Utrecht University

Survival chance of young mussel beds during fall

Deijl, E.C. van der

31-3-2013

Universiteit Utrecht

MOSSELWAD

Survival chance of young mussel beds during fall

Assignment
MSC master research (30 ects)
University of Utrecht, Utrecht

Author
Eveline Christien van der Deijl (3361233)

Guidance
Donker, J.J.A.
Van der Vegt, M

Date
31 March 2013

Abstract

To increase mussel areal in the Dutch Wadden Sea, restoration or creation of mussel beds is considered. Because Mussel beds often not survive their first winter, project Mosselwad studies stability and restoration opportunities. In order to determine the most effective way to restore an intertidal mussel bed an experiment was performed. Mussel plots were created from mussels transplanted from edges of the mussel bed to uncovered areas in front and in the middle of the bed, 5 at each location. For each location 4 control plots were created at the same height on a bare area south of the mussel bed. The hypothesis is that the plots represent young mussel patches in fall. Sheltered from waves they are expected to prosper in the middle of the mussel bed, but they erode in the other areas.

The height variations of plots and their surroundings were monitored by a high resolution 3D laser scanner. Density changes were monitored by photographs, the bed stability by sediment samples and both the strength and direction of currents and waves by pressure sensors and velocity meters.

Over successive monitoring days, the change in height was small and there was little variation in hydrodynamic conditions. Plots at the bare sand bank were however influenced by the direction of currents and waves. The height increase over plots in the mussel bed was constant and the decrease in mussel coverage minimal. Decrease in mussel coverage was the largest for plots at the bare sandbank. For these plots was the bed stability the smallest.

Mussel patches inside the mussel bed, had a constant increase in height, a very small decrease in coverage and large bed stability and are considered to be most viable. Plots in front of the bed are however more viable than plots at the bare sandbank, which had a significant lower bed stability and a larger decrease in mussel coverage. Because mussel patches are more viable at a sheltered than at a new/bare location, it is recommended not to create new beds, but to restore the current mussel beds.

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1 Introduction

The Wadden Sea is a shallow inshore sea of approximately 6000km^2, which extends from the northern part of the Netherlands along Germany, to the southwest of Denmark. The Dutch part of the Wadden Sea, of approximately 3000km^2, lies in between the Dutch mainland and a series of barrier islands, which separates it from the North Sea (de Jonge et al., 1993). Before 1990 the Wadden Sea contained many littoral and sub littoral mussel beds, estimated at approximately 4000 ha (Dankers et al., 2003). Littoral mussel beds are located on tidal flats and can both be exposed and submerged during high water and low water. Sub littoral mussel beds lie in tidal channels and are always submerged (Mosselwad, 2008). In 1990 the amount of mussel beds however reached an all-time low due to intensive fishery of mussels, mussel larvae; and severe autumn storms (Dankers et al., 2004; Mosselwad, 2012).
Recovery and establishment of new beds is favourable, since mussel beds form an important class of characteristic structures with a habitat rich in organic matter and low in oxygen, which is favourable for other species (Commito and Rusignuolo, 2000). In mussel beds are high biomass densities found, combined with high species richness and high biochemical activity (Brinkman et al., 2002). Also are mussels an important part of the food chain, because many other species as eider ducks, oystercatchers, herring gulls, sea stars and crabs feed on them. The large decrease in mussel areal in 1990 therefore resulted in a high mortality of several specialised bird species (Beukema and Dekker, 2007). Mussels are however not only important for ecology, but also for management purposes. Sediment is stabilised by mussels (Dolch and Reise, 2010; Borsje et al., 2011) and current- and wave energy is reduced, because mussels are extra roughness elements. Both the stabilisation of sediment and decrease in flow and wave energy leads to protection of marshes and dikes (Borsje et al., 2011). Furthermore mussels are suspension feeders, which inhale water with suspended sediment and organic matter. The parts they can use for growth are taken up; the rest is excreted as faecal pellets. This excretion and deposition is called bio-deposition (Wotton and Malmqvist, 2001), it influences the sediment dynamics of the Wadden Sea. The decrease in mussel areal resulted in a change from a silty to a sandy Wadden Sea (Zwarts, 2004).
The importance of mussels as ecosystem engineers has been recognised by the Dutch and European governments, since national policies as Natura 2000 and international obligations due to the water framework directive, have led to the target of 2000 to 4000 hectares stable mussel beds present in the Wadden Sea (Dankers et al., 2003; Mosselwad, 2008). Restrictions to the intensive fishery in some areas of the Wadden Sea have resulted in recovery of some mussel beds. The development of the mussel beds is however far from optimal. Despite the presence of large amounts of mussel larvae, especially in the Western part of the Wadden Sea, no new mussel beds develop or survive their first winter period (Mosselwad, 2008). Nowadays there is still a shortage of 1000 to 2000 ha of mussel beds. The development of mussel beds by man is very expensive and many of the developed beds disappear, therefore the Mosselwad project has been initiated. The Mosselwad project tends to stimulate the sustainable restoration of the mussel beds in the Wadden Sea. EUCC-The Coastal Union, Wageningen IMARES, Utrecht University, SOVON en NIOZ work together to study the reasons for why almost no new stable mussel beds develop (Mosselwad, 2008).
By analysis of the current knowledge of mussels, their environment and the Wadden Sea, it is concluded that several factors limit the development of stable mussel beds. In total five hypotheses are given for the limited development of stable mussel beds (Mosselwad, 2008):

1. The food availability in the Wadden sea is too low, so the mussels die of starvation
2. Mussel seeds have a larger chance for survival when they settle down in a mature mussel bed and there are not enough mature mussel beds, so the mussel seed cannot survive.
3. Climate change or a decline in large fish species results in the fact that the amount of small predators as shrimps and crabs increase. These predators eat too much mussels and the beds cannot reach the stable amount of mussels, needed to survive.
4. The mussel seeds have to settle together in enormous amounts to be able to survive and create stable structures
5. Waves and wind or tidal currents limit the establishment of new mussel beds or erode the young mussel beds, since especially the last years the amount and magnitude of western and southerly storms has increased in the autumn.

Five hypotheses were given for the decrease in development of stable mussel beds. Utrecht University deals with the fifth hypothesis, therefore this thesis will focus on the development of young mussel beds during fall. This development comprises both the differences in height and composition of the mussel bed. It is the composition of the bed, which determines the stability of the bed, because the mussels are connected to the bed by byssal threads.

Mussels influence the sediment dynamics, both by bio-deposition and by forming a physical obstacle to the flow (Widdows et al., 2002; van Duren et al., 2006). They influence the stability of the bed by covering the sediment (Widdows and Brinsley, 2002), by increasing the organic matter and clay content (Grabowski et al., 2011) and by the creation of faecal pellets, which are more resistant to erosion than the original sediment (ten Brinke et al., 1995; Wotton and Malmqvist, 2001; Grabowski et al., 2011). Mussels however not only influence the hydrodynamics and sediment dynamics, these conditions are also of influence on the growth and stability of the mussels itself. Mussels filter phytoplankton out of the water column. Plankton concentrations are larger when flow velocities are larger, because plankton becomes resupplied by the flow (van Duren et al., 2006; van de Koppel et al., 2008). However when the velocities are too high, mussels are eroded (Donker et al., in press). Furthermore the location and submergence time of the mussel bed determines, how long and to what kind of predators the mussels are exposed. Therefore it can be concluded that mussels are in constant interaction with their environment, and especially with the hydrodynamic conditions.

The several interactions between mussels and their environment have been studied. Dankers et al. (2004) for example examined the formation and disappearance of mussel beds in the Wadden Sea. During the study the size and coverage of several mussel beds was monitored. The weather conditions were used to forecast the disappearance of mussel beds. The relation between weather conditions and mussel survival was very weak. For this research there were however no measurements of the hydrodynamic conditions at the mussel beds itself, which would have made it easier to make predictions, or give the reasons for the disappearance afterwards of the winter period.

Grabowski et al. (2011) examined the erodibility of the sediment as a function of composition and biomass. The influence of mussels on sediment is however not mentioned directly. Others have shown the effect mussels have on the sediment composition, for example: Flemming and Delafontaine (1994), ten Brinke et al. (1995), Wotton and Malmqvist (2001) and van Leeuwen et al. (2010). In their articles possible effects of mussels on the sediment composition are mentioned, but not quantified or linked to erosion or sedimentation.

Stability of the mussels itself has been studied too. Most of these studies took however place in flumes in the lab, for example: Widdows et al. (2002), van Duren et al. (2006) and Folkard and Gascoigne (2009); or were based on model results, as was the case for the study of van Leeuwen et al. (2010). Lab and model studies are approximations of the natural situation. It is better to study mussels in their natural environment, so in the field, where all conditions are present. This makes it however very difficult to indicate and quantify all variables of influence. Until recently it has for example not been possible to link short term variations in the hydrodynamic conditions to variations in the sediment dynamics. Due to strong vertical gradients in the sediment composition over the water column it is very difficult to measure the sediment concentrations in shallow water. Furthermore it was not possible to determine changes in the bed level very accurate. Nowadays however a laser scanner can be used to determine changes in height in 5mm accurate (RIEGL laser measurement systems, 2013).

1.1 Problem definition

To increase mussel areal, two options are under consideration: creation of new mussel beds or restoration of damaged ones. Until now newly created mussel beds experienced erosion, but this erosion was not studied, because changes in height and thus erosion of the mussel beds could not be monitored very accurate. Nowadays there is however 3D laser scanner.

Mussel beds are in constant interaction with the hydrodynamic conditions and the resulting sediment dynamics. The several interactions have been studied separately or in the lab, but not all together in the field. In the field it is not possible to exclude some conditions. Therefore it is important that these conditions are all monitored. Only when the changes in height, bed stability and the different hydrodynamic conditions are monitored, it becomes possible to identify whether it are indeed the hydrodynamic conditions, which influence the survival chance of young mussel beds and to see whether there are proper locations at which mussel beds can survive.

1.2 The research objective and research questions

During summer, newly developed mussel beds are stable and outliving. A large part of these new mussel beds however not survives their first winter. The objective of this research is to find out when the young mussel beds are more viable and have a larger chance of survival during winter. The coverage, height and composition of a young mussel bed can be used to determine the survival chance of the mussel beds. It is fall, which forms the transition from the calm conditions during summer, to more rough conditions of winter. During fall the mussel beds will start to show adaptation to the more rough conditions. Therefore it is the condition of the mussel bed after fall, which can be used to indicate the survival chance of that bed during the winter. To determine this survival chance, the following research question has been raised:

What are the sediment dynamics around young mussel beds during fall?

The sediment dynamics in this question includes both the composition (stability) and the change in height of the mussel bed. These sediment dynamics are however strongly related to the imposed hydrodynamic conditions. Therefore the following sub questions will be used to come to an answer on the main question:

1. How does the height of the mussel bed and of the individual mussels evolve during the several hydrodynamic conditions that occur during fall?
2. In what way does the composition and thus stability of the bed change?
3. What is the consequence of differences in bed stability, patch height and mussel height for the further survival chances of the mussel bed during winter?

1.3 Outline of this thesis

This thesis is based on both a literature research and on the results of a fieldwork period. Chapters 2 to 4 will give some more in depth information about sediment transport, the blue mussel and the relation between these two. In chapter 5 hypotheses are given for the sub questions, mentioned in the former paragraph. Then in the second part of the report the methodology and results of the fieldwork period are given. In chapter 6 the material and methods of the fieldwork are described, followed by the results in chapter 7. The results are discussed and coupled back to the hypotheses and theoretical information, in the discussion in chapter 8. Finally in chapter 9 the research questions are answered and a conclusion and proposal for management of mussel beds is given.

2 The Blue Mussel (Mytilus Edulis)

Mussels live in mussel beds, because mussels rarely live alone, but form colonies (van Leeuwen, 2008). It is stated that the amount of stable mussel beds has reached an all-time low in 1990. What is however a mussel bed and when is that mussel bed stable? This chapter will give an answer on these questions by giving first the definition of a mussel bed and secondly an analysis of the blue Mussel, which is the most common mussel in the Wadden Sea.

2.1 The definition of a mussel bed

A colony of mussels is not always called a mussel bed. To come to a better monitoring program in The Netherlands, it was decided to create an uniform definition for a mussel bed. The definition translated from the Dutch is as follows (Brinkman et al., 2003): "A mussel bed is a benthic community in which mussels are dominant and which consists of a clearly defined area of large and small patches of mussels, rising above the surrounding area and separated by open spaces." In this definition the presence of small patches of mussels is mentioned, since mussel beds are not always continuous. The definition is however not yet complete. Dankers et al. (2003) expanded the definition by defining that mussel patches are only part of a mussel bed, when the distance between patches is no more than 25m.

2.2 The stability of a mussel bed

Mussel beds are often considered to be stable, when they are present over a large period. The stability of a mussel bed can however be analysed by all of the following criteria (Brinkman et al., 2003):

- Age: a young bed with only mussel larvae or very young mussels is instable, while an older bed is more stable
- Coverage: when the percentage of coverage by mussels is high and when also young mussels are present in the bed, then will the bed during the next years often have a high percentage of coverage too.
- Structure: when patches of mussels are closer together, they can protect each other to the impact of waves
- Age structure: a mussel bed with mussels of different ages, indicates that the bed is able to stay stable, because dead old mussels are replenished by younger ones
- Stability and structure of the bed: when the bed is stable and compacted, the anchorage of the mussels by threads is much more stable than when the bed consists of loose material
- Location of the mussel bed: the location of the mussel bed determines whether the bed receives enough food; whether it is prone to large or small currents and waves; and too large or small rates of predation.

Following these criteria, it can be stated that the stability of a mussel bed is determined by the ability of the bed to rejuvenate and to sustain at the location where the mussel bed is established. Therefore these factors will be addressed extra attention in the third and fourth paragraph of this chapter.

2.3 Anatomy

The Blue Mussel is a bivalve animal, with a long triangular shell, which can in general become up to 8 cm long (Delbare, 2005) . The shell is smooth and has concentric and sometimes radial lines, but it is not ribbed (van Leeuwen, 2008). Furthermore the shell often has a blue or blackish colour (Delbare, 2005). Since the mussel is a bivalve animal, the shell consists out of two mantels, which can be both opened or closed. At the hinge between the two mantels, the foot of the mussel is present, which the mussel can use to move. The ability of movement however decreases with age (Dankers et al., 2004) and the amount of byssal threads present. The byssal threads are very sticky threads, which are excreted by a glance in the foot (Delbare, 2005; Moeser et al., 2006). They provide the mussel a strong connection with the bed or other mussels (Delbare, 2005; van Leeuwen, 2008).
When the two mantels of the mussel are opened, water can be inhaled in the gut/gill system of the mussel. Mussels are suspension feeders, because they filter water in the water column. When the mussels filtrate the water, they ingest among else sediment and phytoplankton.

This ingestion rate of sediment and phytoplankton increases with increasing phytoplankton concentrations, until the maximum ingestion threshold is reached. This threshold depends on water temperature and food quality (ten Brinke et al., 1995). The filtrated material comes into the gut of the mussels, where abrasion, changes in pH and the action of enzymes break down the organic matter into more labile compounds, which can be taken up by the cells of the mussels (Wotton and Malmqvist, 2001). Mussels however only need phytoplankton and other organic material for growth and reproduction. The parts of the ingested material which are not taken up by the cells are repacked and excreted as faecal pellets. However when the ingestion threshold is reached, no more filtered material can be ingested and enter the gut so it becomes excreted as pseudo faeces. The outside anatomy and the filter system of the blue mussel are shown in Figure 2-1.

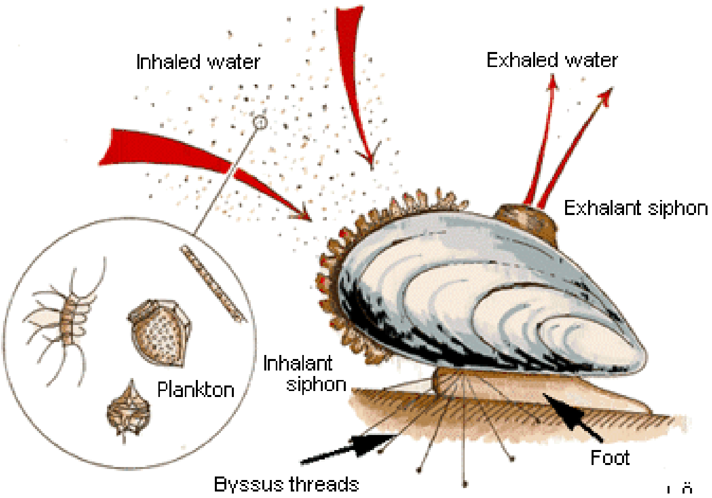

Figure 2-1 Respiration and nutrition of a common mussel (Mytilus Edulis) (Aquascope, 2001)

2.4 Reproduction

Mussels have a very opportunistic reproduction mechanism. Per animal, often in the months May to June, more than a million eggs are produced (Brinkman et al., 2002 ; Brinkman et al., 2003). These eggs develop to mussel larvae, which start to search for a substratum, when they have a length of approximately 0.2mm and have developed one small triangular shell. Larvae are transported by the flow, so the hydrodynamics of the Wadden Sea determine whether the larvae can settle on substrate. The larvae often settle at places where the depth and thus the flow velocity decreases or at places where a watershed is located, since at those locations low velocities occur, so the larvae can sink to the bottom (Dankers et al., 2003). The larvae prefer hard or other strong substratum, therefore they can choose to be lifted off by the flow again and reach other locations. Only a very small amount of the larvae indeed settles and the amount of good substratum present determines how much of the larvae will be able to become strongly connected to the subsoil and protected to erosion (Brinkman et al., 2003). The Wadden Sea however has a limited amount of hard substratum, because the sea consists mainly out of muddy intertidal flats and sandy tidal channels (Andersen et al., 2005; van Leeuwen, 2008). Before 1990 were however many stable mussel beds present in the Wadden Sea, which indicates that mussels are able to survive on the softer substratum. The survival of the mussels on softer substratum is among else possible due to the interconnection between the mussels itself and by the presence of older mussel shells and more coarse sediment in the bed.

2.5 Survival

When mussel larvae are settled, new factors as food availability, predation and resistance to erosion start to determine the survival chance of mussels (Dankers et al., 2003). These factors are related to the hydrodynamic conditions around the mussels. Currents supply phytoplankton, which serves as a food source for mussels. When currents are stronger, more phytoplankton becomes replenished. When only a small current over the mussels is the case, depletion of phytoplankton in the boundary layer takes place (van Duren et al., 2006; van de Koppel et al., 2008). When not enough food is available, mussels stop to grow or even die. The effect of depletion of phytoplankton is therefore often visible by a decrease in mussel density in shoreward direction. Food availability at the most seaward edge is larger, because at that location no depletion has occurred yet. At the seaward edge are however much stronger hydrodynamic conditions, since the currents and waves have not yet been affected by the mussel bed. Therefore the mussels at the seaward edge have to be stronger and more resistant, because they will otherwise experience erosion (Donker et al., in press).

Mussels produce byssal threads for a connection with other mussels or bed sediment. When the density of a mussel patch is large, mussels are more connected with each other than with the bed, while for lower densities the connection with the bed is much stronger, since more byssal threads are connected to the bed (Meadows et al., 1998; Widdows et al., 2002). This means that especially for higher densities, the erosion of mussels often occurs by detachment of complete patches and not by detachment of individual mussels.

The strength of the mussel attachment is determined by both the amount of byssal threads, the mechanical quality of threads and the rate at which treads decay (Meadows et al., 1998; Moeser et al., 2006). Byssal threads can be influenced by many factors as salinity, oxygen, water flow, wave action, water temperature, food supply, predators and the presence of metals needed for the building of the thread. Variations in the attachment strength are controlled by the availability of resources, energy needed to increase the attachment strength; and the need to increase the attachment strength (Donker et al., in press). For increasing velocities up to $10cms^{-1}$ thread production increases, but the production starts to decrease when the velocity further increases. This is the case, because the foot of the mussel has no connection with the bed for higher flow velocities. The production of threads is however especially influenced by the water temperature, followed by the wave height. The relation of thread production with temperature, can however be as strong as it is, because other mechanisms, which also influence the tread production (for example nutrient abundance and salinity), also vary with temperature (Moeser et al., 2006). Because of the strong relation with temperature, most threads are produced during summer and fall. Typically 5 to 40 threads a day can be produced by an individual mussel (Meadows et al., 1998). In fall the strength of the threads is however the weakest and least extensible, while the strength and the extensibility is intermediate during winter and summer. Threads produced in the spring are 1.6 to 2.4 times stronger and almost twice as extensible compared to threads produced in other seasons. Furthermore the quality of the threads is the weakest during fall, when the water temperature is the highest. Also is the strength of the threads influenced by the food availability (Moeser and Carrington, 2006).

Threads become less strong and extensible after 19 days. Therefore most threads are decayed or break within four weeks after their formation. The maximum observed lifespan is nine weeks (Moeser and Carrington, 2006). In summer the decay of threads is the largest, but then the production is the highest, which compensates the large rate of decay (Moeser et al., 2006). More treads break and decay during fall and winter, because the initial strength and length of the threads is lower and threads have to withstand higher forces.

To conclude: not only the settling of the mussels, but also the survival after settling, is strongly dependent on water temperature, hydrodynamic conditions, food availability and the strength of the substratum they are attached too. Fortunately mussels are able to influence two of these factors: the hydrodynamic conditions and strength of the substratum.

3 Sediment dynamics

The height of a mussel bed increases when the bed becomes older, since deposition takes place in the bed (van Leeuwen et al., 2010). The sediment budget over a young stable mussel bed is thus positive. The budget is determined by the gradient in sediment transport over the mussel bed. Sediment transport consists out of three phases: (1) entrainment of sediment; (2) transport (bed load or suspended load) by the fluid; and (3) settling and deposition of sediment (Masselink and Hughes, 2003). This chapter describes these three phases. Secondly the stability of sediment is discussed.

3.1 The three phases of sediment transport

3.1.1 Sediment entrainment

Entrainment takes place, when forces acting on sediment are out of equilibrium; otherwise the sediment stays in its rest position at the bed. The forces involved are lift, drag, weight and cohesion (van Rijn, 1993; Masselink and Hughes, 2003). The lift force arises due to faster flow over the top, than along the lower part of grains, which creates a pressure differential over the grains. Drag forces arise due to skin friction between the fluid and grains. These two forces are thus interactions between grains and the fluid. They act directly on the surface of grains (Paterson and Black, 1999). A grain starts to move when lift and drag forces (shear stress) together are larger than the gravitational force, which arises due to the mass of the grain; and the attraction force between the grains, the cohesion (Paterson and Black, 1999; Masselink and Hughes, 2003). The shear stress at which grains start to move is the critical bed shear stress.

The gravitational force of the grain is easy to quantify by the medium grain size (d50) and sediment density (ρ), but it is difficult to quantify the drag and lift forces. Therefore the flow conditions which are needed to create the drag and lift forces and the initiation of motion, are not easy to predict. These flow conditions are therefore often predicted by data from numerous laboratory experiments (van Rijn, 1993).

When the water depth is relatively small, waves influence the entrainment too. The cyclic character of a rise and fall in water level creates an orbital motion. A particle under the crest of the wave moves forward, while it moves backwards under the through (van Rijn, 1993). This creates turbulence and entrainment of sediment.

In intertidal areas the water depth varies due to the rise and fall in water level. Because of the linear relationship between the maximum wave height and the water depth, it is especially during high water, that waves produce a net increase in the amount of sediment, which becomes entrained. When the water level is low, waves are lower too and will entrain less sediment and the entrainment is mainly controlled by currents (Bassoullet et al., 2000).

3.1.2 Sediment transport

When sediment is entrained, it can be transported. Transport can occur as bed-load or suspended-load, depending on the size of the particles and flow conditions. Particles will start rolling and sliding in continuous contact with the bed, when the value of the bed-shear stress just exceeds the critical bed shear stress (van Rijn, 1993) but they show jumps/saltation's for increasing values of the bed shear stress. When the fall velocity of a particle is exceeded by the bed shear stress, suspended sediment transport can take place, because particles are then supported by turbulence of the fluid (van Rijn, 1993; Masselink and Hughes, 2003).

3.1.3 Sediment deposition

Sediment deposition takes place, when the gravitational force of a grain becomes larger than the drag and lift forces exerted by the flow (van Rijn, 1993). This is the case when the flow velocity and thus the shear stress decreases. At that moment the bed load transport stops. The particles transported in suspension are further away from the bottom and thus have to settle over a distance. Therefore it takes more time to settle and a time lag is present between the moment the shear stress decreases and the moment of deposition (van Leeuwen, 2008). The settling time is dependent on the size, density and shape of the grain; and by the sediment concentration, because particles can hinder each other during settling (van Leeuwen, 2002; Winterwerp and van Kesteren, 2004).

3.2 The sediment stability

The rate of sediment transport is among else determined by the characteristics of the sediment, since these characteristics determine the sediment stability. In general it is stated that the critical bed shear stress can be quantified by the medium grain size (d50) and sediment density (ρ). These factors are both physical. There are however also other factors of influence on the bed stability. These factors can be physical, geochemical and biological (Widdows et al., 1998; Lundkvist et al., 2007; Grabowski et al., 2011) and will be discussed in this paragraph.

3.2.1 Physical factors

Physical factors influence the bed stability by a change in the size or quantity of sediment constituents (Lundkvist et al., 2007; Grabowski et al., 2011). Two physical factors which influence the sediment stability have already been mentioned: the medium grain size and the sediment density. The water content and temperature are however also of influence.
The grain size division of the sediment is the most recognised factor for the bed stability. It is more easily to erode fine than coarse sediment. When however the clay content increases to a percentage of 30 to 50%, the bed becomes more resistant to erosion. The addition of clay creates a larger adhesion force between the grains; furthermore the clay fills in the pores between the sand, so the bed surface becomes smoother and more difficult to erode (Houwing, 1999; Grabowski et al., 2011). When however the clay content exceeds 50% the main grain size becomes very small and the sediment is easier to erode. This is especially caused by a decrease in the bulk density. The bulk density is determined by the particle density, the density of the water in the pores and the presence of air or other gasses. Beds with denser sediment have higher erosion thresholds and lower erosion rates. The density of clay is low, because the water content in unconsolidated clay is high. When the water content decreases due to compaction and consolidation, the density of the bed increases. Therefore have compacted clays a larger resistance to erosion. This effect of the water content is less or not apparent for the larger grain size regions, since the larger grain sizes cannot compact as much as clay can. A decrease in water content will then mainly be caused by an increase of air in the pore spaces. The Postma diagram, as shown in Figure 3-1, shows the relation between the threshold for erosion; transport and deposition; and the grain size and water content of the bed sediment.

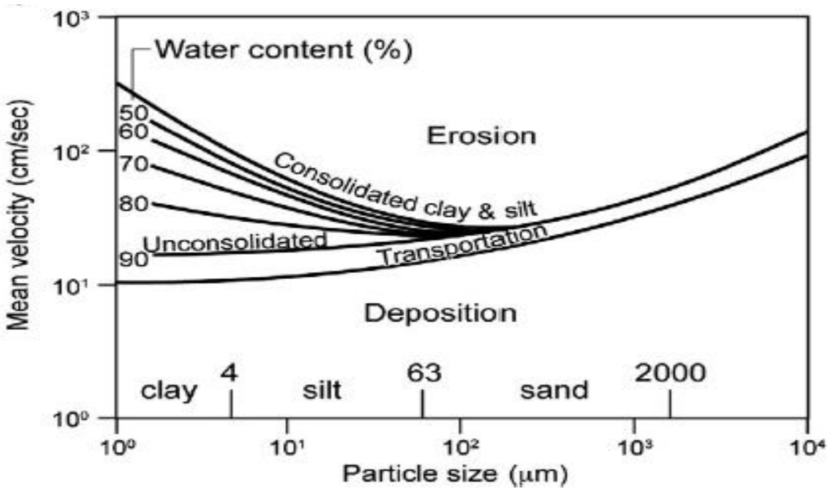

Figure 3-1 The Postma diagram for the threshold of erosion and deposition according to average particle size and water content. Redrawn from Dade et al., 1992 (Grabowski et al., 2011)

The last physical factor of influence on the sediment stability is the temperature, but this effect has not directly been investigated.

3.2.3 Geochemical factors

Geochemical factors influence the stability of sediment too. The clay mineralogy, the water chemistry and organic matter content are geochemical properties of sediment, which determine the stability of that sediment, because they influence the electrochemical attraction between soil particles (Grabowski et al., 2011).

The clay mineralogy is used to describe the type of clay minerals. In total three groups of clay minerals are present. These groups are based on the size and the electro-chemical activity of the minerals and include the kaolinites, micas and smectites respectively. The size and electro-chemical activity of the clay minerals determine the attraction between the minerals, therefore the groups can be sorted on erodibility. Smectite clays have the highest erodibility, followed by micas and kaolinite (Grabowski et al., 2011).

The water chemistry is the second geochemical factor, which influences the stability of the bed. The presence of dissolved ions, the pH and the metal content can all influence the stability of the bed (Paterson and Black, 1999; Grabowski et al., 2011), but it is not expected that they will be influenced by mussels. The effect of the organic matter content of the water and sediment is however important, because mussels are suspension feeders and filter phytoplankton out of the water. In general it is stated that organic matter stabilises cohesive sediment by adhesive effects (Paterson and Black, 1999), since it influences the inter-particle attraction. Therefore is sediment with less than 2% organic matter considered as erodible and is assumed that the erodibility decreases with an increasing organic matter content, up to 10% (Grabowski et al., 2011)

3.2.4 Biological factors

Biological factors are the most interesting for this report, because mussels are living organisms. Biological factors can alter both the sediment surface and the structure and composition of the sediment. The organisms can be organized in three groups: bio-turbators, bio-stabilisers and bio-destabilisers respectively:

- Bio-turbators modify the physical properties of the sediment, by for example burrowing or bulldozing (Grabowski et al., 2011).
- Bio-stabilisers influence their physical environment, because they reduce tidal currents, wave action, sediment resuspension and turbidity. Furthermore do they enhance the sedimentation and cohesiveness of the bed sediment (Widdows and Brinsley, 2002).
- Bio-destabilisers increase the erosion and resuspension of sediment and increase the turbidity by an increase in the bed roughness. Furthermore they graze on bio-stabilisers and produce faecal pellets (Widdows and Brinsley, 2002).

The division of organisms in the three groups, mentioned above, is very difficult, since an organism can have both stabilising as destabilising impacts on the bed.

4 The influence of mussels on the sediment dynamics

As mentioned in chapter 3 is the magnitude of sediment transport determined by both the hydrodynamics as the stability of the sediment. Mussels are able to influence both. This chapter will identify interactions between mussels and sediment; and between mussels and the hydrodynamic conditions to see in what way mussels are able to change the sediment dynamics of the Wadden Sea. First the effect of the suspension feeding mussels will be described. Secondly the effect of mussels on hydrodynamic conditions will be indicated, followed by the effect of mussels on the sediment dynamics.

4.1 Mussels as bio-depositors

As mentioned in paragraph 2.3, mussels are suspension feeders, which filter the water in the water column. Mussels inhale water with suspended sediment and organic matter. A part of this becomes ingested in the gut, until the ingestion threshold is reached. The parts of the ingested material which the mussel cannot use for growth and reproduction, become repacked and excreted as faecal pellets. Faecal pellets are much larger aggregates than the original ingested sediment. Therefore they behave different in the water column. Pellets often travel as bed load and are soon deposited (Wotton and Malmqvist, 2001). Deposition can even take place at locations where normally the wave or current energy is too high to promote sedimentation (Flemming and Delafontaine, 1994). When faecal pellets are deposited, they are more resistant to erosion than the original ingested sediment (ten Brinke et al., 1995; Wotton and Malmqvist, 2001; Grabowski et al., 2011), because they are formed by repacking of the particles and bound together by mucous or covered with an organic coating (Wotton and Malmqvist, 2001).

The part of the sediment that is not ingested, because the maximum ingestion rate has already been reached, is immediately rejected as pseudo faeces. These pseudo faeces have a higher erosion rate, since they are lighter and thus easier to erode (ten Brinke et al., 1995; Wotton and Malmqvist, 2001; van Leeuwen et al., 2010).

By the active removal of suspended particles from the water column, mussels influence the particle size distribution in both the suspended load as in the bed sediment (Grabowski et al., 2011). The ingestion rate depends on temperature and food quality, therefore mussels filtrate more water during spring and summer than during fall and winter. Especially during the months May to September, water temperatures are higher and large rates of bio-deposition occur (Kautski and Evans, 1987). Therefore bio-deposition rates are much larger during spring and summer (Flemming and Delafontaine, 1994; ten Brinke et al., 1995). Erosion of bio-deposited material is larger during fall and winter, because of high energetic hydrodynamic conditions. A part or all of the bio-deposited material is eroded again (Flemming and Delafontaine, 1994). Bio-deposits have a critical threshold for resuspension of $0.2 ms^{-1}$, below this threshold bio-deposition is larger than erosion, but above this threshold net erosion occurs (Widdows and Brinsley, 2002). This means that during spring and summer a part of the bio-deposited material will be resuspended, when the erosion threshold is reached. Furthermore is also a part of the bio-deposition broken down by bacteria or ingested by other organisms, which prefer to live at locations where bio-deposition takes place, because the concentrations of organic matter are large over there (Wotton and Malmqvist, 2001). The breakdown by bacteria occurs faster in summer, when temperatures are higher, and favourable for bacteria (Kautski and Evans, 1987). This results in a 5 to 10cm thick layer of sediment containing 20 to 30% faecal pellets in area's surrounding suspension feeder aggregations (ten Brinke et al., 1995). The faecal pellets enhance the cohesiveness of the bed, since they contain especially small particles and organic matter, which enhance the stability of the bed (explained in paragraphs 3.2.1 and 3.2.2). In general the amount of bio-deposited material in the bed depends on the weather and resulting hydrodynamic conditions (Flemming and Delafontaine, 1994).

4.2 Mussels in interaction with the hydrodynamic- and sediment processes

To explain the influence of mussels on the hydrodynamic conditions of the Wadden Sea, first a short analysis of the hydrodynamic conditions without mussels will be given. Secondly the effect of mussels on that situation will be described.

4.2.1 The influence of mussels on the flow profile

In the Wadden Sea are currents mainly determined by the magnitude and direction of the tidal wave. The tidal wave has both a horizontal and a vertical component. The vertical component comprises the water level variation and the horizontal component represents the current (Kragtwijk, 2001; Wang et al., 2012). When the tidal wave propagates through the Wadden Sea, the tidal current experiences friction by the bed. The friction initially only influences the fluid motion in direct contact with the bed, but over a longer distance the effect of friction rises in the flow profile (Masselink and Hughes, 2003). The part of the flow profile directly influenced by frictional effects is the boundary layer (Boudreau and Jørgensen, 2001; Masselink and Hughes, 2003; van Rijn, 2011).

Due to the effect of the friction, the flow velocity profile in the boundary layer is assumed to be logarithmic. The profile can be represented by the law of the wall, which is applicable when roughness elements are relatively small, so only viscous drag shapes the velocity profile (van Duren et al., 2006). Below the logarithmic layer, the viscous sub layer is present. This layer is only a few centimetres thick and develops, when internal friction in water rivals with eddy mixing. Below the viscous sub layer often a diffusive boundary layer or diffusive sub layer is present, which is only a few millimetres thick. In this layer molecular diffusion exceeds eddy diffusion (Boudreau and Jørgensen, 2001). The height of the viscous sub layer and the diffusive sub layer decreases and they disappear when the bed becomes rougher and turbulent flow develops (Nowell and Jumars, 1984).

The flow profile is however not only influenced by the tidal currents, but also by waves. The orbital motion of the waves, can either oppose or enhance the tidal current. During each wave cycle a new boundary layer grows and decays twice, under the crest and under the through respectively. This new boundary layer, also called the oscillatory or wave boundary layer, develops inside the boundary layer, produced by the tidal current. The layer is very thin, because the flow direction changes, by the oscillatory flow, before the boundary layer can grow in height. Since the oscillatory boundary layer is relatively thin, the bed shear stress for a given free-stream velocity will be larger under oscillatory flow than under steady flow conditions (Nowell and Jumars, 1984; Masselink and Hughes, 2003; van Rijn, 2011).

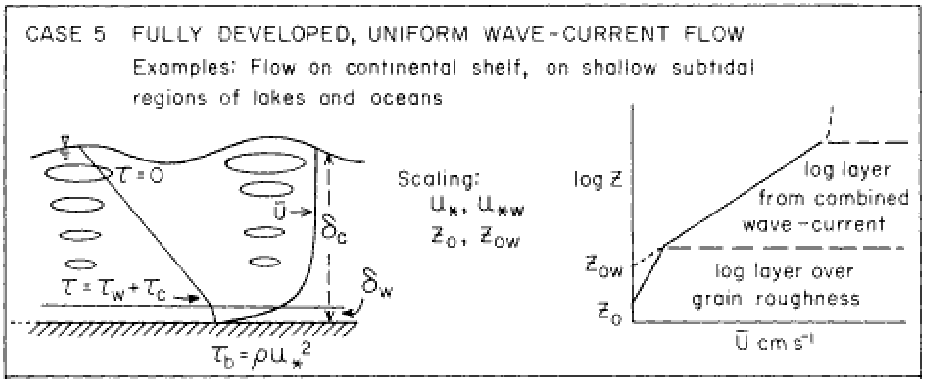

Figure 4-1 The fully developed profile for uniform wave-current flow (Nowell and Jumars, 1984)

Mussels increase the bed roughness and thus alter the drag force of water (Widdows et al., 2002; van Duren et al., 2006). Due to extra bed roughness the turbulence of the flow increases. The increase in turbulence is enhanced since mussels are suspension feeders and emit vertical jets of filtered water (Folkard and Gascoigne, 2009).

The increased turbulence creates over the mussel beds, instead of a viscous sub layer, a small turbulent boundary layer, in which complex and non-logarithmic velocity profiles are present (Widdows et al., 2002; Folkard and Gascoigne, 2009). Van Duren et al (2006) however state that mussels can be both open and filtering or closed and inactive. Therefore differences in the flow profiles exist between the case with open and filtering mussels and the case with closed inactive mussels. When mussels are closed and inactive, a nice new (internal) boundary layer of around 4cm develops within the logarithmic layer of the already present boundary layer, while there is none or a masked internal boundary layer when the mussels are filtering (van Duren et al., 2006). The results of van Duren et al., 2006 are however based on flume experiments, with currents only. A mussel bed with constant density was used, so it was possible that the lower part of the water column was able to adapt to the new roughness conditions. This is not the case, when the mussels are filtering and inactive, because then extra turbulence results in constant changing conditions. Therefore no clear new internal boundary layer can develop and a turbulent boundary layer is present

Increased roughness and turbulence, decreases the current velocity (Widdows et al., 2002). The decrease in current velocity is especially apparent close to the mussels, so an sharp increase in the velocity gradient of the flow profile develops. This effect is however more apparent for low and intermediate flow velocities than for high flow velocities (van Duren et al., 2006).

Due to increased friction and turbulence, mussels not only reduce flow velocities, the wave energy decreases too. Both the wave height and orbital velocity decreases, so higher rates of sedimentation take place (Ragnarsson and Raffaelli, 1999). Therefore mussels can be seen as bio-stabilisators, which protect the bed sediment by a decrease in the flow velocity and wave energy; and an increase in sedimentation (Widdows and Brinsley, 2002)

4.2.2 Flow and sedimentation around an obstacle

Mussels interact in several ways with hydrodynamic processes. The most apparent interaction is that mussels act as a physical obstacle to the flow (van Duren et al., 2006; Folkard and Gascoigne, 2009). The water layer, which comes in contact with an obstacle is the shear layer, because this layer experiences the shear stress between the flow and the obstacle. Figure 4-2 shows that in the shear layer streamwise voritices develop due to the precense of an obstacle. These vortices influence the recirculation region and recovery region downstream of the obstacle, (Martinuzzi and Tropea, 1993).

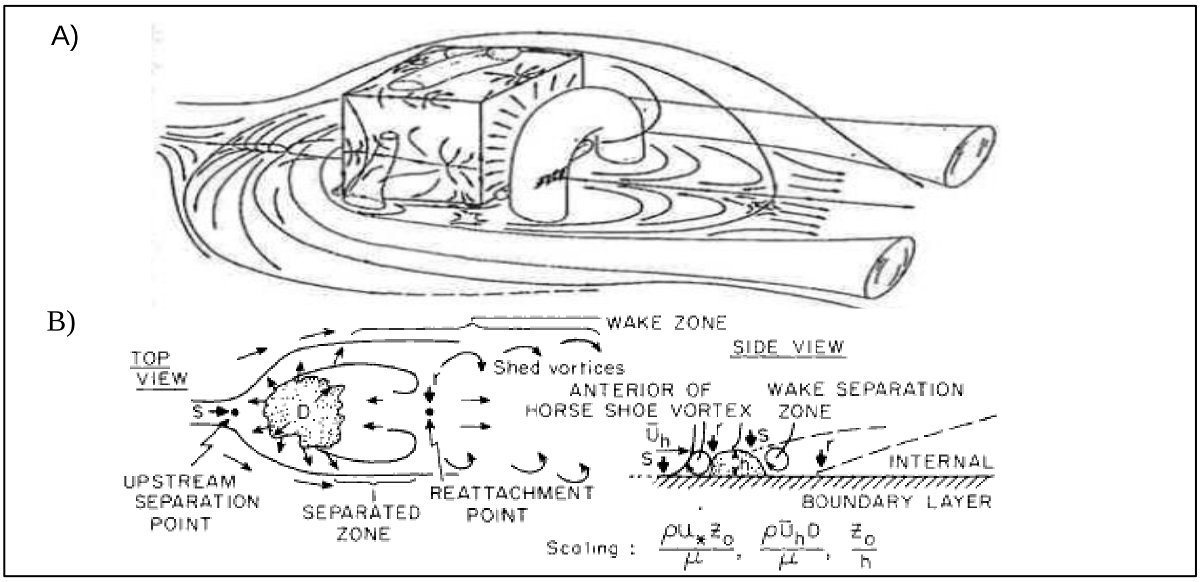

Figure 4-2 Flow around an obstacle. A) Shows the vortices (Martinuzzi and Tropea, 1993)*, B) shows the reattachment and development of a new internal boundary layer* (Nowell and Jumars, 1984)

In front of the obstacle a serie of vortices can be present too. When the width/height (W/H) ratio of an obstacle is large, these vortices start to move over the obstacle. When the W/H ratio is small, a separation point develops in front of the obstacle. A part of the flow and vortices moves over the obstacle, but another part is forced along the sides. Behind the obstacle is then a horseshoe vortex present, because the upstream circulation of the vortices moving along the sides and top of the obstacle, reaches the leeside of the obstacle. The pressure gradient at the leeside is only small, so the upstream recirculation of the vortices becomes easier (Martinuzzi and Tropea, 1993).

At some point behind the obstacle the flow starts to reattach again. The lee effect decreases with distance, due to the imput of energy by both the vortices moving along the sides and top. After the reattachment point a new internal boundary layer can start to develop (Nowell and Jumars, 1984). The point at which the flow starts to reattach again is also determined by the W/H ratio of the obstacle. For obstacles with a smaller W/H ratio more water flows along the sides of the obstacle and the flow attaches earlier than when only water moves over the obstacle, as is the case for obstacles with a large W/H ratio (Martinuzzi and Tropea, 1993).
When obstacles occur in clusters, as is the case in a mussel bed, the density of the obstacles is very important. The density determines the amount of water which can flow through the cluster of obstacles and is not forced over or along the cluster. Several flow conditions can be distinguished for flow over a bottom with obstacles that intrude into the water column (Bouma et al., 2007):

- Independent flow: the spacing between the obstacles exceeds the height of the obstacle, so the interactions between the wake of neighbouring structures is absent
- Skimming flow: the spacing between the obstacles is smaller or equal to the height of the obstacle and at least one twelfth of the bottom is covered with the obstacles. This results in the development of three flow regions: (1) a boundary layer above the obstacle, (2) a mixing layer around the top of the obstacle and (3) flow in between the obstacles, dominated by vortices (Nowell and Jumars, 1984; Bouma et al., 2007)

Skimming flow is often the case, when the obstacle density within a cluster is large. For the higher densities the decrease in flow velocity inside the cluster with obstacles is larger than for lower densities, since more vortices are present. The developing boundary layer on top of the obstacles is clearer for larger densities. This effect of a total decrease in flow velocity is more apparent for higher flow velocities. (Bouma et al., 2007)
When the flow velocity inside a cluster with a high density decreases, the lift and drag force of the flowing water will decrease too, resulting in deposition of the particles with high gravitational forces. This means that a small decrease in flow velocity can result in deposition of coarse or even finer particles, depending on the original flow velocity. Also in the wake deposition occurs, because the upstream returning vortices at that location result in a decrease in flow velocity and thus deposition. At the front, at the sides and after the wake of the cluster, erosion takes place, due to scouring effects of the vortices and increasing velocities. (Meadows et al., 1998; Bouma et al., 2007; van Leeuwen et al., 2010)
It is difficult to apply this information of flow around an obstacle directly on a mussel bed, since a mussel bed consists of several groups and clusters of obstacles. First off all there is the risen bed, which forms one large obstacle. Because the bed has risen and no through flow can occur, the flow is forced over the top or along the sides of the bed. This means that the mussel bed is a large obstacle, with deposition in the of the bed, while erosion occurs along the sides (Nowell and Jumars, 1984; Martinuzzi and Tropea, 1993; van Leeuwen et al., 2010). At the top of the bed are often several patches with mussels present. These patches are groups of mussels, which form obstacles to the flow and thereby decrease the flow velocity over the bed and increase the deposition in the wake. Deposition in the wake of the mussel bed is larger when the density of the mussel patches is smaller, because the flow velocities through/over the open parts of the mussel bed are larger than when the bed would be completely covered with mussels. This is the case because through the patches independent flow occurs. The higher flow velocities in between the patches result in more erosion and less deposition in the open parts (Widdows et al., 1998), but the roughness of the patches also results in a larger decrease in energy momentum. This decrease in energy momentum results in an overall decrease of the flow velocity and thus an increase in deposition in the wake of the mussel bed.
The patches itself however consist out of individual mussels, which can all be seen as individual obstacles. The mussel density in the patches is often large, therefore skimming flow occurs inside the patches. Higher densities of mussels in the patches, result in lower flow velocities, because of increased vortices by the large amount of roughness elements (Nowell and Jumars, 1984; Bouma et al., 2007).

4.3 Mussel patches as self-organising structures

Mussels influence both inactively and actively the hydrodynamic processes and sedimentation in their surroundings. Sedimentation is inactively influenced by increased roughness, which lowers flow velocities. Mussels actively enhance sedimentation by bio-deposition of faecal pellets and pseudo faeces (Hertweck and Liebezeit, 1996). Increased rates of sedimentation result in a rise of the bed. Especially young mussels are able to climb 6 $cmday^{-1}$ up the deposited sediment. Then the mussels act again as a physical obstacle to the flow and protect underlying sediment (Widdows et al., 2002).

Downstream of a mussel bed a sheltered area is present, with enhanced rates of deposition, because the increased height of the mussel bed applies extra friction to the flow and waves. At the end of the sheltered area wave forcing increases again (Donker et al., in press).

Van Leeuwen et al., 2010 show a relationship between the density of the mussels and the rate of deposition inside, in the wake and at the sides of the mussel bed. Widdows et al., 2002 also states that a nonlinear relation between the mussel density and resuspension exists. For a coverage of 25 to 50%, sediment resuspension is about four to five times higher than for a bare bed. This increase in resuspension is caused by increased turbulence and scouring around mussel clumps. When for these percentages of coverage the flow velocity increases, clumps of mussels start to detach from the bed. When the percentage of coverage becomes higher, sediment erosion and detachment of mussels is lower, with a minimum at 100% coverage. The mussels protect the underlying sediment and the large amount of byssal threads between the individual mussels prevents the detachment (Widdows et al., 2002). The relation between mussel coverage and erodibility of the bed indicates that classification of mussels as a bio-stabilisator of sediment is not completely true. Mussels enhance the erosion both along the sides of the bed (van Leeuwen et al., 2010) and in the bed for a lower mussel coverage (Widdows et al., 2002).

Parts of (young) mussel beds are eroded during storms and mussels tend to redistribute. Therefore many of the mussel beds consists out of some sort of pattern with higher located bulges, covered with mussels (patches) and bare strokes in between (Dankers et al., 2003; van de Koppel et al., 2008). The patterns of the mussel patches are often determined by the density of the mussels. Younger mussel beds or very old beds have often a higher density and a near-homogeneous distribution. When the density decreases, a labyrinth like pattern develops, with regularly spaced clusters of 5 to 10cm in width. When the density is very low, more isolated clusters of mussels are present (van de Koppel et al., 2008). The spatial pattern of patches has a large impact on hydrodynamic processes. When the number of patches and gaps in a mussel bed increases, the flow velocity decreases, due to the many adaptations of the boundary layer to changing bed roughness and obstacles (Folkard and Gascoigne, 2009). At the upstream edge of a patch, water in the lowest part of the water column is blocked and strongly decelerated by frictional and form drag of mussels. Therefore the shear stress suddenly decreases as a consequence water in the upper part of the column accelerates. In this way extra turbulence is created. The opposite happens at the downstream end of the patch. By this mechanism the water column is better mixed (Folkard and Gascoigne, 2009), which could lead to a larger availability of phytoplankton for the next patch of mussels (van de Koppel et al., 2008). Over the patches itself there is however a constant turbulence, which does not penetrate as high in the water column, as would be the case when only one large patch would be present, because the smaller patches are not long enough (Folkard and Gascoigne, 2009).

Van Leeuwen et al., 2010 suppose that the slower deposition in a mussel bed with spatial patterns is favourable. A patterned mussel bed will rise less soon and high as an uniform and densely covered mussel bed. The rise of the mussel bed and its close surroundings above the general bed level is favourable, since it will be less affected by predation from crabs and sea stars. The resulting increase in turbulence leads to less depletion of phytoplankton in the lower part of the water column, so more mussels can be located together. However the higher the mussel bed rises, the shorter the submergence time and thus the shorter the possibility for filtration. Also is the bed longer exposed to predation by birds. These factors act both as a negative feedback mechanism, because the mortality of the mussels increases, resulting in a less dense bed, more erosion and formation of spatial patterns. Therefore it is expected that mussel beds will form and sustain a certain spatial pattern, depending on the flow conditions (van de Koppel et al., 2008; van Leeuwen et al., 2010).

5 Hypotheses for the fieldwork

In the former chapters the relations between mussels and both the hydrodynamic conditions and sediment dynamics have been described. This chapter will give some hypotheses for the research questions raised in the introduction of this report. Based on the theoretical information of the former chapters, the hypotheses describe the expected results for the fieldwork period.

In what way does the composition and thus stability of the bed change?
Mussels are bio-depositors, which excrete faecal pellets and pseudo faeces. These consist among else out of small sediment particles and organic matter (Wotton and Malmqvist, 2001). This means that when bio-deposition rates are large and rates of resuspension and breakdown small, that the bed will become enriched with fine sediment and organic matter. At the end of the bed, the hydrodynamic conditions are tempered most, therefore it is expected that these parts of the bed will rise faster by the bio-deposition and consist of finer sediment. Close to the seaward edge of the mussel bed the hydrodynamic conditions are more energetic. Therefore it is expected that at these locations more resuspension of the sediment occurs, resulting in a relatively coarser bed, with a lower organic matter and clay content than in other parts of the mussel bed. The mussels however cover a part of the sediment of the bed, so it is expected that also at the most seaward part of the mussel bed, the sediment will have more fine and organic material than at the locations without mussels.

How does the height of the mussel patch and of the individual mussels evolve during fall?
Deposition of sediment takes place, when the drag and lift forces exerted by the flow are lower than the gravitational force of the particle. Sediment will start to settle when the flow velocities and thus drag and lift forces decrease below the critical shear stress of those grains (van Rijn, 1993; Masselink and Hughes, 2003). Small flow velocities occur at slack water and when the weather is calm. Therefore it is expected that during calm weather, deposition of sediment takes place, resulting in an increase in height of the mussel patch. During more energetic weather erosion is expected, because the velocities are then often high enough to entrain the bed sediment and too high for deposition.
Since the edges of the mussel bed experience the most energetic hydrodynamic conditions, it is expected that the largest difference in erosion or deposition will be visible at the edges of the mussel bed.

What is the consequence of differences in bed stability, patch height and mussel height for the further survival chances of the mussel bed during winter?
In paragraph 2.4 became apparent that mussel larvae can settle at different locations. The mussel larvae can for example settle at a bare bed, but also inside existing mussel beds. It is expected that the patches inside an original mussel bed lie more sheltered to the waves and currents, due to the frictional effects of the mussel bed. Furthermore are both the organic matter concentrations and the clay content larger for the patches, which developed inside an existing mussel bed, because there are more mussels and thus more bio-deposited material.
Because of the larger bed stability and the shelter effect of the mussel bed, it is expected that patches, which develop inside an existing mussel bed are more viable than patches originated at a bare location.

6 Material and methods

The research is focussed on the sediment dynamics around young mussel beds in fall. It is however difficult to monitor both differences in height and the hydrodynamic conditions of several mussel beds very accurate. Mussel beds however often consist out of many mussel patches. Therefor it is decided to monitor plots of mussels instead of complete mussel beds. The mussel bed near De Cocksdorp is chosen as study area. Around this mussel bed 19 plots were created in four different study areas. As well in the middle of the mussel bed; in front of the mussel bed; in the middle and in front of a bare sand bank, plots were created. In this way it is possible to see whether the hypothesis is true that newly developed mussel patches are more viable inside an existing mussel bed than patches, established at a bare location.

6.1 Study area

Close to De Cocksdorp, which lies in the north west of Texel, the most southward located Island of the Wadden Sea, a mussel bed is present. This mussel bed is easily accessible by foot. Only the mud flat near the dike and one small channel has to be crossed. Because the mussel bed is easily accessible and relatively close to the NIOZ institute on Texel, it was chosen as the first location for constant observation by a camera pole. This camera pole has been placed for research to both the wave patterns, predation and changes in the mussel bed (Mosselwad, 2012). It is because of the presence of this camera pole and the accessibility of the mussel bed that this mussel bed is chosen for the fieldwork, as exerted for this report.
In Figure 6-1 the study area is shown. The height map shows that the mussel bed itself lies approximately between – 0.2m and +0.3m NAP. This means that the tidal level has to become under 0.2m NAP before the entire mussel bed is accessible and can be monitored by the laser scanner. This is approximately the case between approximately 2 hours before and after the moment the minimal tidal level is reached.

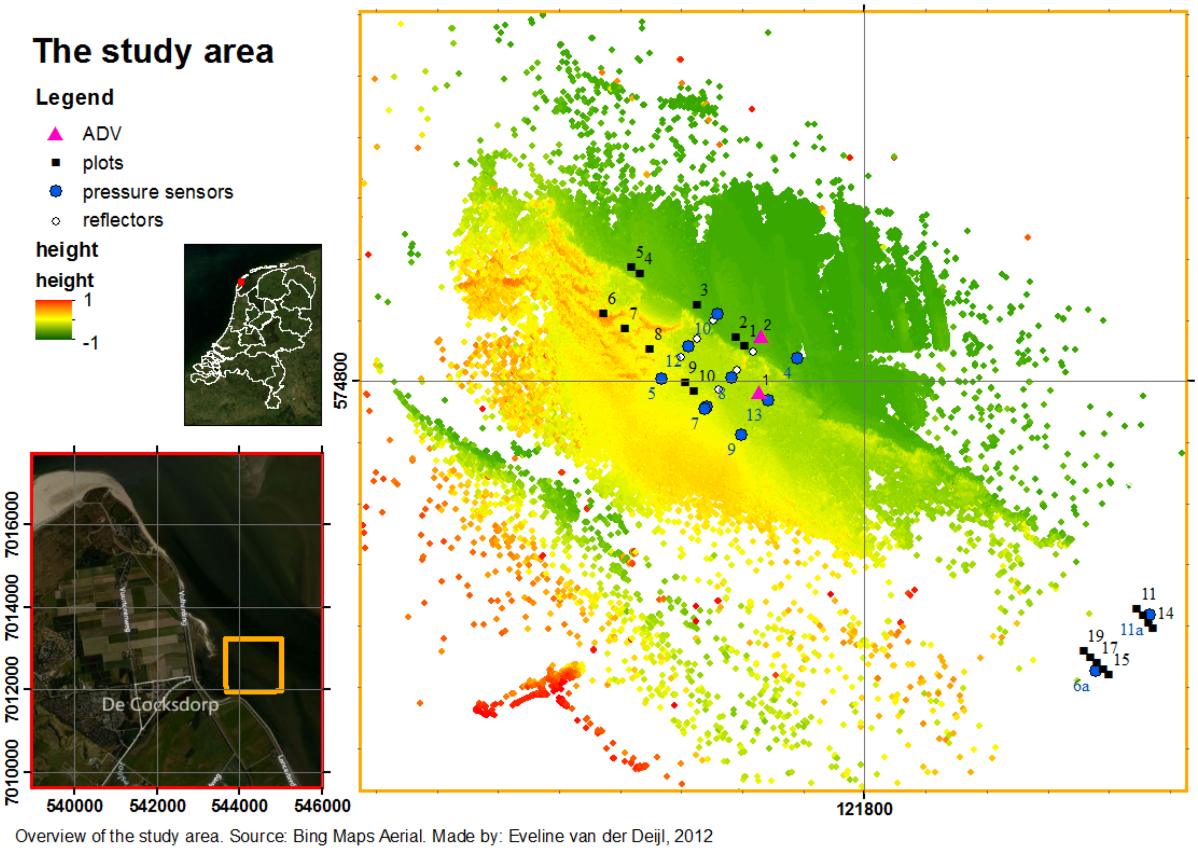

Figure 6-1 Overview ofthe study area, with the locations of the measurement instruments and the plots.

6.1.1 Morphodynamics and hydrodynamics at the intertidal flat

The mussel bed near De Cocksdorp lies along a channel of the flood tidal delta of the Eierlandse Gat Inlet. This inlet has the smallest surface area and tidal prism of all tidal inlets along the Dutch Wadden Sea (Wang et al., 2012). At the edge of the channel, the intertidal flat consists mainly of fine sand, probably with a grain size of about 200 μm, which is common for the Wadden Sea. The Wadden Sea however has a significant larger amount of mud fraction close to the landward boundaries and close to the watersheds. This effect is among else caused by the fact that coarser sediment is deposited first (van Leeuwen, 2002). The mud content of the intertidal flats and channels is in constant interaction, due to changing hydrodynamic and morphological conditions. In general mud accretes on the intertidal flats during summer, when wind speeds and thus waves are relatively low (Andersen et al., 2005), while the channels show erosion of mud (Chang et al., 2006; van Leeuwen, 2008). In the winter the opposite is the case, because then wind speeds and thus the wave heights are larger. The water depth at the flats is shallower than in the channels, leading to a larger wave shear stress at the intertidal flats. This seasonal change in mud deposition and resuspension, results in the fact that the composition and especially the mud content of the intertidal flats changes during the year. The interaction is larger on the sandy flats than on the more muddy flats (Zwarts, 2004).

The tidal flat near De Cocksdorp is a sandy flat, which is covered with long straight bed forms (Donker et al., in press). Since the waves that come from the North Sea, break on the ebb delta of the Eierlandsegat inlet, only locally generated waves are present near this flat (Kragtwijk, 2001). The height and the direction of the wind waves are determined by the direction and the strength of the wind and by the length of the fetch, over which the wind blows. The local waves are especially formed in the tidal channels. The fetch over which the wind can generate waves is very limited at the mussel bed near De Cocksdorp, because land or intertidal flats are present in the west, north east and south east of the mussel bed (Donker et al., in press). This means that the intertidal flat lies in a sheltered area and that large waves and rough hydrodynamic conditions can only occur, when the wind is coming from the east, where the tidal channel from the Eierlandse Gat inlet extends for about 6km.

Wind waves are however not the only hydrodynamic conditions which are present in the Wadden Sea. The hydrodynamics in the Wadden Sea can be divided into currents due to waves or tides respectively (Borsje, 2006). The mean flow direction in the tidal inlets of the Wadden Sea is for approximately 98% determined by the tidal currents (Wang et al., 2012). The tidal currents vary during a tidal cycle, since the tide does represent a long period wave, which consists out of several components, caused by gravitational attraction between the earth, moon and sun and by the rotation of the earth (Kragtwijk, 2001). The tidal wave comes from the North Sea basin and enters and fills in the basins of the Wadden Sea.

6.2 Plots

In total 19 plots of approximately 1x1m were created at 17 and 18 September 2012. The location of these plots is shown in Figure 6-1. In other field researches, in which plots were used as small scale experiments, plots were created out of individual mussel larvae, caught in the channels. These plots often survived for no more than three weeks. For this study it is the intention to follow a young mussel bed during fall. During summer mussels already form byssal threads for connection to each other and the bed, therefore it was decided to develop a new method to create the plots. Plots are build up from plaques of mussels of about 20x20cm, which were dug out the original mussel bed (see Figure 6-2 and Figure 6-3). Complete plaques of mussels, of about 5 to 10 cm thick were transplanted, so the internal structure in between the mussels; and the mussels and sediment is maintained. At the location of the plots, the upper layer of sediment was removed and the mussel plaques were dug in the sediment of the bed (see Figure 6-4).

Figure 6-2 Mussel plaques are dug out and placed on a sledge to be transported to their new

Figure 6-3 The gaps, left over at the site, where the plaques of mussels were taken from

To test the hypothesis that young patches of mussels are more viable inside an original mussel bed, as well in front of the mussel bed (Area A) as on empty spots in the mussel bed (Area B), five plots were created. The plots are plot 1 to 5 and 6 to 10 respectively. The mussel bed in between these plots is not constant. The bed is the highest and contains most mussels between plots 1, 2 and 9 and 10. Between plots 3, 4, 5 and 6, 7 and 8 the mussel bed has a lower coverage with mussels, since more separate patches/bumps of mussels are present and the bed has a much higher concentration of 'dead' shell material.

As a control situation, nine plots were created at the bare sandbank in the extension of the mussel bed. Four plots were created in front of a bare sand bank (Area C) and five plots at the bare sand bank (Area D). The distance between these areas is the same as between areas A and B, but there are no mussels in between. By this approach it can become apparent, whether it is indeed the mussel bed, which results in differences in the plots inside and in front of the mussel bed.

Figure 6-4 The plaques of mussels are dug in at their new location.

For all plots, plastic poles were placed at the corners. These poles indicate the edges of the plot, so the development of the plot can be monitored over time. One of the poles was marked with an flag. In clockwise direction, starting at the corner with the flag, the geographic position of all corner poles was measured by a DGPS. The location and the bed level of the corners are shown in Appendix A1.

6.3 The sediment dynamics

The research is focussed on the sediment dynamics around the plots. It is difficult to measure changes in sediment concentration at different locations and heights in the water column very accurate, therefore it was chosen to determine the sediment dynamics by changes in the height of the plots and their surroundings and by changes in the sediment composition.

6.3.1 Changes in height of the plots and their surroundings

A laser scanner of the type RiegL-VZ400 was used. This scanner measures the x, y and z coordinates up to 5mm accurate and repeatable. The location of the laser scanner itself is used as centre point of the coordinate system (RIEGL laser measurement systems, 2013). The laser scanner uses several reflectors. When the reflectors are placed on the same positions every time, it becomes possible to overlay the scans as made by the laser scanner.
For the mussel bed there are six permanent steel poles located in two transects. For each pole the DGPs was used to measure the coordinates and height of the poles. When the reflectors are placed on these poles and scanned by the laser scanner, it is possible to georeference the several scans, made from the mussel bed. When this is done for all the monitoring days, it is possible to determine at which day and thus under which circumstances erosion or deposition in or around the plots took place.
At the bare sand bank there are no permanent steel poles for the reflectors. It was decided to place the reflectors on the outermost corner poles of plots 11, 14, 15 and 19.

Monitoring

The plots were created at 17 and 18 September, therefore 17 September is defined as the first day of the monitoring campaign. It was chosen to monitor only eight of the nineteen plots with the laser scanner, because the time that the mussel bed is accessible and the plots are above the water level is limited. Also are the batteries of the laser scanner limited to about 8 to 10 scans.
It was chosen to monitor plots 1, 2, 9, 10, 12, 13, 16, and 17, if the weather and tide are favourable, because these plots lie in the area where also monitoring of the waves and currents takes place. Plots 1 and 2; 9 and 10; 12 and 13; and 16 and 17 lie close to each other, therefore these plots are scanned together. The laser scanner is placed both at the channel- and at the bed-side, in the middle between the two plots. In this way each plot is scanned from two sides, so most shadow effects in each scan are compensated for by the results of the other scan. The laser scanner has however a relatively large reach, so it also obtains information about plot 9 and 10, when plot 1 and 2 are the focus, and vice versa. This means that for most of the days four scans of each plot are available.

Figure 6-5 The laser scanner of the type RiegL-VZ400

Table 6-1 shows at which days the height of the plots was monitored. Furthermore the table shows how much scans were made from each plot at those days. It was not possible to monitor the height of each plot each day, because it had both to be dry during the entire scan and the wind should not be stronger than 4 Bft. Also was it decided to decrease the monitoring interval after 26 September to once a week.
Table 6-1 shows that during most of the days that scans have been made, it was possible to scan each plot four times. At some days however less scans were available, because of showers, for which the scans had to be aborted. When less scans are made from a plot, less data is available. This is especially the case, when only the scans, made the furthest away, are available for the plots. For plots 12 and 13 the height scans of day 4 and day 9 are not used, because of the limited amount of data points. Therefore day 5 is the first monitoring day for plots 12 and 13, while day 4 is the first monitoring day of plots 16 and 17 and day 3 the first monitoring day for the plots around the mussel bed.

Table 6-1 The amount of scans made by the laser scanner for all of the plots

Date	Day	Plot 1	Plot 2	Plot 9	Plot 10	Plot 12	Plot 13	Plot 16	Plot 17
19-9-2012	3	5	5	5	5				
20-9-2012	4	4	4	4	4	1	1	1	1
21-9-2012	5					4	4	4	4
22-9-2012	6	4	4	4	4				
23-9-2012	7	4	4	4	4	4	4	4	4
25-9-2012	9					2	2	2	2
26-9-2012	10	4	4	4	4	4	4	4	4
2-10-2012	16	4	4	4	4	2	2	2	2
11-10-2012	25	4	4	4	4	4	4	4	4
29-11-2012	74	3	3	3	3	4	4	4	4

Data analysis

The laser scanner measures the height of its surroundings in 5mm accurate and repeatable. The laser scanner uses its own location as the centre of the coordinate system and the initial direction of the laser is seen as north. The scanner is however programmed to search for reflectors, when it measures the height of an area.

All scans and data of the reflectors, as made by the laser scanner, are loaded in the program RiSCAN PRO, which uses tiepoints to link several scans of one area. For the mussel bed the tiepoints are defined by inserting the size of the six reflectors (5cm) and their location and height, which was measured by the DGPS. Then the program recalculates the coordinate system and height of a scan, to come to the best link between the reflectors found and the defined tiepoints. Thereby the difference between the new location of the reflector and the tiepoints should be less than 50mm. In this way all scans, made at the mussel bed, can be recalculated. The best combination of at least 4 reflectors was used, so the standard deviation between the reflectors and the tiepoints is minimal. For all scans the standard deviation was less than 15mm, which means that the height of the recalculated scans is in x and y direction up to 15mm accurate. This is within the chosen gridsize of 25mm, used for further analysis

It was not possible to georeference the scans, made at the bare sand bank, because the exact location and height of the reflectors was not measured. Another problem was that the plastic corner poles started to lean or were even pulled out by the flow or by seaweed. Therefore the location of the reflectors differed over time and it was only possible to link the scans made at one monitoring day to each other, but not to the scans made at other monitoring days. Therefore another approach was used for the scans made at the bare sand bank. All tops of the corner poles of all nine plots were assigned to be a tiepoint. This was done for all individual scans for all directions and all monitoring days. There were nine plots, with each four corners, so for each scan there are 36 tiepoints in total for each scan. The 36 tiepoints, measured at 2 October, were used as input for the other days. 2 October was chosen, because this day laid approximately in the middle of the fieldwork period. The difference in the location of the top of this day and both the first and the last monitoring day is smaller than the difference between the location of this top at the first and at the last day.

Again the tiepoints of all scans were compared to the tiepoints of 2 October. Thereby the difference between the new location of the reflector and the tiepoints should again be less than 50mm. Only the best combination of approximately six tiepoints was used to recalculate the coordinate system. These six tiepoints were however often found in the area close to the position of the laser scanner. The standard deviation was for these scans smaller than 30mm. The recalculation of the scan is however the most accurate in the area between the tiepoints. The tiepoints were often only found close to the laser scanner, so the other parts of the area were extrapolated. This means that a maximal error of 5mm in the height prediction inside the area, becomes extrapolated with distance. The result is that all scans at the sand bank have

the same coordinate system, but a tilt in the height for areas further away from the laser scanner (see Figure 6-6).
Therefore there is an additional correction needed for the height measurements at the bare sand bank. For each day the linear trend for the combined scans of one day is determined. These linear trends are removed from the measured height. Now the height of all scans can be compared and the difference in height between the several monitoring days can be calculated too. The initial height map of the area does however not show the actual height of the area anymore, but a reference height.

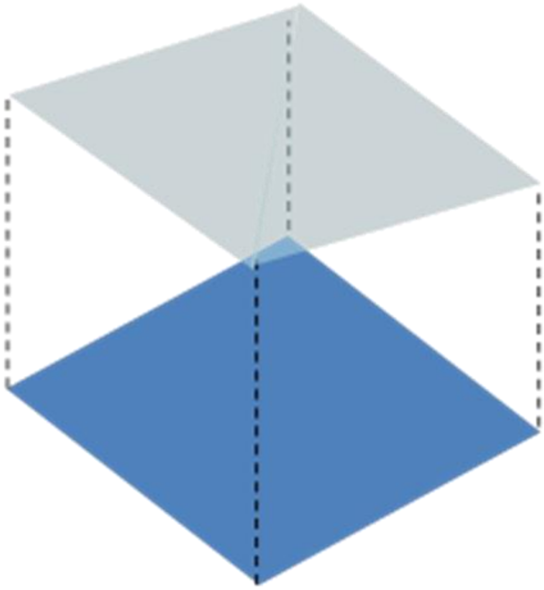

Figure 6-6 Two scans with the same coordinate system, but one scan is tilted

In Appendix A2 a sensitivity analysis can be found. In this appendix the sensitivity of the height maps to the method for combining the individual scans of one monitoring day is analysed. Based on the analysis it is chosen to create the height maps by averaging the height of the two most nearby scans. The average of the two scans, made further away, is only used to fill in the gaps, for which no data was available in the two most nearby scans. In this way the most smooth and accurate height map is created.

6.3.2 The stability of the bed

The stability of the bed is important for the survival chance of mussels, because mussels are connected with byssal threads to each other and to the bed. When the bed is not stable, both the bed and the mussels on top of that bed will erode. In paragraph 3.2 the factors of influence on the bed stability were mentioned. The most important physical factors are the median grain size and the sediment density. The sediment density is however influenced by the compaction and the amount of water inside the pores between the grains. The water content of the mussel bed varies during the tidal cycle, because of submergence and emergence during high and low water. Therefore the water content and sediment density cannot be used to determine the stability of the bed. The median grain size can however be monitored and is therefore used as one of the indicators for the stability of the bed.
A second indicator for the bed stability is the clay content. The organic matter content is used. as a third indicator for the bed stability.

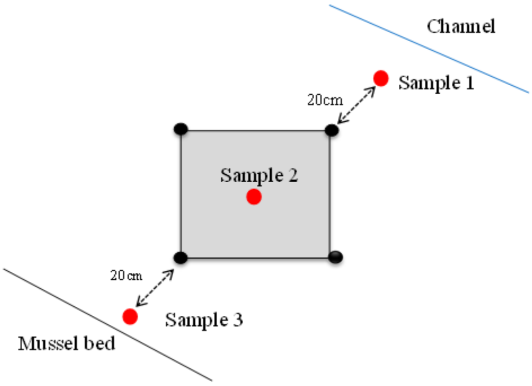

Figure 6-7 Locations around/in the plot where the three sediment samples are taken

There are thus three indicators for the stability of the bed, used in the analysis. For these indicators sediment samples are taken in plots 3, 8, 13 and 17. Not all plots were monitored, because the budget was limited. Furthermore the height in and around the plots is disturbed, because it is necessarily to approach the plots.
Sediment samples were taken at 19 September (day 3), 26 September (day 10), 2 October (day 16) and 11 October (day 25) in and around each plot. One sample was taken 20cm before the most exposed side of the plot, one sample in the middle of the plot and the last sample at 20 cm behind the plot, so at the most sheltered location. The sampling locations are shown in Figure 6-7.
At each location two sediment samples of the top 1 cm were taken, by inserting a small tube in the bed. The top of the tube was closed, so no more air could enter and the tube with the sample was pulled out of the bed. When the presence of mussels below the surface resisted a 1cm deep sample, a sample was taken at another location, where it was possible to reach a depth of 1cm. The two samples taken at each location are stirred together.
The organic matter content of the samples is determined by the loss of ignition (LOI) method. This method consists out of several steps. The sediment is done in a bin, with a known weight (Wb). The weight of the sample and the bin together is the wet weight (Wn). The samples are oven-dried at 105°C, for at least 24 hours. At this temperature the water inside the soil samples evaporates so, when the sample is weighted again, the dry weight (Wd) of the sample is known. The third step is to heat the sample to 550°C for about 4 hours. At the temperature between 500°C and 550°C organic matter becomes oxidised to carbon dioxide and ash and only the dry weight of the grains is left over (Wg). The following formula (Heiri et al., 2001) shows how the organic matter content can be calculated, using the dry weight of the sample (Gd) and the actual weight of the grains (Gg):

$$LOI = \frac{Gd - Gg}{Gd} * 100 = \frac{(Wd - Wg) - (Wb - Wn)}{(Wd - Wg)} * 100$$

Furthermore the samples were send to the NIOZ lab at Texel, where a grain size analysis took place.

6.4 Mussel coverage

Each time the mussel bed was visited, photographs were taken of the plots. The photographs were made by two persons, holding a 3m long stick at the tips, or by one person holding a 2m stick. At the stick a camera was attached. By this method, it was possible to make photographs of the plots from above, while staying at a distance of about 1m from the plots, so the disturbance is minimal.

Figure 6-8 The method used, to make the photographs of the plots, from above

Data analysis

The photographs are rectified using the four plastic poles that were placed at the corners of the plots. An example is shown in the first two images of Figure 6-9. The third image in Figure 6-9 shows that by using the RGB values of the images as well the percentage of mussels, sediment and shell material is determined. By this approach it is possible to calculate the mussel coverage of the plot over all monitoring days and to determine the change in the mussel coverage over time.

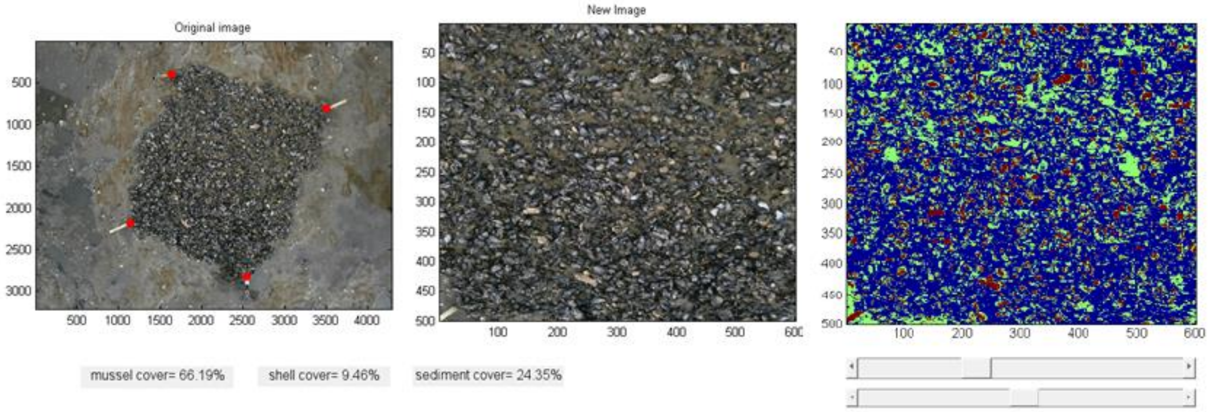

Figure 6-9 This figure shows the original image made from plot 1 at 19 September. The corners are assigned and the image is turned and corrected in size. Furthermore the coverage of the mussels, sediment and shell material is determined by the RGB values

6.5 Hydrodynamic conditions

To explain the changes in height and composition of the plots, the hydrodynamic conditions will be used. This paragraph will explain how these conditions are determined and analysed.

6.5.1 Waves

Ten pressure sensors of the type Ocean sensor systems OSSI-010-003B Wave Gauge have been used to determine the wave characteristics during the fieldwork period. The Ossi's not only measure the water pressure, but also the water temperature.

The pressure sensors were installed in the field at Thursday 13 September and measured until 31st of October. The sensors were attached close to the bed to a steel pole, placed vertical in the bed (see Figure 6-10). It is sufficient to attach them to one steel pole, because these sensors are not sensitive to vibrations. On top of the pole a large plastic stick was attached, so the sensors were also during flood recognisable for ships. Figure 6-1 shows the locations at which the pressure sensors were installed. The ten pressure sensors are placed in several transects, so it is possible to determine the change in wave characteristics over the mussel bed. In this way becomes apparent how much the plots in the middle of the bed are sheltered to the influence of the waves, when compared to the plots in front of the bed.

The wave height and orbital velocity are determined out of the data of the pressure sensors by the approach as described in Donker et al., (in press). The pressure sensors are not always submerged, therefore it was decided only to use the data, when the water depth is at least 10cm. In this way less errors will occur, due to only partly submergence of the sensors.

Figure 6-10 One pressure sensor, attached to a steel pole.

6.5.2 Currents

Three Acoustic Doppler Velocity meters (ADV's) were used for velocity measurements. Two ADV's were placed at the same location, but at different heights in the water column. This location is at the front of the mussel bed. The third ADV is placed in the middle of the mussel bed. The ADV's are attached to a steel frame with a three sided prism as base, so the base is stable and the ADV's are not prone to vibrations of the frame. For the ADV's one steel pole is not enough, because the ADV's are in contrary to the pressure sensors, very sensitive to vibrations.

The ADV's are used to determine the velocity and direction of the currents, which can be used to indicate the main pathway of sediment transport at the mussel bed. The approach to calculate the strength and the direction of the currents are described in Donker et al., (in press).

Figure 6-11 The frame and two ADV's, placed in front of the mussel bed

7 Results

7.1 Sediment Dynamics

To analyse the effect of the plots with mussels on the sediment dynamics, a systematic approach is used. First in paragraph 7.1.1 regional patterns in sedimentation and erosion over the entire fieldwork period are identified, by an analysis of the mussel bed. Than in paragraph 7.1.2 the change in the mussel coverage of all plots is discussed. This is followed by an analysis of the change in height of the eight plots, as monitored during the fieldwork period. Both the change in height and coverage are discussed to see whether the changes in height are caused by displacement or removal of mussels; or by erosion or sedimentation of bed material. Thirdly in paragraph 7.1.3 an area of 3m around each plot is studied. It becomes apparent whether the plots influence the local sediment dynamics, or that the sediment dynamics in the areas are mainly caused by regional patterns.

All analysis as described above, is done over the entire fieldwork period. Paragraph 7.1.4 will however identify differences in sediment dynamics over time. Again the plots are studied first, followed by the area of 3m around the plots. In the paragraph 7.1.6 results of the sediment samples are shown. Both differences in the organic matter content and grain size division are studied for the different locations as different monitoring intervals during the fieldwork period.

7.1.1 Regional patterns in erosion or deposition

In this paragraph regional patterns in erosion and deposition are identified for the mussel bed. The left part of Figure 7-1 shows that there are several higher located fronts in the area in front of the mussel bed. These fronts are banks, which consists out of a higher located top and a lower located through. Furthermore it is visible that the height of the mussel bed is not constant. Near the edge relative high bulges are present and the height decreases towards the middle of the bed. In the middle there are even some locations, which are still submerged and therefore do not contain height data. Plots 9 and 10 are however created in the area, where the height starts to increase again. The height of this area around plots 9 and 10 is lower than in the north west and south of the plots.

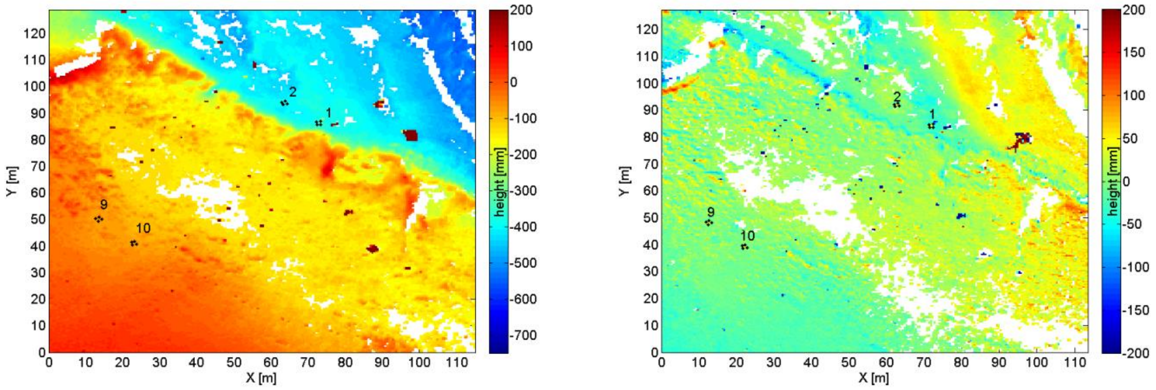

Figure 7-1 The figure shows both the initial height of the mussel bed [mm above NAP] as the difference in height [mm] over the field work period.

The map in the right of Figure 7-1 shows the difference in height between the initial situation at 19 September and the final situation at 29 November. Height variations on the bare flat at the sea ward side of the mussel bed are bed forms which propagate in shore ward direction. The height variations caused by these bed forms influence the observations, as initially plot 1 and 2 where on the top and edge of a bed form. Shore ward propagation of these bed forms results in a decrease in height for plot 1 and an increase in height for plot 2.

Another regional pattern is that both the initial higher located edges of the mussel bed, as the higher located bulges in the bed, experience the largest increases in height over the fieldwork period. The initial lower lying middle of the mussel bed, has experienced an increase in height too, while it is the higher located sandbank along the south west edges of the mussel bed, at which plots 9 and 10 are located, which experiences erosion.

In the left of Figure 7-2 the overview of the south east edge of the mussel bed is shown for 21 September. The southwest edge of the mussel bed is present in the north west, while the channel of the inlet lies in the north east. The higher area in the lower left corner of the figure is part of the sandbank, on which the mussel bed is located too. There is however a channel in between this sand bank and the mussel bed. This channel is formed due to the fact that currents are bend by the mussel bed and concentrated over one area. The channel is formed by erosion of the sand bank in that area. Along the edge of the channel and at some locations inside the channel are however several higher located ridges present, which indicates that the sand bank is not continuous and contains more areas in which the flow is concentrated and erodes the bed, when the water rises or when the area is drained.

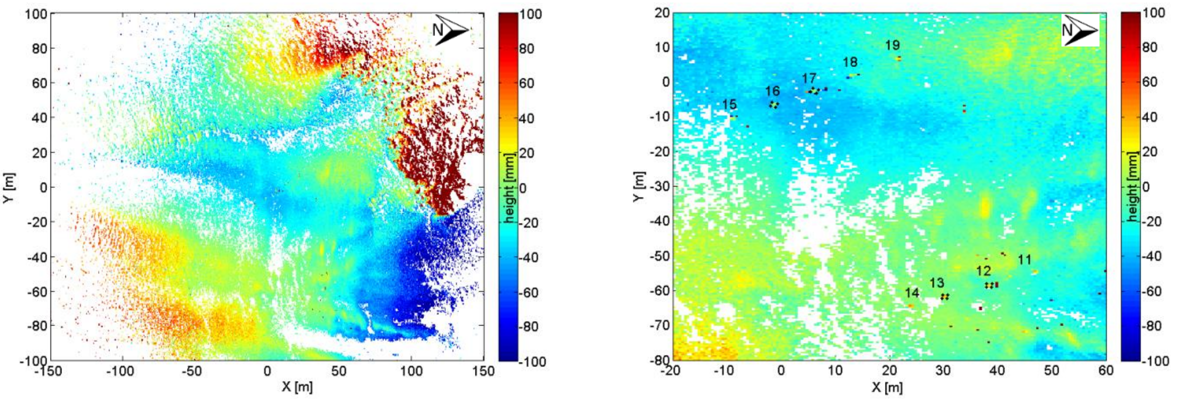

Figure 7-2 The overview of the bare sand bank and location of the plots at 21 September. The relative height is shown in mm and cannot be compared to the height of Figure 7-1.

In the right part of Figure 7-2 the small channel is visible. Plots 15 to 18 are created in the channel itself, while plots 11 to 14 lie at higher locations. It was not possible to create a height difference map for the entire area on the sand bank, because too less tie points were found in the scans of 29 November. On smaller scales it is possible to link the scans too each other, but on a larger scale the error of tilted tiepoints becomes extrapolated with distance from the tiepoints. This leads to very strange differences in height, further away from the plots, when the initial and final scans are compared to each other.

7.1.2 Change in mussel coverage and height in the plots

This paragraph describes the change in mussel coverage and height of the plots. The coverage is discussed first, since a change in height inside the plots is not only caused by sedimentation or erosion of bed material, but also by erosion or displacement of mussels.

Change in mussel coverage

Photographs of all plots were made at all monitoring days. The mussel coverage is however only determined for the third and last day of the fieldwork, because the difference in coverage between the successive monitoring days, was smaller than the error of the method used to determine the coverage. The third day is used because it is the first day after the creation of the plots. Table 7-1 shows the initial mussel coverage of the plots, which differs between 58 and 76%. This difference is either caused by the initial differences in coverage of the transplanted mussels; by displacement of the mussels or by erosion or sedimentation of sediment in between the mussels over the first two days.

Table 7-1 The initial mussel coverage (at 19 September) of all 19 plots

Area A	Initial mussel coverage [%]	area B	Initial mussel coverage [%]	area C	Initial mussel coverage [%]	area D	Initial mussel coverage [%]
plot 1	75,65	**plot 6**	74,73	**plot 11**	66,57	**plot 15**	69,90
plot 2	72,18	**plot 7**	77,96	**plot 12**	67,46	**plot 16**	66,02
plot 3	68,39	**plot 8**	75,60	**plot 13**	57,83	**plot 17**	69,25
plot 4	68,81	**plot 9**	74,17	**plot 14**	70,12	**plot 18**	67,23
plot 5	63,90	**plot 10**	73,62			**plot 19**	64,30

The final coverage as determined at 29 November is divided by the initial coverage and multiplied by 100%. Figure 7-3 shows the results. Area A comprises the plots in front of the mussel bed, area B the plots inside the mussel bed, area C the plots in front of the bare sand bank and area D the plots in the middle of the bare sand bank. The differences in the change in mussel coverage of the four areas is clearly visible. All plots at the bare sand bank have experienced a larger decrease in coverage than all the plots inside and three of the five plots in front of the mussel bed. The differences in the coverage between the locations at the bare sand bank and the locations around the mussel bed are thus significant. The difference between areas C and D is however not significant, because the final coverage of all plots in those areas lies in between 80 and 93%. The difference between areas A and B is larger, but not significant, since the spread for area A lies between 86 and 98%, while the spread of area B lies between 86 and 98%.

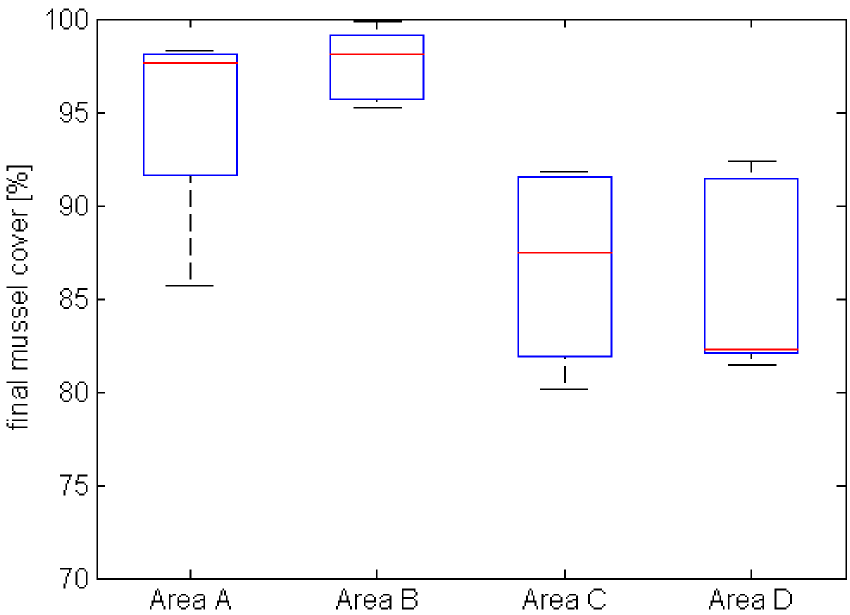

Figure 7-3 The final mussel coverage is compared to the initial coverage. The four areas represent plots 1 to 5, plots 9 to 10, plots 12 to 14 and plots 15 to 19 respectively.

Change in height

In the first part of this paragraph became apparent that for almost all plots the mussel coverage decreases during the fieldwork period. This means that increases or decreases in height are not only caused by sedimentation or erosion of bed material, but also by displacement or erosion of mussels. In this part of the paragraph differences in height inside the plots will be examined. For all plots the coverage was monitored, but the change in height is only monitored for eight of the 19 plots, respectively two in all four study areas. Differences in height are determined for intervals of 45 degrees around the centre of the plot. The blue lines in Figure 7-4 show the results. It is apparent that the average change in height over all intervals inside the plots is positive, but it is the largest inside plot 2. In paragraph 7.1.1 was however mentioned that this is among else caused by the displacement of bed forms, in front of the mussel bed, which results in a relatively large increase in height inside plot 2 and a smaller increase in height inside plot 1.

The variation in height between the intervals inside the plots is the smallest inside plots 9 and 10, which lie in the mussel bed. These plots have an almost constant increase in height over the intervals. For plot 10 there is however one relatively large difference in height between the two intervals from 225 to 315 degrees.

The plots at the bare sand bank show approximately an equal trend, with the largest amount of sedimentation in the intervals at one side of the plot and erosion or only small amounts of sedimentation at the opposite intervals. Plots 12 and 13 are the best examples, which show this trend. These plots have the largest amount of sedimentation over the first 90 degrees, with the maximal increase in height in the north east, while the smallest rates of sedimentation occur between 225 and 315 degrees, so in the west of the plots. For plot 16 there are more wiggles over the several intervals, but the same trend is visible. Only plot 17 shows a different trend. This plot has both in the east as in the west a larger increase in height, then in the north and south.

For the plots in front of the mussel bed the difference between the increase in height for the intervals in the plots is larger than for plots 9 and 10, but less than for the plots at the bare sand bank. Plot 1 and 2 have both a smaller increase in height in the southern intervals of the plot, between 135 and 270 degrees, than in the northern intervals.

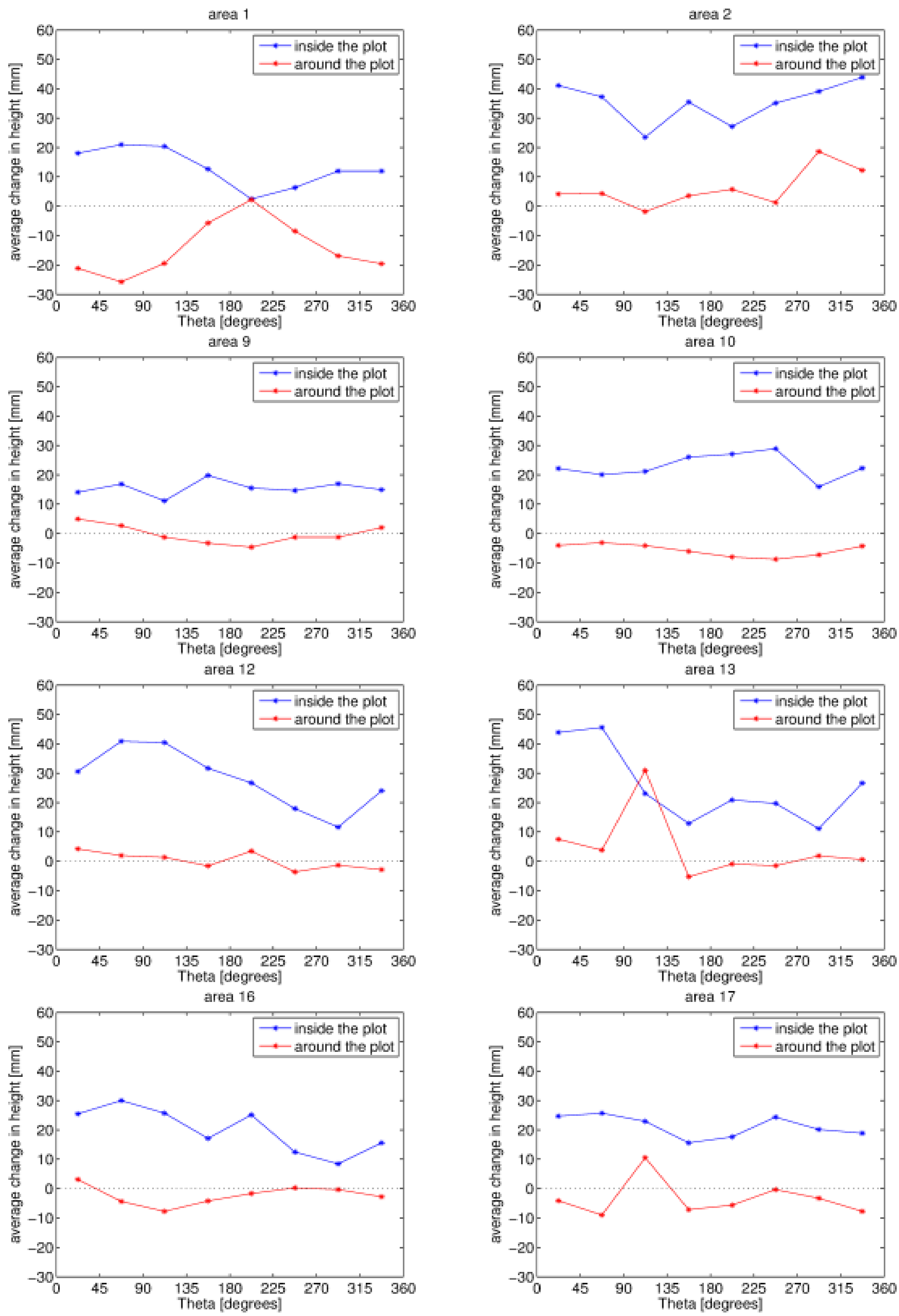

Figure 7-4 The average change in height for all data points in intervals of 45 degrees. The angle is determined between the data points and the centre of the plot.

7.1.3 Change in height in the 3m areas around the plots

In the former two paragraphs both the large scale variation in height (the regional patterns) and the small scale variation in height (inside the plots) was described. Figure 7-5 shows however an overview of the 3m areas around the plots, indicated by the squares. These areas are examined to see, whether the change in height inside the plots (small scale) is determined by or influences the trends in the areas around the plots (medium scale) or that it is the regional pattern (large scale), which has the largest influence.

Although both plot 1 and 2 lie in front of the mussel bed, local differences in height exist. Figure 7-5 shows that the height of area 1 is in general larger than that of area 2. Furthermore it is visible that plot 1 lies relatively higher than its surroundings, while plot 2 has almost the same initial height as area 2. In paragraph 7.1.1 became apparent that these height differences are caused by sand banks in front of the mussel bed. Another difference between the plots is formed by the distance between the plots and the mussel bed. Plot 1 is located closer to the mussel bed than plot 2. Therefore area 1 also contains a part of the edge of the mussel bed.

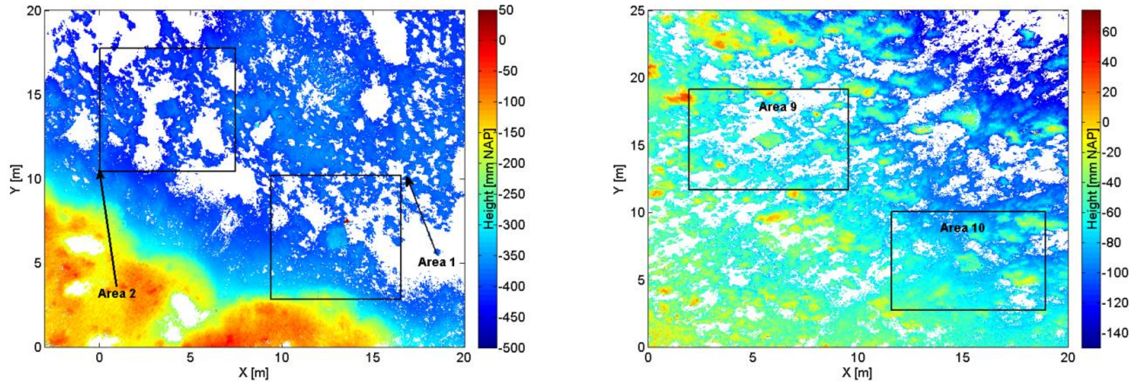

Figure 7-5 The initial height [mm NAP] of areas 1, 2, 9 and 10 at 19 September 2012 respectively

Plots 9 and 10 are created at empty places inside the mussel bed. Figure 7-5 shows that this part of the mussel bed is in general lower than the edge of the bed, visible in the left part of Figure 7-5. Large parts of area 9 do not contain data, because they are still submerged. For area 10 more data is available, although a large part of this area lies lower than area 9.

In the left of Figure 7-6 is visible where areas 12, 13, 16 and 17 are located. The figure shows that plots 16 and 17 were created in the channel, which was already visible in Figure 7-2. Plots 12 and 13 were however created on or in the neighbourhood of one of the higher ridges in the area.

More data is available for area 12 than for area 13. This can either be caused by the shadow effect of higher located areas, or by submergence of the area. It is expected that the last is the case, because there are no high ridges in area 13 and the area is located close to one of the laser scanner positions, which means that the shadow effect should be very small.

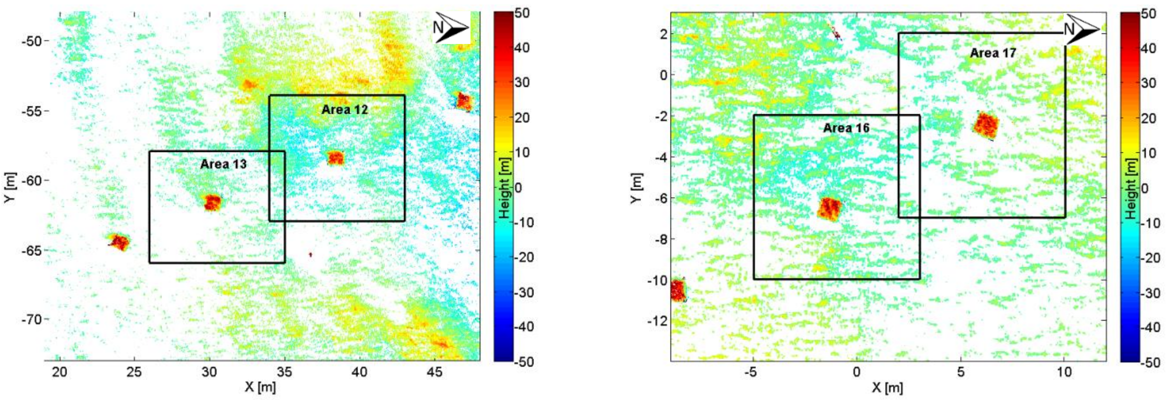

Figure 7-6 The initial height [mm] of areas 12 , 13, 16 and 17 at 21 September 2012

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For all areas, as indicated by the squares in Figure 7-5 and Figure 7-6, the change in height over the fieldwork period is shown in Figure 7-7. In this figure are the corners of the plots indicated by black dots, which represent the four corner poles. Without these black dots, the plots itself are however still clearly visible, since all plots have a relatively large change in height, compared to other parts of the area.

Although all plots are clearly visible by a relatively large increase in height, different patterns in sedimentation and erosion are present in the areas around the plots. Some of these patterns are regional. So experiences a large part of area 1 erosion, while area 2 experiences sedimentation. Only the locations in area 1, which are either covered with mussels or are close to an area covered by mussels, experience sedimentation.

The amount of sedimentation in the bare parts of area 2 (20 to 30 mm) is comparable to the rate of sedimentation in the parts of area 1, covered by mussels. The largest rates of sedimentation in area 2 (40 to 50 mm), however occur in the plot itself. These rates of sedimentation are larger than the rates of sedimentation for the plot or the edge of the mussel bed in area 1, which lie in the range between 30 to 40mm.

The differences in height between area 9 and 10 are less than the differences in height between areas 1 and 2. Both the amount of erosion and the amount of sedimentation in areas 9 and 10 is in general lower than in areas 1 and 2. Area 9 experiences more sedimentation than area 10, but the sedimentation especially occurs inside the plot, or along the edges of the areas for which data is available. The bare areas, show either a decrease in height or there is no data available because of submergence.

For areas 12, 13, 16 and 17, which are located at the bare sandbank, there are relatively large areas, for which no data is available because of either submergence of those areas at the beginning or at the end of the fieldwork period. The locations for which data is available however indicate that although the plots of mussels are created at a bare sand bank, at which no other patches or bulges with mussels are present, that the areas still experience local differences in sedimentation or erosion. The magnitude of the changes in height in the areas around the plots at the bare sand bank is approximately the same. It however differs at which part of the area mainly sedimentation takes place and at which part erosion occurs. These differences are caused by local variability in the initial height and thus local variability in waves and currents. It is however also visible that not only in the north east of plots 12 and 13 itself, but also in the area north east of those plots, larger rates of sedimentation occur, while some erosion takes place in the area south west of the plot.

To examine the effect of the plots on the sedimentation in the area around the plot it is decided to calculate the average change in height in several intervals around the plots. For the analysis an area of 3m around each plot was selected. Since a constant grid of 2.5cm is used, it is possible to determine the average changes in height for each grid cell by summing all changes in height and dividing that by the amount of grid cells, which contain data. The first area examined is the plot itself. All data points in between the four corner poles are used to determine the average change in height in the plot itself. Then the first interval of 10 cm around the plot is analysed, by using all data points between the edge of the plot and 10cm around the plot. The same is done for all successive 10cm intervals, to a distance of 3m around the plot. The results are shown in Figure 7-8. This figure shows among else that the average change in height inside the plots is larger than in the areas around the plots. All plots have experienced an increase in height from 14 to 28 mm. In the first two intervals (up to 20 cm) around the edges of the plot the change in height is much lower (10 to 25 mm) than inside the plot or it becomes even negative, but it is often still more positive or less negative than in the intervals further away from the plot. Only for plot 9 is in the intervals between 30 and 60 cm around the plot, the change in height more positive than in the first two intervals, but it is still lower than the change in height inside the plot. After the 60cm interval the change in height decreases again to close around zero.

Plot 17 has large wiggles in the change in height over the first 1.5m, this is however caused by the small amount of data points. The other plots have smaller wiggles of 5 to 10 mm. These wiggles can either be caused by local differences in the initial morphology and thus hydrodynamics of the area, or by differences in sedimentation and erosion patterns around the plot itself.

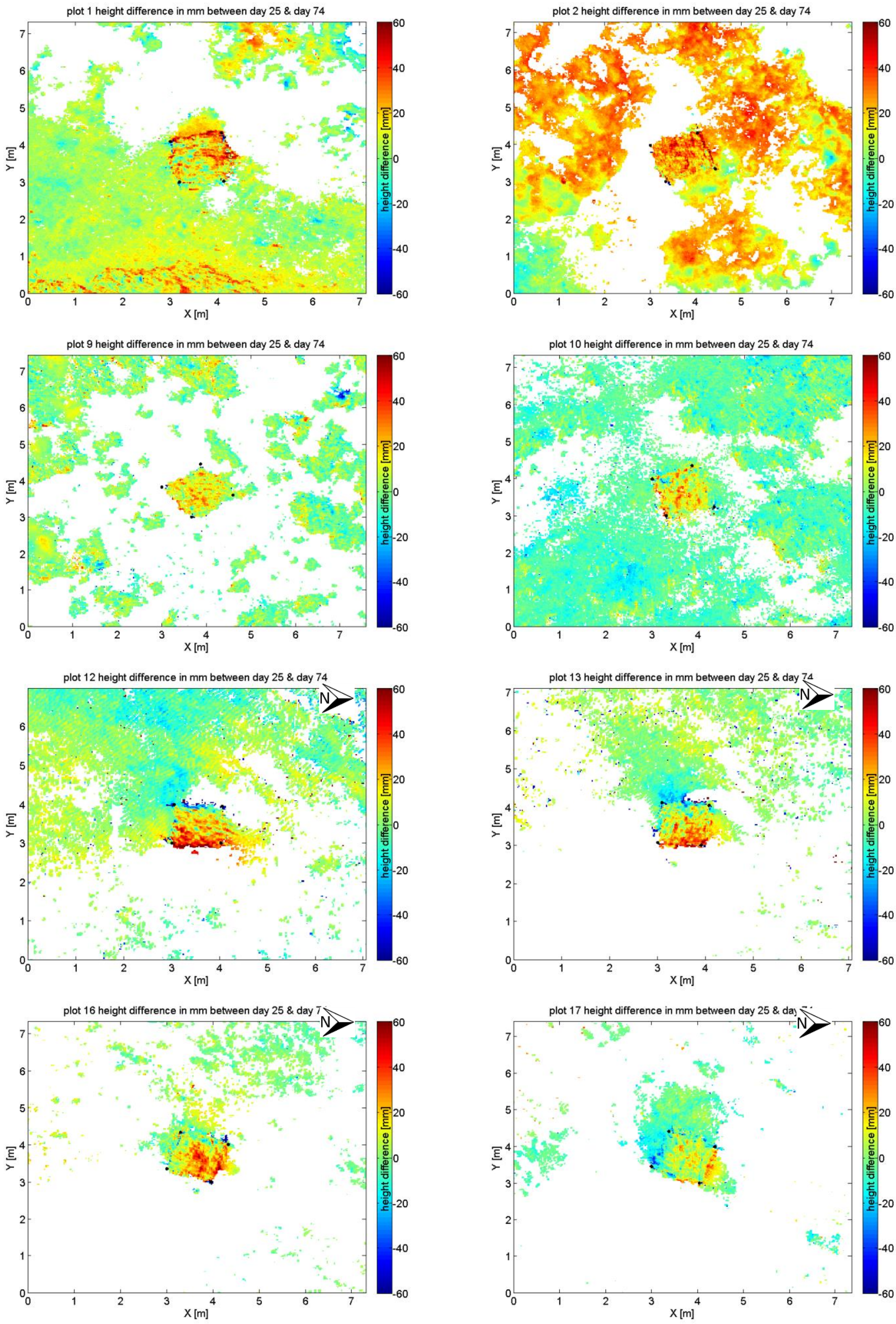

Figure 7-7 The height difference [mm] over the entire fieldwork period is shown for areas of 3m around the plots.

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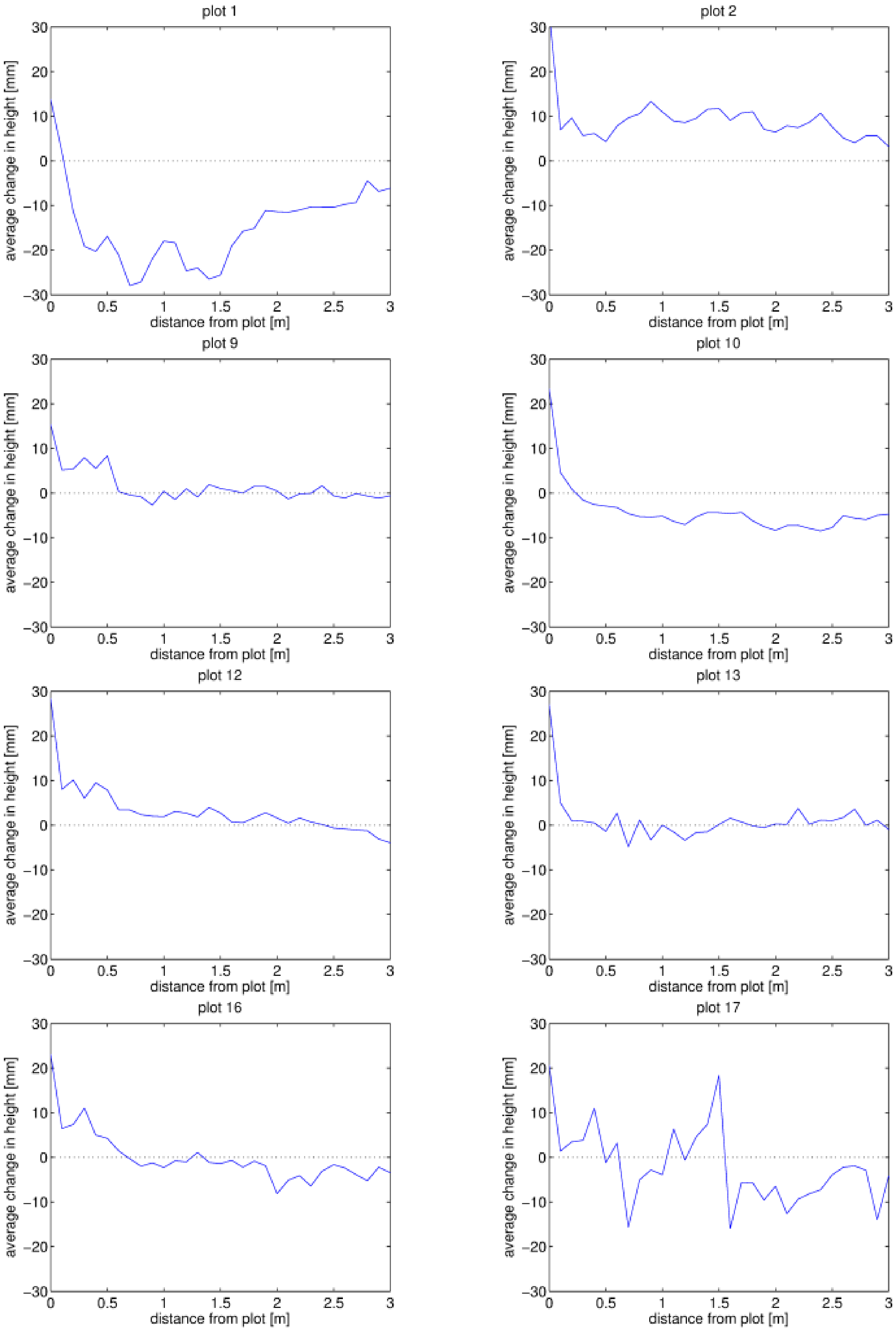

Figure 7-8 The average change in height [mm] for 10 cm intervals around the plots

Figure 7-8 also shows that most areas have either a less positive or more negative change in height in the intervals further away from the plot, than in the more nearby intervals. This means that the influence of the plot has a maximal extend and that the change in height in the intervals further away from the plot, represents the general change in height of the entire area. For most areas the trend of the area varies with 5 (plot 9 and 10) to 10 mm. Only area 1 has in the intervals further than 1.5m around the plot, a less negative change in height, than in the intervals in between the plot and the first 1.5m. In the southern part of area 1 lies however the edge of the mussel bed. The average change in height for the intervals further than 1.5m around the plot is only lower than in the plot itself, because in the east, west and north of the plot still erosion takes place.

Figure 7-8 has indicated that the influence of the plot on the amount of sedimentation or erosion in the area around the plot, decreases with distance from the plot. Furthermore are wiggles present in most of the graphs. It was stated that this wiggles are probably caused by local differences in the morphology or by differences in sedimentation and erosion trends for several directions around the plot. In Figure 7-4 was already the average change in height for 45° intervals inside the plots shown. This figure however also contains the average change in height for the area outside the plots, which is shown by the red lines.

Figure 7-4 shows that the change in height in the areas around the plots lies close around zero. The change in height in the areas around the plots is thus much lower than in the plots itself and the height can even be negative.

In plot 1 a negative change in height occurs at almost all directions around the plot. Only in the south west a positive increase in height occurs. Furthermore is it striking that the change in height in the plot is controversial to the change in height in the area around the plot. For area 16 this is also the case for most intervals, but for this area it is less apparent than in area 1. The trend is however not observed in the other areas. These areas have in general approximately the same pattern in the change in height over the intervals, as over the plots .

Area 2 experiences a positive change in height at almost all directions around the plot. The increase in height is however the largest in the north west, while it is slightly negative in the south east.

Area 9 has a very small variation in the change in height around the plot. Also is the difference in the change in height inside the plot and the area around the plot relatively small. The height increases slightly in the north west to north east, but it is negative over most of the directions. The largest decrease in height occurs in the south west, in the interval between 180 and 225°. The same pattern is visible in area 10. This area experiences a decrease in height in all intervals, but the decrease is the largest in the south west, and the smallest in the north east. In paragraph 7.1.1 was however already mentioned that it is the south of the mussel bed, which experienced a general decrease in height, while the middle of the mussel bed (in the north east of the plots) experiences an increase in height.

For the areas at the bare sand bank the variation between the several intervals is most of the time relatively small. The variation over the intervals follows approximately the variation for the intervals in the plot, the magnitude of the variation is however much smaller. Both in areas 13 and 17 there is however a relatively large difference in the change in height between the interval of 90 to 135° and the other intervals around the plots. These areas lie on one line and the trend of the average change in height for these intervals is relatively similar. Areas 12 and 16 lie also along one line, but these areas have different trends for the intervals around the plots and there are no large scale wiggles.

Until now the average change in height and coverage of the plots has only been analysed separately. Figure 7-9 shows however two comparisons between the initial height map and the map, with the differences in height; and the initial and final photographs of the plots.
In plot 1, which experienced a decreases in mussel coverage, mussels have moved close towards each other, or mussels and dead mussel shells disappeared. Empty spots are formed. The spots are often connected to each other and form bends. A labyrinth like pattern between higher located mussels and the lower located bare spots is present. The mussels lie higher due to the clustering and sedimentation below them, while the bare spots experience a decrease in height both due to the disappearance of the mussels and due to erosion of bed material. The bare places developed at locations, which were initially bare, or lied relatively high. The mussels are mainly located at the places which were also in the initial situation covered with mussels and lied relatively low.

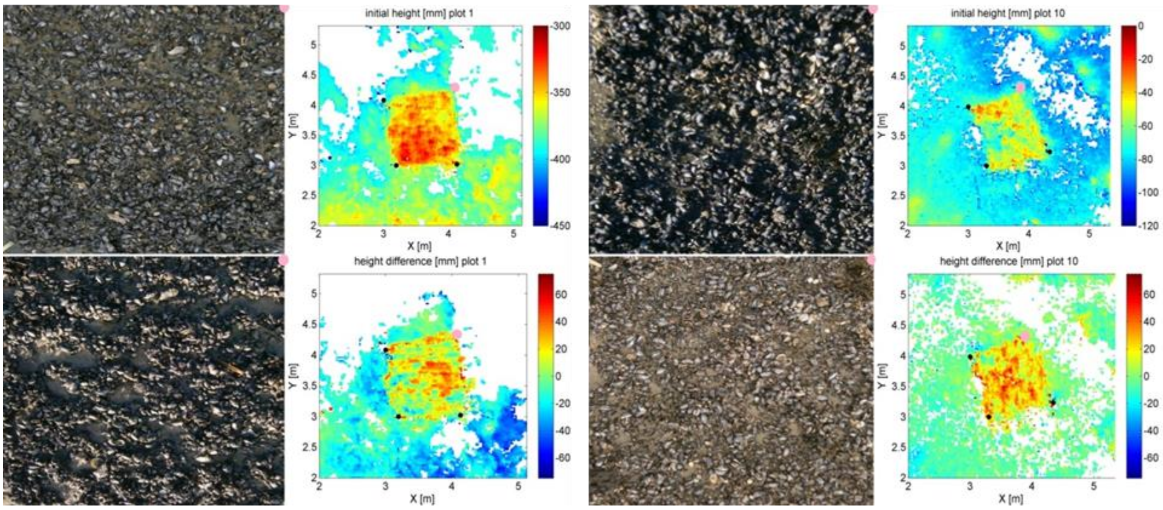

Figure 7-9 The figure shows both the photographs of the initial and final situation of plots 1 and 10. Furthermore is a map with the initial height of the plot and the difference in height over the fieldwork period shown. In all the separate figures is the most northwards located corner pole indicated by a pink dot.

The trend, as described by the photographs and height map of plot 1, is however different for the other areas, examined during the fieldwork period. So are for the plots inside the mussel bed also relatively large rates of sedimentation observed in between the mussels and it are especially the initial differences in height inside the plot, which are smoothened out. This is visible in the right part of
Figure 7-9.
The plots at the bare sand bank, show again another trend. It are locations below mussels, which experience larger increases in height, than bare locations. There is also a larger trend in the sediment dynamics over the plot, since all plots in these areas experience an increase in height in the north and north east of the plot, while the height decreases in the south west. This trend is larger than the differences between sedimentation or erosion for the locations with or without mussels.

7.1.5 The general trend in the sediment dynamics over time

The change in height in the 3m areas around the plots

Until now differences in height were only shown for the entire fieldwork period. This paragraph will identify the general erosion or deposition trend in the area over time, too see whether the change in height during the fieldwork was constant or varied.
For the analysis the 3m area around the plots are used. Only grid cells, which contain data for all monitoring days are selected to calculate the average change in height. The results are shown in Figure 7-10.

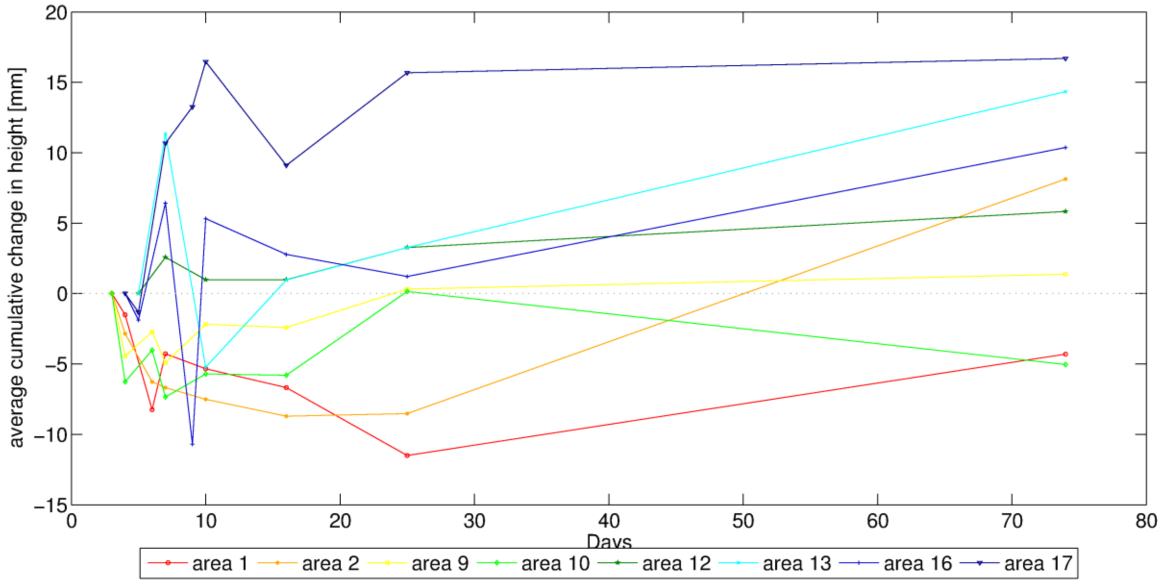

Figure 7-10 The cumulative change in mass for the areas around the plots

The figure shows that there is no general trend in the change in height for the areas over time. There are similar changes in height for the areas, which lie close together, but even for those areas, there is often a period with different behaviour of the areas.
Area 1 and 2 show similar trends, until day 16. The change in height for area 1 is often larger than for area 2, but the total cumulative change in height at day 16 is approximately the same for both areas. Between day 16 and day 25, the height of area 2 however starts to increase, while the height of area 1 still decreases. From day 25 to day 74 the height of both areas increases, but then the increase in height of area 2 is much larger than the increase in height of area 1. The final result at day 74 is a negative cumulative change in height for area 1 and a positive cumulative change in height for area 2. In the former paragraphs became however already apparent that this difference in the average change in height between area 1 and 2 is caused by the fact that area 1 lied on top of the bank, which moved inside area 2, so area 1 became to lie in the through.
Areas 9 and 10 show similar trends up to day 25. The change in height of area 10 is however larger than that of area 9. The same trend was also visible by areas 1 and 2. At day 25 both areas have approximately the same cumulative change in height, close around zero. After day 25 the height of area 9 increases further, while the height of area 10 decreases again. Therefore the total cumulative change in height at day 74 is negative for area 10 and positive for area 9.
Day 5 is for areas 12 and 13 the first monitoring day. From day 5 to day 7 the height of both areas increases. The increase for area 13 is larger than for area 12. After day 7 larger differences become visible. Between day 7 and day 9 the height of area 13 decreases by a large amount, while area 12 shows still an increase in height. Between day 9 and 16 the change in height is still opposite. Area 13 has an increase in height, while the height of area 12 decreases. Between day 16 and 25 the differences in the cumulative change in height between the two areas, become very small, because area 13 than experiences a much larger increase in height than areas 12. After day 25 the height of both areas stays increasing, but

the increase for area 13 is smaller than for area 12. Therefore at day 74 the cumulative change in height for area 12 is more positive than for area 13.
Area 16 and 17 show most of the time opposite trends. Only between days 4 and 7 and 10 and 16, the trends are the same. The largest difference in the change in height between the two areas, occurs between day 7 and day 9. Over this period the height of area 16 decreases with a very large amount, while the height of area 17 increases.
It became apparent that both areas 12 and 13 and areas 16 and 17 show opposite trends. Areas 16 and 13 show and areas 12 and 17 have the same trend in the change in height over time. This could be caused by the fact that these areas lie in one line, probably in the same direction as the currents.

The change in mass for the plots itself
Figure 7-11 shows the average cumulative change in height for the plots. In contrary to the 3m areas, all plots show a positive change in height, over the entire fieldwork period. The change in height of the plots is more similar than in the 3m areas. The change in height of plot 2 now resembles the change in plots 9 and 10. Only plots 1, 12 and 13 show large differences for some monitoring intervals.
Plot 1 shows a different trend between days 16 and 25. The difference has become more abrupt when only the plot itself is examined. This means that the plot itself has the largest average change in height. The surrounding area has either a smaller or an opposite change in height. Another abrupt difference occurs for plots 12 and 13, between day 7 and 16.
In paragraph 6.4 became however already apparent that differences in height are not only caused by patterns in sedimentation, but also by displacement or even erosion of mussels. Furthermore was apparent that not all parts of the plot showed the positive or negative changes in height. It is expected that these factors cause the irregularities of the change in height of the individual plots.

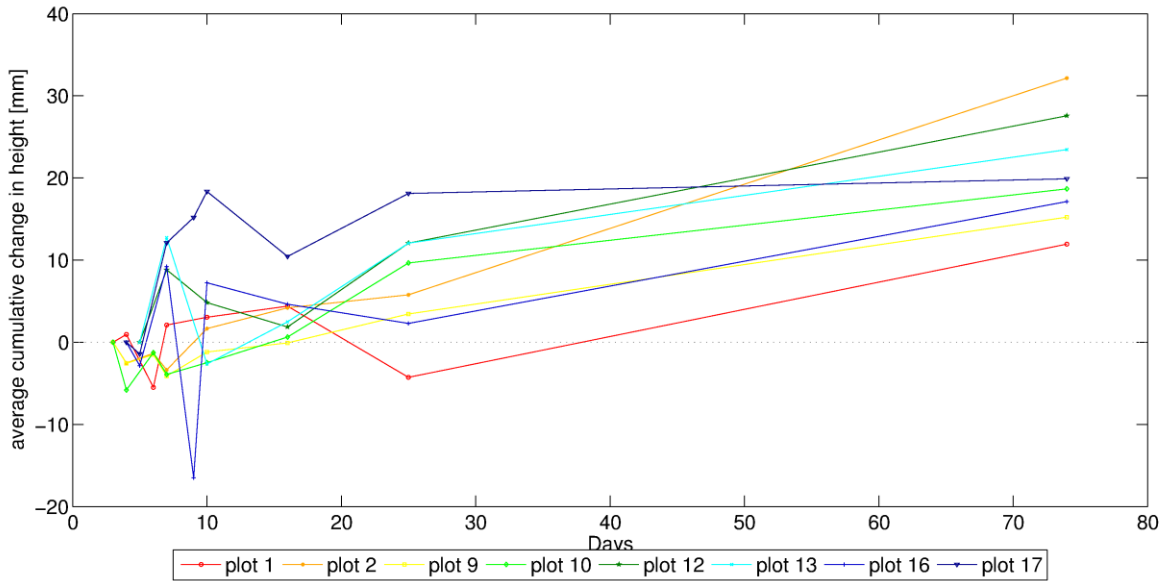

Figure 7-11 The cumulative change in height for the plots itself

By comparing Figure 7-10 to Figure 7-11, it becomes apparent that the change in height differs for the plots and the surrounding area. This was also concluded in paragraph 7.1.2. In that paragraph the change in height over the entire fieldwork period was analysed for 10cm intervals around the plot. The change in height however varies for the monitoring intervals. Therefore is the analysis of paragraph 7.1.2 applied to intervals between successive monitoring days. The results of this analysis can both be found in Appendix A3 and Table 7-2. The table summarizes the appendix. It is apparent that for most of the areas, the plots itself have a larger positive or less negative cumulative change in height over time. The table shows for all plots the amount of monitoring intervals, in which the highest increase, the smallest decrease, the smallest increase or the highest decrease in height took place.

Table 7-2 The table shows the percentage of the time between two monitoring events, that the plots have either the smallest; or the smallest or highest change in height, when compared to the intervals around the plot.

Plot	Total intervals	Highest increase	Smallest decrease	Smallest increase	Highest decrease
1	7	4	1	0	0
2	7	4	0	0	0
9	7	3	1	1	0
10	7	4	0	1	0
12	5	2	0	0	1
13	5	3	1	1	0
16	7	2	0	0	3
17	7	3	0	0	2

Table 7-2 shows that the plots created in or around the original mussel bed (plots 1, 2, 9 and 10) have either enhanced rates of sedimentation inside the plot, or decreased amounts of erosion, compared to the areas around the plot. When this is not the case, Appendix A3 shows that it are often other parts of the mussel bed, or the first 10cm around the plots in which even lower rates erosion or higher amounts of sedimentation are found than in the plot itself.
For the plots, created at the bare sand bank, the amount of sedimentation inside the plots is often larger than in the surrounding area. When the sedimentation inside the plot is not the highest, it is often again in the 10cm area around the plots that higher rates of sedimentation occur. It can however not be concluded that the amount of erosion inside these plots is lower than in the surrounding areas, because there are more monitoring intervals over which the plots at the sandbank experience an enhanced amount of erosion, compared to the surrounding areas. This could however be caused by the fact that especially in these plots at the bare sand bank, large gaps developed in the mussel coverage. Mussels became eroded or became partly disconnected and were placed in the first intervals around the plots. This results than in larger increases in height in the intervals around the plots, but a decrease in height in the plot itself.

Differences in height for the several monitoring intervals

In paragraph 7.1.2 maps were shown, with the changes in height for the 3m areas around all plots over the entire fieldwork period. These maps with the differences in height are also made for all monitoring intervals. It is decided not to show all maps, but to show as an example only the development of 2 plots during some monitoring intervals. Plot 10 is chosen to represent the plots inside and in front of the mussel bed. Plot 17 is chosen as example for the plots at the bare sand bank. These plots were either the most representative or contained the largest amount of data.
In Figure 7-12 the height difference for the 3m area around plot 10 is shown for four intervals in the fieldwork period. The first interval is the only interval, during which more monitoring took place. In this period the height was measured approximately every two days. The changes between the individual successive monitoring days was however minimal and varied for all days. The same processes, patterns and variation in erosion or deposition are visible in the maps, which are now shown in the figure. The maps indicate that the differences in height over time are minor and can either be positive or negative. This variation is probably caused by the variation in both the orbital velocities below the waves and tidal velocities, which will be examined in the second part of this chapter. It is however apparent that in some monitoring intervals, local differences in height are created, which are smoothened out again during another period. This trend is however not visible in the plot. In the plot there is a variation between increases and decreases in height, but it are often the same locations in which a positive change in height occurs during the several periods. It are other locations in the plot, which experience a negative or sometime a small positive change in height during almost all periods. Also is visible that it are often the edges of the plot, or other higher located areas, which experience the largest changes in height. This could however be caused by the shadow effect of the laser scanner, which is examined in Appendix 2.

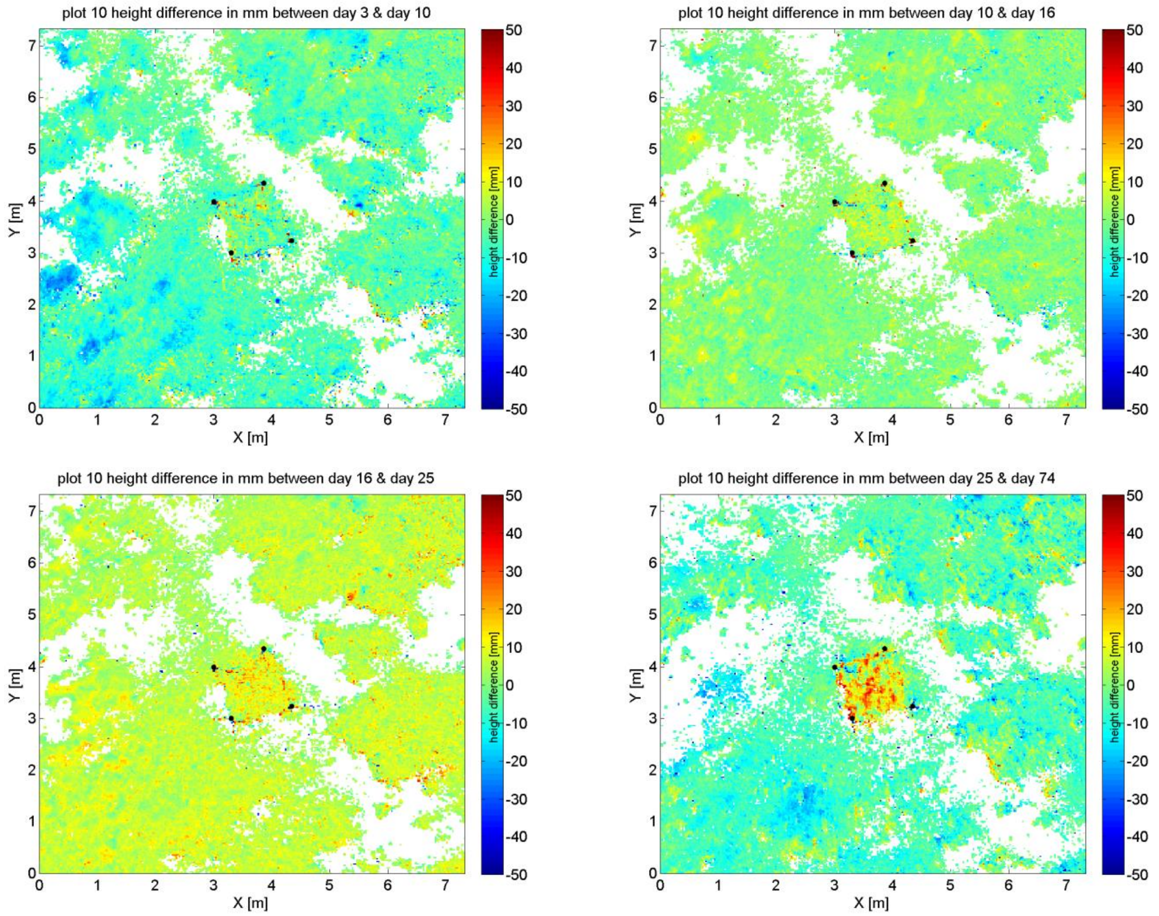

Figure 7-12 The differences in height [mm] for area 10, shown for four intervals.

Figure 7-13 shows height differences for area 17. Six monitoring intervals are shown, so small scale variations, which occurred around the plots at the bare sand bank, are visible too.
Over the first interval there are only minor changes in height in the area around the plot. There is however often a sequence between an increase and a decrease in height. This sequence is caused by ripples, moving through the area. In the plot is the same sequence visible, but the width of the bands is wider and in another direction than in the area outside the plot. Therefore it is expected that changes in height inside the plot are caused by moving and clustering mussels, instead of by sand ripples moving through the plot.
The second monitoring interval lasts 2 days. The general change in height in the area is positive. Especially the plot itself experiences a relatively large increase in height. The largest increase however occurs at the edges of the plot.
The third map has a relatively large amount of data points. The map shows that over the entire area the ripples are elongated in the same direction. The sequence between troughs and tops of all ripples is over a northeast-southwest transect. In the meanwhile it is both the northern part of the plot and the area north of the plot, which experience the largest decrease in height, while both the south of the plot and the area in the south of the plot experience a relatively large increases in height.
Over the fourth monitoring interval is the difference in height between the north and south of the plot, smoothened out. An increase in height occurs along the northern edge, while the height of the southern edge decreases. Inside the plot are the differences in height smoothened out too. Locations with an increase in height during the third interval, have a decrease in height and vice versa.

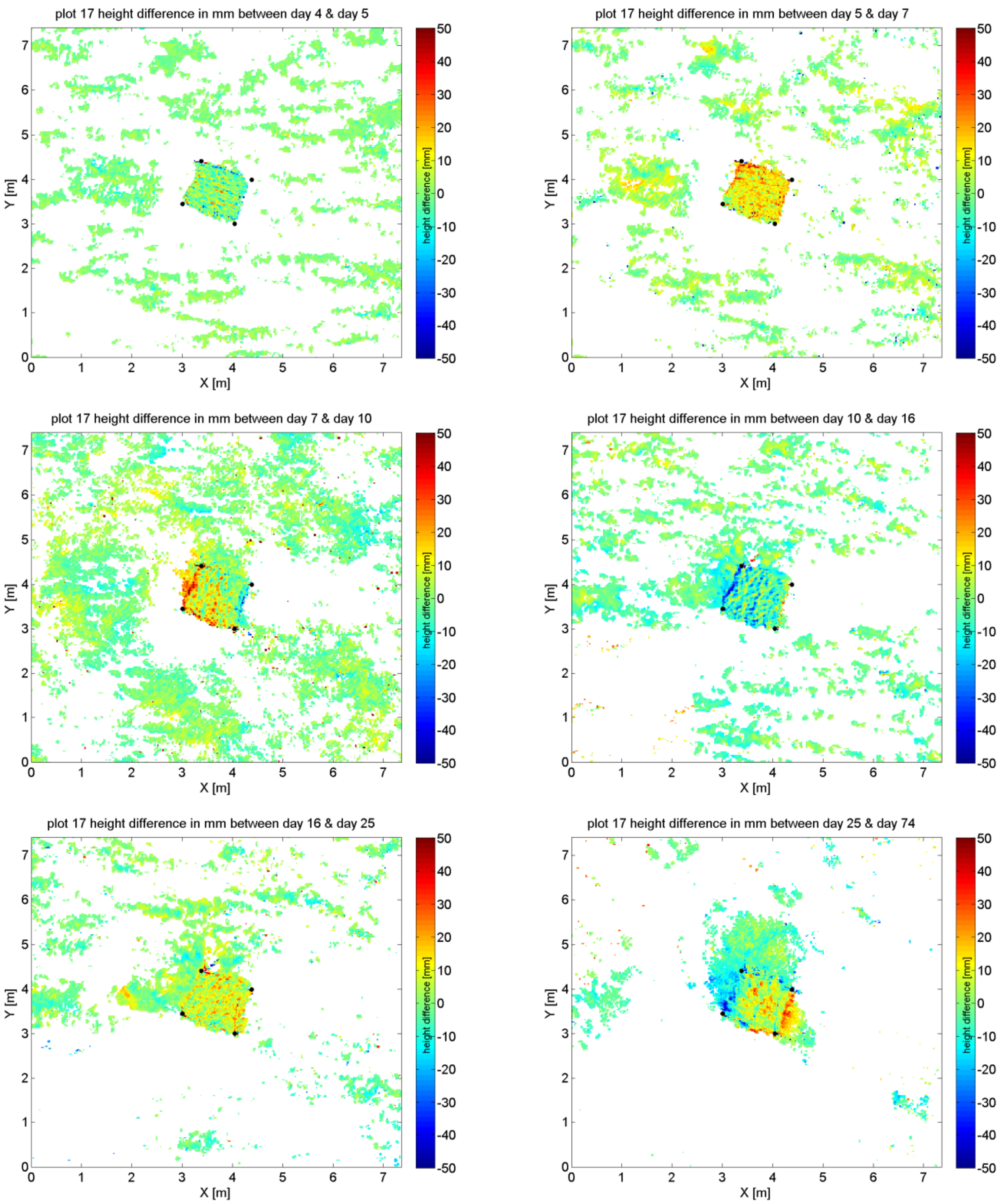

Figure 7-13 The differences in height [mm] for area 17, shown for six intervals during the fieldwork period.

Over the fifth period the major part of the plot experiences an increase in height. Also the areas close to the edge of the plot are raised. In the area around the plot is furthermore still the sequence between increases and decreases in height, due to moving ripples, visible.
The most apparent observation for the last period is that the north east corner of the plot and the area around this corner, have experienced a relatively large increase in height. In the meanwhile the height of the south west corner and area around the plot has decreased. In paragraph 7.1 became already apparent that almost all plots at the sandbank experienced an increase in height along the north east corner or along the eastern part of the plot, while the south west corner or western part of the plot experienced a decrease in height. The photographs of two monitoring days, shown in Figure 7-14 indicate that the part of the plot and the area behind the plot, which experiences the largest rates of sedimentation, changes over time. For 2 October (day 16), shown in the left part of the figure, is visible that the area in the southwest of plots 13 and 14 (in the right of the photographs) is emerged above the water, while the other areas around the plot are submerged. This probably means that the

emerged area lies higher than the submerged areas. At 29 November (day 74), shown in the right of the figure, it becomes however apparent that it is now the area in the north east of the plot, which is emerged. The other parts of the area around the plot and even parts of the area in the southwest of the plot, which was completely emerged at day 16, are now emerged. It is expected that this variation is caused by the direction of the currents, which can vary over time.

Figure 7-14 Photographs of plots 13 and 14, made at 2 October (day 16) and 29 November (day 74)

The large scale variation between sedimentation at one side of the plot and erosion at the opposite site, is only visible for the plots at the bare sand bank. Figure 7-12 and the maps of the other plots around the mussel bed, indicated that for these plots there is no clear pattern found between sedimentation in one part of the area and erosion in another part. For these plots it was only apparent that it are mainly the initial differences in height, which are smoothened out and that the plots or patches with mussels, experiences almost always the largest increase or the smallest decrease in height.

7.1.7 Difference in sediment composition

The organic matter content

During the fieldwork period several sediment samples have been taken, at 20 cm in front, in the middle and 20 cm behind plots 3, 8, 13 and 17, which lie in study areas A, B, C and D respectively. As well the amount of organic matter, as the grain size division and clay content of the samples are determined. Figure 7-15 shows the percentages of organic matter at the measurement locations.

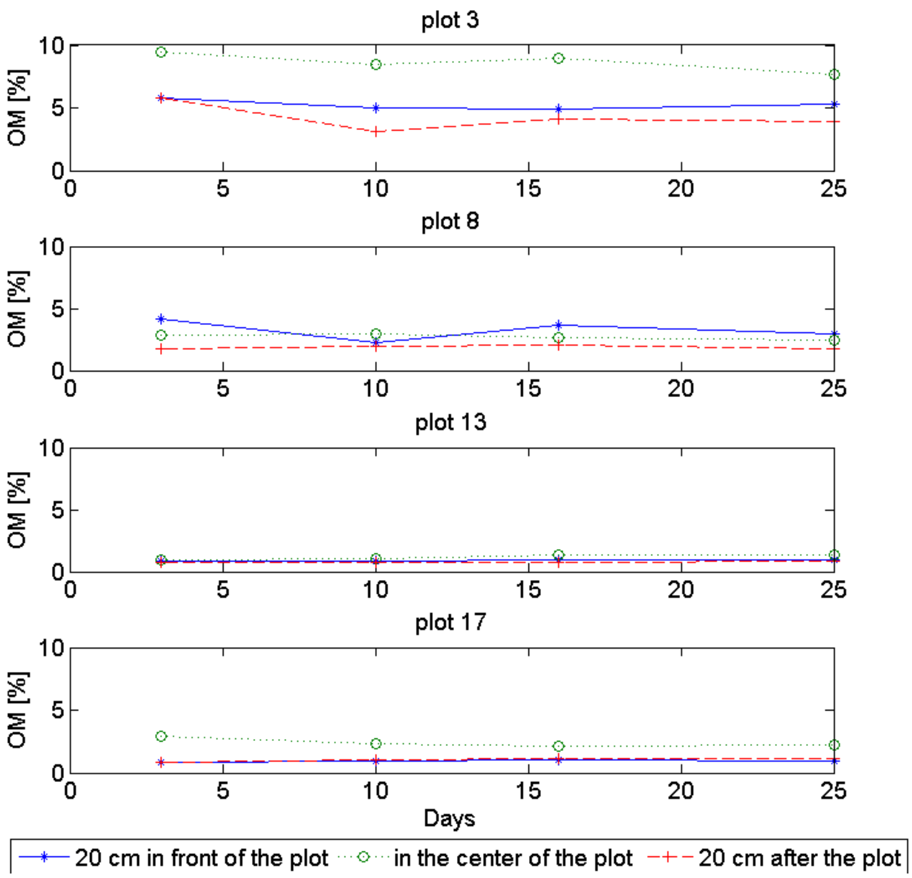

Figure 7-15 Change in the percentage of organic matter for the four plots over time

In the figure is visible that although mussel plaques for the plots were taken out of the same area of the mussel bed, already large differences in the organic matter (OM) content of the plots are present at day 3. Plots were created at day 1 and 2 and the plots could have shown a fast adaptation to their new circumstances. This is expected, because the figure indicates that in general the variation in OM over time is much lower than the initial difference in the OM of the plots. It is especially plot 3, which has a much larger OM content than the other plots. Plot 3 was however created in a very muddy area in front of the mussel bed, with algae at the surface, while the other plots were created in more sandy areas without algae mats.
The figure shows that except for plot 8, the percentage of OM is almost always the largest in the centre of the plot. The difference between the OM content in the plot and outside the plot is relatively large. Furthermore is the variation inside the plots larger than the variation around the plots and it is not possible to state whether it is the location in front or behind the plot, which resembles the trend of the organic matter content of the plot the best. For plots 3 and 8, it is the location behind the plot, which shows the same variation, while it is the location in front of plot 13. For plot 17 both the variation in the plot and difference between the locations in front and behind the plot are very small.
In the figure is furthermore visible that the samples not always show the same variation in OM over time. For the first period, from day 3 tot day 10, plots 3 and 17 show a decrease in OM, while the OM of plots 8 and 13 stays approximately the same. Almost all locations around the plots show also either a decrease or an almost constant OM content. During the second period it are plots 3 and 13 for which the OM content increases. The increase in OM for plot

13 is however much larger than for plot 3. In the meanwhile plots 8 and 17 show a small decrease in OM, while the OM in front of plot 8 increases and the OM behind plot 8 and around plot 17 stays the same. For the last period, three plots show a decrease in OM, plot 3, 8 and 13 respectively, while plot 17 shows an increase in OM. Furthermore is visible that again the areas around the plots have all different changes in their OM content.
It has thus become apparent that over time, the OM content of the several plots, differs too much to find a general trend in the OM content. In paragraph 7.1.4 became however apparent that there is also a large variation in the height of the several plots over time.

The median grain size

In the contrary to the organic matter content, the median grain size (D_{50}) is determined by the NIOZ institute. A part of the samples token during the fieldwork, were send to the institute. Some of these samples were too small for analysis. Therefor also the final part of the initial soil samples was send. For some of the locations there was now enough material to determine the D_{50} several times. Other samples however only contained just enough material to determine the D_{50} once. In Table 7-3 is the standard deviation for the several locations shown. It is apparent that the standard deviation for some of the measurement locations is relatively high. So is the largest deviation found in the middle of plot 3 The variation behind plot 13 is relatively high too. For the other locations the standard variation is lower than 8µm.

Table 7-3 The standard deviation [µm] for all measurement locations over time

location	Stdev Day 3 [µm]	Stdev Day 10 [µm]	Stdev day 16 [µm]	Stdev Day 25 [µm]
In front of Plot 3	1,95	0,95	0,35	3,00
In the middle of Plot 3	16,77	14,35	20,54	18,47
Behind Plot 3	5,10	2,02	1,30	3,05
In front of Plot 8	5,91	4,71	3,89	3,40
In the middle of Plot 8	1,49	3,63	0,00	1,00
Behind Plot 8	5,47	3,85	7,70	4,90
In front of Plot 13	2,85	0,00	0,20	2,60
In the middle of Plot 13	1,10	0,90	1,90	0,82
Behind Plot 13	16,25	2,20	9,30	1,60
In front of Plot 17	2,00	1,40	5,04	2,40
In the middle of Plot 17	0,05	0,45	1,69	2,55
Behind Plot 17	1,05	6,29	3,04	1,55

In Figure 7-16 the median grain size (D_{50}) is shown for the samples, taken during the fieldwork period. For all the plots, the variation in the median grain size over time, is significant larger than the standard deviation in between the samples taken at one measurement location. This means that the variation over time is significant. There is however no general trend in the variation in D_{50} of the four plots visible.
Relatively large differences exist in the initial D_{50} of the study areas. This observation was also done for the initial variation in the organic matter content. With a variation between 60 and 125µm plot 3 (area A) has both in front, in the middle and behind the plot, lower grain sizes than all other areas. Plot 8 (area B) comes with a D_{50} in the range between 100 to 160µm at the second place, with a higher D_{50} than plot 3, but lower than plots 13 and 17. The differences between plots 13 and 17 (areas C and D) are minor. For both plots the D_{50} for the location in front, in the middle and behind the plot, lies in the range, between 150 and 190µm.
Except for plot 8, the D_{50} in the middle of the plots is always lower than the D_{50} in front of the plot. Furthermore is the D_{50} for plots 3 and 17 in the middle of the plot always lower than behind the plot and this is during half of the time the case for plot 13. There are however no other trends visible, in the variation in D_{50}.

When however the variation in the organic matter content in Figure 7-15, is compared to the variation in the median grain size, shown in Figure 7-16, it becomes apparent that a decrease in D_{50} is often accompanied by an increase in OM and vice versa. This is logical, because organic matter particles have a relatively small grain size.

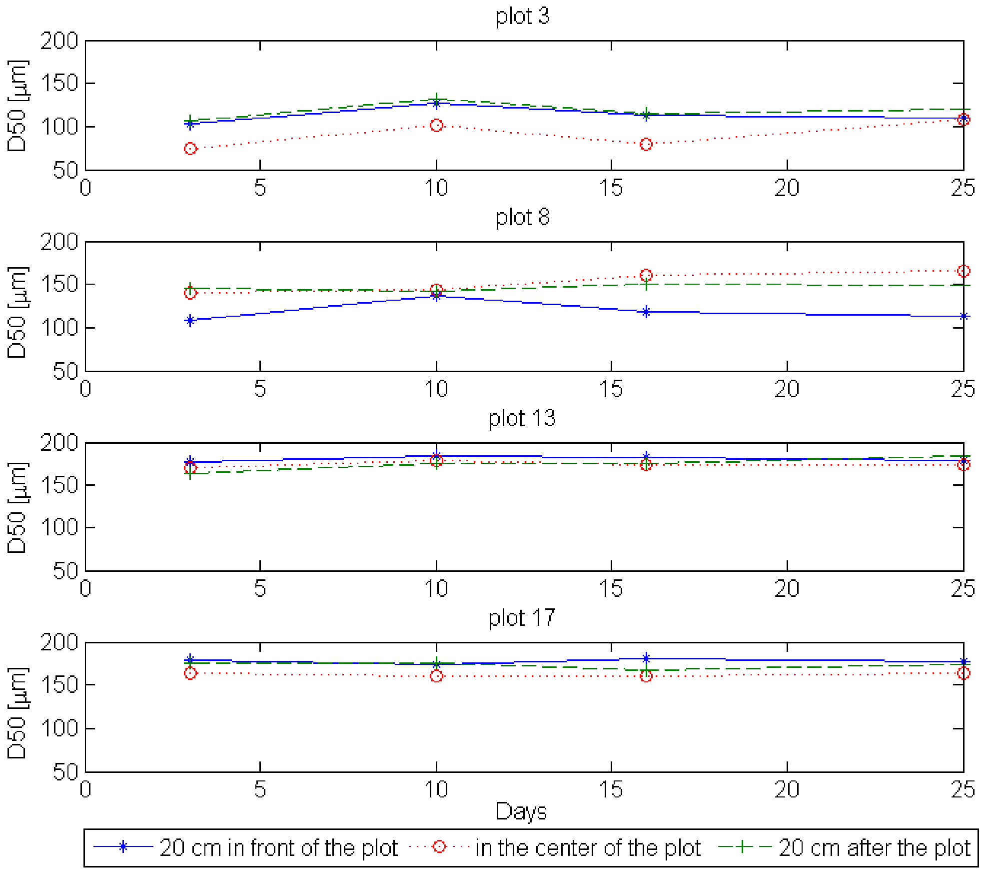

Figure 7-16 Change in the median grain size (D_{50}) for the four plots over time

The clay content

The clay content is the last factor of influence on the stability of the bed, examined in this research. The clay fraction contains all grains smaller than 2 µm. The clay content was also determined by the sediment analysis in the NIOZ institute. This means that also for the clay content multiple results for one sample were available. The standard deviation for each sample is shown in Table 7-4.

The standard deviation for the clay content seems smaller than the standard deviation for the median grain size, but the clay content is shown as a percentage. When the standard deviation is compared to the variation in the clay content over time, which is shown in Figure 7-17 it is apparent that the magnitude between the standard deviation and the variation over time is approximately the same for the clay content as for the gain size. Also is apparent that the standard deviation is again the largest in the middle and around plot 3.

Table 7-4 The standard deviation [%] in the clay content of all measurement locations over time

location	Stdev Day 3 [%]	Stdev Day 10 [%]	Stdev day 16 [%]	Stdev Day 25 [%]
In front of Plot 3	0,07	0,39	0,44	0,43
In the middle of Plot 3	0,60	0,74	0,81	0,69
Behind Plot 3	0,45	0,35	0,29	0,34
In front of Plot 8	0,10	0,04	0,38	0,26
In the middle of Plot 8	0,32	0,22	0,00	0,24
Behind Plot 8	0,12	0,07	0,03	0,08
In front of Plot 13	0,03	0,00	0,01	0,39
In the middle of Plot 13	0,04	0,04	0,08	0,09
Behind Plot 13	0,32	0,05	0,05	0,05
In front of Plot 17	0,05	0,06	0,07	0,04
In the middle of Plot 17	0,03	0,10	0,06	0,02
Behind Plot 17	0,01	0,07	0,07	0,12

In Figure 7-17 the volume of clay is shown as a percentage of the total volume of the sediment sample. Both the variation between the monitoring days and the difference between the four plots is visible. Over the monitoring days the variation in the clay content shows the same pattern as the organic matter content and a pattern controversial to the median grain size. For the individual plots there is however again no general pattern found in the variation in the clay content over time and for the locations in and around the plots. Differences between the four study areas are however clear. The plot in Area A, has a significant larger clay content than the plot in area B and the plots in areas C and D. Furthermore is it most of the time again the plot itself, for which the clay content is the largest. The clay content in front and behind the plots are approximately the same.

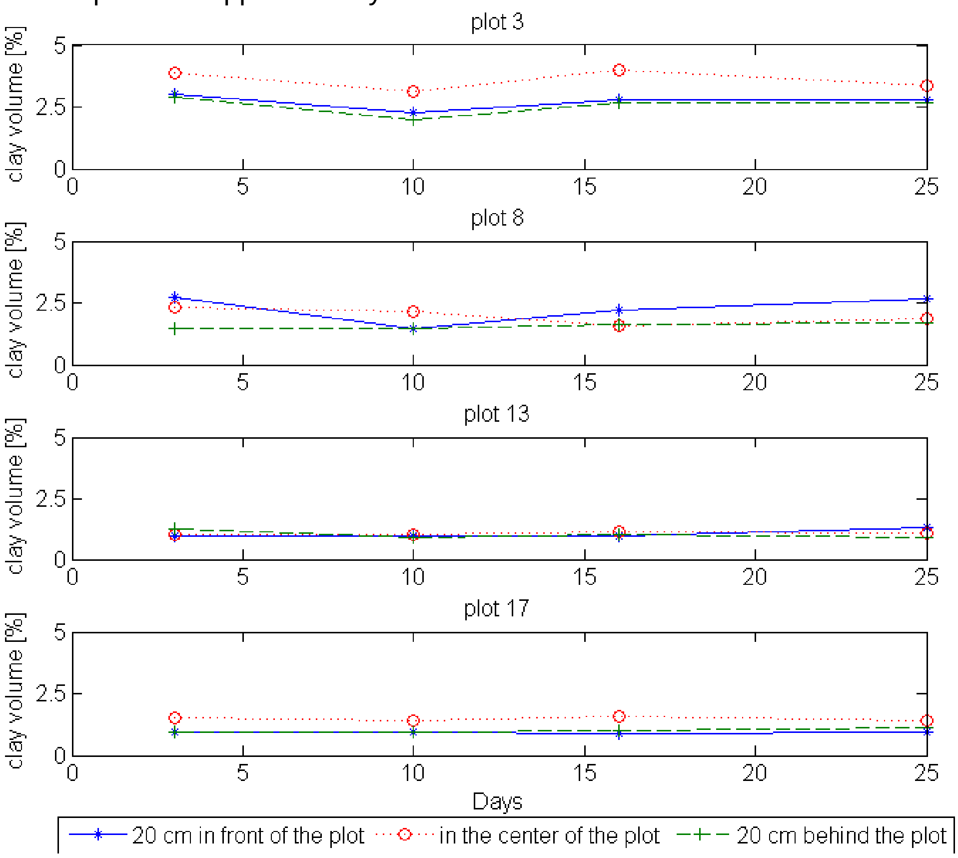

Figure 7-17 Change in the clay content for the four plots over time

7.2 Hydrodynamic conditions

7.2.1 The tide

It is the tidal water level, which determines whether the mussel bed and bare sand bank near De Cocksdorp are emerged or submerged. It is however the flow velocity of the tidal currents, which is important for the sediment dynamics, because the flow velocity determines the transport capacity and the shear stress between the bed and the water (van Rijn, 1993). ADV's measured the flow velocity at two locations. ADV1 was placed inside the mussel bed, while ADV2 was placed in front of the mussel bed. ADV2 is placed at a lower location, therefore this ADV contains more data for the ebb period. Figure 7-18 shows both the water level variation and the flow velocities at the locations of ADV1 and 2 for one monitoring day. The positive flow velocities indicate a flow in north wards direction (235 to 45 degrees), while the negative flow velocities indicate flow in southwards direction (45 to 235 degrees).

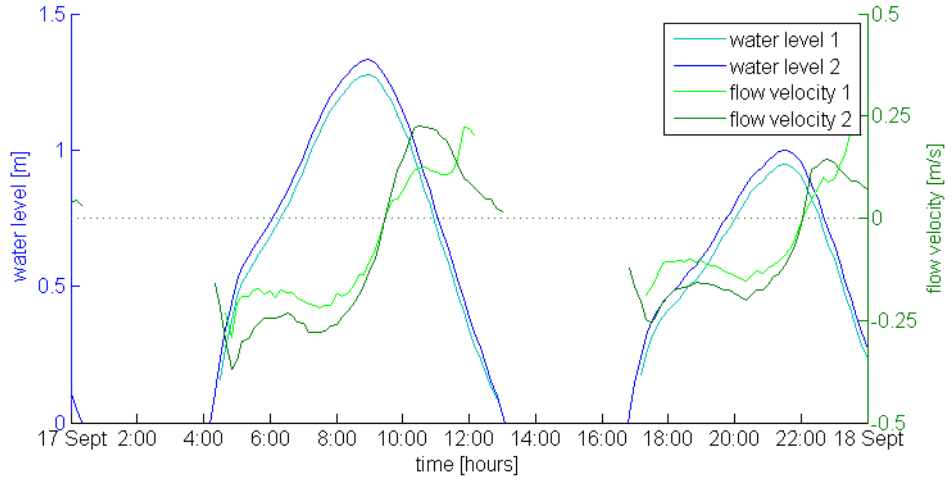

Figure 7-18 The figure shows the water level [m NAP] measured by pressure sensors 4 and 8 and the flow velocity [m/s], measured by ADV1 and ADV2.

Figure 7-18 shows that the tide near De Cocksdorp is a semidiurnal tide, since high water occurs twice a day. Flow velocities vary both for the individual tidal waves, and for the two locations. Velocities at location 1 are in general lower and the graph shows more deformations and wiggles, due to irregularities in cover and height of the mussel bed. For the second, lower tidal wave at 17 September, the maximal flow velocity at location 1 is larger than at location 2. The only common observation for both locations is that just after the moment that the maximal water level during flood is reached, the flow velocity changes its sign.

The semidiurnal variation is not the only variation over time. There is a 28 days spring, neap tide period. In the Netherlands spring tide occurs both two days after new and full moon, while dead tide occurs two days after the first and last quarter (Rijkswaterstaat, 2012). The first new moon during the fieldwork period was at 16 September 2012, so it was springtide at 18 September and 2 October, while it was neap tide at 25 September and 9 October. The spring and neap tide events are visible by the relatively high or low water levels in Figure 7-19, which shows the variation in the water level near De Cocksdorp, as measured by pressure sensor 4. Most of the time the average flow velocity is negative , due to the fact that the flow velocities during flood are in general larger than during ebb. However during neap tide the average flow velocity becomes positive.

The ADV measures the flow and magnitude both in north- and southwards as in east- and westwards direction, therefore it is possible to calculate the exact flow direction. In Figure 7-20 is visible that the largest part of the flow is going in a southwest direction for ADV2 and almost west direction for ADV1. Furthermore is visible that the largest flow velocities occur for the flow in these directions. This means that although the mussel bed is located in an intertidal area it cannot be stated that the ebb and flood flows compensate each other.

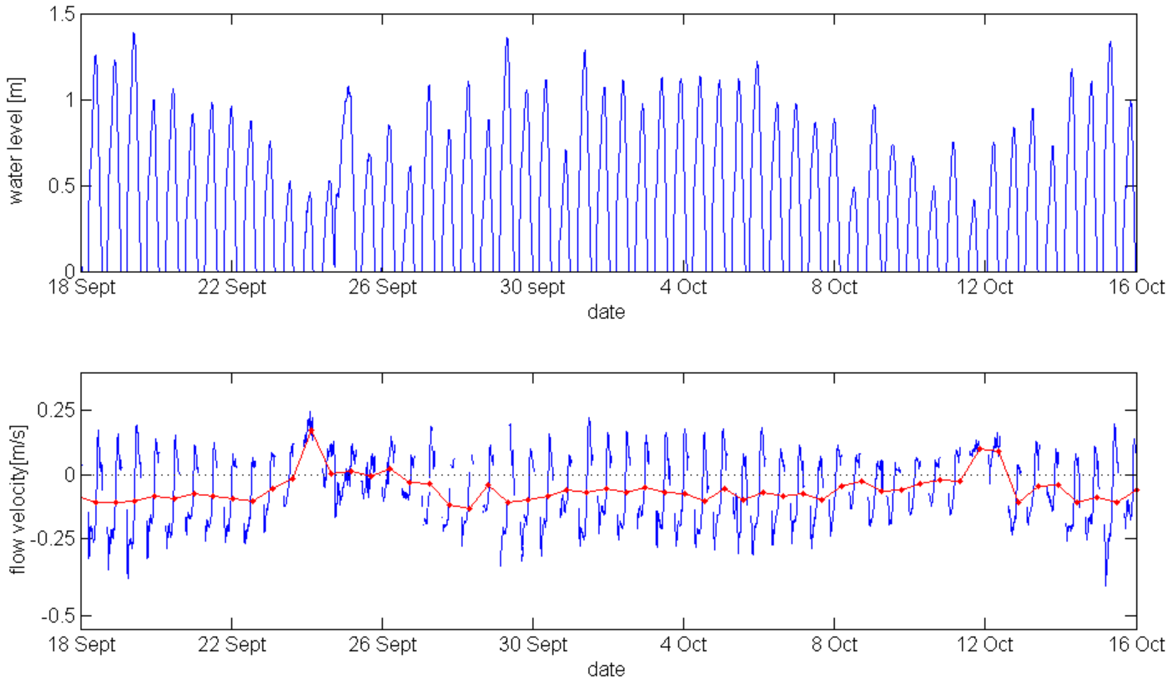

Figure 7-19 The upper part of the figure shows the water level for the first tidal cycle, starting with spring tide at 18 September 2012. The data is from pressure sensor 4. The lower part of the figure shows both the flow velocities (in blue) as the average flow velocity of one tidal wave, as measured by ADV2

Figure 7-20 shows that the major part of the flow and thus probably the major part of the sediment transport, will take place in a southwest direction. Furthermore the figure indicates that not only the maximal flow velocity is higher, but also that in general all flow velocities in front of the mussel bed are larger than the velocities in the mussel bed, which could result in an import of sediment in the mussel bed.

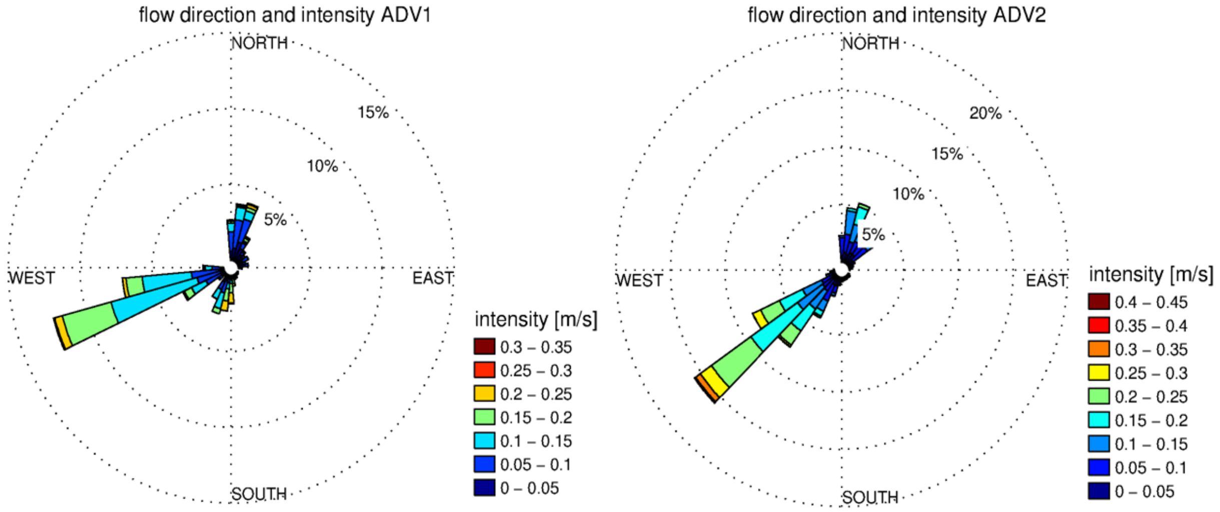

Figure 7-20 The figure shows for ADV1 both the intensity of the flow as the direction to which the flow is going

7.2.2 The waves

In the Wadden Sea waves are mainly locally formed by the wind (Kragtwijk, 2001). The direction, the strength and the duration of the wind are of influence. The direction of the wind determines the direction of the waves, while the strength and the duration determine the shear strength between the water and the wind, and thus the height of the waves.
Land or intertidal flats are present in the north, northeast, southeast, south and west of the mussel bed, so the fetch for wind coming out of these directions is limited. Therefore the mussel bed lies sheltered, and can only be exposed to higher waves, when the wind comes from the East (Donker et al., in press). In Figure 7-21 the wind direction during the fieldwork period is shown.

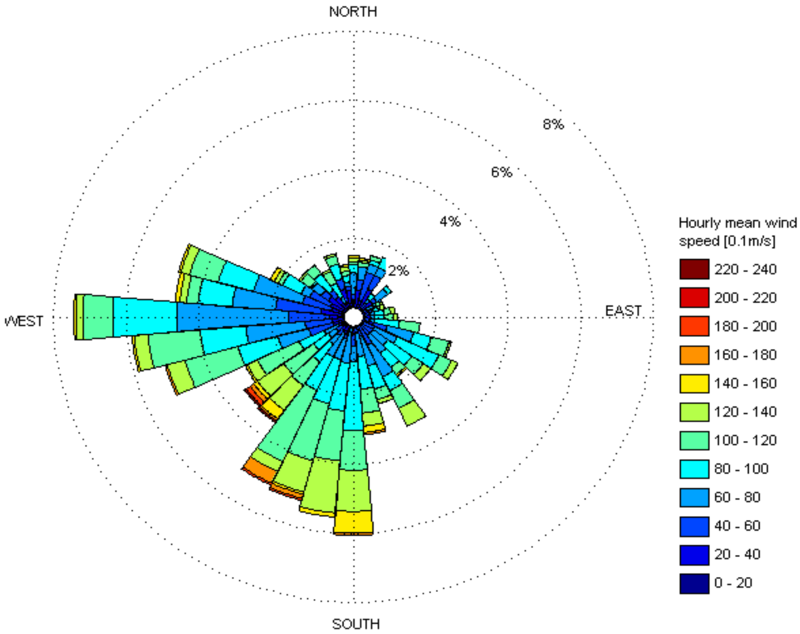

Figure 7-21 The hourly mean wind direction and intensity at Vlieland from 01-09-2012 to 21-11-2012 (KNMI, 2012)

The figure shows that the wind blew mainly out of a south to northwest direction and that he largest wind speeds came from this direction too. Periods with easterly winds (45° to 135°) occurred only during a minor part of the fieldwork period. Figure 7-22 shows that from 22 to 24 September and from 19 to 27 October two periods with eastern winds occurred. Furthermore there were some individual days with wind from the east. Neither for these periods with easterly winds, nor for the other wind directions a relation was found between the wind direction, wind strength and the wave height. This means that the wind data could not be used to predict the height and direction of the waves, during the last month of the fieldwork period, for which no hydrodynamic data is available.

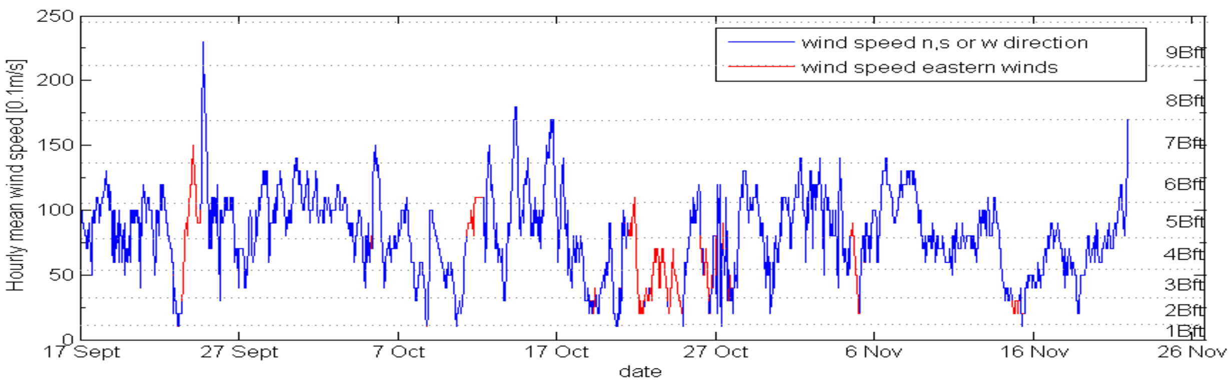

Figure 7-22 Hourly mean wind speed in 0.1 m/s at Vlieland during the fieldwork period (KNMI, 2012), *periods with eastern wind are shown in red*

Differences in the wave characteristics for the plots

Because of the variation in morphology, the wave height differs for the several plots. This paragraph analyses these differences, because they will result in differences in the sediment dynamics. In Figure 7-23 the difference in wave height is shown for the several locations. The figure shows that the wave height for all plots lies in a range from 0 to 25cm. Almost all data points in the upper left figure plot below the line y=x, so the wave height for plots 1 and 2 is higher than the wave height for plots 9 and 10. It is the friction of the mussel bed, which results in the lower wave height for plots 9 and 10. The difference in wave height between plots 12 and 13 and 16 and 17 is only minor. All points plot lie relatively close along the line y=x. The major part of the points however plots just below the line, so the wave height near plots 12 and 13 is during more than half of the time larger than near plots 16 and 17.

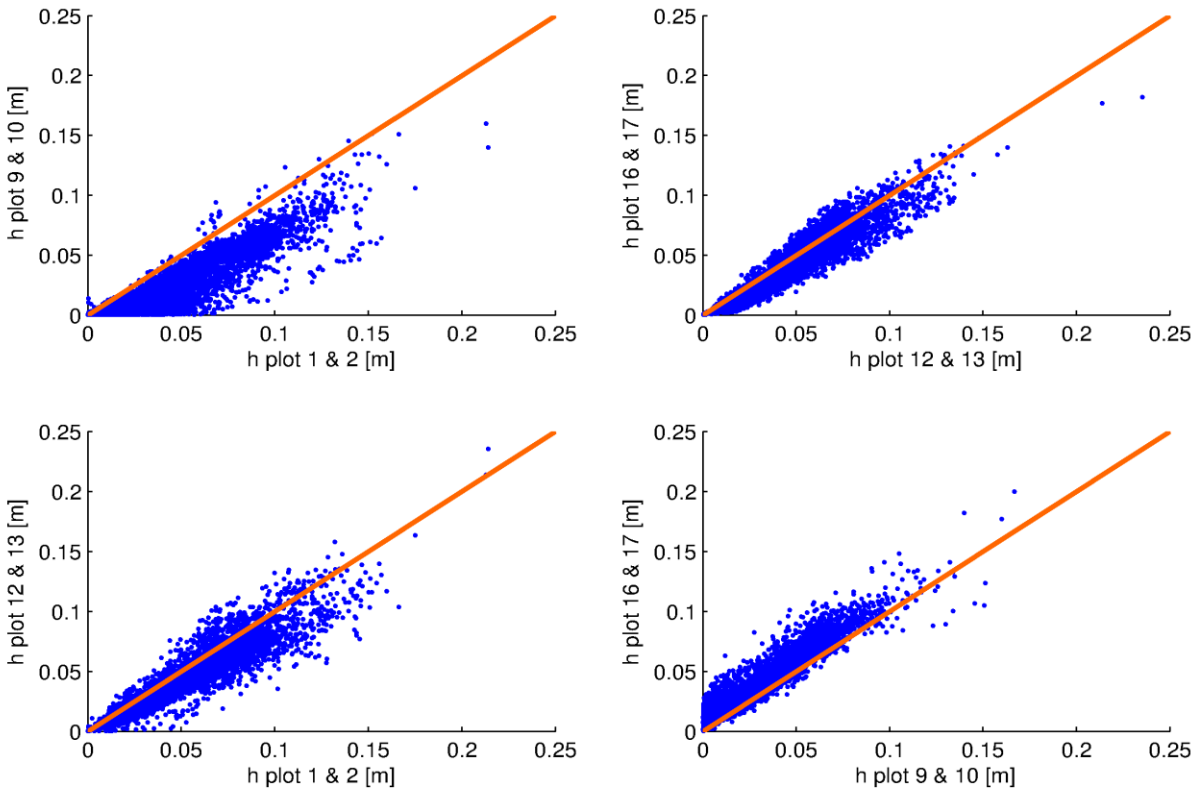

Figure 7-23 The upper figures show the relation between the 10 minutes mean wave height for the plots in the mussel bed and at the sand bank. The lower figures show the relation between the 10 minutes mean wave height of plots in front of and in the middle of the mussel bed or sand bank.

The upper two plots in Figure 7-23 indicate that plots 9 and 10 lie more sheltered than plot 1 and 2, while there is almost no difference in the amount that plots 12 and 13 and plots 16 and 17 are exposed to the waves. This was expected, because the mussels and the higher located mussel bed result in higher friction and thus an reduction in the wave height. When the wave height of plots 9 and 10 and 16 and 17 is compared to each other in the lower right part of Figure 7-23, it becomes apparent that plots 16 and 17 are almost all the time exposed to larger waves then is the case for plots 9 and 10. In the meanwhile plot 12 and 13 experience during the major part of the time smaller waves than plots 1 and 2. It is thus indeed the mussel bed, in between plots 1 and 2 and plots 9 and 10, which results in a larger reduction in the wave height over the mussel bed.

Until now only the wave height was given attention. However when linear wave theory is applied to the data, the maximal orbital velocity can be calculated too. It is this orbital velocity which is most interesting for the sediment transport, since it is this water movement, which can enhance or counteract the tidal currents. Furthermore it is the orbital velocity, which generates turbulence and thereby stirs the sediment. The orbital velocity is linearly related to the wave height, but it is also dependent on the wave period and the still water depth (Donker et al., in press). Figure 7-24 shows that the highest waves and thus highest orbital velocities occur, around the moment that the water level is maximal too. This means that for larger water depths more sediment is stirred by the waves than for smaller water depths. In paragraph 7.2.1 was however apparent that the flow velocity is close around zero, when the water level is maximal. The settling velocity of the sediment is however relatively low and the waves keep stirring the sediment, so a large part of the sediment stays in suspension and becomes transported when the velocities increase again.

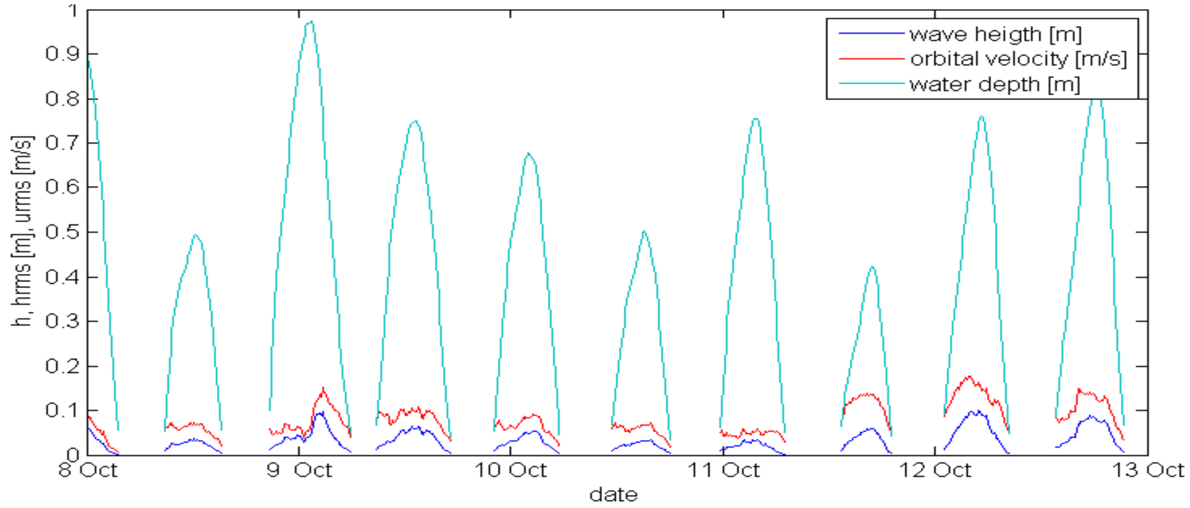

Figure 7-24 The figure shows both the wave height, orbital velocities and water depth variation due to the tide.

7.2.3 The general trend in hydrodynamic conditions over time

In the former two paragraphs the wave and tidal currents were discussed separately. It is however the combination between the stirring of sediment or mussels by the waves and the transport by the currents, which determine whether sedimentation or erosion of bed material and mussels take place. Figure 7-25 shows both the variation in the orbital velocity and average tidal velocity for the fieldwork period. The dotted lines indicate the days at which sediment samples were taken. These days, determine the several monitoring intervals. The figure however shows that there is no significant difference between the monitoring intervals. Only the second interval, between day 10 and day 16 differs significantly from the other intervals, because in this interval relatively low orbital velocities are accompanied by a small positive or small negative average tidal velocity. The daily variation in both the orbital velocity and average tidal velocity is however in general larger than the variation between the periods.

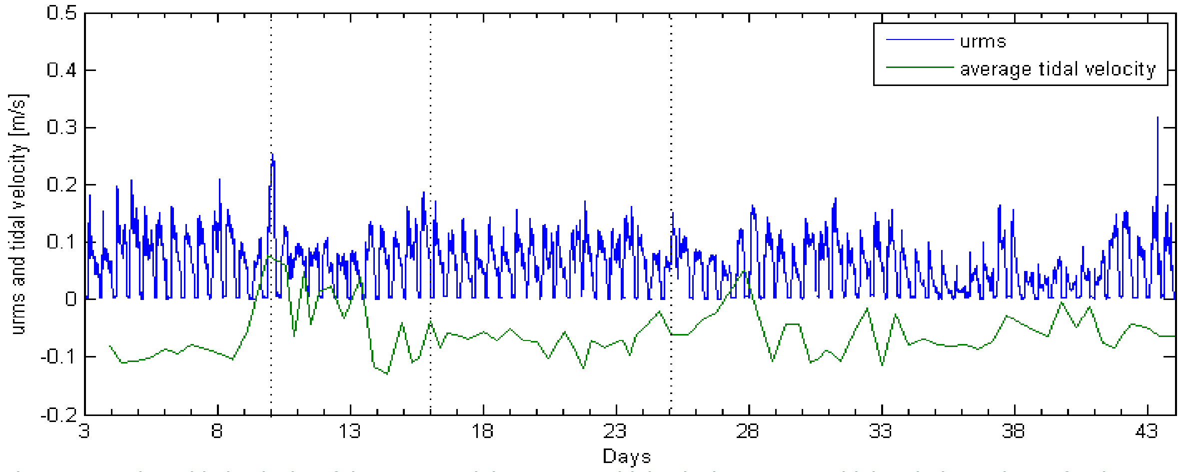

Figure 7-25 The orbital velocity of the wave and the average tidal velocity over one tidal period are shown for the monitoring days. The dotted lines indicate the several monitoring intervals

8 Discussion

The objective of this thesis was to closely follow the development of several newly created plots with mussels during fall. It was not the first fieldwork experiment, for which plots were created. Earlier research projects had also used plots of mussels. During those fieldworks the plots often disappeared within three weeks. Therefore it was expected that the plots created at the mussel bed near De Cocksdorp would disappear very soon too, or that only a few plots, would survive. By analysing the differences between the plots, which disappeared and survived, it would have become clear, what the best conditions are for young mussel beds to survive their first winter. Plots were created at four different locations. Area A lies in front of the mussel bed, area B in the middle of the mussel bed and areas C and D in front of and on top of a bare sand bank. Both the variation in height and sediment composition of the plots was monitored. Furthermore waves and tidal currents were measured. In the former chapter all individual results were given. To come to an answer on the research question it is however necessarily to combine these results. Therefore several sub questions were raised. The answers to these sub questions and the main research question, are given in this chapter.

Sub question 1: How does the height of the mussel patch and of the individual mussels evolve during the several hydrodynamic conditions that occur during fall?
Differences in height of the plots and hydrodynamic conditions have been described separately. Plots 2, 9 and 10 show approximately the same trend in erosion or sedimentation over the first days, but even for these plots there is no consistency between the magnitude of the orbital velocity, the average tidal velocity and the magnitude of either an increase or decrease in height. Differences in hydrodynamic conditions are however relatively small. Storm events occurred, but none with easterly winds, during which high waves can develop.
Only the spring and neap tide cycle did result in a significant difference in the average velocity and direction of the tidal wave. Plots at the bare sand bank were sensitive to these changes. Either the west or the east of the plots and the area close around that part of the plot, experienced a relatively large increase in height, while erosion was found in the opposite direction. Bouma et al., (2007) observed the lee effect, with erosion in the front and along the sides of an obstacle and sedimentation in the wake. During the fieldwork for this research another pattern is found. During neap tide (ea. between monitoring day 7 and 10) the average tidal velocity is directed towards the north east, while then the largest amount of sedimentation occurs in the south west. This is in front of the plot, not in the wake. The main flow direction is south west, while the largest rates of sedimentation occur in the north east. This sedimentation in however partly caused by the fact that mussels at this edge of the plot receive larger amounts of phytoplankton and therefore have a higher rate of biodeposition. The same pattern is observed in plot 1, in front of the mussel bed.
Another observation is that plots around the mussel bed showed either enhanced rates of sedimentation, or decreased rates of erosion, compared to the surrounding area. This was also observed by Widdows et al. (2002) and van Leeuwen et al. (2010). For the plots at the bare sand bank the trend was however different, because there were periods during the fieldwork that inside the plots an enhanced decrease in height took place. A change in height is not directly an indicator of sedimentation or erosion of bed material. Removal or displacement of mussels results in a change in height too. This is especially the case at the bare sand bank, where the coverage of the mussels decreased significant. The change in height however also contains some measurement errors. The lasers canner measures the height up to 5mm accurate and repeatable (RIEGL laser measurement systems, 2013). Errors are also introduced by combining the separate scans and interpolation of the data over a constant grid. A sensitivity analysis to different methods of combining the different scans, can be found in Appendix A2. It is mainly the direction of the laser scanner, which creates a shadow effect and differences in height between scans, because the height of a mussel is not constant for the different locations at which a laser beam measures the mussel. Interpolation of these measurements creates uncertainties up to 25mm, especially in the height of the edges of the plots.
For the plots at the bare sand bank there is however another factor of influence on the accuracy of the height maps. Reflectors were placed at plastic poles, which started to lean or were even pulled out, so less accurate tiepoints were available. To create more accurate

height maps of all plots, it is advised that only solid poles are used to place the reflectors on. Also is it advised to place an extra ADV in this study area too. Now are the direction and strength of the tidal currents only measured in front and inside the mussel bed and not at the bare sand bank. This makes it difficult to see, whether the tidal currents have indeed another direction and strength at the bare sand bank than around the mussel bed.

Sub question 2: In what way does the composition and thus stability of the bed change?
When differences in height are compared to differences in the organic matter (OM) content, the median grain size (D_{50}) or the clay content of the bed, there is no trend found. The D_{50}, OM content and clay content could both increase or decrease when the height of the plots or the surroundings increases or decreases. This can among else be caused by the fact that particles rich in OM and clay (faecal pellets) only erode for currents stronger than 0.2m/s, while other soil particles can erode at lower velocities (ten Brinke et al., 1995; Wotton and Malmqvist, 2001; Grabowski et al., 2011). A decrease in height is thus not always accompanied by a decrease in OM and clay. In the contrary an increase in height not always indicates an increase in OM and clay, because deposition not only takes place due to the filtration of mussels, but also due to increased friction and lower flow velocities. When flow velocities are relatively high, it is especially bio-deposition, which takes place, and the OM and clay content increases. The amount of bio-deposition and thus OM and clay is however relatively low, when flow velocities are lower. A third factor of influence is the variation in water temperature over time. From May to September, water temperatures are high, resulting in large rates of bio-deposition (Kautski and Evans, 1987). Smaller rates of bio-deposition occur when water temperatures decrease.
It was however clear that an increase in OM and clay, which have a relatively small grain size, is often accompanied by a decrease in D_{50} and vice versa. Furthermore was apparent that the four different locations are clearly visible by the initial differences in both the OM and clay content and D_{50} of the plots. In paragraph 3.2 was mentioned that the D_{50} is the most used indicator for bed stability. The Postma diagram shows that when the D_{50} becomes lower, the bed becomes more easy to erode. However when the D_{50} becomes under approximately 150μm, it is also the water content/compaction of the bed which is important for the bed stability. It was however not possible to monitor the water content during the fieldwork, because of the different submergence conditions, during which the sediment samples were taken. For the plots in front and in the mussel bed the D_{50} is however lower than 150μm, so depending on the compaction, the bed stability can be larger for these than for the plots at the bare sand bank.
Besides the D_{50} are also the clay and OM content of influence on the bed stability. For almost all plots the percentage of OM and clay is the highest inside the plot and lower at the locations in front and behind the plot. Furthermore was observed that the plot in front of the mussel bed, has the highest OM and clay content, closely followed by the plot inside the mussel bed. Plots at the bare sand bank had smaller percentages of clay and OM.
The addition of small percentages of clay creates a larger adhesion force between clay and sand than between sand grains only, furthermore the clay fills in the pores between the sand, so the bed surface becomes smoother and thus is more difficult to erode (Houwing, 1999; Grabowski et al., 2011). In general it is stated that organic matter stabilises cohesive sediment by adhesive effects (Paterson and Black, 1999), because it influences the inter-particle attraction. Therefore is sediment with less than 2% organic matter considered as erodible and is assumed that the bed stability increases with an increasing organic matter content, up to 10% (Grabowski et al., 2011). The plots around the mussel bed have both the largest clay and OM content. The OM content is however still under 10% and the grain size in the sandy region. This indicates that the bed stability of these plots is larger than for the plots at the sand bank. This could be the reason that less mussels became detached by the flow, that less gaps developed inside the plots around the mussel bed and that mussels are more uniform distributed.

Sub question 3: What is the consequence of differences in bed stability, patch height and mussel height for the further survival chances of the mussel bed during winter?
A new method was used to create the plots. Instead of individual mussels, plaques of mussels of 20 by 20cm were transplanted. The interconnection between mussels was maintained. The plots better resembled a young mussel bed in fall, for which the interconnection is formed during summer. It is unclear, whether it is the new method, or the relatively calm weather conditions without strong easterly winds, which resulted in the survival of all plots during autumn and the first part of winter.
It is however still possible to identify the best conditions for survival of mussel plots. Plots created at the bare sand bank, were less viable than plots created around or in the original mussel bed, because relatively large gaps in the coverage of mussels developed in the plots at the bare sand bank. Strings of mussels became partly disconnected by the flow and became to lie outside the plots. Van de Koppel et al. (2008) stated that young mussel beds have a high density and almost homogeneous distribution, while a labyrinth like pattern develops for mussel beds with lower densities. The labyrinth like pattern starts to develop in plot 1 (in front of the mussel bed), which has regularly spaced clusters with mussels from 5 to 10cm in width. The pattern is however much better visible in the plots at the bare sand bank, where the density decreased even more. Plots 9 and 10, created in the mussel bed itself, do not show a pattern in the mussel coverage, because the amount of mussels, which are displaced or disconnected, was only minor. These plots not only show a uniform distribution of mussels at the end of the fieldwork period, also the change in height over the plot is relatively constant. The plots experience in general a small increase in height. It are only the initially highest points, which experience a small decrease in height. The pressure sensors did also indicate that the wave height inside the mussel bed was lower than at all other locations. This means that the plots inside the mussel bed have not only a larger bed stability, but are also more sheltered and less prone to the influence of the waves.
It is a pity that the plots are not monitored after more after 29 November. The mussel bed was however covered with sea ice, so the photographs, as taken by the camera pole could not be used to monitor the development of the plots. It is beyond the scope of this research project, but it is advised that the mussel bed is visited after winter too see, whether indeed the plots in the mussel bed were more viable than the other plots during their first winter.

Main question: What are the sediment dynamics around a young mussel bed during fall?
To conclude, the main research question will be answered. The sediment dynamics, mentioned in the question include both the change in height and composition of the bed. By answering the sub questions, it became already apparent that the sediment dynamics around a young mussel bed varies during fall. Over the individual monitoring days the variation in erosion or deposition is however relatively small and could not be linked to differences in the hydrodynamic conditions, for which the variation was relatively small too. The differences in the development of the plots in the four study areas were however significant. It is apparent that the more exposed plots at the bare sand bank are more prone to variations in the hydrodynamic conditions, because the variation in height in and around these plots is larger than for the plots inside and in front of the mussel bed. The plots at the bare sand bank form a relatively large disturbance to the flow in the area, while the plots in or around the mussel bed are only one of many disturbances. This means that the reduced flow velocities behind the plots are more apparent for the plots at the bare sand bank than for the plots at the mussel bed, where the turbulence is larger. These plots have mainly sedimentation at one side of the plot, which is probably caused by larger concentrations of phytoplankton and therefore larger rates of bio-deposition. Plots at the mussel bed experience an increase in height in the entire area close around the plot. This indicates that especially for a young mussel bed at a new location, the variation in height over time is relatively large, compared to the more sheltered locations inside an original mussel bed. The mussels are not only larger disturbances to the hydrodynamic conditions of the area, these hydrodynamic conditions are of larger influence on the mussels too. The plots at the bare sand bank show a larger decrease in the mussel coverage than the plots inside the mussel bed. Furthermore the bed stability is lower too, because both the organic matter and clay content of the bed are lower.

9 Conclusion

During summer, newly developed mussel beds are stable and outliving. A large part of these beds however not survives their first winter. The objective of this research is to find out when young mussel beds are more viable and have larger survival chances during winter. Because of the presence of sea ice is monitoring of a mussel bed difficult during winter. Therefore the main question of this report comprises the sediment dynamics around a young mussel bed during fall. Development of 19 newly created plots of mussels was monitored. Plots were created in four study areas to test the hypothesis that mussel patches developed at a bare location are less viable than patches, inside an existing mussel bed. The coverage, height and composition of the patches is used to determine the survival chance.

The first sub question comprises the study to changes in height of mussel patches for several hydrodynamic conditions. The four study areas have different hydrodynamic conditions because of the shelter effect of the mussel bed. The difference in development of plots in the four study areas is clear. Plots inside and in front of the mussel bed have either a larger increase or a lower decrease in height, than surrounding areas. Changes in height are relatively constant over the plots and their surrounding is elevated. Plots at the bare sand bank show patterns, with sedimentation in and around one part of the plot and erosion or lower rates of sedimentation along other parts. These plots are more sensitive to a change in hydrodynamic conditions, therefore do locations with sedimentation and erosion vary over time.

The second sub question comprises the changes in composition and stability of the bed. The composition of the bed is significantly different for the four study areas. Plots inside the mussel bed have larger organic matter and clay contents. Organic matter and clay smooth the bed and enhance the attraction between grains, which leads to a larger stability of the bed.

To answer the third sub question about the survival chance of the mussel patches during winter, changes in patch height, bed stability, mussel coverage and mussel height have to be combined. To analyse the survival chance of the mussels, mussel coverage is monitored. Plots inside the mussel bed had only a minor decrease in coverage. Plots in front of the mussel bed show a labyrinth like pattern, because the coverage decreased, by erosion or displacement of mussels. Plots at the bare sand bank have however a much larger decrease in coverage. Strings of mussels are detached an lie outside the plots. Large bare areas develop and the labyrinth like pattern with bare areas and areas with mussel is very clear.

Because plots inside the mussel bed have an almost constant positive change in height, a stable bed and a low decrease in mussel coverage, it is concluded that these plots are the most viable during fall. Plots in front of the mussel bed are less viable, because they have a larger decrease in mussel coverage and start to show a labyrinth like pattern. Plots at the bare sand bank are not considered to be viable, because the height of these plots is sensitive to small changes in strength and direction of currents and waves. Furthermore is the stability of the bed significant lower and the decrease in mussel coverage significant larger.

It can thus be concluded that the hypothesis that mussel patches, developed at a bare location are indeed less viable than mussel patches, developed inside an existing mussel bed. Also is it apparent that patches developing in the neighbourhood of an existing mussel bed are less viable than patches developed inside the mussel bed, but much more viable than patches at a bare location.

10 Recommendations for management

To increase mussel areal, two options are under consideration: creation of new mussel beds or restoration of damaged ones. Until now newly created mussel beds experienced erosion, but this erosion was not studied, because changes in height and thus erosion of the mussel beds could not be monitored very accurate. However for this master thesis a 3D laser scanner was used to study the development and the survival chance of young mussel beds during fall.

By comparing the development of patches of mussels in four study areas, it became apparent that mussel patches inside the mussel bed have an almost constant positive change in height, a stable bed and a low decrease in mussel coverage. It is concluded that these patches are most viable during fall. Mussel patches in front of the mussel bed are less viable, because they have a larger decrease in mussel coverage and start to show a labyrinth like pattern. Patches at a bare sand bank are not considered to be viable, because the height of these patches is sensitive to small changes in strength and direction of currents and waves. Furthermore is the stability of the bed significant lower and the decrease in mussel coverage significant larger. Based on these results it is advised to restore original mussel beds, instead of creating new beds on a bare location.

For the research in this thesis mussel patches were created by a newly developed method. Mussel plaques were dug out of a mussel bed and transported with a part of the bed. In this way the interconnection between the mussels and the bed was maintained. All our patches have survived during fall. In other researches are mussel patches created by dropping individual mussels, dug out of the intertidal channels on a new location on the intertidal flat. These plots did however often not survive longer than three weeks. Because of the fact that the plots, created by our newly developed transportation method, were more viable it is advised that for restoration of mussel beds this newly developed method is used. This means that to restore mussel beds, mussel plaques in which already an interconnection between the mussels and the bed is formed, should be used. These mussel plaques could be taken out of already disappearing beds. It could however also be chosen that the interconnection between the mussels, taken out of the intertidal channels, is established first at a sheltered location.

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A1 Location and height of all plot corners

Plot corner	Y [m]	X [m]	Z[m]	Plot corner	Y [m]	X [m]	Z[m]
1,1	574836,9	121682,4	-0,275	**10,3**	574791	121633,9	-0,008
1,2	574835,9	121682,6	-0,268	**10,4**	574792,1	121633,5	-0,002
1,3	574835,9	121683,5	-0,29	**11,1**	574577,3	122066,5	-0,208
1,4	574837,2	121683,5	-0,312	**11,2**	574577,3	122067,7	-0,229
2,1	574844,4	121673,1	-0,401	**11,3**	574578,3	122067,7	-0,216
2,2	574843,5	121673,4	-0,365	**11,4**	574578,3	122066,6	-0,2
2,3	574843,8	121674,5	-0,324	**12,1**	574570,1	122073,1	-0,187
2,4	574844,8	121674,1	-0,361	**12,2**	574570,4	122074,1	-0,211
3,1	574876,3	121635,2	-0,348	**12,3**	574571,4	122073,8	-0,202
3,2	574875,4	121635,6	-0,335	**12,4**	574571,1	122072,8	-0,201
3,3	574875,8	121636,7	-0,37	**13,1**	574563,3	122078,5	-0,181
3,4	574876,8	121636,2	-0,384	**13,2**	574563,4	122079,5	-0,213
4,1	574907,5	121578,9	-0,31	**13,3**	574564,4	122079,3	-0,208
4,2	574906,7	121579,6	-0,311	**13,4**	574564,3	122078,2	-0,204
4,3	574907,3	121580,5	-0,323	**14,1**	574558,3	122082,8	-0,207
4,4	574908,2	121579,9	-0,312	**14,2**	574558,1	122083,7	-0,224
5,1	574913,2	121570,6	-0,293	**14,3**	574559,3	122083,9	-0,226
5,2	574912,3	121571,3	-0,3	**14,4**	574559,4	122083	-0,215
5,3	574912,9	121572,2	-0,292	**15,1**	574512,4	122041,4	-0,177
5,4	574913,9	121571,6	-0,285	**15,2**	574512	122040,4	-0,185
6,1	574868,3	121543,2	0,024	**15,3**	574511,1	122040,7	-0,187
6,2	574867,5	121543,8	0,023	**15,4**	574511,4	122041,8	-0,218
6,3	574868,1	121544,7	-0,029	**16,1**	574518,3	122035,7	-0,197
6,4	574869,1	121544,1	-0,025	**16,2**	574518,3	122034,6	-0,192
7,1	574853,2	121564,8	0,037	**16,3**	574517,3	122034,6	-0,175
7,2	574852	121564,8	0,013	**16,4**	574517,2	122035,7	-0,2
7,3	574852,2	121565,8	0,045	**17,1**	574524,3	122029,7	-0,203
7,4	574853,2	121565,8	0,042	**17,2**	574524,4	122028,6	-0,205
8,1	574833,2	121589,3	0,047	**17,3**	574523,3	122028,5	-0,208
8,2	574832,2	121589,3	0,044	**17,4**	574523,2	122029,5	-0,209
8,3	574832,1	121590,3	0,023	**18,1**	574529,6	122023,4	-0,199
8,4	574833,1	121590,4	0,017	**18,2**	574529,5	122022,4	-0,197
9,1	574800,5	121623	-0,013	**18,3**	574528,4	122022,6	-0,164
9,2	574799,7	121623,6	-0,006	**18,4**	574528,6	122023,5	-0,191
9,3	574800,3	121624,6	-0,005	**19,1**	574536,4	122016,2	-0,166
9,4	574801,1	121623,8	-0,026	**19,2**	574536	122015,3	-0,175
10,1	574791,7	121632,6	0,007	**19,3**	574535,1	122015,8	-0,143
10,2	574790,7	121632,9	0,003	**19,4**	574535,6	122016,6	-0,169

A2 Accuracy of the laser scanner and height maps

The direction of the laser scanner

This paragraph will analyse the effect of the direction at which the laser scanner is placed, on the height map of the area around plot 9. Plot 9 is chosen for this analysis, since most parts of this area are dry during ebb. Furthermore this area also contains mussel budges.

During most of the days, two scans were made, close to each plot. The two scans were made from two sides, to decrease the shadow effect. Figure A2-1 shows the height maps, made from the two separate scans close to plot 9. Furthermore the figure contains a map with the height difference between these two scans.

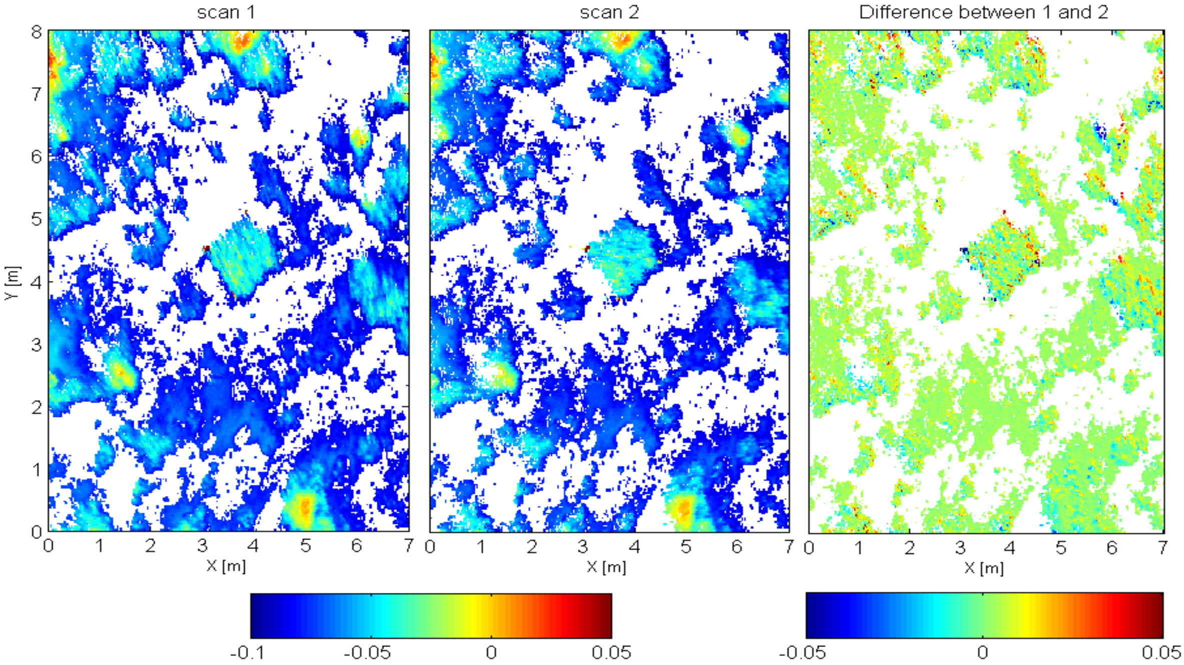

Figure A2-1 The height for the area around plot 9, for the two closest scans, scan 1 and 2 respectively. Furthermore the difference between these two scans is shown.

The third map in Figure A2-1 shows the difference between the two methods. In the figure is visible that height differences up to 5cm occur. These are caused by the plastic poles, standing at the corners of the plot. The difference is caused by the fact that the poles started to lean or were pulled out by the flow, during the fieldwork period. The data of the poles is therefore filtered out during the analysis for the thesis. Other height differences in the area are all smaller than 5cm. The height differences especially occur in parallel transects and are often present at the edges of a mussel patch or a higher located bulge in the area.

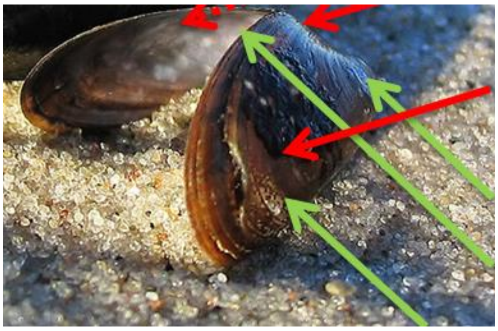

Figure A2-2 The laser beam is measuring the height of a mussel from two directions

The laser scanner measures the height by the reflectance of the laser on the bed. This means that when the laser reflects at for example a mussel, no laser continues in the same direction behind that mussel and thus no data is available in the area after that mussel, this is indicated by the green lines in Figure A2-2. Because of the grid size of 25mm, it can however be possible that the value as obtained from the front shell of the mussel is extrapolated over the grid, and is thus also used for the backside shell of the mussel. When however the laser scanner is placed at the second position, the same mussel can be measured at both shells, since now a value can be obtained for both the front and the back of the mussel (see the red lines in Figure A2-2). This results in a height difference between the two scans. Because of the fact that the plots contain many mussels, most of the time only one beam of the laser scanner will fall on an individual mussel. Therefore the effect of the direction from which the laser beam comes, will be enhanced. This effect of the direction of the laser scanner and thus the

shadow effect of the beams, as explained in Figure A2-2, is also visible in Figure A2-1, since the direction at which the laser scanner stood, can be seen in the maps by the pattern of light and dark blue colours in either diagonal (scan 1) or horizontal (scan 2) direction. For the first scan, the laser scanner stood in the southeast of the plot, while the laser scanner stood in the northeast to east for the second scan. The maps also indicate that because of the different directions from which the plot is monitored, that data is obtained for a larger part of the area. For the figure in the left, there is mainly along the south east, south and western edges of higher located areas data available. In the figure in the middle there is less data for these areas, but more data along the northern and eastern edges. This difference is caused by the different directions of the laser scanner.
Until now only the two scans, made the closest to plot 9 were examined. For most days there are however also two scans of the plot obtained, when the laser scanner stood much further away. Because of the fact that the laser scanner stood further away, it is expected that less data points are present in these scans. Further is assumed that the data is less accurate than for when the laser scanner stood closer to the plots. Figure A2-3 shows both the height maps and the map with the difference between the two scans, made further away from the plot.

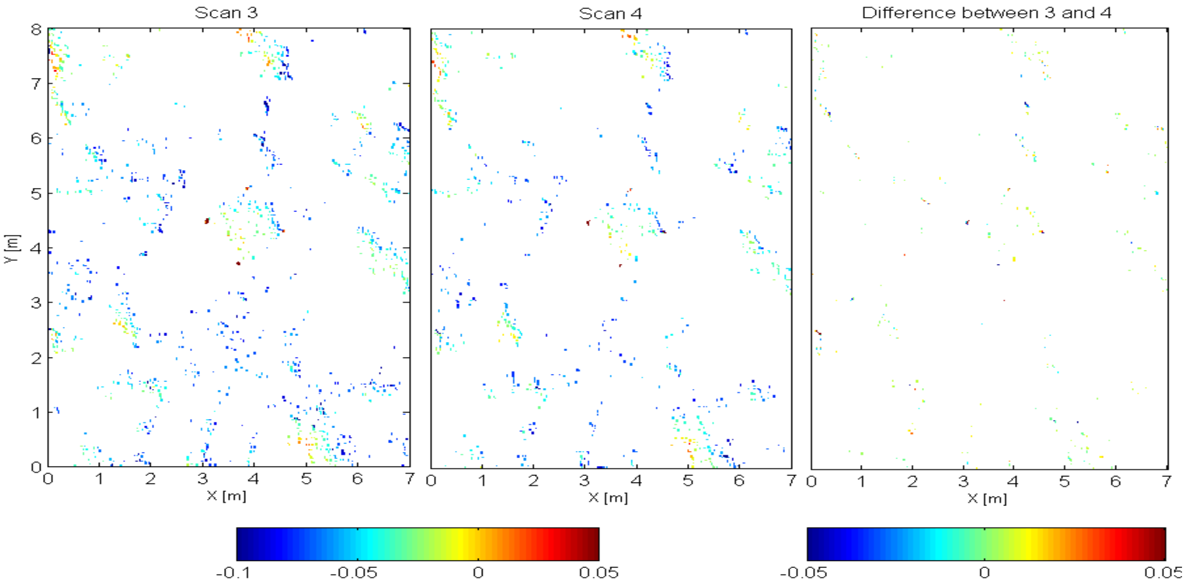

Figure A2-3 The height for the area around plot 9, for the two furthest scans, scan 3 and 4 respectively. Furthermore the difference between these two scans is shown.

In Figure A2-3 is visible that indeed less data points are available for the area around plot 9. There are only a few grid cells for which information is obtained by both scans. This makes it difficult to compare the difference between these two scans. It seems however that the difference between the two scans, made further away, is smaller than the difference between scan 1 and 2. This is caused by the fact that the distance and angle between the two locations of the laser scanner are negligible, because of the large distance between the scanner and the plot. It mainly the highest points, which are measured
The difference between the two scans, made further away, is smaller than the difference between the two closest scans. It is however most interesting how large the difference is between one of the closest scans and one of the scans, made further away, because by this difference it is possible to make a statement about the measurement errors of the scan. Figure A2-4 shows the height difference between scan 1 and 2, scan 1 and 3 and scan 1 and 4 respectively.

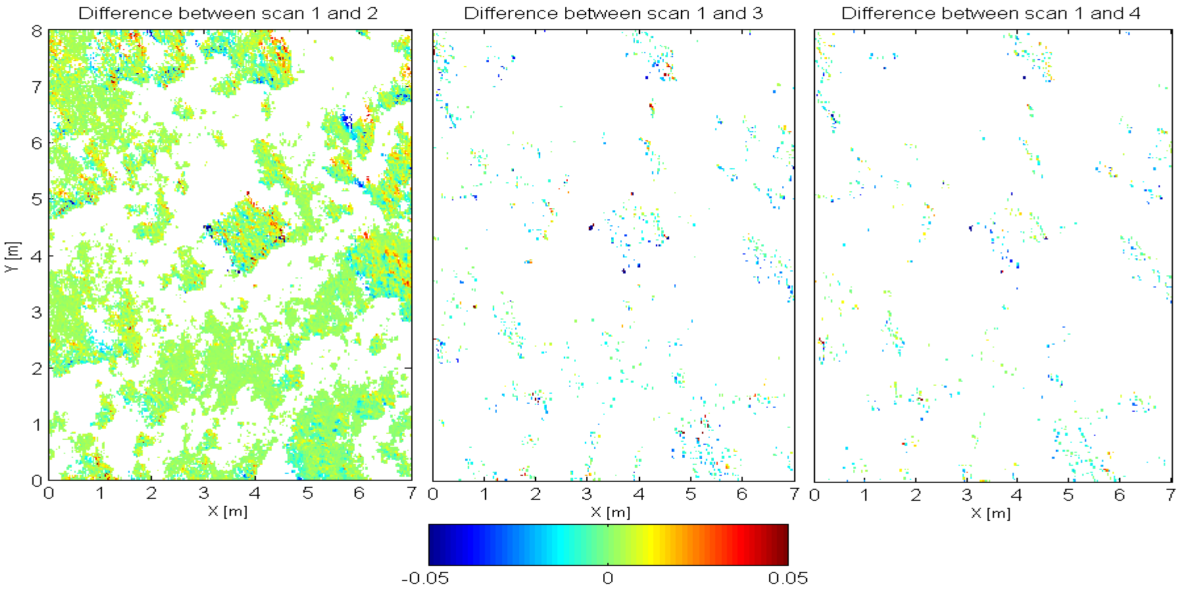

Figure A2-4 The difference in height between scan 1 and the other scans, shown for the area around plot 9.

In Figure A2-4 is visible that almost all points, which are measured by both the two closest scan and the two scans from further away, show a slightly negative or positive height difference, this difference is often smaller than the height difference between scan 1 and 2. Furthermore is visible that the height difference of most grid cells is negative, which indicates that the measured height for a grid cell is larger, when the laser scanner stood further away. This can be explained by the fact that when the laser scanner stands further away, only the highest parts of an object are measured. When the laser scanner stands closer to the object, the object is measured at several heights (see Figure A2-2) and this height is averaged out over the grid cell. Figure A2-5, shows the differences between scan 2 and 1; scan 2 and 3; and scan 2 and 4. The height differences between scan 2 and 3; and 2 and 4 are smaller than the height differences between scan 1 and 3; and 1 and 4 respectively. This effect is caused by the fact that the positions of the laser scanner for scan 2, 3 and 4 are all in the northeast of the area around plot 9, while the position for scan 1 is in the southeast of plot 9. This indicates that still the direction of the laser scanner and the resulting shadow effect is important for the scans, made further away. All differences in height, between the individual scans, made from plot 9 are however in a range of -5 to 5 cm. This means that the original accuracy of the laser scanner (5mm) has decreased, by the fact that the laser scanner is not placed in the same direction at all monitoring days. It are however mainly the edges, for which the largest differences in the measured height occur. For the other locations the differences in height between the scans are most of the time smaller than 1cm.

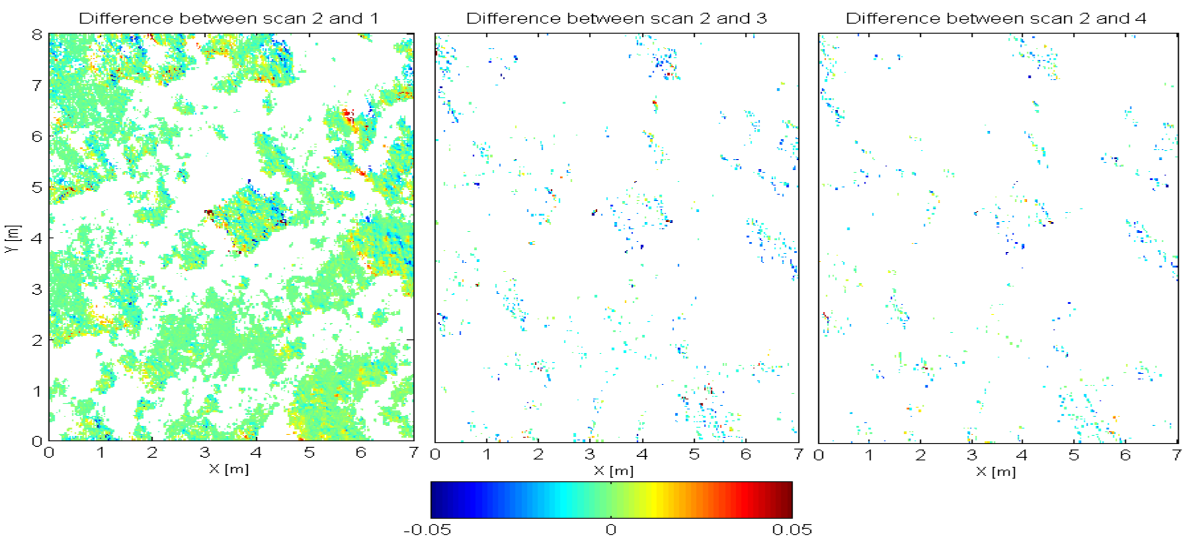

Figure A2-5 The difference in height between scan 2 and the other scans, shown for the area around plot 9.

The chosen grid size

This paragraph will analyse, whether another grid size in smaller height differences between the individual scans. Besides the 25mm grid, which was analysed in the former paragraph, both the height maps of scan 1 and 2 and the height difference between the two scans have been determined for a 10 mm grid. Figure A2-6 shows the resulting height maps. When this figure is compared to Figure A2-1, it is visible that now much more points without data are present. This is caused by the fact that still the same amount of datapoints are available. This data is however extrapolated over a smaller grid cell, so more empty cells are present. There are thus fewer cells with data, and less datapoints per cell. The difference in height between the two scans of the 10mm grid is however comparable to that of the 25mm grid. The same patterns are visible and it are still the edges, which have the largest difference in height. It can be concluded that it is better to use a grid size of 25mm then 10mm, since the height map with a 25mm grid still shows height differences on a small scale, but also has a more smoothened height map, with a higher percentage of data.

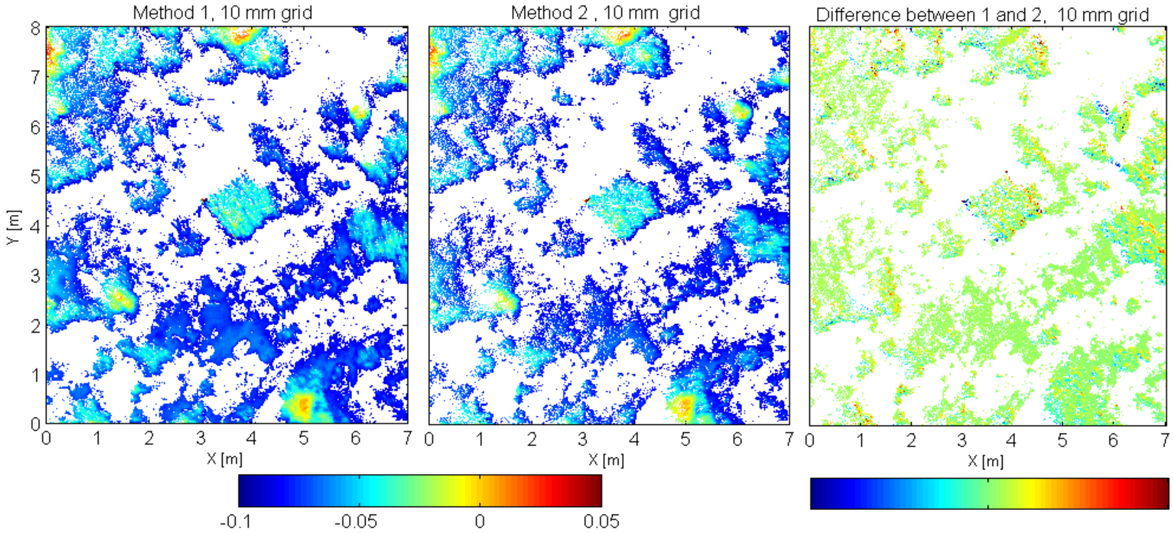

Figure A2-6 The height for the area around plot 9 shown on a 10 mm grid, determined by methods 1 and 2. Furthermore the difference between these two methods is shown in mm.

Averaging the scans

To decrease the effect of the different locations of the laser scanner, it is decided to average the two scans, when both scans contain data points for a grid cell. Figure A2-7 shows both the height map of the separate scans as the average of these scans. In the figure is visible that now the height map is much smoother and that less shadow effects are present.

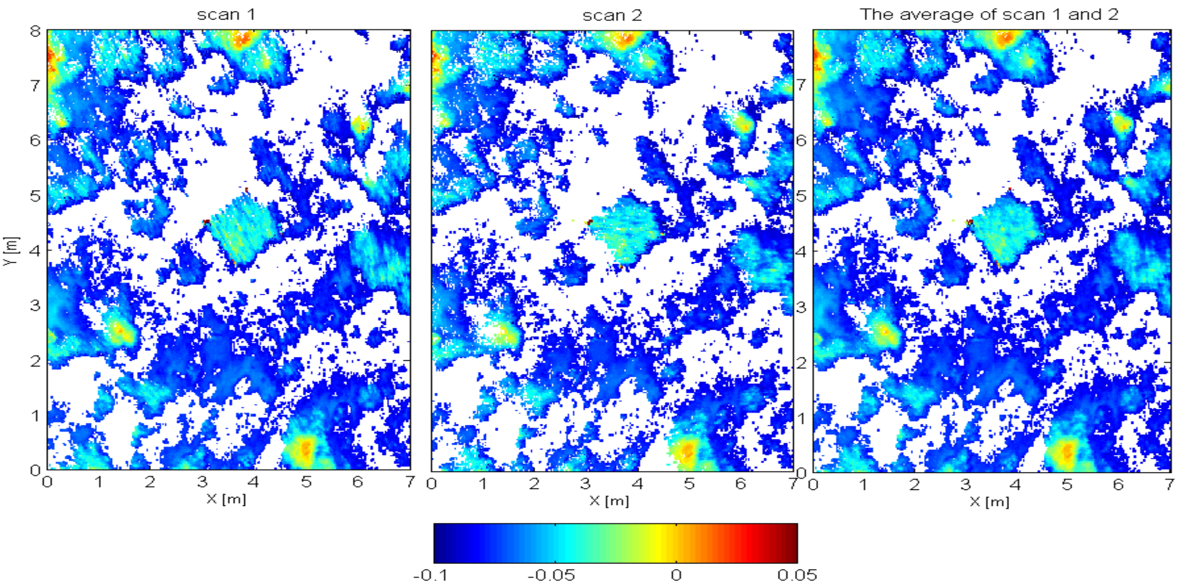

Figure A2-7 The height for the area around plot 9, determined by methods 1 and 2. Furthermore the height determined as the average of these two methods is shown

Conclusion

In this appendix became apparent that it is mainly the direction of the laser scanner, which results in differences in height. These differences could be up to 5cm for the edges of higher located areas. The largest part of the area had however almost no difference in height, as measured between the different scans. All differences were in a range of 1cm. Since the accuracy of the laser scanner itself is 5mm (RIEGL laser measurement systems, 2013), it would indicate that the accuracy of the height difference between individual monitoring days is 55mm for the edges of the higher located areas and 10mm for the other parts of the area. This accuracy can however be increased, when the average height of the individual scans, made at one monitoring day, are used. When the average height is used, the accuracy of the height difference between individual monitoring days increases up to 25mm for the edges of higher located areas and up to 7.5mm for the other parts of the area.

In the analysis became also apparent that a decrease in the grid size did only result in a minor decrease in the height difference of the individual scans. There were however much more grid cells, without data and the map was less smooth. Therefor the grid size of 25mm was chosen. The third observation made, was that the height differences between the scans made nearby and made further away mainly consisted out of the fact that when the laser scanner stands further away, that mainly the highest points are measured. There are however only a very small amount of datapoints in the scans further away.

Because of these three observations it was decided that for the analysis in this report, both the two nearby scans and the two scans, made further away, are averaged over a 25mm grid, when both scans contain datapoints for the same grid cell. It is mainly the data of the two nearby scans, which is used to make the height map of the area. Only the grid cells, for which no data is available in the most nearby scans, are filled up with the average height measurements of the two scans further away.

A3 Average change in height for all monitoring days.