
Layertype                = 1
Numtopsig                = 0
SigmaGrowthFactor        = 1

[numerics]
CFLMax                   = 0.7
AdvecType                = 33
TimeStepType             = 2
Limtyphu                 = 0
Limtypmom                = 4
Limtypsa                 = 4
TransportMethod          = 1
Vertadvtypsal            = 5
Icgsolver                = 4
Maxdegree                = 6
FixedWeirScheme          = 0
FixedWeirContraction     = 1
FixedWeirfrictscheme     = 1
Fixedweirtopwidth        = 3
Fixedweirtopfrictcoef    = -999
Fixedweirtalud           = 0.25
```

```
Izbndpos                    = 0
Tlfsmo                      = 0
Slopedrop2D                 = 0
Chkadvd                     = 0.1
Teta0                       = 0.55
Qhrelax                     = 0.01
Jbasqbnddownwindhs          = 0
cstbnd                      = 0
Maxitverticalforestersal    = 100
Maxitverticalforestertem    = 0
Jaorgsethu                  = 1
Turbulencemodel             = 3
Turbulenceadvection         = 0
AntiCreep                   = 0
Maxwaterleveldiff           = 0
Maxvelocitydiff             = 0
Epshu                       =c0.0001

[physics]
UnifFrictCoef               = 0.012
UnifFrictType               = 1
UnifFrictCoef1D             = 0.012
UnifFrictCoefLin            = 0
Umodlin                     = 0
Vicouv                      = 1
Dicouv                      = 1
Vicoww                      = 0
Dicoww                      = 0
Vicwminb                    = 0
Smagorinsky                 = 0
Elder                       = 0
irov                        = 0
wall_ks                     = 0
Rhomean                     = 1025
Idensform                   = 1
Ag                          = 9.81
TidalForcing                = 0
Doodsonstart                = 55.565
Doodsonstop                 = 375.575
Doodsoneps                  = 0
Salinity                    = 0
InitialSalinity             = 0
Sal0abovezlev               = -999
DeltaSalinity               = -999
Backgroundsalinity          = 31
Temperature                 = 0
InitialTemperature          = 25
Secchidepth                 = 1
Stanton                     = -1
Dalton                      = -1
Backgroundwatertemperature= 25
SecondaryFlow               = 0
EffectSpiral                = 0
BetaSpiral                  = 0

[wind]
ICdtyp                      = 2                # ( ), Cd = const, 2=S&B 2 breakpoints, 3= S&B 3 breakpoints
Cdbreakpoints              =                   0.0006300          0.0072300          # ( ),   e.g. 0.00063  0.00723
Windspeedbreakpoints       = 0.0000000         100.0000000        # (m/s), e.g. 0.0     100.0
Rhoair                      = 1.0000000        # Air density (kg/m3)
PavBnd                      = 101325.0000000#Average air Pressure on open boundaries, (N/m2)
Gapres                      = 101325.0000000

[waves]
Wavemodelnr                 = 3
WaveNikuradse               = 0.01
```

```
Rouwav                      = FR84
Gammax                      = 0.78

[time]
RefDate                      = 20161120
Tzone                        = 7
DtUser                       = 150
DtNodal                      =
DtMax                        = 15
DtInit                       = 1
Tunit                        = S
TStart                       = 0
TStop                        = 158400

[external forcing]
ExtForceFile      = wind_bnd.ext
ExtForceFileNew   = wlev_bnd.ext

[trachytopes]
TrtRou                      = N
TrtDef                      =
TrtL                        =
TrtDt                       = 60

[output]
OutputDir                   =
FlowGeomFile                =
ObsFile                     = semarang.xyn
CrsFile                     =
HisFile                     =
HisInterval                 = 300
XLSInterval                 =
MapFile                     =
MapInterval                 = 3600
RstInterval                 =
S1incinterval               =
WaqInterval                 = 1800
StatsInterval               = -600
Writebalancefile            = 0
TimingsInterval             =
MapFormat                   = 1
Wrihis_balance              = 1
Wrihis_structure_gen        = 1
Wrihis_structure_dam        = 1
Wrihis_structure_pump       = 1
Wrihis_structure_gate       = 1
Wrimap_waterlevel_s0        = 1
Wrimap_waterlevel_s1        = 1
Wrimap_velocity_component_u0= 1
Wrimap_velocity_component_u1= 1
Wrimap_velocity_vector      = 1
Wrimap_upward_velocity_component= 0
Wrimap_density_rho          = 1
Wrimap_horizontal_viscosity_viu= 1
Wrimap_horizontal_diffusivity_diu= 1
Wrimap_flow_flux_q1         = 1
Wrimap_spiral_flow          = 1
Wrimap_numlimdt             = 1
Wrimap_taucurrent           = 1
Wrimap_chezy                = 1
Wrimap_turbulence           = 1
Wrimap_wind                 = 1
Wrimap_heat_fluxes          = 0
Richardsononoutput          = 1
```

E.10 MDW-file

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[WaveFileInformation]
   FileVersion                 = 02.00
[General]
   ProjectName                 = wave_nested
   ProjectNr                   = 00
   ReferenceDate               = 2016-11-20
   DirConvention               = nautical
   SimMode                     = stationary
   TimeStep                    = 1
   TScale                      = 60
   OnlyInputVerify             = false
   FlowBedLevel                = 2
   FlowWaterLevel              = 2
   FlowVelocity                = 2
   FlowVelocityType            = depth-averaged
   FlowWind                    = 2
   DirSpace                    = circle
   NDir                        = 36
   StartDir                    = 0
   EndDir                      = 360
   NFreq                       = 24
   FreqMin                     = 0.05
   FreqMax                     = 1
   WaterLevel                  = 0.0000000e+000
   XVeloc                      = 0.0000000e+000
   YVeloc                      = 0.0000000e+000
   WindSpeed                   = 4.4000000e+000
   WindDir                     = 2.8000000e+002
   Description                 = wave_nested
[Constants]
   WaterLevelCorrection        = 0
   Gravity                     = 9.81
   WaterDensity                = 1025
   NorthDir                    = 90
   MinimumDepth                = 0.05
[Processes]
   GenModePhys                 = 3
   WaveSetup                   = false
   Breaking                    = true
   BreakAlpha                  = 1
   BreakGamma                  = 0.73
   Triads                      = false
   TriadsAlpha                 = 0.1
   TriadsBeta                  = 2.2
   BedFriction                 = jonswap
   BedFricCoef                 = 0.019
   Diffraction                 = false
   DiffracSteps                = 5
   DiffracProp                 = true
   DiffracCoef                 = 0.2
   WindGrowth                  = true
   Quadruplets                 = true
   WhiteCapping                = Komen
   Refraction                  = true
   FreqShift                   = true
   WaveForces                  = radiation stresses
[Numerics]
   DirSpaceCDD                 = 0.5
   FreqSpaceCSS                = 0.5
   RChHsTm01                   = 0.02
   RChMeanHs                   = 0.02
   RChMeanTm01                 = 0.02
   PercWet                     = 98
   MaxIter                     = 15
```

```
[Output]
   MapWriteInterval          = 60
   WriteTable                = true
   WriteSpec1D               = false
   WriteSpec2D               = false
   UseHotFile                = false
   WriteCOM                  = true
   COMFile                   = DFM_OUTPUT_demak/demak_com.nc
   COMWriteInterval          = 60
   AppendCOM                 = true
   MassFluxToCOM             = true
   TestOutputLevel           = 0
   TraceCalls                = false
   MapWriteNetCDF            = true
   NetCDFSinglePrecision     = false

[Boundary]
   Name                      = BoundaryCondition01
   Definition                = orientation
   Orientation               = northeast
   SpectrumSpec              = parametric
   SpShapeType               = jonswap
   PeriodType                = mean
   DirSpreadType             = degrees
   PeakEnhanceFac            = 3.3000000e+000
   GaussSpread               = 0.0000000e+000
   WaveHeight                = 0.7000000e+000
   Period                    = 4.7000000e+000
   Direction                 = 3.0000000e+002
   DirSpreading              = 1.5000000e+001
[Boundary]
   Name                      = BoundaryCondition02
   Definition                = orientation
   Orientation               = northwest
   SpectrumSpec              = parametric
   SpShapeType               = jonswap
   PeriodType                = mean
   DirSpreadType             = degrees
   PeakEnhanceFac            = 3.3000000e+000
   GaussSpread               = 0.0000000e+000
   WaveHeight                = 0.7000000e+000
   Period                    = 4.7000000e+000
   Direction                 = 3.0000000e+002
   DirSpreading              = 1.5000000e+001
[Domain]
   Grid                      = waves_fine_250m_ldb.grd
   BedLevel                  = waves_250m_UTM50s_ldb.dep
   Output                    = true
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   Grid                      = nest1.grd
   BedLevel                  = nest1.dep
   NestedInDomain            = 1
   Output                    = true
```

Appendix F Sediment dynamics

This chapter contains all the reasoning and results of the sediment dynamic analysis. It starts with the comparison of sediment transport between a spring-tidal cycle composed of spring tides and neap tides. Subsequently, the interpretation of the behaviour of the three different sediment particles is explained and the initial nourishment position is showed. Finally, the sediment displacement and sediment concentration per nourishment configuration is summarized for all three hydrodynamic scenarios and the two bottom topographies.

The results show residual transport, the net result of sediment transport without intermediate steps. It does not include morphological bed updating and only shows sediment displacement through diffusive spreading.

The North-West monsoon and South-East monsoon results are taken after three months while the results of the storm scenario are taken after 5 days.

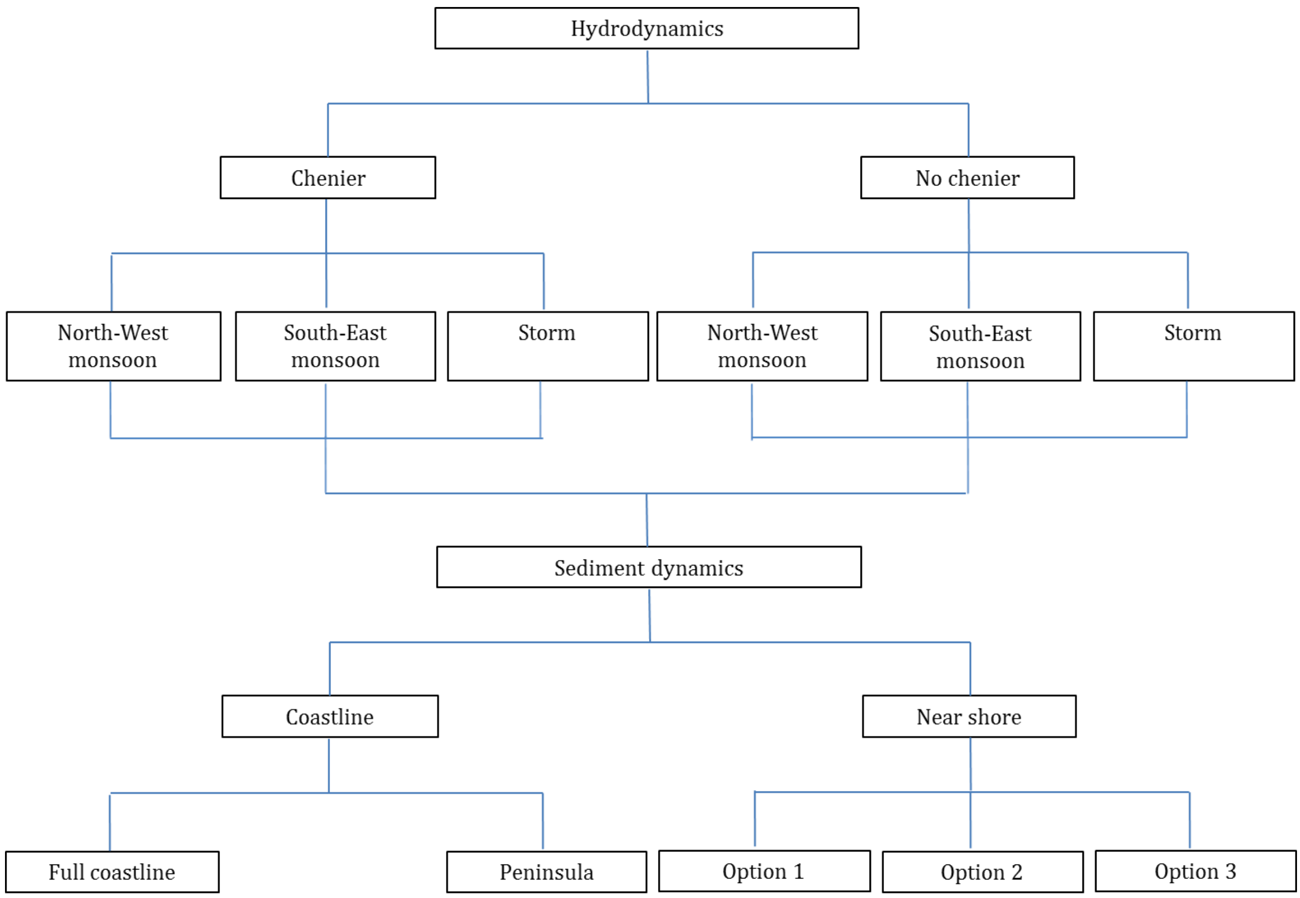

Figure F- 1 Overview scheme hydrodynamics and sediment dynamics

F.1 Spring tide and neap tide comparison

This paragraph elaborates on the difference between sediment transport during an artificial tide with only spring tides and neap tides. This is investigated for all nourishment options and in all hydrodynamic scenarios. The nourishment along the coastline in the North-West monsoon is demonstrated below. The sediment concentration and sediment deposition is investigated after two months of the North-West monsoon with an artificial tide composed of only spring tide cycles and neap tide cycles, Figure F- 2 and Figure F- 3.

The difference in the end situation of the concentration and deposition is very small, negligible. This is conducted to the small difference of shear stress in the area of the nourishment and the flow pattern is the same during the spring tidal cycle and the neap tidal cycle. This is demonstrated in E.2 Spring tide and neap tide comparison.

From here on the sediment dynamic runs in DELWAQ are executed with hydrodynamic runs based on an artificial tide with only spring tidal cycles.

SPRING TIDE

Concentration | Nourishment deposition

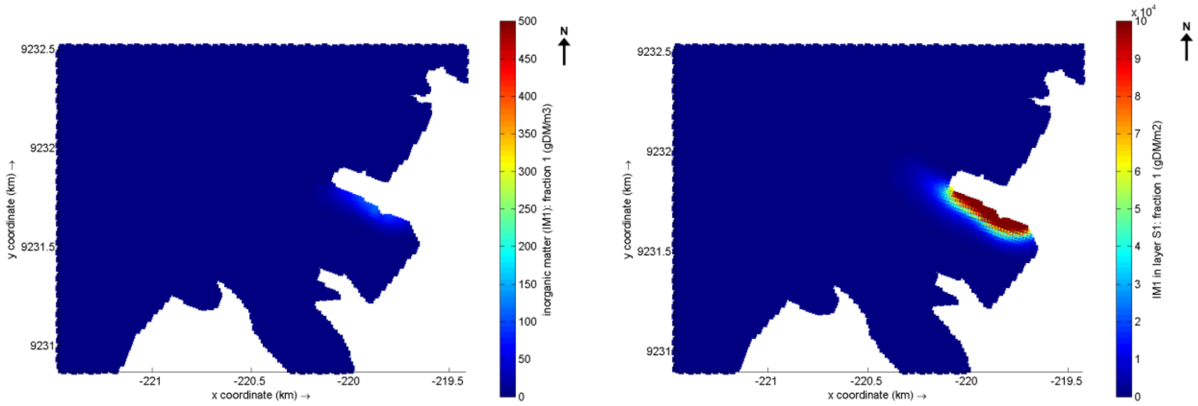

Figure F- 2 Concentration and sediment storage in bed after 3 months NW monsoon - full coastline

NEAP TIDE

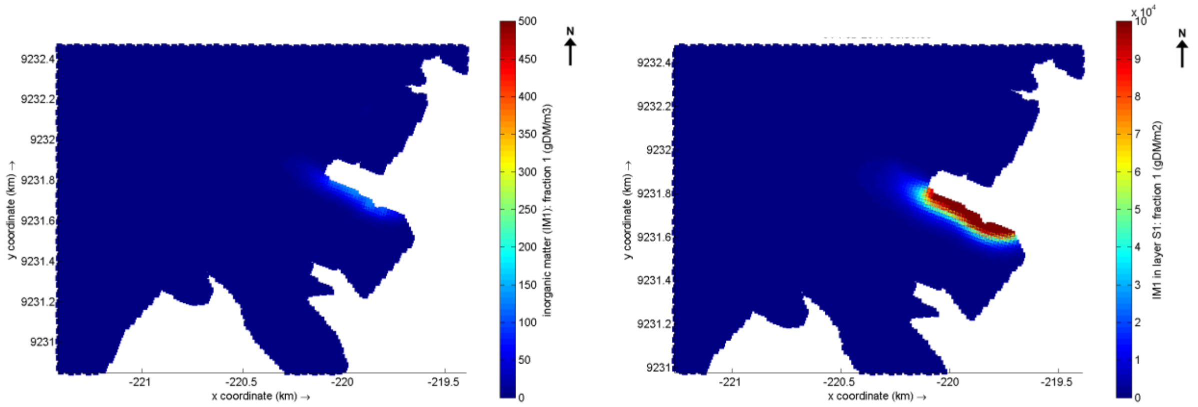

Figure F- 3 Concentration and sediment storage in bed after 3 months NW monsoon - full coastline

F.2 Interpretation behaviour IM1, IM2 and IM3

Three sediment particles (IM1, IM2 and IM3) with different fall velocity are used in the nourishment, see Table F- 1 . Though, each particle has a critical shear stress for erosion of 0.5 N/m^2 and an erosion factor of 1 g/m^2 s. This is assumed constant for each particle since the nourishment functions as one solid unit. It is recognized that the individual particles have a smaller critical shear stress for erosion and a higher erosion factor.

This section elaborates on the differences in concentration and deposition for the three particles in the full coastline nourishment. This behaviour is independent of the nourishment option and purely provides insight in the spreading and deposition of particles with different fall velocity.

The ambient shear stress, critical shear stress for erosion, the water depth and the horizontal flow velocity are the same during the simulations with different particle size. Reasoning and the model approves that sediment with a smaller (vertical) fall velocity travels larger horizontal distances. Once the particle is brought into re-suspension it needs more time to travel through the water column to the bottom. In this period the particle is transported over an extra horizontal distance. This has led to larger observed concentrations outside of the nourishment area for IM2 and IM3. The sediment deposition pattern follows the range of the concentration spreading because the deposition depends on the concentration, fall velocity, ambient shear stress and critical shear stress for erosion. The results are illustrated in Figure F- 4, Figure F- 5 and Figure F- 6.

From here on the concentration and sediment deposition are demonstrated for only the IM1 particle in order to reduce the amount of figures.

Settling velocity IM1	1	[mm s^{-1}]
Critical shear stress for erosion	0.5	[N m^{-2}]
Critical shear stress for deposition	1000	[N m^{-2}]
Erosion parameter	1	[g m^{-2} s]
Settling velocity IM2	0.5	[mm s^{-1}]
Critical shear stress for erosion	0.5	[N m^{-2}]
Critical shear stress for deposition	1000	[N m^{-2}]
Erosion parameter	1	[g m^{-2} s]
Settling velocity IM3	0.25	[mm s^{-1}]
Critical shear stress for erosion	0.5	[N m^{-2}]
Critical shear stress for deposition	1000	[N m^{-2}]
Erosion parameter	1	[g m^{-2} s]

Table F- 1 General input parameters sediment dynamics

Concentration | Nourishment deposition

IM1

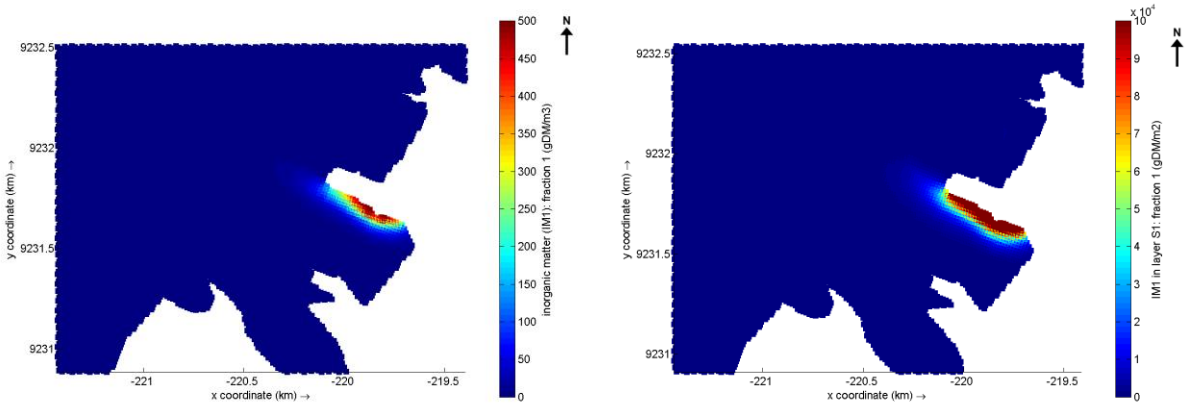

Figure F- 4 Concentration and sediment storage in bed after 3 months North-West monsoon - IM1

IM2

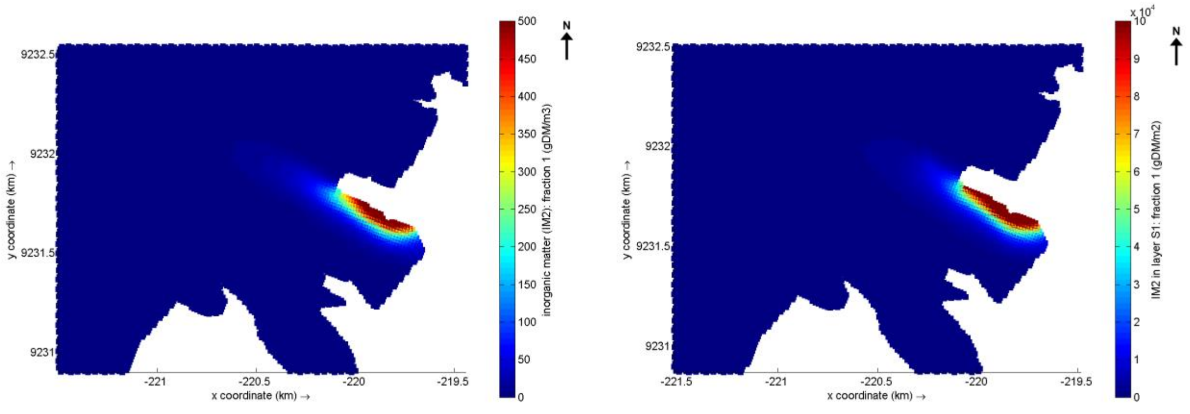

Figure F- 5 Concentration and sediment storage in bed after 3 months North-West monsoon – IM2

IM3

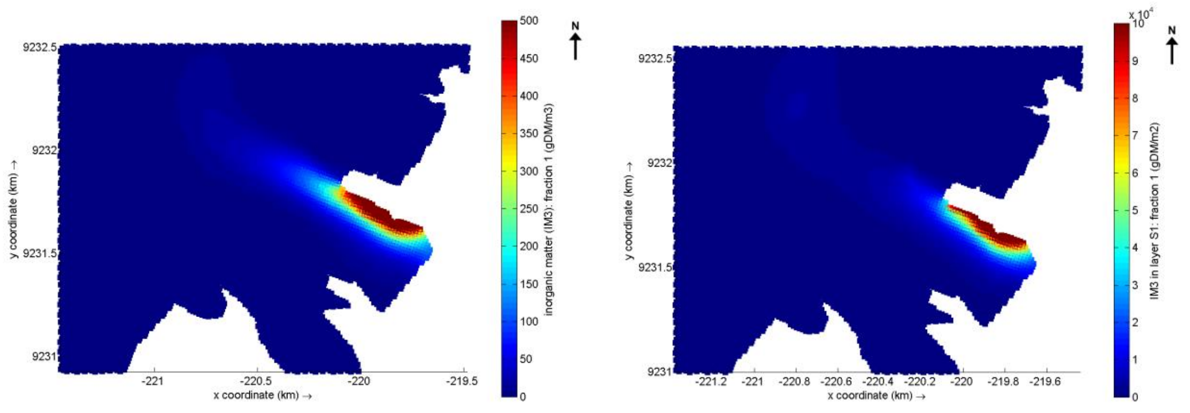

Figure F- 6 Concentration and sediment storage in bed after 3 months North-West monsoon – IM3

F.3 Initial conditions sediment nourishment

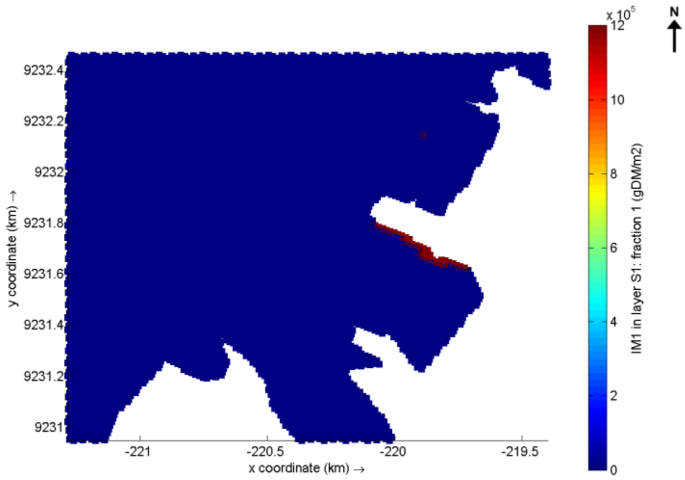

Figure F- 7 Nourishment coastline – option full coastline

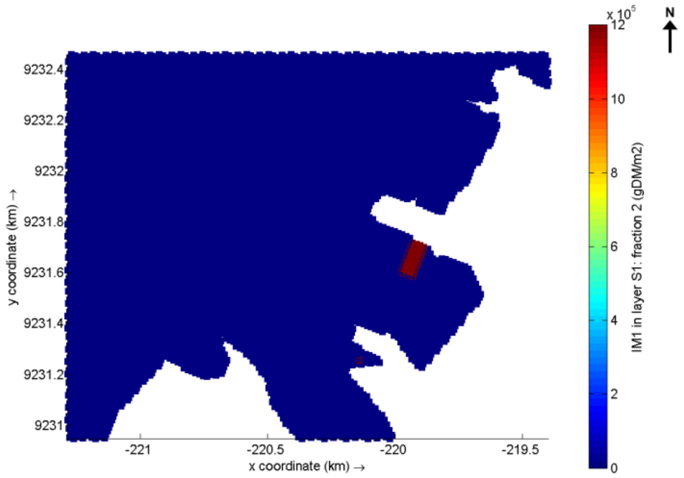

Figure F- 8 Nourishment coastline – option peninsula

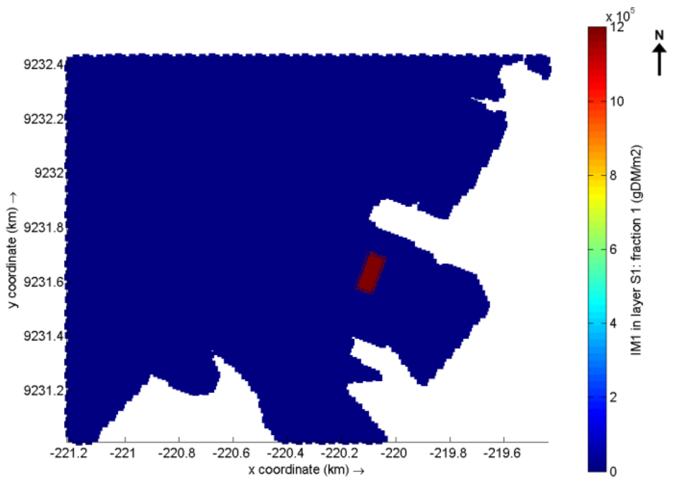

Figure F- 9 Nourishment nearshore – option 1

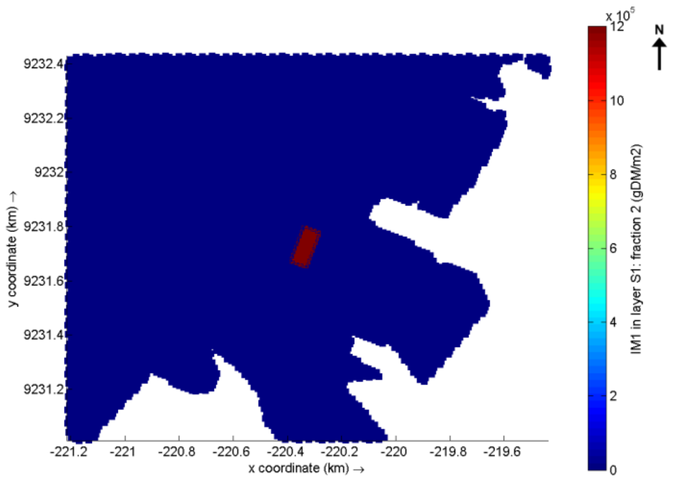

Figure F- 10 Nourishment nearshore – option 2

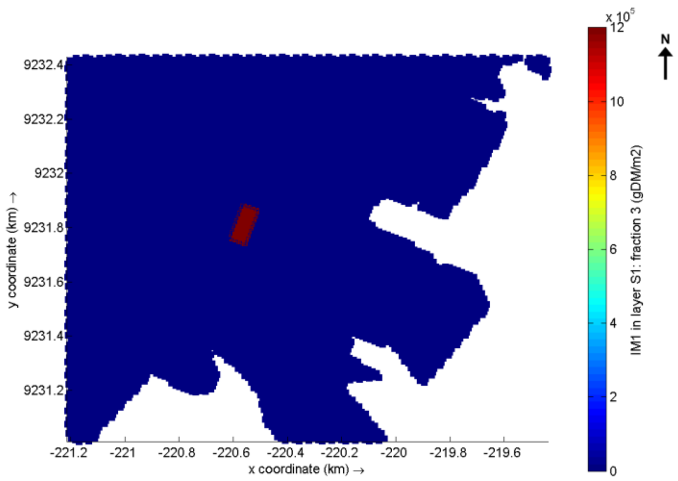

Figure F- 11 Nourishment nearshore – option 3

F.4 Option full coastline

NO CHENIER

Concentration | Nourishment deposition

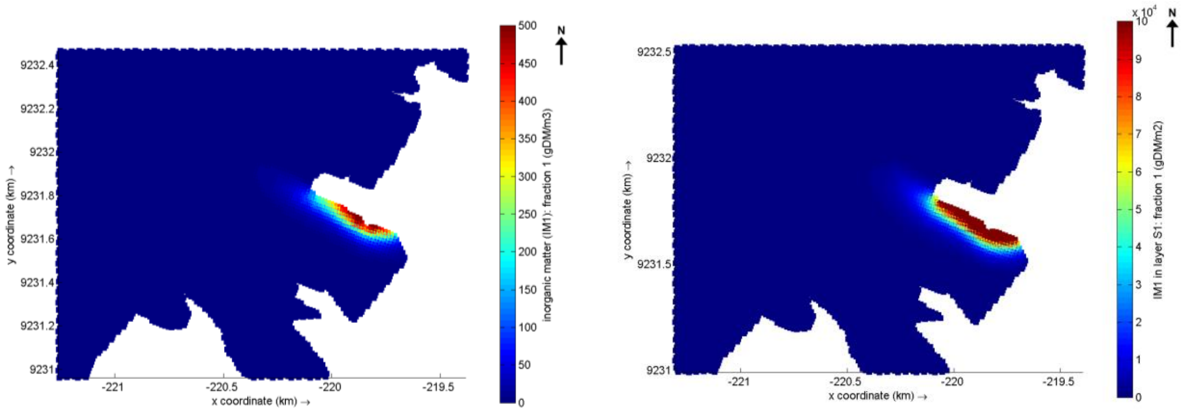

Figure F- 12 Concentration and sediment storage in bed after 3 months NW monsoon - full coastline

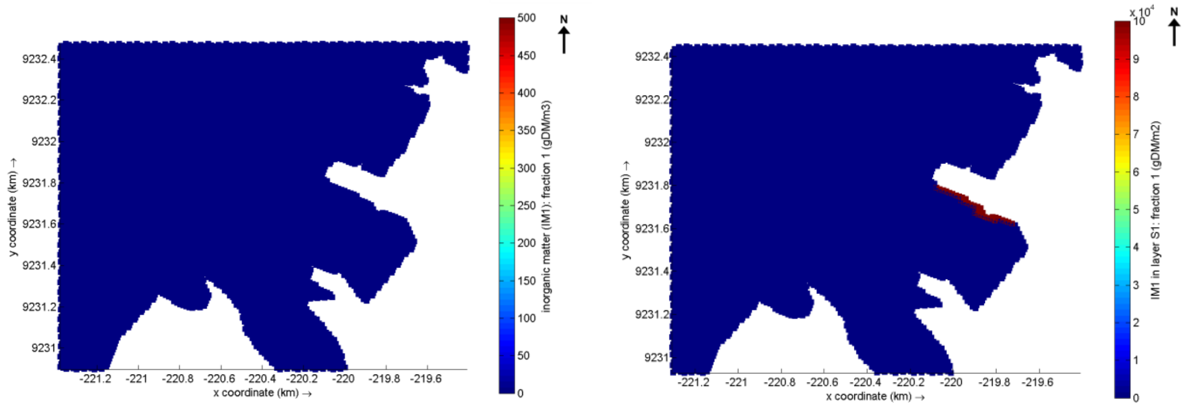

Figure F- 13 Concentration and sediment storage in bed after 3 months SE monsoon - full coastline

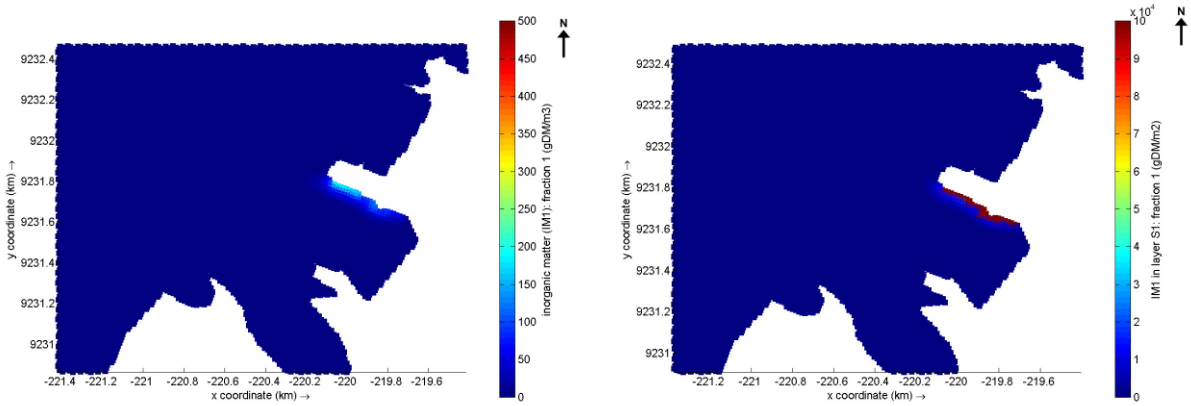

Figure F- 14 Concentration and sediment storage in bed after 5 days storm - full coastline

CHENIER

Concentration | Nourishment deposition

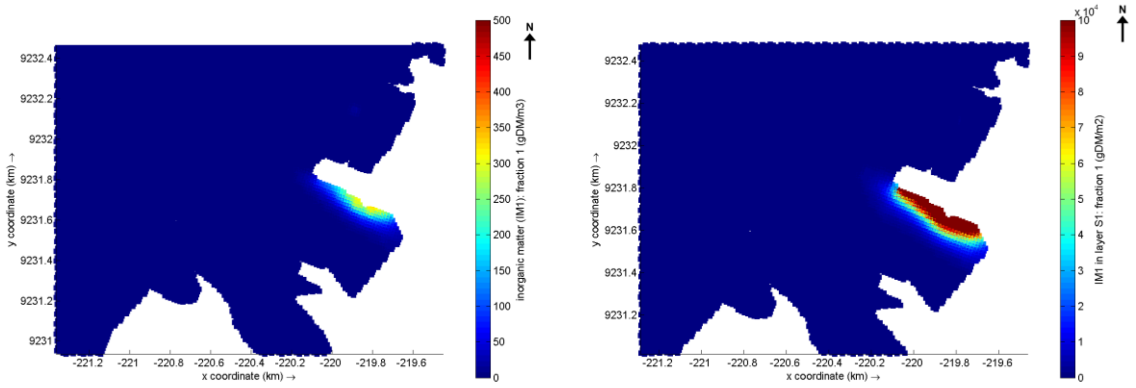

Figure F- 15 Concentration and sediment storage in bed after 3 months NW monsoon - full coastline

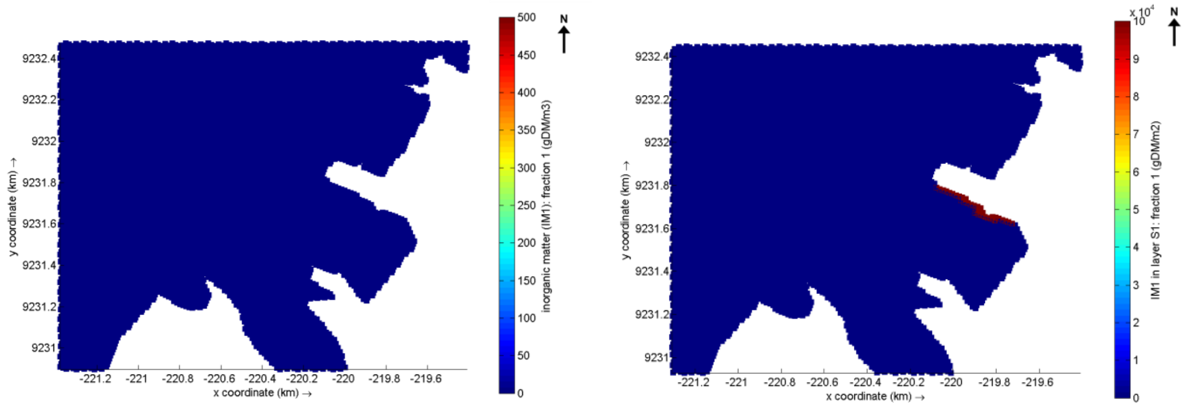

Figure F- 16 Concentration and sediment storage in bed after 3 months SE monsoon - full coastline

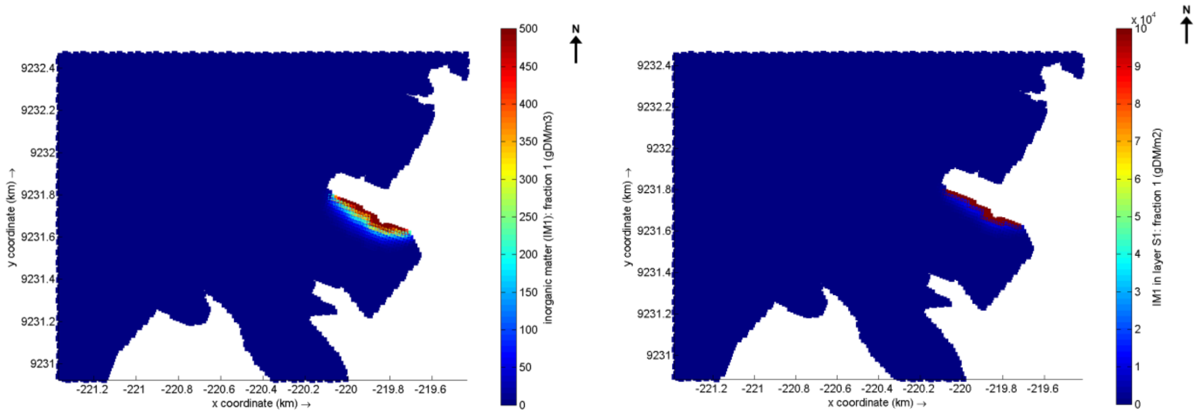

Figure F- 17 Concentration and sediment storage in bed after 5 days storm - full coastline

F.5 Option peninsula

NO CHENIER

Concentration | Nourishment deposition

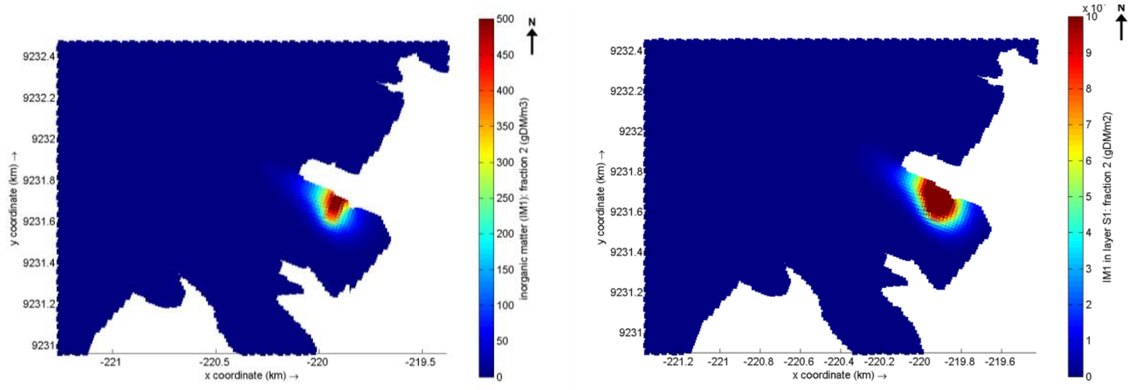

Figure F- 18 Concentration and sediment storage in bed after 3 months NW monsoon - peninsula

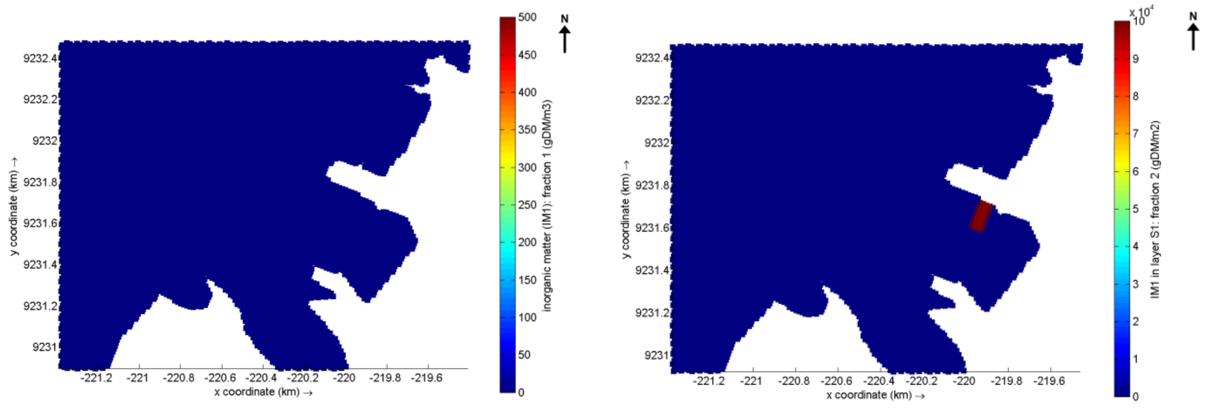

Figure F- 19 Concentration and sediment storage in bed after 3 months SE monsoon - peninsula

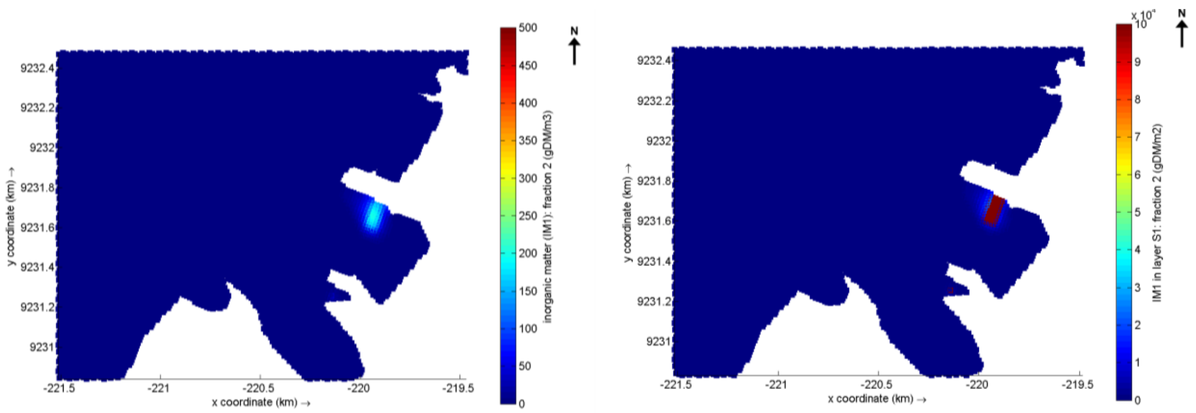

Figure F- 20 Concentration and sediment storage in bed after 5 days storm - peninsula

CHENIER

Concentration | Nourishment deposition

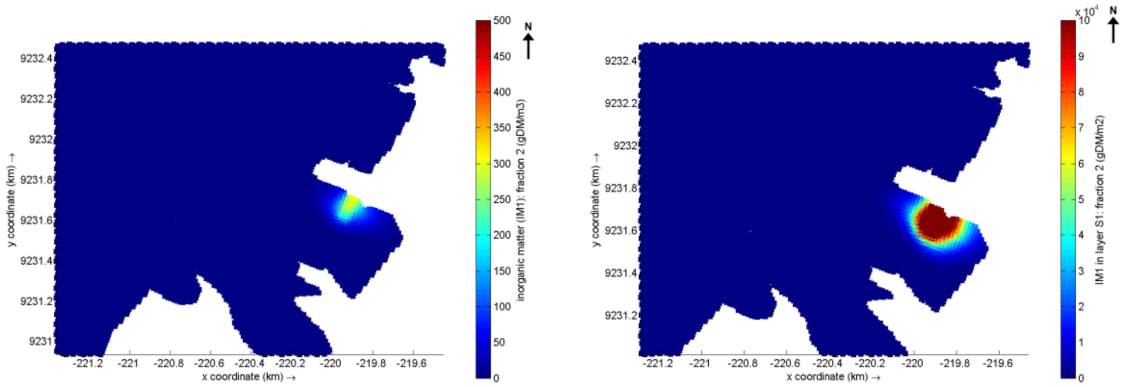

Figure F- 21 Concentration and sediment storage in bed after 3 months NW monsoon - peninsula

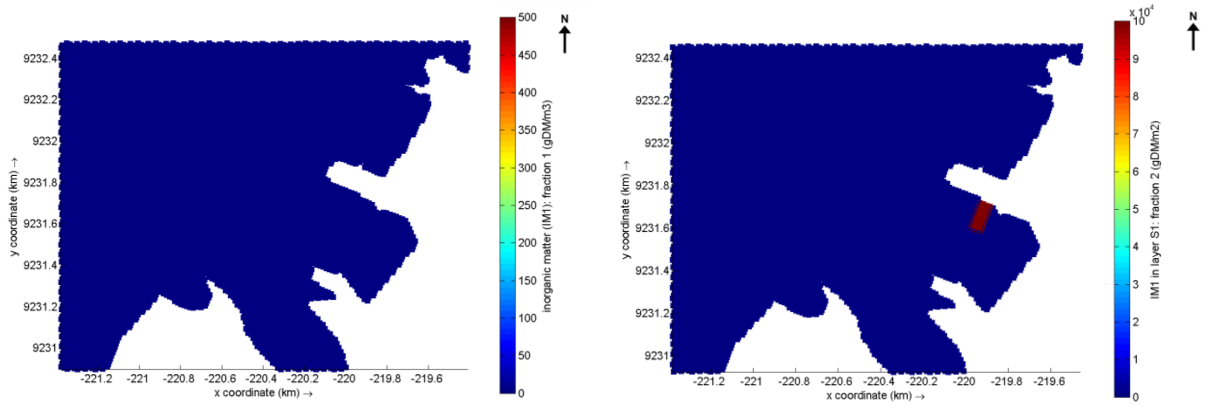

Figure F- 22 Concentration and sediment storage in bed after 3 months SE monsoon - peninsula

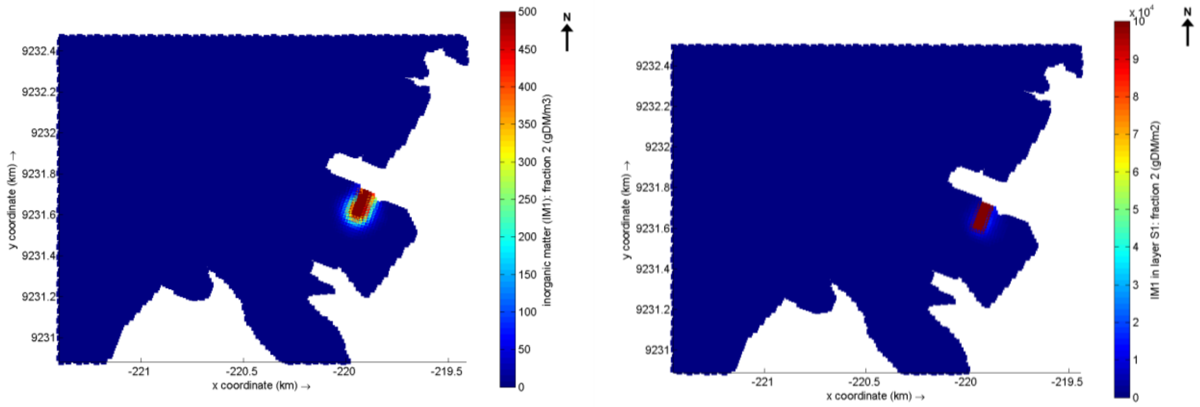

Figure F- 23 Concentration and sediment storage in bed after 5 days storm - peninsula

F.6 Option 1 nearshore

NO CHENIER

Concentration — Nourishment deposition

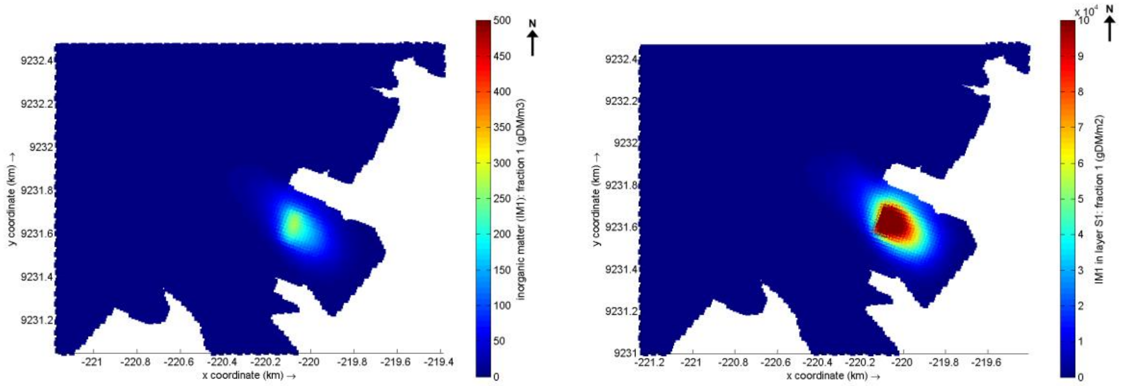

Figure F- 24 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 1

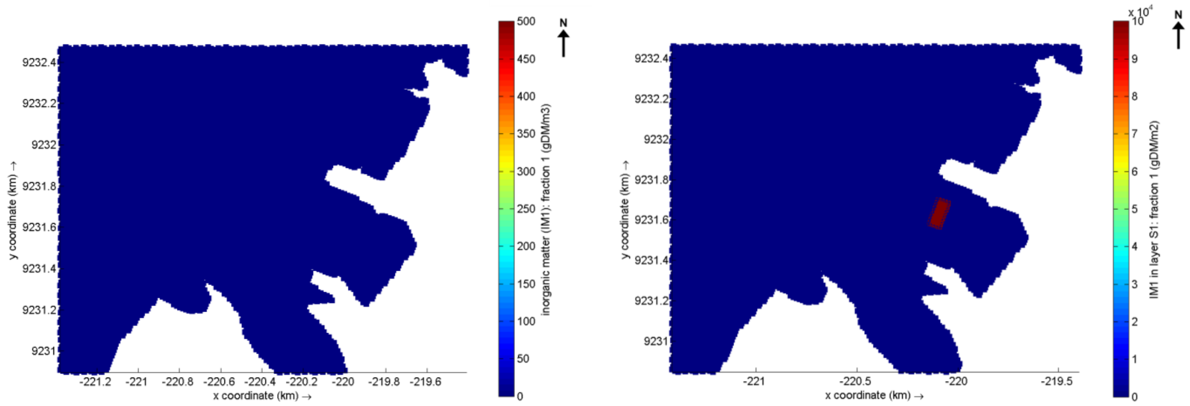

Figure F- 25 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 1

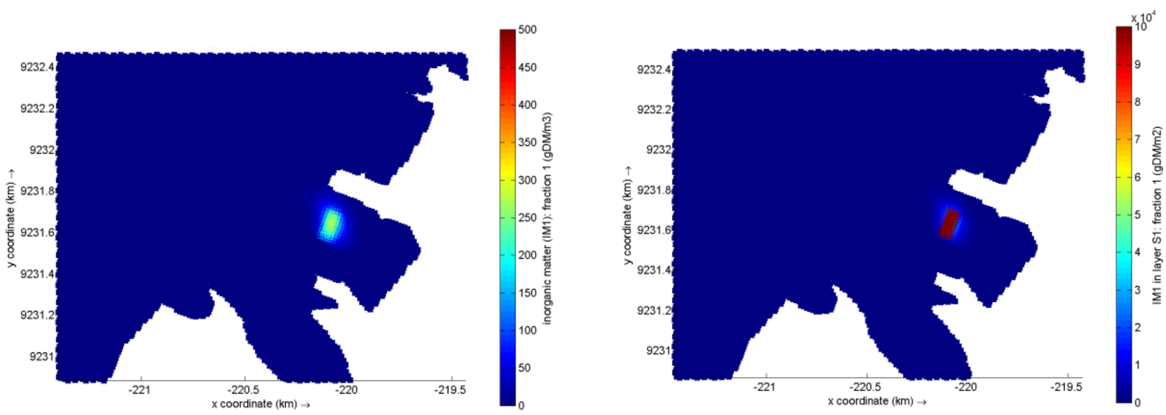

Figure F- 26 Concentration and sediment storage in bed after 5 days storm –nearshore 1

CHENIER

Concentration | Nourishment deposition

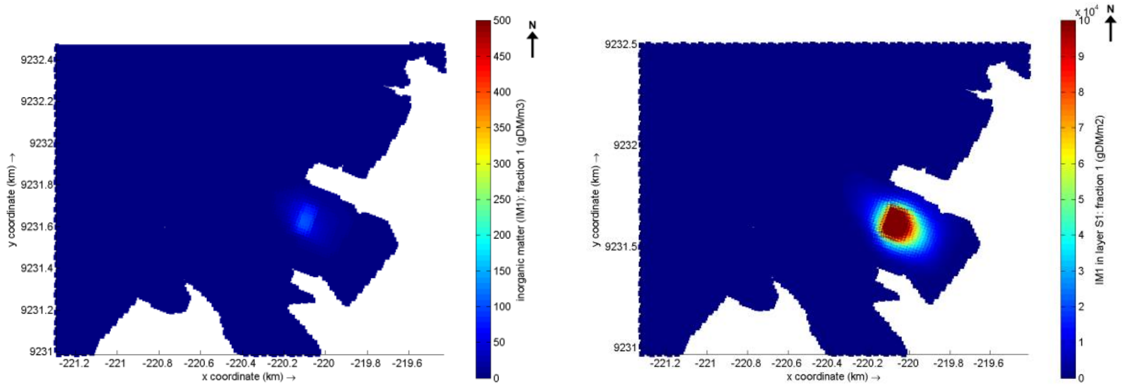

Figure F- 27 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 1

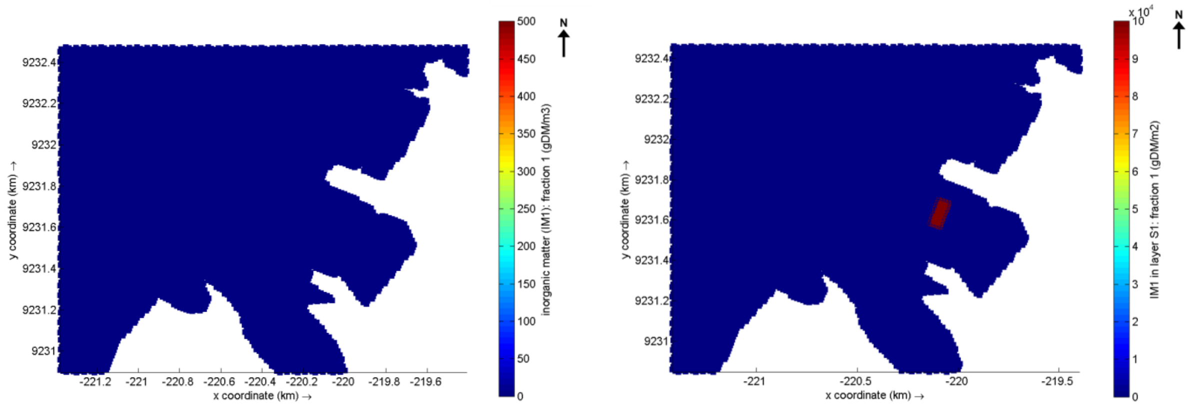

Figure F- 28 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 1

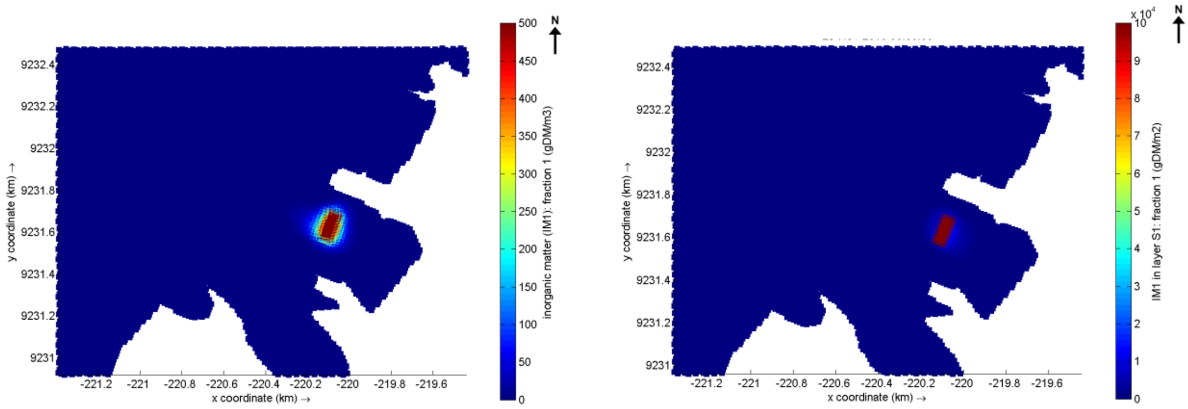

Figure F- 29 Concentration and sediment storage in bed after 5 days storm –nearshore 1

F.7 Option 2 nearshore

NO CHENIER

Concentration | Nourishment deposition

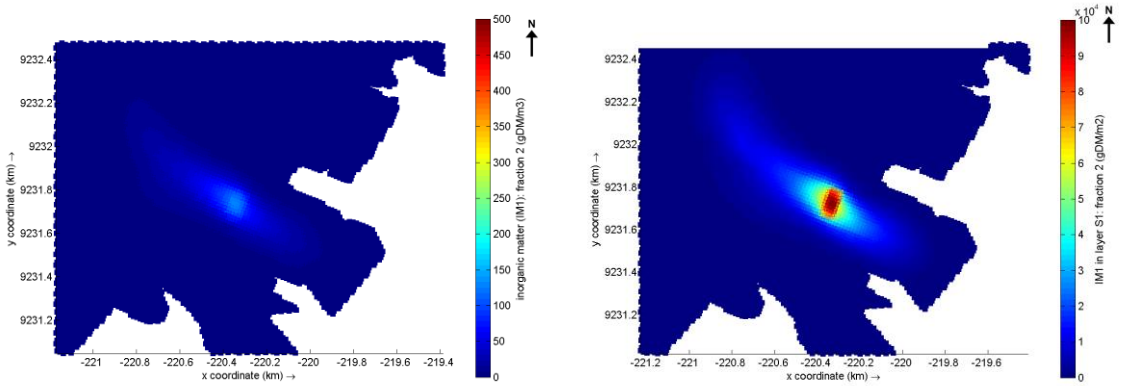

Figure F- 30 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 2

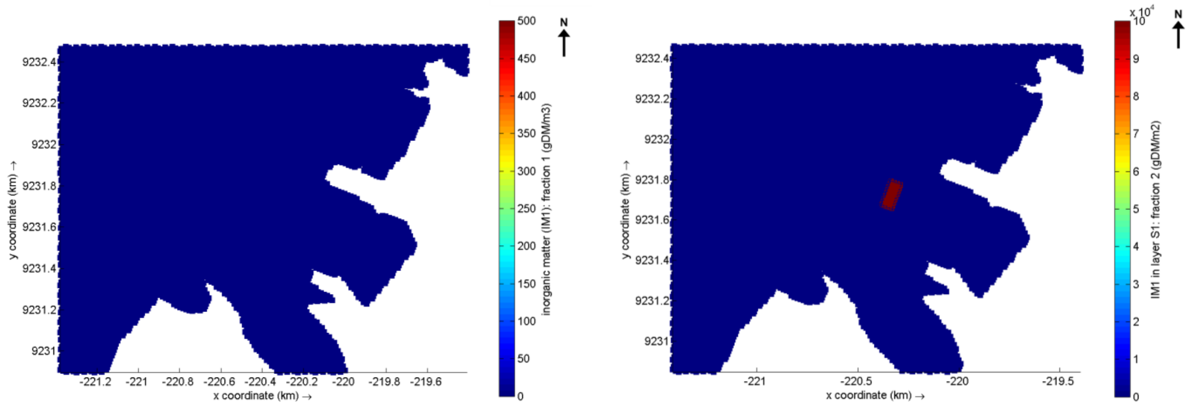

Figure F- 31 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 2

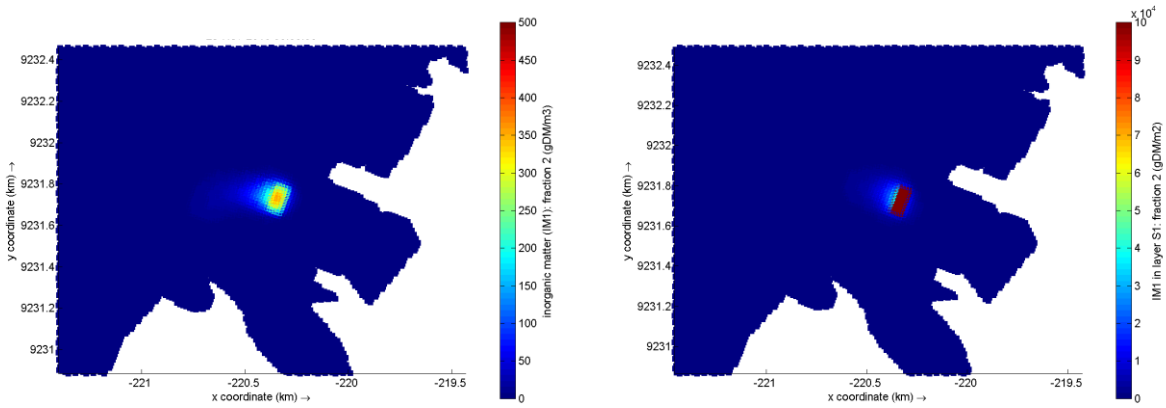

Figure F- 32 Concentration and sediment storage in bed after 5 days storm –nearshore 2

CHENIER

Concentration Nourishment deposition

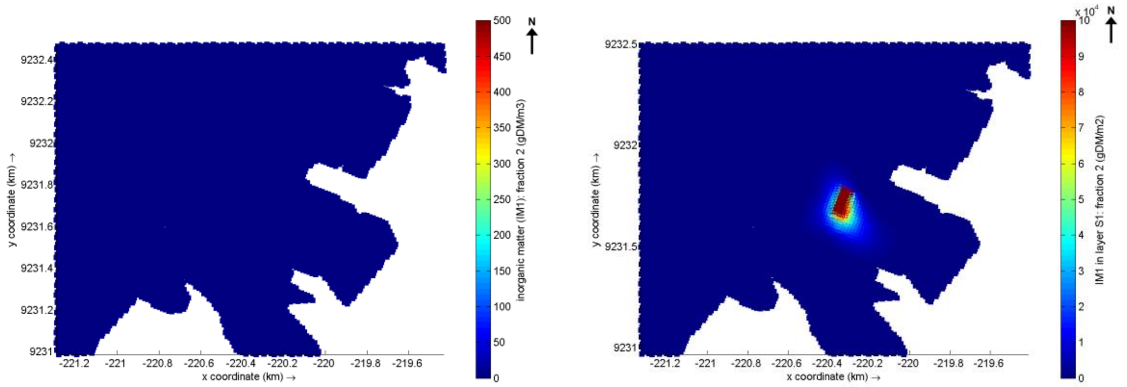

Figure F- 33 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 2

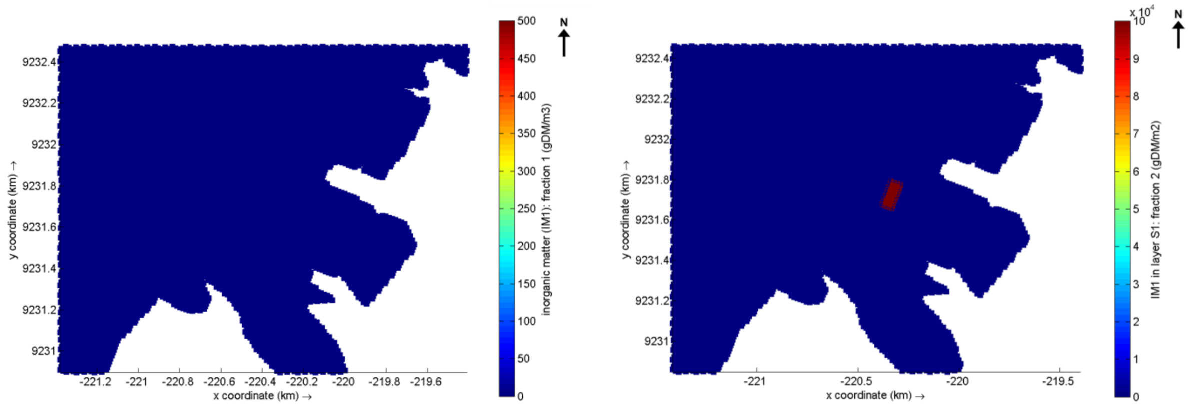

Figure F- 34 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 2

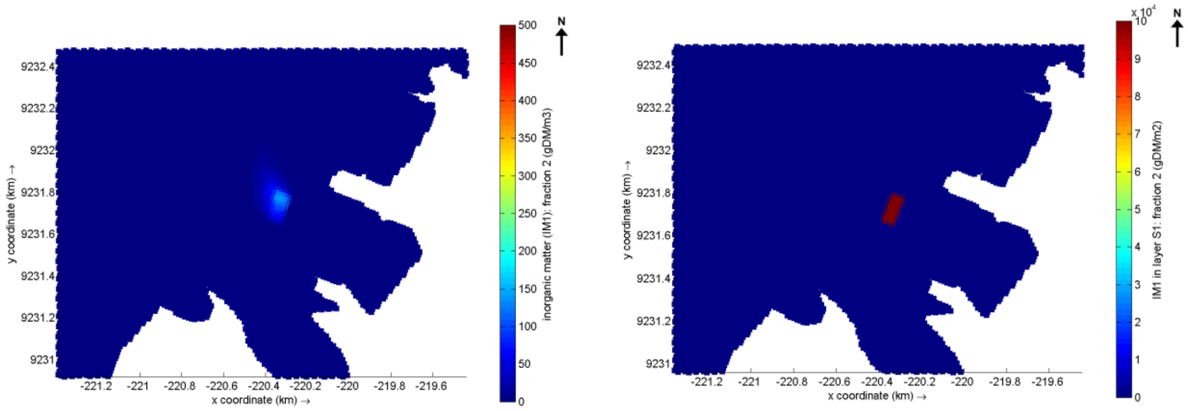

Figure F- 35 Concentration and sediment storage in bed after 5 days storm –nearshore 2

F.8 Option 3 nearshore

NO CHENIER

Concentration | Nourishment deposition

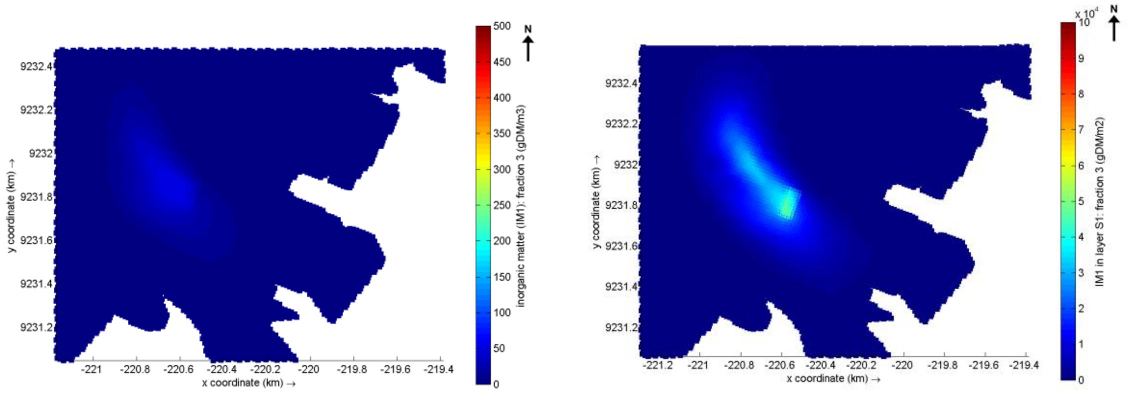

Figure F- 36 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 3

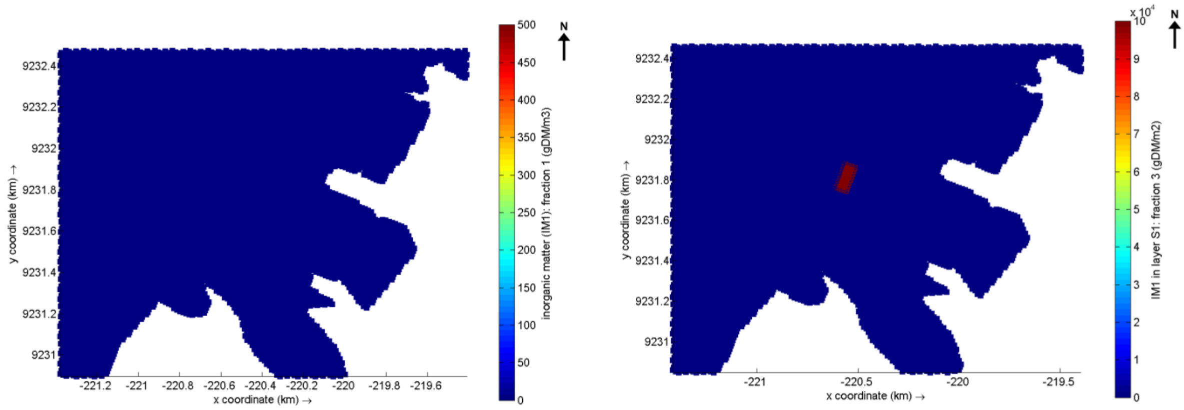

Figure F- 37 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 3

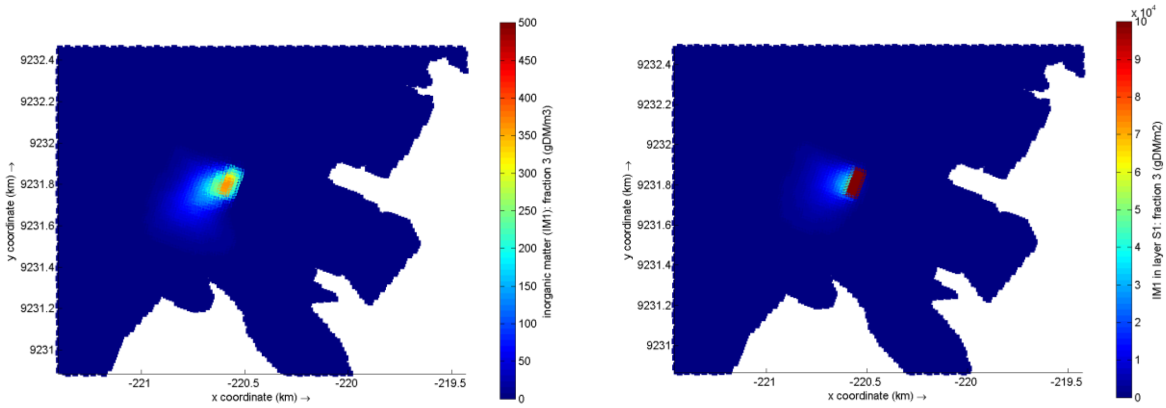

Figure F- 38 Concentration and sediment storage in bed after 5 days storm –nearshore 3

CHENIER

Concentration   Nourishment deposition

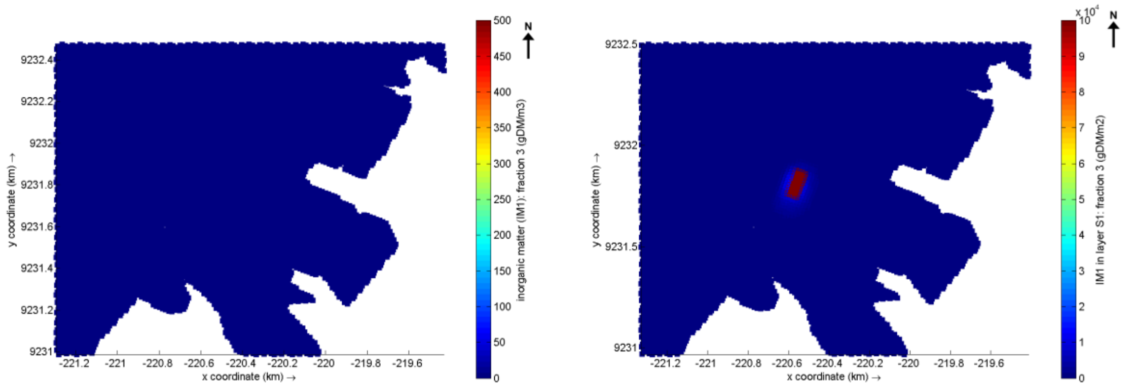

Figure F- 39 Concentration and sediment storage in bed after 3 months NW monsoon –nearshore 3

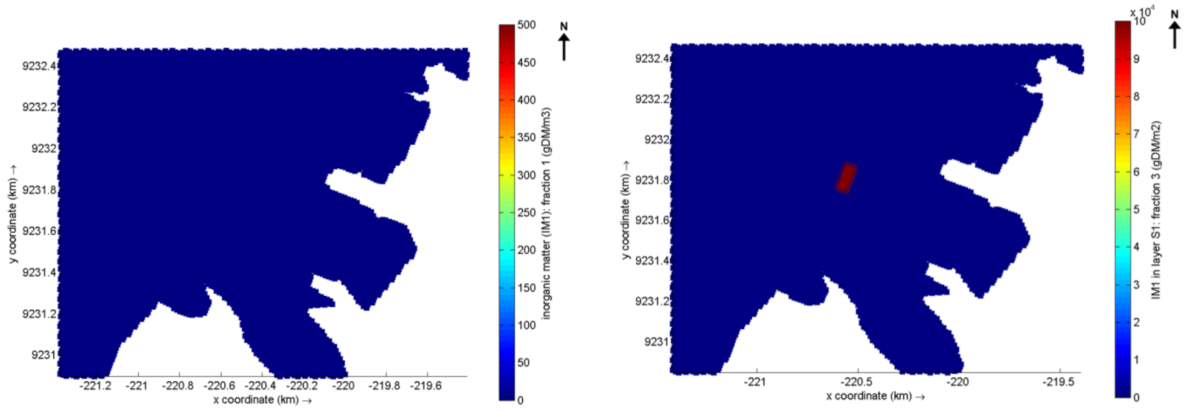

Figure F- 40 Concentration and sediment storage in bed after 3 months SE monsoon –nearshore 3

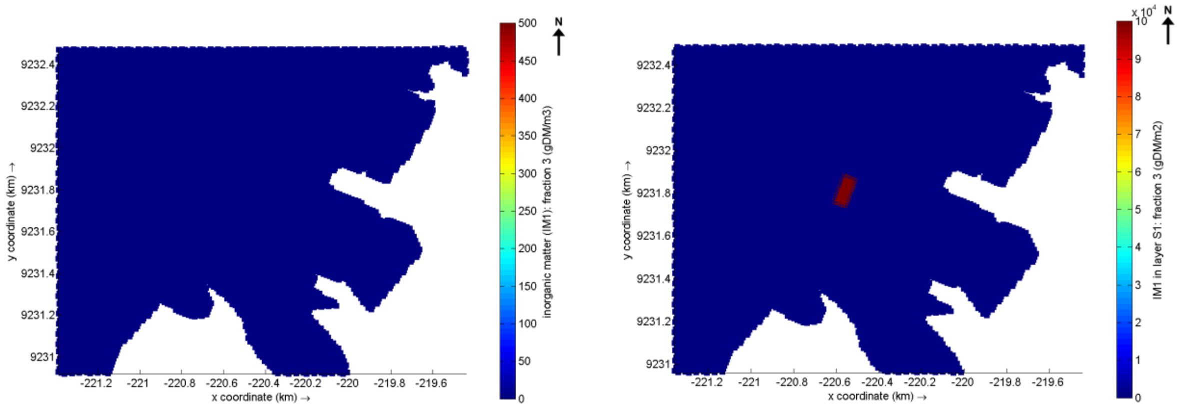

Figure F- 41 Concentration and sediment storage in bed after 5 days –nearshore 3

F.9 DELWAQ-file

```
; first block: identification
'---final - Bed sediment availability from 1 location with labelled sedi-
ments - IM101 IM201 IM301'
'---[labelling only useful when have >1 locations - so have to add a second
location 02]'
'---'
'T0: 2016.11.20 00:00:00  (scu=       1s)'
;
; substances file: IM1_IM2_IM3_EJ.sub ;[have to check if this contains still
the correct information]
; hydrodynamic file: demak
;
; areachar.dat: demak.srfold
;
  3  6    ; number of active and inactive substances

; Index  Name
      1 'IM1' *3
      2 'IM2' *3
      3 'IM3' *3
      4 'IM1S1' *3
      5 'IM2S1' *3
      6 'IM3S1' *3
      7 'IM1S2'
      8 'IM2S2'
      9 'IM3S2'
;
#1 ; delimiter for the first block
;
; second block of model input (timers)
;
; integration timers
;
 86400  'ddhhmmss' 'ddhhmmss' ; system clock in sec, aux in days
 22.70    ; integration option
 2016/11/20-20:00:00      ; start time
 2017/02/20-20:00:00      ; stop time
 0                  ; constant timestep
 0000500      ; time step
;
 1     ; monitoring points/areas used
 0   ; number of monitoring points/areas
 2     ; monitoring transects not used
;
; start time      stop time     time step
 2016/11/20-20:00:00        2017/02/20-20:00:00      0003000      ; monitor-
ing
 2016/11/20-20:00:00        2017/02/20-20:00:00       0003000      ; map,
dump
 2016/11/20-20:00:00        2017/02/20-20:00:00       0003000      ; history
;
#2 ; delimiter for the second block
;
; third block of model input (grid layout)

; Name of coordinates file - conforming to UGRID conventions
```

```
 59976      ; number of segments
 2        ; grid layout not used
INCLUDE 'demak.atr'  ; attributes file
;
; volumes
;
-2  ; first volume option
'demak.vol'  ; volumes file
;
#3 ; delimiter for the third block
;
; fourth block of model input (transport)
 118111  ; exchanges in direction 1
 0  ; exchanges in direction 2
 0  ; exchanges in direction 3
;
 0  ; dispersion arrays
 0  ; velocity arrays
;
 1  ; first form is used for input
 0  ; exchange pointer option
'demak.poi'  ; pointers file
;
 1  ; first dispersion option nr
 1.0 1.0 1.0   ; scale factors in 3 directions
 1.00000e+000 1.00000e+000 ; dispersion in 1st and 2nd direction
 1.00000e-007 ; dispersion in 3rd direction
;
 -2  ; first area option
'demak.are'  ; area file
;
 -2  ; first flow option
'demak.flo'  ; flow file
;
; No explicit velocity arrays
;
  1  ; length vary
 0   ; length option
'demak.len'  ; length file
;
#4 ; delimiter for the fourth block
;
; fifth block of model input (boundary condition)
'1 (North - 1)' '1 (North - 1)' '1/1 (North - 1)'
'2 (North - 1)' '2 (North - 1)' '1/1 (North - 1)'
[…]
'62 (West - 1)' '62 (West - 1)' '2/1 (West - 1)'
'63 (West - 1)' '63 (West - 1)' '2/1 (West - 1)'
;
; Thatcher-Harleman timelags
;
   2 ; use defaults
   000000000000000
   63    ; Number of overridings
          1     00000000000000   ; North - 1
          2     00000000000000   ; North - 1
```

```
          […]
         62     00000000000000   ; West - 1
         63     00000000000000   ; West - 1
ITEM
 '1/1 (North - 1)'
CONCENTRATIONS
   USEFOR 'IM101' 'IM101'
   USEFOR 'IM102' 'IM102'
   USEFOR 'IM103' 'IM103'
   USEFOR 'IM201' 'IM201'
   USEFOR 'IM202' 'IM202'
   USEFOR 'IM203' 'IM203'
   USEFOR 'IM301' 'IM301'
   USEFOR 'IM302' 'IM302'
   USEFOR 'IM303' 'IM303'


TIME LINEAR
DATA
'IM101' 'IM102' 'IM103' 'IM201' 'IM202' 'IM203' 'IM301' 'IM302' 'IM303';
[have to check when second location 02 is added]

2016/11/20-20:00:00  0.0000e+000  0.0000e+000  0.0000e+000 0.0000e+000
0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000;  frequentie
getallen deze regel moeten overeenkomen met frequentie substanties hierboven
2017/02/20-20:00:00 0.0000e+000  0.0000e+000  0.0000e+000 0.0000e+000
0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000
ITEM
 '2/1 (West - 1)'
CONCENTRATIONS
   USEFOR 'IM101' 'IM101'
   USEFOR 'IM102' 'IM102'
   USEFOR 'IM103' 'IM103'
   USEFOR 'IM201' 'IM201'
   USEFOR 'IM202' 'IM202'
   USEFOR 'IM203' 'IM203'
   USEFOR 'IM301' 'IM301'
   USEFOR 'IM302' 'IM302'
   USEFOR 'IM303' 'IM303'
TIME LINEAR
DATA
'IM101' 'IM102' 'IM103' 'IM201' 'IM202' 'IM203' 'IM301' 'IM302' 'IM303'

2016/11/20-20:00:00  0.0000e+000  0.0000e+000  0.0000e+000 0.0000e+000
0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000 ; frequentie
getallen deze regel moeten overeenkomen met frequentie substanties hierboven
2017/02/20-20:00:00 0.0000e+000  0.0000e+000  0.0000e+000 0.0000e+000
0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000 0.0000e+000
;
 #5 ; delimiter for the fifth block
;
; sixth block of model input (waste loads)
   0 ; no waste loads/continuous releases

;
 #6 ; delimiter for the sixth block
;
; seventh block of model input (process parameters)
```

```
;
CONSTANTS
; 72 - number of constants; handy to keep up to date
  'TauShields'
  'GRAIN50'
  'GRAV'
  'KinViscos'
  'RHOSAND'
  'RhoWater'
  'PORS2'
  'ThickS2'
  'MinDepth'
  'MaxResPup'
  'FactResPup'
  'VSedIM1'
  'TaucSIM1'
  'FrIM1SedS2'
  'FrTIMS2Max'
  'SWResIM1'
  'SWResusp'
  'VResIM1'
  'ZResIM1'
  'TaucRS1IM1'
  'TaucRS2IM1'
  'VSedIM2'
  'TaucSIM2'
  'FrIM2SedS2'
  'SWResIM2'
  'VResIM2'
  'ZResIM2'
  'TaucRS1IM2'
  'TaucRS2IM2'
  'VSedIM3'
  'TaucSIM3'
  'FrIM3SedS2'
  'SWResIM3'
  'VResIM3'
  'ZResIM3'
  'TaucRS1IM3'
  'TaucRS2IM3'
  'TaucRS1DM'
  'TaucRS2DM'
  'psedminIM1'
  'ACTIVE_VERTDISP'
  'ACTIVE_TOTDEPTH'
  'ACTIVE_DYNDEPTH'
  'CLOSE_ERR'
  'ScaleVDisp'
  'MaxIter'
  'Tolerance'
  'Iteration Report'
  'MaxIterations'
  'SwTauVeloc'
  'ONLY_ACTIVE'
  'ACTIVE_CalTau'
  'ACTIVE_Sed_IM1'
  'ACTIVE_S12TraIM1'
  'ACTIVE_Sed_IM2'
```

```
  'ACTIVE_S12TraIM2'
  'ACTIVE_Sed_IM3'
  'ACTIVE_S12TraIM3'
  'ACTIVE_DynDepth'
  'ACTIVE_S1_Comp'
  'ACTIVE_Veloc'
  'ACTIVE_Chezy'
  'ACTIVE_TotDepth'
  'ACTIVE_Res_Pickup'
  'ACTIVE_Sed_IM1'
  'ACTIVE_Res_IM1'
  'ACTIVE_Sed_IM2'
  'ACTIVE_Res_IM2'
  'ACTIVE_Sed_IM3'
  'ACTIVE_Res_IM3'
  'ACTIVE_S1_Comp'
  'ACTIVE_S2_Comp'
  'nothreads option'

DATA
 8.00000e-001; TauShields ; calibration parameter - look at bed shear
stresses in the model
 3.00000e-004 ; GRAIN50
 9.80000e+000 ; GRAV
 1.00000e-006 ; KinViscos
 2.60000e+006 ; RHOSAND
 1.02000e+003 ; RhoWater
 4.00000e-001 ; PORS2
 3.00000e-001 ; ThickS2
 1.00000e-002 ; MinDepth
 3.60000e+003 ; MaxResPup
 3.00000e-008 ; FactResPup
 8.60000e+001 ; VSedIM1     ; settling velocity of IM1 (m/day) - IM1 coars-
est - (calibration parameter)
 1.00000e+008 ; TaucSIM1 ; critical shear stress sedimentation IM1
 1.50000e-001 ; FrIM1SedS2
 1.00000e+000 ; FrTIMS2Max
 1.00000e+000 ; SWResIM1
 1.00000e+000 ; SWResusp
 1.00000e-001 ; VResIM1
 8.64000e+004 ; ZResIM1
 5.00000e-001 ; TaucRS1IM1; critical shear stress for resuspension from lay-
er S1 - IM1 - (calibration parameter)
 1.00000e+003 ; TaucRS2IM1; critical shear stress for resuspension from lay-
er S2 - leave it very high - we don't usually use
 4.30000e+001 ; VSedIM2  ; settling velocity of IM2 (m/day) - IM2 middle -
(calibration parameter)
 1.00000e+008 ; TaucSIM2 ; critical shear stress sedimentation IM2
 1.50000e-001 ; FrIM2SedS2
 1.00000e+000 ; SWResIM2
 1.00000e-001 ; VResIM2
 8.64000e+004 ; ZResIM2
 5.00000e-001 ; TaucRS1IM2 ; critical shear stress for resuspension from
layer S1 - IM2 - (calibration parameter)
 1.00000e+003 ; TaucRS2IM2 ; critical shear stress for resuspension from
layer S2 - leave it very high - we don't usually use
 2.10000e+001 ; VSedIM3     ; settling velocity of IM3 (m/day) - IM2 middle
- (calibration parameter)
```

```
 1.00000e+008 ; TaucSIM3 ; critical shear stress sedimentation IM3
 1.50000e-001 ; FrIM3SedS2
 1.00000e+000 ; SWResIM3
 1.00000e-001 ; VResIM3
 8.64000e+004 ; ZResIM3
 5.00000e-001 ; TaucRS1IM3 ; critical shear stress for resuspension from
layer S1 - IM3 - (calibration parameter)
 1.00000e+003 ; TaucRS2IM3 ; critical shear stress for resuspension from
layer S2 - leave it very high - we don't usually use
 1.00000e+003 ; TaucRS1DM
 1.00000e+003 ; TaucRS2DM
 1.00000e-001 ; psedminIM1  ; deposition efficiency - (calibration parame-
ter)
 0.00000e+000 ; ACTIVE_VERTDISP      ; all below this related to activated
processes; 1 is on 0 is off
 0.00000e+000 ; ACTIVE_TOTDEPTH
 0.00000e+000 ; ACTIVE_DYNDEPTH
 1.00000e+000 ; CLOSE_ERR
 1.00000e+000 ; ScaleVDisp
 1.00000e+002 ; MaxIter
 1.00000e-007 ; Tolerance
 0.00000e+000 ; Iteration Report
 1.00000e+002 ; MaxIterations
 2.00000e+000 ; SwTauVeloc
 1.00000e+000 ; ONLY_ACTIVE
 1.00000e+000 ; ACTIVE_CalTau
 1.00000e+000 ; ACTIVE_Sed_IM1
 1.00000e+000 ; ACTIVE_S12TraIM1
 1.00000e+000 ; ACTIVE_Sed_IM2
 1.00000e+000 ; ACTIVE_S12TraIM2
 1.00000e+000 ; ACTIVE_Sed_IM3
 1.00000e+000 ; ACTIVE_S12TraIM3
 1.00000e+000 ; ACTIVE_DynDepth
 1.00000e+000 ; ACTIVE_S1_Comp
 1.00000e+000 ; ACTIVE_Veloc
 1.00000e+000 ; ACTIVE_Chezy
 1.00000e+000 ; ACTIVE_TotDepth
 1.00000e+000 ; ACTIVE_Res_Pickup
 1.00000e+000 ; ACTIVE_Sed_IM1
 1.00000e+000 ; ACTIVE_Res_IM1
 1.00000e+000 ; ACTIVE_Sed_IM2
 1.00000e+000 ; ACTIVE_Res_IM2
 1.00000e+000 ; ACTIVE_Sed_IM3
 1.00000e+000 ; ACTIVE_Res_IM3
 1.00000e+000 ; ACTIVE_S1_Comp
 1.00000e+000 ; ACTIVE_S2_Comp
 1.00000e+000 ; nothreads option
;
PARAMETERS
; 2 - number of parameters
 'SURF'
 'bottomdept'
ALL
 ; parameters in binary file
BINARY_FILE  'demak.par'  ; binary file [have to check where this is created
and what it does]
; 0 - number of functions
SEG_FUNCTIONS
```

```
'TauFlow' ; name of segment function
ALL
BINARY_FILE 'demak.tau'  ; binary file
;
#7 ; delimiter for the seventh block
;
; eighth block of model input (initial conditions)
  0  ;
'restart_demak.map';
;
 #8 ; delimiter for the eighth block
;
; ninth block of model input (specification of output)
  1 ; output information in this file
  2 ; all substances and extra output
6 ; number of extra variables
  'Tau' ' '
  'TauFlow' ' '
  'Depth' ' '
  'SURF' ' '
  'LocalDepth' ' '
  'TIM' ' '
  2 ; all substances and extra output
6 ; number of extra variables
  'Tau'
  'TauFlow'
  'Depth'
  'SURF'
  'LocalDepth'
  'TIM'
 2 ; all substances and extra output
6 ; number of extra variables
 'Tau' ' '
 'TauFlow' ' '
 'Depth' ' '
 'SURF' ' '
 'LocalDepth' ' '
 'TIM' ' '
2 ; all substances and extra output
6 ; number of extra variables
 'Tau'
 'TauFlow'
 'Depth'
 'SURF'
 'LocalDepth'
 'TIM'

  1 ; binary history file on
  1 ; binary map     file on
  1 ; nefis  history file on
  1 ; nefis  map     file on
;
 #9 ; delimiter for the ninth block
;
; Statistical output - if any
;
 #10 ; delimiter for the tenth block
```

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