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The efficiency of oyster reefs on coastal protection areas: Oesterdam case

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Abstract

Since the dramatic event of February 1953, the Dutch coast security is in center of attention. At that time the water spilled over the dikes into the South of Holland with great force provoking a huge disaster which claimed more than 1830 lives. Due to this, in 1954, the Delta Commission started creating a structured plan called Delta Plan with the aim to improve the safety in the region, strengthening dikes and closing off river estuaries. The Eastern Scheldt Storm Surge Barrier is the largest of the thirteen ambitious Delta Works. Its construction, together with the closure all the fresh water connections, turned the Eastern Scheldt from an estuary into a tidal bay. With this new system the flow of water decreased, the tidal height differential reduced, with the result of no new sand deposition. Therefore the slow erosion of sand bars caused the complete change of the coastal characteristics. The hydrodynamical and geomorphological characteristics changed compared to the past, creating an imbalance between erosion and sedimentation. One of the areas where this erosion is occurring is precisely Oesterdam. Oesterdam case is a particular place because the erosion of tidal flat can also produce a negative impact on the biodiversity of the present ecosystem, that has to be preserved as Nature-2000 area. In order to solve the problem of the erosion, Building with Nature research group, with the help of other different research institutes, universities, as well as governmental institutions, found a possible solution which started in 2011. This pilot project includes a big sand nourishment protected by eco dynamic breakwater structures filled with oysters. The main purpose of the considered structures is to dampen the waves and trap sediment behind them, stabilizing the sand nourishment, keeping it in place for a longer period. The other aim is the reduction of the dike's maintenance. The breakwaters realized are submerged structures made of gabions filled with alive pacific oysters; and this is the real challenge of the experiment. In fact this is one of the first time in Europe where oysters are used as ecosystem engineers. The use of oysters adds habitat heterogeneity and thus promotes biodiversity but, from an engineering point of view, it can influence the flow, the wave action, the sedimentation and the erosion patterns around the reefs. In order to confirm if these structures are effectively working, the thesis will be focused mainly on the tidal flat monitoring activities with the use of DGPS, but also sediments and hydrodynamic monitoring activities for a total period of almost three years. The results of this thesis will definitively give several information about the use of oyster reefs for the coastal protection. The research is challenges to conventional engineering structures for the coastal defense. The goal of this thesis is to validate the possible use of these systems and ensure that their use will possibly increase in the following years.

Abstract (Italian)

Dopo il drammatico evento del febbraio 1953, la sicurezza della costa olandese è divenuta al centro dell'attenzione. Allora l'acqua si riversava sopra gli argini nel sud dell'Olanda con grande forza, provocando un enorme disastro che ha causato più di 1830 vittime. A causa di quanto avvenuto, nel 1954, la Delta Commision ha dato vita alla realizzazione di un piano strutturato chiamato Delta Plan con l'obiettivo di migliorare la sicurezza nella regione, rafforzando dighe e chiudendo gli estuari dei fiumi. La Eastern Scheldt Storm Surge Barrier è il più grande dei tredici ambiziosi progetti (Delta Works). La sua costruzione, insieme alla la chiusura di tutte le connessioni con i sitemi di acqua dolce, ha trasformato la Eastern Scheldt da un estuario ad una baia tidale. Con questo nuovo sistema il flusso di acqua è diminuito, il dislivello di marea si è ridotto, provocando alcuna nuova deposizione di sedimenti di sabbia. Pertanto la lenta erosione dei banchi di sabbia ha provocato un completo cambiamento delle caratteristiche costiere. Le caratteristiche idrodinamiche e geomorfologiche sono state completamente modificate rispetto al passato, dando origine ad uno squilibrio tra erosione e sedimentazione. Una delle aree in cui l' erosione si sta verificando è proprio quella di Oesterdam. Oesterdam è un sito particolare perché l'erosione dell'area tidale può anche causare un impatto negativo sulla biodiversità dell' ecosistema presente che deve essere conservato, siccome considerata area protetta Natura-2000. Al fine di risolvere il problema dell'erosione, il gruppo di ricerca Building with Nature, con l'aiuto di altri istituti di ricerca, università, così come istituzioni governative, ha trovato una possibile soluzione, che ha preso vita nel 2011. Questo progetto pilota comprende un ampio ripascimento di sabbia riparato da strutture frangiflutti ecosostenibili, realizzate con ostriche. Obbiettivo principale di tali strutture è quello di smorzare l'energia delle le onde e bloccare i sedimenti dietro di esse, stabilizzando il ripascimento, o comunque mantenendolo in vita per un periodo più lungo possibile. L'altro obiettivo è la riduzione della manutenzione dell'argine marino. I frangiflutti realizzati sono strutture sommerse con gabbioni metallici riempiti di ostriche del Pacifico; è proprio questa la vera sfida del corrente esperimento. Infatti questa è proprio una delle prime volte in Europa in cui le ostriche sono utilizzate come 'ingegneri dell'ecosistema'. L'uso delle ostriche aggiunge eterogeneità all' habitat e quindi promuove la biodiversità, ma,allo stesso tempo, da un punto di vista ingegneristico, può influenzare il flusso, l'azione delle onde, la sedimentazione e gli schemi di erosione intorno alle scogliere. Per poter confermare che queste strutture siano effettivamente lavorando, la presente tesi si concentrerà principalmente sulle attività di monitoraggio della piana tidale con l'utilizzo di DGPS, ma prevede anche attività di monitoraggio sedimentologiche e idrodinamiche, svolte su un periodo complessivo di quasi tre anni. I risultati della presente tesi daranno definitivamente molte informazioni circa l'uso di barriere di ostriche per la protezione delle coste. La ricerca è di per sé una sfida alle opere di ingegneria convenzionale per la difesa costiera. L'obiettivo di questa tesi è quello di validare il possibile uso di questi sistemi e garantire che il loro utilizzo possa aumentare negli anni a seguire.

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1. Introduction

People living in rivers, estuaries and deltas areas always faced difficult challenges resulting mainly from coastal management problems. Historically, humans always wanted to protect themselves from floods to the extent that their tools permitted. In that way, flooding and its consequences have been dealt in many ingenious ways. Simple methods to provide safe areas are still common in developing countries where scarce resources are available. More elaborated flood protections are used in countries where greater economic resources are available to provide personal safety. Due to their geographical position, the Netherlands is one of the countries where a large variety of coastal protection techniques are applied. It is a country with high risks of flooding since 2/3 of the land is located below the sea level (Kamphuis 2010).

Up to recent years, a very dramatic event after the Second World War took the Dutch coast security to the center of attention. In the first of February 1953, the water level became extremely high during the spring tide. The sea remained at flood level and a storm from the northwest with wind force 12 according to the scale of Beaufort increasingly pushed up the water level. The water spilled over the dikes and flashboards into the South of Holland with great force. This huge disaster claimed more than 1830 lives. Due to this, the Delta Commission started creating the Delta Plan in 1954: a structured plan aimed at strengthening dikes and closing off river estuaries in order to improve the safety in the region (Kamphuis 2010). One of these former estuaries is the Eastern Scheldt (Dutch: Oosterschelde), located between Schouwen-Duiveland and Tholen, in the north and Noord-Beveland and Zuid-Beveland in the south. The Eastern Scheldtkering (Eastern Scheldt Storm Surge Barrier) is the largest of the thirteen ambitious Delta Works. It is a four-kilometer long section of the Delta Works that closes the estuary off from the sea if necessary. Huge sluice-type gate doors, which normally open, can be closed under adverse weather conditions. In addition to this, two compartment dams were constructed in the back area of Eastern Scheldt, the Oesterdam and the Philipsdam (Niehnhuis and Smaal 1994).

Upon completion of this barrier in 1986, long term physical, chemical and ecological studies were done to understand the changes induced by the structures of the storm-surge barrier. With this new system the flow of water has been decreased and the tidal height differential has been reduced, at the same time all the fresh water connections were cut turning the Eastern Scheldt from an estuary into a tidal bay. As a result, no new sand is deposited on the estuarine sand bars, which slowly erode, changing the coastal characteristics. Its hydrodynamic and geomorphological characteristics became different than the past situation, creating an imbalance between erosion and sedimentation (Niehnhuis and Smaal 1994). The induced erosion lead to the loss of the intertidal flats creating also negative impact on the biodiversity of the ecosystem, that has to be preserved as Nature-2000 area. These aspects are visible in the area of Oesterdam, located at the end of the basin. Different research institutes, universities, as well as governmental institutions started detailed studies in order to improve the situation of the erosion of sand banks. The Building with Nature research group from the Applied Research Centre of Delta Academy is one of these research groups that started in 2011. This pilot project included sand nourishment protected by eco dynamic structures. The main purposes of the considered structures are to dampen the waves and trap sediment behind them, stabilizing the sand nourishment, keeping it in place for a longer period. Another reason for the addition of these ‘soft structures’ in the foreshore of Oesterdam is to reduce (and postpone) the maintenance of the dike itself. The ‘soft structure’, placed in front of the dike, is expected to provide extra safety, and presumably also a reduction of the structure’s maintenance. As a consequence, the lifespan of the dike will increase. The breakwater structures are made of pacific oysters shells. In this case, the use of oysters adds habitat heterogeneity and thus promotes biodiversity but, on the other hand, from an engineering point of view, it can also influence the flow, wave action, sedimentation, erosion patterns within and around the reefs (Troost 2010).

This MSc thesis will focus on oyster reef structures for the coastal defense of the Oesterdam. The study will present results about their function, behavior and the possible improvement obviously linked with the already made sand nourishment. The goal of this research is to try to understand which design is the most optimal for the safety buffer in front of the dam. Therefore the main question that has been formulated is: *"Can oyster reefs be effectively a good solution to limit the coastal erosion in Oesterdam, satisfying also the hydrological and geomorphological aspects?".* Background studies, monitoring and analysis of data will help to answer the question.

The following thesis will be divided into eight chapters. The structure of this work comprises a revision of the existing literature (Chapter 2) based on infrastructures for coastal protection,. Chapter 3 explains the study area of the project, followed by a short in-depth explanation about the innovation program, which is behind the project in research (Chapter 4). Chapter 5 will investigate the methodology used and the processing of the data and Chapter 6 will show the results obtained from the their implementation. In Chapter 7 there will be the part of the discussion of the research. The final chapter (Chapter 8) contains the conclusions and a discussion of the main outcome of the thesis.

2. Literature review

2.1 Principles and processes of sediment transport in intertidal areas

A sedimentary environment is defined as the set of physical, chemical and biological conditions where sediment builds up. There are different types of sedimentary environments: deep ocean, as well as estuary, beaches or anywhere else where there is water movement (Open University 1999). In every sedimentary environment there is a combination of causes and effect. In fact sedimentary environments are part of a dynamic frame which continuously change and re-model. Sedimentary environments are characterized by transport and deposition of sediments. In fact in every water system there is a certain equilibrium between the contribution of sediments and losses. The main sediment sources are rivers, streams, adjacent segments to the coast; the losses are mainly caused by storms due to the wind (Syvitski 1991).

Transport and deposition processes are governed by different parameters. The ones which permit to understand the sediment transport are: size, shape, density and forces between particles; water depth and velocity of the waves and/or tidal current have also a big influence (Open University 1999). The particle size is a fundamental property of sedimentary materials which can give many information about their origins and history: dynamical conditions of transport and deposition of the constituent particles of rocks is usually inferred from their size (Syvitski 1991). Different reference scale are used to study the particle size. The Wentworth scale is one of them. It has been chosen as the reference scale for this thesis and it is showed in Figure 2.1 It will be used for the samples analysis which will be showed in Chapter 6. The Wentworth scale takes into account the grain size and, depending from the size range, it divides the sediments in mud, clay, silt, sand and gravel.

SEDIMENT GRAIN SIZE: THE WENTWORTH SCALE
(after Wentworth, 1922; Krumbein, 1934)

mm	µm (microns)	ϕ (phi)	size class		rock type	
			boulder	GRAVEL	conglomerate or breccia	
256		-8.0				
128		-7.0	cobble			
64		-6.0				
32		-5.0	pebble			
16		-4.0				
8		-3.0				
4	4000	-2.0				
			granule			
2	2000	-1.0				
			very coarse sand	SAND	sandstone	
1	1000	0				
			coarse sand			
0.5	500	1.0				
			medium sand			
0.25	250	2.0				
			fine sand			
0.125	125	3.0				
			very fine sand			
0.0625	62.5	4.0				
0.031	31	5.0	silt	MUD	siltstone	mud-
0.0156	15.6	6.0				
0.0078	7.8	7.0				
0.0039	3.9	8.0				
			clay		claystone	stone

Figure 2.1- Wentworth scale

There are three principal categories of material: gravel (d > 2mm), sand (2 mm < d< 0.0625 mm) and mud, that is further divided into silt (0.0625 mm < d < 0.0039) and clay (d < 0.0039 mm). The figure shows also the other method used to expressthe particle sie. The unit of the particles is Φ, linked to the diameter (in mm) with the following relation: $\emptyset = -\log_2(d)$

(www.virtual-geology.info)

The density of the sediment is another important factor. In fact, depending from the load of the particles, the particles movement can happen more or less easily. Heavy particles are harder to move, light particles are easier to move. The shape of the particles, linked with the forces interaction, also influences the sedimentation process. For example sand particles, which have more circular shape, are governed by mass forces. On the other hand, clay mineral particles are flaky and really small, they are governed by the combination of electrostatic attraction and surface tensions. Due to this, clay sediments are also called cohesive sediments, while, sand and gravel are non cohesive sediments. The surface forces are stronger than mass forces. This means that it is harder to separate clay particles from sand particles. The energy needed to divide clay particles is always bigger than the one needed for the sand. Sand particles do not have this physic-chemical interaction that exist between clay particles, so they can move more independently (Open University 1999).

Sedimentary environments can also characterized by a geomorphologic and dynamic point of view. In fact from a geomorphological aspect, the littoral zone is a quite complex system and it can mainly be divided in: simple or open coast (that is exposed to the open sea); complex or protected coastline (which forms a barrier between the open sea and the protected area). At the same time, from a dynamic point of view, it can be divided in high-energy environments (with the prevailing transport and sedimentation of sand) and low power environments (prevailing suspended mud transportation). Due to these observations, geomorphology and dynamic of the coastal system can be summarized in the influence of the water depth, velocity of the waves and of the tidal currents.

The particle movement occurs when the instantaneous fluid force on a particle is bigger than the resisting force related to the submerged particle weight and the friction coefficient. Therefore the basic principles of the sand transport can be showed in Figure 2.2 and summarize as follow. Considering the problem of initiation of motion of a particle with diameter D lying on a bed of identical grains, there are 3 ways that grains can move: lifting of the grain off the grains beneath it; sliding of the grain up and out of its position on the bed; rotation of the grain about a pivot point formed by neighboring grain.

In the first case, the lift force exceeds the “gravity force” (i.e. the weight, because gravity itself is an acceleration); in the second case, the drag force in the flow direction exceeds the combined frictional and gravitation force in the opposite direction. In the last case, the moment of the fluid forces exceeds the moment of the gravitational force.

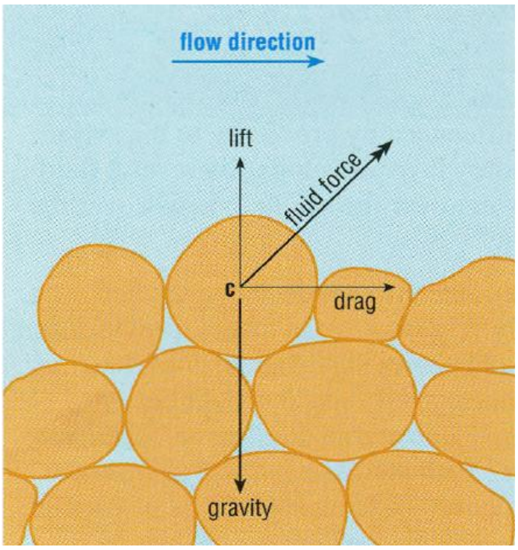


Figure 2.2 - Particles movement (Open University 1999)

The particles movements are different, depending from their size. The bigger grains are located in the surf zone because it is the zone with the maximum mechanical energy. The smaller one are going in the coast direction, due to the translation wave, or in the sea direction due to the compensation current. The bigger particles move sliding, saltating or rolling. In the first case they remain in continuous contact with the bed, sliding on the sea bed; in the second one 'jumping ' along the bed; in the third case they also remain in continuous contact with the bed, but rolling on the bed. These three mechanism form the bed load transport. Instead finest particles move in suspension: the grains lift and follow irregular paths until they deposit. They are represented in Figure 2.3. Sliding and rolling particles are prevalent in slower flows, the saltating and suspensions in faster flows (Open University1999). The trajectories of the granules are in a zigzag or more complicated because of the vortices that are created (Syvitski 1991).

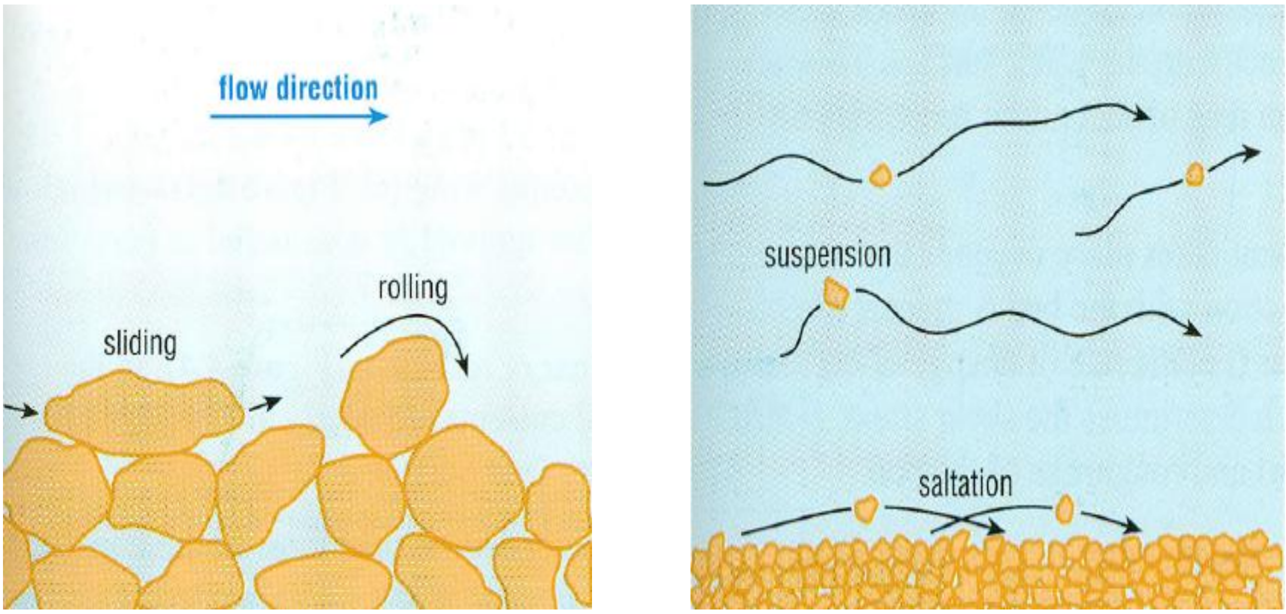


Figure 2.3- Forces acting in a stationary sediment grain and moved of sediments transport (Open University 1999).

Sediments transport is also influenced by the presence of waves or of the currents . Therefore it is important to specify that there are two main littoral systems: one dominated by waves, one by tidal currents. The waves are mainly activated by the action of the wind. The water surface is in motion due to the action of the wind and in general the atmospheric circulation. The winds can blow offshore as in sheltered areas, with different intensity. Wave form because the wind pushes the surface water layer, yielding part of its kinetic energy and momentum, and providing it to a speed above the water layer below; viscous friction for each layer of water with different speed tends to drag the slower underlying layer and at the same time to slow down, from which, if they are not continuously fed or not first meet an obstacle, are intended to dissolve or dissipate rapidly . For the tides the matter is more complicated. All tidal system have neap-spring cycle with regular fluctuation of high-low water levels in about 14 days. Moreover the most frequently occurring tidal system is the semidiurnal one, with two tidal cycle in more than two days (24h 40 min). Therefore there can be a big difference in tidal amplitude which defines differences in current velocities in both the cycles (Eisma 1997). Tidal currents are originated by the tidal range. The phenomenon is present in marine and oceanic basins (also in extended lakes). In such contexts, on low coasts and slightly inclined, tidal currents can reach speeds and remarkable strength (up to several meters per second), and can erode coastal sediments forming real channels that penetrate inland from the sea. The ebb and flow of the tide, in the zone between the low level and high tide (intertidal zone) then gives rise to erosion, transportation and redistribution of the sediments and towards the ground and towards the sea, forming a particular sedimentary environment: tidal flats. Where tides have a considerable range, the transport of water and sediment along the coast is generally very limited. In fact, when there is the low tide phase, there is an increment of the wave steepness; in the opposite case, i.e. when there is the high tide phase, the wave steepness decreases. Therefore the water flow can be laminar or turbulent because waves or currents, but close to the sea bed it may be essentially laminar. The wave velocity is slowed down by friction along the bed. With increasing of the distance from the bed, water layers start to move a little faster because the effects of the friction with the bed decrease. Considering layers of water, the velocity of each one decreases with increasing distance from the bed: the top of each layer is acted by a shear stress (frictional force) that controls the movement of sea-bed sediments. Therefore it is possible to affirm that sediments move more in shallow water than in deep sea depths: in fact waves can affect the sea bed and tidal currents are typically stronger in shelf sea than in open ocean (the tidal range increases), (Open University 1999).

One of the most important example that can explain all these factors is the case of the tidal flats. Here at low tides, the bottom of the lagoon (or estuary) is cyclically exposed to the atmosphere, playing a decisive role in the sediment distribution (Syvitski 1991). Intertidal mudflats are present in all over the world coastlines in a wide variety of situation: in high and low tidal range, in sheltered estuaries, in inlets, on considerable wave exposed coasts. The tidal flat is a intertidal depositional area predominantly flat, composed by a mixture of sand and mud. Due to the presence of mud, as already described, part of the sediments have sufficiently cohesive properties which influence the particles movement. Other factors like intense biological, sedimentary and physical processes are also influencing the erosion and sedimentation in those locations (Black et al.1998). Tidal flats occur mainly in areas where salt and fresh water mix. Many intertidal areas are also protected because considered important for the flora (ex. salt marshes), fauna and for birds migrations linked to them (Eisma 1997). Mudflats can be distinguished on basis of the size (area), the morphology, the tidal range, the vegetation, the benthic fauna and the possibility of the human use.

Even if grain size is a reflection of the transport capacity of the hydrodynamic system, fauna and vegetation living in the tidal flat may be considerable in influencing erosion and sedimentation. The term *bioturbation* is used to explain reworking of soils and sediments by animals or plants. Sediment reworking occurs in all coastal areas. Its effects include changing the texture of sediments, their movements and bioirrigation (it refers to the process of benthic organisms flushing their burrows with overlying water). Several authors (Black 1998, Cadée 2001, Herman et al. 2001, Netto et al.1994) talk a lot about the sediment disturbance by organisms in relation to their different activities: food gathering, hole and tube building, locomotion, resting and escape. Even birds that walk over the tidal flat, or fauna that moves underground, between sand grains, rework surface sediments (Cadée 2001). An example of sediment reworking is given in Figure 2.4.

Figure 2.4 - Examples of trampling holes.

Trampling holes that Shelduks made in the Dutch Wadden Sea in search of food on tidal flats. This example of hole has an average diameter of 40 cm (Cadée 2001).

In high energy environments, the contribution of bioturbation is relatively less important than in low velocity environments. In the first case the reworking of the sediments is mainly physical, due to the increase of current strength and/or wave exposure; in the second one, bioturbation is more relevant. Moreover if sand transport by physical-turbation is mainly horizontal along the bottom (due the flow direction), then Bioturbation is mainly vertical. This model is explained in Figure 2.5. One example of vertical transport of sediments is given by the deposit feeders (Cadée 2001).

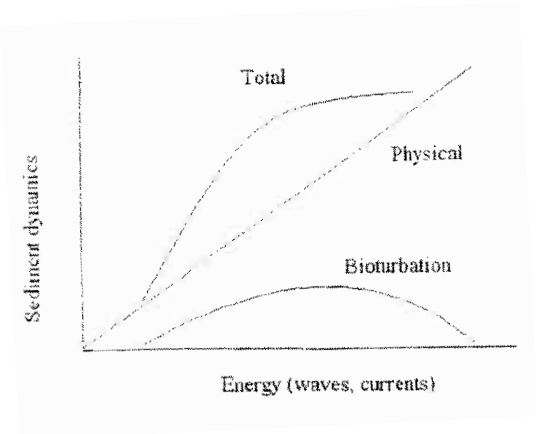


Figure 2.5 - Simplified model of sediment reworking.

The graph represents physical (mainly horizontal) and biological (mainly vertical) sediment reworking. The X-axis represents the wave/current energy, the Y-axis the sediment reworking. This graph shows that bioturbation is mainly active at intermediate energy levels (Cadée 2001).

There are many bioturbators: examples of deposit feeders are flounders, eels, haddock, bass, crabs, shellfish, snails and sea cucumbers. They may transport sediments from the deeper layer to the surface or the way around; they can also mix the surface sediment layer by deposit feeding or grazing. Therefore even if they mainly influence the sediments in vertical direction, they can also increase horizontal transports. Some studies were done in the Danish Wadden Sea about *Arenicola marina* (a worm): it helps with the erosion process depositing the fecal casts on the tidal flat during the low tide and bringing fine particles into suspensions. Figure 2.6 gives an example of bioturbation made by an *Arenicola marina* worm.

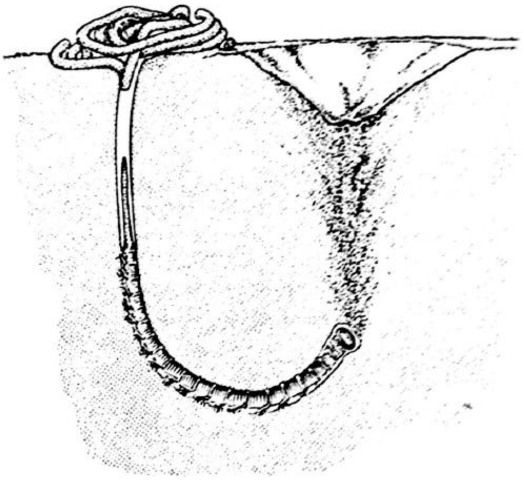


Figure 2.6 - Examples of bioturbation by *Arenicola marina*.

On the right there is an example of *Arenicola marina* in its burrow , it can be 15 cm deep (Image elaborated by the author). On the left the example of the its feces on the seabed during low tide (Eisma 1997). Moreover, in the second image it is possible to see some spots of benthic biofilm wich can influence the sediment erodibility.

Another important aspect regards the biostabilisation that can influence the erosion-sedimentation condition. This aspect regards the benthic biofilm (Figure 2.6) which is commonly found in shallow coastal areas and in intertidal environments. The biofilm consists of microbial cells (e.g., diatoms, cyanobacteria, or heterotrophic bacteria) aggregated within a gel, which is a matrix of extracellular polymeric substances (EPS). Biofilm plays a important role in ecology and morphology: it is at the base of several food chains, contributing to primary production but it also promotes biostabilization, i.e., a decrease in sediment erodibility (Mariotti and Fagherazzi 2012).

In addition to this, several authors (MacIntyre et al. 1996; Decho 2000; de Brouwer and Stal 2001) demonstrate that that, during hydrodynamic disturbances (such as currents and waves), when sediments are covered by biofilm, the entrainment process does not take place in a manner akin to that of a single rolling particle. In fact the entrainment occurs via biomat failure and carpet-like erosion of the biofilm-sediment composite. This means that surface biofilm removal occurs in an “all-ornothing” fashion. This phenomenon derives from the fact that the thickness of the biofilm is much smaller than the one of the sediment active layer. In fact his layer is mobilized during recursive erosive events, such as tidal currents and wind waves in intertidal muddy environments (Mariotti and Fagherazzi 2012).

2.2 Conventional coastal engineering structures: hard and soft defenses

Coastal defenses are structures designed to protect coastlines from flooding and coastal erosion. They are used to stabilize and retain beaches, to reclaim land, as well as to increase the amenity value of the coast (e.g. beach use, surfing, etc),increase tourism; or also improve or restore natural habitats in certain cases.

Causes of the coastal erosion problems are different. They can be natural, like wind and waves; induced by human activities (such as the increase of the urbanization of the coast); or a combination of both, such as the impact of global warming and climate change (sea level rise, storm surges, coastal floods) which are and will become additional important factors for the future. In fact, coastal flood risks are likely to increase over the coming decades owing to global and regional changes that include increasing storm intensity, accelerating sea-level rise and land subsidence.

For these reasons, over the past century, coastal defense structures have become omnipresent features of coastal landscapes. The use of coastal defense structures has an important impact on the coastal landscape which is closely related to the techniques used. In fact, coastal defense structures have a strong influence on the configuration of the shoreline. Artificial structures can influence sediment transport, reduce the ability of the shoreline to respond to natural forcing factors and fragment the coastal space. The proliferation of defense works affects over half of the natural shoreline in some regions and results in dramatic changes to the coastal environment, paying little attention to their consequences (Airoldi et al. 2005). Coastal defense structures are increasingly common throughout Europe and they will increase their diffusion over the next 10-30 years (Moschella et al. 2005). Some of there defense structures (e.g. breakwaters, groynes, seawalls, dykes or other rock-armored structures) have proliferated, leading to severe artificialization of coastal areas. In fact, in some regions, they cover over half of the natural shoreline resulting in dramatic changes to coastal landscapes and environments (Bacchiocchi and Airoldi 2003).

2.2.1 Distinction between hard and soft engineering

A distinction has to be made between hard and soft coastal defense options and between short-term (construction, maintenance) and long-term impacts (operation). There are two fundamental approaches to limit coastal erosion: one with soft designed structures; the other one with hard designed structures. The approach with the soft type provides for the stabilization of the coastline with the help of artificial solutions but using natural material. It consists in the use of granular material which characteristics (texture, color, etc.) are compatible with those of the native material. The advantage of these solutions is the possibility of stabilizing the beach and, at the same time, reducing the impact on the environment, avoiding interference with the natural phenomena of coastal shipping. On the contrary, the costs are high; the time of realization constitutes problems at times. The rigid (hard) structures are characterized by the possibility to intervene in case of localized problems, arrest the erosion only along the coasts where it occurs. They are characterized by high durability, generating, if succesfull, the progress of the shoreline favored by the deposition of sediments along the coast in which they are placed. The presence of these structures always require intense monitoring activities aimed at identifying possible negative effects brought about by the new structure and to plan possible corrective actions (Agenzia nazionale per la protezione dell' ambiente 2007). The Table 2.1 gives an overview of some techniques used for coastal defense.

Categories of structures	Description
Soft Techniques	
Beach drainage	Beach drainage decreases the volume of surface water during backwash by allowing water to percolate into the beach, thus reducing the seaward movement of sediment. It is still debated about its efficiency.
Beach nourishment	Artificial increase of sand volumes in the foreshore via the supply of exogenous sand.
Dune regeneration	Wind blown accumulation of drifted sand located in the supra-tidal zone. Wind velocity is reduced by way of porous fences made of wood, geotexile, plants, which encourage sand deposition. At some sites debris from beach cleaning is being used.
Marsh creation	Planting of mudflats with pioneer marsh species, such as *Spartina sp*. Marsh vegetation increases the stability of sediment due to the binding effects of the roots, increasing shear strength and decreasing likelihood of erosion. Marshes also provides cost-effective protection against flooding by absorbing wave energy.
Mudflat recharge	Supply of existing mudflats with cohesive sediments. This is achieved via trickle charging, rainbow charging, and polders.
Sand by-passing	Reactivation of sediment transport processes by re-introducing material intercepted by a coastal structure and down-drift of it. A variant of sand by-passing is to use materials dredged for navigational purposes to reactivate the sediment transport.
Sand back-passing	Sand moved from long shore drift is shifted backwards.
Underwater sand nourishment	Artificial increase of sand volumes in the near-shore area via the supply of exogenous sand.
Vegetation planting and/or stabilization	Colonization of coastal soils by vegetation whose roots bind sediment, making it more resistant to wind erosion. Vegetation also interrupts wind flow thus enhancing dune growth. As for cliffs, vegetation increases cohesion of surface soils on cliff slopes to prevent downhill slumping and sliding.
Hard Techniques	
Breakwater	Protective structures placed offshore, generally made of hard materials such as concrete or rock, which aim to absorb wave energy before the waves reach the shore. Artificial reef balls are being tested at some sites.
Dikes	Longitudinal artificially raised shore, consisting of a soft (sand, loam, *etc.*) core topped with a layer of for example grass or r asphalt. Some dikes are covered by artificial sand dunes.
Gabions	Metal wire cages filled with rocks, about 1 meter by 1 meter square. Gabions are stacked to form simple walls.
Seawall	Bulkheads and seawalls completely separate land from water. Bulkheads act as retaining walls, keeping the earth or sand behind them from crumbling or slumping. Seawalls are primarily used to resist wave action. Design considerations for these types of structures are similar. Seawalls may be topped with a promenade.

Table 2.1- Categories of structures for the coastal defense

Since the research presented in this thesis takes into account different kind of these coastal protections (like breakwaters and beach nourishment), it is important to explain their design, function and behavior. Therefore a small excursus will be made in the following section.

2.2.2 The sand nourishment

Multiple the causes of shore erosion are. For example, the interruption of longshore transport by coastal structures; the reduction of sediment supply by rivers; dune and beach erosion by storm surges; the shifting of tidal channels; alongshore migration of large sand waves; relative sea level rise and beach mining. In order to solve the problems of shore erosion, the sand nourishment is a possible solution.

Beach nourishment, also referred to as sand nourishment, is a used soft technique for coastal defense. It is an artificial nourishment of the beach with the deposit of suitable landfill, extracted from borrow pits in the ground or at sea (Pilarczyk et al. 1986). An example of beach nourishment is given in Figure 2.7. The objectives of nourishments can be different. It can be done for creation/restoration of recreational beaches; for land reclamation; to ensure the maintenance of shoreline; as a reinforcement of dunes against breaching; as a protection of coastal structures (seawalls, etc.); to reduce the wave energy arriving at a beach/dune (submerged artificial bars along non-barred profile); as a protection and feeding of beach/dune system; to create a huge localized buffer of sand generally placed up drift of the zone to be nourished; it may also be used to stop erosion due to near shore rip/swash channels by making a stockpile (large dump) up drift of the channel (Van Rijn L.C. 2013).

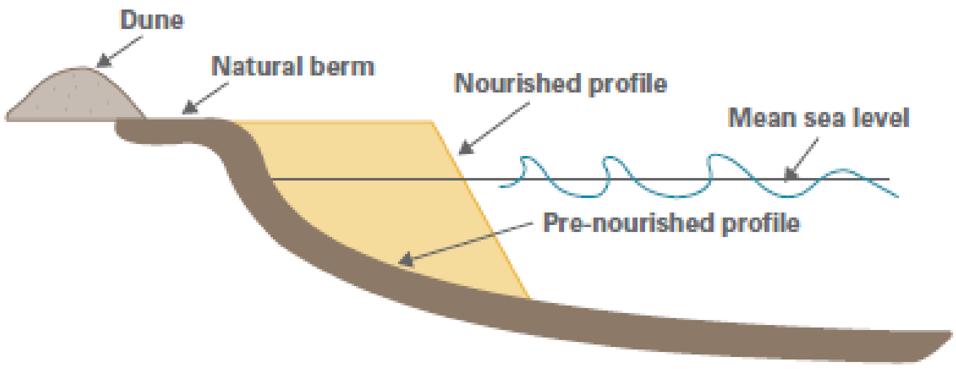


Figure 2.7 - Example of a sand nourishment to extend the natural berm seaward (www.asbpa.org)

The causes of beach erosion are determined by the study on morphological and hydro-sedimentological processes, including the analysis of data realized with extrapolation techniques and mathematical models (Pilarczyk et al. 1986). These models are also used to realize new projects to solve the erosion problem. In fact, the beach nourishment, as a possible solution to this, should be stable in plan form to ensure minimum maintenance, and in order to ensure the its efficiency, it is important to deepen different factors for the design. In fact the performance of beach nourishment is influenced by many factors. They are: 1) location, 2) wave energy, 3) sediment grain size of the borrow material, 4) volume of sand necessary, 5), local reversal and/or gradient in longshore sediment transport 6) presence of hard structures, 7) variation of the shoreline orientation, and so on (Davis et al. 2000). Since elements to consider are numerous, in this chapter only some of these will be examined. Orientation, sand composition, volume of sand and shape profile can be considered the main elements related to the design of a beach nourishment which need further knowledge. At first, the beach orientation: the headland and the change of shoreline orientation may have considerable influence. Due to this, the sand nourishment should be as much as possible perpendicular to the prevailing wave direction (Van Rijn L.C. 2013). In fact the benefit of beach nourishment comes from wave energy dissipation: when waves run up a beach and break, they lose energy. Different beach profile shapes and gradients interact with waves to differing extent. The cross-sectional shape of a beach therefore affects its ability to attenuate wave energy. A 'dissipative' beach – one that dissipates considerable wave energy – is wide and shallow while a 'reflective' beach – one that reflects incoming wave energy seawards – is steep and narrow (French 2001).

Secondly, regarding the sand composition, it's important to say that the selected beach fill material should be similar to that of the original beach. In fact ,ideally, the fill material should be slightly coarser than the native beach material located in the beach zone. Sand coarser than the native material is harder to move from waves; moreover it can be placed with a steeper slope. In fact the slope will remain somewhat steeper than the original slope until most of the fill material is removed by wave action. Sometimes it can happens that fine sand fill material will not be effective in the beach zone. Fine particles (between 0.06 and 0.125 mm) will be washed out easily during dredging operations and carried to the offshore zone where slopes are lower; the finer fractions dumped on the beach will be removed rapidly by wave action until a big volume of sand will be (again) required to compensate the losses. The sand size and composition mainly depend on the available sand in the borrow area. In case the borrow area has relatively fine sand deposits , the finer sand fractions (<0.125 mm) can be eliminated (partially) by using proper dredging methods. Almost 10 - 30% of the base material may be lost during dredging operations and, for this reason, the grain size may increase by 10% to 30%; but nourishment cost will also increase (due to the larger volumes required). (www.leovanrijn-sediment.com) Therefore, depending from the material use for the nourishment, it is possible to distinguish two different situations:

- 1st case - sand of the nourishment similar to the sand resent in loco.
- 2nd case - sand of the nourishment different from the sand resent in loco.

There are different methods to realize a beach nourishment: two of them are explained in Figure 2.8.

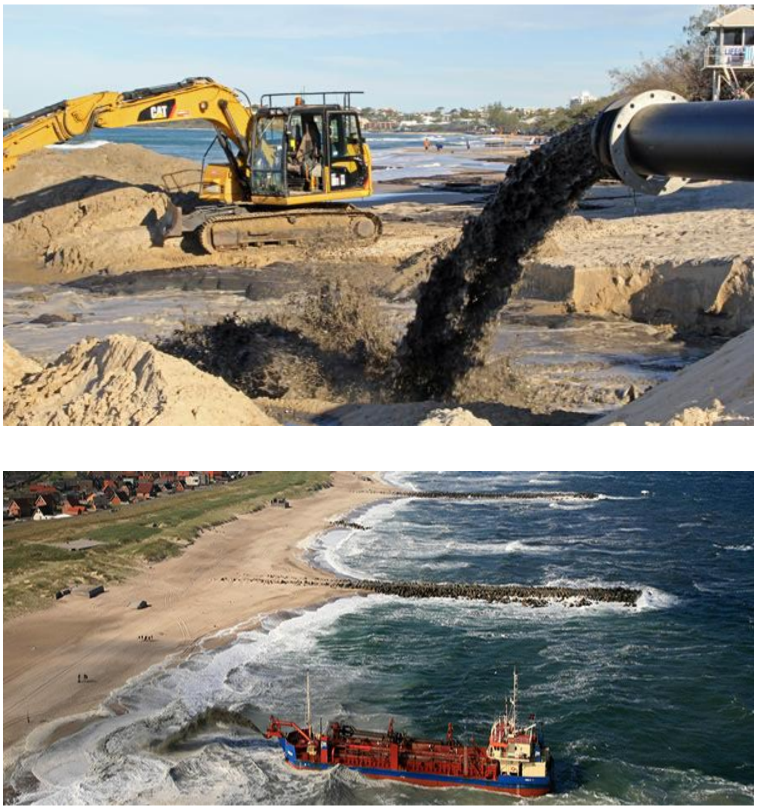


Figure 2.8 – How to realize a sand nourishment

On the top, an example of sand nourishment realized pumping the sand (www.viewnews.com.au). On the bottom, one realized with a dredger boat (www.rohde-nielsen.dk). The amount of sand that is necessary has to be established according to the deficit of sediments along the coastal stretch in question, as well as the characteristics of native sediments and the borrow deposits. Since beach nourishment is the process of dumping or pumping sand from elsewhere onto an eroding shoreline, it can be realized in different ways. Common approaches involve either pumping sand in watery slurry through pipes to the beach or carrying it in dump trucks. To avoid rapidly losing the sand offshore, the sand is usually then spread out on the dry beach (above the high-tide line) using bulldozers. In some cases, where seabed is deeper (not less than 50 m), ships are also used.

Of course the design of the nourishment is dependent from the grain size of the sand that has to be placed. Therefore the dimension of the grains is really important because it is a factor that modifies the width of the beach. In general, the bigger the dimension of the grain size is, the wider the length of the beach will be that has to be nourished (Pilarczyk et al. 1986). For this reason, the volume of sand is another important factor that has to be designed. the volume of send required depends from the wave energy of the location. According to Van Rijn, it is possible to divide the coasts in three different types:

- low-energy coasts which require 10 -50 m3/m/yr ;
- moderate-energy coasts which require 50 - 150 m3/m/yr;
- for high-energy coasts which require 150 - 300 m3/m/yr.

Moreover, it's important not to over nourish the beach profile: the fill volume should not be too big to prevent excessive initial erosion, due to steep beach profiles. In general, the profile adapts itself rather quickly to the actual wave impact. Erosive profiles occur under severe wave conditions and lead to the so-called "bar profiles". Accretive profiles are characterized by moderate wave Impact and are referred to as step-profiles (Pilarczyk et al. 1986). Related to the profile, beach nourishments should have a relatively gentle initial slope 1 to 30/50 (for the upper beach above -1 m depth line) or 1 to 20/30 (for the lower beach between -1 and -3 m depth lines). The precise slope of the lower beach immediately after nourishment is not so important as long as it is not too steep because the profile will be reworked by the first autumn storms to a more natural profile. However the initial losses of beach nourishments are largely determined by the initial beach slope and profile shape (Van Rijn L.C. 2013).

Considering what has just been said, many researchers have studied the development of coastal profiles under wave attack in order to derive relations between profile shape, wave motion and sediment characteristics. Most of the derived relations are based on the results of small-scale tests. In models, generally, one type of sand is mostly used as bed material. In addition to this, the results of model testing have usually been obtained by applying fixed wave conditions: elements that are quite variable in nature. As a matter of fact, the whole wave climate is responsible for the shape of the coastal profile; while also other factors play a role, such as tides, surf beat, coastal currents, etc. Obviously the complexity of the factors has also caused that the analyses of measurements in nature have not lead to applicable relations for predicting the shape of coastal profiles (Pilarczyk et al.1986).

Typically, artificial nourishment turns out to be a feasible and attractive method to restore, protect, extend and maintain beaches. The essence of the reported advantages is its flexibility and harmony with nature. (Pilarczyk et al. 1986). The uses of beach fill is becoming always more and more important in the countries of the European Union. There are significant differences among these countries: project type and objectives, design and evaluation procedures, legal framework, and financial aspects. A study carried out by Hamm et al. (2002) explains how this procedure is very profitable to solve the erosion problem and how Dutch and German practices should be examples for the southern European countries. In particular practices regarding the long-term coastal management and the regular monitoring of the coastal morphology (Hamm et al. 2002).

As a conclusion, theoretically the artificial beach replenishment, as a solution for the sand deficit, does not solve the erosion problem at the root, but it helps to stabilize and/or reduce erosion. In fact it is not supposed to be a permanent solution: a periodic repetition the nourishment is necessary to balance the losses of natural sand caused by the action of the waves (Tommasicchio 2011). For this reason the sand nourishment is typically a repetitive process (periodic feeding), since it does not eliminate the physical forces that cause erosion, but simply mitigates their effects. The limits of this type of intervention are represented essentially by the availability, in economic costs, of materials suitable for the nourishment (Agenzia nazionale per la protezione dell' ambiente 2007). Due to this, beach nourishment is typically designed as a part of a larger coastal defense scheme. Therefore, for beaches suffering from coastal erosion, the sand nourishment is just one of three commonly accepted methods for protecting shorelines; the second (structural) alternative involves constructing a seawall, revetment, groin or breakwater; the third one involves the combination of both the approaches.

2.2.3 Detached breakwaters

Detached breakwater are hard structures which absorb wave energy before the waves reach the shore: in fact their goal is to protect the section of the shoreline by forming a shield to the waves, wherein the incident wave energy is reduced. These structures can be positioned in a parallel way or also occasionally obliquely to the shore. They can also have difference in shape: generally their section must be trapezoidal (or sometimes rectangular). Great care should be exercised when deciding the shape of a breakwater. Breakwaters in general are supposed to reduce the wave energy. In fact when the wave arrives this rather than directly hitting the pier or the beach, it breaks on the breakwater and this being a complex and large-surface structure (whether fixed or floating structures), the wave force is reduced by friction. On the contrary, vertical seawalls, do not absorb wave energy incident on them and reflect everything back (US Army Corps 1992). Their crest (the top part of the structure) may be positioned above the still water level (emerged) or below the still water level (submerged). Therefore the height of the structure is always in relation to the local water depth. Therefore, if these reefs are submerged, they are called "Low Crested Submerged Structures" (abbreviation LCSs). The design is really similar for both of them: emerged and submerged. Thanks to the difference in height, the advantage of LCS structures is mainly the fact that they are capable to combine the protection of the coastline reducing significantly the environmental impact and landscaping. For large-scale beach protection, detached breakwaters (emerged and submerged) can be constructed as a single structure to localize shore protection or as multiple breakwaters with gaps between the segments (Agenzia nazionale per la protezione dell' ambiente 2007). An example of a submerged breakwater is give in Figure 2.9.

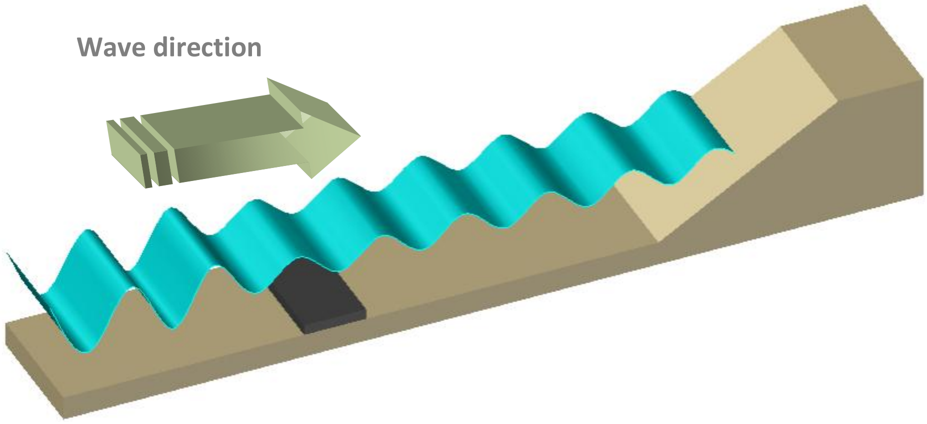


Figure 2.9 – Explanation of the energy decrease in presence of a breakwater structure.

When the wave reaches the shoreline, the wave length decreases, the height increases until the wave itself breaks. When the wave is lowered from a breakwater structure, it absorbs the wave energy. Reducing the energy, the waves that reach the shoreline are less aggressive and they have less influence the erosion of the coast (Image elaborated by the author).

2.2.5 Design parameters involved

Whenever a breakwater has to be built at a certain location and the environmental impact of such a structure has already been evaluated, it is necessary a deep study of some parameters. Wave height investigation has a great significance in terms of design. The height of wave incident on a breakwater generally determines the size and behavior of the structure. It is therefore one of the utmost necessary importance to obtain realistic values of the waves expected in a particular area. Wave disturbance is also felt to a considerable depth and, consequently, the depth of water has an effect on the character of the wave. Their height, depending from shape, waves, location, etc, is never bigger than two or three meters. As the seabed rises towards the shore, waves eventually break. In addition, it is essential to determine what the sea bed consists of: it can be made of soft or hard rock (such as coral reefs or granite), sand (as found on beaches), clay (as in some mangrove areas) and silt (or mud, as found along some river banks, mangroves and other tidal areas). A geotechnical investigation of the seabed is necessary to determine the type of foundation material. This study is important to determine the load that the ground can effectively support: if a foundation is or not necessary, and which kind of material can be used related to it. Therefore the material is another significant factor involved (US Army Corps of Engineers1992). Figure 2.10 and Figure 2.11 will give an overview of the main examples of breakwater structures.

Trapezoidal rubble mound breakwaters

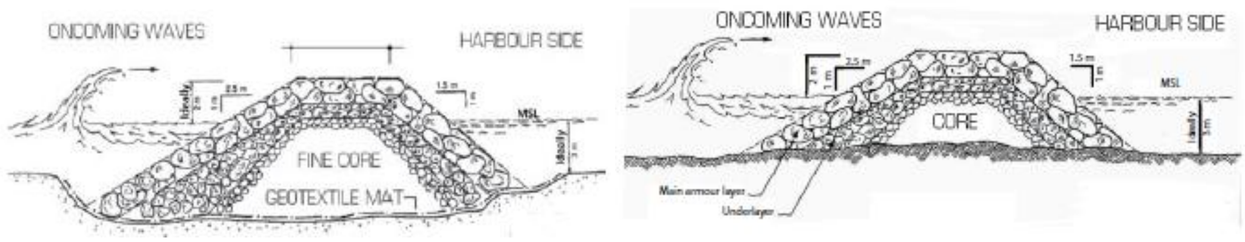


Figure 2.10 – Example of trapezoidal breakwater

There are two example of rubble mound breakwaters: on the left the one placed on soft ground, on the right the one on hard ground. These examples show that, if the foundation material is very soft and thick, a geotexile filter should be placed under the rock to prevent it from sinking and disappearing into the mud. If a thin layer of loose or soft material exists above a hard layer, then this should be removed to expose the hard interface and the breakwater built on this surface (US Army Corps of Engineers 1992).

Solid vertical breakwaters

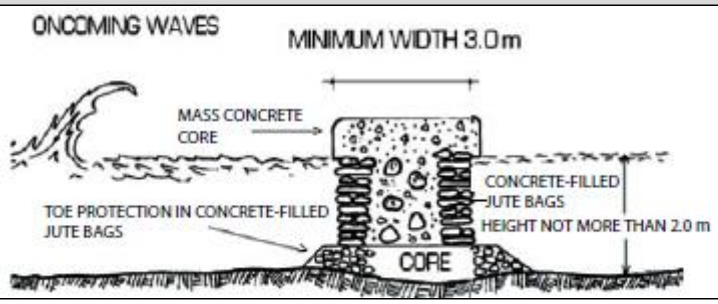


Figure 2.11 – Example of vertical solid breakwaters

Vertical solid breakwaters are only suitable when the foundation is a firm surface (rock, stiff clay, coral reef); thick sand deposits may also be suitable under certain conditions. In the presence of thick sand deposits, a rubble foundation with adequate scour protection is recommended for strong tidal streams, water currents or wave turbulence scour away the sand underneath the foundation (US Army Corps of Engineers 1992).

Since most breakwaters consist of either rock or concrete or a mixture of both, it is evident that if these primary construction materials are not available in the required volume in the vicinity of the project site.

Some solutions need to be found. Either the materials have to be shipped in from another source (by sea or by road) or the harbor design has to be changed to allow for the removal of the breakwater (the site may have to be moved elsewhere). To calculate the volume of material required to build a breakwater, equidistant cross-sections are required. Each cross-section consists of the proposed structure outline superimposed on a cross-section of the seabed. Mathematically, this can be expressed as half of the total area multiplied by the distance between two sections (US Army Corps of Engineers 1992). Figure 2.12 shows the cross section profiles used for this calculation.

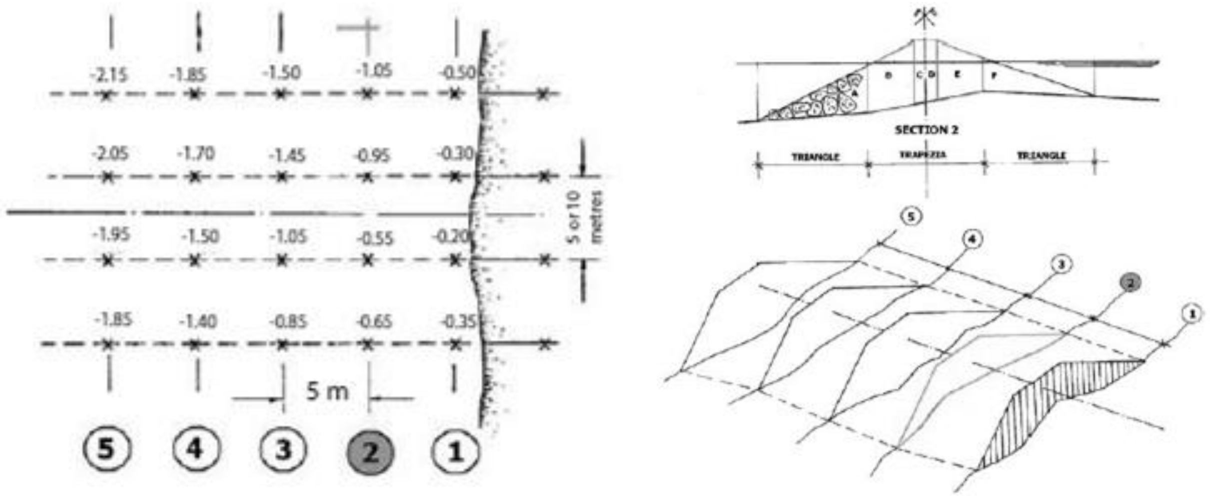


Figure 2.12 - Volume of rocks in breakwater (US Army Corps of Engineers 1992)

2.2.5 Design of a breakwater

Generally a breakwater barrier detached from the beach is a fixed structure, consisting of a stable foundation (base), a nucleus of tout-Venant and an outer protective layer characterized by natural rocks or concrete units. The reefs mainly have trapezoidal cross-section with a particular structure, which can be divided into a substructure and a natural infrastructure. The former is suitable to distribute loads on the ground and, for the most part, consists of natural stones. When the ground under the structure is in compressible nature - or silty clay - a reasonable thickness of material, crushed stone or sand, is used having the function of filter. Instead, the natural infrastructure is made with blocks (concrete, in case of really strong waves) in which weight is determined as a function in size of the stress wave agent, arranged according to different slopes and configurations in according to their location (Agenzia nazionale per la protezione dell' ambiente 2007).

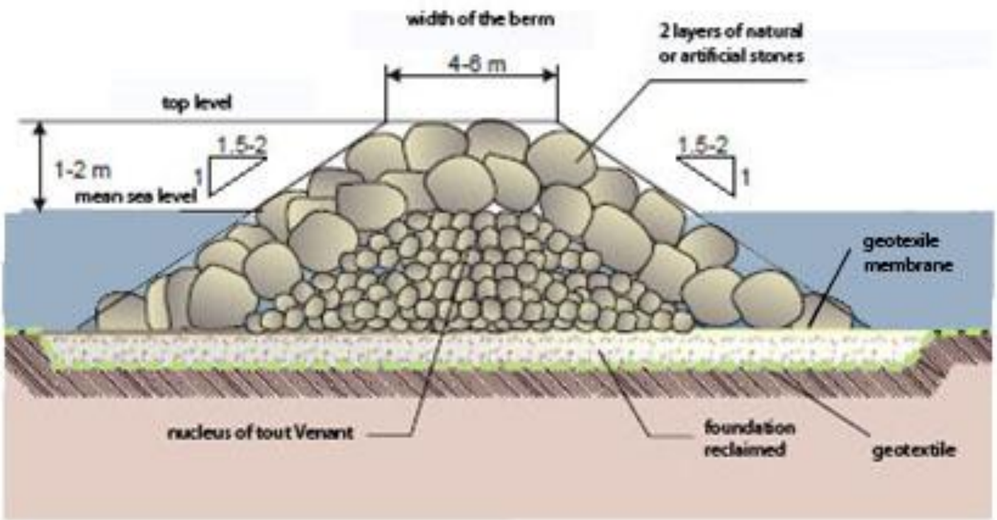


Figure 2.13- Geometry of a breakwater (Agenzia nazionale per la protezione dell' ambiente 2007)

The horizontal top structure is called berm, the two parts inclined towards the sea are defined ''slopes'' of the structure. The nature and arrangement of the material of which the top layer is made, the roughness and the voids existing between rock and boulder contribute efficiently dissipate most of the energy of the wave incident, limiting the rate of reflected energy. An incorrect positioning of the blocks (for example, in mosaic fashion) can create an increase of the reflected energy with a consequent increase in the height of the wave front of the dam and risk for its stability. The inner core, almost entirely unaffected by the action of the waves, is usually realized with quarry material and is called core in tout-Venant, whose particle size can vary within boundaries rather extensive. The core must be protected with the help of natural or artificial boulders, arranged in successive layers (layers filter), whose size is increasing towards the top of the structures. The values of the slopes oscillate around 1 / 1.5-5 (emerged structures) and around 1 / 2-5 (submerged structures), while the value of the width top varies between 2 and 7 meters for emerged structures. In the case of the submerged ones, the top widths are between 10 and 14 meters (Agenzia nazionale per la protezione dell' ambiente 2007).

Figure 2.14 - Example of barrier with natural boulders (Agenzia nazionale per la protezione dell' ambiente 2007)

To reduce cost of the design and to avoid the rapid water eutrophication, it is often preferred to realize barriers with openings along the same structure in order to ensure sufficient room through these parts of water. However, though these cases should be taken into account, there is still the possibility that deposited sands which are transported by coastal drift creates tombolos and deposits against the structures. More rarely, other types of structures are used: some consists gabions filled with stones, others made of reinforced concrete poles connected by horizontal membrane, or others consisting of geotubes made of geotexile (or propylene or polypropylene) filled with sand. This consists geotexile bags filled with sand and piled on each other (Agenzia nazionale per la protezione dell' ambiente 2007).

However, it is possible to use every kind of material for their construction. From Figure 2.15 to Figure 2.26 are shown some examples.

Structure	Example

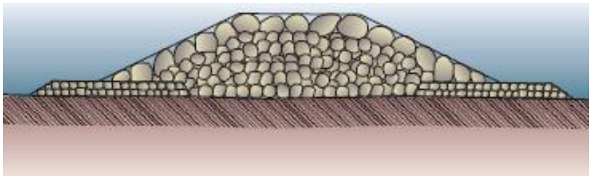



Figure 2.15 - Cross section of breakwaters realized with rocks (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.16 - Example of breakwaters in Rimini (Italy) (Agenzia nazionale per la protezione dell' ambiente 2007)**

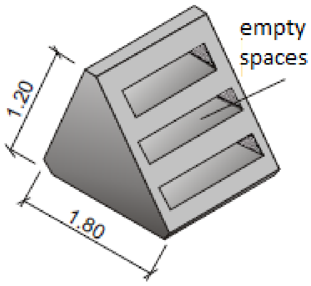



Figure 2.17- Breakwaters realized with modules Surgebreaker (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.18 - Example of positioning of this module (Agenzia nazionale per la protezione dell' ambiente 2007)**

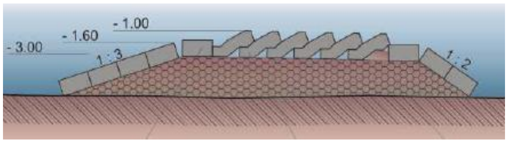
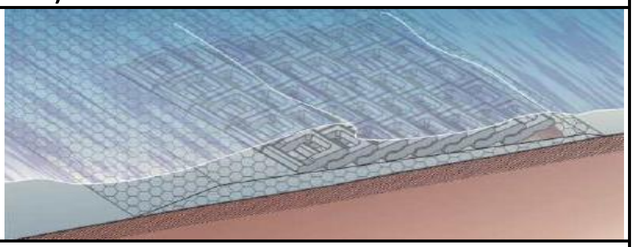

	

Figure 2.19 - Breakwaters realized with Aqua-Reef modules (Aqua Blocks) (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.20 - Example of Aqua-Reefs (Agenzia nazionale per la protezione dell' ambiente 2007)**

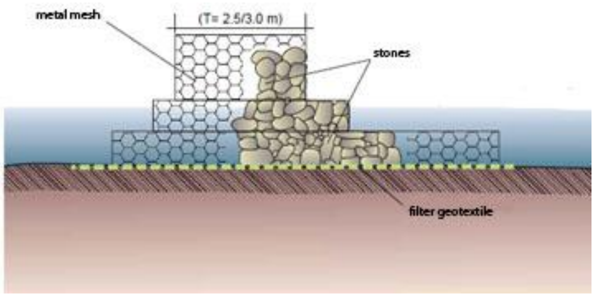


Figure 2.21 - Structure consisting of gabions filled with stones (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.22 – Example of gabions filled with stones (www.maccaferri.com)**

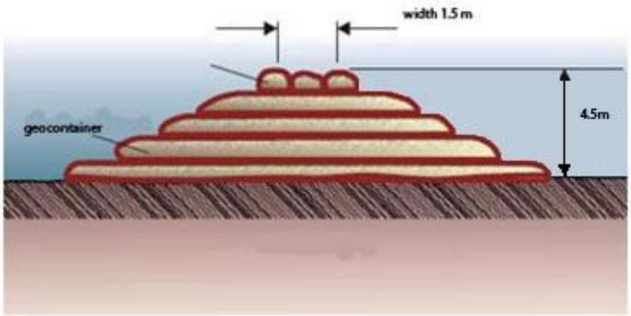



Figure 2.23 - Barriers of geocontainers (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.24 – Examples of geocontainers for caostal protection (www.ecobarrier.ae)**

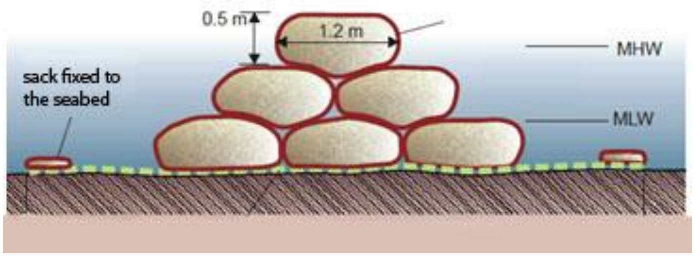



Figure 2.25 - Barriers of bags filled with sand (Agenzia nazionale per la protezione dell' ambiente 2007)	**Figure 2.26 – Example of barriers of bags filled with sand (www.ecobarrier.ae)**

2.2.6 Hydraulic and morphodynamic effects of breakwater structures

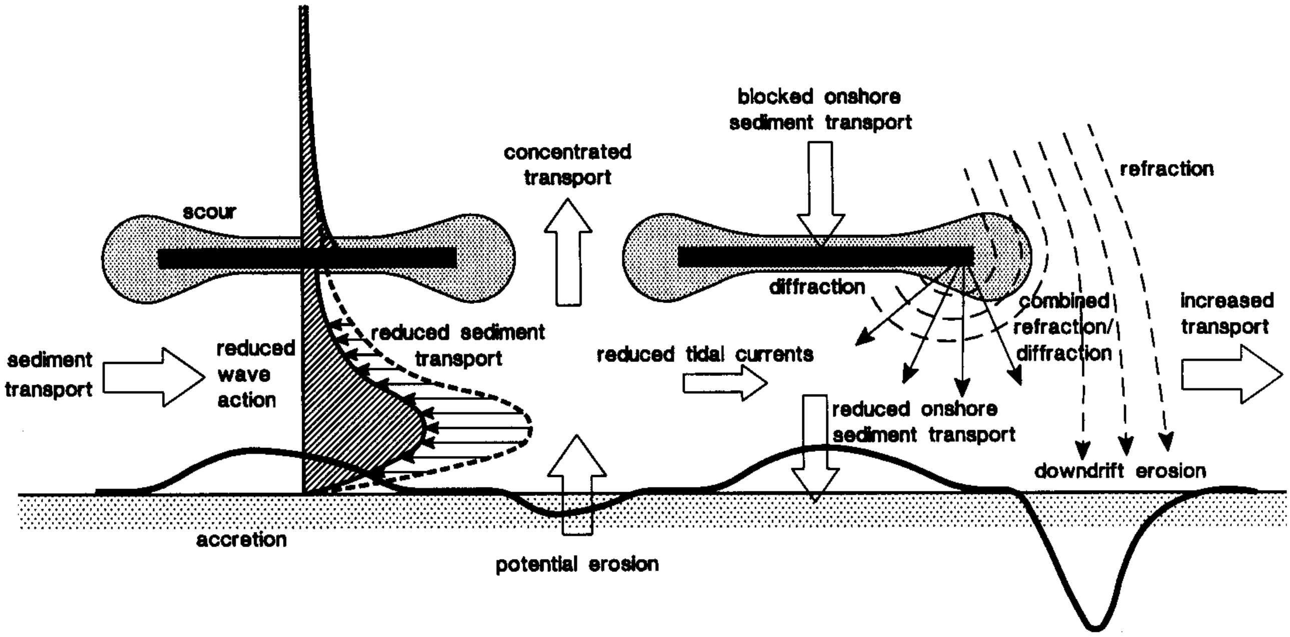


Figure 2.27 - Hydrodynamic and transport processes near detached breakwaters (Van Rijn L.C. 2013)

Basically the wave energy at the shoreline is reduced by the presence of the structure because of wave breaking and reflection at the breakwater. Some of the incoming waves arrive in the lee zone driven by different transformation processes: diffraction around tips and through gaps; transmission through the breakwater; overtopping of the submerged breakwater. Diffracted and transmitted waves will continue to propagate towards the shoreline in the lee zone; in this way the longshore transport capacity in the lee zone will be substantially be reduced and sedimentation should take place. The sand movement just explained, is represented in Figure 2.28.

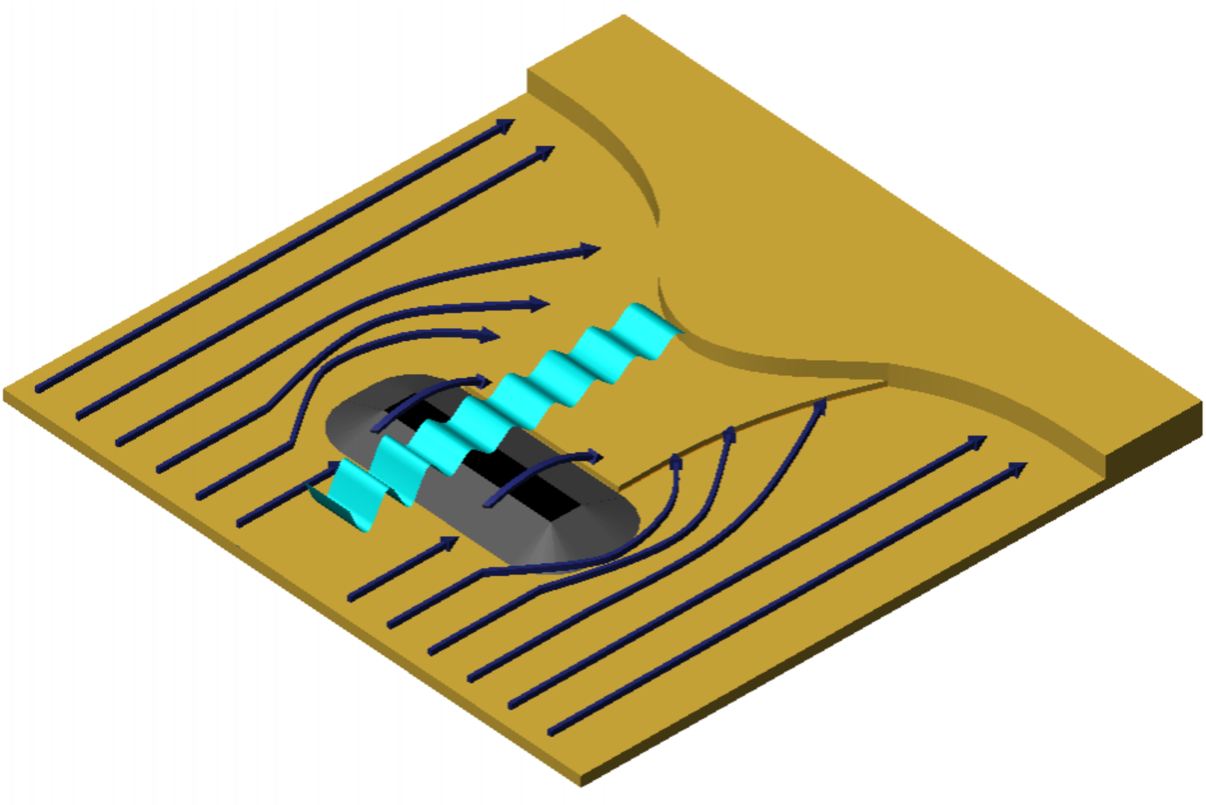


Figure 2.28 – **Scheme of sand movements around the reef**

The sand moving along the shore will go behind the structure and trapped there. The result of this movement is the local deposition of littoral sands within the protected lee of the breakwater. Long shore currents toward the tip points will be generated. Sometimes, if there is considerable transport of water through the (permeable) structure and over the structure (submerged breakwater), it can result erosion of the sand from the lee zone by these currents and by rip currents through gaps between segmented breakwaters (downdrift erosion). In case of normal-incident waves, the diffracted waves will transport sand from the adjacent beaches into the lee of the structure until the shoreline is sufficiently aligned that the waves break parallel to the shoreline and the long shore transport becomes zero everywhere yielding a symmetrical salient or tombolo[1] pattern. The shoreline will then erode on both sides of the structure. In case of oblique-incident waves a system with long-shore currents and transport is generated, which may remain in function if a salient is formed. The shoreline near the structure will adjust in such a way that the smaller waves behind the structure can transport the same amount of sand as the larger waves updrift and downdrift of the structure; the salient shoreline causes the smaller diffracted waves to break at a more oblique angle.

[1] A tombolo, from the Italian *tombolo*, derived from the Latin *tumulus*, defined as 'mounds', is a deposition landform in which a structure is attached to coast by a narrow piece of land such as a bar or split.

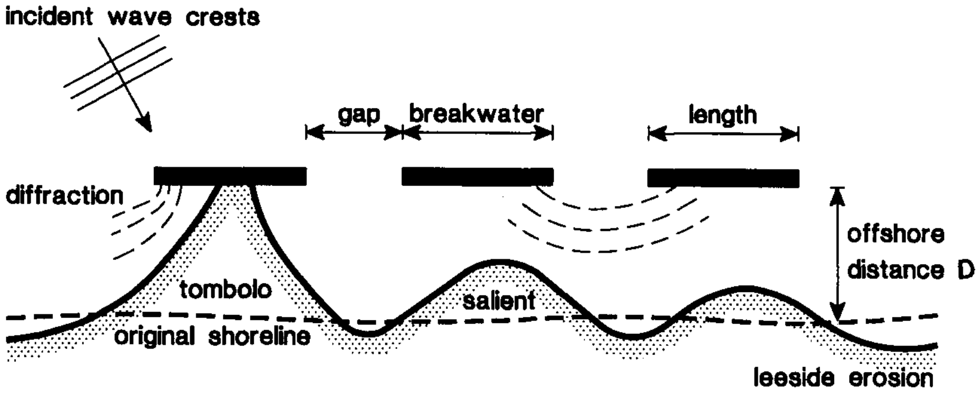


Figure 2.29 - Tombolo and salient behind detached breakwater (Van Rijn 2013)

The crest elevation determines the amount of wave energy transmitted over the top of the breakwater. High crest elevations preclude overtopping by all but the highest waves, whereas low crest elevations allow frequent overtopping. Occasional overtopping of a nearshore breakwater by storm waves can prevent tombolo formation or remove a tombolo once it has formed. Submerged breakwaters allow almost continuous passage of the lower waves.

2.3 Challenges to conventional coastal engineering: ecosystem-based coastal defense

Although beach nourishment and breakwater structures are some of the most effective methodologies for shoreline restoration and stabilization, it is not always environmentally suitable for some locations. As mentioned before, breakwaters are artificial reefs that can be realized in different ways but their goal stays the same: reduce the wave energy reaching the shore, but also to provide environmental and recreational benefits out of it (Harris 2009).

Nowadays there are different type of environmental improvement. They can include marine habitat, mitigation of damages, and recreational benefits such as swimming, snorkeling, diving, fishing and surfing. One of the most important ones can be the enhancement, recreation or also stabilization of the habitat for flora and fauna living in some locations. One example of this solution is given by the ReefBall, artificial reef units which have even been placed in the Caribbean (Island of Grand Cayman, Curacao, Antigua and so on). They are artificial reef balls made concrete block which, thanks to the presence of cavities, have the function of protecting the habitat for the development of the life of marine organisms. Depending on the material used to construct the submerged breakwaters, they can provide habitat for benthic and pelagic flora and fauna, they can be used for aquaculture and eco-tourism. These artificial reefs provide stable bases upon which, for example, coral can be attached (Harris 2009).

Figure 2.30 - Artificial reef balls in concrete block in the Island of Grand Cayman (Agenzia nazionale per la protezione dell' ambiente 2007, (Harris 2009).

The case of the ReefBalls is only a small scale example of what it can be realized with breakwater structure for natural purpose. Starting from this, at the present time different solution have been studied in order to move from conventional coastal engineering systems to new ones, taking care of the environment, the ecosystems and the nature itself.

2.3.1 New ecosystem-based flood defense

In recent years, a more sustainable and cost-effective solution has been sought to replace the conventional coastal engineering one. It's a solution favorable at locations which have sufficient space between urbanized areas and the coastline to accommodate the creation of ecosystems. It is appropriate for ecosystem-based flood defense like tidal marshes, mangroves, dunes, coral reefs and shellfish reefs. They have the natural capacity to reduce storm waves and storm surges. They have the capacity to grow together with sea-level rise by natural accretion of mineral and biogenic sediments. This latter process ensures the long-term sustainability of ecosystem-based coastal protection. These ecosystems provide also several added benefits: for example water quality improvement, fisheries production and creation, and so on. (Temmerman et al. 2013) For these reasons this solution could be more cost effective than conventional defenses. As said by Temmerman, this ecosystem-based approach is not suitable for all coastal areas and its global application is still scarce but, on the basis of current knowledge, it could be argued that the approach has the potential to protect many of the world's largest flood-prone coastal populations.

The applicability of ecosystem-based approaches depends on different factors: the type of coastal area and location of the city at risk. For cities located in estuaries or deltas, the creation (or restoration) of large tidal marshes or mangroves between the city and the sea can be favorable: it can provide extra water storage areas and, at the same time, attenuate the propagation of storm surges and reduce flood risks in the hinterland. Instead, for cities located behind sandy coastlines, beach and dune barriers are considered as crucial defenses against coastal flooding. Figure 2.31 will illustrate the previously explained difference.

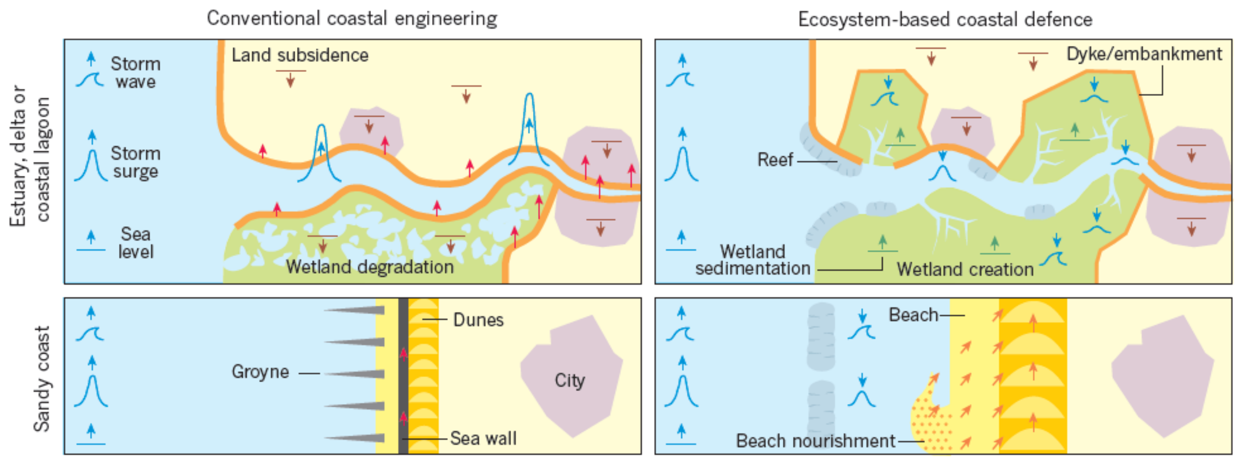


Figure 2.31 - Conventional coastal engineering compared with new ecosystem-based defense. (Temmerman et al. 2013)

It illustrates the basic principles of flood protection by conventional coastal engineering (left) and new ecosystem-based defenses (right) for an estuary, delta or coastal lagoon (top) and a sandy coast (bottom). Blue arrows indicate an increase or decrease in intensity of storm wave, storm surge and sea level; red arrows indicate the increase or decrease of need for maintenance and heightening of dykes, embankments and sea walls with sea-level rise. In the case of ecosystem-based defenses compared to conventional defenses, wetland and reef creation attenuate landward storm surge propagation and storm waves and stimulate wetland sedimentation (green arrows) with sea-level rise. For what concerns engineered sandy coasts (bottom left), groynes and sea walls may cause dune degradation due to hindered sand supply, whereas for ecosystem-based defense along a sandy coast (bottom right). Reefs help to attenuate storm waves and surges, while offshore sand nourishment stimulates beach and dune sedimentation with sea-level rise (orange arrows). Table 2.1 gives an overview of potential and limitations of these systems.

Affected variable	Conventional coastal engineering	Ecosystem-based coastal defence
Natural habitat	Degradation or destruction	Conservation or restoration
Sediment accumulation (after sea-level rise)	Disturbed or stopped by embankments, groynes, dams, and so on.	Sustained (if enough sediment is available)
Land subsidence	Exacerbated by wetland reclamation, soil drainage, groundwater and gas extraction	Counterbalanced by sediment trapping, but continues behind ecosystems
Storm surge propagation through an estuary or delta	Wetland reclamation reduces water storage and friction, enhancing inland storm surges	Wetland restoration enlarges water storage and friction, lowering inland storm surges
Long-term sustainability	Low: regular maintenance is needed at high cost	High: ecosystems are self-maintaining (if enough sediment is available)
Cost–benefit appraisal	Moderate to high	Mostly high due to added benefits
Water quality of estuary, delta and coastal sea	May degrade by organic matter accumulation and toxic algal growth in closed-off estuaries	Improved and sustained by nutrient and contaminant cycling in restored wetlands
Climate mitigation through carbon sequestration	None	Mangroves and marshes are important carbon sinks
Fisheries and aquaculture production	Reduced: less habitat for young fish, shellfish and crustaceans due to wetland reclamation	Improved: more habitat for young fish, shellfish and crustaceans due to wetland and reef restoration
Human recreation potential	Negative perception of artificial landscape	Positive perception of natural landscape
Required space	Moderate	High, therefore, not applicable for cities on the coast
Difficulty of creating the defence structure	Moderate	Relatively high due to natural dynamics and variability
Existing implementation and experience	Substantial, but many failures in the past	Limited so far. More research is urgently needed
Social and political acceptance	Widely accepted	So far, only accepted in certain areas (Europe and United States)
Health hazards (other than flooding)	None	Wetlands with stagnant water may facilitate breeding of mosquitoes that could spread disease

Table 2.2 - Potential and limitations of conventional compared with ecosystem-based coastal defense (Temmerman et al. 2013)

2.3.2 Ecosystem engineers and oyster reefs as eco-engineers

Ecosystem engineers are organisms that directly (or indirectly) modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. They can be autogenic or allogenic engineers. The first ones, like corals, change the environment via their own physical structures (i.e. their living and dead tissues). The second ones, like beavers, change the environment by transforming living or non-living materials from one physical state to another. Organisms act as engineers when they modulate the supply of a resource or resources other than themselves (Jones, Lawton, and Shachak 1994).

Many examples of these ecosystem engineers are found in the coastal ecosystem. An example of an allogeneic engineer is the Australian isopod *Sphaeroma Quoyanum* which increases salt marsh erosion in California, due to its burrowing and filter feeding activity (Talley et al. 2001). *Arenicola Marina* is an "allogeneic engineer" as it destabilizes the sediment by bioturbation (Montserrat et al. 2011). Coastal vegetation, such as kelp forest, mangroves, marsh plants and sea grasses, are known as "autogenic ecosystem" engineers, as they reduce water flow within their canopy or root system (Neumeier and Ciavola 2004), promoting sedimentation within the vegetation and provide substrate for both sessile mobile organisms (Bos et al. 2007, Bouma et al. 2005, Bouma et al. 2014,). In temperate climate zones, sea grasses trap sediment between their leaves during summer, whereas in winter no leaves are present to fix the trapped sediment (Paul and Amos 2011). Coral reefs and bivalve reefs are also autogenic engineers as they provide structure and complexity on bare sediment (Ruesink et al. 2005).

Oysters can also be considered as ecosystem engineers which can be potentially used to provide a natural solutions for coastal defense. In fact oysters create, modify or maintain habitats and ecosystem processes through their activities and the structures they create.. They are capable of forming conspicuous habitats that influence tidal flow, wave action and sediment dynamics in the coastal ecosystem and, in doing so, reduce hydrodynamic stress and modify the patterns of local sediment transport, deposition, consolidation, and stabilization processes. Bivalve reefs also provide habitat for numerous species of fish, crustaceans and other invertebrates and can contribute to food security and livelihoods for coastal people. A 'living shoreline' with artificial oyster reefs could be a self-sustained element for coastal protection and provision of ecosystem goods and services (Hossain et al. 2013).

The species of Pacific oyster is commonly considered as an ecosystem engineer (Troost 2010). The Pacific oyster has the ability to form reefs. Oyster reefs are valued for the many ecosystem services they generate, such us a potential stabilization of the shoreline (Meyer et al. 1997), improvement of the water quality (Newell et al. 2005) and influences many ecological processes such as maintenance of biodiversity, population and food web dynamics, and nutrient cycling (Ruesink et al. 2005). Oyster reefs facilitate settlements and shelter for living species in and around the oyster reefs. The ecological result is a greatly increased biodiversity in and around them (Troost 2010). The vertical relief characterized by an oyster reef has a sufficient effect on the water flow, creating turbulence. This change in water flow generates a different kind of habitat than at a soft substrate area and will increase the species richness (Coen et al. 2007). Oyster reefs can function as natural, living breakwaters (as opposed to human-designed), bulkheads, or jetties because they are structures that interact with tidal and wave energy just like engineered shoreline stabilization devices by baffling waves and increasing sedimentation rates (Meyer et al. 1997). The rate of vertical oyster reef growth on detached reefs is far greater than any predicted sea-level rise rate and therefore reefs could serve as natural protection against shoreline erosion, intertidal habitat loss, and property damage and loss along many estuarine shorelines. The current standard practice for inshore erosion protection is the use of engineered shoreline stabilization devices (Titus 1998). Table 2.3 is a summary of the ecosystem services and processes which can or not be applied.

Ecosystem service	Ecosystem process	References	Bioeconomic model valuation method
Water quality improvement	Chlorophyll a removal	Newell et al. 2002, Grizzle et al. 2006	Replacement cost of using sewage treatment plant to remove nitrogen, nitrogen credit market
	Reduce turbidity	Newell and Koch 2004	
	Denitrification	Piehler and Smyth 2011	
	Increase benthic algal or pseudofecal production	Newell et al. 2002	Not applicable
	Bacterial biomass removal	Cressman et al. 2003	Not applicable
Seashore stabilization	Shoreline stabilization	Meyer et al. 1997	Cost of a sill to stabilize salt marsh and seagrass habitat, value of protected habitats
Carbon burial	Bury carbon dioxide	Not applicable	Traded carbon pollution credits
Habitat provisioning for mobile fish and invertebrates	Increased fish production	Peterson et al. 2003	Commercial dockside landings value, recreational fisher willingness to pay for improved fishing
Habitat for epibenthic fauna	Increased epibenthic faunal production and biodiversity	Wells 1961, Bahr and Lanier 1981, Lenihan et al. 2001	Already captured in fish values
Diversification of the landscape	Synergies among habitats	Micheli and Peterson 1999, Grabowski et al. 2005	Not applicable
Oyster production	Increased oyster production	Heral et al. 1990, Rothschild et al. 1994, Lenihan and Peterson 1998, 2004, Grabowski and Peterson 2007	Commercial oyster dockside value, recreational value-license program

Table 2.3 - Ecosystem services provided by oyster reef habitat (Grabowski et al. 2012)

In locations where property owners would otherwise use these engineered devices, their cost can be used as a reasonable proxy for the economic value of oyster reef restoration. This assumes that reefs are perfect substitutes for human-made devices. Since oyster reefs can grow vertically faster than sea levels are expected to rise, an argument can be made that they are more resilient to sea-level rise than a fixed engineered device, thus, they would have a higher value as a shoreline stabilizer. However, the relative risk of storm damage to engineered and oyster reef structures needs to be considered. Given that oyster reefs and unnatural engineered devices constitute similar physical structures, the equivalence of value could be assumed (Grabowski et al. 2012).

Nowadays oysters, as eco- engineering systems, are increasing to protect the coasts in the world. For this reason different approaches are used. There are mainly two methods which can be adopted, depending from the location of the reef in the intertidal area. Examples of the applications of these approaches for the shoreline restoration are briefly explained below (Figure 2.32). The Sister Lake located in Louisiana is an example of location where reefs were used for the protection of the shoreline. In this case, reefs of *Crassostrea Virginica* were built as closed as possible to the shoreline, demonstrating that, in low energy environments, this system provide a useful shoreline stabilization (Piazza, Banks, and La Peyre 2005). A similar example comes from the North Carolina (Harjer's Island, Swansboro and Snead's Ferry) where stabilization of sediments was produced resulting from oyster cultch which are not located adjacent the marshes (Meyer, Townsend, and Thayer 1997). Another case is the Viane and de Val (Eastern Shelde), the Netherlands, where three artificial oyster reefs are placed, demonstrating supporting facts that they can locally protect tidal flat and shoreline against erosion (Walles 2015). Another example is the coastline of Bangladesh. In this case, a research study has been designed to explore the use of reef structure with oysters for enhancing coastal habitats in the near shore. This last project consists of the use of circular concrete rings placed as a reef to observe the eco-morphological changes in the tidal mudflat. The project is still ongoing but it is expected to provide new information on the use of ecosystem engineers combined with the coastal protection.

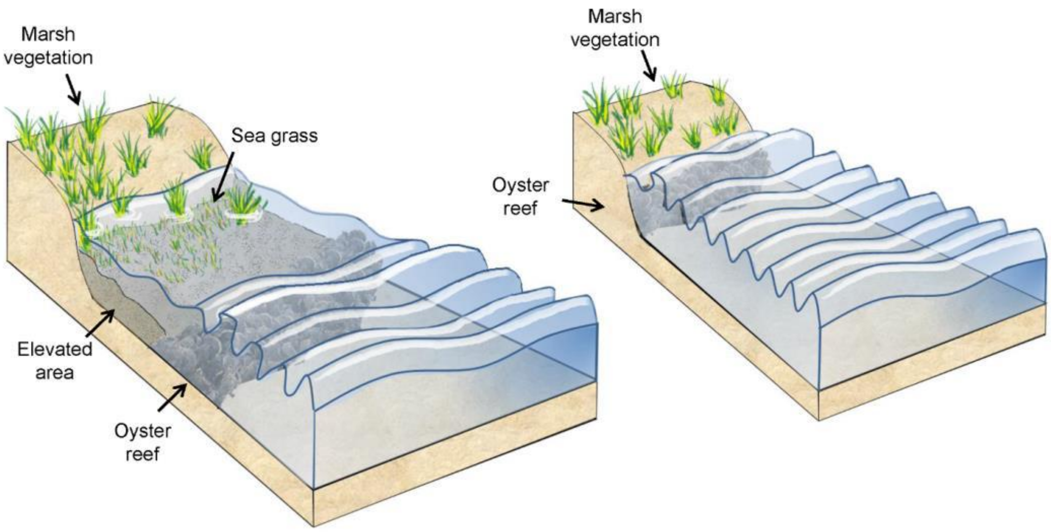


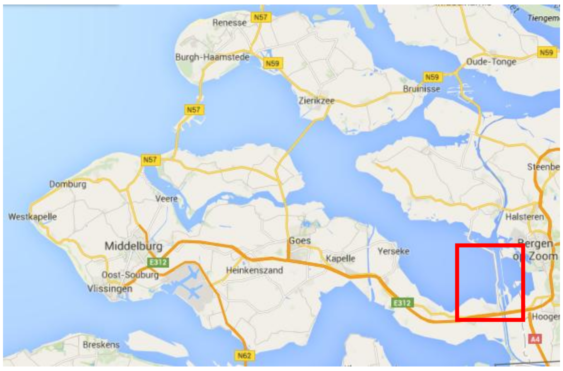
Figure 2.32 - Different approach of placing oyster reefs (Walles 2015)

The figure shows the difference between the two approaches. The image on the left shows an eco-engineering structure placed at a certain distance from the shoreline, instead, the one on the right is located at the edge of marsh vegetation. Both of them perform as breakwaters to prevent shoreline erosion, but the first one also promotes the shoreline growth (Walles 2015). In the first case, mangrove and vegetation can grow behind the reef. This vegetation can break the waves before they reach the land. At the same time, it forms a natural habitat for fish, crabs and recreates a new ecosystem. The second one is a more natural protection instead that artificial, and protects the land from the waves recreating the habitat around it.

3. The study area

3.1 Location

The Oesterdam is a dam located in the Eastern Scheldt basin (Oosterschelde in Dutch). The basin is located in the province of Zeeland, in the Southwestern part of the Netherlands (Figure 3.1). Historically, the Eastern Scheldt was an estuary but now it is considered a tidal inlet/basin. There are a lot of intertidal areas, shoals and tidal flats present in the basin. One of them is the Oesterdam area. Oesterdam is located in the est part of this basin, between Tholen and South Beveland. The dam is 10.5 kilometers in length and is the longest dam of the Delta Works, which were designed after the disastrous flood of 1953. Oesterdam was built to protect the nature in Eastern Scheldt. The dam is a so-called *compartimenteringsdam*: it separates the Scheldt-Rhine Canal from the Eastern Scheldt. This creates a secure connection for shipping between Rotterdam and Antwerp.



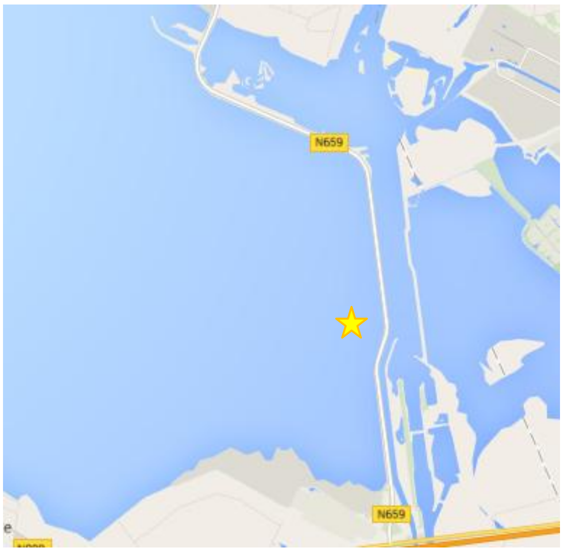


Figure 3.1 - Location of the Eastern Scheldt estuary and Oesterdam

On the top left, the map shows where the Eastern Scheldt estuary is located in the Netherlands. On the top right map is it possible to see a zoom of all the basin. On the bottom right, the area of Oesterdam with the indication of the project area.

3.2 Problem definition

On the 1st of February 1953 a huge storm surge claimed more than 1830 lives in large part of the Netherlands. Due to this, the Delta Commission started creating the Delta Plan in 1954: a structured plan aimed at strengthening dikes and closing off river estuaries in order to improve the safety of the region (Kamphuis 2010). The goal of this plan was to protect the country against flood. Different protection dams were made but the biggest one was the storm surge barrier located at the mouth of the Eastern Scheldt basin (Figure 3.2).

Figure 3.2 - Storm surge barrier (1986) . On the top left, the location in the Eastern Scheldt basin. On the top right, an aerial view of the barrier (footage.framepool.com). On the bottom, two representative pictures of the barrier (www.neeltjejans.nl).

Within the framework of the Delta plan, the Grevelingen dam (1964) and Volkerak dam (1969) were built, which go through the northern branch of the Easter Scheldt from other estuaries (Figure 3.3).

Figure 3.3 - Map of the dam realized in order to improve the hydraulic safety in the Eastern Scheldt (www.deltawerken.com)

In 1969, the construction of these dams (Grevelingen and Volkerak dam) caused a gradual increase in tidal volume in the open Eastern Scheldt basin. This increase in tidal volume resulted in a significant increase of the current velocities, which caused erosion and a shift of tidal channels (Vroon 1994). Instead in 1986, at the end of the construction of the storm surge barrier, the effective cross-sectional area at the mouth of Eastern Scheldt decreased from 80.000 m^2 to 17.900 m^2 (wet cross-sectional area below mean sea level in N.A.P. - *Normaal Amsterdams Peil* or *Amsterdam Ordnance Datum*), leading to an effective reduction of about 77%. The resulting reduction of the tidal volume is seen in Figure 3.4. This design had an enormous impact on the hydrodynamics, and thus on the morphology in the tidal estuary.

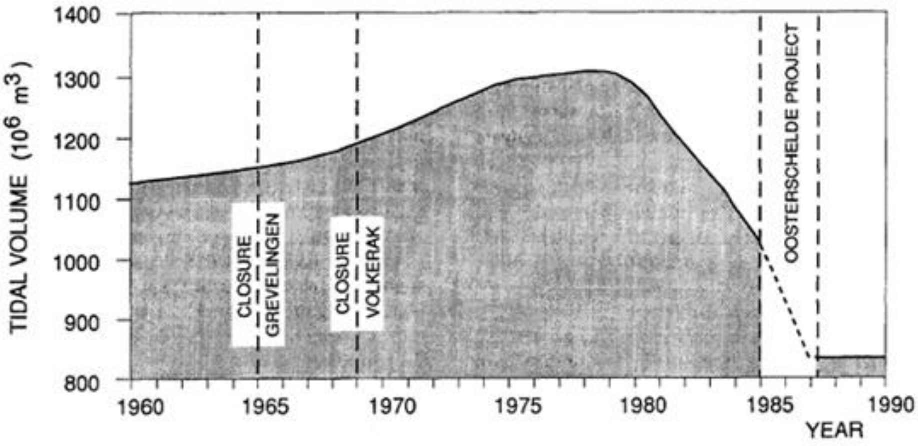


Figure 3.4 - Tidal volume decrease (Vroon 1994)

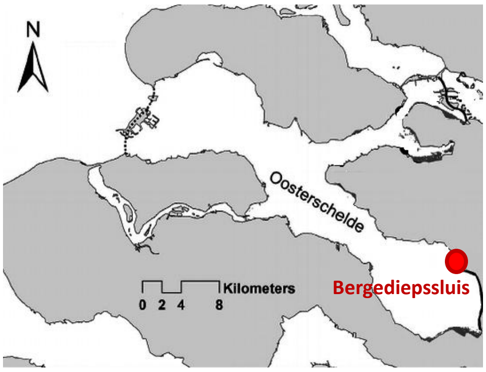
Form an hydrological point of view, after these constructions, there are different factors that ha to be taken into account: tide excursion and tidal currents; waves; sand deficit and consequent erosion of the tidal flats; the sea level rise. Relating the tides, the decision to build a storm surge barrier caused a reduction of the tidal range. After the construction of the storm surge barrier, a construction of two auxiliary dams was also necessary. Therefore two auxiliary dams were placed at the lee-side of the Eastern Scheldt: the Philipsdam and the Oesterdam. The construction of these dams was necessary because the reduced cross-sectional area of the Eastern Scheldt caused a reduction of the tidal range. The result would have been that salt marshes and mudflats would have come into jeopardy. With the construction of the Philipsdam and the Oesterdam, the Eastern Scheldt surface area was reduced from 452 km^2 to 351 km^2. Consequently, the total decrease in tidal volume resulted in 30% at the mouth (25% due to the barrier and 5% to compartmentalization). But more important, the reduction in tidal range was only 13% instead of 25% at Yerseke due to the construction of these two dams (Vroon 1994). Due to this limitation in the tidal range reduction, the storm surge barrier would have lower impact on the salt marches, mud flats and the oyster farming in Yerseke. Besides this ecological function, these dams also created a tide-free Scheldt-Rhine canal, which is an important access channel between the Volkerak and the port of Antwerp. The change in hydrodynamics due to the Eastern Scheldt project was not uniform over the tidal basin; a maximum reduction in current velocity was observed in the northern branch of the basin and just behind the storm surge barrier (north of the Hammen channel). The overall consequences of the Eastern Scheldt project are summed up in Table 3.1.

	Pre-barrier	Post-barrier	% change
Total surface area [km^2]	452	351	-22
Intertidal surface area [km^2]	183	118	-36
Tidal volume [$10^6 m^3$]	1283	915	-29
Average current velocity [cm s^{-1}]	120	80	-33
Residence time water [days]	50	100	+100
Fresh water input [$m^3 s^{-1}$]	70	25	-63
Salinity [‰]	>25	>30	+15
Average depth [m]	8	8	0
Maximum depth [m]	55	55	0
Average tidal range (Yerseke) [m]	3.70	3.25	-12
Average concentration suspended matter [mg l^{-1}]	25	15	-40

Table 3.1 - Eastern Scheldt characteristics (Brinke et al.1994)

Relating to the waves, because they are generated locally by the wind and its regime is unchanged, not much ad changed in the wave regime. The wave regime decreased only near the construction of the storm surge barrier, but the rest of the basin stayed the same. It is found that the wind-generated waves erode high intertidal flats present in basin. Because of the erosion of these areas, the morphology of the area changes and the water has to be considered deep (not shallow anymore). Lowering of the intertidal foreshore means that higher waves will no longer break on these shallow areas. The dykes surrounding the tidal basin will have to withstand a more severe wave impact. So, as a consequence, this change cause erosion. As the tidal range has become smaller, the waves are dissipating in a narrower intertidal zone. This kind of change in wave dissipation would increase the erosion . It is found that large areas of intertidal shoals are being eroded (Royal 2008).

Another consequence of the construction of the delta work is the decrease of tidal prism which, with the reduction in tidal currents, causes a sand deficit in the basin. This happens because the cross-sectional area is not anymore in equilibrium (due to the volume of water flowing through the channel). Figure 3.5 shows the difference in tidal range at , during the Delta plan.



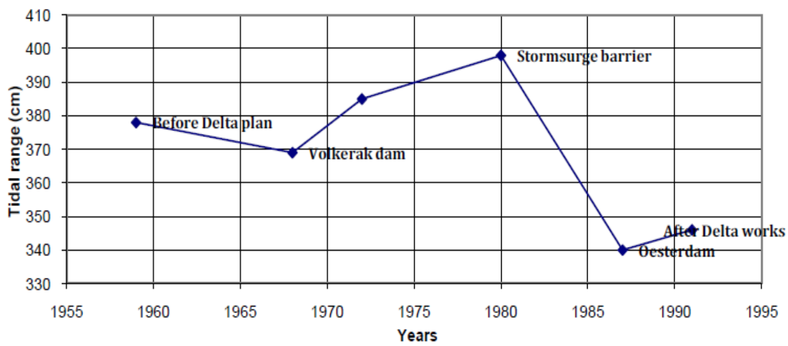


Figure 3.5 - The tidal range at Bergediepssluis (De Graaf 2012).

From 1960 to 1970, the Grevelingen- and Volkerakdam caused an increase in tidal volume. The channel system in the Eastern Scheldt responded to this disturbance of equilibrium by increasing the cross-sectional area of the channels. The strong currents transported the sediment out of the channels onto the intertidal shoals. Between 1980-1990 the construction of the storm surge barrier caused a decrease of almost 30% of the tidal prism. To restore equilibrium between then tidal volume (m^3 of water) the cross-section of the channels will have to decrease. (De Graaf 2012)

When a tidal basin is in equilibrium the sedimentation by tidal currents, it is also in a dynamic equilibrium with the erosion by waves. Nowadays the Eastern Scheldt is out of equilibrium and until this relation is restored, the tidal currents will be much smaller and have a smaller transport capacity. There will not be sufficient transport onto to shoals to compensate for the erosion during storm conditions that continues unchanged. This results in erosion of flats, often also referred to as “sand hunger”. However, channels are not actively pulling sediments from the shoals as if they are “hungry”. The channels capture the sediment because the cross-sectional area is too large in comparison to the tidal volume passing through the cross-section. The building forces are no longer strong enough to compensate storm erosion that has always been present. Moreover a theoretical sea level rise (made more extreme by global warming) and continuing land subsidence might make further upgrades to the flood control and water management infrastructure necessary. The expectations range of the Mean Sea Level (MSL) is from 0.25 to 0.85 m for the coming century. The increase of the High Water levels (HW) will increase with 5 cm/century faster than the MSL rise, while the low water level rises 5 centimeters per century slower than the MSL. Each century the tidal range is thus expected to rise with 10cm (De Ronde et al. 2011).

As a consequence of all these factors, in the future the tidal flats present in the Eastern Scheldt would will be submerged during a longer time of the tidal cycle, or even disappear completely under the water (De Pater 2012). Moreover 60 ha of intertidal area will drown due to sea level rise every year (De Ronde et al. 2011).

3.3 Oesterdam as a part of the Delta Plan

As previously mentioned, the construction of the primary defense in the Eastern Scheldt created an important morphodynamic imbalance between erosion and sedimentation in the water basin. These changes resulted in an adjusted tidal landscape and sand deficit intertidal flats present in basin (Niehnhuis and Smaal 1994). In order to give a possible solution to this “sand hunger” a lot of projects are going on in the Eastern Scheldt. They are the result of a combined initiative between national authorities, dredging contractors, engineering consultants and research institutes, which aims on finding an applicable solution against the sand deficit in the basin. Oesterdam project is one of these. It is a pilot project realized with the collaboration *Rijkswaterstaat* (Dutch Ministry of Infrastructures and Environments) and *Building with Nature’s* research group. Oesterdam project is an innovation project, committed to the integration of infrastructure, nature and society in new or alternative forms of engineering, meets the need for global solutions intelligently and sustainably. This is the philosophy of *Building with Nature* which use natural processes in such a way that they will work in human advantage. These approaches are potentially more durable, low in maintenance and more aesthetically appealing than traditional approaches. The use of natural processes for coastal protection has been a concept since the 1980s and scientists have been working on ways to imply this in the framework of the terminology ‘Building with Nature’. More natural solutions can provide space for nature development, thereby increasing the biodiversity.

3.4 Nourishing intertidal foreshore of Oesterdam as a possible solution

In order to give a possible solution to the present erosion in the Eastern Scheldt, sand nourishments on the flat of Oesterdam was considered the most suitable solution. The nourishment, accompanied by breakwaters, is not able to provide a lasting solution, but at least keeps intertidal flats for the near future, namely 50 years.

Since it exists, the Oesterdam dike is designed to reach the intended safety standard of the region but, in 2010, the revetment on the Oesterdam has been classified as unsafe and needs to be replaced (ARCADIS

2010). This aspect, added to the other problems, was one reason to encourage the project more. So the new foreshore was heightened with a sand nourishment to compensate for the erosion, increasing the intertidal area for wader birds and increasing safety by breaking the waves on the shallow foreshore and at the same time increasing the lifetime of the newly designed revetment. At that time, thanks to all these factors, this plan was considered the best solution of investment. Therefore, due to the necessity to ensure the safety of Oesterdam and of the region itself, the new project was designed in 2011. The plan was to add a 'soft structure' in the foreshore in front of the southern part of the Oesterdam with the aim of protect the traditional and existing dike. The soft structure placed in front of the dike is expected to provide extra safety and, presumably, also a reduction of the maintenance of the dike. The previously mentioned soft structure is planned to be mainly constituted by a sand nourishment. Additional structures, like eco-engineering structures, were added to the sand nourishment, with several benefits for the project. The Eco dynamic structures considered in this solution are oyster reefs. The main purpose of these structures is to dampen the waves and trap sediment behind them, stabilizing the sand nourishment in place for a longer period.

The Oesterdam case represents an example of a project that is building with nature, where infrastructure development is in line with the natural systems within which they were implanted. This is also one of the first examples where oysters are used as eco-engineers solution to limit the coastal erosion. In this case the choice was to use *Crassostrea gigas* reefs. They could potentially be used in erosional tidal systems for sediment stabilization and wave attenuation. *Crassostrea gigas* could potentially be used in artificial reefs as breakwaters for sediment stabilization and wave attenuation, in about 50 km^2 of the Eastern Scheldt with the advantage of adaptability to changing climate conditions.

3.5 Research definition

Taking all the problems explained before into account, the purpose of this research is to assess the suitability of the oyster reefs as a sustainable coastal protection method for the intertidal areas of the Eastern Scheldt. In order to stabilize the situation of this area, the research focus on the processes of sedimentation/erosion around the artificial oyster reefs using all the possible long-term data obtained from monitoring activities as well as collecting new ones. The research is focused not only on the behavior that the oyster reefs in relation to sedimentation and erosion, but also the effects that are caused close and around them.

The main goal of this research is to understand the actual situation of the oyster reefs placed in the Eastern Scheldt. With the help of studies, monitoring and eventually developing new propositions, this paper aims to find a good solution that improves the situation from the point of view of the ecosystem but especially for the safety of the area. Having said, the question could then be formulated:

"Can oyster reefs be effectively a good solution to limit the coastal erosion in Oesterdam, satisfying also the hydrological and geomorphological aspects?"

In order to answer the question, several elements have to be deepened within this report.

4. The project: defense structures in the Oesterdam foreshore

The Oesterdam project is the union of different types of coastal defense structures. The project involves hard and soft structures and, at the same time, uses them as ecosystem engineers for the coastal environment. Its aim is to improve the safety of the coast, protecting, conserving and restoring the ecosystem in the area. This plan has a potential role of a pilot project with the purpose of validating the role of a specific type of reef (oyster reefs) as an ecosystem-based coastal protection and conservation structures in soft sediment environments.

4.1 Soft defense structure: the sand nourishment as a safety buffer

To delay the process of erosion, 300.000 m^3 of sand was placed to create an elevation over the length of 2 km, with a width of 200 m to 800 m. The height of the nourishment is between 0.5 m and 1 m. The nourishment that was done in the area has a hook shape. The reason behind its shape is the wind. In fact the main wind directions come from two directions: south and southwest. Constructions of the nourishment are planned to start at end of 2012 or beginning of 2013. Three parties fund the project: *Natuurmonumenten* (1 million euro), the ministry of I&M (*Infrastructuur en Milieu*) (1.4 million euro) and the province of Zeeland (125.000 euro). The nourishment is aimed at delaying the necessary maintenance / renewal of the Oesterdam revetment by 20 years.
As previously mentioned, oyster reefs have been placed around the sand nourishment. Oyster reefs can influence the local behavior of sediment, which is an example of ecosystem engineering (van Leeuwen et al. 2010). These living oyster reefs should reduce the hydraulic energy of the water and reduce the erosion of the sand nourishment (Borsje et al. 2011). The sand nourishment just described provides shelter for the dike in order to delay the necessity of dike reinforcement or repairs, increasing the intertidal area and improving, at the same time, the ecosystem. This answer to the problem will not provide a lasting solution, but at least keeps intertidal flats for the near future ($\pm$ 50 years). Moreover, this sand nourishment is a possible solution to improve the safety of Oesterdam, but it's not a natural solution the sand deficit: as said before, there are no feasible structural solution that solves the cause of the sand deficit of Eastern Scheldt by increasing either the tidal prism or the sand transport. Only mitigation measures such as nourishment or erosion protection are realistic for the near future, even if possible measures for restoring the equilibrium are discussed (Van Zanten E. , Adriaanse L.A. 2008).

Before the construction of nourishment, the median grain size of the intertidal area varied between 165 and 187 µm (Boersema et al. 2015). This value is confirmed by other observations which argue that the bottom of the Eastern Scheldt mainly consists of fine sand with a median grain diameter of 150-200 µm (Huisman and Luijendijk 2009).

After construction, median grain sizes of the nourishment varied between 276 and 290 µm, with outliers to 320 µm (Boersema et al. 2015). The constructed nourishment consists of coarser sand, obtained from a channel in the Eastern Scheldt.

Therefore, it has been considered a uniform median grain size of 180 µm in the intertidal area, for the location of the nourishment, a grain size of 285 µm is considered.

Figure 4.1 - Location of the Oesterdam nourishment (www.rijkswaterstaat.nl)

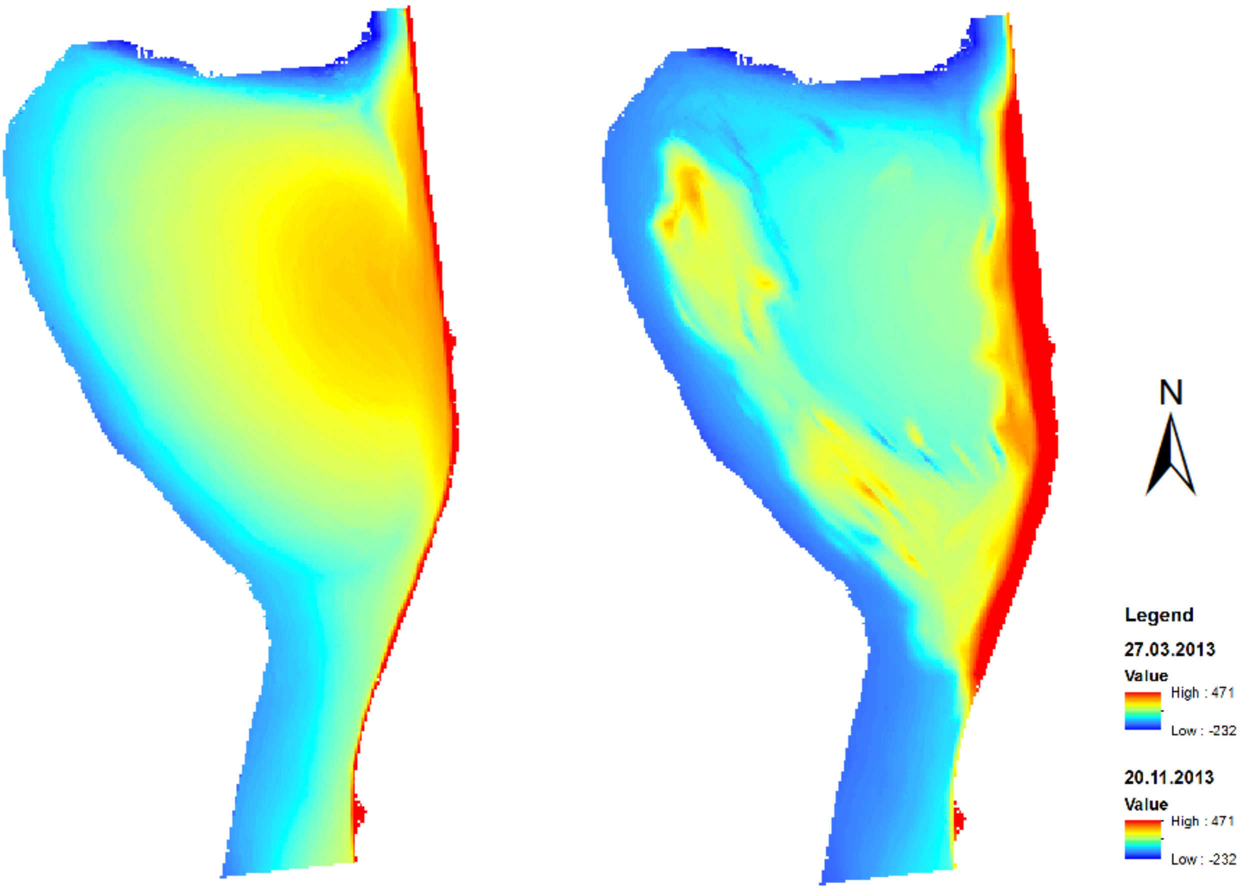


Figure 4.2 - **Oesterdam before and after the sand nourishment** - On the left, the map shows the situation in Oesterdam before the sand nourishment; on the right, the situation after the sand nourishment. the elevation maps are both in centimeters.

Figure 4.3 - Oyster reef around the sand nourishment; aerial picture from the north side(www.rijkswaterstaat.nl)

Figure 4.4 - Oyster reef around the sand nourishment; aerial picture from the west side (www.rijkswaterstaat.nl)

4.2 Oyster reefs as breakwaters: the structure

The area of study consists 100 ha, which extend in a Y-shape in the middle of Oesterdam. As showed in Figure 4.5, four reefs are placed in the area. For convenience, they have been denominated with the letters, following a counterclockwise direction. They are placed in different positions: reef A and B in the north, the others, C and D, in the south west of the location.

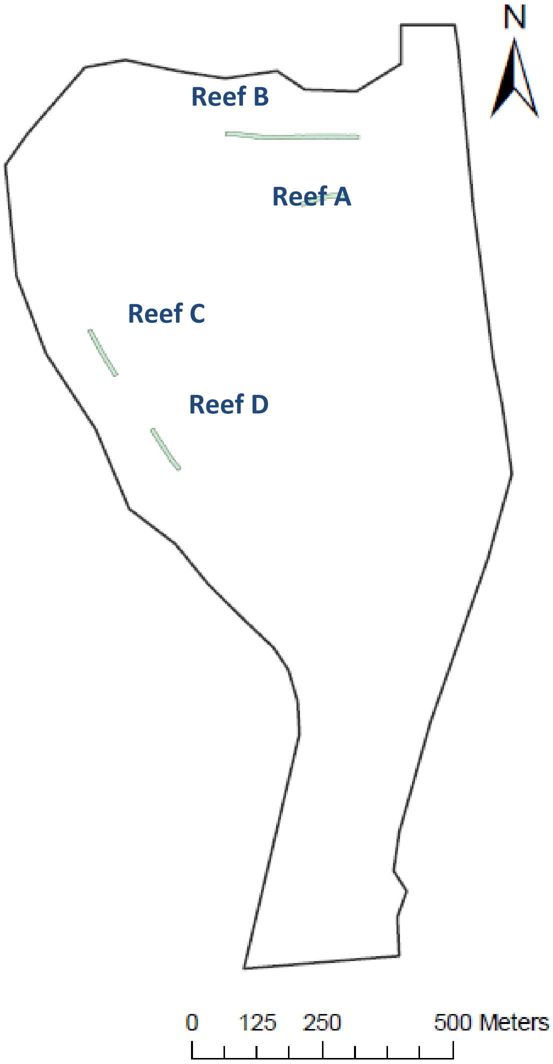


Figure 4.5 - Area of the project and reef location

In terms of length, width and height, the reefs differ from each other. In Table 4.1, the dimensions of the reefs are shown:

REEF -	Length [m]	Width [m]	Height [m]
A	90	7.5	0.25
B	255	7.5	0.25
C	100	8	0.50
D	90	8	0.25

Table 4.1 - Reef dimensions

The reefs are realized by cages close to each other and opportunely connected. The cages are made of iron. They have a rectangular shape but have different sizes and frames. They consist in one main structure divided into three parts: a main cage reinforced by the help of extra iron sheet in the middle, featuring internal reinforcements that show the structure as divided three parts (only reef C has cages divided in two). Figure 4.6 is shows an example of the structure described. Figure 4.7 give and idea of the mesh of the cages.

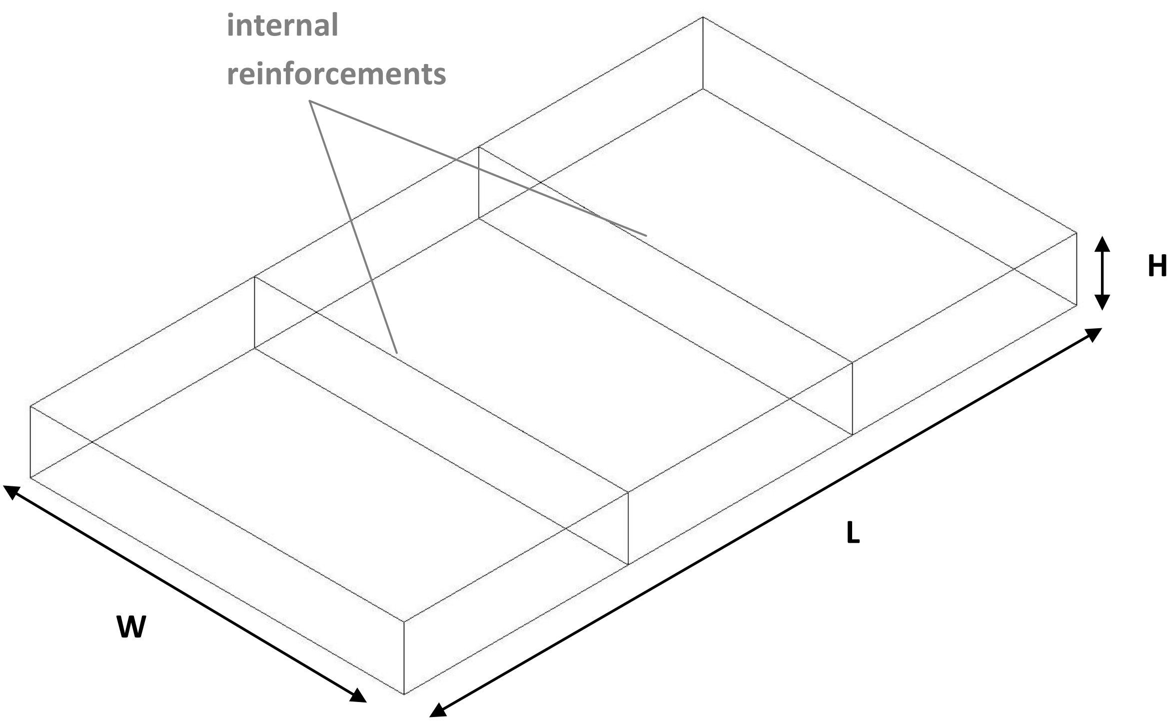


Figure 4.6 - Schematic example of a cage

The material used for their construction is wire mesh with hexagonal weaving. Each reef has appropriate dimensions of it, which will be showed in Table 4.2.

REEF	Size of the cage LxWxH	Dimension of the mesh	
-	[m]	L_1 [m]	L_2[m]
A	1.85x 3.00x0.25	0.025	8.5
B	1.85x 3.00x0.25	0.025	8.5
C	1.08x1.85x0.50	0.035	8.5
D	1.85x 3.00x0.25	0.025	8.5

Table 4.2 - Dimensions of wire mesh with hexagonal mesh

Reef C is the only one that has different gabions, the cages are smaller than the others and reinforced only by one sheet in the middle.

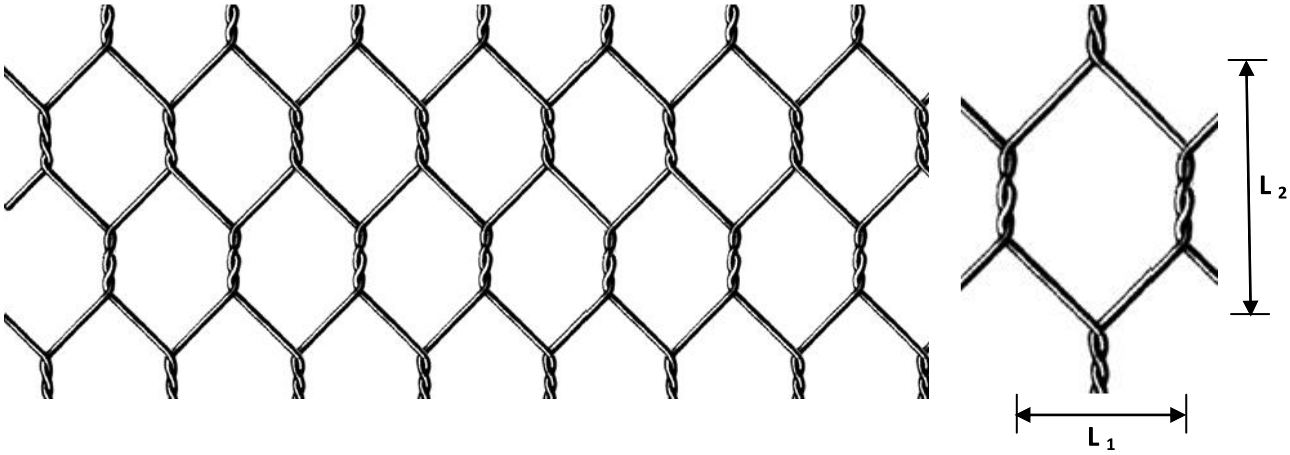


Figure 4.7 - Example of hexagonal mesh

As breakwater structures, these oyster reefs should present a substructure. Nevertheless they do nothave substructure or any kind of foundation. The reason is why the substructure is absent is because the material that is inside (oysters) has to cooperate with the ecosystem below and around it. An example of the oyster reef of Oesterdam in given in Figure 4.8.

Figure 4.8 - Example of oyster reef in Oesterdam

4.2.1 The material: the natural purpose of Crassostrea gigas

All the reefs placed in Oesterdam are filled of *Crassostrea gigas* oysters: a specific oyster that appeared in Netherlands around 1964. More than once during the 19th century, attempts have been made to revive exploited stocks of the European oyster (*Ostrea edulis*) with American oysters (*Crassostrea virginica*) and 'Portuguese oysters *Crassostrea angulata*' at several sites in coastal waters of Northern Europe. These attempts largely failed (Diederich et al. 2005). Dutch oyster farmers imported spat of the Pacific oyster (*Crassostrea gigas*) from British Columbia (Canada) for aquaculture activities in the Eastern Scheldt estuary. In the following years more imports of spat and adult specimens followed, also from Japan starting in 1966. In 1975 and 1976 natural spat falls occurred during very warm summers and resulted in millions of so-called weed oysters in the Eastern Scheldt estuary. Within several years the Pacific oyster has developed explosively and in the 1980's other Dutch estuaries started to be colonized (Diederich et al. 2005, Smaal et al. 2009). After its introduction, *C. Gigas* spread rapidly through the estuary following natural spat fall event in 1970s. At present *C. Gigas* covers more than 9 km^2 (8%) of the intertidal habitat (Smaal, Kater, and Wijsman 2009), typically forming dense reefs of different sizes. These dense reefs persist longer than the lifespan of an individual oyster. In the Eastern Scheldt estuary reefs older than 30 years, with oysters above 7 years of age can be found (Walles 2015).

4.2.2 Species identification

The *Crassostrea gigas* (Figure 4.9) is a member of the *Ostreidae* family and it is originating from the waters around Japan and the east coast of China (Troost 2010). The *C. Gigas* has a great variation in shell form. This variation varies with the environment where the oyster is attached (Büttger and Nehls 2007).

Figure 4.9 - Example of a single exemplar of Crassostrea gigas.

On the left an example of oyster compared with the euro coin; in the middle a single exemplar of Crassostrea gigas in loco; on the right Gabion of oysters Crassostrea gigas.

The Pacific oyster shell is extremely variable and irregular in shape. Its shape depends on the type of bottom in which it is grown, as well as the degree of crowding. The shells are sculpted with large, irregular, rounded, radial folds with overlapping, concentric lamellae in mature specimens. The color is usually white with many purple streaks and spots radiating away from the umbo. The interior of the shell is white, with a single muscle scar that is sometimes dark, but never purple or black. Normally the length of shells is 80 - 200 millimeters, but exceptional specimens can attain 400 millimeters. A Pacific oyster may live up to thirty years (Nehring 2011).

4.2.3 Habitat of the pacific oyster

The habitat suitability for the Pacific oyster is dependent on different environmental conditions. The environmental conditions should be optimal for every life stage, otherwise oysters will not form oyster reefs. Other important environmental factors during the life of an oyster are temperature, salinity and the inundation of time.

The physiology of the Pacific oyster is strongly influenced by the temperature of the water. The feed intake, the respiration and the reproduction are dependent to the temperature. Experiments have shown that the Pacific oyster is resistant to short periods of very high temperatures whereby mortality is observed at a water temperature of 30°C. Total mortality is observed at an exposure time of over one hour at temperatures of 42°C (Rajagopal et al. 2005). Low temperatures can also cause mortality, especially juvenile oysters are sensitive to low temperatures. When the water temperature is lower than 3°C and lasts for three weeks, juvenile oysters will perish (Child and Laing 1998). During periods when the oysters are not inundated by water, the oysters can resist air temperatures of -4°C (Pauley et al.1988).

Another parameter that has an influence on the physiologic activity of the Pacific oyster is the salinity of the water. Oysters are sensitive to a variation in salinity concentration. Optimal salinity concentration lies between 25% and 35%.

The exposure time – the time the oyster is out of the water during low tide – is also an important factor for the appearance of the Pacific oyster. Oysters have the ability to survive during exposure, but the exposure time should not be too long because the oyster cannot breathe and filtrate during the exposure. Most of the oysters occur at an exposure time less than 40%. At an exposure time between 40% and 70%, which is quite a big intertidal surface at the Eastern Scheldt, fewer oysters grow (Wijsman et al. 2013).

4.2.1 The Pacific oyster as an ecosystem engineer in Oesterdam

As already explained, *C. Gigas* , a Pacific oyster, is generally considered as an ecosystem engineering species. According to Glabowski & Peterson 2008, oyster reefs provide many ecosystem services. Table 4.3 gives an overview of the main ecosystem services of oyster reefs:

Ecosystem services	Benefit/value
Production of oysters	↑*market and recreational value*
Water filtration & concentration of pseudofeces	↓*suspended solids,* turbidity, phytoplankton biomass, & microbial production. ↑denitrification, submerged aquatic vegetation & recreational use
provision of habitat	↑biodiversity & productivity
carbon sequestration	↓greenhouse gas concentration
Augmented fish production	↑market & recreational value
Stabilization of adjacent habitats and shoreline	↑ submerged aquatic vegetation & salt marsh habitat ↓effects of sea-level rise
Diversification of landscape and ecosystem	↑ synergies among habitats

Table 4.3 - Ecosystem services that are provided by oyster reefs (Glabowski & Peterson 2008)

- Due to the filtration of nutrients, sediments and phytoplankton the light penetration through the water column increases which has a positive impact on the submerged aquatic vegetation.
- Due to benthic pelagic coupling (transfer of materials and energy between the bottom community and the water column, Coen et al. 2007) oysters remove nitrogen through denitrification.
- Oyster reefs provide habitat for many species of fish and crustaceans in dominantly soft substrate environment. The structure of oyster reefs is ideal for juvenile fish which utilize the reefs as nursery and foraging grounds.
- Oyster reefs accumulate carbon from the water to form the structure of their shells which consist of calcium carbonate, which results in lower concentration of this greenhouse gas.
- Oyster reefs accumulate wave energy and reduce erosion in the salt marches of the Eastern Scheldt.

5. Methodology and data

The execution of the experiment is the results of research objectives defined in the proposal. The set up of the experiment is divided into four parts: preparation of the field experiment; execution; data processing; data interpretation. The first two steps will be explained in the following chapters. In particular, they show aspect like the design of the experiment, the instruments used, and the logistic of the experiment itself. The purpose is to collect the data, which will be processed and interpreted in the next chapter (Chapter 6). Instead, the preparation and the execution of the experiment will be explained in this section.

The information that have been collected regards three main categories of data: firstly the information about the hydrodynamic of the location; secondly the data regarding the beach monitoring activity (bed level of Oesterdam); and, at last, the sedimentological information obtained from the data of the sand samples collected in the area. The period of these monitoring activities starts the 27th of March 2013 and finishes the 6th of April 2016. This long period has been subdivided in other small ones, depending form the data of the beach monitoring activity. In order to give an overview of all the data collected, Table 5.1 will show the time line of the complete monitoring activity which will be constantly explained in each following chapter.

Periods	Dates of the period	Type of monitoring activity		
		Hydrodynamic	Beach	Sedimentological
1	27.03.2013-20.11.2013	✔	✔	
2	20.11.2013-18.02.2014	✔	✔	
3	18.02.2014-14.05.2014	✔	✔	
4	14.05.2014-14.08.2014	✔	✔	
5	14.08.2014-08.11.2014	✔	✔	
6	08.11.2014-11.11.2014	✔	✔	
7	11.11.2014-09.12.2014	✔	✔	
8	09.12.2014-15.12.2014	✔	✔	
9	15.12.2014-06.02.2015	✔	✔	
10	06.02.2015-24.02.2015	✔	✔	
11	24.02.2015-23.03.2015	✔	✔	
12	23.03.2015-20.04.2015	✔	✔	✔
13	20.04.2015-20.05.2015	✔	✔	
14	20.05.2015-12.11.2015	✔	✔	✔
15	12.11.2015- 12.02.2016	✔	✔	✔
16	12.02.2016-22.02.2016	✔	✔	✔
17	22.02.2016-10.03.2016	✔	✔	✔
18	10.03.2016-23.03.2016	✔	✔	✔
19	23.03.2016-06.04.2016	✔	✔	✔

Table 5.1 – Summary table of the monitoring activities

5.1 Hydrodynamic and wind monitoring

All the Netherlands is equipped with a big measurement network for water level and wind. Only in the Zealand area, Rijkswaterstaat (the Dutch ministry of infrastructures) has forty-eight locations where water level is measured, as part of the national monitoring network. Figure 5.1 shows these locations and Table 5.2 shows the names and Ids for all the stations presented in the figure.

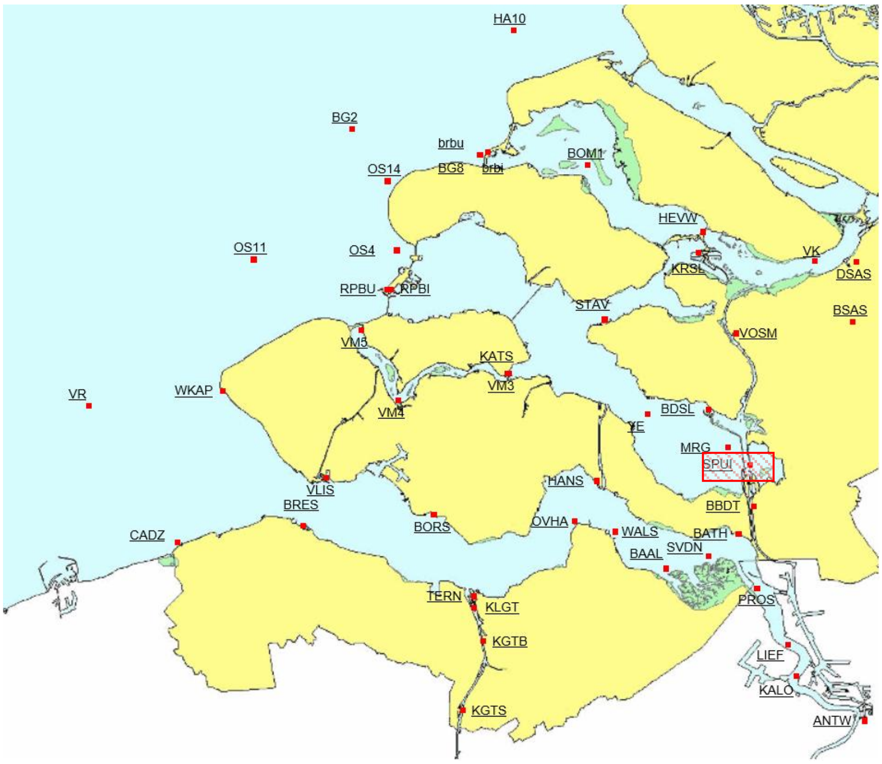


Figure 5.1– Measuring station (www.waterberichtgeving.rws.nl)

On the left an overview of RWS water level measurement locations and some of the Belgian ones located in the Zealand Delta area. The reference station used in this project is highlighted. On the right an image of the Marollegat , measuring station of the project.

Nr	Id	Full name	Nr	Id	Full name
1	ANTW	Antwerpen	25	LIEF	Liefkenshoek
2	BAAL	Baalhoek	26	MRG	Marollegat
3	BATH	Bath	27	NPT	Nieuwpoort
4	BBDT	Bathsebrug Spuikanaal	28	OOST	DE Oostende
5	BDSL	Bergsediepsluis West	29	OS11	Oosterschelde 11
6	BG2 B	rouwershavensche Gat 2	30	OS14	Oosterschelde 14
7	BG Br	ouwershavensche Gat 8	31	OS4	Oosterschelde 4
8	BOM1	Bommenede	32	OVHA	Overloop van Hansweert
9	BORS	Borssele	33	RPBI	Roompot Binnen
10	BRBI	Brouwerssluis Binnen	34	RPBU	Roompot Buiten
11	BRBU	Brouwerssluis Buiten	35	SPUI	Inloop Bathse Spuikanaal
12	BRES	Breskens handelshaven	36	STAV	Stavenisse
13	BSAS	Bovensas	37	SVDN	Schaar van de Noord
14	CADZ	Cadzand	38	TERN	Terneuzen
15	DSAS	Dintelsas	39	VK V	olkerak Galathea
16	EURP	FM Euro Platform	40	Vlis	Vlissingen
17	HA10	Haringvliet 10	41	VM3	Veersemeer 3
18	HANS	Hansweert	42	VM4	Veersemeer 4 (Oranjeplaat)
19	HEVW	Grevelingendam Hevel West	43	VOSM	Vossemeer
20	KALO	Kallo	44	VR V	lakte van de Raan
21	KATS	Sluis Kats Buiten	45	WALS	Walsoorden
22	KGTB	Sluiskil	46	WKAP	Westkapelle
23	KLGT	Kanaal Gent-Terneuzen	47	VOI	Yerseke
24	KRSL	Krammersluizen West	48	ZBR	Zeebrugge

Table 5.2 - List of water level stations in the Zealand Delta area. The reference station used in this project is highlighted (realized by the author based on the information of waterberichtgeving.rws.nl).

Regarding the monitoring of the water level and the waves, the measurements are performed using either a stilling well with a float or radar inside, or a step gauge or radar mounted on a fixed platform (e.g. a pole). The electronics connected to the float performs a 1.25 seconds sampling interval, while the step gauge and the radar internal software maintain a 0.4 second (2.5 Hz) sampling interval. All signals are averaged over 10 minutes before being sent through the network and logged in the databases. (If a radar or step gauge functions as a wave gauge, the logging frequency is 2.5 Hz). The uncertainty of the measurements in stilling wells which are in rivers or sheltered in harbors is less than 2.5 cm. (Deltares 2013) The data of water level are measured every ten minutes; the data regarding the waves every thirty minutes. Instead, regarding the monitoring of the wind, no reliable source specific instrumentation used but it is assumed a cup anemometer is used: when the wind is blowing on cups, rotates around a vertical axis; an electrical or mechanical counter, measures the number of revolutions that they are running in a certain time interval. The speed data and wind direction are measured every ten minutes.

5.2 Tidal flat monitoring

The coastal monitoring is considered as a major challenge in anticipating the response to coastal hazards (Ruggiero et al. 2000). The aim of the coastal management monitoring is to use uses scientific data in different ways: developing a conceptual understanding of the coastal system, planning coastal environment, permitting and reviewing shoreline stabilization projects. The scientific data collection program would provide information to support each of these functions. A detailed understanding and predictive capability on both sides of all time and space scales would engage optimally informed decision-making.

The beach monitoring used in this research consist mainly in two different methodology: the first one is the long term analysis, realized by *Rijkswaterstaat;* the second one consist in the short term analysis, realized by the author of this thesis.

5.2.1 Long term analysis

Since the 18th of January 2012 until present, Rijkswaterstaat measures the bed level of Oesterdam two-three times a year, with irregular interval. These measurements regard all the Oesterdam project area (100 ha). These data are measured with the use of the DGPS. They give a detailed overview of the development of the bed changes in all the site, so they will help to understand the trend of sedimentation / erosion. Taking into account the data measured, Rijkswaterstaat realized an ArcGIS map for each measurement. Nowadays, there are nine maps available. In the Table 5.3, the summary of the data is stated; the maps obtained with ArcGIS will be available in Appendix C.

Date of the maps
18.01.2012
05.06.2012
02.11.2012
27.03.2013
20.11.2013
18.02.2014
14.05.2014
14.08.2014
08.11.2014

Table 5.3- Maps of the total area, realized by Rijkswaterstaat

5.2.2 Short term analysis

The long term analysis of the erosion/ sedimentation in the area is complemented with a short term analysis: a detailed height measurements around the four reef at a small scale sedimentation patterns using as well differential GPS (DGPS).

The collection of the data is realized with a time interval (one a month normally), over a period of eighteen months (October 2014 until April 2016). The area of measurement differs for the reefs present in the area. This small scale monitoring is based on the idea that each reef has to have a precise area of monitoring. Therefore, since the beginning of the monitoring, the area to measure was established with some conditions. The plan was to realize a monitoring area with rectangular shape and with the specific dimensions. Taking into account the length L of the reef, the rectangle for the monitoring will have the dimensions showed in Figure 5.2.

In order to measure the area, the method that was used consists the realization of transects in front, behind and in the lateral part of the reef. The distance between the points of the transect is more accurate going closer to the reef (for example, 5 steps), which then becomes bigger moving away from it (for example, 10 steps and sometimes 15 steps). The method of the collection of these data is showed in Figure 5.3. The maps obtained with ArcGIS will be available in Appendix C.

Name of the segment	Dimension of the segment
AB	L/2+L+L/2
BC	L+L/2
CD	L/2+L+L/2
DE	L+L/2

Table 5.4- Dimension of the single area for the reef monitoring

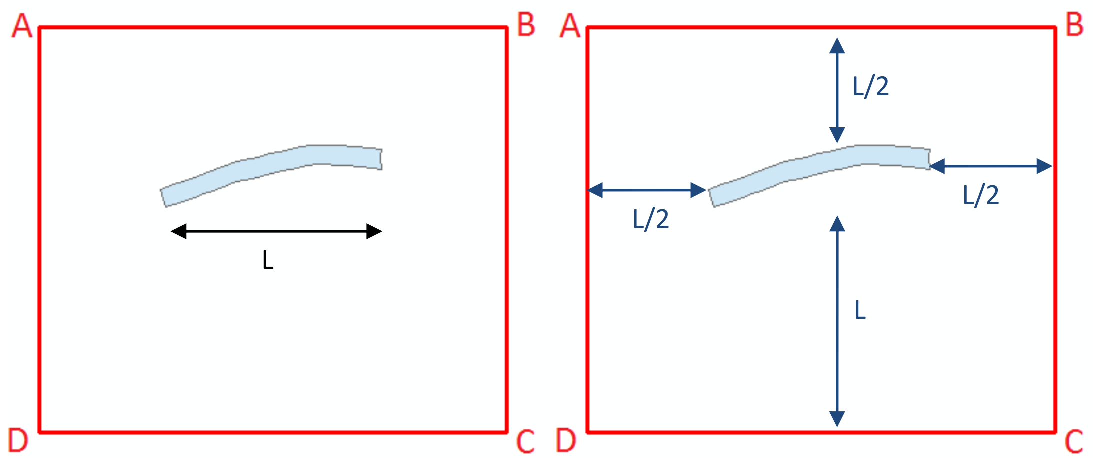


Figure 5.2 - Example of Reef A with the monitoring area

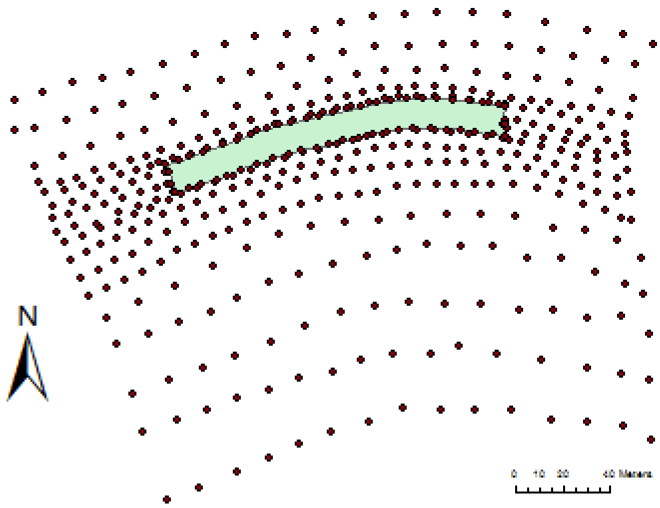


Figure 5.3 - Example of transect made around oyster reef A

5.2.3 DGPS Method

The satellite navigation system started to be developed in the 1960's but only in 1994 the US GPS system NAVSTAR was fully operational. It was initially used for military purposes and later on for civil uses. The aim of the system is to give the 3D position of the user on earth. The GPS is a satellite-based positioning system which encompasses three segments—space, control, and user. The space segment includes the 24 operational satellites that orbit the earth every 12 hours at an altitude of approximately 20,200 kilometres. Each satellite contains several high-precision atomic clocks and constantly transmits radio signals using a unique identifying code. One Master Control Station, five Monitor Stations, and Ground Antennas comprise the control segment. The Monitor Stations passively track each satellite continuously and provide this data to the Master Control Station. The Master Control Station calculates any changes in each satellite's position and timing. These changes are forwarded to the Ground Antennas and transmitted to each satellite daily. This ensures that each satellite is transmitting accurate information about its orbital path.

Nowadays, in addition to the United States system, there are also the GLONASS (Russian) and the GALILEO (European), which all together form the GNSS or Global Navigation Satellite System. The GPS user receives exact time signals from each satellite and can calculate his position with the difference of each time signal. Due to several sources of error, which can delay or lengthen the pass of the GPS signal, the absolute accuracy of the determination of position is better than 13m horizontal and better than 22m vertical.

The differential GPS (DGPS) was created in order to increase the accuracy of the GPS system. The DGPS uses a local reference station, which has a high-quality GPS receiver at a known surveyed location, to estimate the varying error components of each GPS satellite creating a correction signal for each GPS satellite in view. The correction signal is sent in real-time, usually via radio signals or GSM, to the GPS receiver, that are commonly called as 'rover'. The absolute accuracy of the determination of the position is always better than 1cm horizontal and 2 cm vertical depending on the distance to the base station and the local system which is used. To minimize the distance effect the provider uses models to determine the error for each position within the reach of the base station, therefore the GPS rover has to send his approximate position to the base station to receive his personal correction signal.

Currently, rover and reference can be all integrated and mounted on a pole and, with the diffusion of the RTK network, it is possible to work without the Master.

RTK Network is a network of GPS stations and / or permanent GNSS whose data are used to generate the corrections for a rover. Today, RTK networks operates in several countries, such as Germany, Spain, England, Italy, Hong Kong, in some areas of the US and Australia, etc. The networks may have different extensions, from small networks local networks that cover entire countries of Leica Geosystems.

The RTK network requires a minimum of 5 reference stations (there is no upper limit) and a relative spacing between stations up to 70 km. The reference stations are generally permanent installed and form the RTK network. The principle of the RTK operation is based on the transmission of satellite observations from several reference stations to the central server (network servers), in which is running a software for RTK networks, as Leica GNSS Spider. The objective of RTK networks is to minimize, within the boundaries of the network, the influence of dependent errors away on the calculation of the rover position.

The software installed on the central server performs this process: fixing the ambiguities of the satellites (seen from reference stations) within the network; using data from all the reference stations to generate the corrections which have to be sent to the rover. The RTK rover is to connect to the server with a device unidirectional or bidirectional connection (as a radio modem, GSM or Internet) and, upon receipt RTK data, calculates its position using the appropriate algorithm. There the algorithm chosen and the way in which the errors dependent on the distance are minimized, depend on the mode used by the RTK network.

The methods currently available on the market minimize the errors in a different way and, in function of the method, the modelling is made by network server or on board the receiver. for such reasons, the relationship between RTK network rover is different for each method (which can lead to differences significant in performance, accuracy, reliability and traceability for the rover.

In this monitoring program, the DGPS has been used is the Leica Viva GS08plus (Figure 5.4). It is one of the various models of the multipurpose field controller which is used with GNSS and TPS instruments. Fully integrated wireless Antenna technology (Bluetooth, WLAN, TPS Radio, GSM/UMTS 3.5G),(www.surveyequipment.com).

Regarding the network used, the monitoring activities carried out by the research group have referred to the Leica system. In fact the service of network calculation for the territory of the Netherlands (in Western Europe) including the provision of the correction data stated in sub-section by Dutch private limited liability company Leica Geosystems B.V. ("Leica Geosystems") shall bear the designation SmartNet the Netherlands.

Leica Geosystems has access to the reference station infrastructure for the territory of the Netherlands. The reference station data shall be provided to Leica Geosystems by LNR Globalcom B.V. ("LNR Globalcom"). The reference station data provided shall comprise the official coordinates of the reference stations, the centring parameters of the reception locations and the satellite geodetic raw observations on GNSS satellites determined on the reference stations. The Dutch Land Registry Office (in Dutch: "kadaster")

annually checks and calculate all SmartNet reference stations. Network RTK correction service supplies calculated highly reliable and accurate network corrections from SmartNet reference stations. Network RTK correction service allows measurement accuracies by use of two frequency geodetic receiver. The accuracy in the field is not dependent on distance from the nearest station. The correction data is transmitted in a standardized format (RTCM) with an observation interval of 1 second.

The monitoring activity done with the DGPS covers several areas from approximately 10.000 – 20.000 m2. These areas differ to each other because these are located around oyster reefs having different sizes. The purpose of these measurements is to give an overview of the sediment height around artificial oyster reefs.

Figure 5.4- DGPS

On the left , a picture of the DGPS Leica Viva GS08plus, used for the monitoring activities of Oesterdam (www.surveyequipment.com). On the right, an examples of measurements in the field (image elaborated by the author).

5.2.4 GIS Analysis

The measured points in the field have been imported into ArcGIS 10.3 to perform the data analysis. Based on the measured points it is possible to create a recostrucion of the surface by creating a Digital Elevation Model (DEM) from the measured points.

To create a DEM from xyz points ArcGIS provides several methods of interpolation. The Interpolation allows us to create a continuous surface from distinct values, in this case elevation. The DEM is a raster dataset characterized by its cell size which is depending on the density of the measuring points. The interpolation method chosen for this work was the Natural Neighbor Interpolation Method.

Moreover the cut-and-fill procedure has been used. It is a procedure in which the elevation of a landform surface is modified by the removal or addition of surface material. The Cut Fill tool summarizes the areas and volumes of change from a cut-and-fill operation. By taking surfaces of a given location at two different time periods, it identifies regions of surface material removal, surface material addition, and areas where the surface has not changed. This method has been used to evaluate the volume variation of amount of sand present in the influence area of each reef.

With the help of ArcGIS it has been also possible to realize some transects which cross the reefs. The method used is the Slack Profile which is able to create Elevation Profile cross sections profile from elevation maps .

5.3 Sediment size characterization

In order to analyze the sedimentation / erosion around the reef, sand samples are taken. To analyze the situation in front and behind the reef itself five samples were taken: one in front of the reef, and four behind (place where sedimentation is expected to take place). The decision was to take these samples only for two reefs, reef A and reef D as a symbolic sampling of the area. The same samples have been taken in two different periods. Table 5.5 summarizes the date of the sampling activity.

Date of the sampling
23/03/2015
20/05/2015
12/02/2016
22/02/2016
10/03/2016
23/03/2016
06/04/2016

Table 5.5 – Sampling date, realized by the author

In the following figures(Figure 5.5 and Figure 5.6) it is possible to see the reefs A, D and the location of the samples collection.

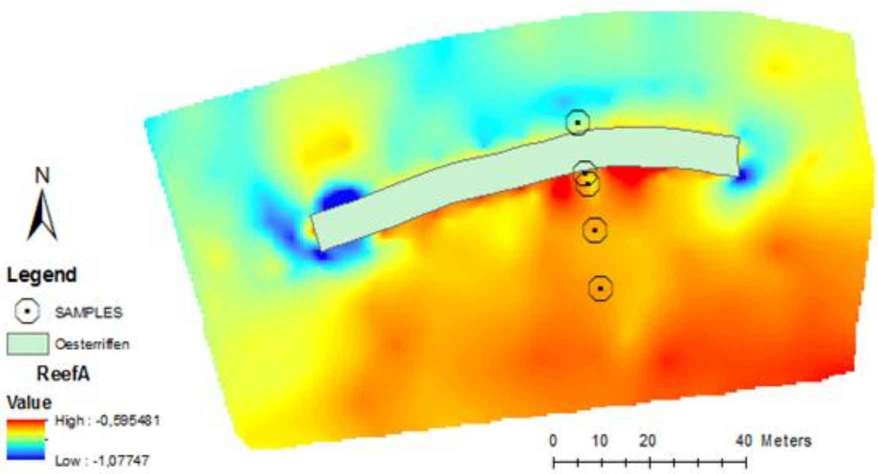


Figure 5.5 - Samples of reef A

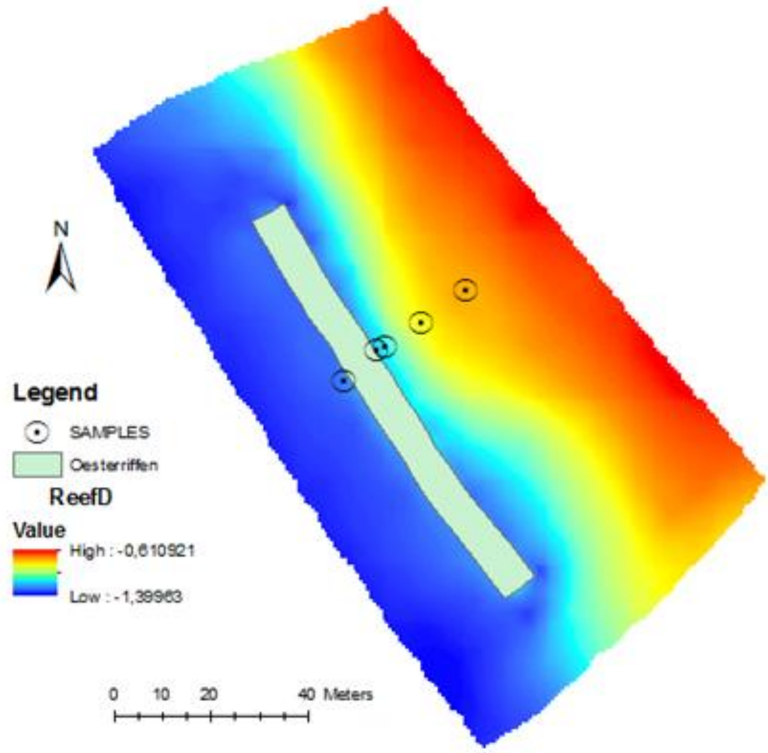


Figure 5.6 - Samples of reef D

5.3.1 Collection method

The samples of the material have been collected with the help of a syringe. The syringe use has a diameter of 1.5 cm. it has been pressed until a depth of almost 4 cm. The material has been cataloged and stored in specific plastic storages, showed in Figure 5.7. After the collection, all the samples have been conserved at a low temperature (like in a fridge) and then stored before be analyzed with the Malvern.

Figure 5.7 – Example of samples collection (Image elaborated by the author).

5.2.1 Grain analysis: Malvern Laser Particle Sizer

The grain size of sediments with dimensions between 2,000 µm and 0.02 µm can be determined by sieving and sedimentation, but also with another indirect, modern, fast and accurate method, which is becoming more and more in recent years. This system is called Malvern Laser Diffraction.

The instrument technology uses the principle of diffraction of light to perform particle size analysis. The particles illuminated by a laser beam scatter light at an angle related to their size. With decreasing particle size, the angle observed scattering (diffusion) increases logarithmically. The scattering intensity also depends on the particle size and decreases in relation to the surface of the cross section of the particle. Simplifying, large particles scatter light with narrow angles and high intensity, while the smaller particles scatter light with wider angles and lower intensity. The primary measure for a system of laser diffraction is the capture of all the light diffused by the particles that are being analyzed. The system consists of a laser light (to provide a source of light with a fixed wavelength coherent and intense), from the sample, and by a series of detectors that are used to measure the pattern of light obtained in a wide range of corners. Field granulometric accessible during the measurement is directly related to the range of scattering angles measurable. In laser diffraction, the particle size distributions are calculated by comparing the scattering of a sample with an appropriate optical model and using a process of reverse mathematics.

For this research, the grain analysis has been realized by the help of a specialized research laboratory: the NIOZ. NIOZ (Royal Netherlands Institute for Sea Research) is the national oceanographic institution for the Netherlands. Their job involves applied scientific research on important processes in delta areas, coastal seas and open oceans. The institute also acts as the national facility for academic marine research in the Netherlands. NIOZ facilitates and supports marine research and education in the marine sciences in the Netherlands and in Europe (www.nioz.nl).

The outcome data of the Malvern analysis have been studied by the author and this analysis will be showed in Chapter 6.

6. Main results: data processing

6.1 Hydrodynamic and wind monitoring

The data regarding tides, wind and waves have been collected from the measuring station located in Oesterdam (Marollegat). The data have been downloaded from the *Rijkswaterstaat* website and, subsequently, the values have been analyzed.

For the implementation of these data, it has been necessary to classify to use the Beaufort scale as a reference Table 6.1– Beaufort scale, reported below.

Wind Force	Speed			Description	
	kmh	m/s	knots		
0	0-1	<0.3	0-1	Calm; Smoke rises vertically	Calm
1	1-3	0.3-1.5	1-3	Direction shown by smoke drift but not by wind vanes	Light air
2	4-7	1.5-3.3	4-6	Wind felt on face; leaves rustle; wind vane moved by wind	Light breeze
3	8-12	3.3-5.5	7-10	Leaves and small twigs in constant motion; light flags extended	Gentle Breeze
4	13-18	5.5-8.0	11-16	Raises dust and loose paper; small branches moved.	Moderate Breeze
5	19-24	8.0-10.8	17-21	Small trees in leaf begin to sway; crested wavelets form on inland waters.	Fresh Breeze
6	25-31	10.8-13.9	22-27	Large branches in motion; whistling heard in telegraph wires; umbrellas used with difficulty.	Strong Breeze
7	32-38	13.9-17.2	28-33	Whole trees in motion; inconvenience felt when walking against the wind.	Near Gale
8	39-46	17.2-20.7	34-40	Twigs break off trees; generally impedes progress.	Gale
9	47-54	20.7-24.5	41-47	Slight structural damage (chimney pots and slates removed).	Severe Gale
10	55-63	24.5-28.4	48-55	Seldom experienced inland; trees uprooted; considerable structural damage	Storm
11	64-72	28.4-32.6	56-63	Very rarely experienced; accompanied by widespread damage.	Violent Storm
12	73-83	>32.6	64-71	Devastation	Hurricane

Table 6.1– Beaufort scale

The Beaufort scale is used in this thesis as the reference scale to understand the wind strength. It describe the power of the wind in relation to the wind speed in m/s (Beaufort, 1806), so that the reader can more easily form an image of the strength of the wind.

The studied that have been done regards: water level; wind speed and direction; significant wave height. H_s. Thanks to the data collected from the measuring station of the Marollegat , it has been possible to find some result which are reported in Table 6.2.

Period	Dates of the period	Maximum wind speed	Relative direction	Direction explanation	Average wind speed	Hs max	Average Hs
		[m/s]	[degrees]		[m/s]	[cm]	[cm]
1	27.03.2013-20.11.2013	21.6	221	S-W	5.98	103	15.96
2	20.11.2013-18.02.2014	21.1	275	W	8.11	120	20.54
3	18.02.2014-14.05.2014	17.3	264	W	5.99	81	15.53
4	14.05.2014-14.08.2014	18.5	356	N	5.12	81	13.99
5	14.08.2014-08.11.2014	19.9	290	N-W	5.76	108	14.67
6	08.11.2014-11.11.2014	11.6	204	S-W	7.47	38	13.54
7	11.11.2014-09.12.2014	12.5	191	S-W	5.31	44	11.78
8	09.12.2014-15.12.2014	18.6	207	S-W	8.40	72	20.03
9	15.12.2014-06.02.2015	19.9	244	S-W	7.81	79	19.83
10	06.02.2015-24.02.2015	16.5	192	S-W	6.09	46	14.53
11	24.02.2015-23.03.2015	16.2	278	N-W	6.19	80	15.51
12	23.03.2015-20.04.2015	21.2	248	S-W	6.39	101	19.56
13	20.04.2015-20.05.2015	20.3	244	S-W	6.34	83	15.56
14	20.05.2015-12.11.2015	20	297	N-W	5.34	104	15.16
15	12.11.2015- 12.02.2016	22.2	241	S-W	8.30	89	19.79
16	12.02.2016-22.02.2016	16.4	228	S-W	6.94	70	16.19
17	22.02.2016-10.03.2016	16.3	242	S-W	6.04	63	16.19
18	10.03.2016-23.03.2016	11.2	74	N-E	5.42	31	14.25
19	23.03.2016-06.04.2016	19.9	181	S	7.19	74	16.32

Table 6.2 – Summary of the Hydrodynamic and wind monitoring

Therefore it is possible to say that:

- the tidal range estimated goes from -2.0 to +2.0 meters;
- the maximum wind speed is 22.2 m/s and comes from S-W;
- the average direction of the wind is South-West;
- the highest Hs registered is equal to 120 cm;
- the average of the Hs is 16.26 cm.

The complete computation is located in Appendix A. Instead, in Appendix B a significance test of the data has been done.

6.2 Tidal flat monitoring: volume variation

Since the objective is to evaluate the sediment transport activity around each oyster reef, the first analysis is based on the volume of sand present in the system. Secondly it was decided to analyze this change of sand in cross sections. Three cross sections have been analyzed during research period: two on the right and on the left of the reef, and one in the middle. The maps used for the calculations will be showed in Appendix D and E.

Taking into account the maps obtained by ArcGIS, it was possible to export the volume of sand present in each single area. There is difference in the number of maps available for each reef: this means that some reefs were monitored more often than the others. (The reason behind this is due to the availability of the instrument, the weather conditions, the time available because of the tides.) Moreover it has been decided to divide the implementation of the data obtained by the long term analysis from the ones obtained from the short term analysis. Therefore, for the first computation, a reference point in the timeline is called T_0, and it refers at the measurement immediately before the sand nourishment. For the second computation, regarding the monitoring activity made by the author, the reference point will be different for each reef and specified in each computation. Having this said, each map has been compared with the reference point. The following table (Table 6.3) will show the summary of the calculations just explained, for each reef. Appendix E will shows all the maps obtained from ArcGIS and used for this calculation.

Long term analysis	
Dates of the monitoring	T
27.03.2013	T_0
20.11.2013	T_1
18.02.2014	T_2
14.05.2014	T_3
14.08.2014	T_4
08.11.2014	T_5

Short term analysis		
Dates of the monitoring	T	Reef
11.11.2014	T_6	D
09.12.2014	T_7	D
15.12.2014	T_8	D
06.02.2015	T_9	A,B,C
24.02.2015	T_{10}	A,D
23.03.2015	T_{11}	A,D
20.04.2015	T_{12}	A,B,C,D
20.05.2015	T_{13}	A,B,C,D
12.11.2015	T_{14}	A,D
12.02.2016	T_{15}	A,D
22.02.2016	T_{16}	A,D
10.03.2016	T_{17}	A,D
23.03.2016	T_{18}	A,D
06.04.2016	T_{19}	A,D

Table 6.3 - Summary of the data used for the calculation of the volume variation

6.2.1 Volume variation of reef A: long term analysis

Reef A			
Long term analysis		Short term analysis	
Dates of the monitoring	T	Dates of the monitoring	T
27.03.2013	T_0	06.02.2015	T_9
20.11.2013	T_1	24.02.2015	T_{10}
18.02.2014	T_2	23.03.2015	T_{11}
14.05.2014	T_3	20.04.2015	T_{12}
14.08.2014	T_4	20.05.2015	T_{13}
08.11.2014	T_5	12.11.2015	T_{14}
		12.02.2016	T_{15}
		22.02.2016	T_{16}
		10.03.2016	T_{17}
		23.03.2016	T_{18}
		06.04.2016	T_{19}

Table 6.4 - Summary of the data used for the calculation of the volume variation of Reed A

Period	Date	Volume
-	-	[m^3]
T_0-T_0	27.03.2013	0.00
T_0-T_1	20.11.2013	104.75
T_0-T_2	18.02.2014	-392.50
T_0-T_3	14.05.2014	-76.75
T_0-T_4	14.08.2014	40.50
T_0-T_5	08.11.2014	102.00

Table 6.5 - Volume variation of the reef A, for the long term analysis

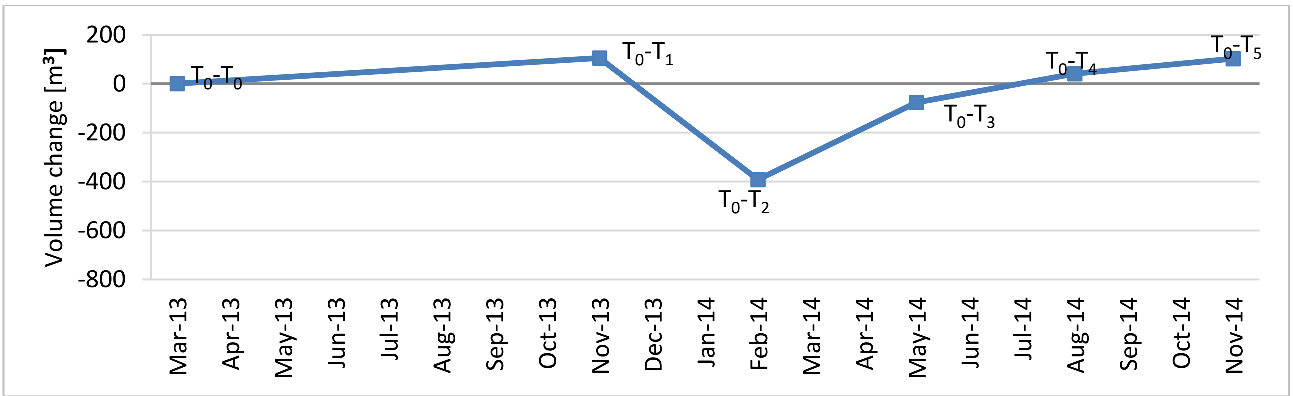


Figure 6.1 - Volume change of reef A for the long term analysis

Figure 6.1 shows the volume variations in the area of the reef A. the reference used in this case is the T_0. The total area analyzed consists about 10,000 m^2, id est one hectare. The data analysis of reef A starts on the 23th March 2013, date before the sand nourishment (T_0). After this, the graph shows an increase of

104.75 m^3. Afterwards, there is a big decrease: the volume from 104.75 m^3 becomes -392.50m^3. This big reduction consist in almost 497 m^3 of sand. After the T_2, 18th of March 2014, the graph shows an increase which continue the end of the long term analysis, in the 8th of November 2014.

6.2.2 Volume variation of reef A: short term analysis

Period	Date	Volume
-	-	[m^3]
T_9-T_9	06.02.2015	0.00
T_9-T_{10}	24.02.2015	43.71
T_9-T_{11}	23.03.2015	-40.67
T_9-T_{12}	20.04.2015	-53.16
T_9-T_{13}	20.05.2015	-124.81
T_9-T_{14}	12.11.2015	30.03
T_9-T_{15}	12.02.2016	-40.00
T_9-T_{16}	22.02.2016	-26.57
T_9-T_{17}	10.03.2016	-4.71
T_9-T_{18}	23.03.2016	-2.81
T_9-T_{19}	06.04.2016	-84.23

Table 6.6 - Volume variation of the reef A, for the short term analysis

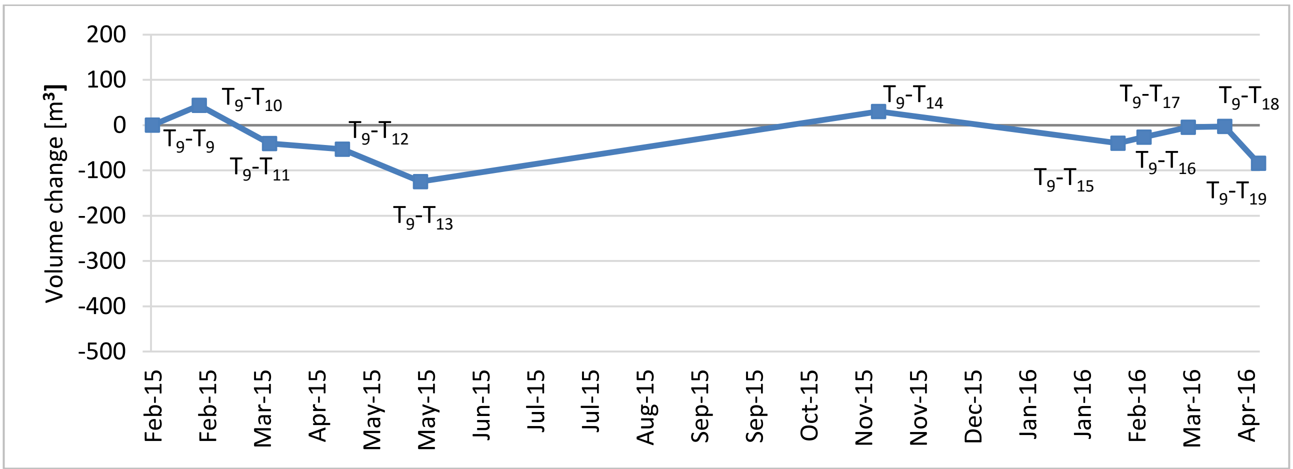


Figure 6.2 - Volume change of reef A for the short term analysis

The graph represents the calculation of the volume variation, taking as a reference the T_9 (6th of February 2015). The total area analyzed is the same considered in the long term analysis, id est 10,000 m^2. The graphs shows an initial constant volume between the first two measurements (T_9 and T_{10}). Afterwards, a decrease of 84.38 m^3 happens in T_{11}, which continues to decrease until T_{13}. At the end of the spring period, in T_{14}, the graph shows a big increase in volume of sand. In December 2015, T_{15}, there is a gain a decrease of volume: the value reaches -40 m^3. After that point, the graph shows again an increase until T_{18}, followed by a next decrease, where the value reach -84.23 m^3.

Table 6.7 represents the daily volume variation between each period of measurement. In the following table is reported the volume variation of the total area, the number of days between each tidal flat monitoring (long term and short term analysis) and the daily volume variation for each period, expressed in m^3/day. Looking at the computation, it is possible to estimate an average of -0.12 m^3/day (erosion) in the long term analysis and of -0.03 m^3/day (erosion) in the short term analysis.

		Total volume variation	n.° of days *	Daily volume variation
		[m^3]	-	[m^3/day]
T_0	27.03.2013	0.00	0	0.00
T_1	20.11.2013	104.75	239	0.44
T_2	18.02.2014	-392.50	328	-1.20
T_3	14.05.2014	-76.75	413	-0.19
T_4	14.08.2014	40.50	505	0.08
T_5	08.11.2014	102.00	591	0.17

*compared to T_0

		Total volume variation	n.° of days *	Daily volume variation
		[m^3]	-	[m^3/day]
T_6	11.11.2014	-	594	-
T_7	09.12.2014	-	622	-
T_8	15.12.2014	-	628	-
T_9	06.02.2015	0.00	681	0.00
T_{10}	24.02.2015	-43.72	699	-0.06
T_{11}	23.03.2015	40.68	726	0.06
T_{12}	20.04.2015	53.16	754	0.07
T_{13}	20.05.2015	124.81	784	0.16
T_{14}	12.11.2015	-30.04	960	-0.03
T_{15}	12.02.2016	40.00	1052	0.04
T_{16}	22.02.2016	26.58	1062	0.03
T_{17}	10.03.2016	4.72	1079	0.00
T_{18}	23.03.2016	2.82	1093	0.00
T_{19}	06.04.2016	84.23	1106	0.08

* compared to T_9

Table 6.7 – Computation of the daily volume variation of reef A

Figure 6.3 – Picture of reef A on the 12.02.2016, tidal flat side (Image elaborated by the author).

Figure 6.4 – Picture of reef A on the 12.02.2016, sea side (Image elaborated by the author).

6.2.3 Volume variation of reef B: long term analysis

Reef B			
Long term analysis		Short term analysis	
Dates of the monitoring	T	Dates of the monitoring	T
27.03.2013	T_0	06.02.2015	T_9
20.11.2013	T_1	24.02.2015	T_{10}
18.02.2014	T_2	23.03.2015	T_{11}
14.05.2014	T_3		
14.08.2014	T_4		
08.11.2014	T_5		

Table 6.8 - Summary of the data used for the calculation of the volume variation of Reed B

Period	Date	Volume
-	-	[m^3]
T_0-T_0	27.03.2013	0.00
T_0-T_1	20.11.2013	-730.00
T_0-T_2	18.02.2014	-329.00
T_0-T_3	14.05.2014	-478.75
T_0-T_4	14.08.2014	-427.50
T_0-T_5	08.11.2014	-571.50

Table 6.9- Volume variation of the reef B, for the long term analysis

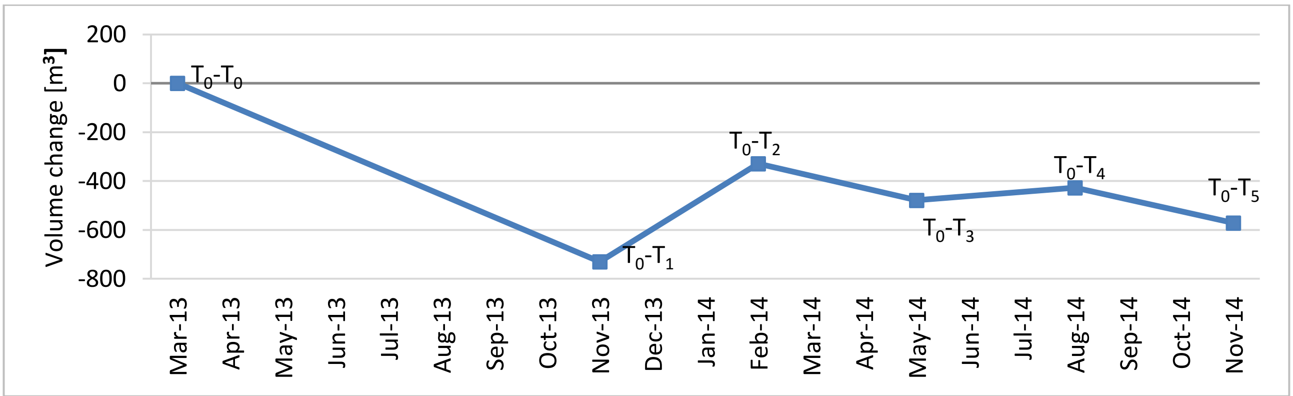


Figure 6.5- Volume change of reef B for the long term analysis

Figure 6.5 shows the volume variations in the area of the reef B. the reference used in this case is the T_0. The total area analyzed consists about 20,000 m^2. The data analysis of reef B starts as well on the 23th March 2013, date before the sand nourishment (T_0). After this, the graph shows a big decrease of sand volume: the value reaches -730 m^3. Afterwards in T_2, there is a big increase: the volume becomes -329 m^3.

Instead in T_3 the volume reduces again, reaching a value of -478.75 m^3, which is almost stable also in T_4. The volume decrease again in T_5.

6.2.4 Volume variation of reef B: short term analysis

Period	Date	Volume
-	-	[m^3]
T_9-T_9	06.02.2015	0.00
T_9-T_{12}	24.02.2015	-183.13
T_9-T_{13}	23.03.2015	-374.84

Table 6.10 - Volume variation of the reef B, for the long term analysis

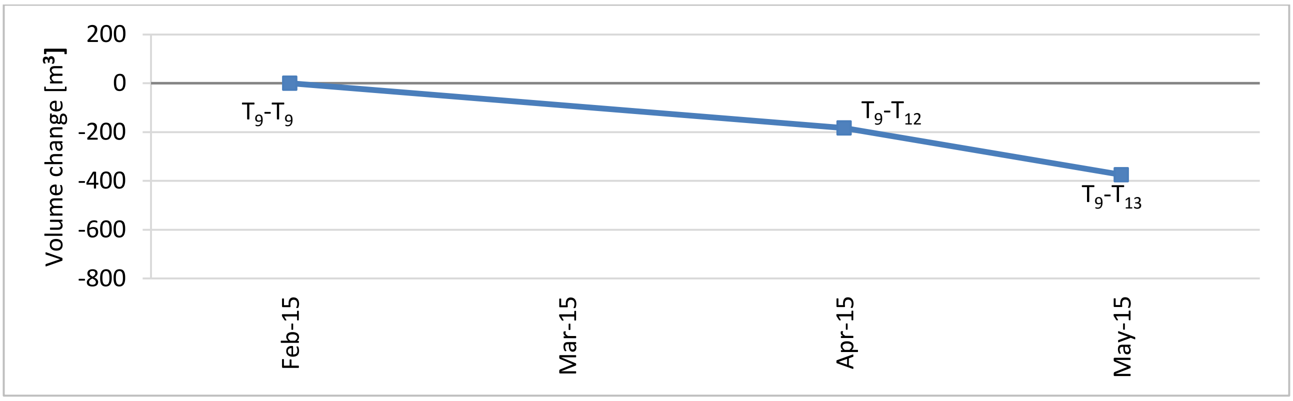


Figure 6.6 - Volume change of reef B for the short term analysis

Figure 6.6 represents the volume variation in the short term analysis. The reference taken into account is the T_9. The total area analyzed is the same considered in the long term analysis, id est 20,000 m^2. The graphs shows a decrease of the total volume of sand since the beginning. In T_{13} the erosion reach a peak of -374.84 m^3.

Table 6.11 represents the daily volume variation between each period of measurement, as already showed for reef A. The daily volume variation is expressed in m^3/day. Looking at the computation, it is possible to estimate an average of -0.17 m^3/day (erosion) in the long term analysis and of -0.24 m^3/day (erosion) in the short term analysis.

		Total volume variation [m^3]	n.° of days *	Daily volume variation [m^3/day]
T_0	27.03.2013	0.00	0	0.00
T_1	20.11.2013	-730.00	239	-3.05
T_2	18.02.2014	-329.00	328	-1.00
T_3	14.05.2014	-478.75	413	-1.16
T_4	14.08.2014	-427.50	505	-0.85
T_5	08.11.2014	-571.50	591	-0.97

* compared to T_0

		Total volume variation [m^3]	n.° of days *	Daily volume variation [m^3/day]
T_6	11.11.2014	-	594	-
T_7	09.12.2014	-	622	-
T_8	15.12.2014	-	628	-
T_9	06.02.2015	0.00	681	0.00
T_{10}	24.02.2015	-	699	-
T_{11}	23.03.2015	-	726	-
T_{12}	20.04.2015	-183.13	754	-0.24
T_{13}	20.05.2015	-374.84	784	-0.48
T_{14}	12.11.2015	-	960	-
T_{15}	12.02.2016	-	1052	-
T_{16}	22.02.2016	-	1062	-
T_{17}	10.03.2016	-	1079	-
T_{18}	23.03.2016	-	1093	-
T_{19}	06.04.2016	-	1106	-

* compared to T_9

Table 6.11 – Computation of the daily volume variation of reef B

Figure 6.7 – Drone picture of reef A and B on the 12.02.2015 (Image elaborated by Rijkswaterstaat).

Figure 6.8 –Picture of reef A and B on the 12.02.2016 (Image elaborated by Rijkswaterstaat).

6.2.5 Volume variation of reef C: long term analysis

Reef C			
Long term analysis		Short term analysis	
Dates of the monitoring	T	Dates of the monitoring	T
27.03.2013	T_0	06.02.2015	T_9
20.11.2013	T_1	24.02.2015	T_{10}
18.02.2014	T_2	23.03.2015	T_{11}
14.05.2014	T_3		
14.08.2014	T_4		
08.11.2014	T_5		

Table 6.12 - Summary of the data used for the calculation of the volume variation of Reed C

Period	Date	Volume
-	-	[m^3]
T_0-T_0	27.03.2013	0.00
T_0-T_1	20.11.2013	5206.00
T_0-T_2	18.02.2014	5388.75
T_0-T_3	14.05.2014	5296.50
T_0-T_4	14.08.2014	5195.75
T_0-T_5	08.11.2014	5380.25

Table 6.13 - Volume variation of the reef C, for the long term analysis

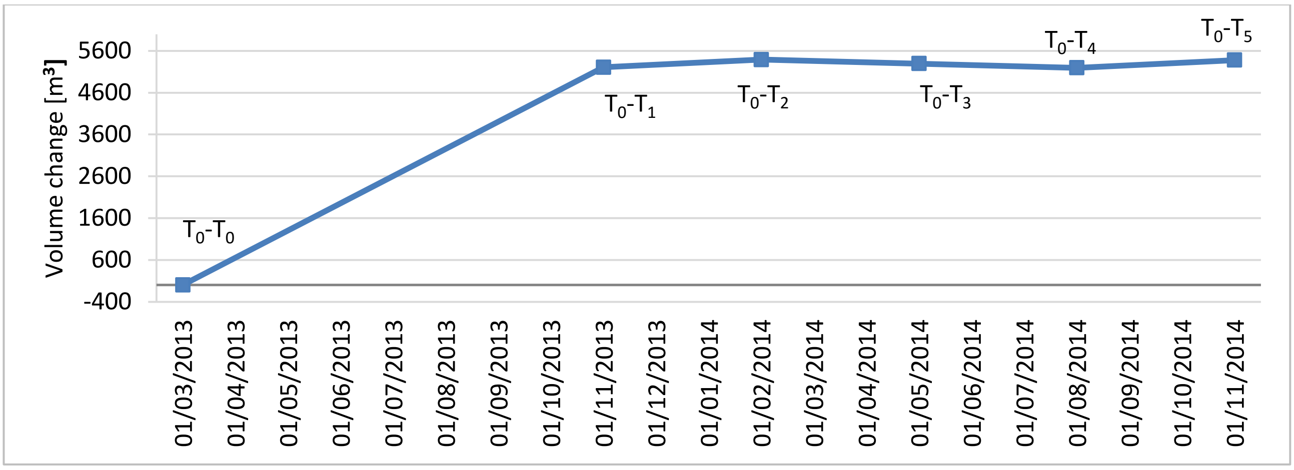


Figure 6.9 - Volume change of reef C for the long term analysis

Figure 6.9 shows the volume variations in the area of the reef C. The reference used is the T_0. The total area analyzed consists about 10,000 m^2. The data analysis of reef C starts as well on the 23th March 2013, date before the sand nourishment (T_0). After this, the graph shows a big increase of sand volume, clearly do to the construction of the sand nourishment: the value reaches 5206 m^3. Afterwards, until T_5, the volume variation is almost stable.

6.2.6 Volume variation of reef C: short term analysis

Period	Date	Volume
-	-	[m^3]
T_9-T_9	06.02.2015	0,00
T_9-T_{12}	24.02.2015	-42.97
T_9-T_{13}	23.03.2015	-213.62

Table 6.14 - Volume variation of the reef C, for the long term analysis

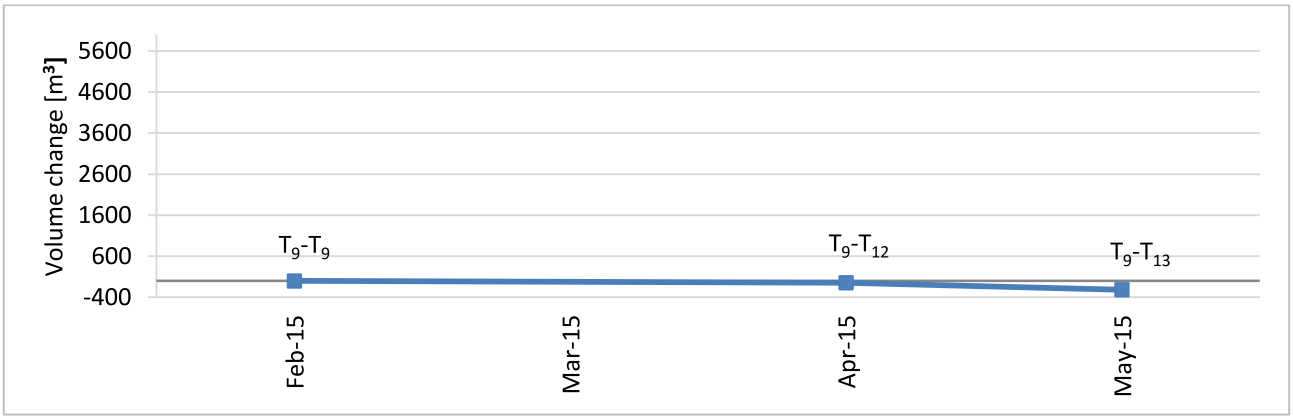


Figure 6.10 - Volume change of reef C for the short term analysis

Figure 6.10 represents the volume variation in the short term analysis. The reference taken into account is the T_9. The total area analyzed is the same considered in the long term analysis, id est 10,000 m^2. The graphs shows that total volume of sand is almost constant. In T_{13} erosion takes place, reaching a peak of --213.62m^3.

Table 6.15 represents the daily volume variation between each period of measurement, as already showed for the other reefs. The daily volume variation is expressed in m^3/day. Looking at the computation, it is possible to estimate an average of 11.74 m^3/day (sedimentation) in the long term analysis and of -0.11 m^3/day (erosion) in the short term analysis.

		Total volume variation [m^3]	n.° of days * -	Daily volume variation [m^3/day]
T_0	27.03.2013	0.00	0	0.00
T_1	20.11.2013	5206.00	239	21.78
T_2	18.02.2014	5388.75	328	16.43
T_3	14.05.2014	5296.50	413	12.82
T_4	14.08.2014	5195.75	505	10.29
T_5	08.11.2014	5380.25	591	9.10

* compared to T_0

		Total volume variation [m^3]	n.° of days * -	Daily volume variation [m^3/day]
T_6	11.11.2014	-	594	-
T_7	09.12.2014	-	622	-
T_8	15.12.2014	-	628	-
T_9	06.02.2015	0.00	681	0.00
T_{10}	24.02.2015	-	699	-
T_{11}	23.03.2015	-	726	-
T_{12}	20.04.2015	-42.98	754	-0.06
T_{13}	20.05.2015	-213.62	784	-0.27
T_{14}	12.11.2015	-	960	-
T_{15}	12.02.2016	-	1052	-
T_{16}	22.02.2016	-	1062	-
T_{17}	10.03.2016	-	1079	-
T_{18}	23.03.2016	-	1093	-
T_{19}	06.04.2016	-	1106	-

* compared to T_9

Table 6.15– Computation of the daily volume variation of reef C

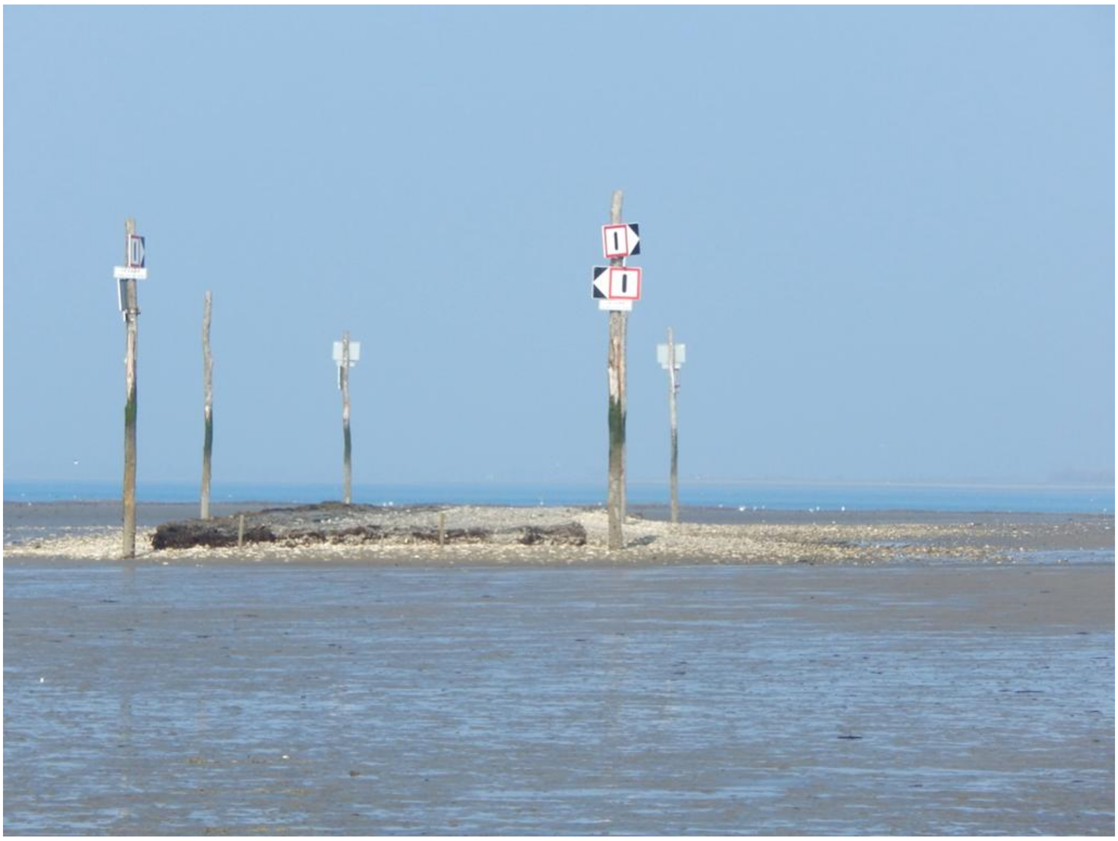


Figure 6.11 - Picture of reef C on March 2016 (image elaborated by the author).

6.2.7 Volume variation of reef D: long term analysis

Reef D			
Long term analysis		Short term analysis	
Dates of the monitoring	T	Dates of the period	T
27.03.2013	T_0	11.11.2014	T_6
20.11.2013	T_1	09.12.2014	T_7
18.02.2014	T_2	15.12.2014	T_8
14.05.2014	T_3	06.02.2015	T_9
14.08.2014	T_4	24.02.2015	T_{10}
08.11.2014	T_5	23.03.2015	T_{11}
		20.04.2015	T_{12}
		20.05.2015	T_{13}
		12.11.2015	T_{14}
		12.02.2016	T_{15}
		22.02.2016	T_{16}
		10.03.2016	T_{17}
		23.03.2016	T_{18}
		06.04.2016	T_{19}

Table 6.16 - Summary of the data used for the calculation of the volume variation of Reed D

Period	Date	Volume
-	-	[m^3]
T_0-T_0	27.03.2013	0,000
T_0-T_1	20.11.2013	1772.00
T_0-T_2	18.02.2014	2096.25
T_0-T_3	14.05.2014	1998.00
T_0-T_4	14.08.2014	2140.75
T_0-T_5	08.11.2014	2326.50

Table 6.17 - Volume variation of the reef D, for the long term analysis

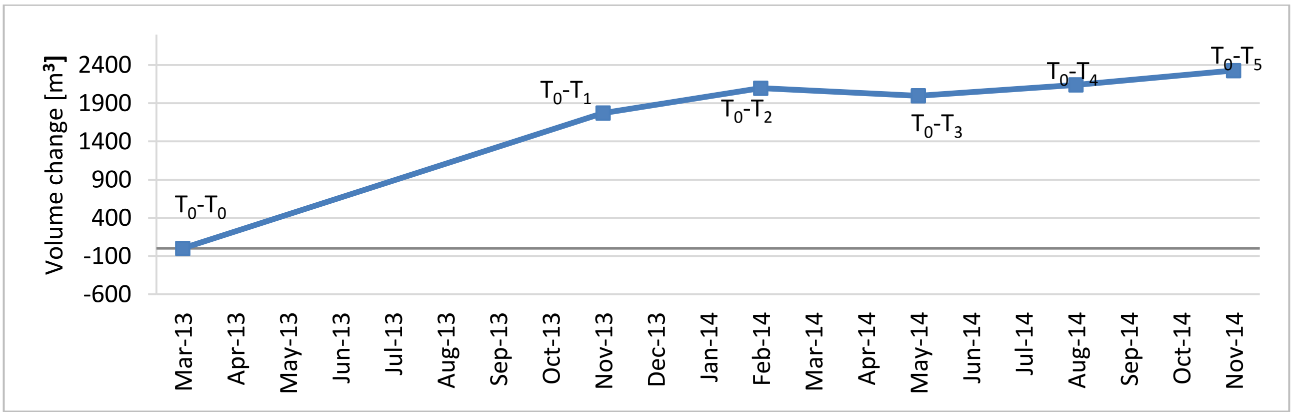


Figure 6.12 - Volume change of reef D for the long term analysis

Figure 6.12 shows the volume variations in the area of the reef D. The reference used is the T_0. The total area analyzed consists about 10,000 m^2. The data analysis of reef D starts as well on the 23th March 2013, date before the sand nourishment (T_0). After this, the graph shows a big increase of sand volume, clearly do to the construction of the sand nourishment: the value reaches 1772 m^3. Afterwards, until T_5, the volume variation continues to increase, reaching a peak of 2326.50 m^3.

6.2.8 Volume variation of reef D: short term analysis

Period	Date	Volume
-	-	[m^3]
T_6-T_6	11.11.2014	0.00
T_6-T_7	09.12.2014	-40.57
T_6-T_8	15.12.2014	-76.81
T_6-T_9	06.02.2015	-128.06
T_6-T_{10}	24.02.2015	-90.08
T_6-T_{11}	23.03.2015	-49.11
T_6-T_{12}	20.04.2015	-117.50
T_6-T_{13}	20.05.2015	-159.47
T_6-T_{14}	12.11.2015	-110.70
T_6-T_{15}	12.02.2016	-9.82
T_6-T_{16}	22.02.2016	40.04
T_6-T_{17}	10.03.2016	-62.10
T_6-T_{18}	23.03.2016	-87.12
T_6-T_{19}	06.04.2016	-29.43

Table 6.18 - Volume variation of the reef D, for the short term analysis

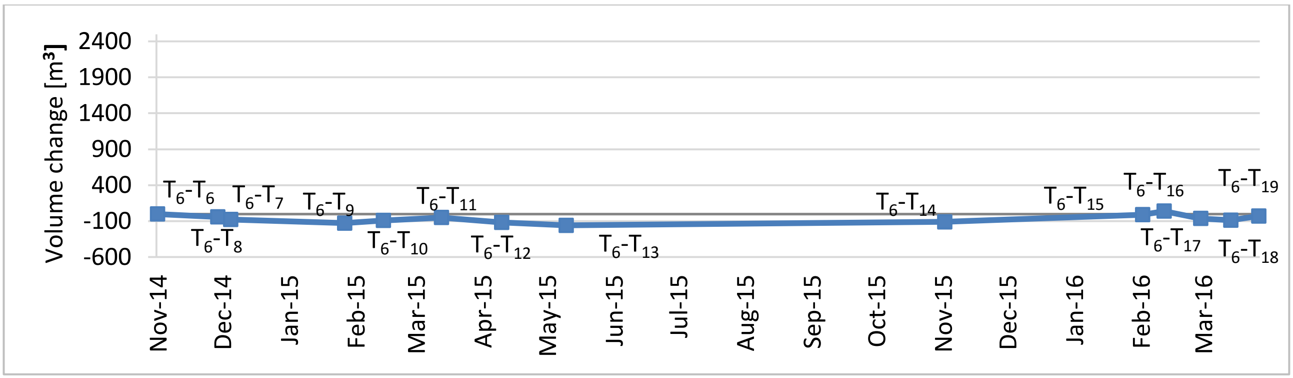


Figure 6.13- Volume change of reef D for the short term analysis

Figure 6.13 represents the volume variation in the short term analysis. The reference taken into account is the T_6. The total area analyzed is the same considered in the long term analysis, id est 10,000 m^2. The graphs shows that total volume of sand is almost constant.

Table 6.19 represents the daily volume variation between each period of measurement, as already showed for the other reefs. The daily volume variation is expressed in m^3/day. Looking at the computation, it is possible to estimate an average of 4.47 m^3/day (sedimentation) in the long term analysis and of -0.08 m^3/day (erosion) in the short term analysis.

		Total volume variation	n.° of days *	Daily volume variation
		[m^3]	-	[m^3/day]
T_0	27.03.2013	0.00	0	0.00
T_1	20.11.2013	1772.00	239	7.41
T_2	18.02.2014	2096.25	328	6.39
T_3	14.05.2014	1998.00	413	4.84
T_4	14.08.2014	2140.75	505	4.24
T_5	08.11.2014	2326.50	591	3.94

* compared to T_0

		Total volume variation	n.° of days *	Daily volume variation
		[m^3]	-	[m^3/day]
T_6	11.11.2014	0	594	0.00
T_7	09.12.2014	-40.57	622	-0.07
T_8	15.12.2014	-76.81	628	-0.12
T_9	06.02.2015	-128.07	681	-0.19
T_{10}	24.02.2015	-90.08	699	-0.13
T_{11}	23.03.2015	-49.12	726	-0.07
T_{12}	20.04.2015	-117.51	754	-0.16
T_{13}	20.05.2015	-159.48	784	-0.20
T_{14}	12.11.2015	-110.71	960	-0.12
T_{15}	12.02.2016	-9.83	1052	-0.01
T_{16}	22.02.2016	40.05	1062	0.04
T_{17}	10.03.2016	-62.10	1079	-0.06
T_{18}	23.03.2016	-87.12	1093	-0.08
T_{19}	06.04.2016	-29.44	1106	-0.03

*compared to T_6

Table 6.19 – Computation of the daily volume variation of reef D

Figure 6.14 – Picture of reef A on the 12.02.2016 (image elaborated by the author).

Figure 6.15 –Picture of oysters present in reef D on March 2016 (image elaborated by the author).

6.2.9 Summary of volume variation

	Volume variation					
	Period	Date	Reef A	Reef B	Reef C	Reef D
	-	-	[m^3]	[m^3]	[m^3]	[m^3]
long term analysis	T0	27.03.2013	0.00	0.00	0.00	0.00
	T1	20.11.2013	104.75	-104.75	5206.00	1772.00
	T2	18.02.2014	-392.50	392.50	5388.75	2096.25
	T3	14.05.2014	-76.75	76.75	5296.50	1998.00
	T4	14.08.2014	40.50	-40.50	5195.75	2140.75
	T5	08.11.2014	102.00	-102.00	5380.25	2326.50
short term analysis	T6	11.11.2014	-	-	-	0.00
	T7	09.12.2014	-	-	-	-40.58
	T8	15.12.2014	-	-	-	-76.81
	T9	06.02.2015	0.00	0.00	0.00	-128.07
	T10	24.02.2015	0.29	-	-	-90.08
	T11	23.03.2015	-83.67	-	-	-49.12
	T12	20.04.2015	-96.00	-183.13	-42.97	-117.51
	T13	20.05.2015	-167.86	-374.84	-213.62	-159.48
	T14	12.11.2015	-12.47	-	-	-110.71
	T15	12.02.2016	-82.83	-	-	-9.83
	T16	22.02.2016	-69.42	-	-	40.05
	T17	10.03.2016	-47.77	-	-	-62.10
	T18	24.03.2016	-46.33	-	-	-87.12
	T19	06.04.2016	-128.12	-	-	-29.44

Table 6.20 - Volume variation of all the reef

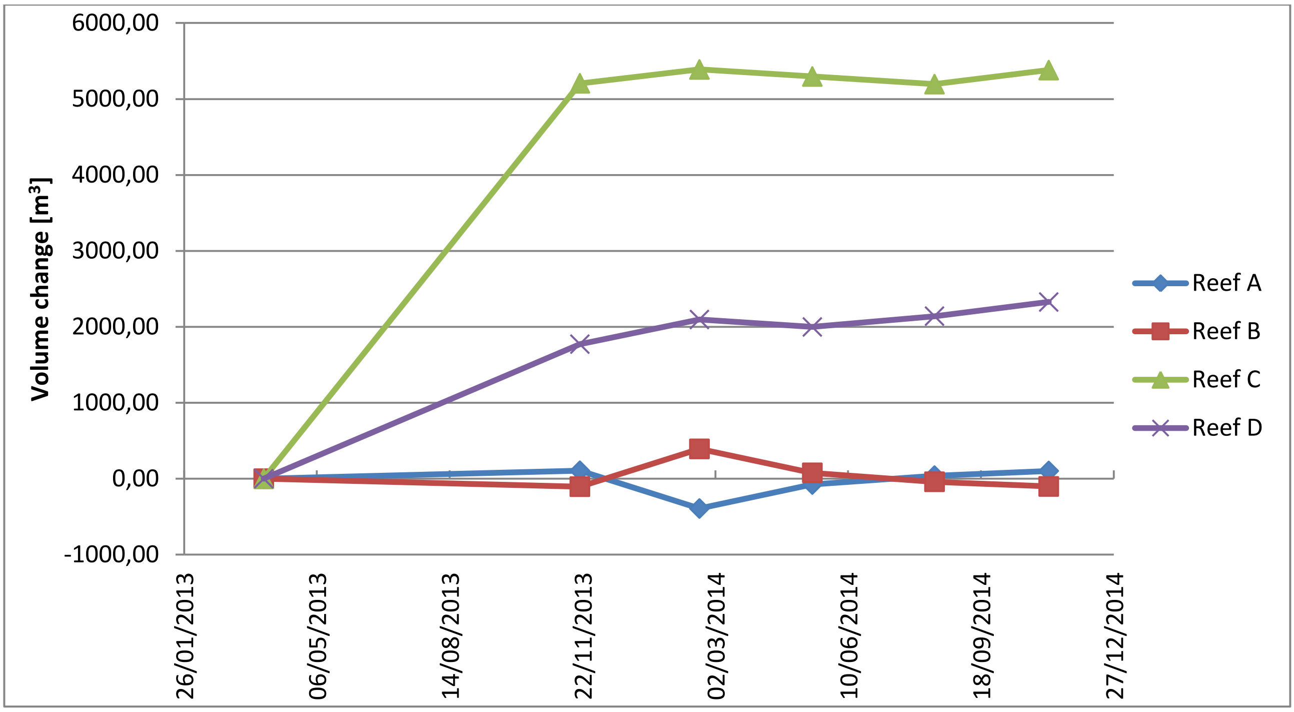


Figure 6.16 - Summary of the volume changes for all the reefs, in long term analysis

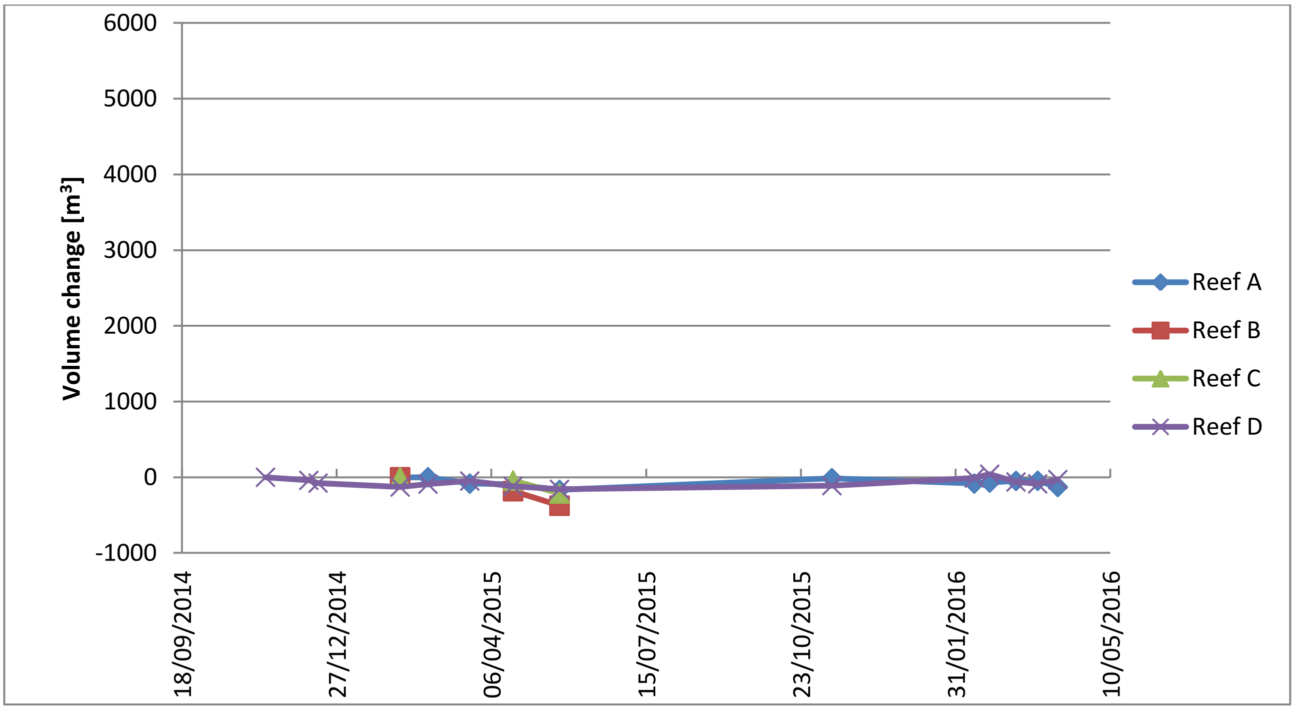


Figure 6.17 - Summary of the volume changes for all the reefs, in short term analysis

6.3 Tidal flat monitoring: elevation profiles

In the previous subchapter, the area of influence of each reef was analyzed. It gives an idea of the amount of sand moving (erosion/ sedimentation) in the system of each reef.

To understand how the reef works, it is necessary to see what happens in the cross sectional profile. A cross section determines if the reef is really keeping the sand in its place, which is the purpose for which it was made. This analysis has been realized for two reefs: A and D. The reason behind this choice is the idea that each of these reefs is characteristic for its single area. Therefore the behavior of two reefs is considered significant enough to understand the situation for all of them. As done in the previous calculation, it was decided to realize a computation divided in long term analysis and short term analysis.

6.3.1 Reef A: elevation profiles of long term analysis

For the first case, regarding the long term analysis, three transect have been analyzed in each reef, taking into account the elevation maps from *Rijkswaterstaat.* The transects realized are called: transect A-A',B-B' and C-C' . The transect C-C' has been realized crossing the reef; the transects A-A' and B-B' have been done outside the area of influence of the reef. Moreover, another calculation has been made, taking into account other three transects, this time inside the area of influence of the reef. These transects are: C-C' (the same as the previous one); D-D' and E-E'. The goal of this analysis is to identify the difference between the resulting transect that is crossing the reef and the ones that are outside it in long and short term conditions.

Figure 6.18 shows the cross sections realized for the reef A. The transects are five in total: A-A',B-B',C-C', D-D' and E-E'. The examination consist in the comparison of all of these in relation to the C-C', which is the one crossing the reef.

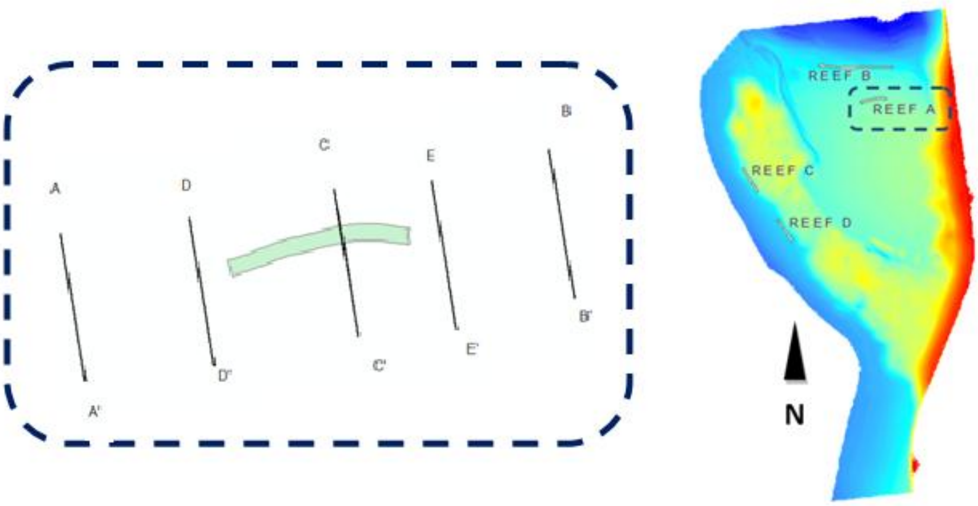


Figure 6.18 - Cross section of reef A, long term analysis

All the transects realized have the same length of almost 70 m each. The transects A-A',B-B' are located at a distance of 40m to the limit of the reef itself; instead C-C' and D-D' at a distance of 15 meters. Transect A-A' and D-D' are located on the left side of the area; transect B-B' and E-E' in the right side; and the C-C' in the middle. The elevations maps used for this calculation are the following one, showed in Table 6.21. The results of the calculation are located in this section. The x-axis shows the total length of the transect and the y-axis shows the elevation in meters N.A.P. (*Normaal Amsterdams Peil* or *Amsterdam Ordnance Datum).* The T_0 line is indicated in red, making it possible to see the difference of all the transects compared to the beginning.

Period	Date
T0	27.03.2013
T1	20.11.2013
T2	18.02.2014
T3	14.05.2014
T4	14.08.2014
T5	08.11.2014

Table 6.21 – Elevation maps used for the calculation: long term analysis of reef A

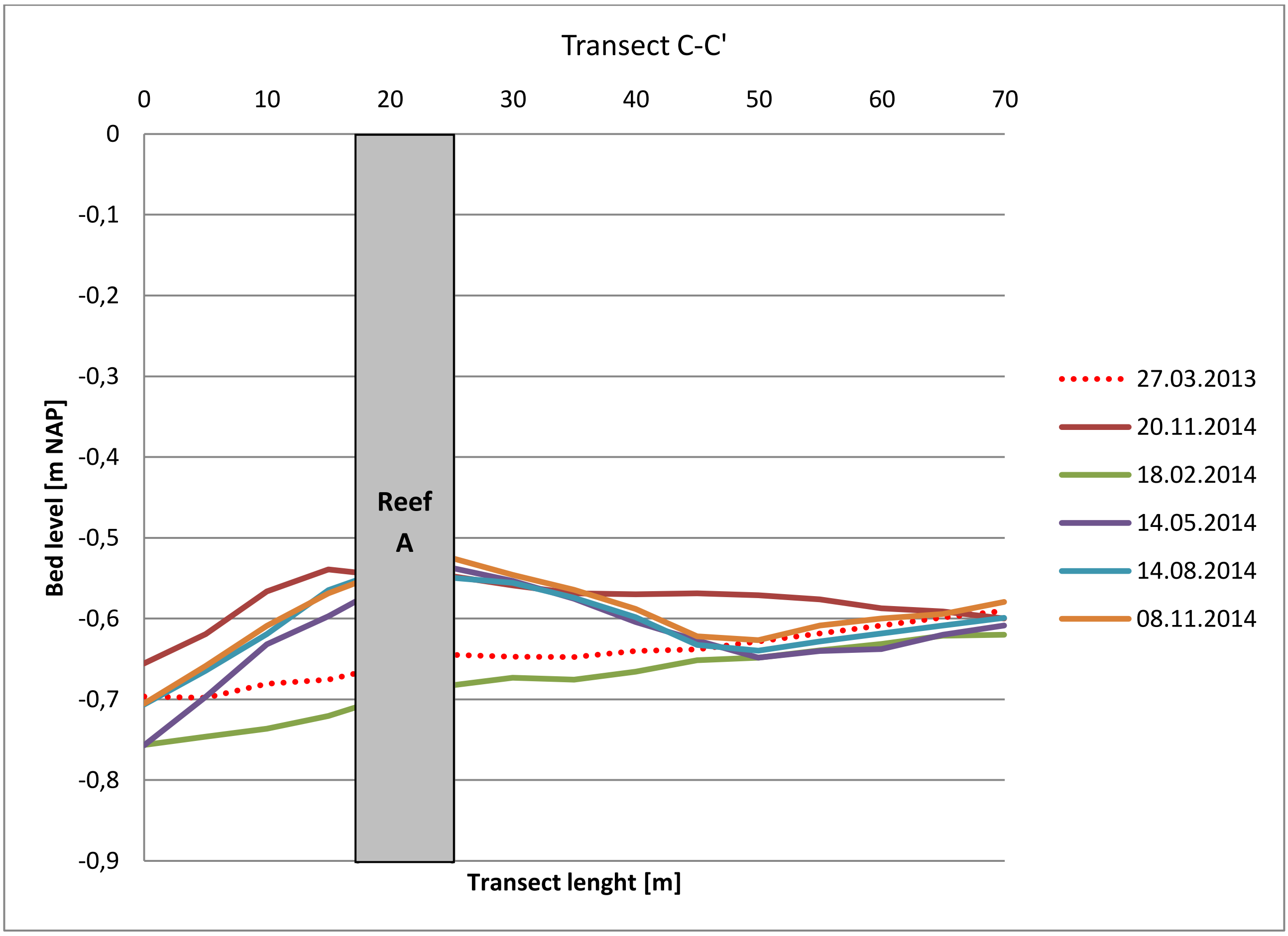


Figure 6.19– Transect C-C' of reef A, in long term analysis

The analysis showed in Figure 6.19 shows the bed level behind and in front of the reef. Behind the reef, which means in the sea side, the level is high for all the measurements, except for the T_0 (27th of March 2013) and T_2 (18th of February 2014). In the front, which means the tidal flat side, the situation immediately close the reef is the same; going forward the bed level decreases reaching almost the same value for all the measurements.

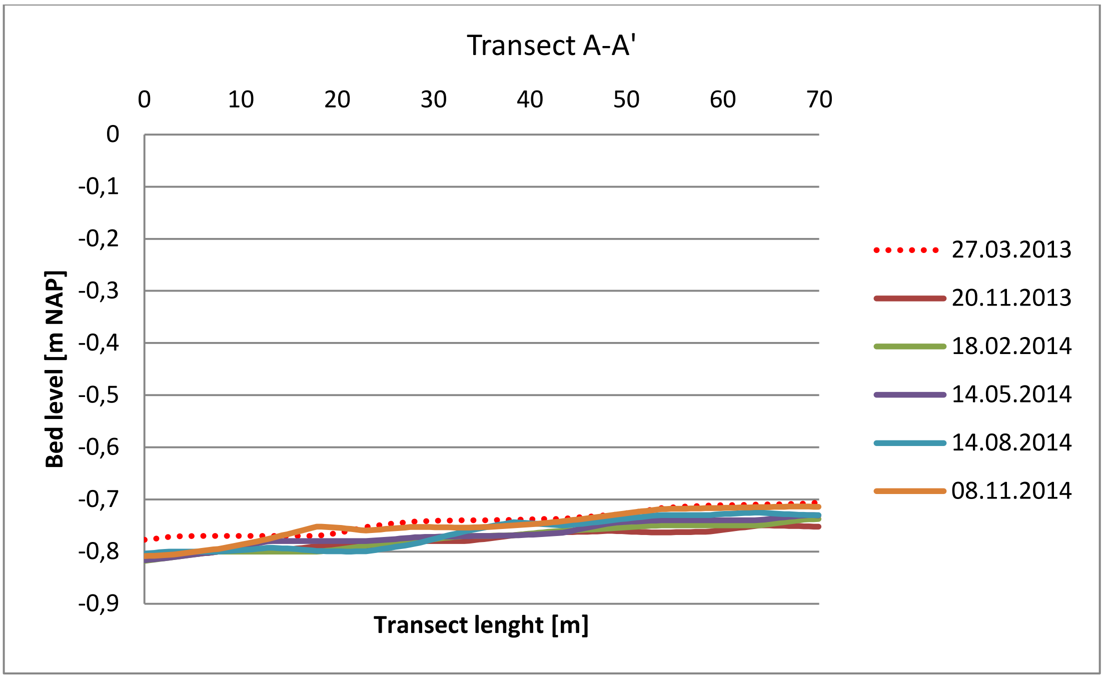


Figure 6.20– Transect A-A' of reef A, in long term analysis

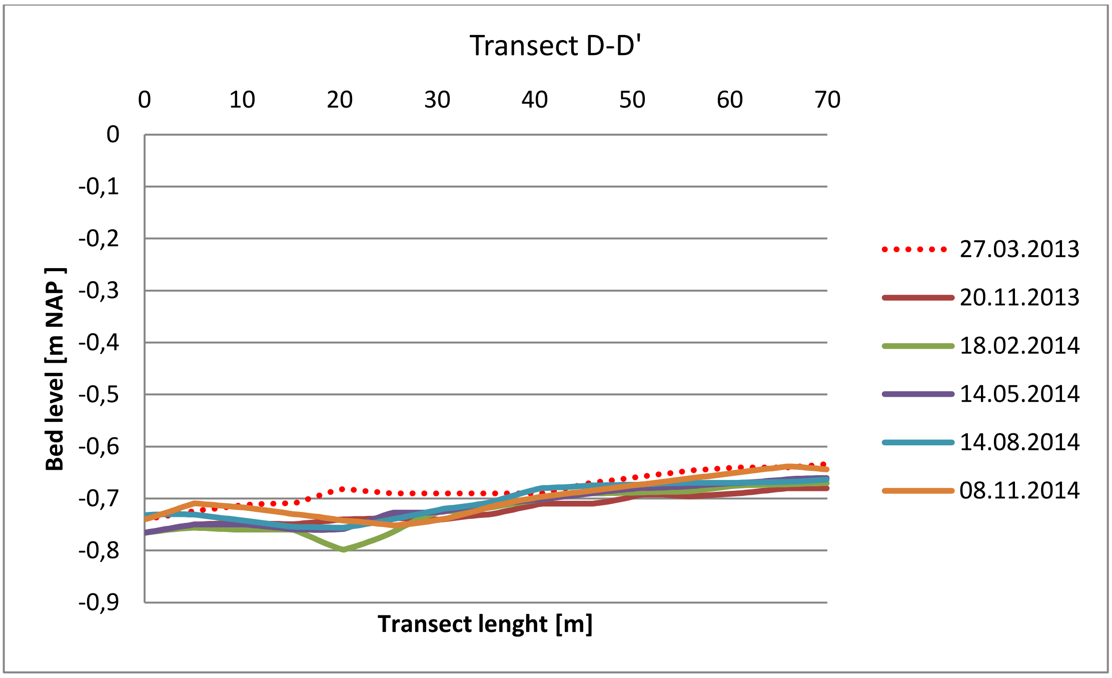


Figure 6.21 – Transect D-D' of reef A, in long term analysis

The situation of the bed level on the left side of the reef is explained by the Figure 6.20 and Figure 6.21. The first one, A-A', is far away from the reef. It shows a stable condition of the bed level. It seems that the elevation profile related to the T_0 is even higher than the others.

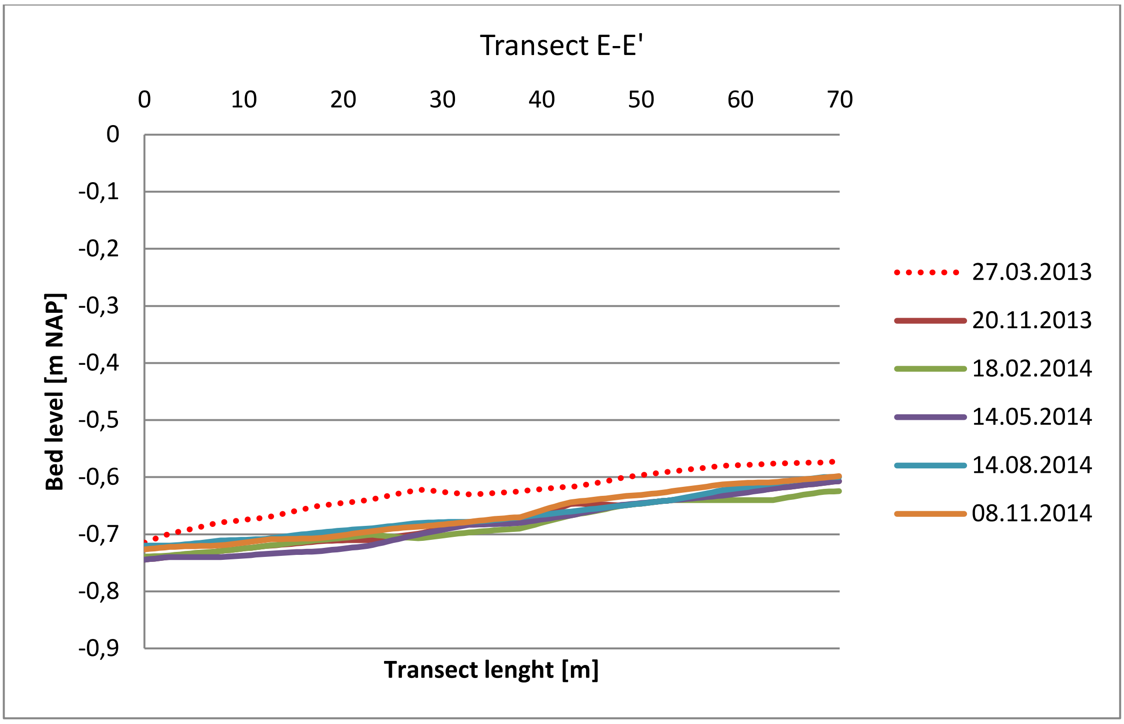


Figure 6.22 – Transect E-E' of reef A, in long term analysis

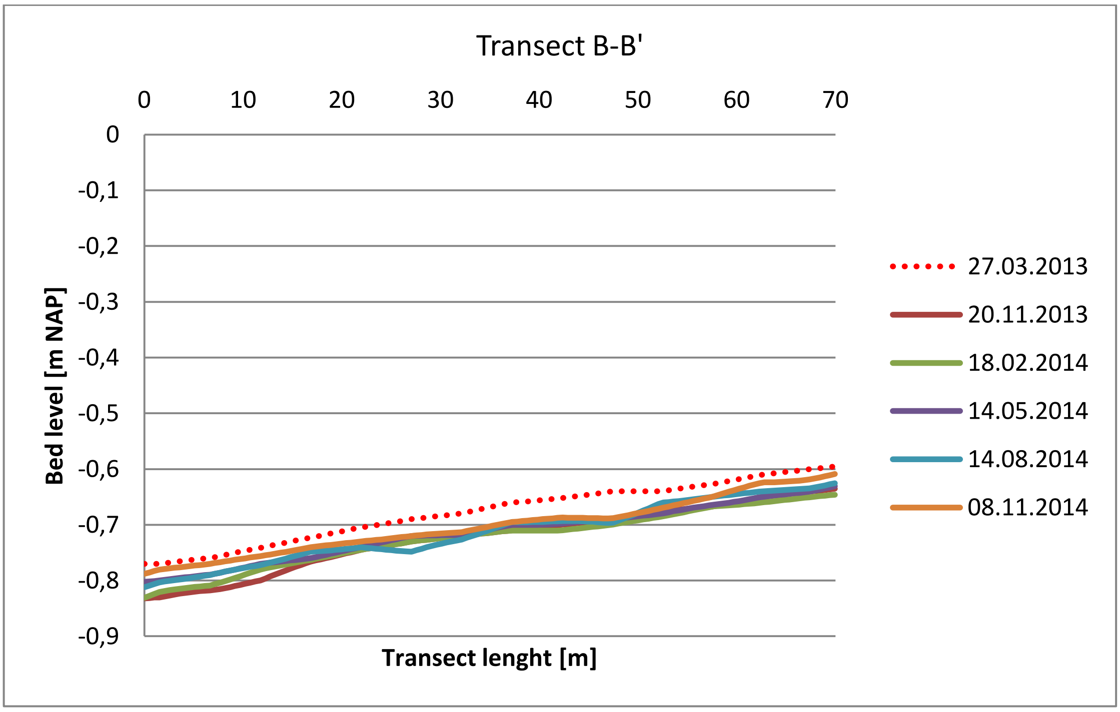


Figure 6.23– Transect B-B' of reef A, in long term analysis

The situation of the bed level on the right side of the reef is explained by the Figure 6.22 and Figure 6.23. Both of them, far away and close to the reef, show a stable condition of erosion of the bed level. In fact elevation profile related to the T_0 is higher than all the others elevation profiles.

Appendix E will give a complete overview of the elevation profile of reef A for each single period.

6.3.2 Reef D: elevation profiles of long term analysis

Figure 6.24 shows the cross sections realized for the reef D. The transects are five in total: A-A’,B-B’,C-C’, D-D’ and E-E’. The examination consist in the comparison of all of these in relation to the C-C’, which is the one crossing the reef.

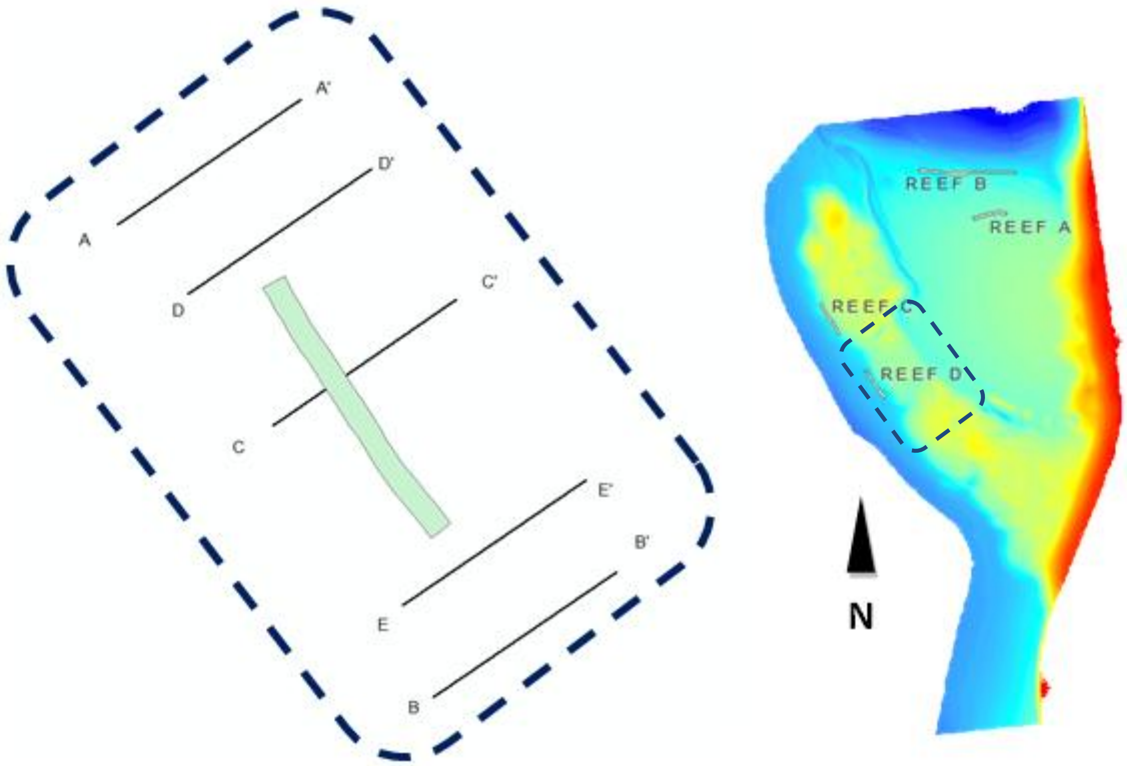


Figure 6.24 - Cross sections of reef D, long term analysis

All the transects realized have the same length of almost 70m each. The transects A-A’,B-B’ are located at a distance of 40m to the limit of the reef itself; instead C-C’ and D-D’ at a distance of 10 meters. Transect A-A’ and D-D’ are located in the upper part of the area; transect B-B’ and E-E’ in the lower part; and the C-C’ in the middle. The elevations maps used for this calculation are the following one, showed in Table 6.22. The results of the calculation are located in this section. The results of the calculation are located in this section. The x-axis shows the total length of the transect and the y-axis shows the elevation in meters NAP. The T_0 line is indicated in red, making it possible to see the difference of all the transects compared to the beginning.

Period	Date
T0	27.03.2013
T1	20.11.2013
T2	18.02.2014
T3	14.05.2014
T4	14.08.2014
T5	08.11.2014

Table 6.22 – Elevation maps used for the calculation: long term analysis of reef D

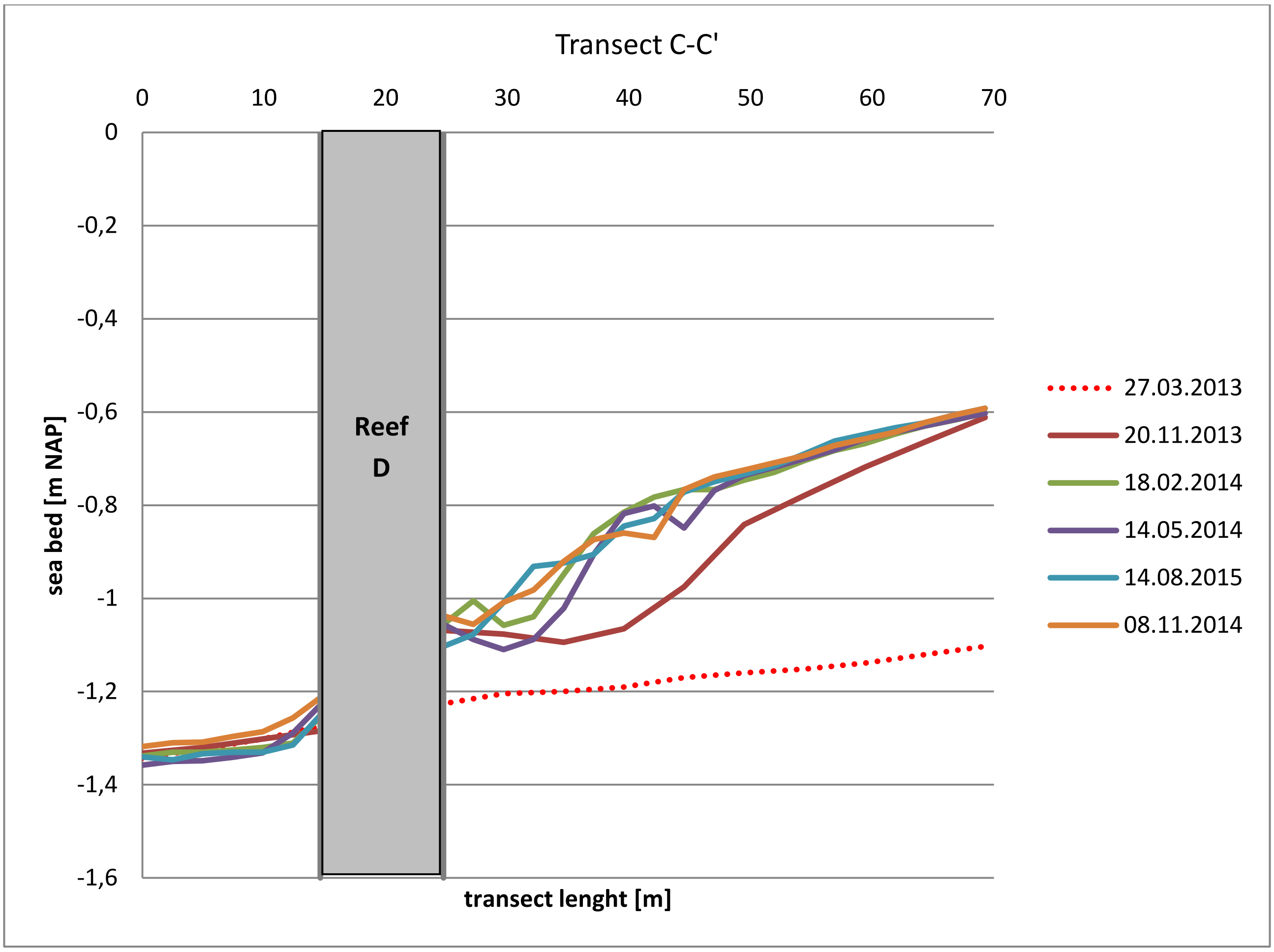


Figure 6.25 – Transect C-C' of reef D, in long term analysis

The analysis showed in Figure 6.25 shows the bed level behind and in front of the reef. Behind the reef, which means in the sea side, the level is the almost the same for all the measurements. Instead in the front, which means the tidal flat side, the situation immediately close the reef is different: in the closest part of the reef there is sedimentation (in all the elevation sections), then erosion, and then sedimentation again (due to the presence of sand nourishment). The behaviors in the back side (tidal flat side) are different in each measurement. T_2 shows a big difference in level, respect the nourishment. in the following ones more sedimentation appears.

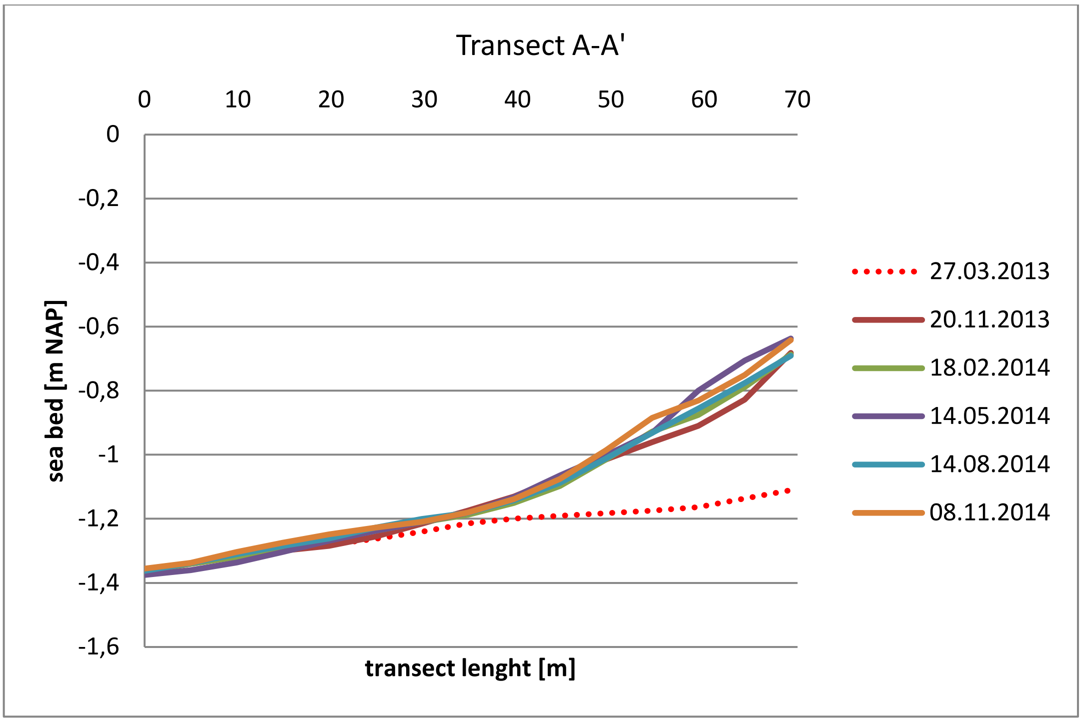


Figure 6.26 – Transect A-A' of reef D, in long term analysis

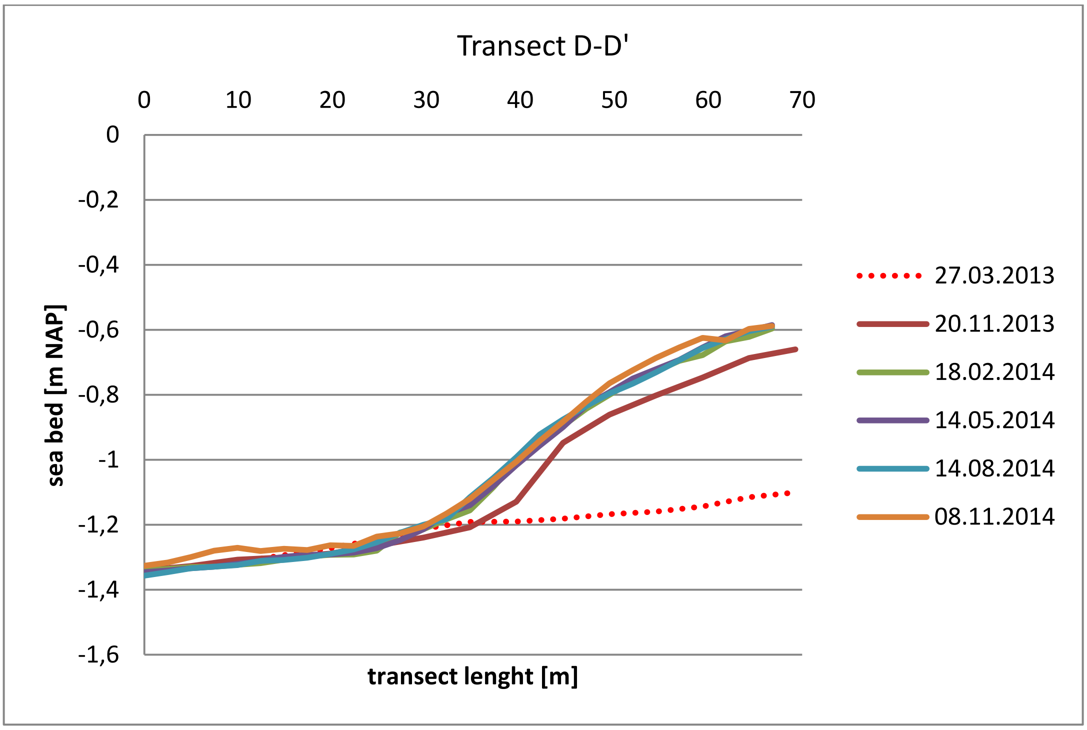


Figure 6.27 – Transect D-D' of reef D, in long term analysis

The situation of the bed level on the upper side of the reef is explained by the Figure 6.26 and Figure 6.27. The first one, A-A', is far away from the reef. It shows a stable condition of the bed level. The same happens for the D-D'. All the elevation profile related to measurements are higher than the elevation profile at T_0. Moreover all the measurement are higher than the T_1 , id est the date immediately after the sand nourishment: this is a clear sign of sedimentation during the time.

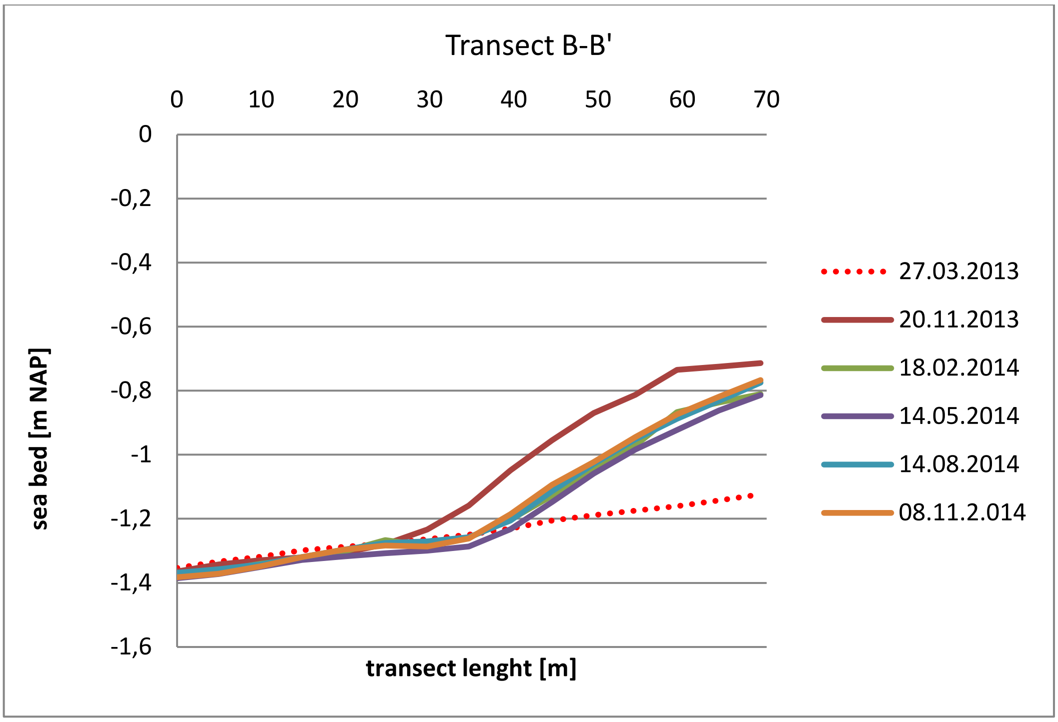


Figure 6.28 – Transect B-B' of reef D, in long term analysis

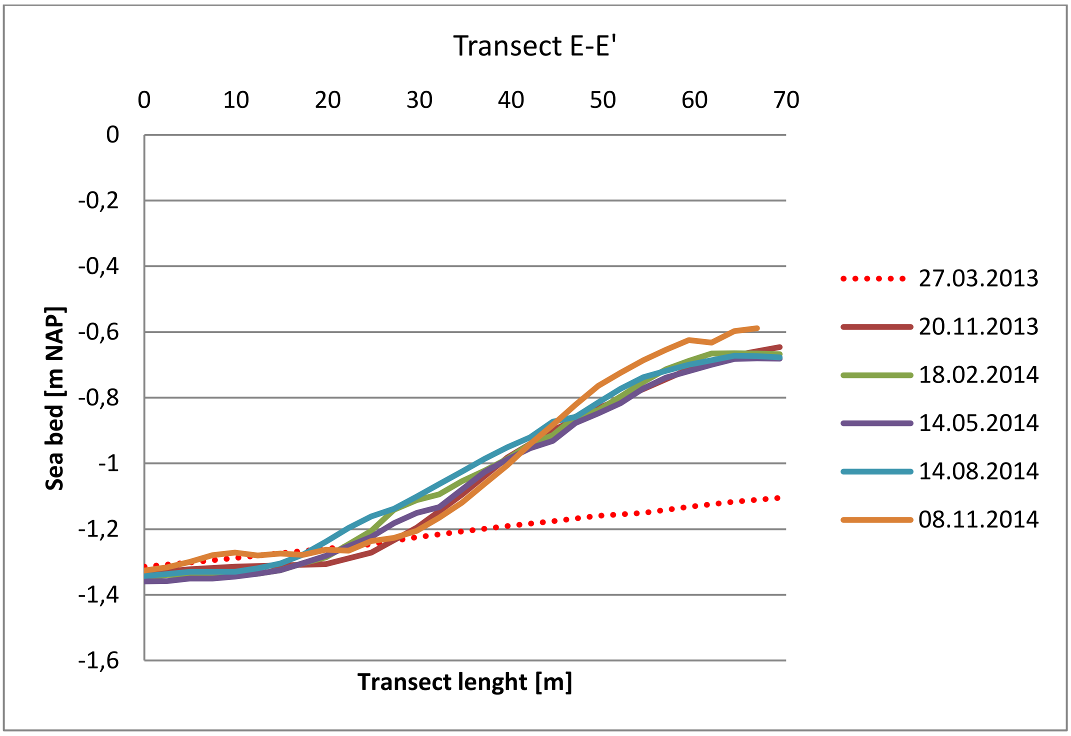


Figure 6.29 – Transect E-E' of reef D, in long term analysis

The situation of the bed level on the lower side of the reef is explained by the Figure 6.28 and Figure 6.29. The first one, B-B', is far away from the reef. It shows a stable condition of the bed level, after the T_1 period. All the elevation profile related to measurements are higher than the elevation profile at T_0. Regarding the elevation profile E-E' stable condition of the bed level is almost the same for all the measurement, always higher than the T_0. Appendix E will give a complete overview of the elevation profile of reef A for each single period.

6.3.3 Reef A: elevation profiles of short term analysis

Regarding the short term analysis, three transect have been analyzed in each reef, taking into account the elevation maps made by the author. The transects analyzed are called: transect C-C', the middle one; D-D' and E-E', respectively the one on the left side and the one on the right side.

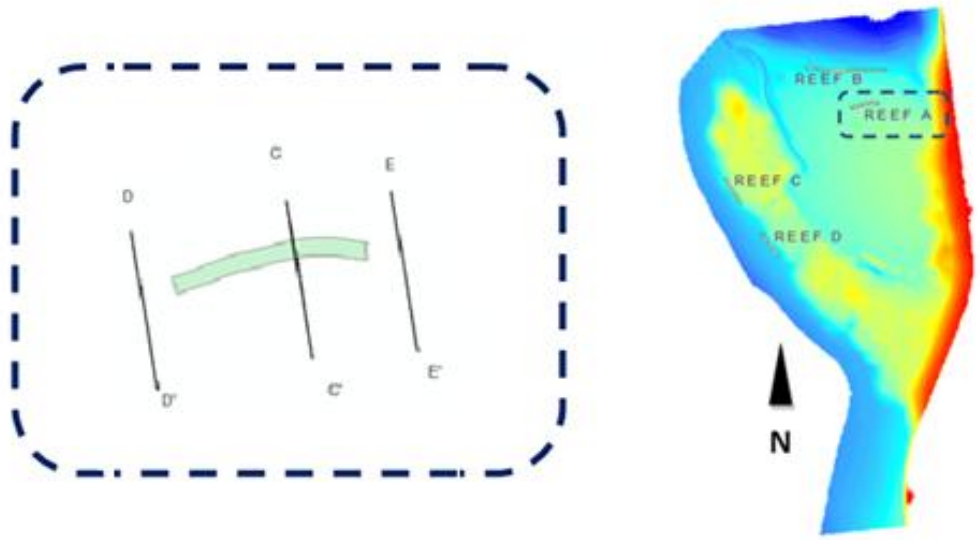


Figure 6.30 - Cross section of reef A, short term analysis

All the transects realized have the same length of almost 70 m each. The transects C-C' and D-D' are located at the same distance as before: that is15 meters from the limit of the reef. The elevations maps used for this calculation are the following one, showed in Table 6.23. The results of the calculation are located in this section. The x-axis shows the total length of the transect and the y-axis shows the elevation in meters NAP. The T_9line, as a reference line, is indicated in red.

Period	Date
T9	06.02.2015
T10	24.02.2015
T11	23.03.2015
T12	20.04.2015
T13	20.05.2015
T14	12.11.2015
T15	12.02.2016
T16	22.02.2016
T17	10.03.2016
T18	24.03.2016
T19	06.04.2016

Table 6.23 – Elevation maps used for the calculation: long term analysis of reef A

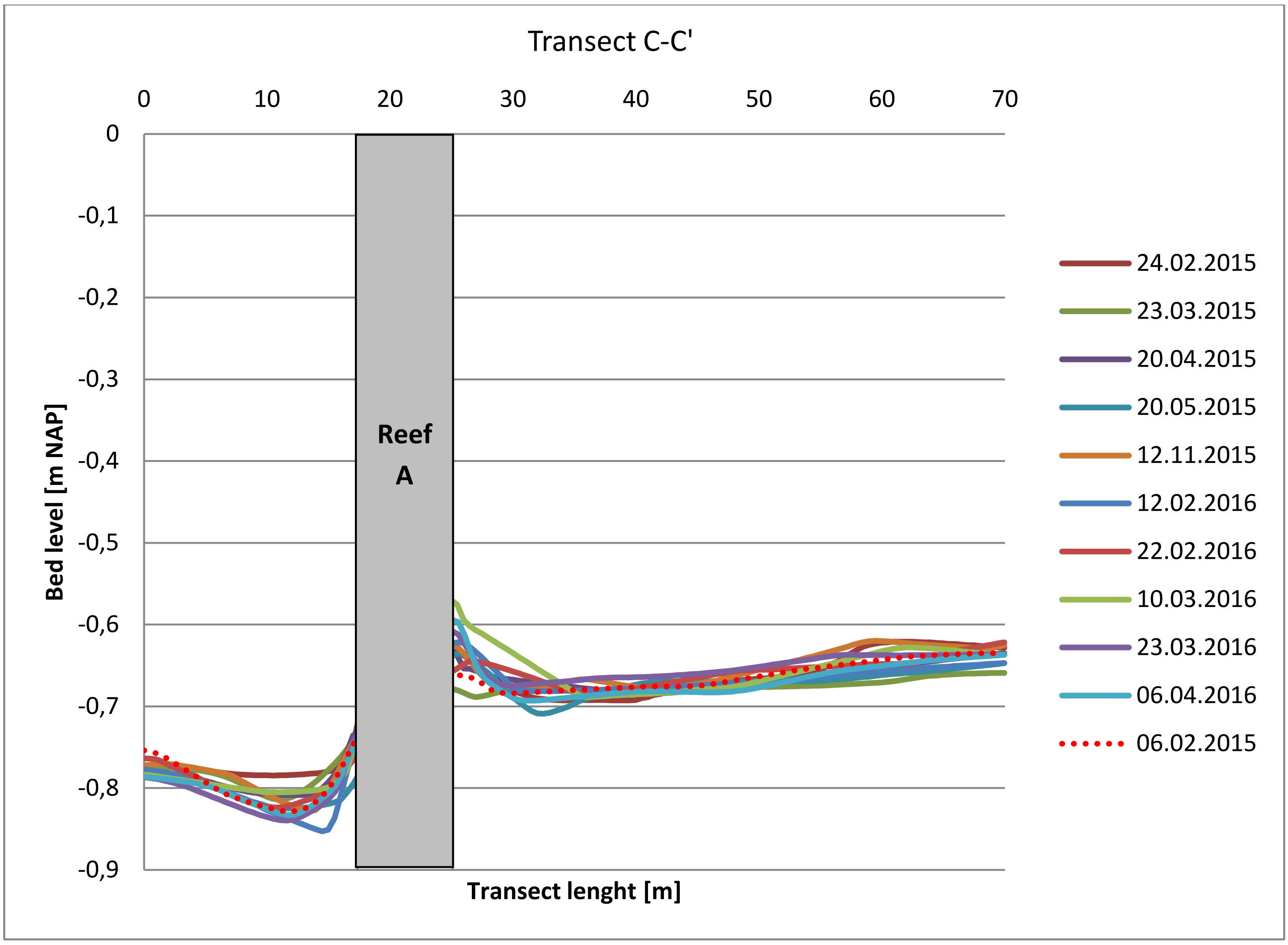


Figure 6.31 – Transect C-C' of reef A, in short term analysis

The analysis shows the bed level behind and in front of the reef A, in the short term analysis. Behind the reef, which means in the sea side, the level is the almost the same for all the measurements. In some measurements it's even higher. Instead in the front, which means the tidal flat side, the situation immediately close the reef is different: in the closest part of the reef there is sedimentation (in all the elevation sections) and further the level of the dial flat seems almost stable. The behaviors in the back side (tidal flat side) are different in each measurement. The maximum height reached corresponds to the 10th of March 2016. Instead, the lowest height correspond to the 23th of March 2015.

The situation of the bed level at D-D' and E-E' is explained by the Figure 6.32 and Figure 6.33. On both the sides the graphs show a stable condition of the bed level. Appendix G will give a complete overview of the elevation profile of reef A for each single period.

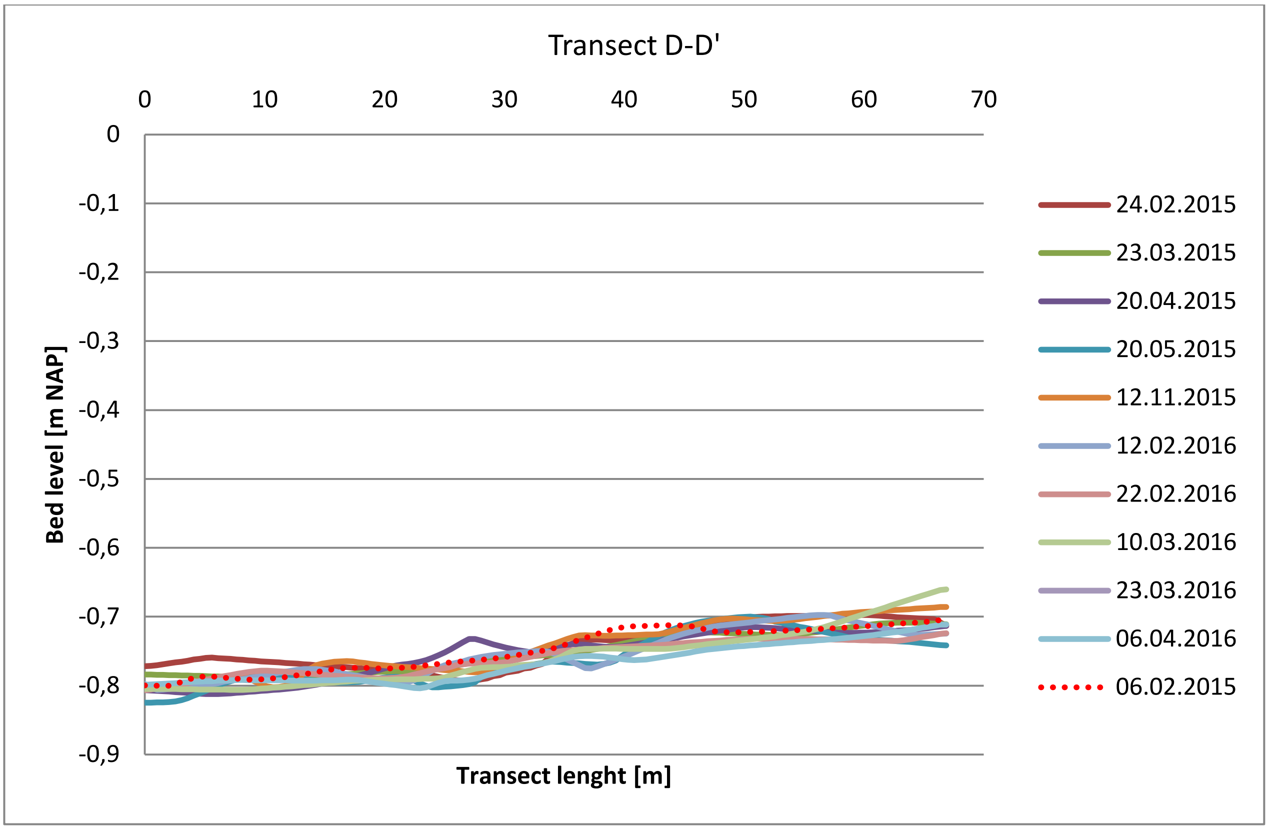


Figure 6.32 – Transect D-D' of reef A, in short term analysis

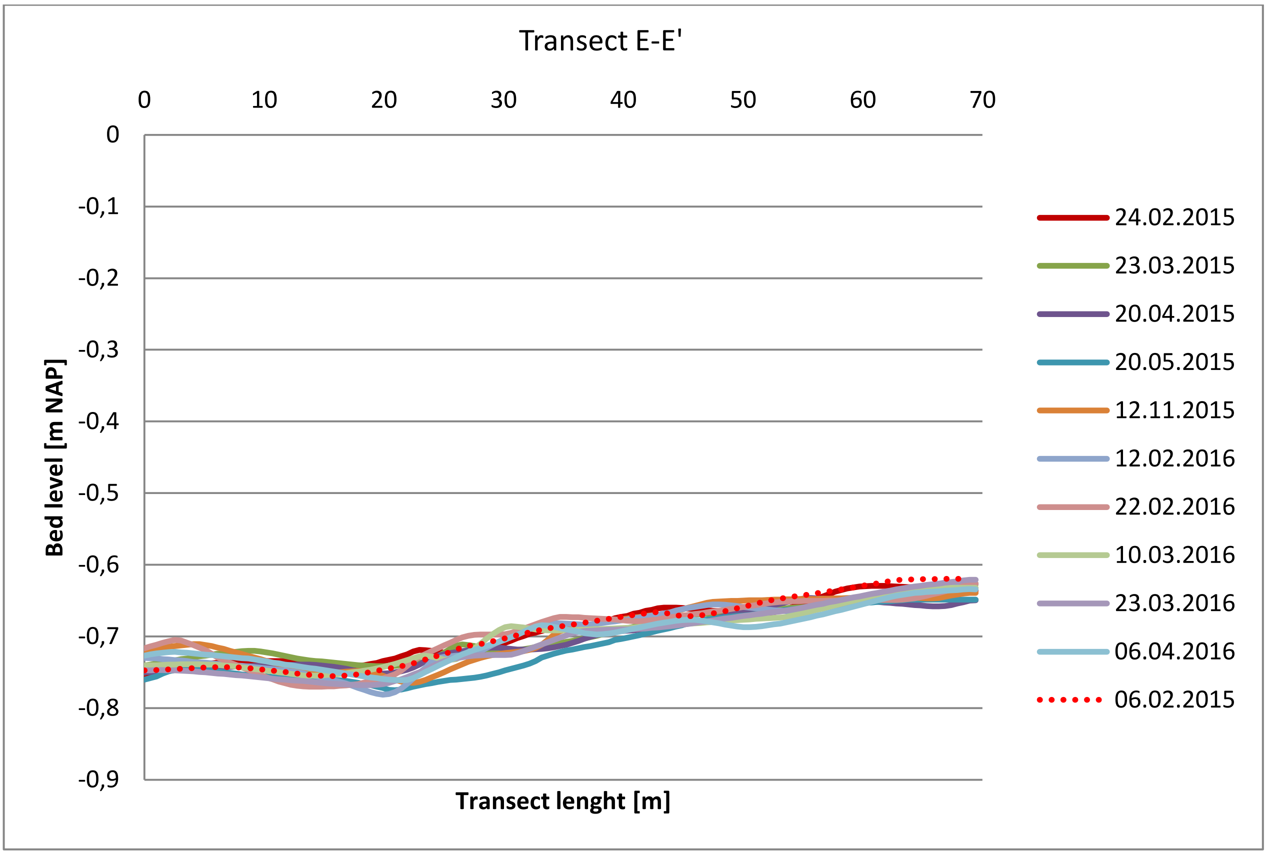


Figure 6.33 – Transect E-E' of reef A, in short term analysis

6.1.1 Reef D: elevation profiles of short term analysis

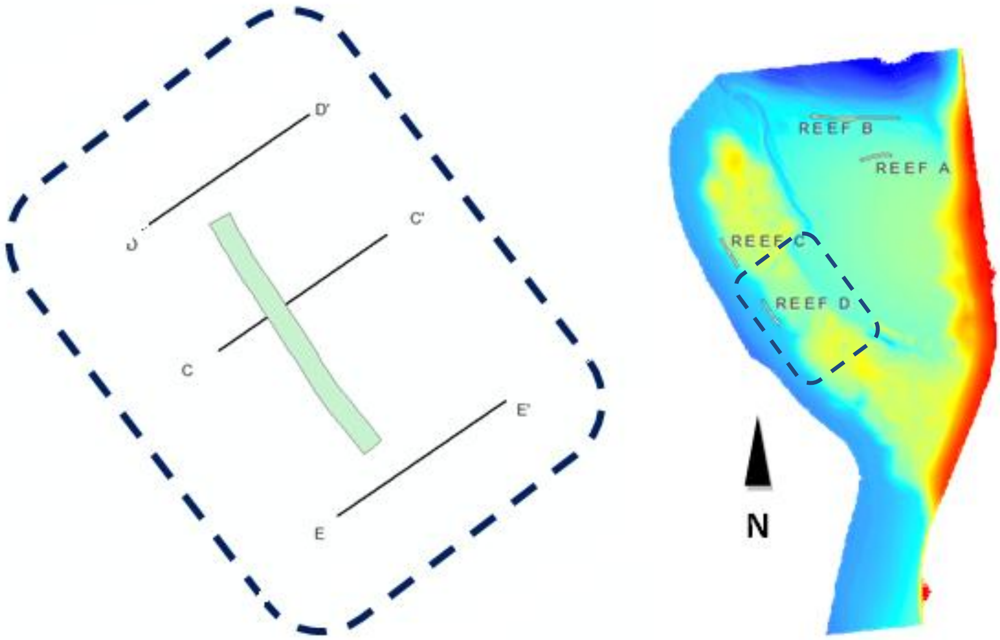


Figure 6.34 - Cross section of reef D, short term analysis

All the transects realized have the same length of almost 70 m each. The transects C-C' and D-D' are located at the same distance as before: that is10 meters from the limit of the reef. The elevations maps used for this calculation are the following one, showed in Table 6.24 . The results of the calculation are located in this section. The x-axis shows the total length of the transect and the y-axis shows the elevation in meters NAP. The T_9line, as a reference line, is indicated in red.

Period	Date
T6	11.11.2014
T7	09.12.2014
T8	15.12.2014
T9	06.02.2015
T10	24.02.2015
T11	23.03.2015
T12	20.04.2015
T13	20.05.2015
T14	12.11.2015
T15	12.02.2016
T16	22.02.2016
T17	10.03.2016
T18	24.03.2016
T19	06.04.2016

Table 6.24 – Elevation maps used for the calculation: long term analysis of reef D

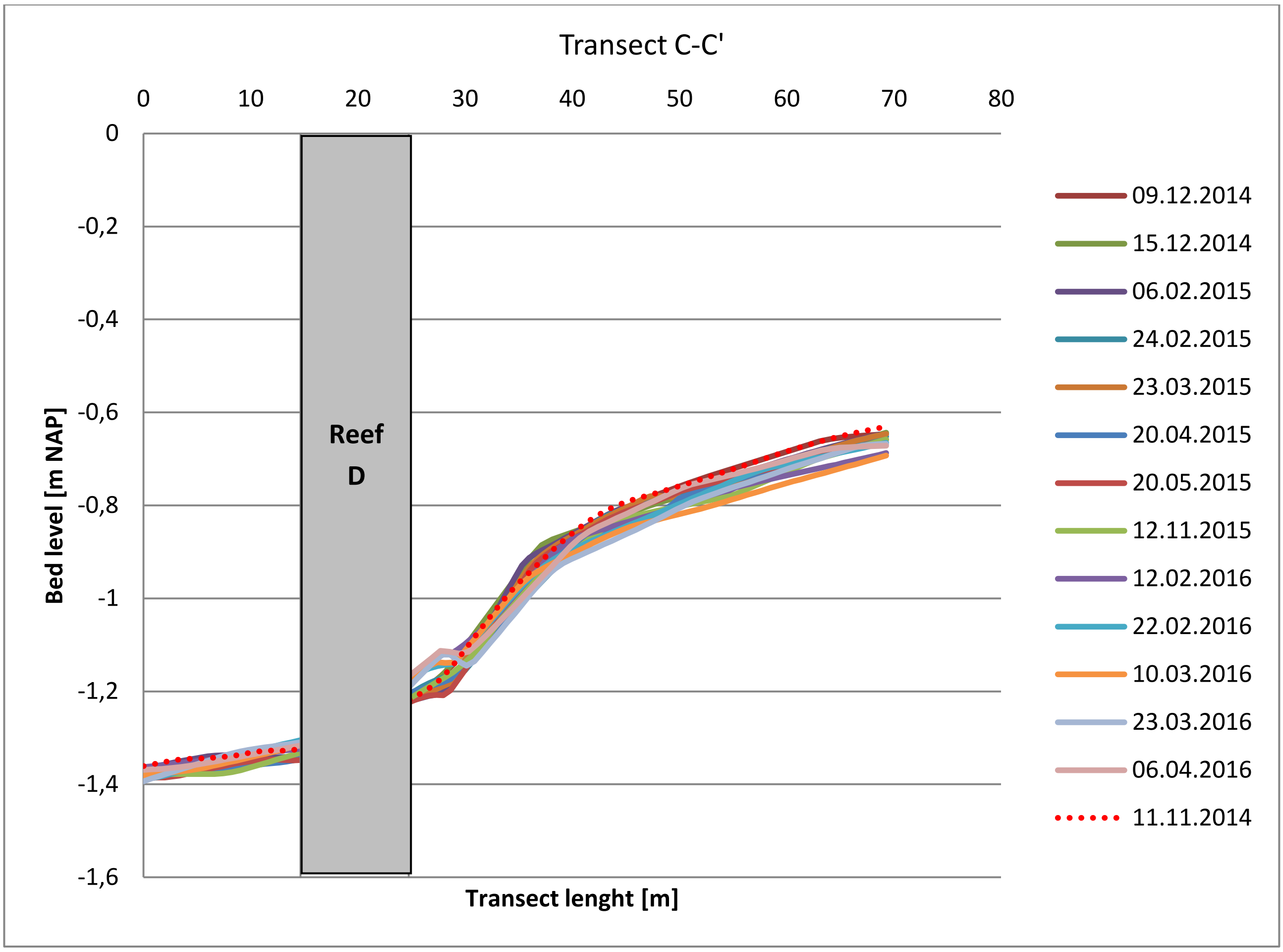


Figure 6.35 – Transect C-C' of reef D, in short term analysis

The analysis showed in Figure 6.35 shows the bed level behind and in front of the reef D, in the short term analysis. Behind the reef, but also in the front, the level is the almost the same for all the measurements. In some measurements, immediately close to the reef in the tidal flat side, the level is higher than in the rest of the measurements. This happens for all the measurements of the 2016.

The situation of the bed level at D-D' and E-E' is explained by the Figure 6.36 and Figure 6.37. On both the sides the graphs show a stable condition of the bed level. Appendix G will give a complete overview of the elevation profile of reef D for each single period. Regarding the transect E-E' it's important to notice that, between the 10th and the 35^{ft} meter, it's showed a good improvement of sedimentation.

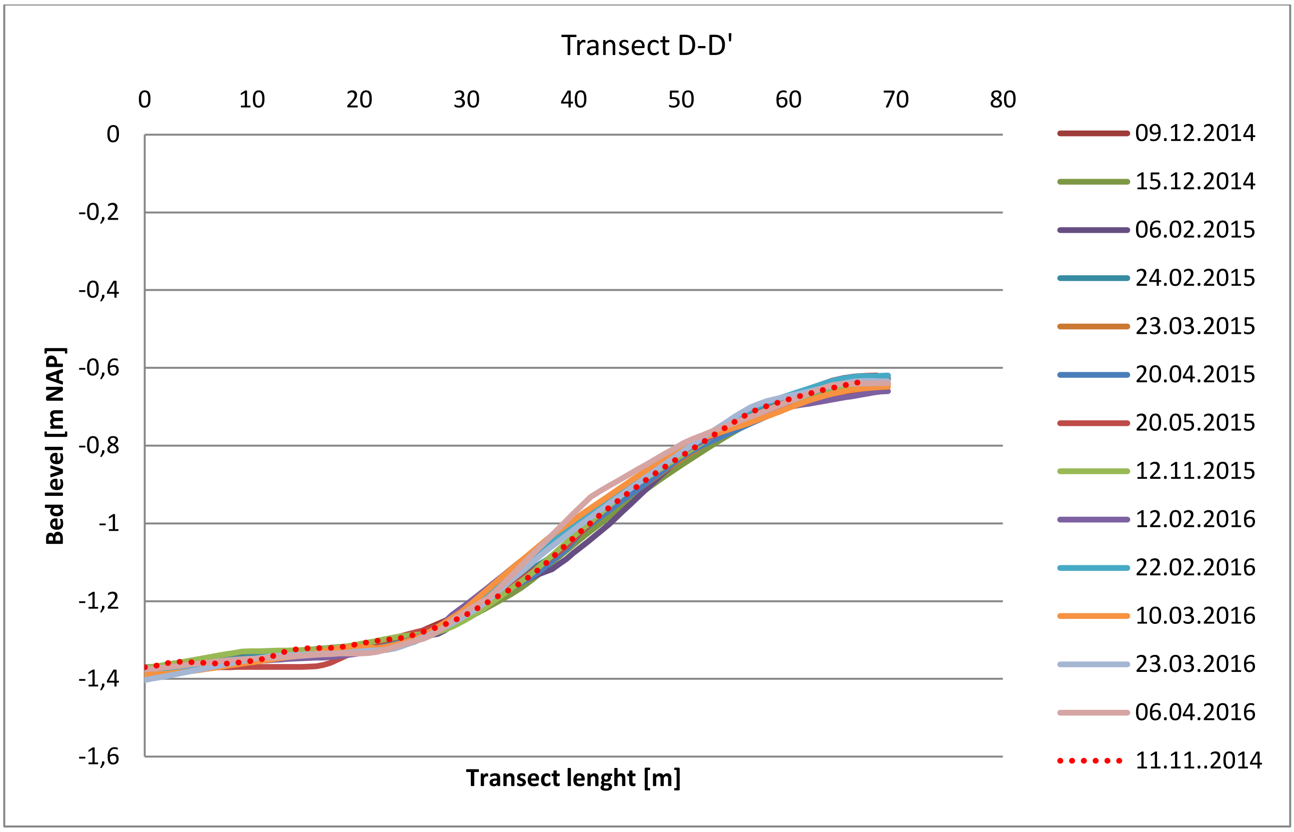


Figure 6.36 – Transect D-D’ of reef D, in short term analysis

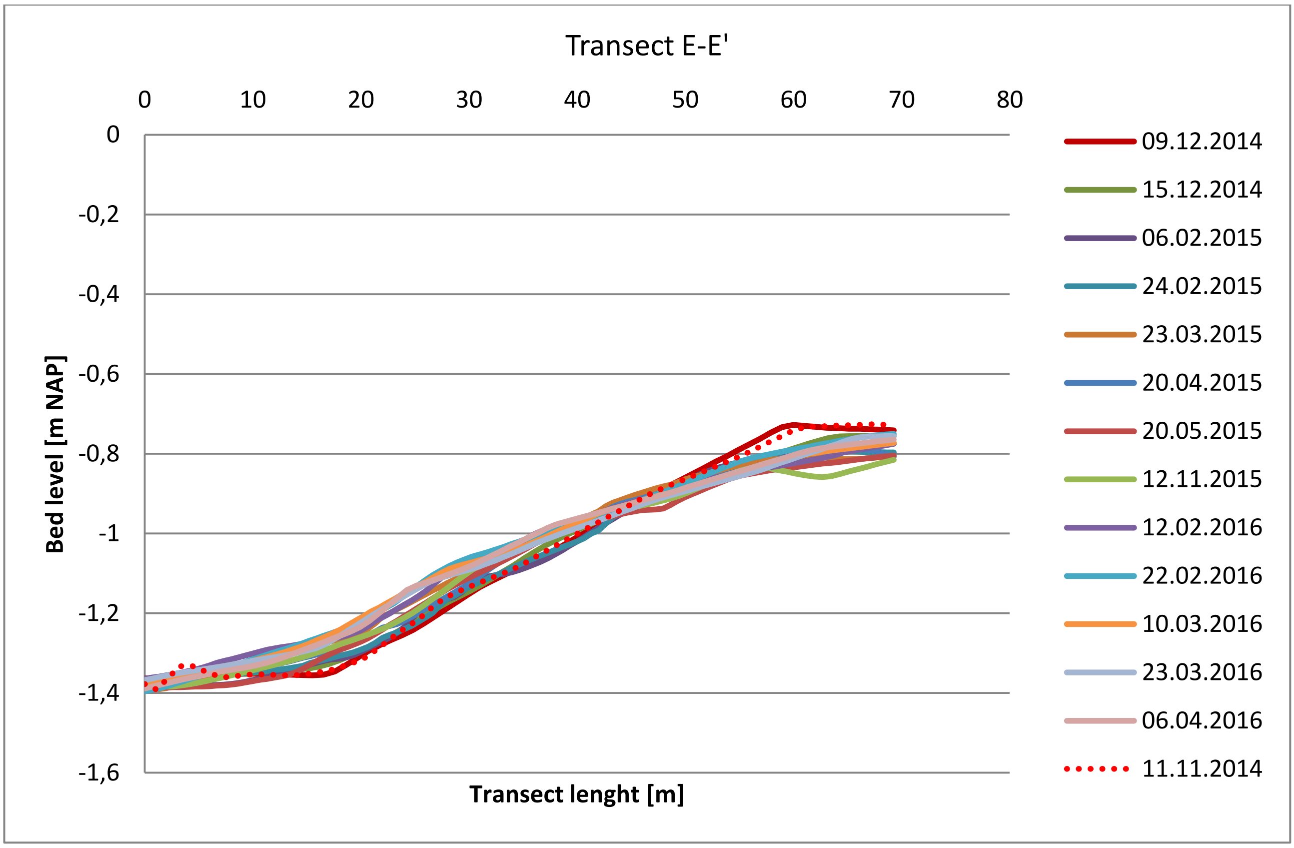


Figure 6.37 – Transect E-E’ of reef D, in short term analysis

6.4 Grain size monitoring

Thanks to the samples collected during the monitoring activities, it has been possible to realize interesting analysis in order to answer to the question of erosion in Oesterdam .

As said before, samples of material have been collected during some monitoring activities; the date of the collection are reported in the table below (Table 6.25).

Date of the sampling
23.03.2015
20.05.2015
12.02.2016
22.02.2016
10.03.2016
23.03.2016
06.04.2016

Table 6.25 – Date of the samples collection

All the samples have been analyzed with the Malvern Laser. In the type of analysis which have been realized by the Nios was not expected to obtain the particle-size distribution of the sediments. Therefore is not possible to have a complete overview of the sample analysis. Consequently all the analysis that have been processed in this thesis regard the information which have been possible to obtain, and they are the following ones:

- Percentage of the material present (sand, clay, silt);
- Grain size (D_{10}, D_{50}, D_{90})

6.4.1 Triangular diagram of the material

The results obtained from the Malvern analysis permit to classify the material of the samples collected. Therefore In this section a classification will be realized with the help of the triangular diagram which is the one proposed by Folk (1954).

The triangular diagram used in this thesis is represented as explained and showed in Figure 6.38. The ternary plot t is a barycentric plot on three variables which sum to a constant, this constant is represented as 1.0 or 100%. The variables used in this case are the percentage of the material, divided in: sand, silt and clay. The plot graphically depicts the ratios of the three variables as positions in an equilateral triangle. On each side of the triangle the scale of measurement is reported. Each point present on a ternary plot represents a different composition of the three components.

There are different methods used to determine the ratios of the three species in the composition. In this case it has been decide to report the variables (sand, silt, clay) and their measuring scale following the clockwise. The measuring scale used goes from zero to 100%, from the bottom to the top of the triangle. The scale in divided in steps of ten, so it's easier to read the percentage. The same happens for silt and clay.

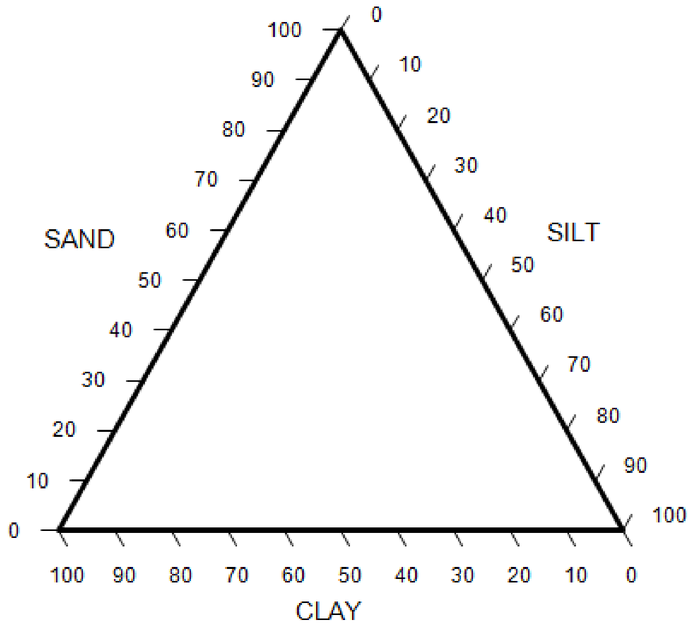


Figure 6.38 – How to read the triangular diagram

In this section the analysis of the samples (with the tri-plot diagram) have been done for all the samples; in a second moment only regarding the samples taken from reef A, and the same with the ones of reef D.

Figure 6.39 represents the complete analysis of all the samples taken in the Oesterdam location by the author.

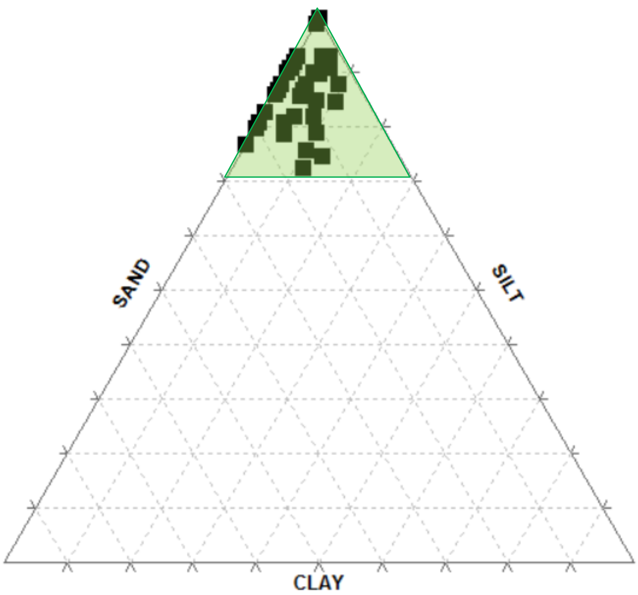


Figure 6.39 – Analysis of the whole material

From this previous analysis, is possible to notice that, in general, the material consists always in more than 70% of sand. It has at max 25% of silt and 30% of clay, in general. The green area in fact correspond to a material reach of sand, with low quantities of silt and/or clay.

After this previous observation, it has been decided to analyze separately the results obtained by reef A and D.

Figure 6.40 shows the results obtained from the analysis of all the samples taken in the reef A. Respect the global analysis, the material is more sandy, with less silt and clay, respect the global analysis. In fact the result shows that there is a lest more than 85% of sand. The percentage of silt is at max around 5%; and the amount of clay is reduced to 15%.

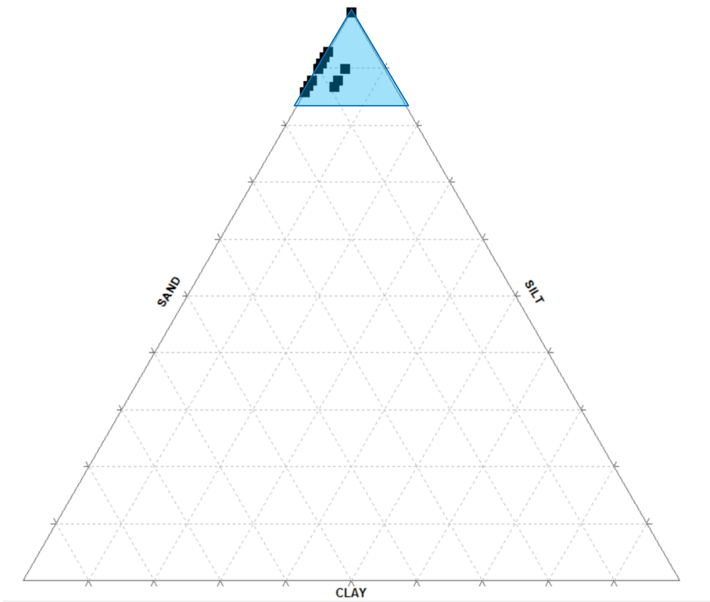


Figure 6.40 – Analysis of the material of reef A

Instead, Figure 6.41 shows the results obtained from the analysis of all the samples taken in the reef D. The analysis of these samples respect the results obtained from global analysis: the material consists in more than 70% of sand. It has at max 25% of silt and 30% of clay.

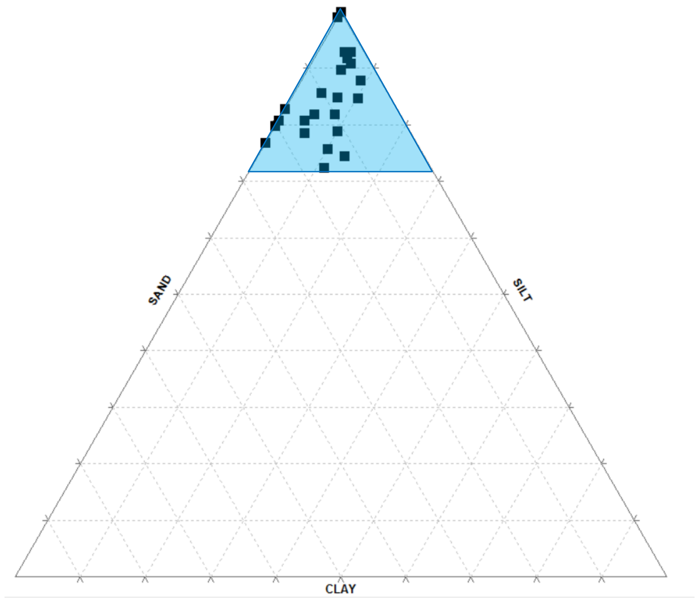


Figure 6.41 – Analysis of the material of reef D

Therefore is possible to conclude that, taking into account the totality of the samples collected in each reef, the material present around the reef A is more sandy, less silty and less clayey than the material of reef D.

In order do a complete study, the triangular diagram has been implemented for each sample, for each reef. The analysis of each single sample is reported in Appendix H.

6.4.2 D_{50} analysis: Reef A

The other type of study that have been done with the results of the Malvern regards the diameter of the grains. It regards in particular the D_{50}, that is the Mass-median - diameter (MMD) of the particle-size distribution (PSD) of the samples.

Period	D_{50} [µm]				
	A1	A2	A3	A4	A5
27.03.2015	177.18	193.88	184.63	177.75	186.19
11.05.2015	189.46	189.96	190.35	189.58	186.00
12.02.2016	189.38	183.66	189.57	185.88	187.91
22.02.2016	185.19	195.14	183.88	188.99	185.97
10.03.2016	183.32	194.88	188.27	187.11	186.64
23.03.2016	182.14	189.76	184.04	184.54	185.02
06.04.2016	181.11	194.87	183.49	185.03	186.96

Table 6.26 –Values of the D_{50} for reef A in all the measurements

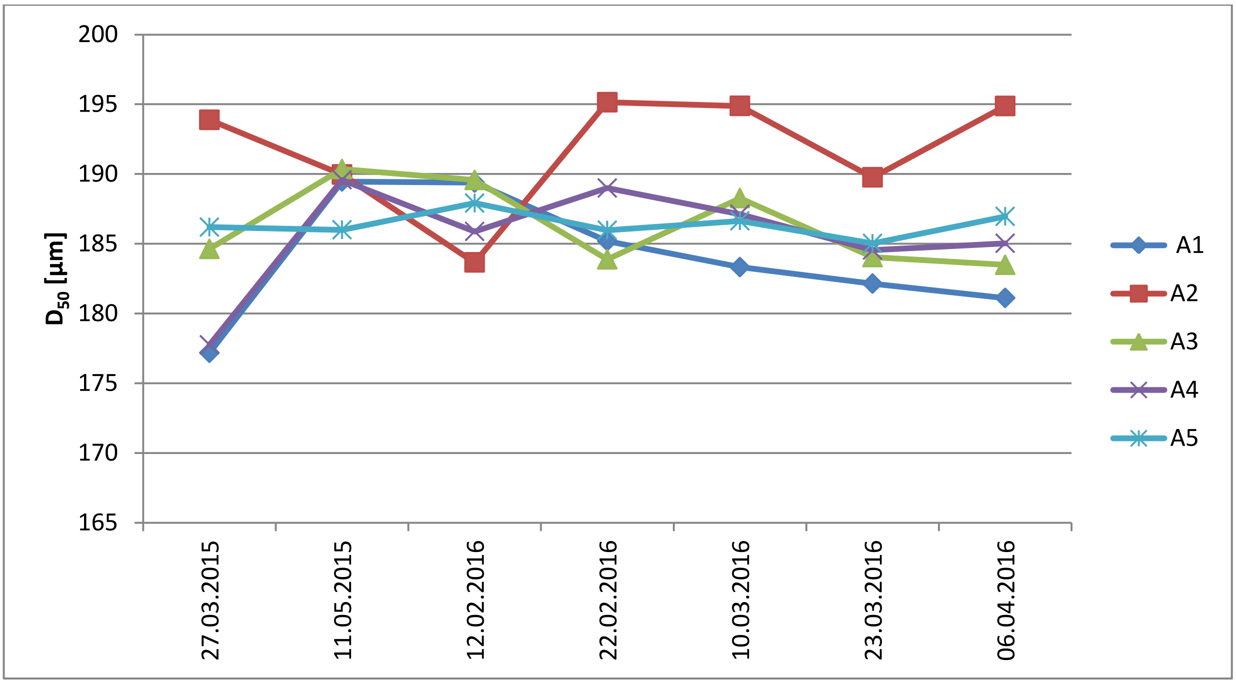


Figure 6.42 – D_{50} analysis in the timeline, for reef A

Figure 6.42 describes the trend of the D_{50} estimated in each point. As said before, reef A is located in the middle of the tidal flat where the median grain size was estimated equal to 180 µm. In the location of A1, which is immediately in front of the reef A (in the sea side), there is peak in the second measurement (11th of May 2015). The value of the D_{50} in this point is almost 190 µm; after this point it decrease until almost 180 µm, on the 6th of April 2016. Immediately behind the reef, that is in A2, there is a big decrease of the size followed by an increase which report the value to the same of the first measurement. After that it has a small decrease but after all it's stable. A3, shows an immediate increase but it maintains stable between 185-190 µm until the end of the measurements. A4 has almost the same behavior of A1; A5 is stable for all the periods.

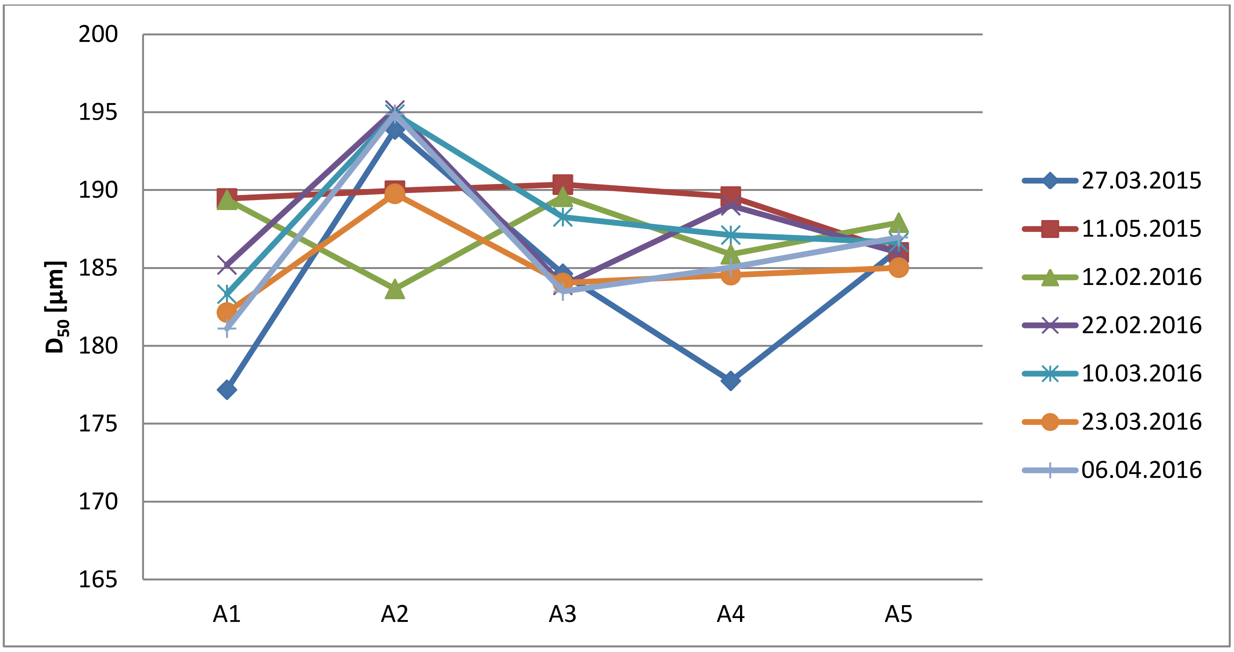


Figure 6.43 – D50 analysis in each transect (in the time), of reef A

Figure 6.43 demonstrates that the average of the grain size in the intertidal are is 180 µm. It shows also a peak in A2, which is the point immediately behind the reef. In the rest of the transect, in the timeline, the situation is almost stable. Only in the 27th of March 2015 in A4 there is a big decrease in D_{50}.

6.4.3 D_{50} analysis: Reef D

Period	D_{50} [µm]				
	D1	D2	D3	D4	D5
27.03.2015	168.38	200.97	267.71	313.62	322.08
11.05.2015	167.76	249.31	288.55	306.25	295.52
12.02.2016	172.46	244.28	287.78	292.36	293.89
22.02.2016	167.97	265.05	281.73	298.29	308.09
10.03.2016	166.18	234.93	299.31	298.41	310.16
23.03.2016	160.85	209.87	291.9	312.29	298.93
06.04.2016	166.61	192.02	302.22	269.18	295.7

Table 6.27 – Values of the D_{50} for reef D in all the measurements

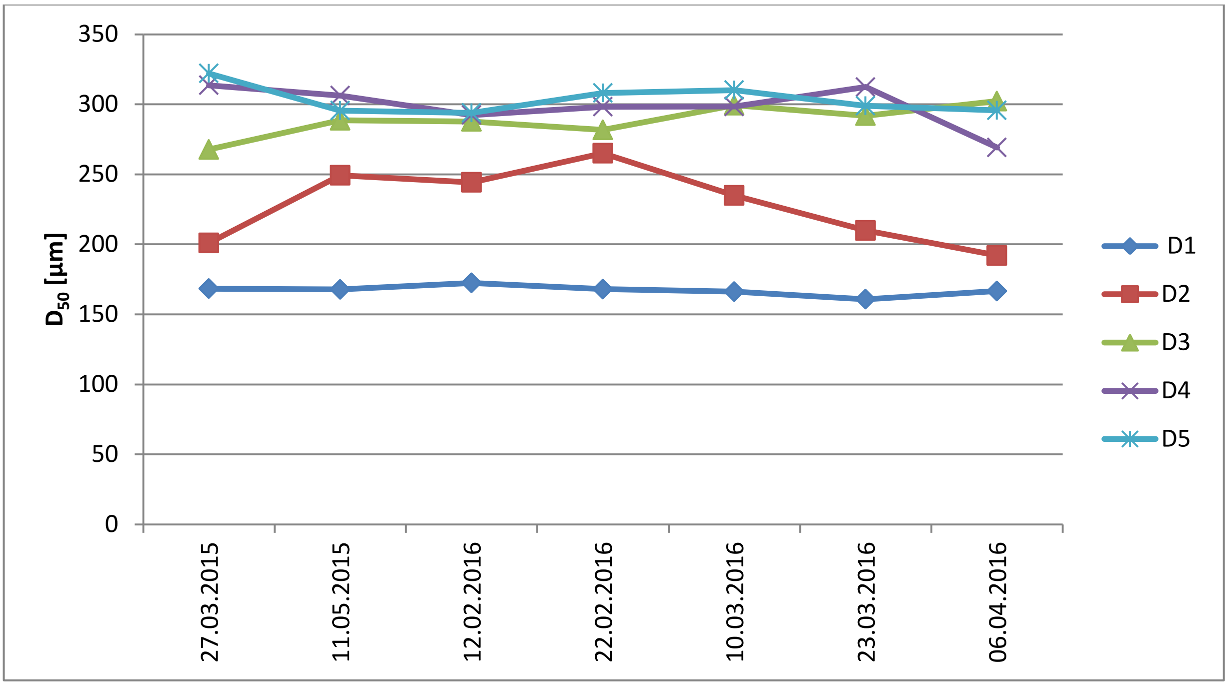


Figure 6.44 – D50 analysis in the timeline, for reef D

Figure 6.44 describes the trend of the D_{50} estimated in each point. As said before, reef D is located in the west part of the area, close to the sand nourishment, where the median grain size was estimated between 276 and 290 µm. Regarding the sample D1, the D_{50} is lower than the average grain size of the nourishment. It is stable around the value of 170 µm, which is more similar to the grain size of the existing intertidal area. D2, immediately behind the reef, in the intertidal part, has an increase until the 22[nd] of February 2016 where the value is 265 µm. Regarding D3, D4, D5 there is almost no variation: the situation is stable in the time.

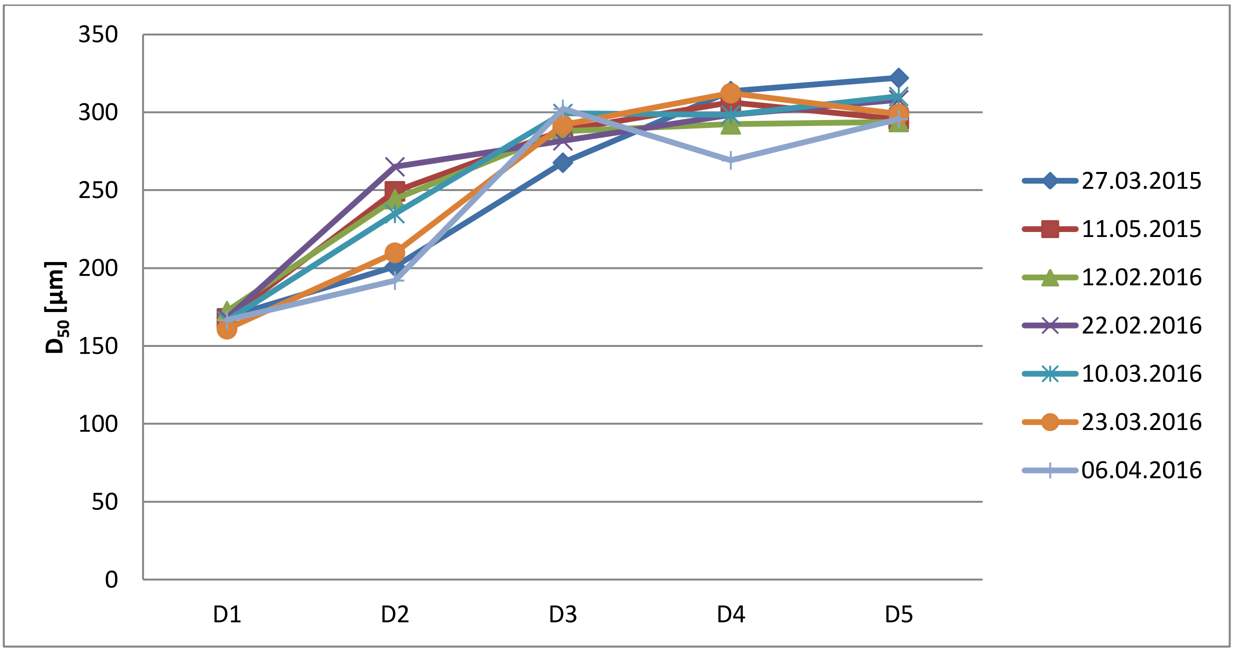


Figure 6.45 – D_{50} analysis in each transect (in the time), of reef D

Figure 6.45 shows the increase of the grain size starting from the sample located before the reef arriving to the one located far away from it. In D1 the value is almost always the same. In D2 there is an important variation. As said in the previous graph, the peak of the dimension of the grain size is showed in the 22nd of February 2016. Instead, the lowest point is in the 6th of April 2016. As noticed already, D3,D4, D5 are always almost stable. Only D4 shows a difference with the lowest point at the 6th of April 2016.

7. Discussion

Previous chapter identified the main results regarding the erosion-sedimentation changes of the Oesterdam nourishment in the specific influence areas of the four reefs.

The findings of present work are discussed and reflected in this chapter. Because reef A and D can be considered representative of the totality of the reefs, the discussion will be addressed regarding their analysis.

7.1 Volume variation

7.1.1 Reef A: long term analysis

The long term analysis goes from the 27th of March 2013, date before the sand nourishment, and the 8th of November 2014 for a total period of 21 months. During this period the volume of the sand located in the influence area of the reef undergoes changes. The analysis of the volume variation shows an immediate peak at the T_1 (20th of November 2014), probably due to the construction of the sand nourishment. after this period, there is a subsequent decrease of the volume of sand. The assumption made is the one that sees a natural readjustment of the nourishment in the location. Moreover, thanks to the wind analysis it has been possible to notice that at that time, between the 27th of march 2013 and the 20th of November 2103, the maximum wind speed was 21.6 m/s, which is one of the highest wind speed detected. Therefore there these are the two main reason of this first erosion. Moreover it is possible to notice that in T_5, date of the last long term measurement, the volume of sand returns at the same value of T_1. This can probably be considered a cyclicity which often manifests for erosion and sedimentation. Especially at the end of the summer season it is usual to have sedimentation, as at the end of the winter it is usual to have erosion. Looking at the erosion-sedimentation maps realized in ArcGIS, it is possible to notice that the amount of sand settled in T_1 and T_5 is placed in a different shape. This can be due to the direction of the wind. In fact the wind direction which has most manifested throughout the period of the long term analysis is from West. Moreover, since, in this thesis, it was demonstrated that, in Oesterdam location, the waves are only generated by the wind, the waves coming from the west have probably caused the erosion of the volume of sand, modifying its form.

In addition to this, the daily volume of sand variation has been estimated, coming to the conclusion that around the reef occurred an average of erosion equal to 0.12 cubic meters per day. Then, considering that the area around the reef A is equal to 10,000 square meters, it has been possible to estimate an average of $1.2x10^{-5}$ m in total elevation profile. The result seems a really small value of erosion but, in order to have a global idea of the situation in this area, the discussion of the short term analysis is also necessary.

7.1.2 Reef A: short term analysis

Because the measurements done the author are very close to each other and, because it has been possible to analyze not only the hydrological conditions but also the sedimentological ones, it has been decided to discuss the results period by period. The graph of the volume variation, which as the T_9 as the reference measurement, shows an immediate increase of almost 44 m^3 on the 24th of February 2014. This raise is followed by a reduction which starts in T_{11} and goes on until T_{13}. In fact T_{13} reaches the minimum value of sand volume. It is equal to -128.81 m^3. Looking the hydrodynamic point of view in period T_{12} really high waves appear: the waves reach the value of 100 cm. In fact the wind speed in T_{12} is around 21.2 m/s and in

T_{13} stays close to the same value, even if the waves reduce. Regarding T_{11} and T_{13} there are also the information obtained by the samples. Between these periods (T_{11} and T_{13}), it is possible to notice a difference of 10 µm in two specific points: A1 and A4. In particular, during the period T_{13} the D_{50} of the grains increases. This means that, probably, the small sediments which were on the top have been removed letting appear the underlying layer of coarse sand. This hypothesis can be confirmed also by the elevation maps of the area. In T_{14} , id est on November 2015, there is sedimentation: the volume raises until +30 m^3. The same season increase have been noticed in the long term analysis, even if whit different values. At T_{15} , that is February 2016 erosion happens again. The wind speed in this period is the maximum ever revealed since the monitoring started. The wind direction is South-West. T_{16}, T_{17},T_{18} characterize an increase of sand which permit to return in balance with the reference point. In T_{18} the value of the volume is almost the same as in T_9. The last measurement, April 2016, that is T_{19} shows again a decrease of sand volume. Also here the wind speed is almost equal to 20 m/s, coming from the South. Looking at the sedimentological results of the same periods, the values of the D_{50} of the samples stay stable. Only the D_{50} at A2, immediately behind the reef, in April 2016, decreases: this can be explained as a confirm of sand erosion, as mentioned before.

Also in this case, the daily volume of sand variation has been estimated, coming to the conclusion that around the reef occurred an average of erosion equal to 0.03 cubic meters per day. Then, considering that the area around the reef A is equal to 10,000 square meters, it has been possible to estimate an average of $3x10^{-6}$ m in total elevation profile. The result is even smaller of the result obtained from the long term analysis.

7.1.3 Reef D: long term analysis

The data analysis of reef D shows a big increase of sand volume, evidently do to the construction of the sand nourishment where the amount of sand reaches 1772 m^3. After that period, until T_5, the volume variation continues to increase, reaching a peak of 2326.50 m^3. Looking at the hydrodynamic pint of view, as already explained for reef A, the wind of these periods were characterized by high wind speed. The minimum registered is 17.3 m/s (related at the T_3 period)and the maximum one is 21.6 m/s, which manifested immediately in T_1, but without evident results of erosion.

In addition to this calculation, the daily volume of sand variation has been estimated, coming to the conclusion that around the reef occurred an average of sedimentation equal to 4.47 cubic meters per day. Then, considering that the area around the reef D is equal to 10,000 square meters, it has been possible to estimate an average of $4.47x10^{-4}$ m in total elevation profile. The result seems really interesting even if it is clearly influenced by the construction of the sand nourishment but, in order to have a global idea of the situation in this area, the discussion of the short term analysis is also necessary.

7.1.4 Reef D: short term analysis

The short term analysis of this reef shows an incredible constant trend respect the long term analysis. But, looking at volume variation graph in details, it's possible to notice that, after the reference T_6, there is only erosion. At the beginning, which means in T_6, is small; but arriving at T_9, there is one of the lowest values registered. In T_9 the erosion is equal to -128 m^3. Looking at the hydrological aspect, the maximum wind speed registered in that period was equal to 19.9 m/s, coming from South-West. The waves are not the highest ever registered, but the values are around 70-80 cm. After this moment, sedimentation restart until on the 20th of April 2015 (T_{12}) when erosion manifests again which reaches the lowest peak in May. The value of the sand volume is almost equal to 160 m^3. The wind in this moment has a maximum speed of 21.2 m/s, always coming from South-West. As already mentioned, it is precisely at this time that the maximum significant wave height manifest. From a sedimentological point of view, it is possible to notice that the D_{50} at D2, immediately close to the reef on the tidal flat side, has an increase of almost 50 µm. The explanation is the same as before: the coarse sand appear after the erosion of the smaller particles. After T_{12} the situation improves until on the 22nd of February 2016, T_{16}, the value of the sand volume reach the positive value of 40 m^3. At T_{17} erosion happens again and goes on until the end of the monitoring activity reaching a lat value of -29.43 m^3. This sedimentation can also be explained by the value of the D_{50} at D2 which undergoes a big degrease respect the previous ones.

7.2 Elevation profile

7.2.1 Reef A: long term analysis

Looking at the elevation profiles, they also confirm what already explained but they can also give other information. For example what is important is that the elevation profile C-C', which is the one crossing the reef, is always higher than the other two (A-A' and B-B'). Moreover, always in C-C', the level of the sand in the back of the structure is always higher than in the front. This means that, even if the volume of sand is decreasing in the area of influence of the reef, the reef is performing its function in a good way. It is keeping the sand in its back. The level of the sand in the back of the structure always higher than in the front can be considered as a clear demonstration of sedimentation.

Moreover, taking in consideration the changes of the other two elevation profiles, it is possible to say that, regarding the long term analysis, the values of B-B' are always higher then the ones of A-A'. The hypothesis of this difference is probably do to the sand nourishment located close to the dike with influence the transect B-B'.

7.2.2 Reef A: short term analysis

As already said for the long term analysis, regarding transect C-C', the elevation profile in the back of the structure is always higher than in the front. In this way, the sedimentation behind the reef is going on also for the short term analysis.

Another important aspect regards transects D-D' and E-E'. In fact, looking at the graphs, it is important to notice how, again, transect E-E' stays higher than D-D'. Even if the A-A' and B-B' were outside of the influence area of the reef and D-D' and E-E' are inside of it, they follows respectively their same behavior. Elevation profile E-E' is always higher than D-D'.

7.2.3 Reef D: long term analysis

Looking at the elevation profiles, the situation is the same as explained for reef A. In fact they confirm that the elevation profile C-C' is higher than the other two (A-A' and B-B'). Moreover , in the same elevation profile, the level of the sand in the back of the structure is always higher than in the front. Also for reef D there is a clear demonstration that the reef is working and creating sedimentation.

Moreover, taking in consideration the changes of the other two elevation profiles, it is possible to say that, regarding the long term analysis, the values of A-A’ are always higher than the ones of B-B’. The hypothesis of this difference is probably do to the presence of reef C. It is possible that the close position of the two breakwaters influences the sedimentation also between them. This is also a nice result which confirm that the plan to realize detached structures also works for this experiments.

7.2.4 Reef D: short term analysis

As already said for the long term analysis, regarding transect C-C’, the elevation profile in the back of the structure is always higher than in the front. In this way, the sedimentation behind the reef is going on also for the short term analysis. Regarding the elevation profiles D-D’ and E-E’, they seem stable in the time.

8. Conclusions and Recommendations

Conclusion

Nowadays the interest in coastal engineering problems by means of ecological engineering is continuously growing. Instead of building artificial structures to stop the coastal erosion, a natural solution like oyster reefs can give a result that can be used effectively for shoreline stabilization.

The Oesterdam case, as pilot project , is only one of the many experiments which is actually going on in the Eastern Scheldt which includes the use of eco dynamic structures. The Oesterdam safety buffer, with its sand nourishment protected by *Crassostrea gigas* oyster reefs, has as the main purposes to protect the area. The aim of this project is to verify if Oesterdam has the right conditions to considers these coastal protection structures effectively efficient.

The results of this thesis demonstrate that the oysters are ecosystem engineers, which interacts with their environment. In fact, from the long and short term trend analysis of data related to the monitoring activities, it is possible to conclude that the presence of oyster reefs has caused sedimentation or at least a decrease in the erosion rates on the reef area and also on its surroundings. Another positive consideration regards also the habitat of the tidal flat of the location. The erosion could cause a loss of valuable intertidal habitat, especially for many estuarine bird species that use these areas as foraging grounds; but thanks to the sedimentation (or better decrease in the erosion rates) the ecosystem can continue to survive and to stay protected, as the Nature 2000 purposes. Moreover the dike will become less exposed to wave action and therefore less exposed to ruptures and flooding during storm surges. Concluding, this result will surely be a positive conclusion for the erosion problem of the Eastern Schelde, even if limited to a small area. Nevertheless, maybe numerous small-scale interventions could improve the overall status of the Eastern Schelde systems.

The present study demonstrates that oyster reef can be definitely used for the coastal protection: the effect of oyster reefs on sand stabilization contributes to give a more than temporary solution at the erosion of the tidal flats in the Oesterdam location. Moreover, oyster reefs are sustainable infrastructure solutions which, with global warming and rising sea levels, will increase maintaining their priority of coastal protection. Of course, to ensure that this happens, oysters need to be alive and grow. Consequently the only thing to do is to monitor their growth with the help of expert biologists.

Recommendations

An important that is significant to mention is that the research has been focused mainly on the monitoring activities regarding the Oesterdam tidal flat. Therefore lot of aspects, such as biodisturbation and biostabilisation, even if really interesting, have not been analyzed. It should be interesting go on with the monitoring activities, including also this aspect. Probably it should be interesting how this factors can really influence the sediment action in Oestedam case.

Moreover, thanks to the important results obtained from this thesis, it could be possible to consider to extending this eco-dynamic project to all the other country that need as well coastal protection. Figure 8.1 demonstrate the occurrence of pacific oysters (*Cassostrea gigas)* population in European and adjacent coastal water (Nehring 2011). This means that this pilot project can be extended to several European coasts. Italy is one of the highlighted country, therefore it could be an interesting suggestion for future coastal engineering projects.

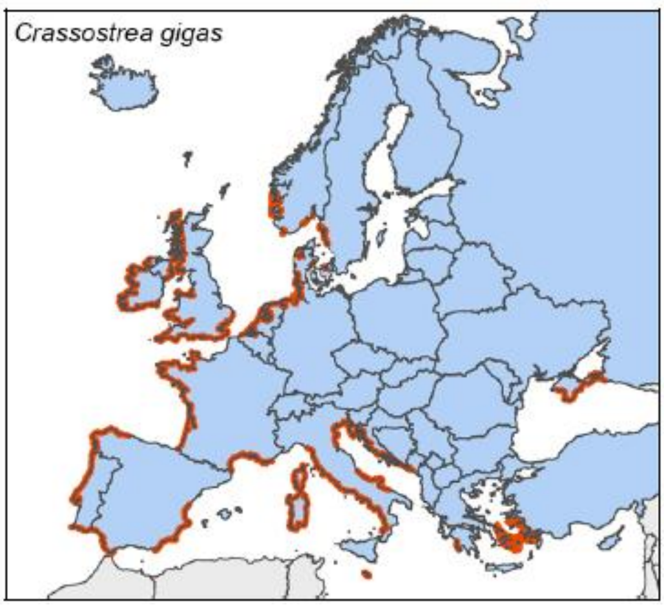


Figure 8.1 – *Crassostrea gigas* population in the European coasts (Nehring 2011).

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Appendices

Appendix A: Implementation analysis of Marollegat meteorological and marine dataset

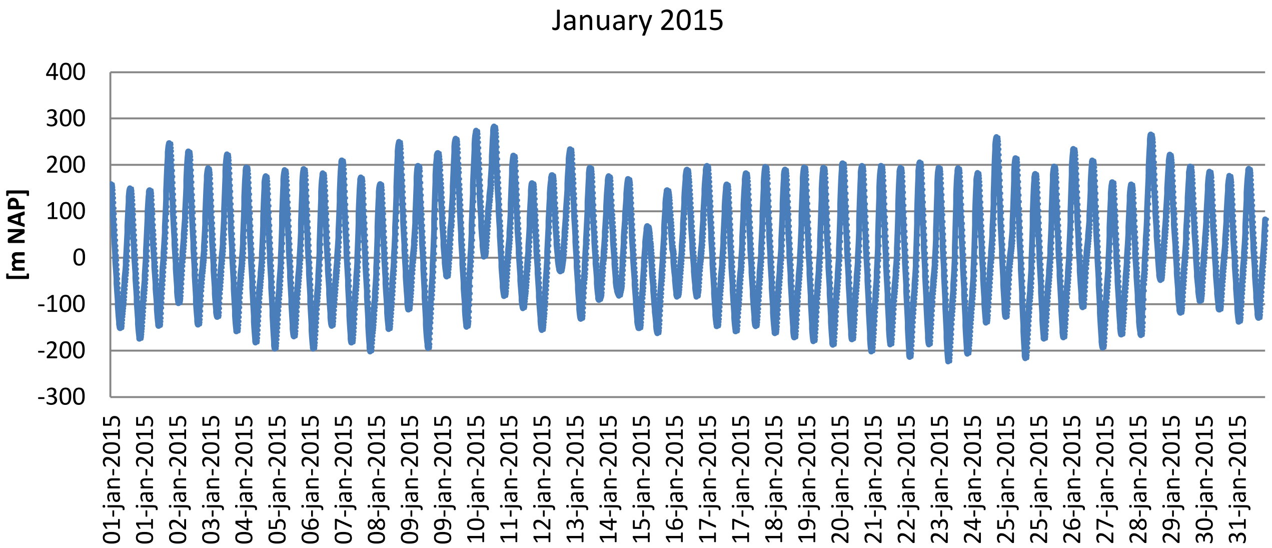
In order to understand and evaluate this research a deep study of the data from Marollegat has been made. The data analyzed are:

- water level;
- wind speed and direction;
- significant wave height. H_s.

Description of the water system and the behavior of water levels

The following paragraph is a short simplified description of the water system. The province of Zealand the shallow water mainly consists of shallow marine, estuarine and fluvial channels. Parts of the Zealand Delta are closed off, are thus no longer influenced by tides and water levels are regulated. In the residue of the Zealand Delta the water levels and flows are predominantly driven by tides. This is the case of Oesterdam. In the Eastern Scheldt the tidal range varies from -2.0 to 2.9 meters at the mouth (Roompot buiten) from -2.3 to 3.1 meters at one of the most inland points at Bergse Diepsluis (Deltares 2013).

At the Marollegat, the tidal range has been estimated from -2.0 to +2.0 meters. Figure below shows an example of the water level for this station. The graph below shows the tidal range of January 2015, taken as a example period in order to show the tidal range of the location.



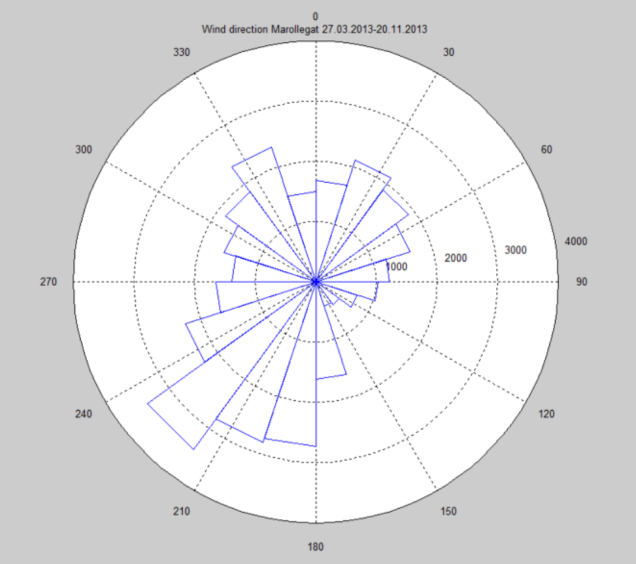
Wind speed and direction

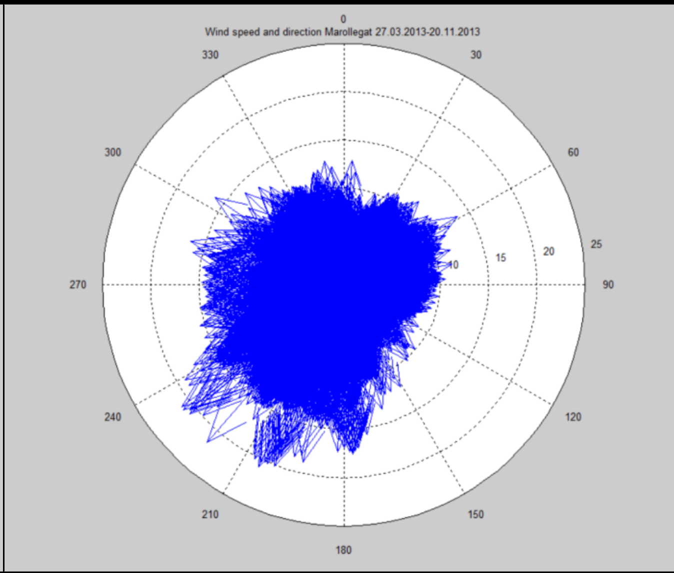
A simulation of wind speed and direction has been performed using the numerical computation realized in Matlab. Two graph are the results of this computation. the analysis has been made for all the periods between the monitoring activities.

The first graph shows the frequency of the wind related to the direction (this means that shows the quantity of winds which blew in that particular direction) ; the second one show the relation between speed and direction. In this case each arrows represent one data measured of a wind and its direction. The direction is expressed in degrees: the zero is the North, 180° represent the South; 9° the Est and 270° the West.

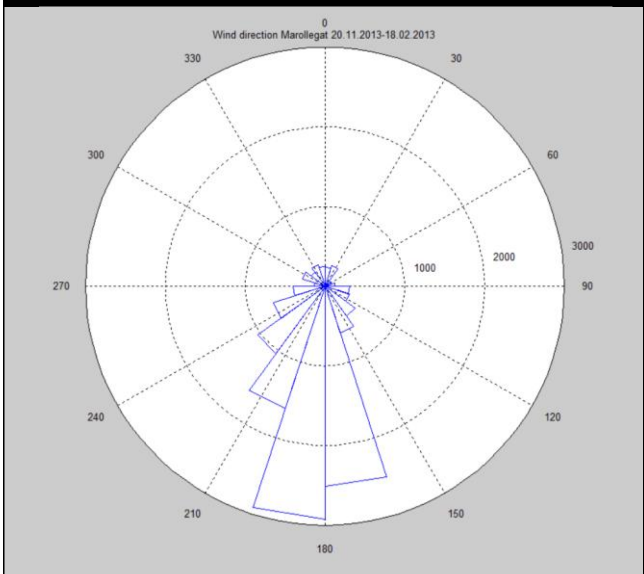
All the periods analyzed are reported below. After a show summary table with the main characteristics of this calculation.

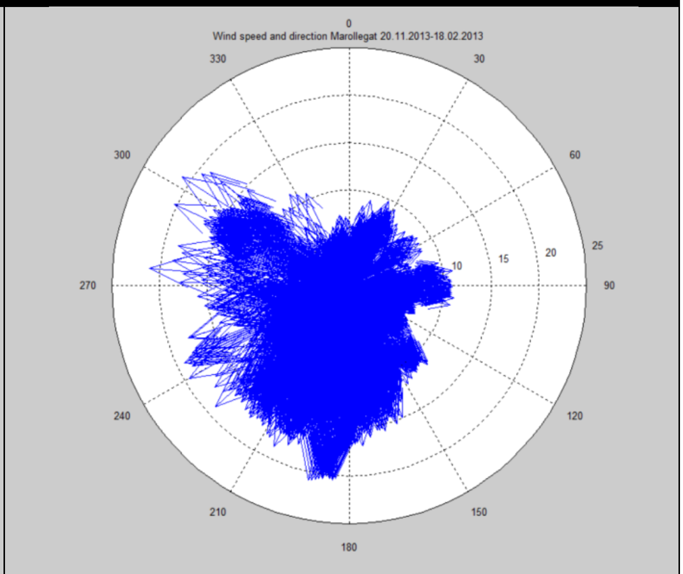
27.03.2013-20.11.2013



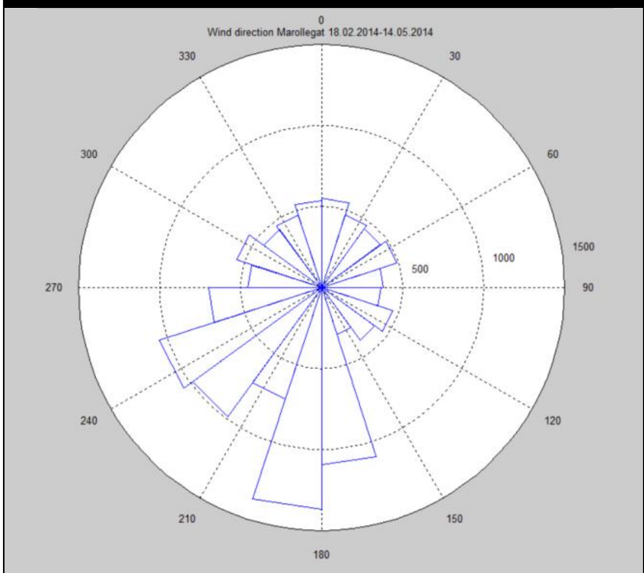


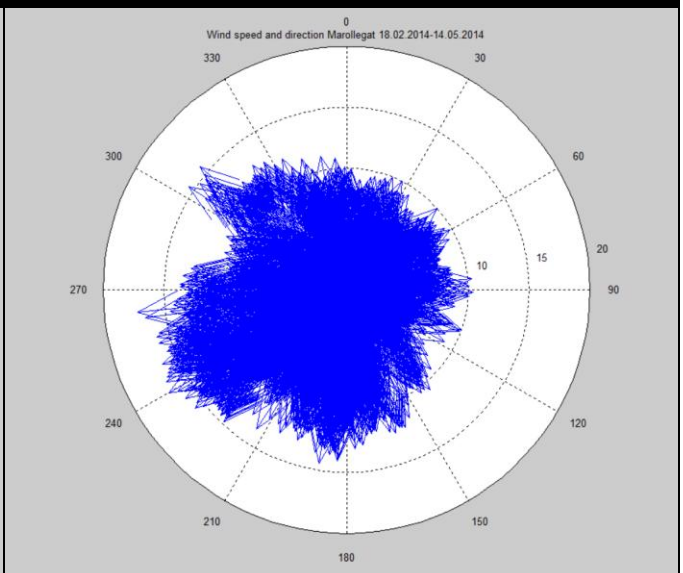
20.11.2013-18.02.2014



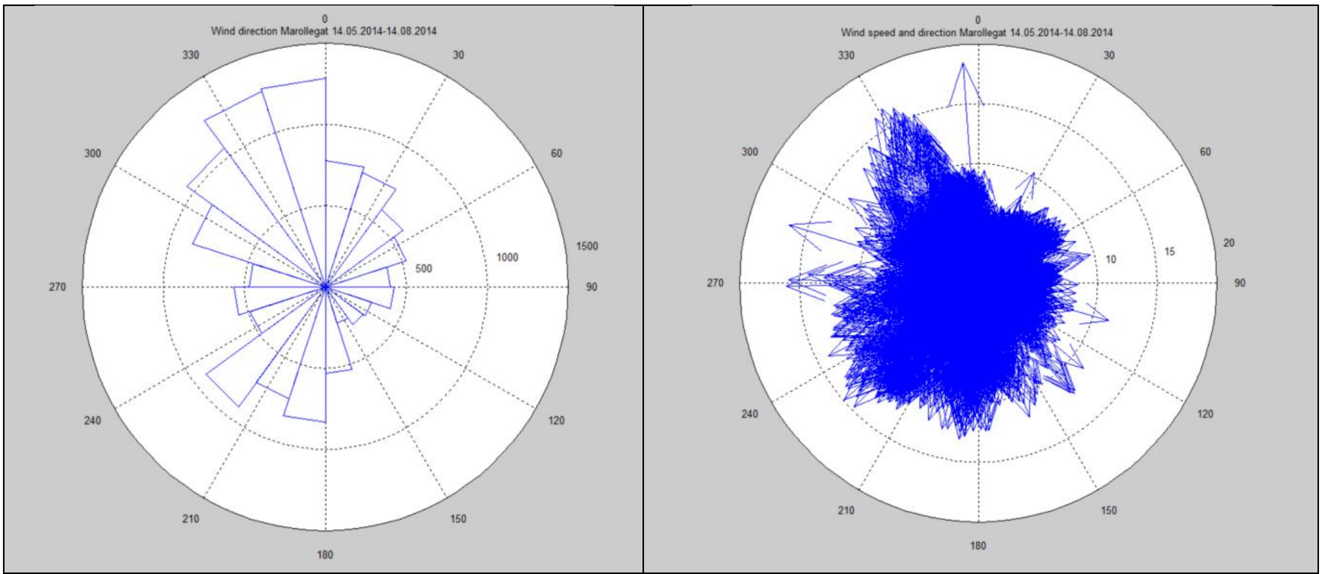


18.02.2014 – 14.05.2014

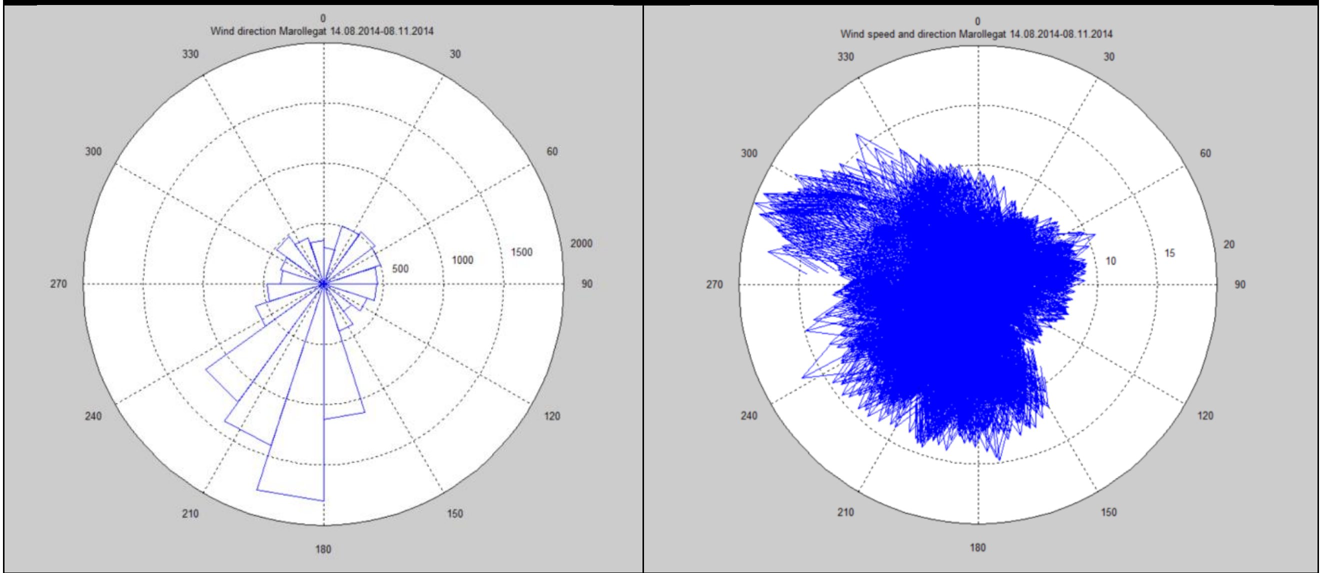




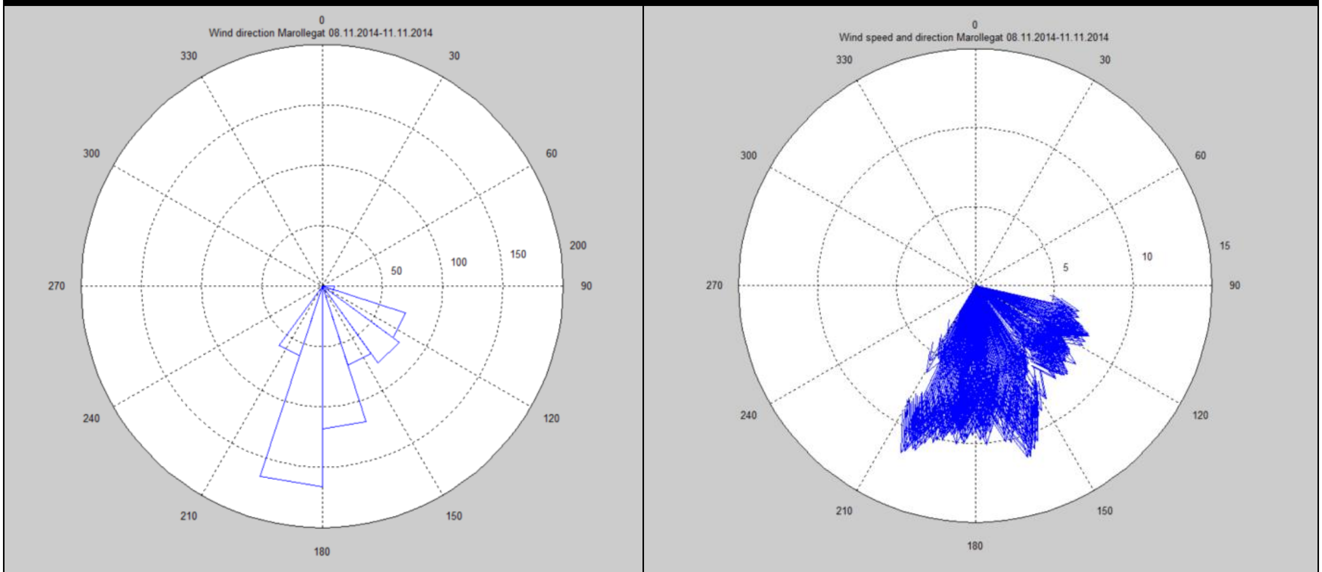
14.05.2014 – 14.08.2014



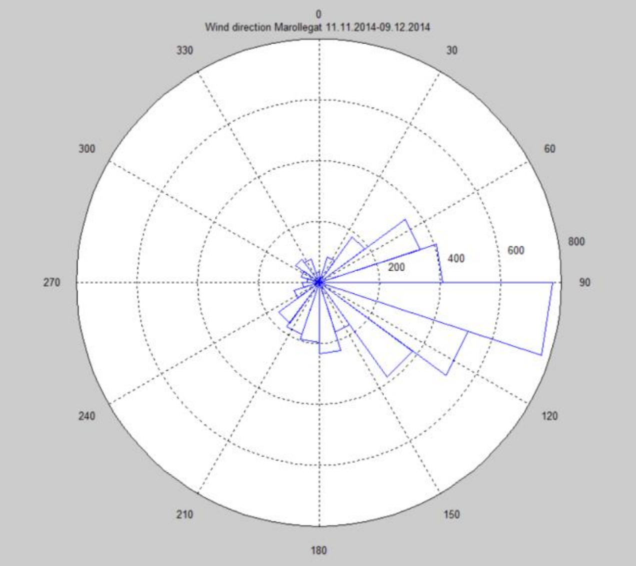
14.08.2014 – 08.11.2014

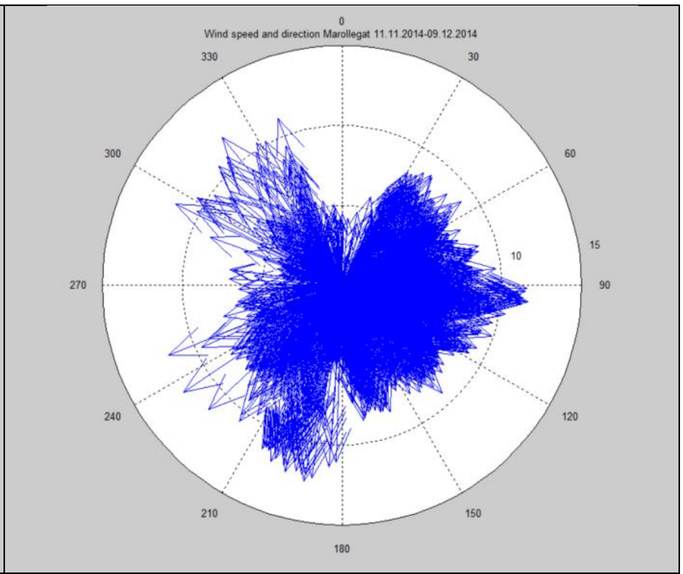


08.11.2014 – 11.11.2014



11.11.2014 – 09.12.2014





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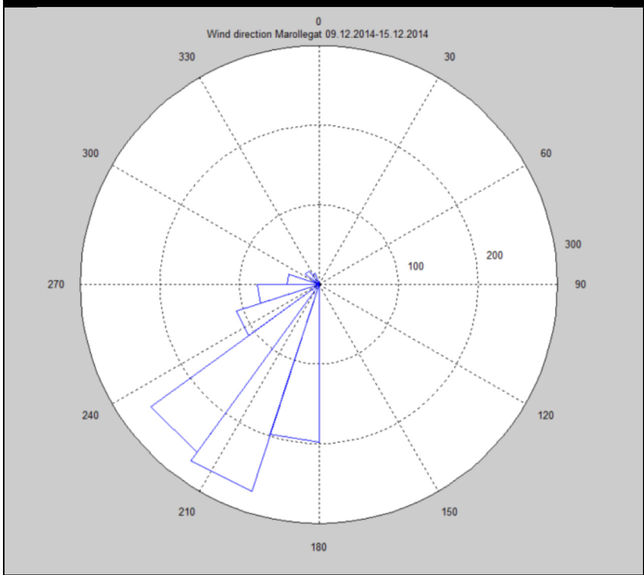
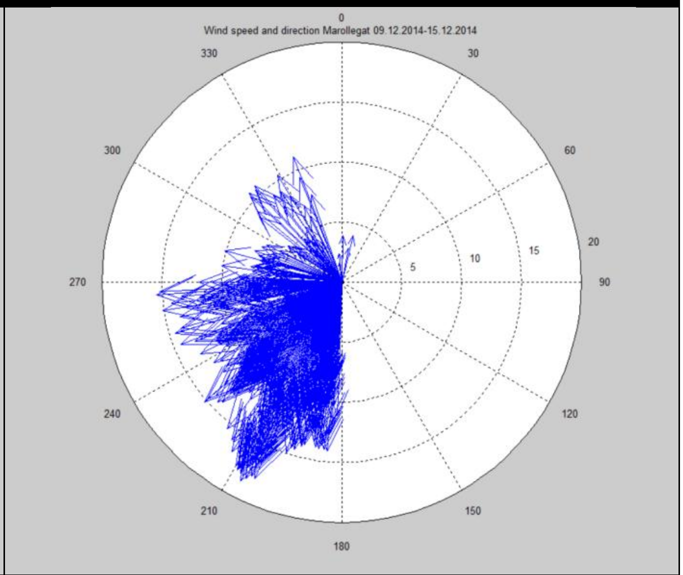
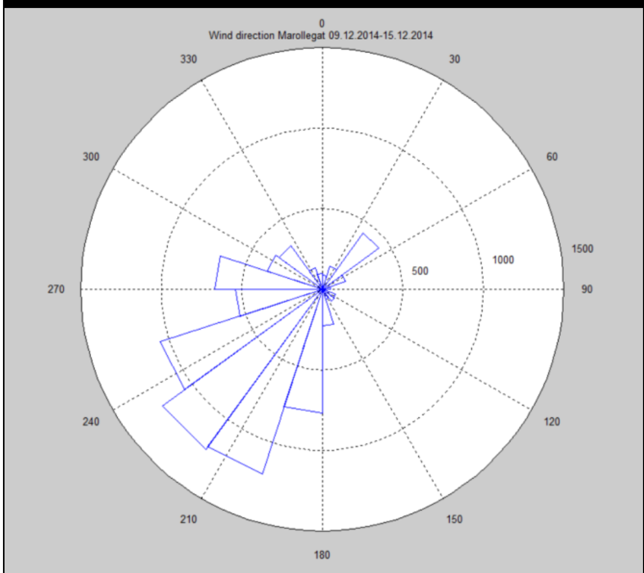
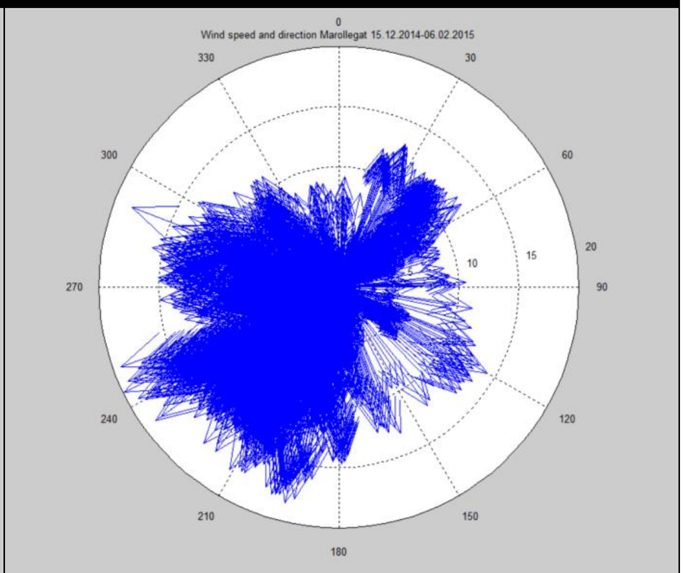


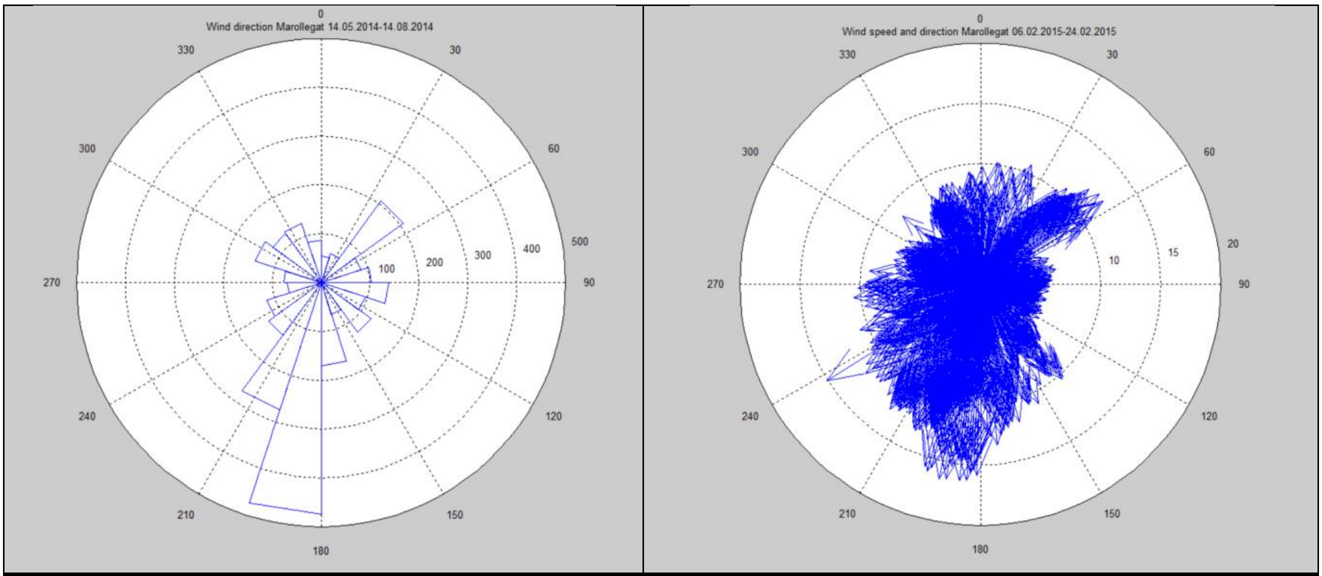


15.12.2014 – 06.02.2015

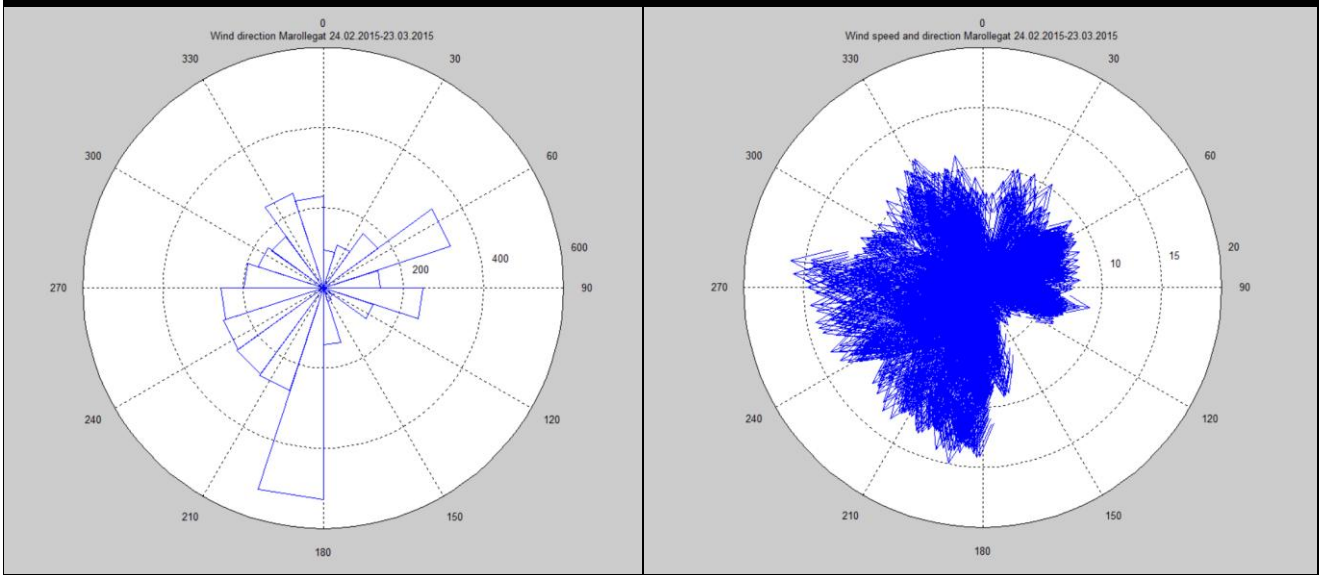




06.02.2015 – 24.02.2015



24.02.2015 – 23.03.2015



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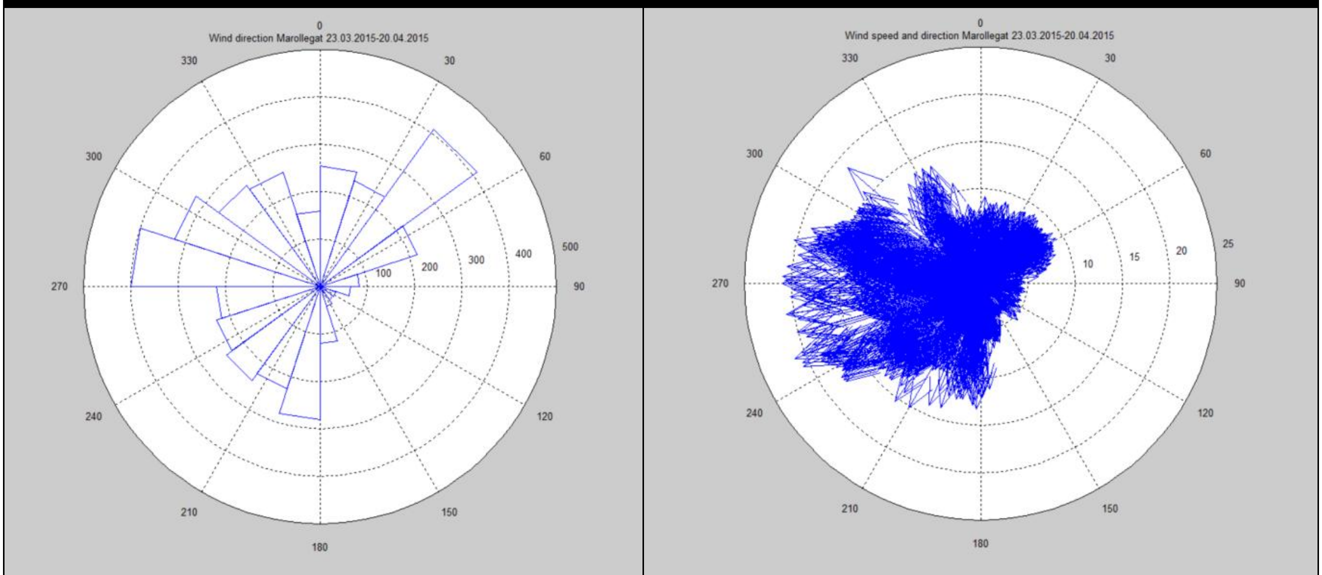

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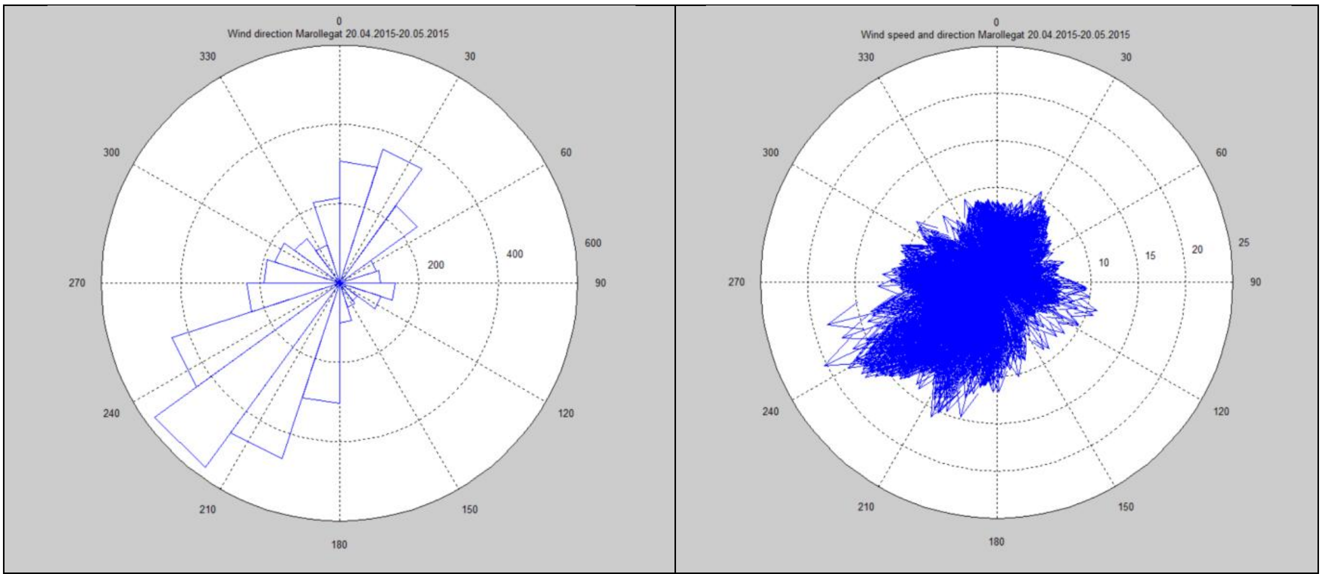

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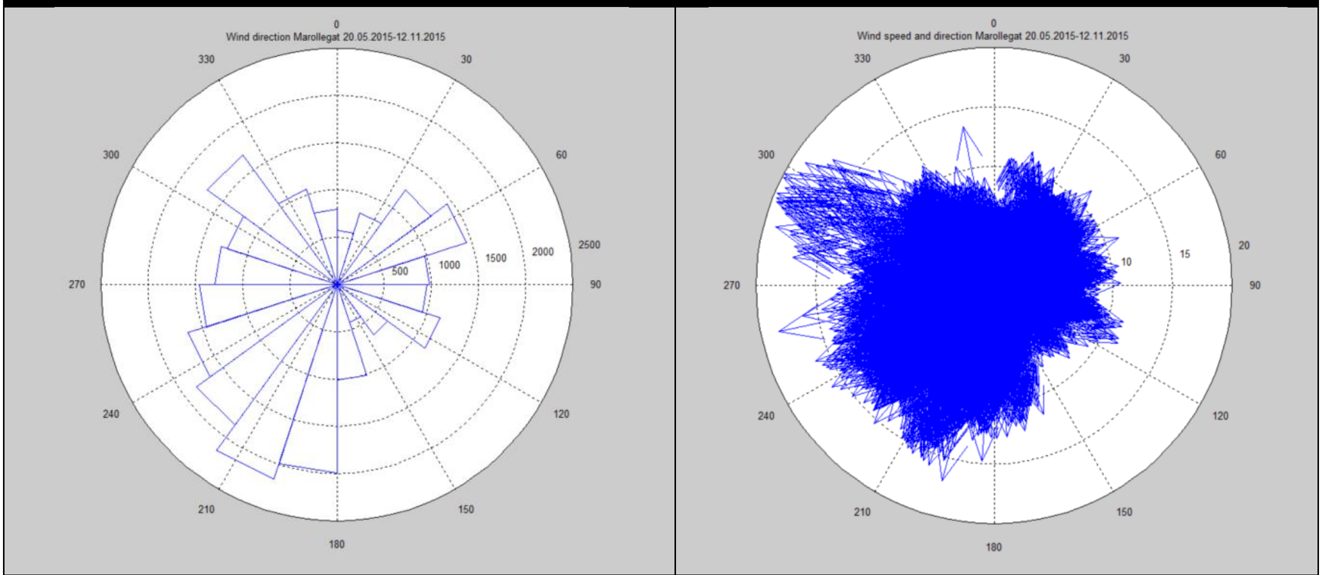

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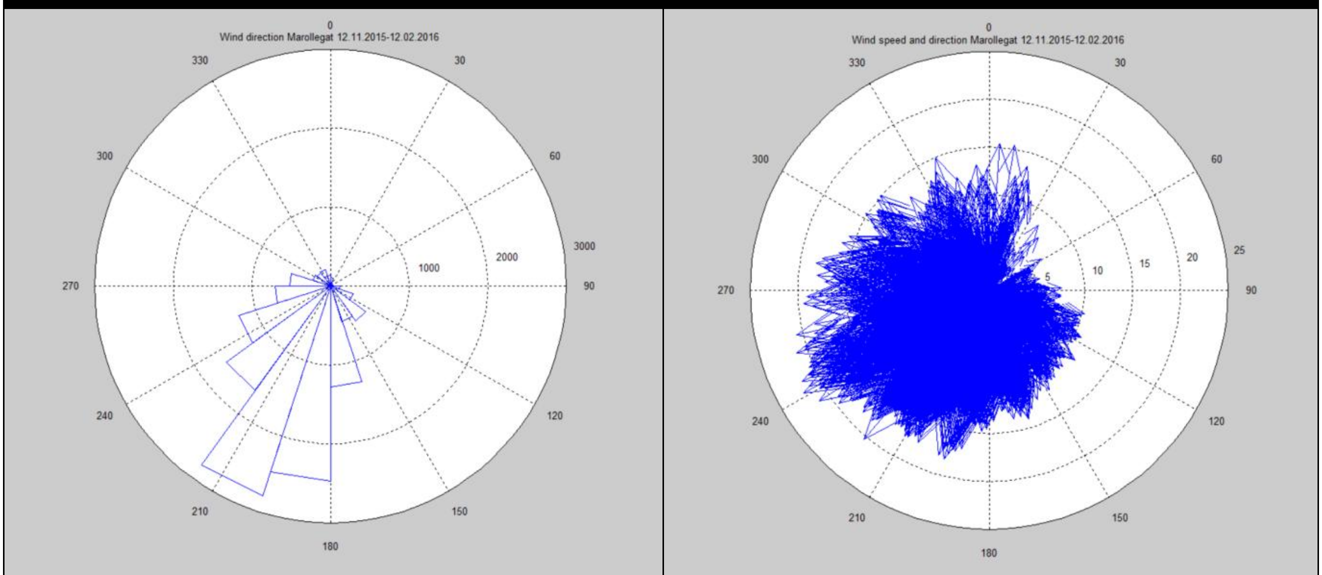

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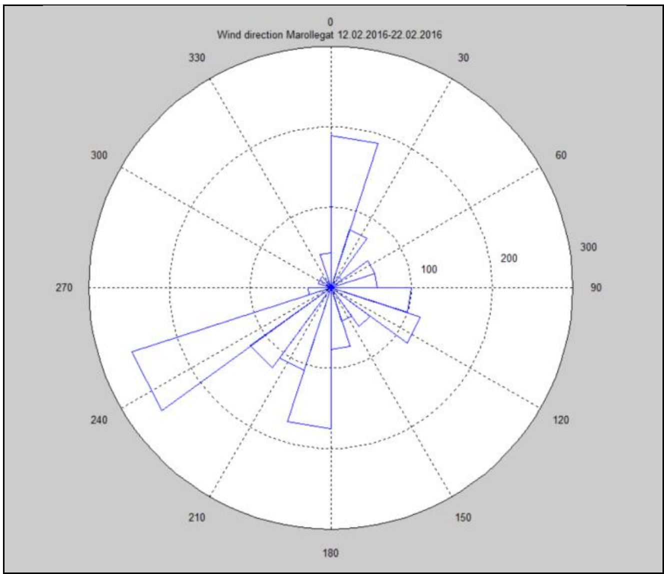

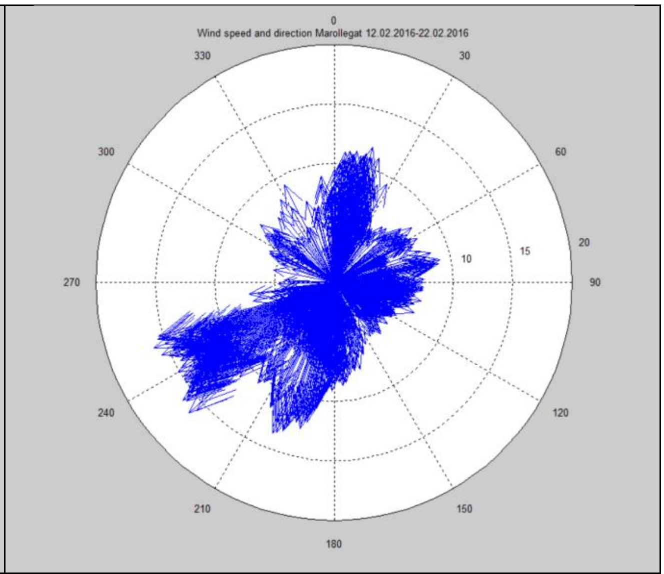

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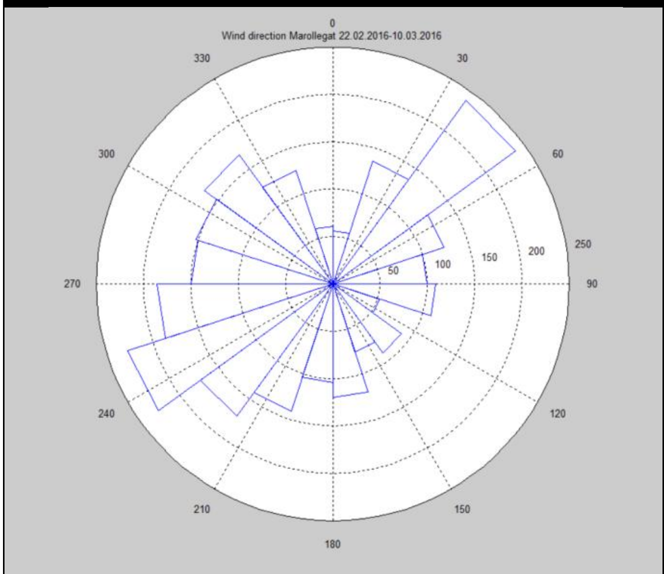

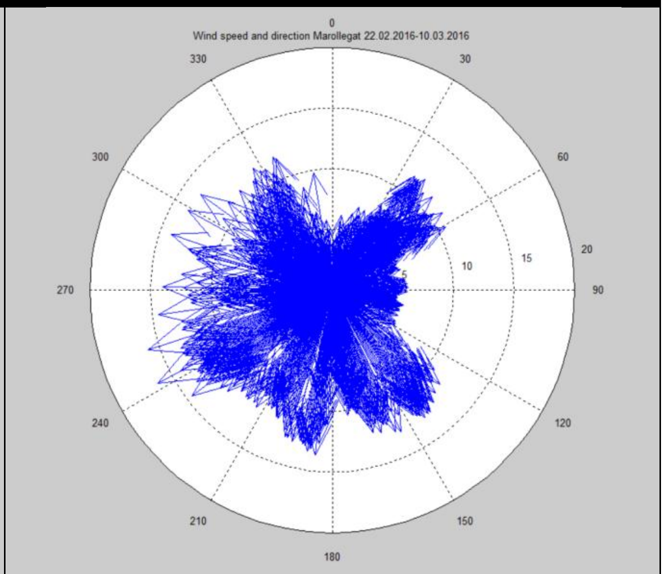

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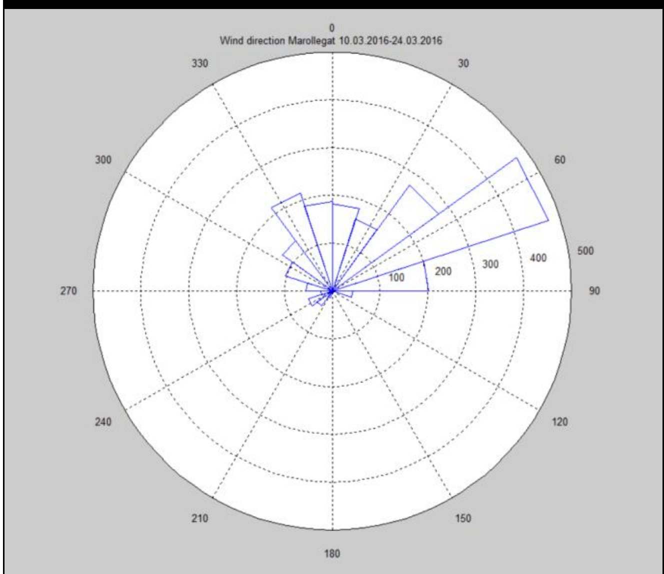
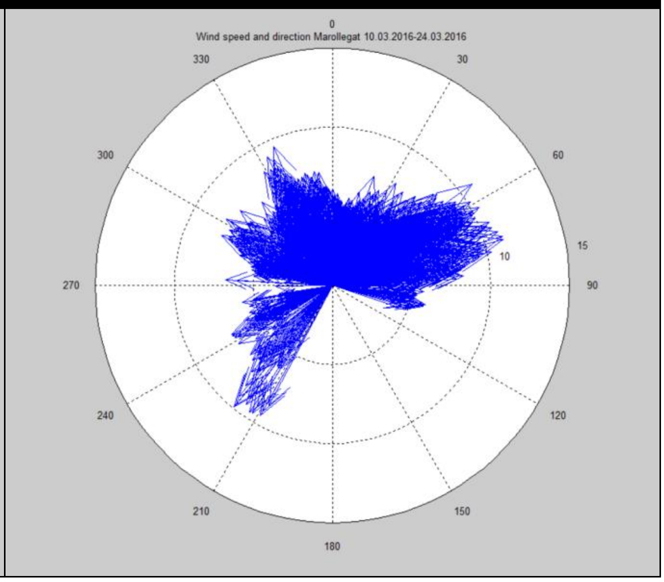
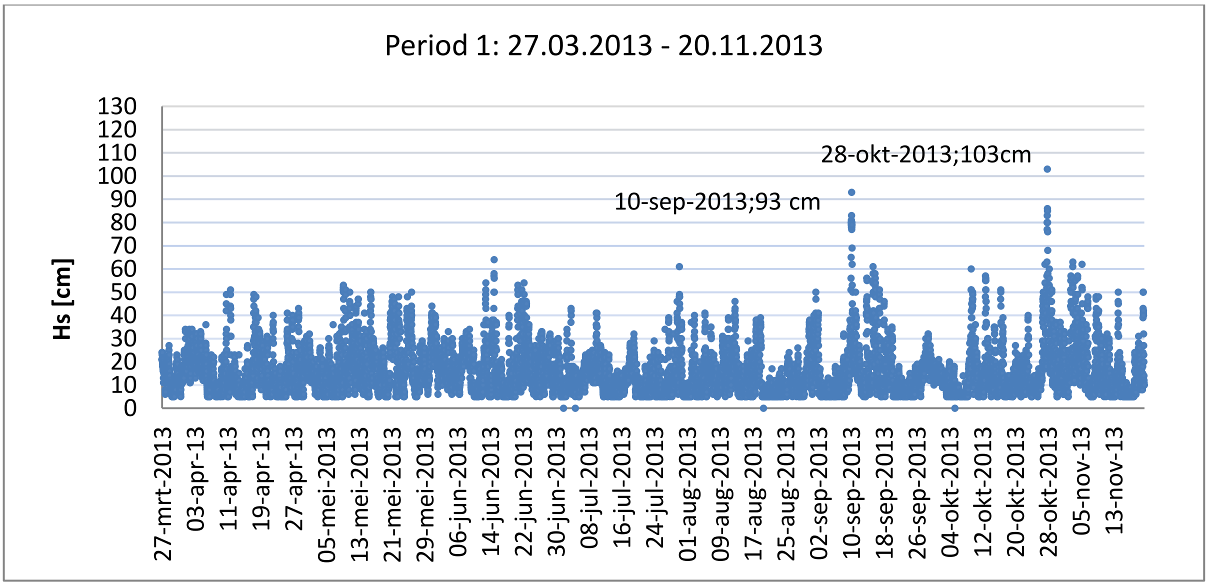


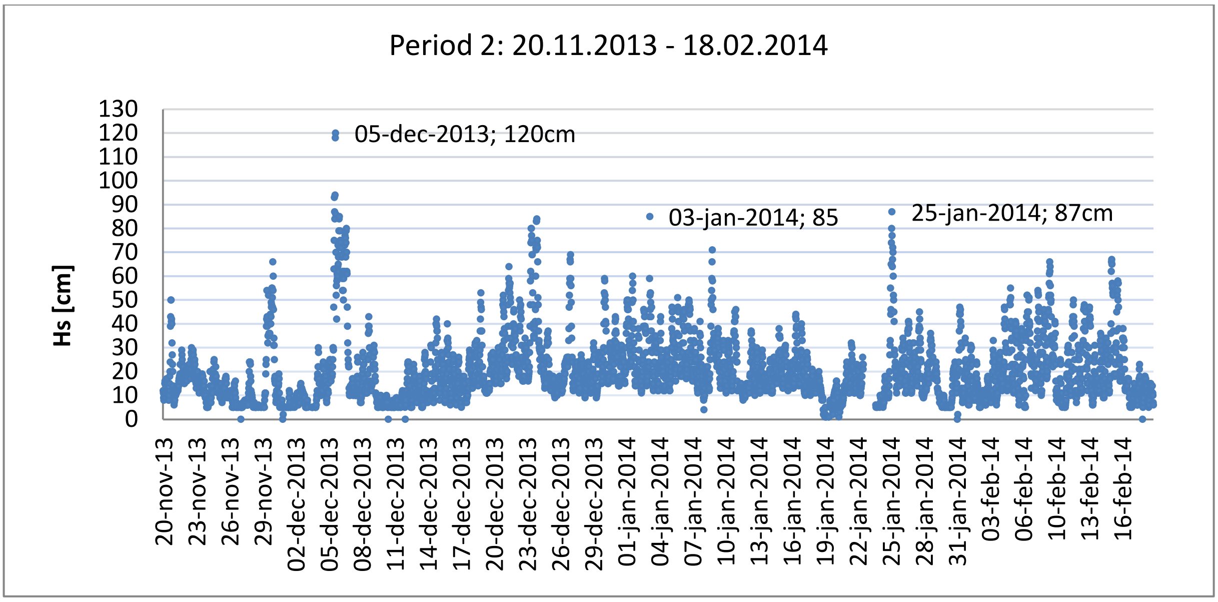


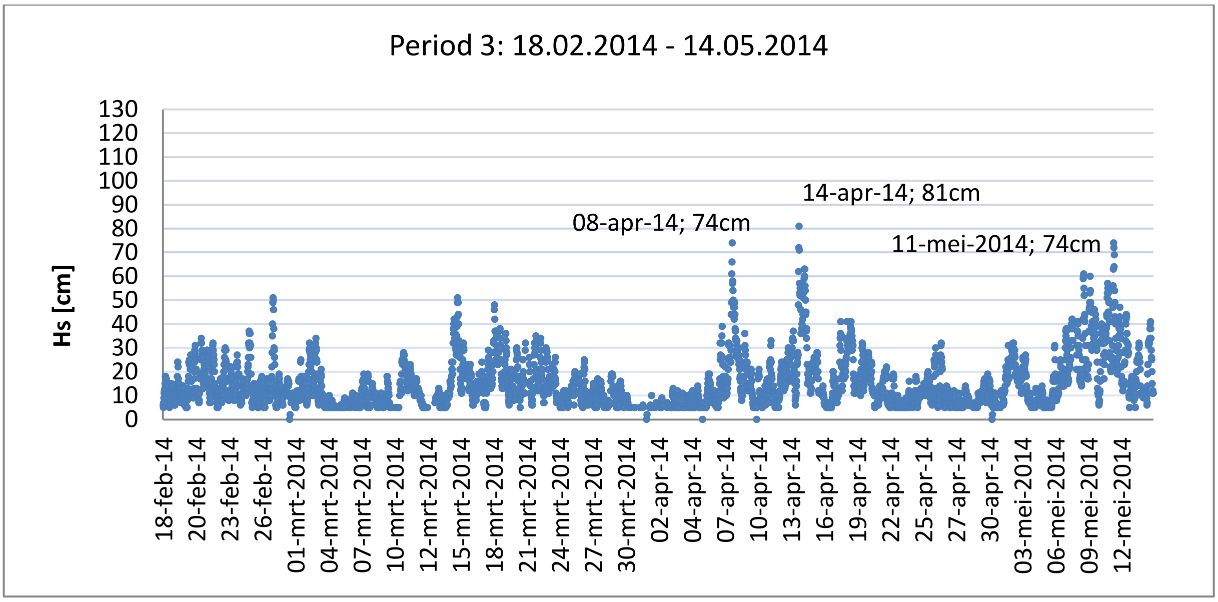
Period	Dates of the period	Maximum wind speed	Relative direction	Direction explanation	Average wind speed
		[m/s]	[degrees]		[m/s]
1	27.03.2013-20.11.2013	21.6	221	S-W	5.98
2	20.11.2013-18.02.2014	21.1	275	W	8.11
3	18.02.2014-14.05.2014	17.3	264	W	5.99
4	14.05.2014-14.08.2014	18.5	356	N	5.12
5	14.08.2014-08.11.2014	19.9	290	N-W	5.76
6	08.11.2014-11.11.2014	11.6	204	S-W	7.47
7	11.11.2014-09.12.2014	12.5	191	S-W	5.31
8	09.12.2014-15.12.2014	18.6	207	S-W	8.40
9	15.12.2014-06.02.2015	19.9	244	S-W	7.81
10	06.02.2015-24.02.2015	16.5	192	S-W	6.09
11	24.02.2015-23.03.2015	16.2	278	N-W	6.19
12	23.03.2015-20.04.2015	21.2	248	S-W	6.39
13	20.04.2015-20.05.2015	20.3	244	S-W	6.34
14	20.05.2015-12.11.2015	20	297	N-W	5.34
15	12.11.2015- 12.02.2016	22.2	241	S-W	8.30
16	12.02.2016-22.02.2016	16.4	228	S-W	6.94
17	22.02.2016-10.03.2016	16.3	242	S-W	6.04
18	10.03.2016-23.03.2016	11.2	74	N-E	5.42
19	23.03.2016-06.04.2016	19.9	181	S	7.19

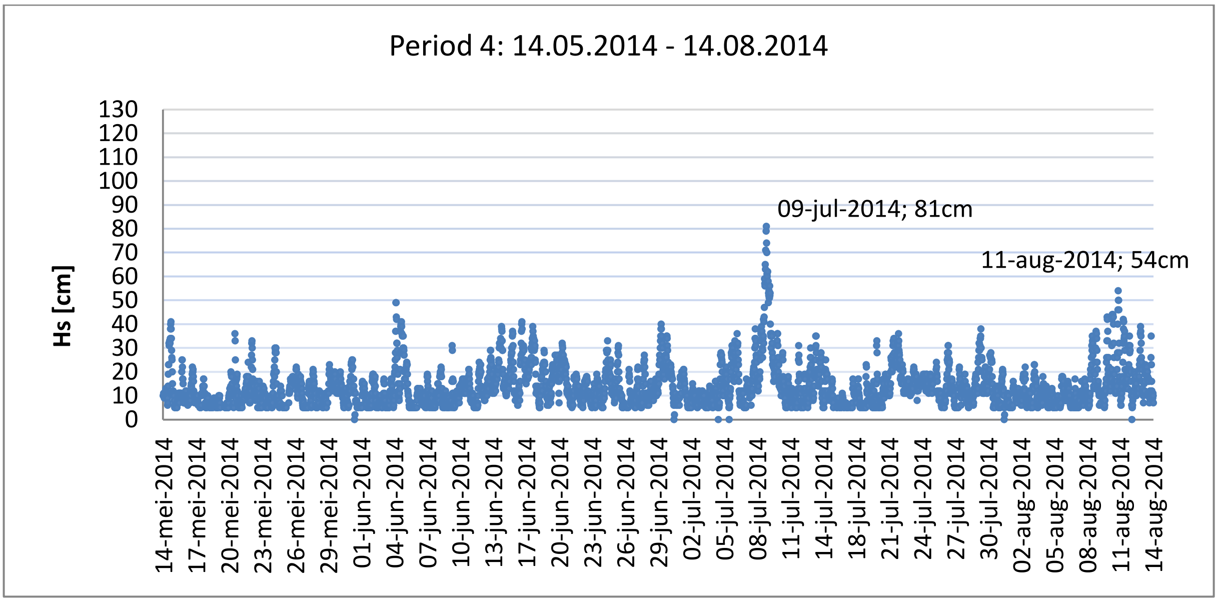
Significant wave height

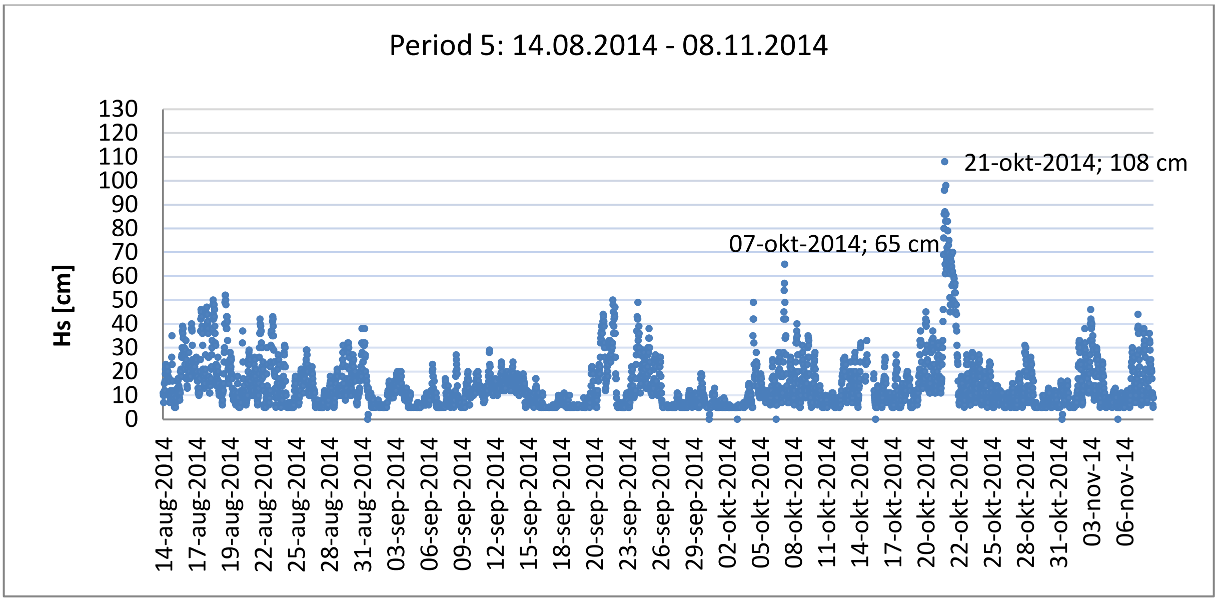
With the term significant wave height (SWH or Hs) is defined the mean wave height of the highest third ot the waves ($H_{1/3}$). This data is helpful to understand the hydrodynamic of the basin. Thanks to the data collected from the measuring station of the Marollegat, it has been possible to analyze the Hs of all the periods. Hs is monitored every 30 minutes from the pole. The graphs below show the trend of the waves for all the monitoring. The maximum wave height are highlighted in each graph.

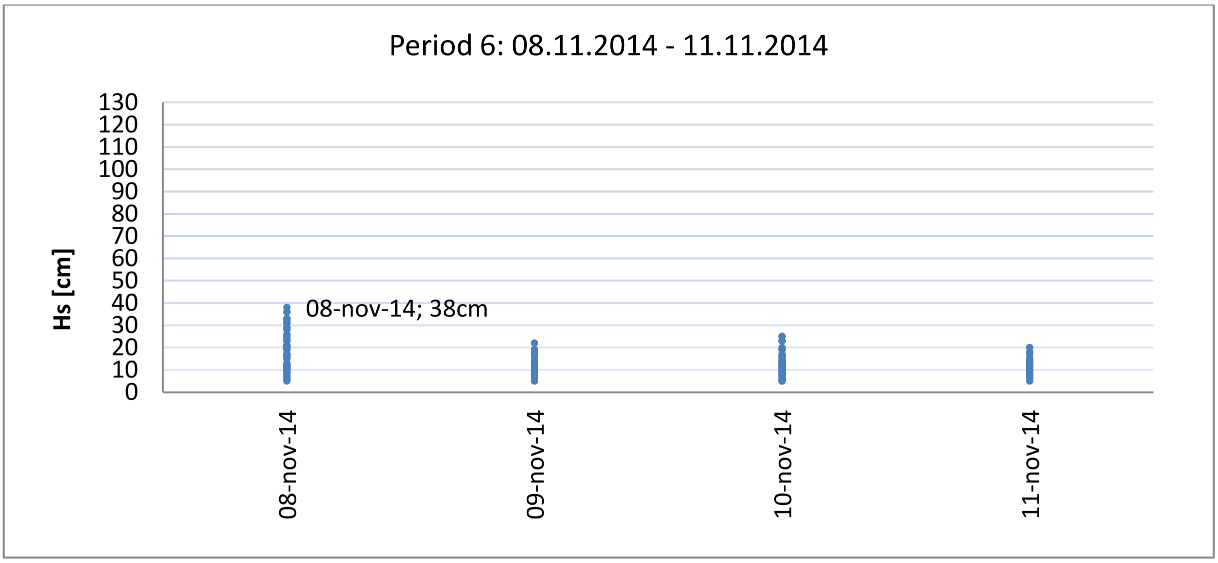


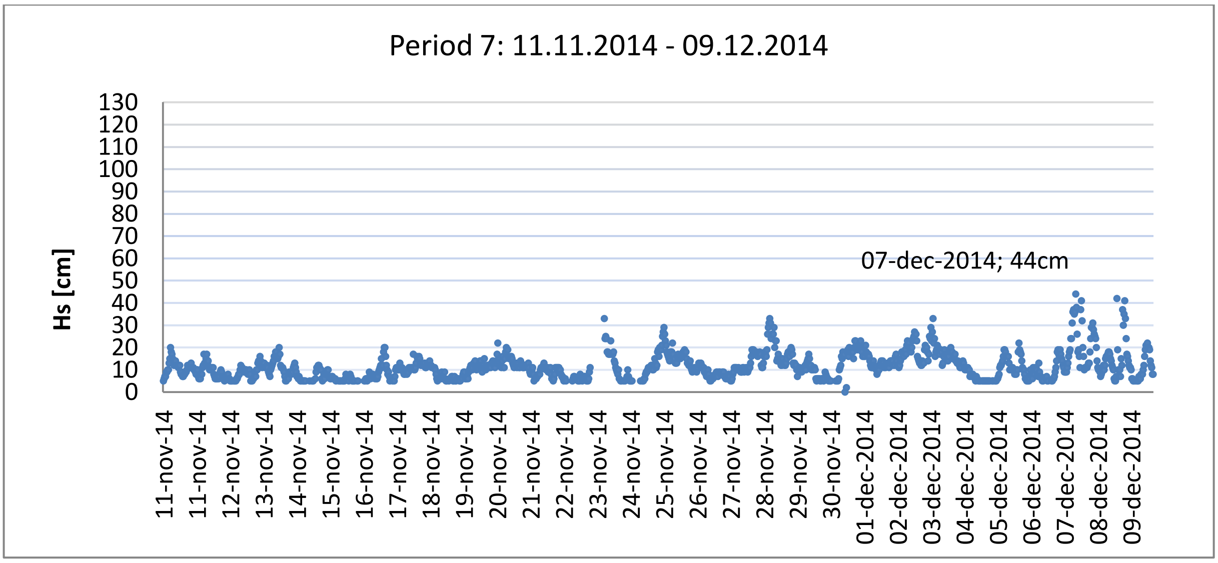

Period 2: 20.11.2013 - 18.02.2014
Hs [cm]
05-dec-2013; 120cm
03-jan-2014; 85
25-jan-2014; 87cm

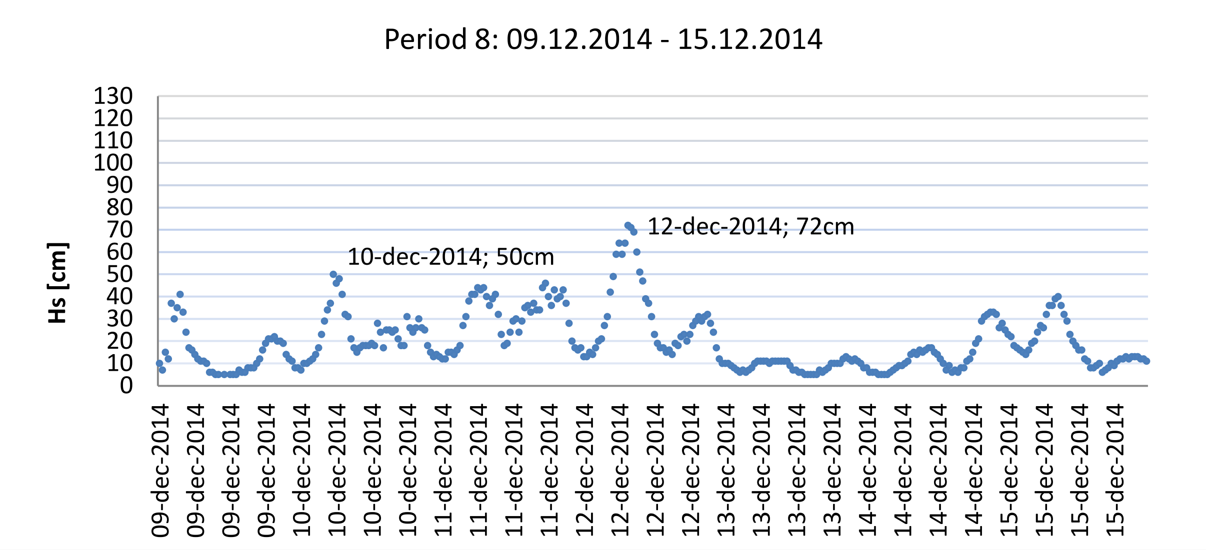

Period 3: 18.02.2014 - 14.05.2014
Hs [cm]
14-apr-14; 81cm
08-apr-14; 74cm
11-mei-2014; 74cm

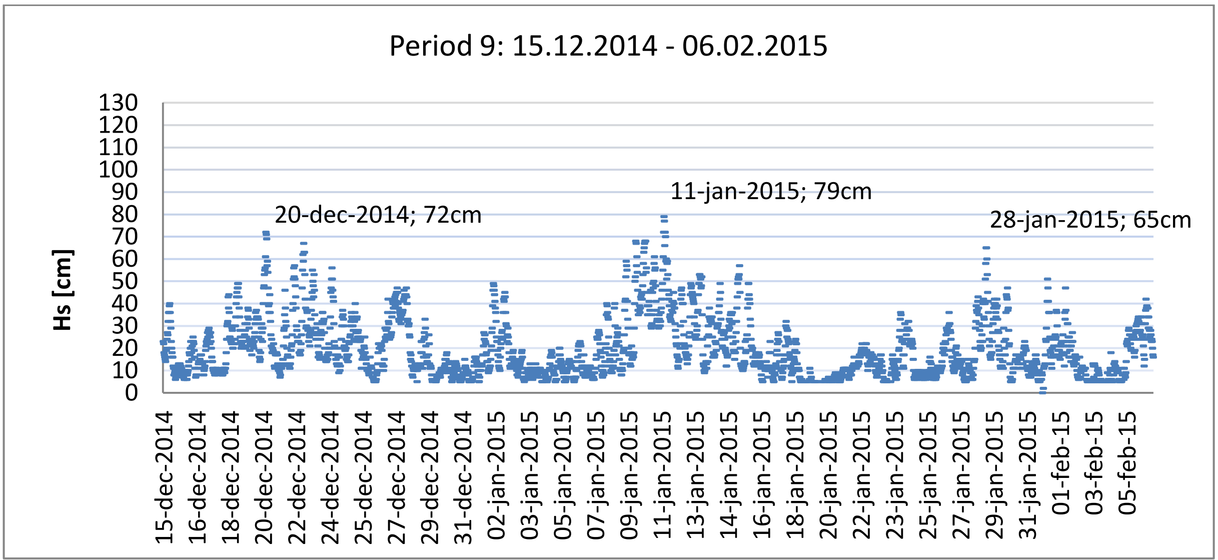

Period 4: 14.05.2014 - 14.08.2014
Hs [cm]
09-jul-2014; 81cm
11-aug-2014; 54cm

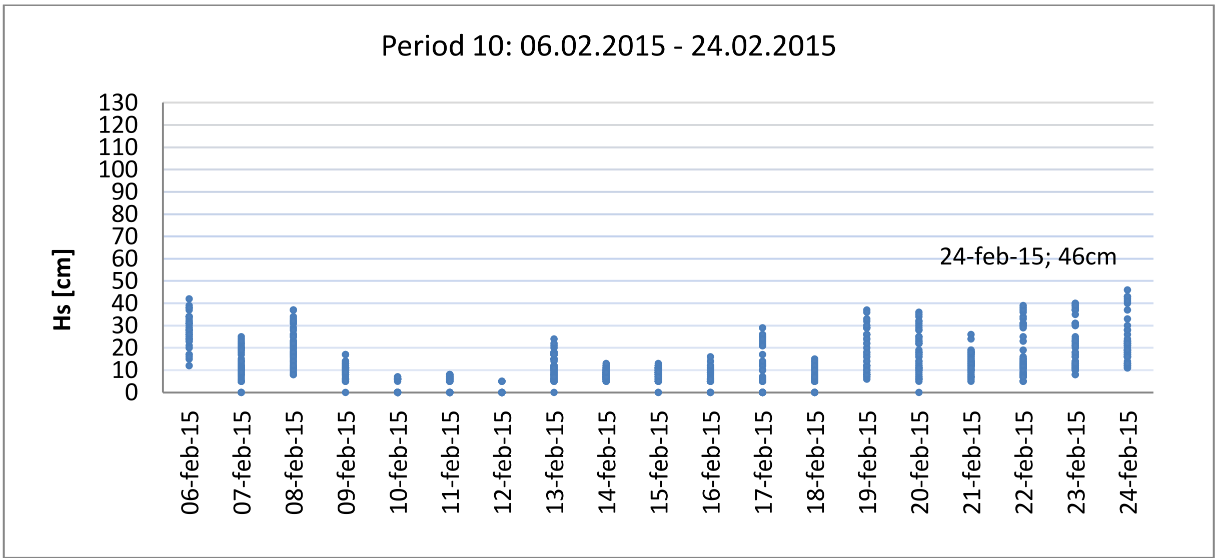

Period 5: 14.08.2014 - 08.11.2014
Hs [cm]
130
120
110
100
90
80
70
60
50
40
30
20
10
0
21-okt-2014; 108 cm
07-okt-2014; 65 cm
14-aug-2014
17-aug-2014
19-aug-2014
22-aug-2014
25-aug-2014
28-aug-2014
31-aug-2014
03-sep-2014
06-sep-2014
09-sep-2014
12-sep-2014
15-sep-2014
18-sep-2014
20-sep-2014
23-sep-2014
26-sep-2014
29-sep-2014
02-okt-2014
05-okt-2014
08-okt-2014
11-okt-2014
14-okt-2014
17-okt-2014
20-okt-2014
22-okt-2014
25-okt-2014
28-okt-2014
31-okt-2014
03-nov-14
06-nov-14

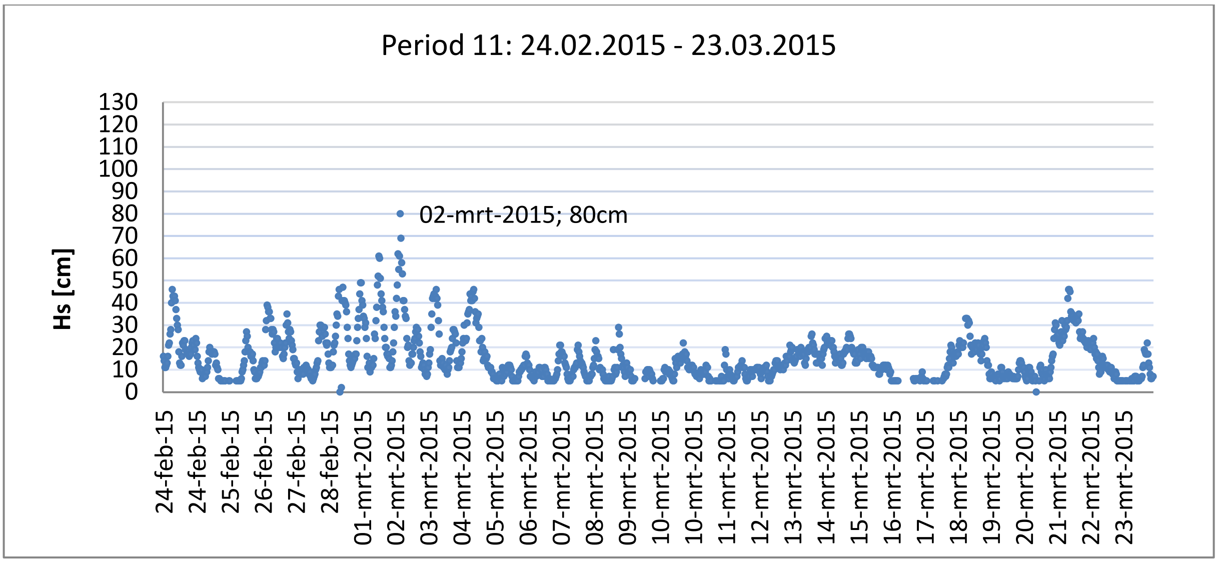

Period 6: 08.11.2014 - 11.11.2014
Hs [cm]
130
120
110
100
90
80
70
60
50
40
30
20
10
0
08-nov-14; 38cm
08-nov-14
09-nov-14
10-nov-14
11-nov-14

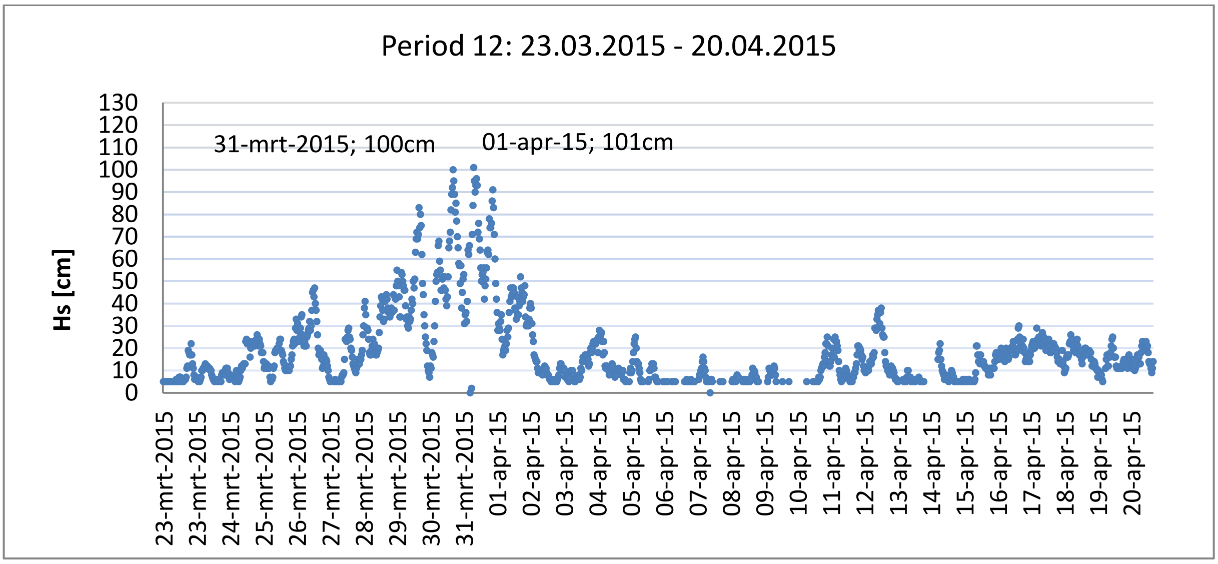

Period 7: 11.11.2014 - 09.12.2014
Hs [cm]
130
120
110
100
90
80
70
60
50
40
30
20
10
0
07-dec-2014; 44cm
11-nov-14
11-nov-14
12-nov-14
13-nov-14
14-nov-14
15-nov-14
16-nov-14
17-nov-14
18-nov-14
19-nov-14
20-nov-14
21-nov-14
22-nov-14
23-nov-14
24-nov-14
25-nov-14
26-nov-14
27-nov-14
28-nov-14
29-nov-14
30-nov-14
01-dec-2014
02-dec-2014
03-dec-2014
04-dec-2014
05-dec-2014
06-dec-2014
07-dec-2014
08-dec-2014
09-dec-2014

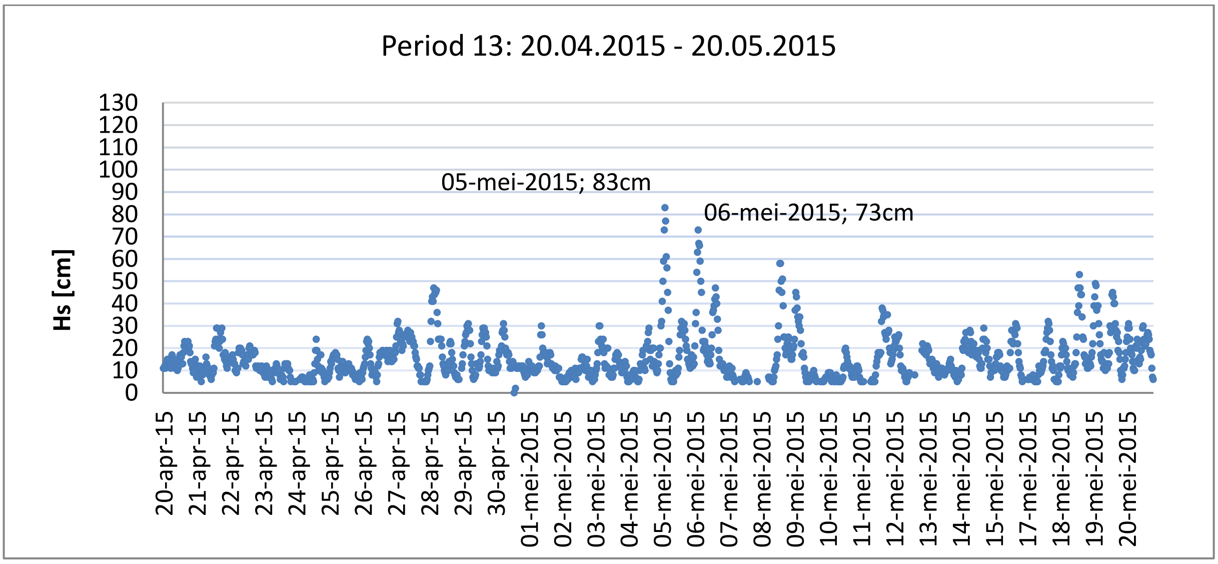

Period 8: 09.12.2014 - 15.12.2014
Hs [cm]
12-dec-2014; 72cm
10-dec-2014; 50cm

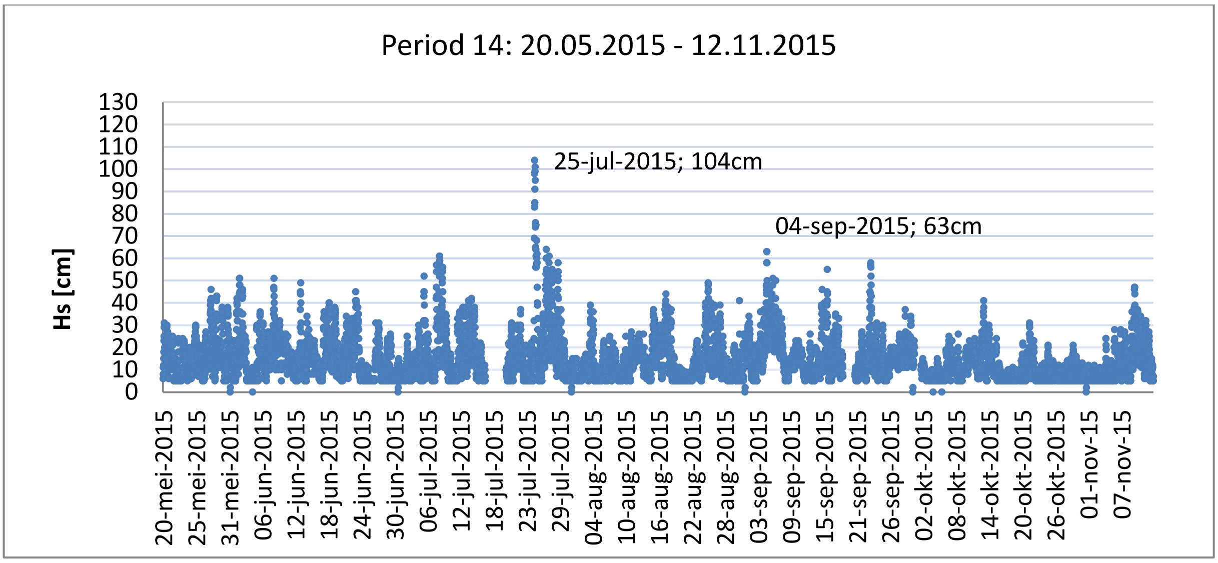

Period 9: 15.12.2014 - 06.02.2015
Hs [cm]
11-jan-2015; 79cm
20-dec-2014; 72cm
28-jan-2015; 65cm

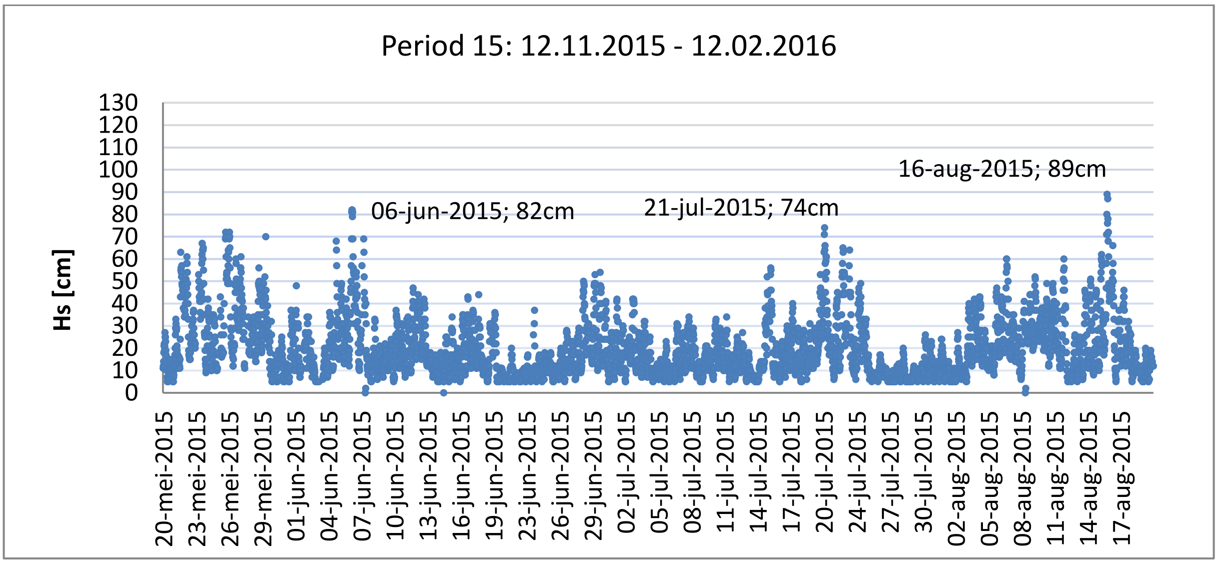

Period 10: 06.02.2015 - 24.02.2015
Hs [cm]
24-feb-15; 46cm

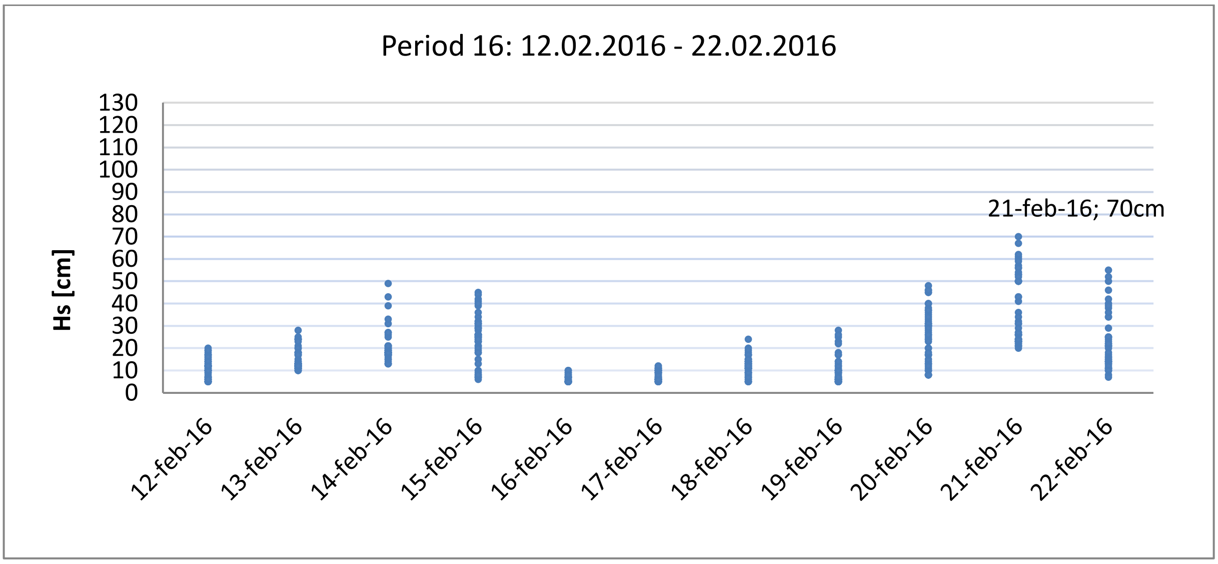

Period 11: 24.02.2015 - 23.03.2015
Hs [cm]
02-mrt-2015; 80cm

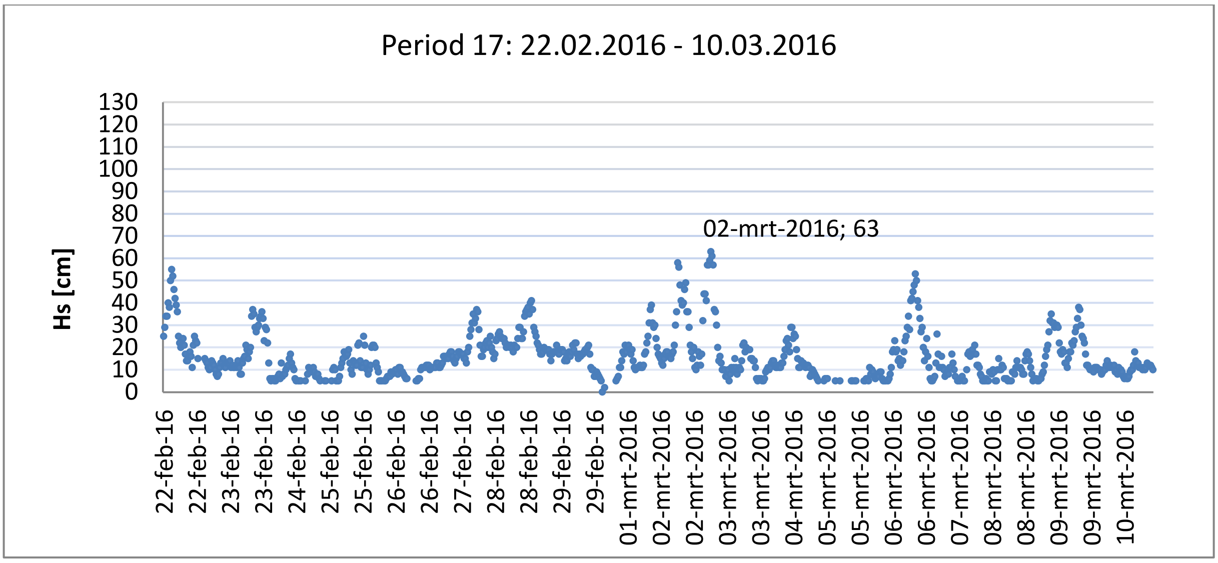

Period 12: 23.03.2015 - 20.04.2015
Hs [cm]
31-mrt-2015; 100cm
01-apr-15; 101cm

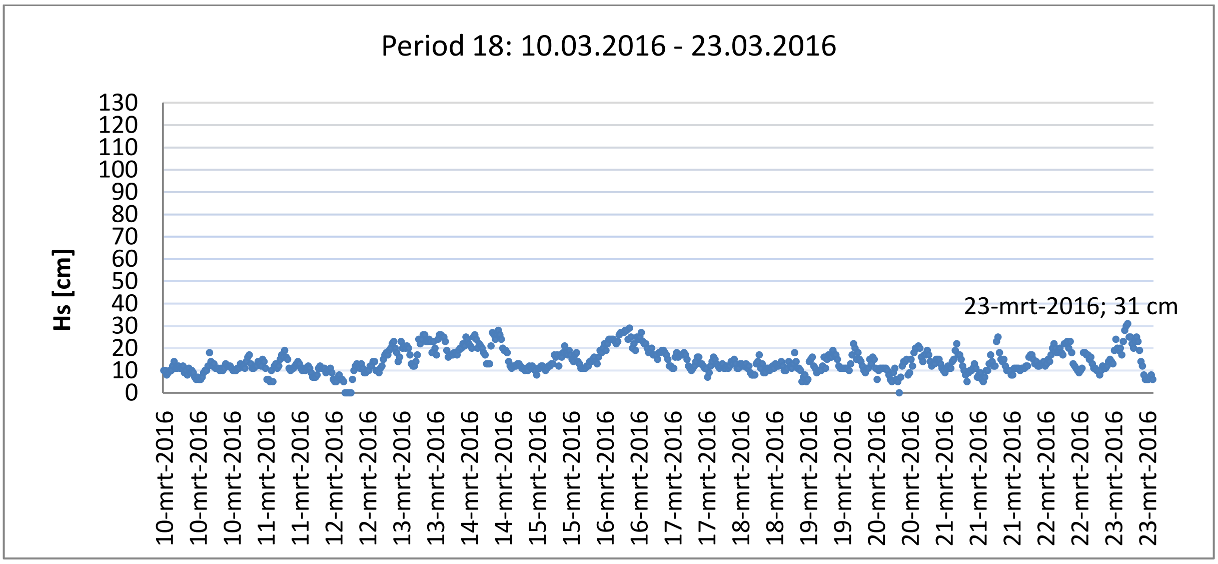

Period 13: 20.04.2015 - 20.05.2015
Hs [cm]
05-mei-2015; 83cm
06-mei-2015; 73cm

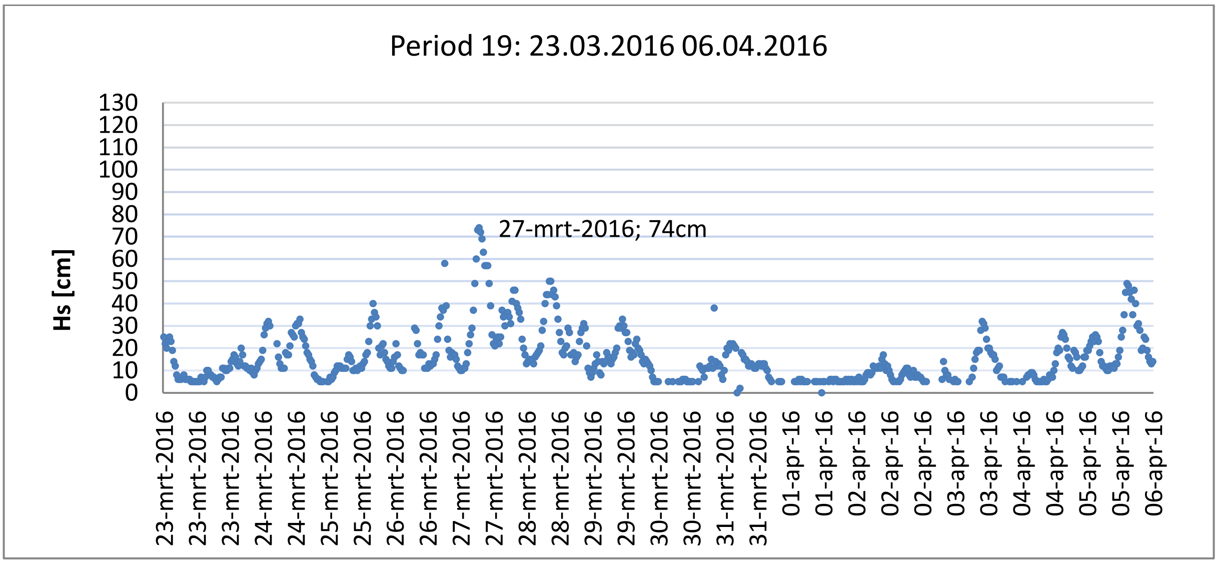

Period 14: 20.05.2015 - 12.11.2015
Hs [cm]
25-jul-2015; 104cm
04-sep-2015; 63cm


Period 15: 12.11.2015 - 12.02.2016
Hs [cm]
06-jun-2015; 82cm
21-jul-2015; 74cm
16-aug-2015; 89cm


Period 16: 12.02.2016 - 22.02.2016
Hs [cm]
21-feb-16; 70cm


Period 17: 22.02.2016 - 10.03.2016
Hs [cm]
02-mrt-2016; 63


Period 18: 10.03.2016 - 23.03.2016
Hs [cm]
23-mrt-2016; 31 cm


Period 19: 23.03.2016 06.04.2016
Hs [cm]
27-mrt-2016; 74cm

Period	Dates of the period	Hs max	Average Hs
		[cm]	[cm]
1	27.03.2013-20.11.2013	103	15.96
2	20.11.2013-18.02.2014	120	20.54
3	18.02.2014-14.05.2014	81	15.53
4	14.05.2014-14.08.2014	81	13.99
5	14.08.2014-08.11.2014	108	14.67
6	08.11.2014-11.11.2014	38	13.54
7	11.11.2014-09.12.2014	44	11.78
8	09.12.2014-15.12.2014	72	20.03
9	15.12.2014-06.02.2015	79	19.83
10	06.02.2015-24.02.2015	46	14.53
11	24.02.2015-23.03.2015	80	15.51
12	23.03.2015-20.04.2015	101	19.56
13	20.04.2015-20.05.2015	83	15.56
14	20.05.2015-12.11.2015	104	15.16
15	12.11.2015- 12.02.2016	89	19.79
16	12.02.2016-22.02.2016	70	16.19
17	22.02.2016-10.03.2016	63	16.19
18	10.03.2016-23.03.2016	31	14.25
19	23.03.2016-06.04.2016	74	16.32

Appendix B: Significance test of correlation: Wind speed and Hs

Correlation between the variables

The present appendix shows the statistic study of the values for wind speed and significant wave height which have been provided by the measuring station of Marollegat, located in the study area.

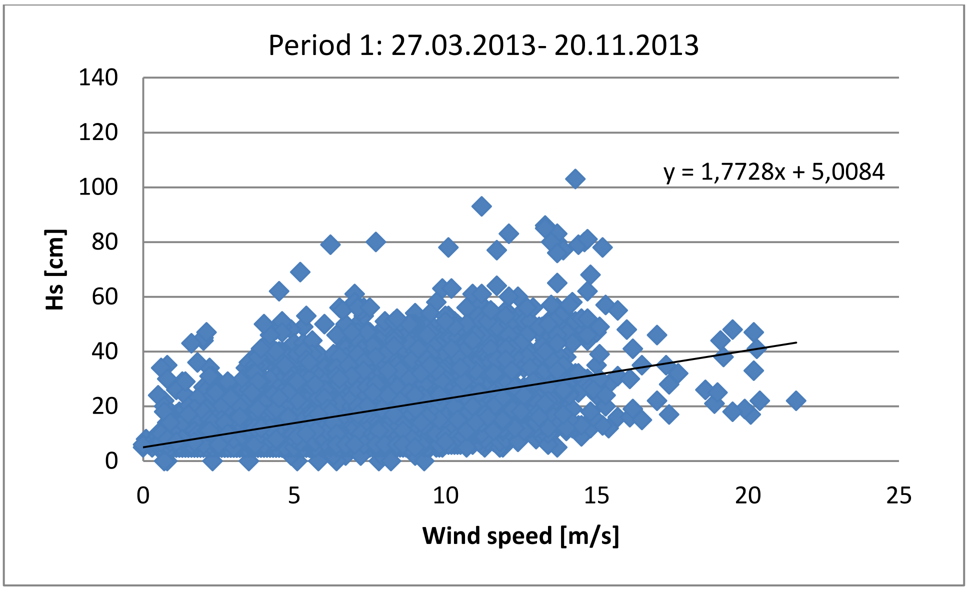
The study have been processed based on a dataset provided for all the periods between the monitoring activities, starting from the 27th of March 2013 till the 6th of April 2016. The periods analyzed are nineteen in total and they are reassumed in the following table.

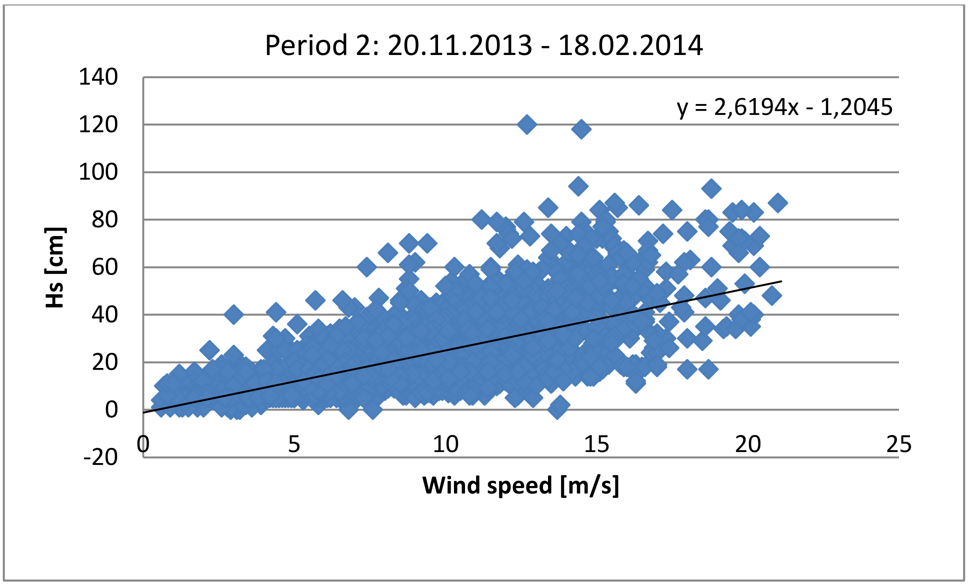
PERIOD	DATES
1	27.03.2013-20.11.2013
2	20.11.2013-18.02.2014
3	18.02.2014-14.05.2014
4	14.05.2014-14.08.2014
5	14.08.2014-08.11.2014
6	08.11.2014-11.11.2014
7	11.11.2014-09.12.2014
8	09.12.2014-15.12.2014
9	15.12.2014-06.02.2015
10	06.02.2015-24.02.2015
11	24.02.2015-23.03.2015
12	23.03.2015-20.04.2015
13	20.04.2015-20.05.2015
14	20.05.2015-12.11.2015
15	12.11.2015- 12.02.2016
16	12.02.2016-22.02.2016
17	22.02.2016-10.03.2016
18	10.03.2016-23.03.2016
19	23.03.2016-06.04.2016

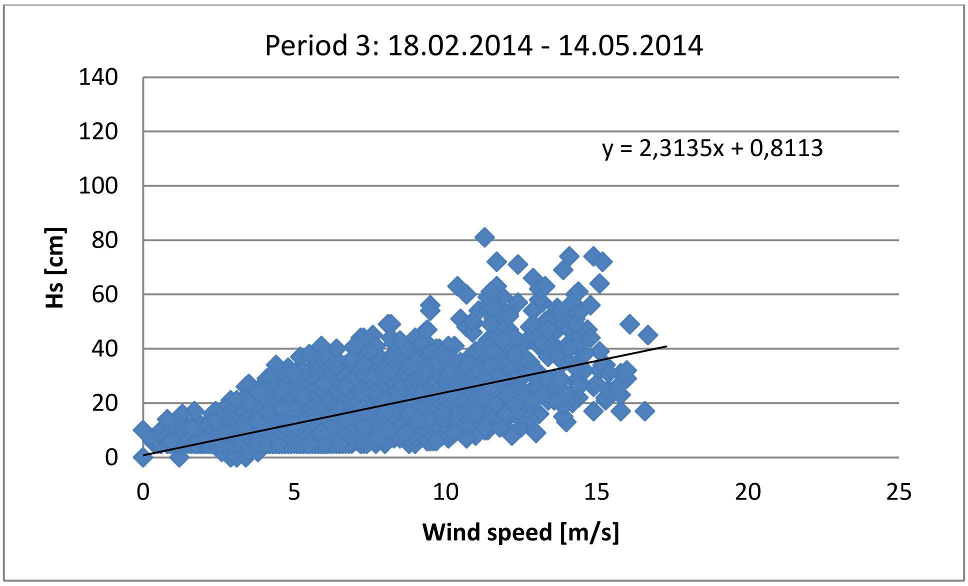
The dataset consist of the following data provided:

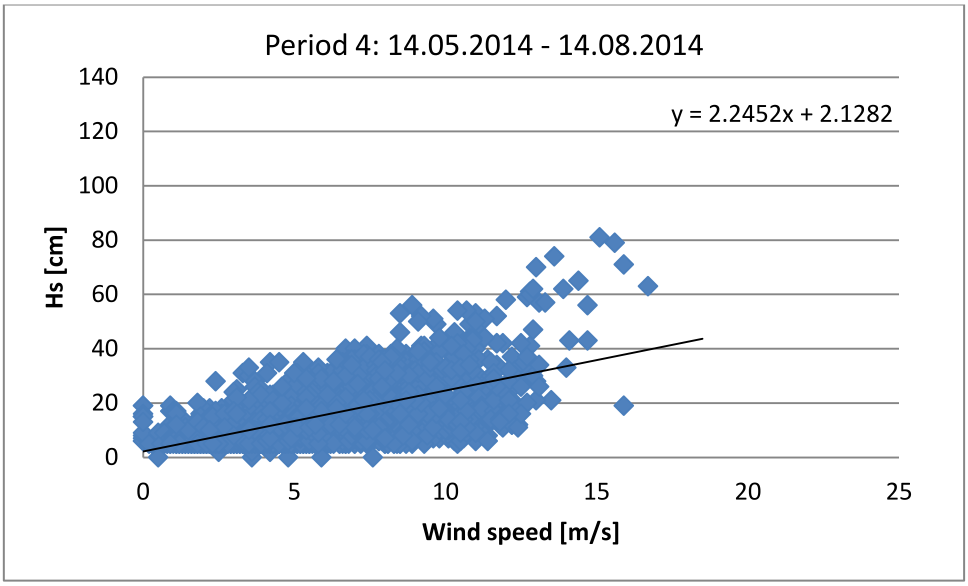
- wind speed [m/s], monitored every 10 minutes;
- significant wave height [cm], monitored every 30 minutes.

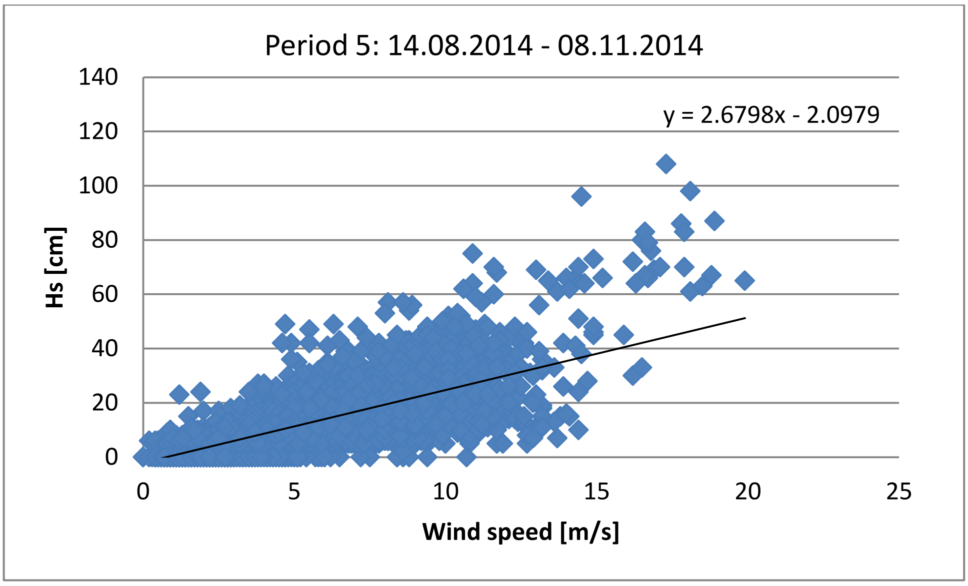
For every period, a graph has been realized with the help of Excel. The x-axis represents the wind speed expressed in m/s; the y-axis represents the significant wave height (or also called Hs) expressed in cm. Every graph shows the relation between the two variables. In all the graphs there are trend line and its equation. The graphs are reported below.

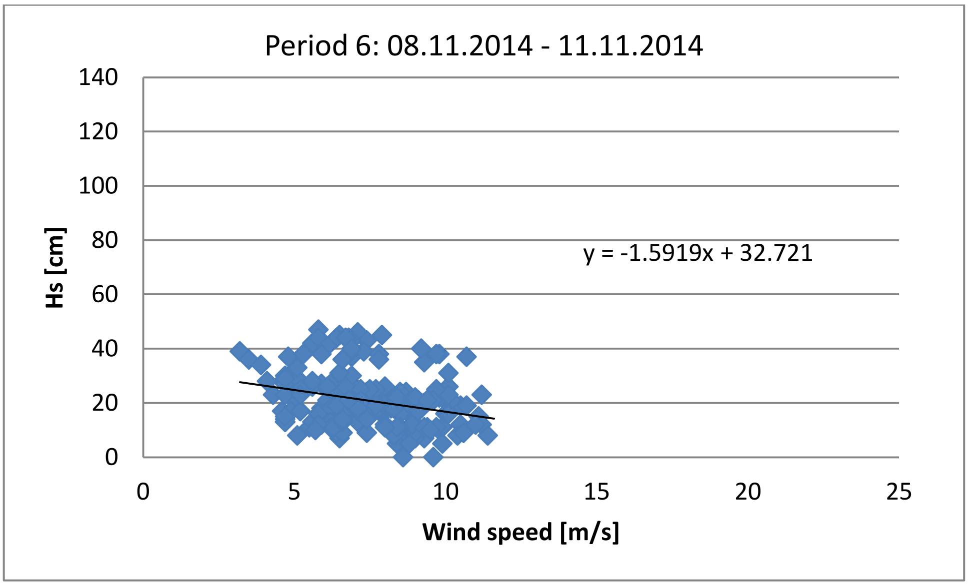

Period 1: 27.03.2013- 20.11.2013
y = 1,7728x + 5,0084
Hs [cm]
Wind speed [m/s]
0
20
40
60
80
100
120
140
0
5
10
15
20
25

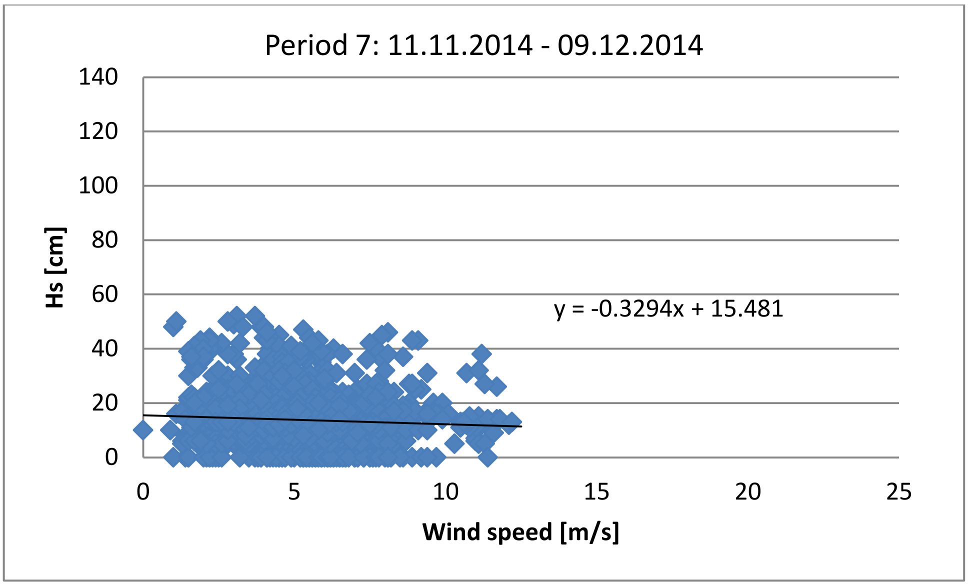

Period 2: 20.11.2013 - 18.02.2014
y = 2,6194x - 1,2045
Hs [cm]
Wind speed [m/s]
-20
0
20
40
60
80
100
120
140
0
5
10
15
20
25

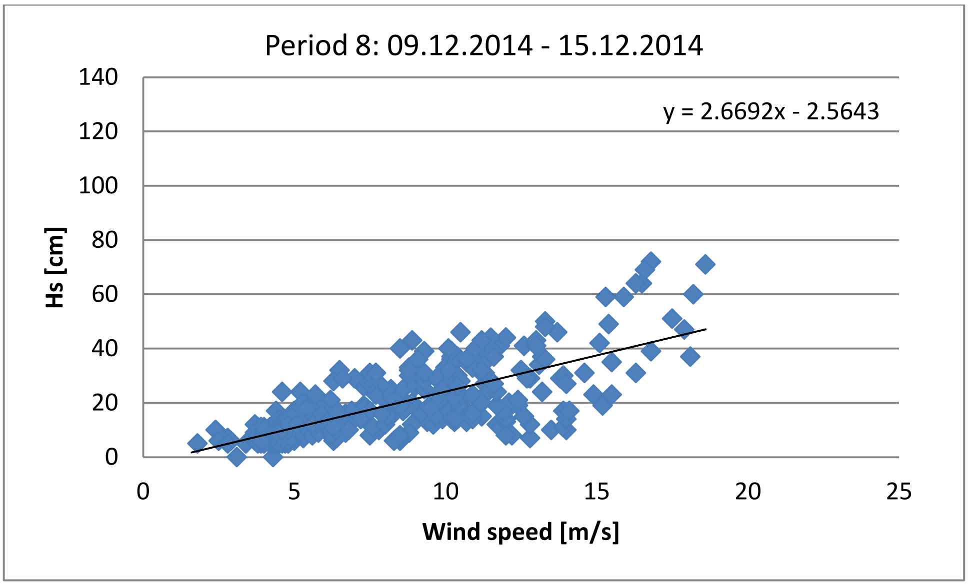

Period 3: 18.02.2014 - 14.05.2014
y = 2,3135x + 0,8113
Hs [cm]
Wind speed [m/s]
0
20
40
60
80
100
120
140
0
5
10
15
20
25

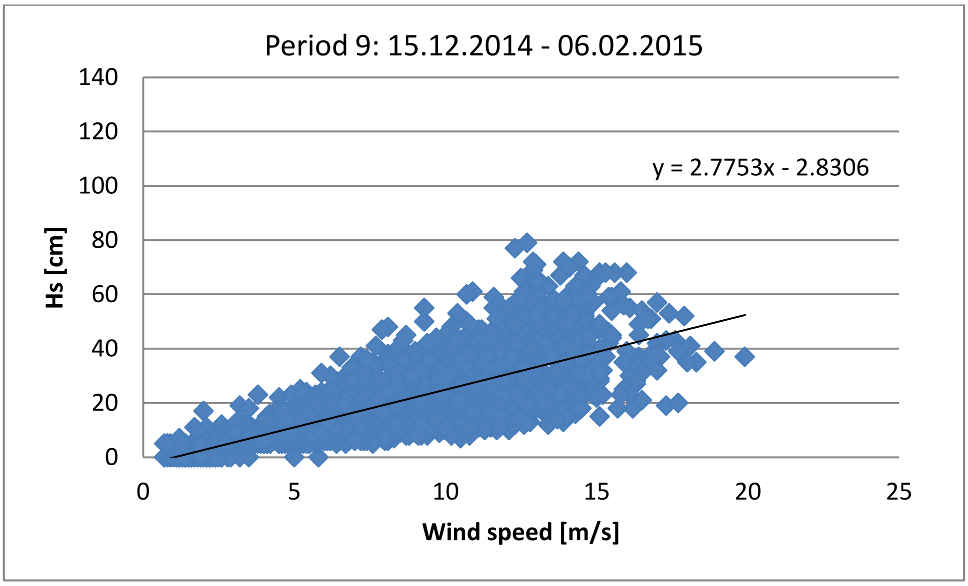

Period 4: 14.05.2014 - 14.08.2014
y = 2.2452x + 2.1282
Hs [cm]
0
20
40
60
80
100
120
140
0
5
10
15
20
25
Wind speed [m/s]

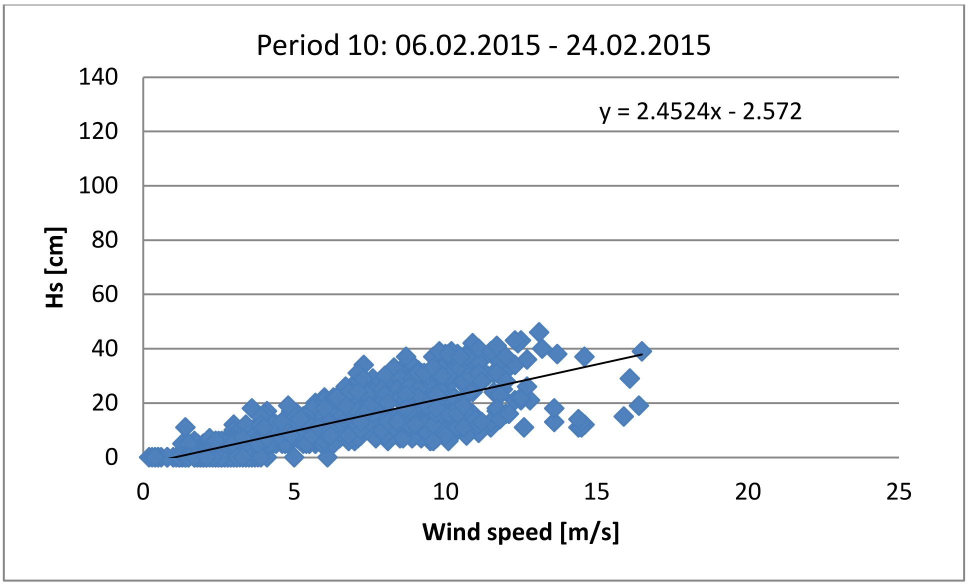

Period 5: 14.08.2014 - 08.11.2014
y = 2.6798x - 2.0979
Hs [cm]
0
20
40
60
80
100
120
140
0
5
10
15
20
25
Wind speed [m/s]

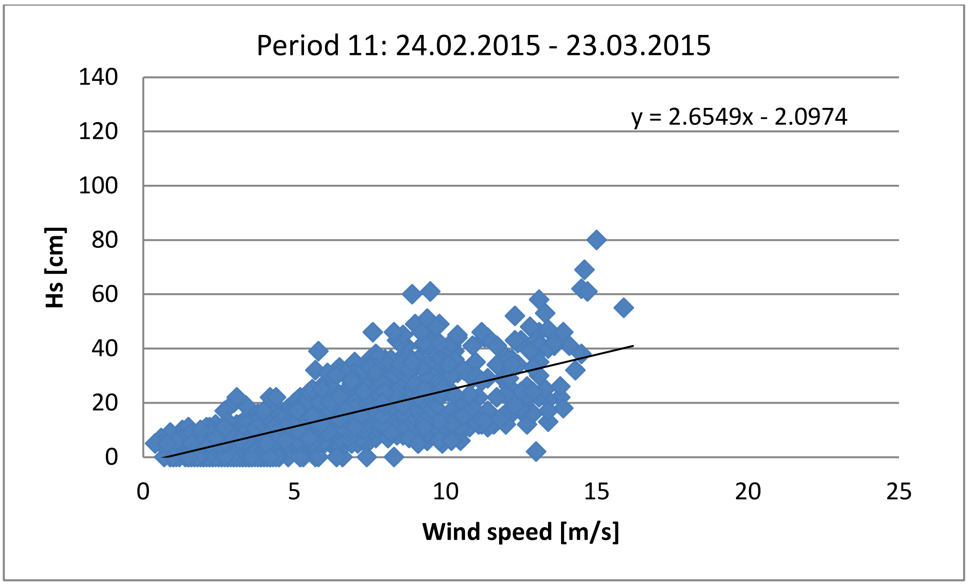

Period 6: 08.11.2014 - 11.11.2014
y = -1.5919x + 32.721
Hs [cm]
0
20
40
60
80
100
120
140
0
5
10
15
20
25
Wind speed [m/s]

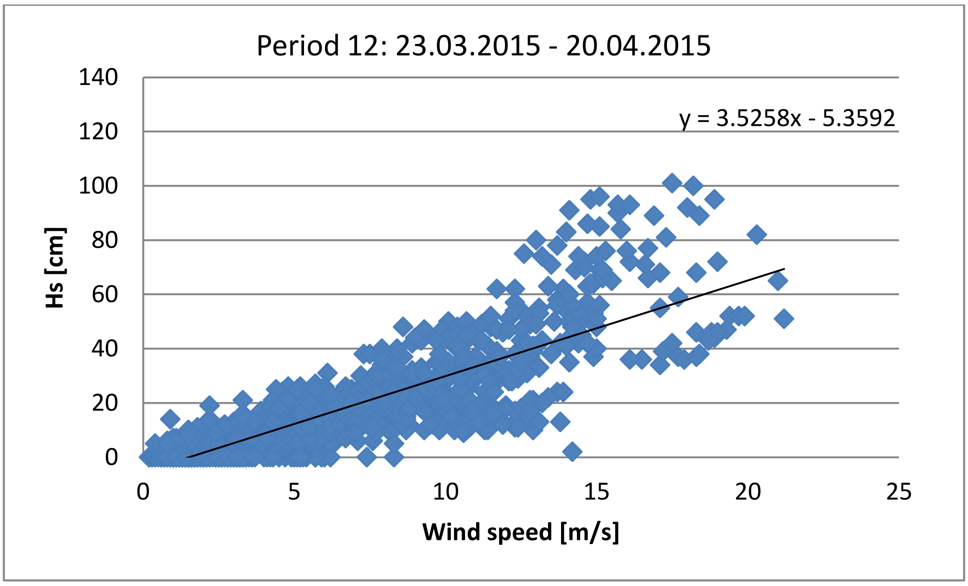

Period 7: 11.11.2014 - 09.12.2014
140
120
100
80
60
40
20
0
Hs [cm]
y = -0.3294x + 15.481
0
5
10
15
20
25
Wind speed [m/s]

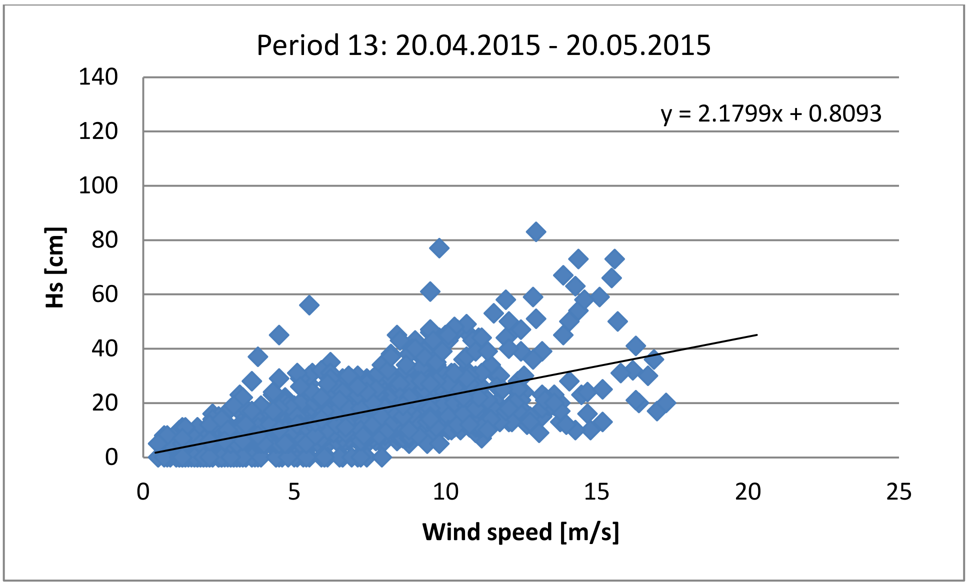

Period 8: 09.12.2014 - 15.12.2014
140
120
100
80
60
40
20
0
Hs [cm]
y = 2.6692x - 2.5643
0
5
10
15
20
25
Wind speed [m/s]

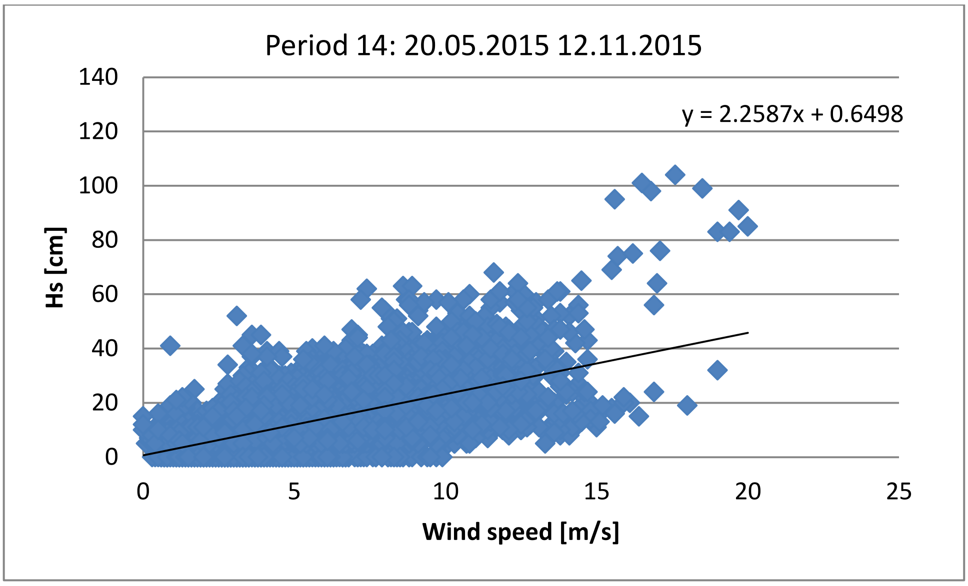

Period 9: 15.12.2014 - 06.02.2015
140
120
100
80
60
40
20
0
Hs [cm]
y = 2.7753x - 2.8306
0
5
10
15
20
25
Wind speed [m/s]

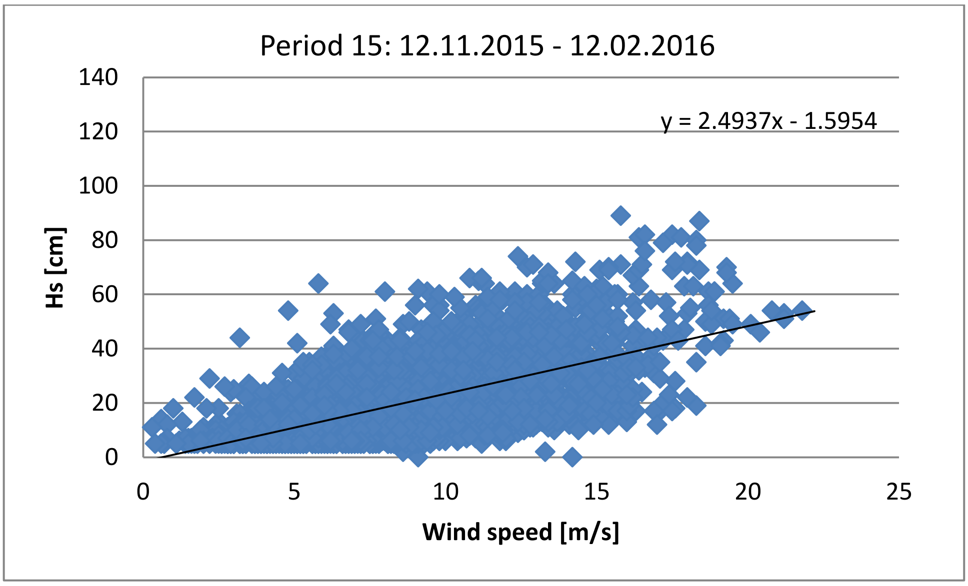

Period 10: 06.02.2015 - 24.02.2015
y = 2.4524x - 2.572
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]

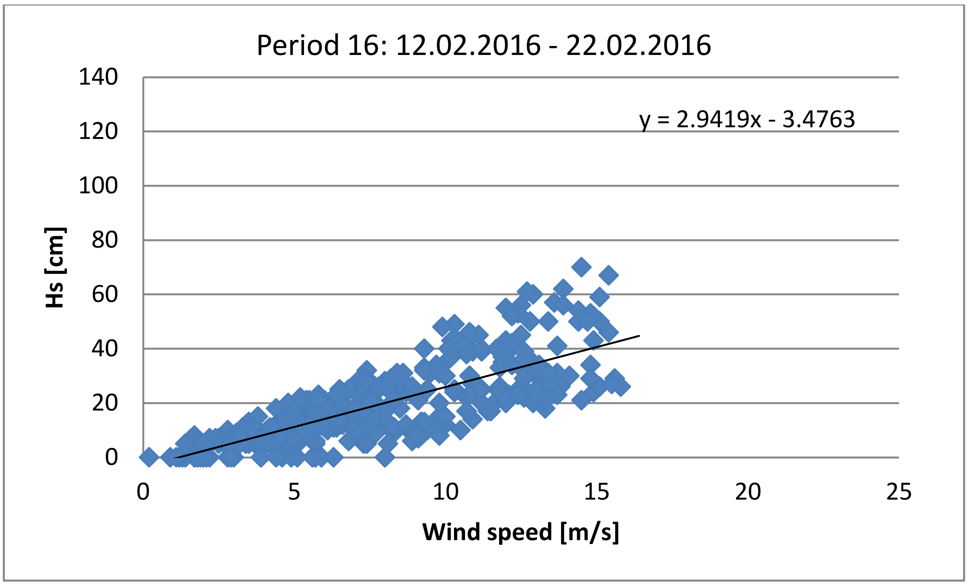

Period 11: 24.02.2015 - 23.03.2015
y = 2.6549x - 2.0974
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]

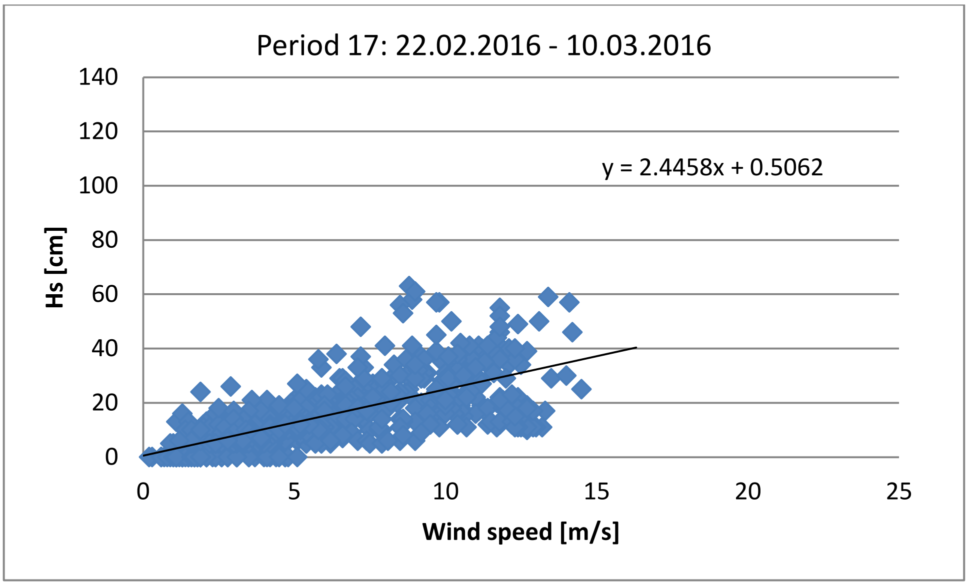

Period 12: 23.03.2015 - 20.04.2015
y = 3.5258x - 5.3592
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]

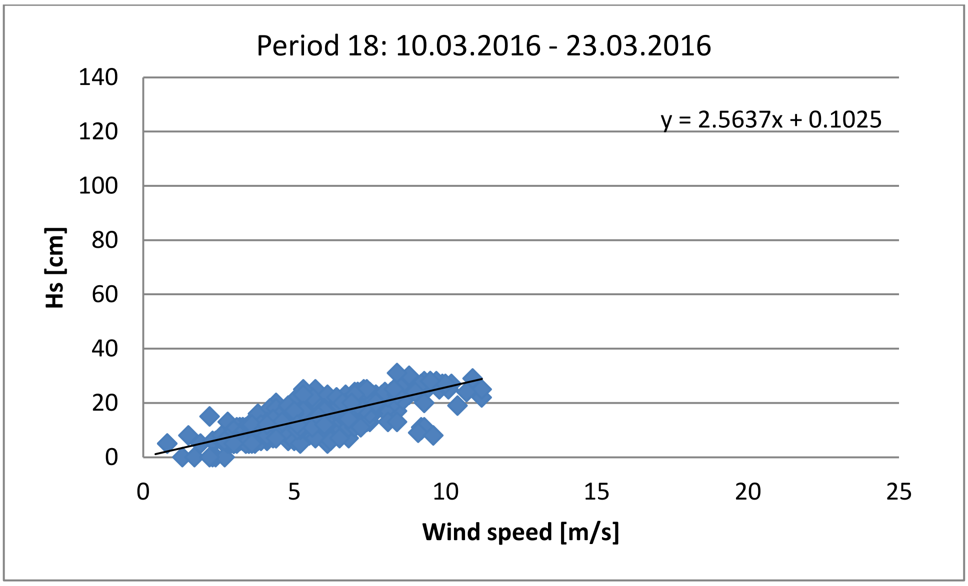

Period 13: 20.04.2015 - 20.05.2015
y = 2.1799x + 0.8093
Hs [cm]
Wind speed [m/s]

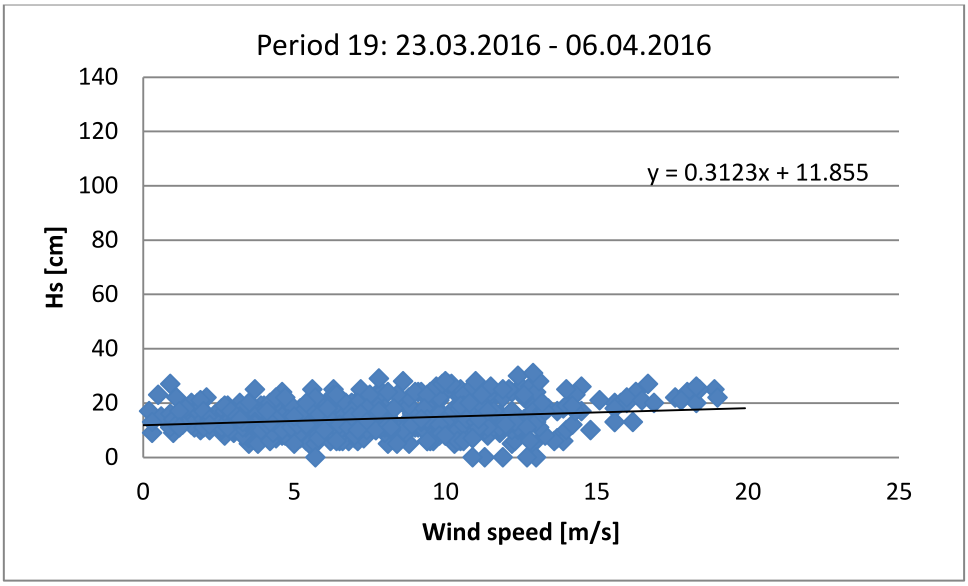

Period 14: 20.05.2015 12.11.2015
y = 2.2587x + 0.6498
Hs [cm]
Wind speed [m/s]

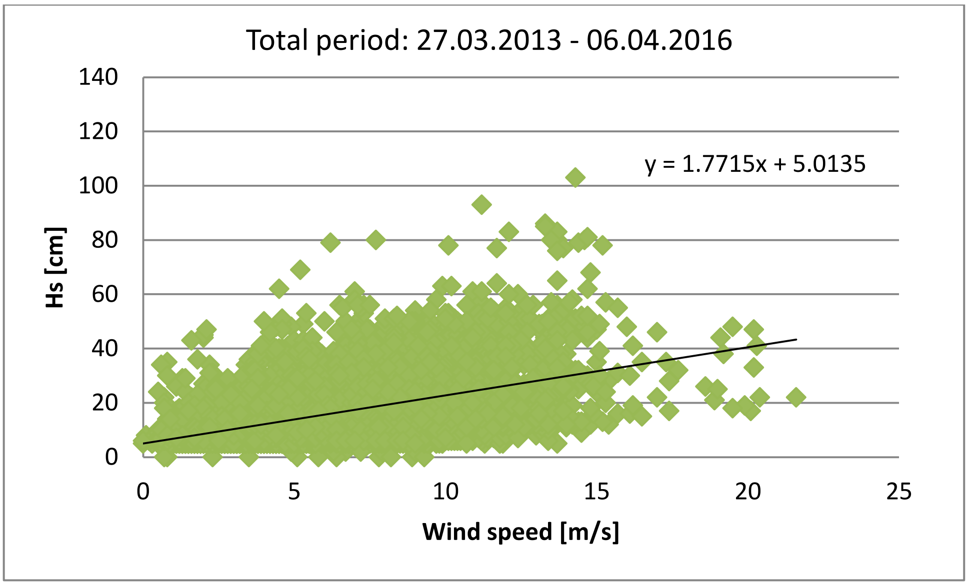

Period 15: 12.11.2015 - 12.02.2016
y = 2.4937x - 1.5954
Hs [cm]
Wind speed [m/s]


Period 16: 12.02.2016 - 22.02.2016
y = 2.9419x - 3.4763
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]


Period 17: 22.02.2016 - 10.03.2016
y = 2.4458x + 0.5062
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]


Period 18: 10.03.2016 - 23.03.2016
y = 2.5637x + 0.1025
Hs [cm]
140
120
100
80
60
40
20
0
0
5
10
15
20
25
Wind speed [m/s]





After this analysis is possible to observe that there is a relation between Hs and wind speed. In particular, thanks also to the trend lines, it's possible to define this correlation as a linear regression. It creates an equation so that values can be predicted within the range framed by the data. This is known as interpolation and it is expressed by the following equation:

$$y = ax + b$$

Where:

- a is the linear correlation coefficient, which represent the gradient of the line;
- b is the y-intercept.

Form the data collected it is possible to say that the linear regression is positive for all the graph except for two of them: in fact the sixth and seventh period shows a negative gradient.

In order to express the existing relation between the two variables, the R value has also been calculated for every period. The R factor is the Pearson correlation index. It is the parameter which will give a statistic idea of the correlation between the two variables, and it can be calculated as follows:

$$R = \frac{\sigma_{xy}}{\sigma_x \cdot \sigma_y}$$

Where:

- σ_{xy} is the covariance;
- σ_x, σ_y are the standard deviations in x,y.

The R factor can vary from -1 to +1. A correlation equal to 0indicates that between the two variables there is no report. Therefore it's possible to have different types of correlations. In particular:

- If R > 0, the variables x,y are directly correlated, or also positively correlated;
- If R=0, the variables x,y are not correlated;
- If R<0, the variables x,y are inversely correlated, or also negatively correlated.

Moreover, in case of variables positively correlated (and similarly in case of negatively correlation) it has to be distinguished:

- If 0<R<0.3, there is a weak correlation;
- If 0.3<R<0.7 there is a moderate correlation;
- If R>0.7, there is a strong correlation.

To test if there is a correlation, it is useful to take as a reference the sampling distribution of R, tabulated in a proper table; there is a critical value of r (r_{crit}) in correspondence with the degrees of freedom (N - 2), where N is the total value of the dataset, and in correspondence of the level of significance (α value).

In this case, the N of the dataset consist in more than 30,000 values per variable; therefore it's is immediate to deduce that the d.o.f (degrees of freedom) are considered equal to ∞. The α is considered equal to 0.01, this means that it has been considered a significance of 99%.

The reference table for the R_{crit} is the following one.

	Level of Significance for a One-Tailed Test					
	.10	.05	.025	.01	.005	.0005
	Level of Significance for a Two-Tailed Test					
df	.20	.10	.05	.02	.01	.001
1	0.951	0.988	0.997	0.9995	0.9999	0.99999
2	0.800	0.900	0.950	0.980	0.990	0.999
3	0.687	0.805	0.878	0.934	0.959	0.991
4	0.608	0.729	0.811	0.882	0.917	0.974
5	0.551	0.669	0.755	0.833	0.875	0.951
6	0.507	0.621	0.707	0.789	0.834	0.925
7	0.472	0.582	0.666	0.750	0.798	0.898
8	0.443	0.549	0.632	0.715	0.765	0.872
9	0.419	0.521	0.602	0.685	0.735	0.847
10	0.398	0.497	0.576	0.658	0.708	0.823
11	0.380	0.476	0.553	0.634	0.684	0.801
12	0.365	0.457	0.532	0.612	0.661	0.780
13	0.351	0.441	0.514	0.592	0.641	0.760
14	0.338	0.426	0.497	0.574	0.623	0.742
15	0.327	0.412	0.482	0.558	0.606	0.725
16	0.317	0.400	0.468	0.542	0.590	0.708
17	0.308	0.389	0.456	0.529	0.575	0.693
18	0.299	0.378	0.444	0.515	0.561	0.679
19	0.291	0.369	0.433	0.503	0.549	0.665
20	0.284	0.360	0.423	0.492	0.537	0.652
21	0.277	0.352	0.413	0.482	0.526	0.640
22	0.271	0.344	0.404	0.472	0.515	0.629
23	0.265	0.337	0.396	0.462	0.505	0.618
24	0.260	0.330	0.388	0.453	0.496	0.607
25	0.255	0.323	0.381	0.445	0.487	0.597
26	0.250	0.317	0.374	0.437	0.479	0.588
27	0.245	0.311	0.367	0.430	0.471	0.579
28	0.241	0.306	0.361	0.423	0.463	0.570
29	0.237	0.301	0.355	0.416	0.456	0.562
30	0.233	0.296	0.349	0.409	0.449	0.554
40	0.202	0.257	0.304	0.358	0.393	0.490
60	0.165	0.211	0.250	0.295	0.325	0.408
120	0.117	0.150	0.178	0.210	0.232	0.294
∞	0.057	0.073	0.087	0.103	0.114	0.146

Therefore , in order to give a complete overview, the following table shows a summary of the data obtained from the previous implementation.

Periods	Dates of the period	R	Verification [r_{calc}>r_{crit}]	Type of correlation
1	27.03.2013-20.11.2013	0.474	**Verified**	moderate
2	20.11.2013-18.02.2014	0.675	**Verified**	moderate
3	18.02.2014-14.05.2014	0.651	**Verified**	moderate
4	14.05.2014-14.08.2014	0.632	**Verified**	moderate
5	14.08.2014-08.11.2014	0.661	**Verified**	moderate
6	08.11.2014-11.11.2014	0.492	**Verified**	moderate
7	11.11.2014-09.12.2014	0.594	**Verified**	moderate
8	09.12.2014-15.12.2014	0.725	**Verified**	strong
9	15.12.2014-06.02.2015	0.723	**Verified**	strong
10	06.02.2015-24.02.2015	0.689	**Verified**	moderate
11	24.02.2015-23.03.2015	0.660	**Verified**	moderate
12	23.03.2015-20.04.2015	0.810	**Verified**	strong
13	20.04.2015-20.05.2015	0.583	**Verified**	moderate
14	20.05.2015-12.11.2015	0.581	**Verified**	moderate
15	12.11.2015- 12.02.2016	0.628	**Verified**	moderate
16	12.02.2016-22.02.2016	0.788	**Verified**	moderate
17	22.02.2016-10.03.2016	0.661	**Verified**	moderate
18	10.03.2016-23.03.2016	0.795	**Verified**	strong
19	23.03.2016-06.04.2016	0.717	**Verified**	strong
Total period	**27.03.2013-06.04.2016**	0.637	**Verified**	moderate

Significance test: t test

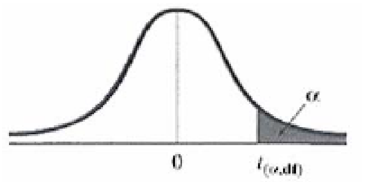
The methods of inference used to support or reject claims based on sample data are known as tests of significance. In this case, the test used is the t-test, realized with the help of the program Excel.

The t test is a statistical significance test used in the analysis of contingency tables. It is valid for all sample sizes. this calculation takes also into account d.o.f. and α value. The degrees of freedom are still considered equal to ∞ and $\alpha = 0.01$. In order to verify the significance of the values, the t value has been calculated with the following formula:

$$t = r \cdot \sqrt{\frac{N-2}{1-R^2}}$$

The reference table for the t_{crit} is the following one.

Tavola della distribuzione T di Student



Gradi di libertà	Area nella coda di destra								
	0.1	0.05	0.025	0.02	0.01	0.005	0.0025	0.001	0.0005
1	3.078	6.314	12.706	15.894	31.821	63.656	127.321	318.289	636.578
2	1.886	2.920	4.303	4.849	6.965	9.925	14.089	22.328	31.600
3	1.638	2.353	3.182	3.482	4.541	5.841	7.453	10.214	12.924
4	1.533	2.132	2.776	2.999	3.747	4.604	5.598	7.173	8.610
5	1.476	2.015	2.571	2.757	3.365	4.032	4.773	5.894	6.869
6	1.440	1.943	2.447	2.612	3.143	3.707	4.317	5.208	5.959
7	1.415	1.895	2.365	2.517	2.998	3.499	4.029	4.785	5.408
8	1.397	1.860	2.306	2.449	2.896	3.355	3.833	4.501	5.041
9	1.383	1.833	2.262	2.398	2.821	3.250	3.690	4.297	4.781
10	1.372	1.812	2.228	2.359	2.764	3.169	3.581	4.144	4.587
11	1.363	1.796	2.201	2.328	2.718	3.106	3.497	4.025	4.437
12	1.356	1.782	2.179	2.303	2.681	3.055	3.428	3.930	4.318
13	1.350	1.771	2.160	2.282	2.650	3.012	3.372	3.852	4.221
14	1.345	1.761	2.145	2.264	2.624	2.977	3.326	3.787	4.140
15	1.341	1.753	2.131	2.249	2.602	2.947	3.286	3.733	4.073
16	1.337	1.746	2.120	2.235	2.583	2.921	3.252	3.686	4.015
17	1.333	1.740	2.110	2.224	2.567	2.898	3.222	3.646	3.965
18	1.330	1.734	2.101	2.214	2.552	2.878	3.197	3.610	3.922
19	1.328	1.729	2.093	2.205	2.539	2.861	3.174	3.579	3.883
20	1.325	1.725	2.086	2.197	2.528	2.845	3.153	3.552	3.850
21	1.323	1.721	2.080	2.189	2.518	2.831	3.135	3.527	3.819
22	1.321	1.717	2.074	2.183	2.508	2.819	3.119	3.505	3.792
23	1.319	1.714	2.069	2.177	2.500	2.807	3.104	3.485	3.768
24	1.318	1.711	2.064	2.172	2.492	2.797	3.091	3.467	3.745
25	1.316	1.708	2.060	2.167	2.485	2.787	3.078	3.450	3.725
86	1.291	1.663	1.988	2.085	2.370	2.634	2.881	3.188	3.407
87	1.291	1.663	1.988	2.085	2.370	2.634	2.880	3.187	3.406
88	1.291	1.662	1.987	2.085	2.369	2.633	2.880	3.185	3.405
89	1.291	1.662	1.987	2.084	2.369	2.632	2.879	3.184	3.403
90	1.291	1.662	1.987	2.084	2.368	2.632	2.878	3.183	3.402
91	1.291	1.662	1.986	2.084	2.368	2.631	2.877	3.182	3.401
92	1.291	1.662	1.986	2.083	2.368	2.630	2.876	3.181	3.399
93	1.291	1.661	1.986	2.083	2.367	2.630	2.876	3.180	3.398
94	1.291	1.661	1.986	2.083	2.367	2.629	2.875	3.179	3.397
95	1.291	1.661	1.985	2.082	2.366	2.629	2.874	3.178	3.396
96	1.290	1.661	1.985	2.082	2.366	2.628	2.873	3.177	3.395
97	1.290	1.661	1.985	2.082	2.365	2.627	2.873	3.176	3.394
98	1.290	1.661	1.984	2.081	2.365	2.627	2.872	3.176	3.393
99	1.290	1.660	1.984	2.081	2.365	2.626	2.871	3.175	3.391
100	1.290	1.660	1.984	2.081	2.364	2.626	2.871	3.174	3.390
101	1.290	1.660	1.984	2.081	2.364	2.625	2.870	3.173	3.389
102	1.290	1.660	1.983	2.080	2.363	2.625	2.869	3.172	3.389
103	1.290	1.660	1.983	2.080	2.363	2.624	2.869	3.171	3.388
104	1.290	1.660	1.983	2.080	2.363	2.624	2.868	3.170	3.387
105	1.290	1.659	1.983	2.080	2.362	2.623	2.868	3.170	3.386
106	1.290	1.659	1.983	2.079	2.362	2.623	2.867	3.169	3.385
107	1.290	1.659	1.982	2.079	2.362	2.623	2.866	3.168	3.384
108	1.289	1.659	1.982	2.079	2.361	2.622	2.866	3.167	3.383
109	1.289	1.659	1.982	2.079	2.361	2.622	2.865	3.167	3.382
110	1.289	1.659	1.982	2.078	2.361	2.621	2.865	3.166	3.381
30000	1.282	1.645	1.960	2.054	2.326	2.576	2.807	3.091	3.291

The results of the significance test are showed below.

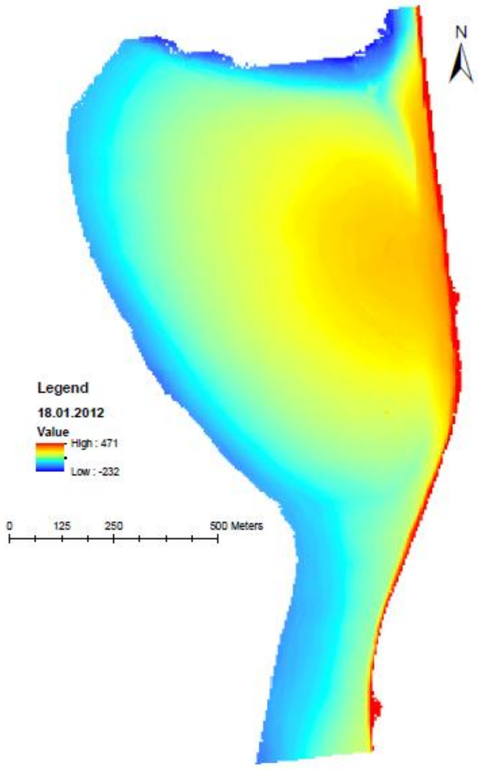
Periods	Dates of the period	t	Verification [r_{calc}>r_{crit}]
1	27.03.2013-20.11.2013	99.973	**Verified**
2	20.11.2013-18.02.2014	104.811	**Verified**
3	18.02.2014-14.05.2014	72.409	**Verified**
4	14.05.2014-14.08.2014	94.485	**Verified**
5	14.08.2014-08.11.2014	98.701	**Verified**
6	08.11.2014-11.11.2014	13.532	**Verified**
7	11.11.2014-09.12.2014	47.733	**Verified**
8	09.12.2014-15.12.2014	33.316	**Verified**
9	15.12.2014-06.02.2015	92.423	**Verified**
10	06.02.2015-24.02.2015	49.697	**Verified**
11	24.02.2015-23.03.2015	55.805	**Verified**
12	23.03.2015-20.04.2015	89.190	**Verified**
13	20.04.2015-20.05.2015	47.924	**Verified**
14	20.05.2015-12.11.2015	114.089	**Verified**
15	12.11.2015- 12.02.2016	93.312	**Verified**
16	12.02.2016-22.02.2016	50.906	**Verified**
17	22.02.2016-10.03.2016	44.886	**Verified**
18	10.03.2016-23.03.2016	60.885	**Verified**
19	23.03.2016-06.04.2016	46.165	**Verified**
Total period	**27.03.2013-06.04.2016**	333.561	**Verified**

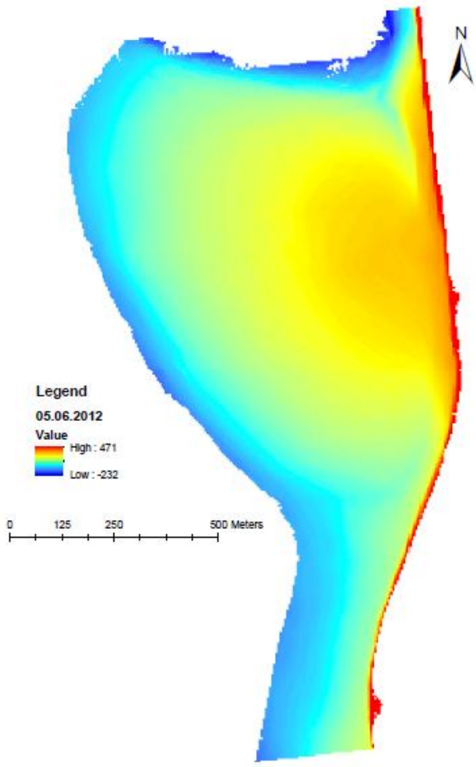
Conclusion

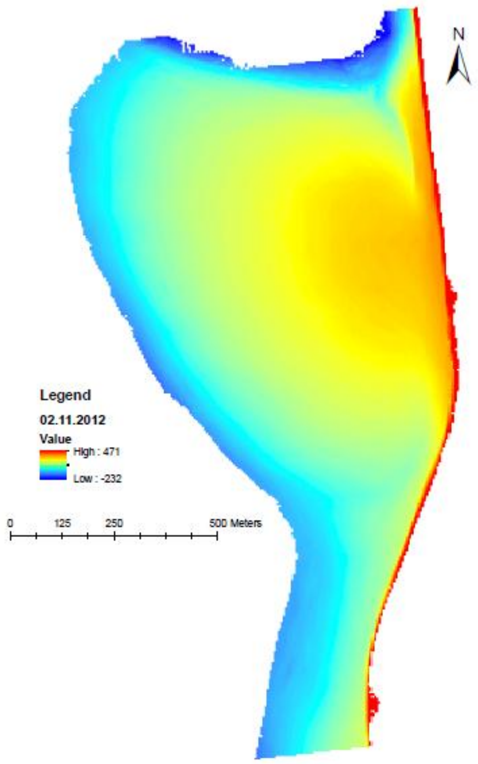
Thanks to the first result, it is possible to say that there is a correlation between significant wave height and wind speed. With the second verification, it is also possible to say that the relation between these two variables is also significance relation.

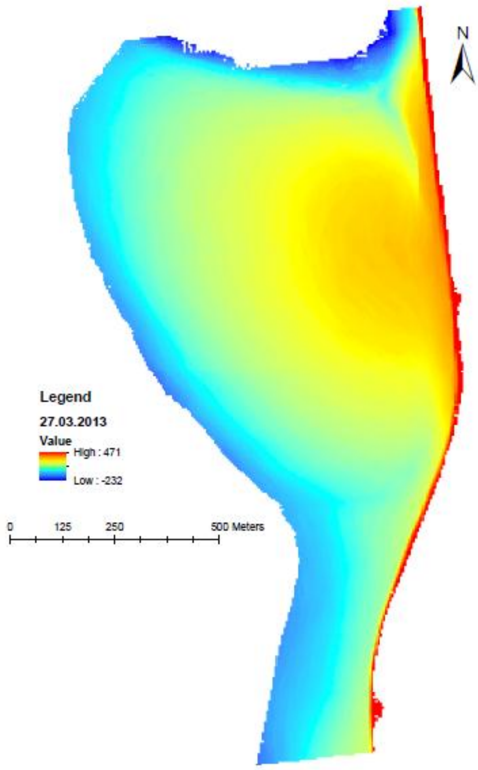
There, in for this research, this significant relation between Hs and wind speed explain finally that all the waves generated in the Eastern Scheldt basin (at the position of Oesterdam), are all generated by the wind.

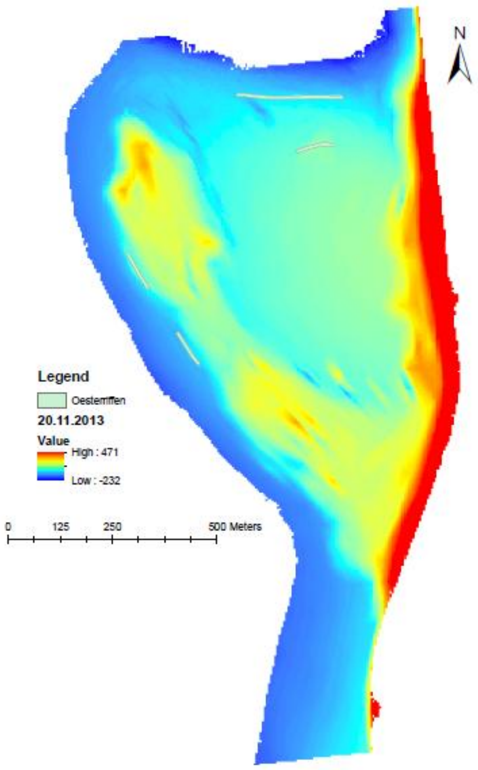
Appendix C: Long term analysis maps (Rijkswaterstaat maps)

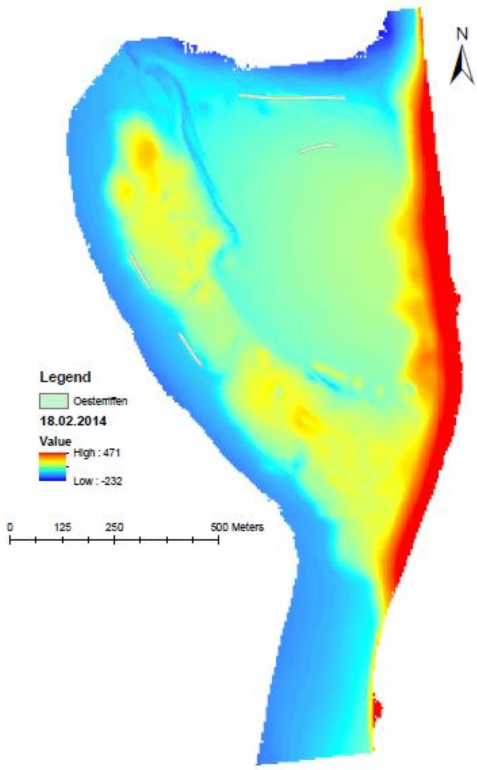









N
Legend
Oesterriffen
20.11.2013
Value
High : 471
Low : -232
0 125 250 500 Meters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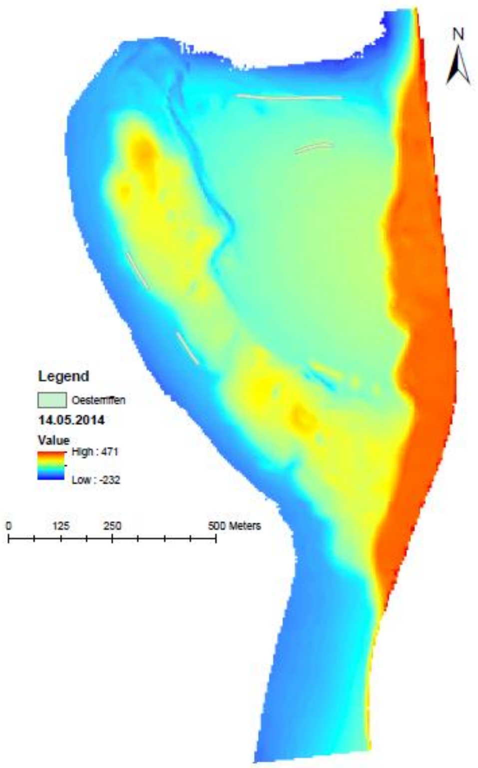
Legend
Oesterriffen
18.02.2014
Value
High : 471
Low : -232
0 125 250 500 Meters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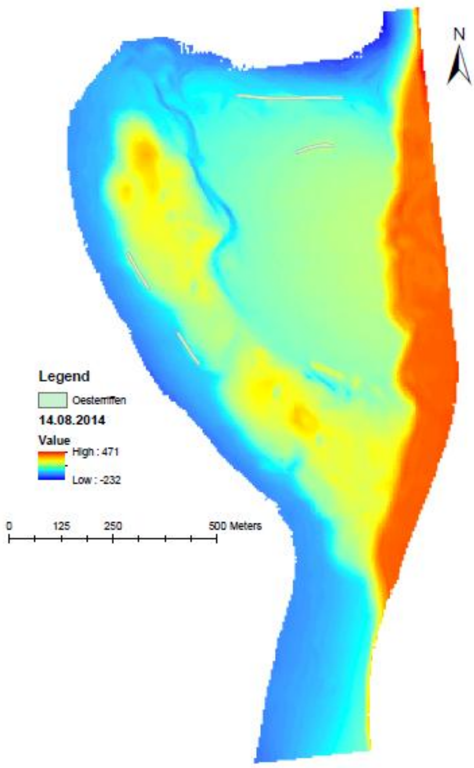
Legend
Oesterriffen
14.05.2014
Value
High : 471
Low : -232
0 125 250 500 Meters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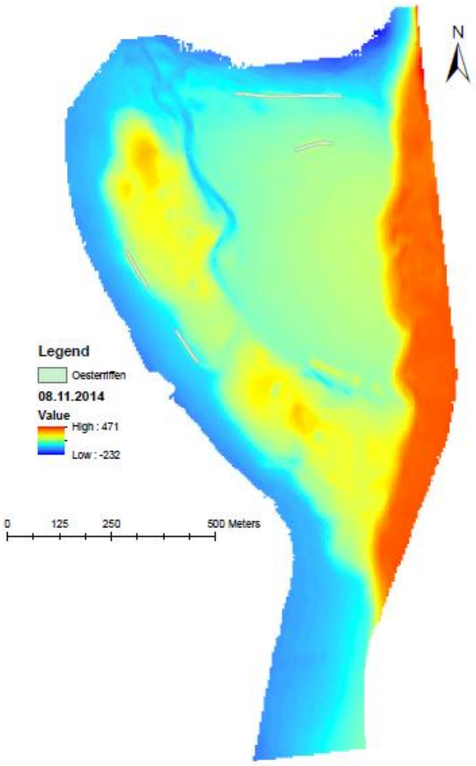
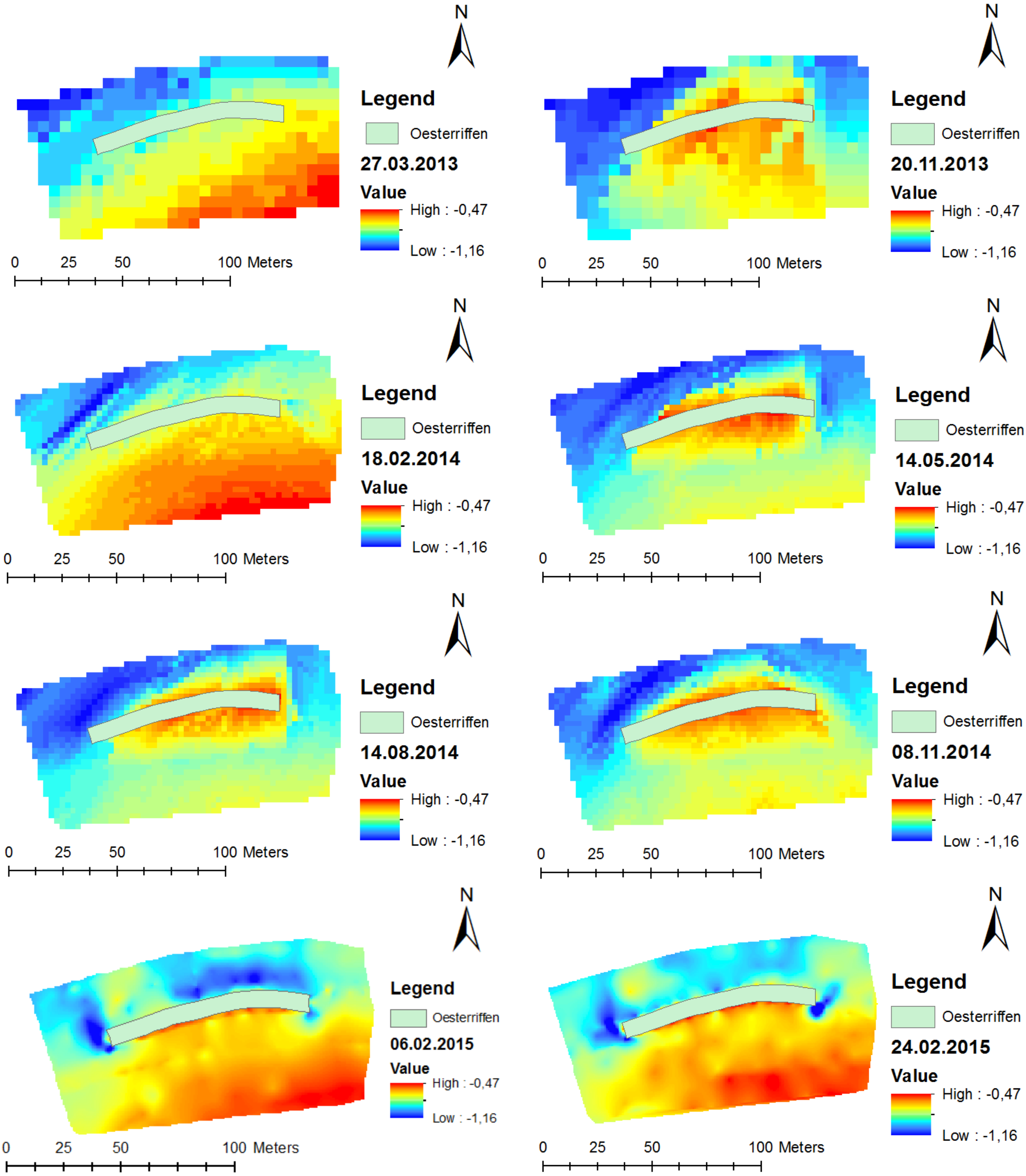
Legend
Oesterriffen
14.08.2014
Value
High : 471
Low : -232
0 125 250 500 Meters

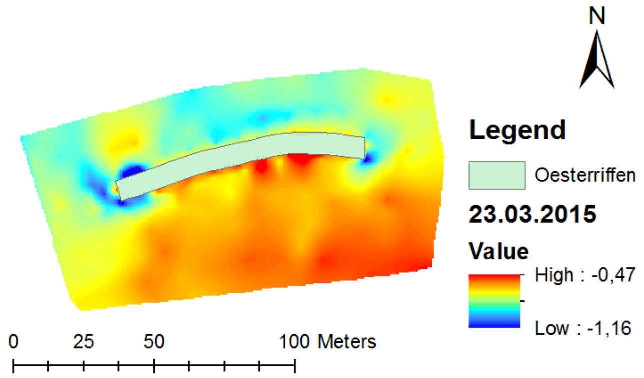

N
Legend
Oesterriffen
08.11.2014
Value
High : 471
Low : -232
0
125
250
500 Meters

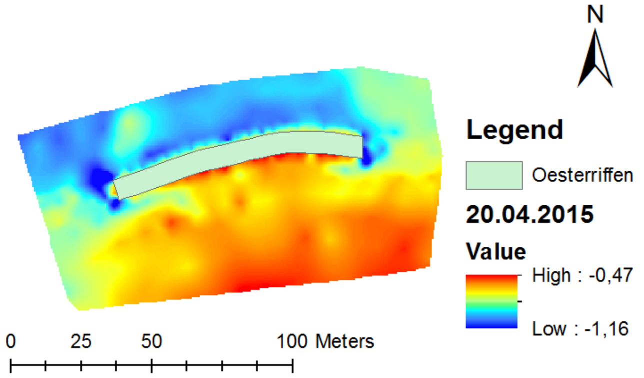
Appendix D: Short term analysis maps

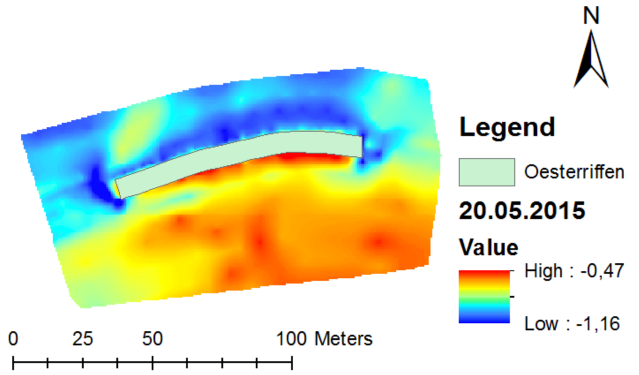
In this section elevation maps of each single reef will be showed; they are placed following the time line, from left side to right side, from the first one (before the sand nourishment) until the end, date of the last measurement.

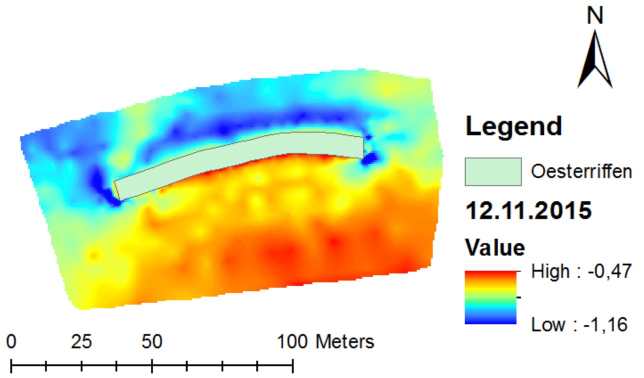
Reef A

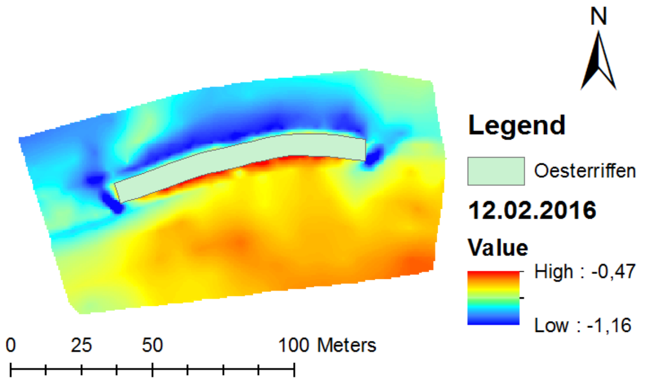


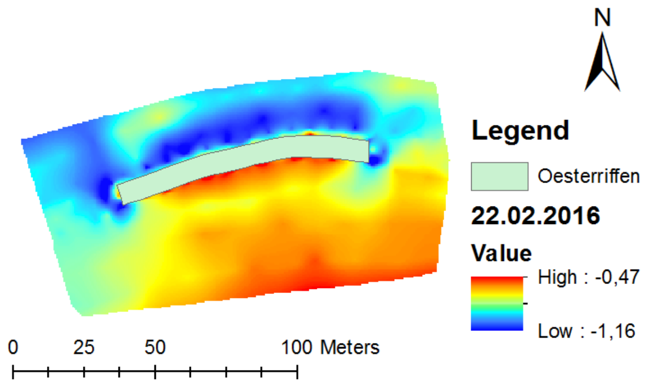

N
Legend
Oesterriffen
23.03.2015
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters

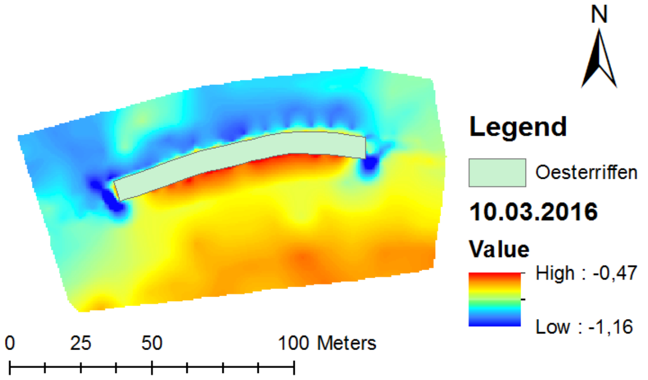

N
Legend
Oesterriffen
20.04.2015
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters


N
Legend
Oesterriffen
20.05.2015
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters


N
Legend
Oesterriffen
12.11.2015
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters


N
Legend
Oesterriffen
12.02.2016
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters


N
Legend
Oesterriffen
22.02.2016
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters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Legend
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10.03.2016
Value
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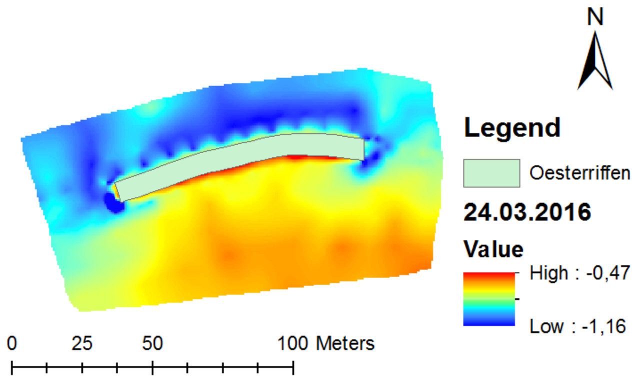
Low : -1,16
0 25 50 100 Meters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Legend
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24.03.2016
Value
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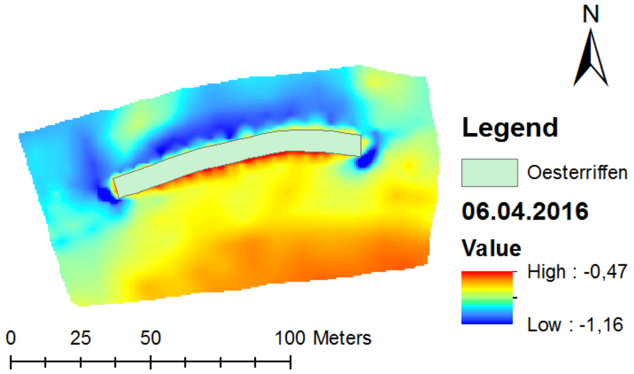
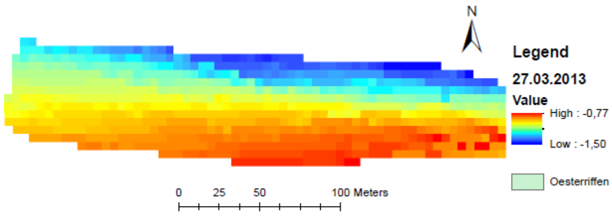
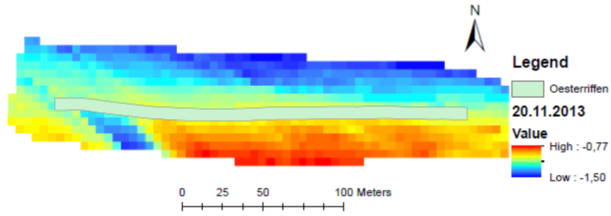
Low : -1,16
0 25 50 100 Meters


N
Legend
Oesterriffen
06.04.2016
Value
High : -0,47
Low : -1,16
0 25 50 100 Meters

Reef B


N
Legend
27.03.2013
Value
High : -0,77
Low : -1,50
Oesterriffen
0 25 50 100 Meters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Legend
Oesterriffen
20.11.2013
Value
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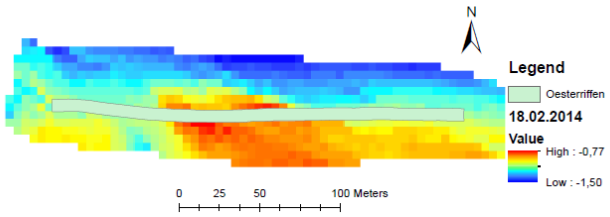
Low : -1,50
0 25 50 100 Meters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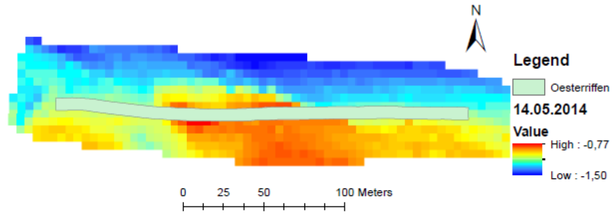
Legend
Oesterriffen
18.02.2014
Value
High : -0,77
Low : -1,50
0 25 50 100 Meters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Legend
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Low : -1,50
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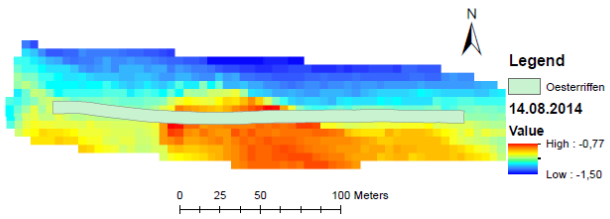
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Legend
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Value
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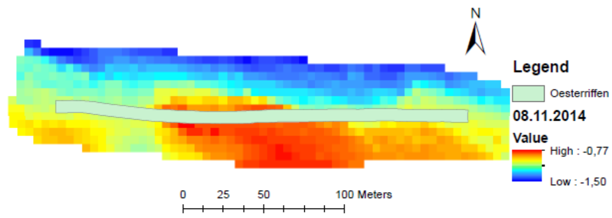
Low : -1,50
0 25 50 100 Meters


N
Legend
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Value
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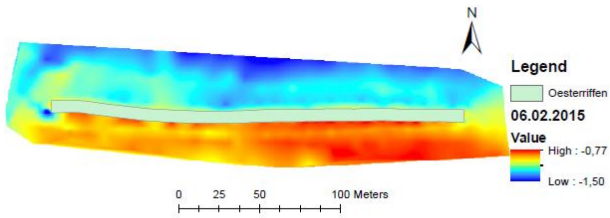
Low : -1,50
0 25 50 100 Meters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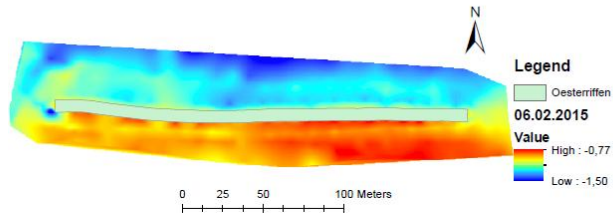
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Value
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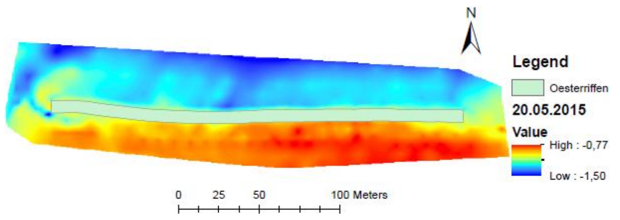
0 25 50 100 Meters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Legend
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20.05.2015
Value
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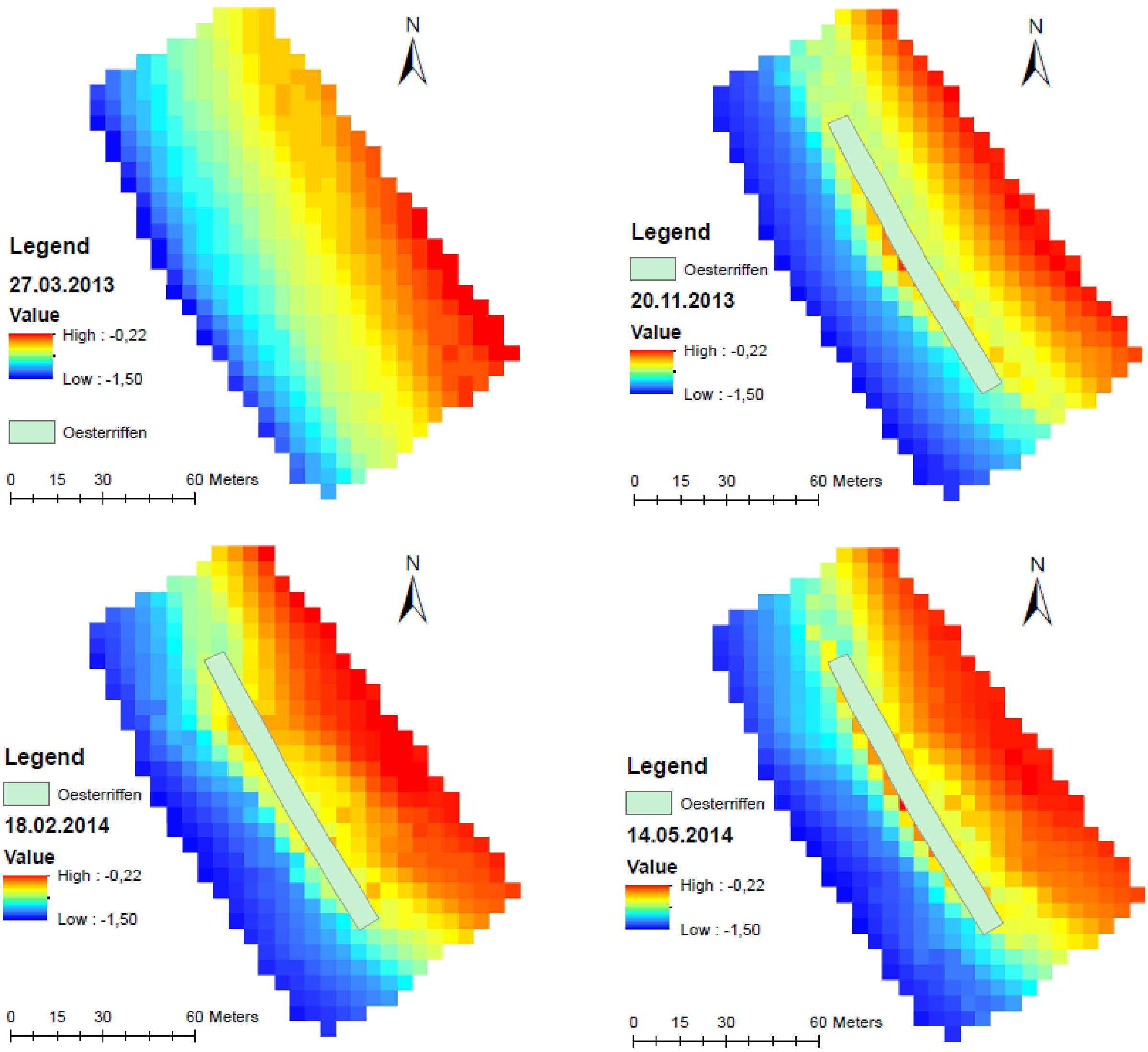
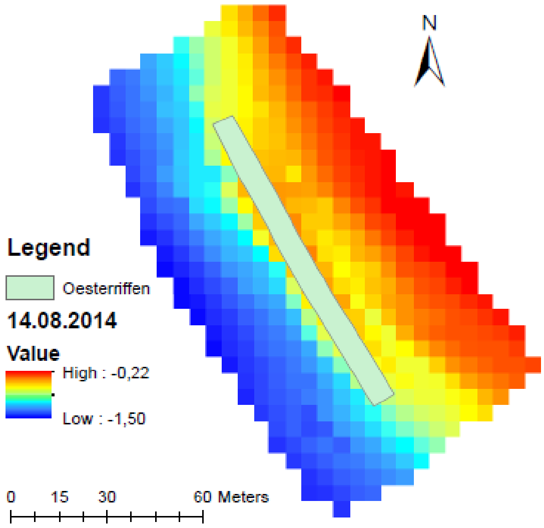
Low : -1,50
0 25 50 100 Meters

Reef C


N
Legend
27.03.2013
Value
High : -0,22
Low : -1,50
Oesterriffen
0 15 30 60 Meters
N
Legend
Oesterriffen
20.11.2013
Value
High : -0,22
Low : -1,50
0 15 30 60 Meters
N
Legend
Oesterriffen
18.02.2014
Value
High : -0,22
Low : -1,50
0 15 30 60 Meters
N
Legend
Oesterriffen
14.05.2014
Value
High : -0,22
Low : -1,50
0 15 30 60 Meters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Legend
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Value
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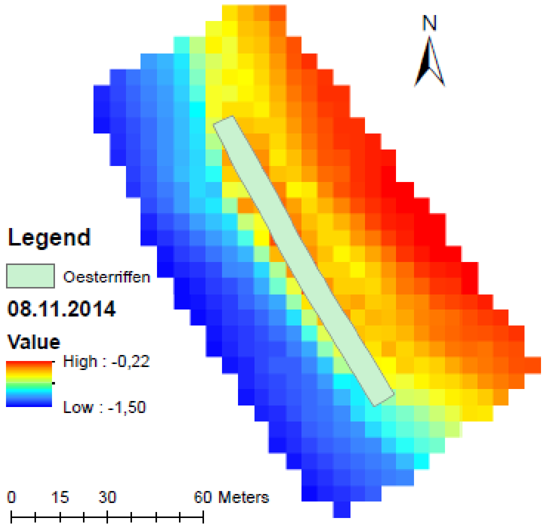
Low : -1,50
0 15 30 60 Meters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Low : -1,50
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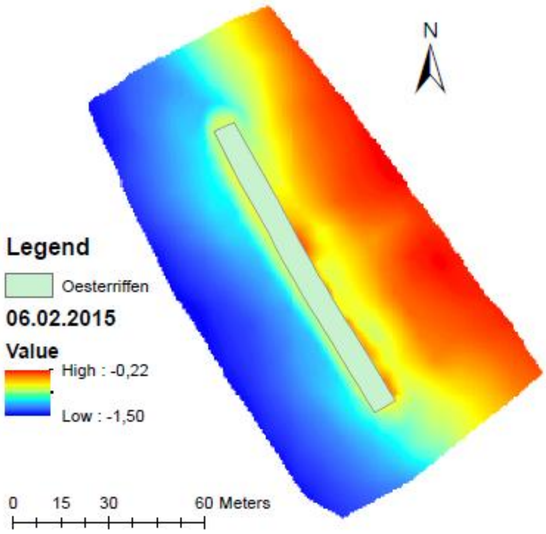
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Value
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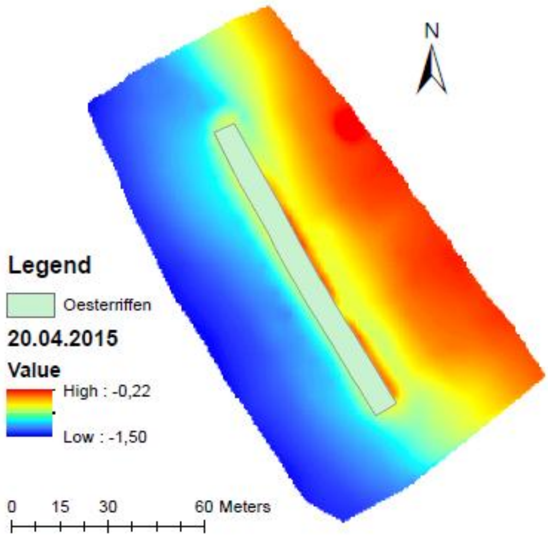
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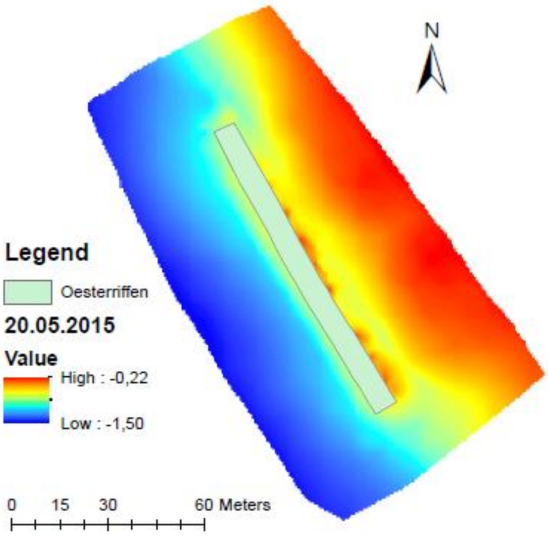
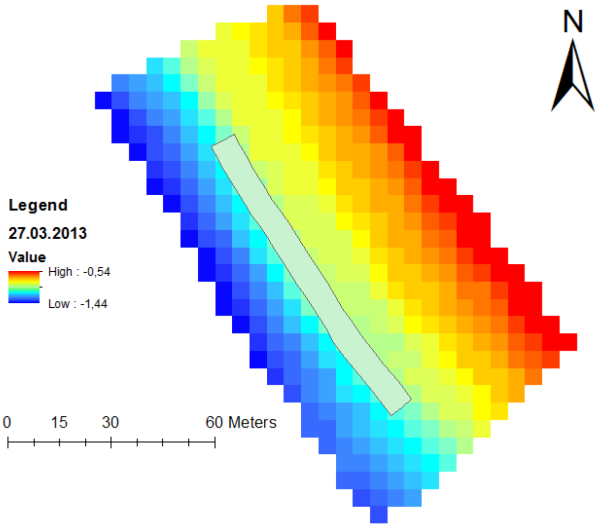

N
Legend
Oesterriffen
20.05.2015
Value
High : -0,22
Low : -1,50
0 15 30 60 Meters

Reef D


N
Legend
27.03.2013
Value
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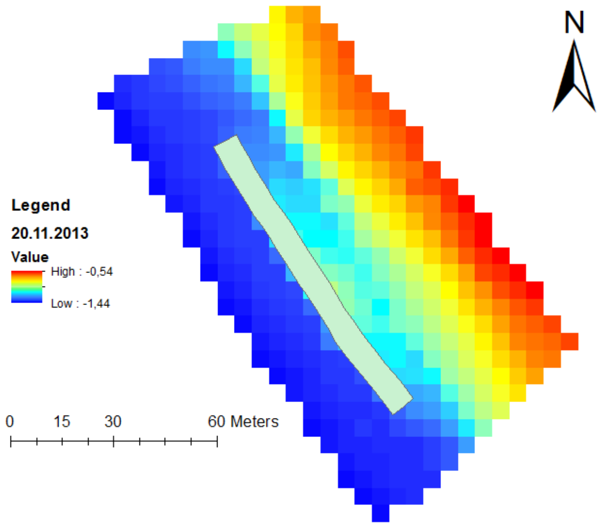
Low : -1,44
0 15 30 60 Meters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Legend
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Value
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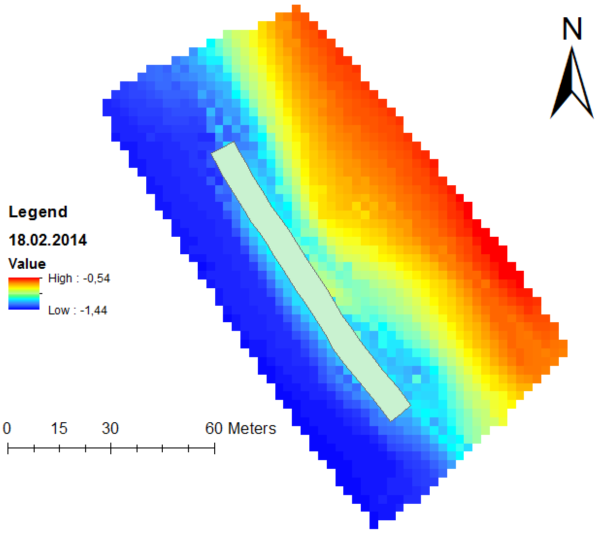
0 15 30 60 Meters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Legend
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Value
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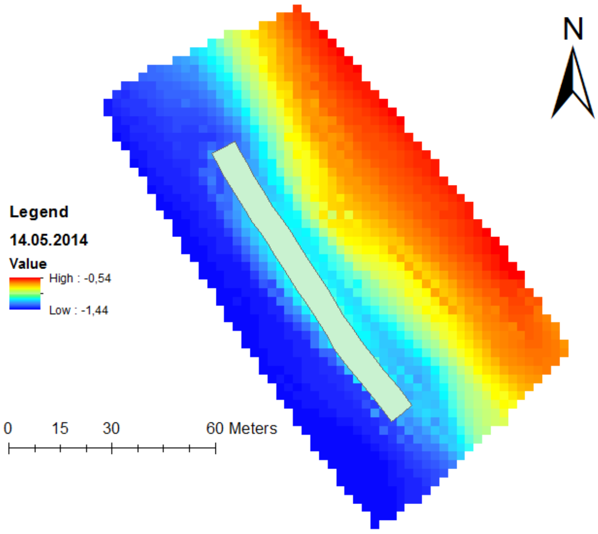
Low : -1,44
0 15 30 60 Meters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Legend
14.05.2014
Value
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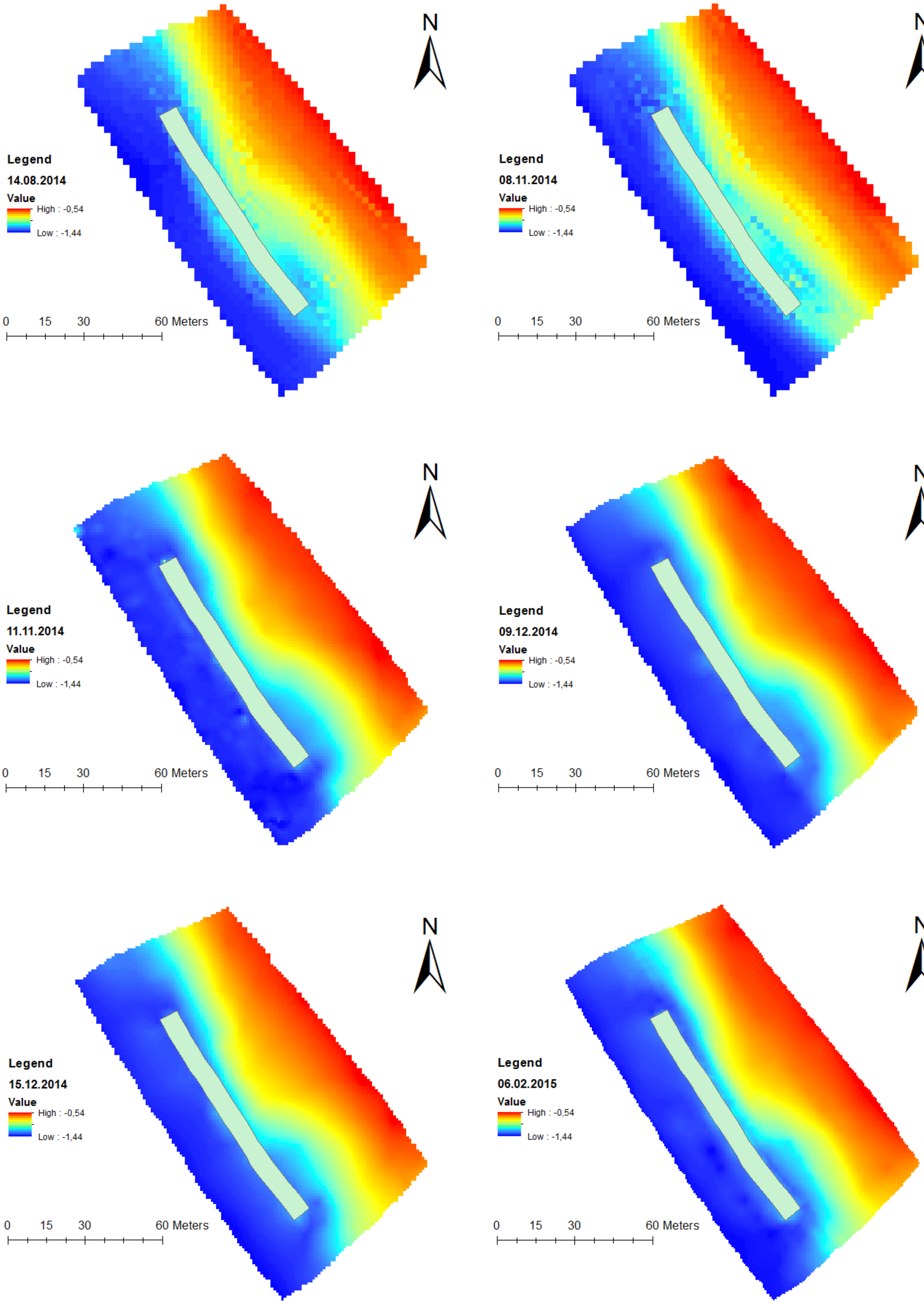
Low : -1,44
0 15 30 60 Meters


N
Legend
14.08.2014
Value
High : -0,54
Low : -1,44
0 15 30 60 Meters
N
Legend
08.11.2014
Value
High : -0,54
Low : -1,44
0 15 30 60 Meters
N
Legend
11.11.2014
Value
High : -0,54
Low : -1,44
0 15 30 60 Meters
N
Legend
09.12.2014
Value
High : -0,54
Low : -1,44
0 15 30 60 Meters
N
Legend
15.12.2014
Value
High : -0,54
Low : -1,44
0 15 30 60 Meters
N
Legend
06.02.2015
Value
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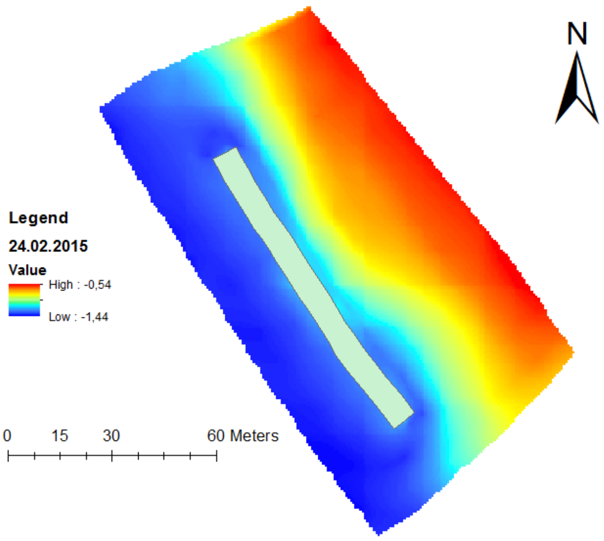
Low : -1,44
0 15 30 60 Meters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Legend
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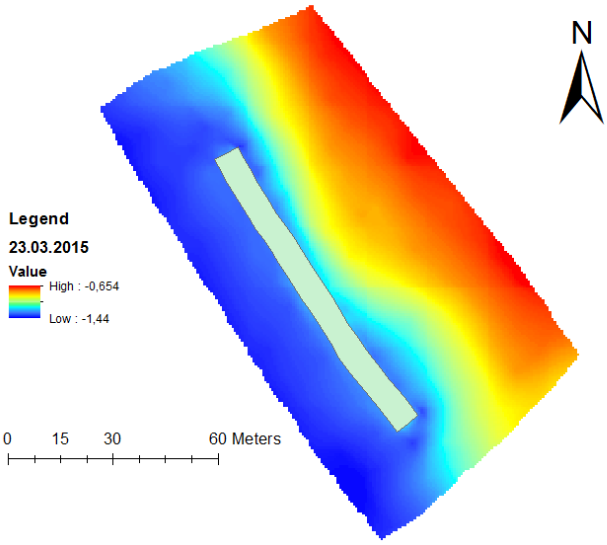
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Legend
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Value
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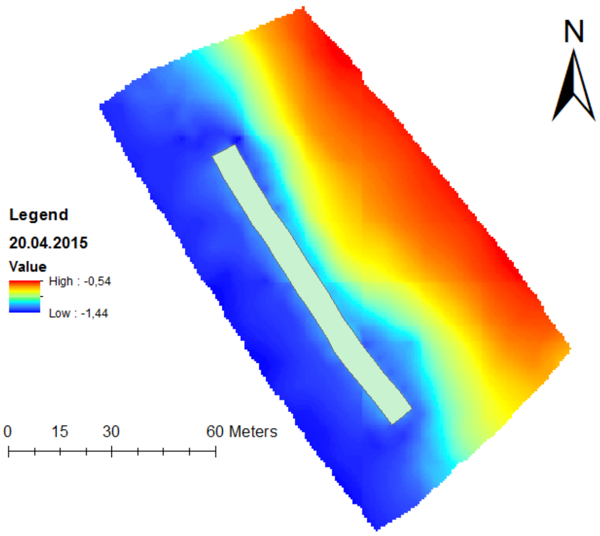
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Legend
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Value
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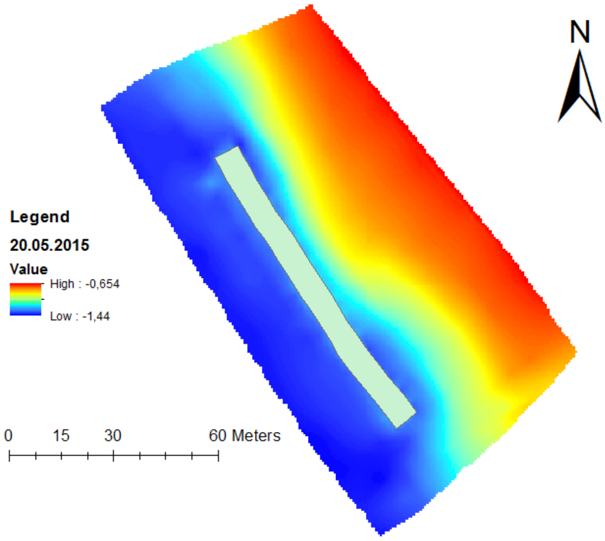
Low : -1,44
0 15 30 60 Meters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Legend
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Value
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Low : -1,44
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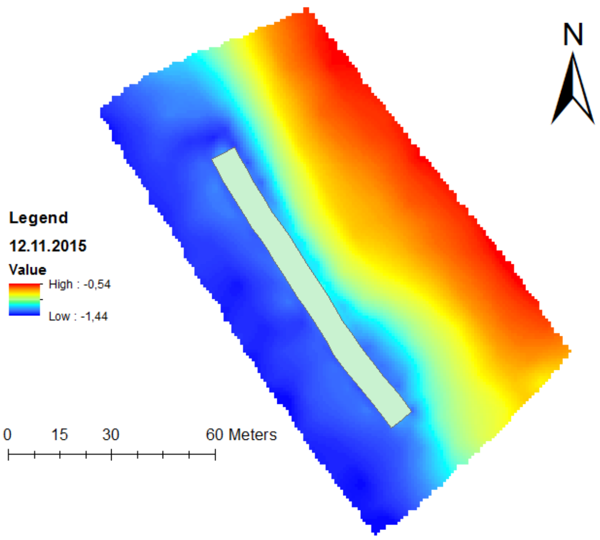
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Legend
12.11.2015
Value
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Low : -1,44
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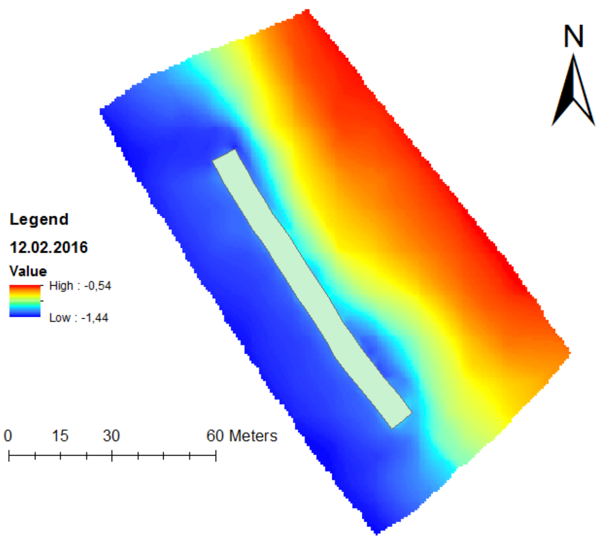
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Legend
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Value
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Low : -1,44
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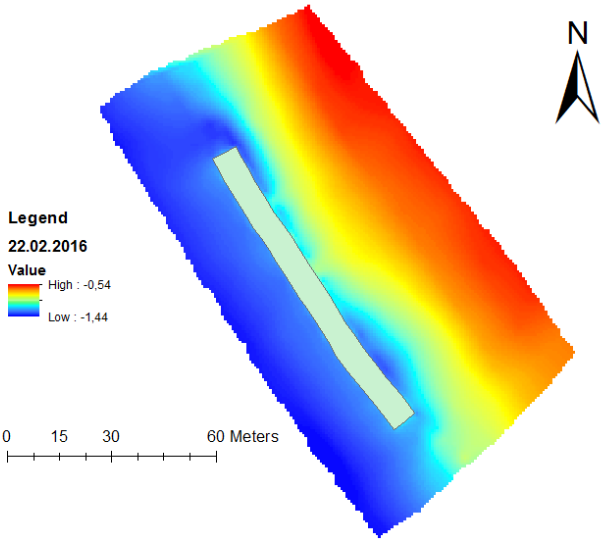
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Value
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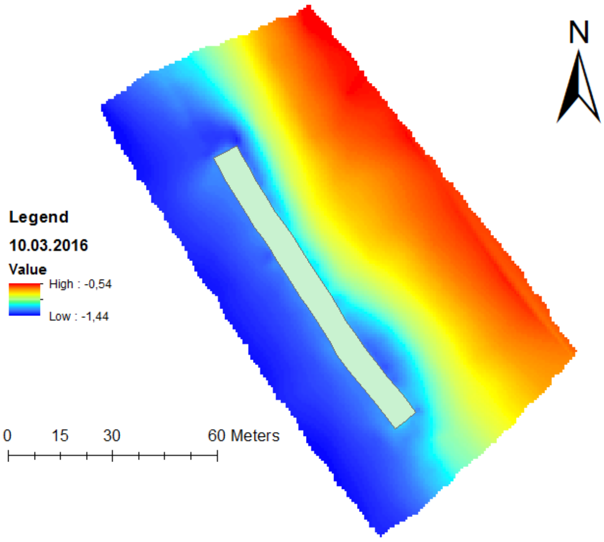
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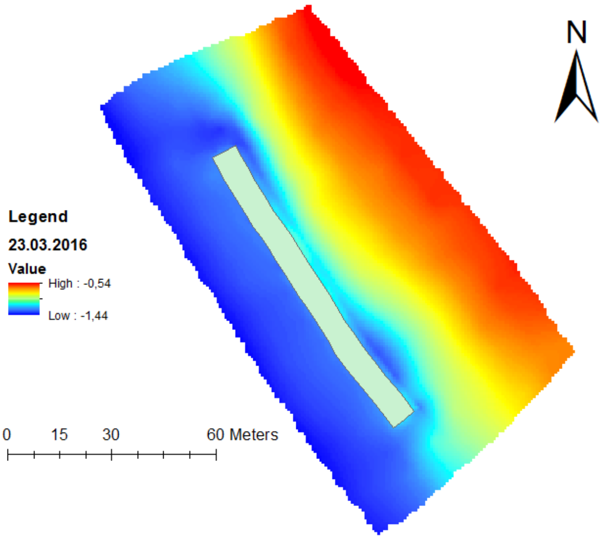
Low : -1,44
0 15 30 60 Meters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Legend
23.03.2016
Value
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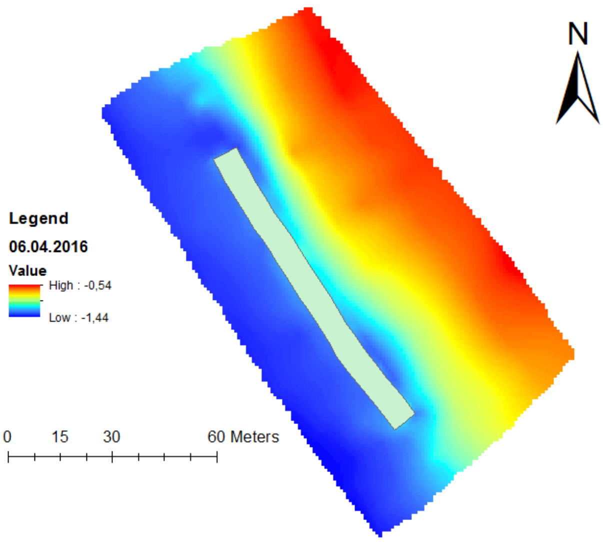
Low : -1,44
0 15 30 60 Meters


N
Legend
06.04.2016
Value
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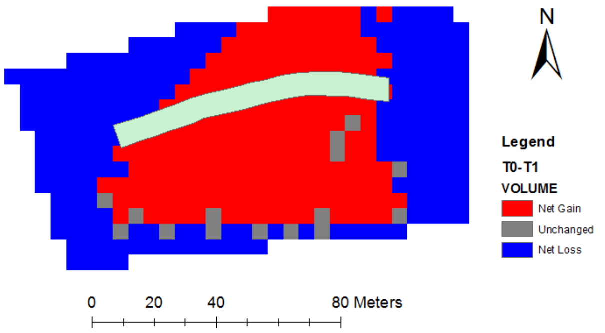
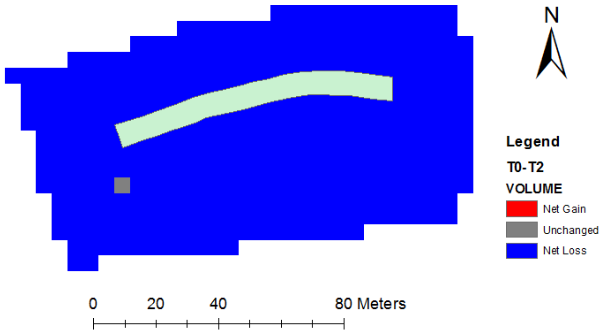
Low : -1,44
0 15 30 60 Meters

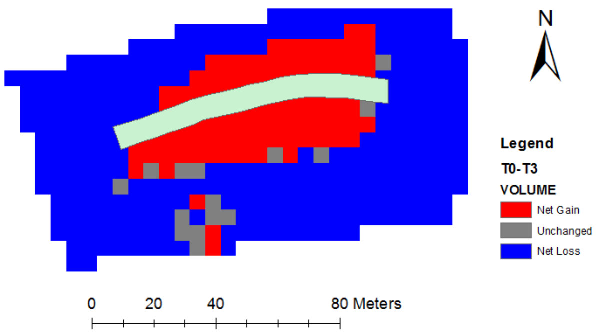
Appendix E: Erosion/sedimentation maps

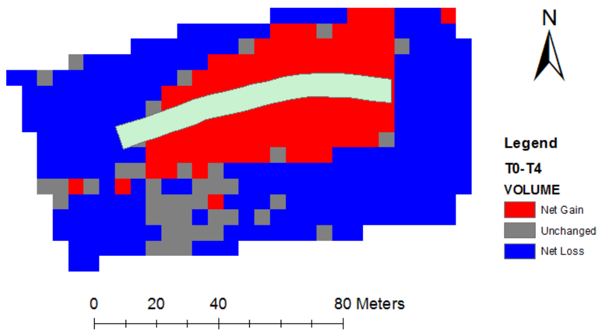
Reef A

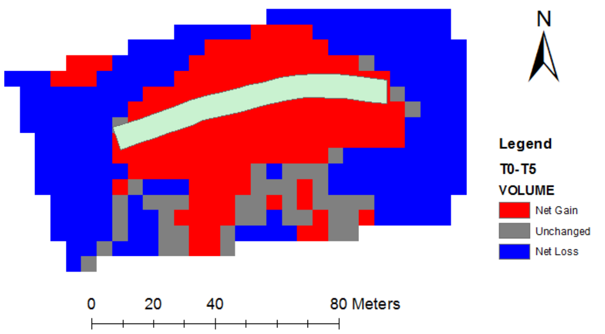
Long term analysis



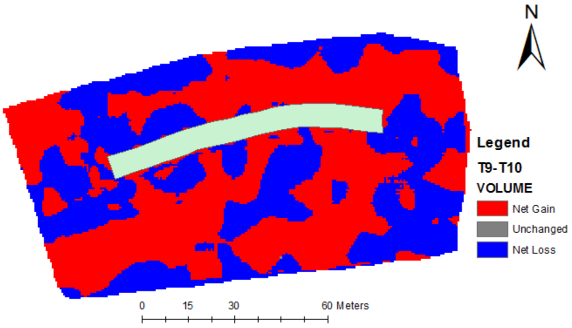


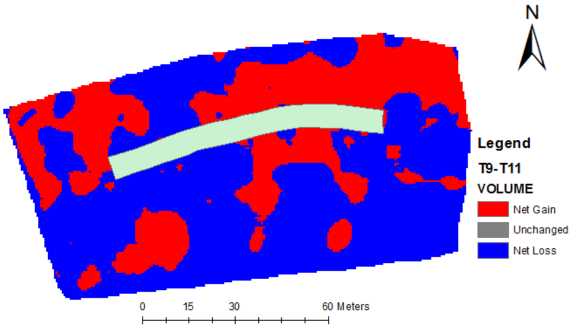


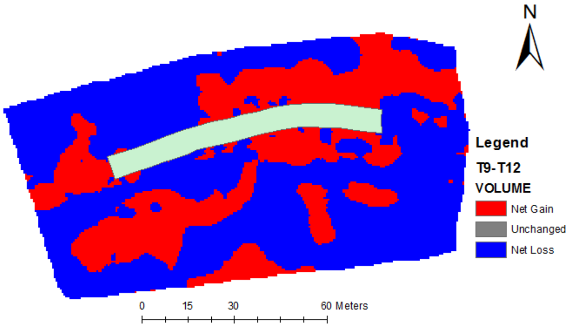


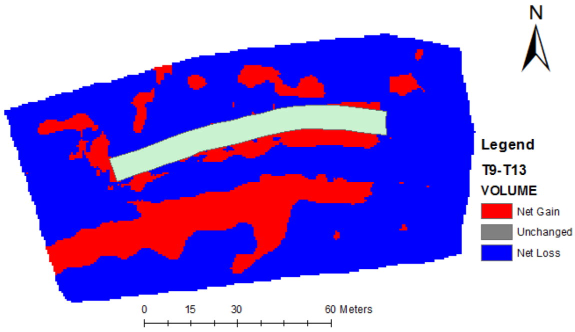


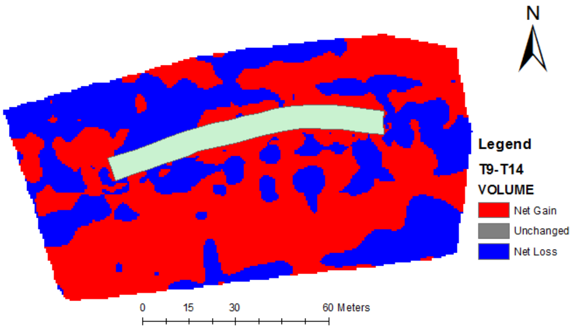
Short term analysis

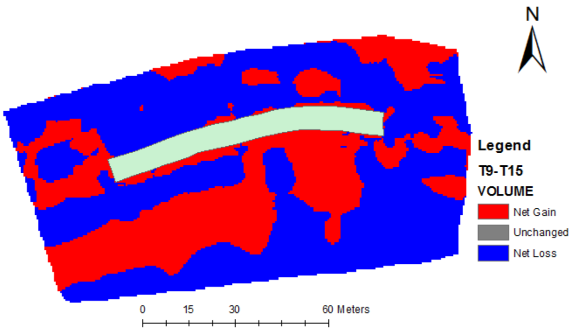


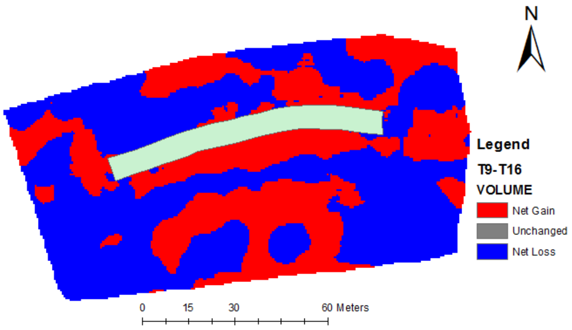


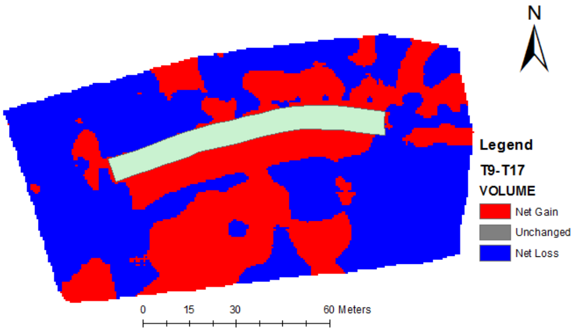


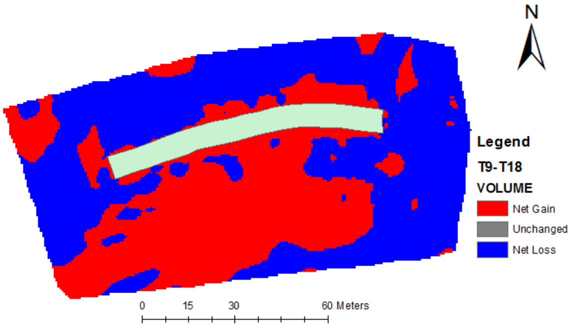


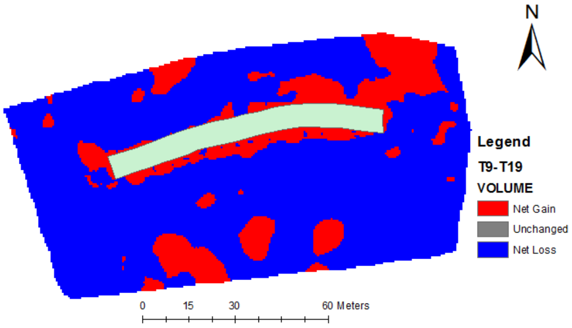






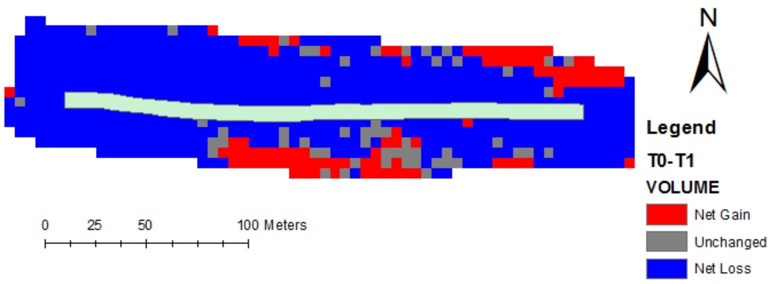


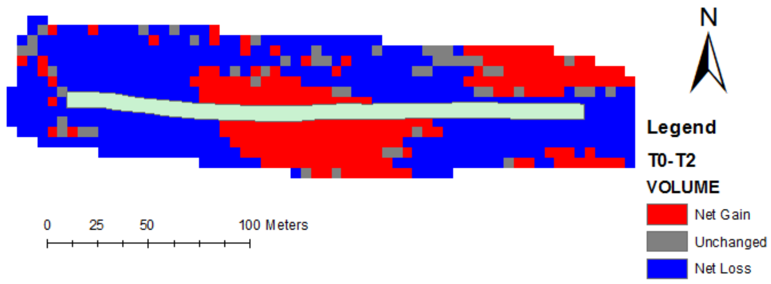

N
Legend
T9-T18
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

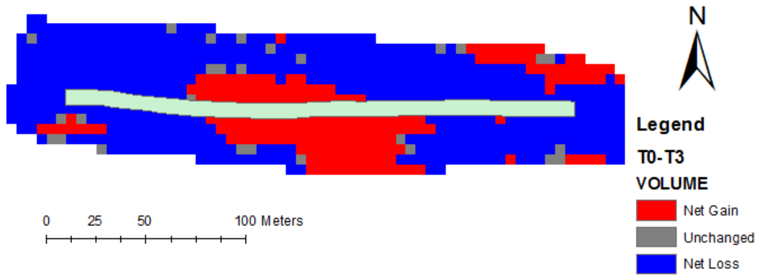

N
Legend
T9-T19
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

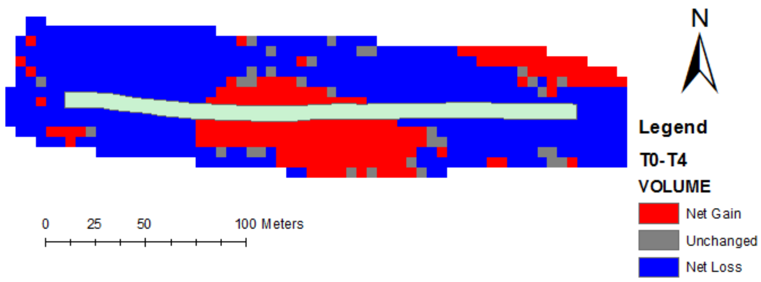
Reef B

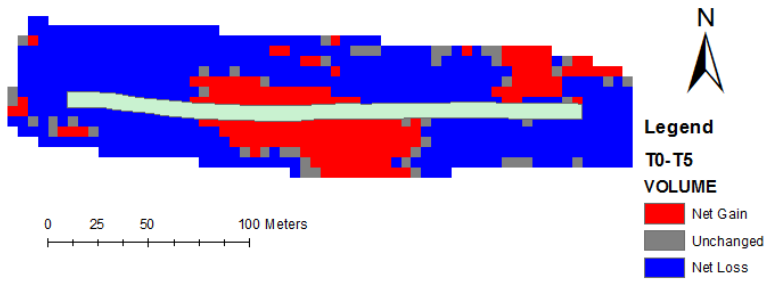
Long term analysis



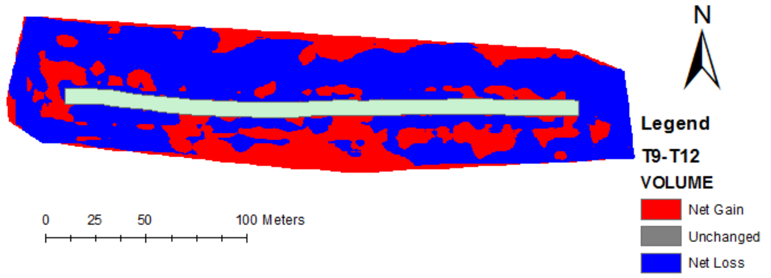


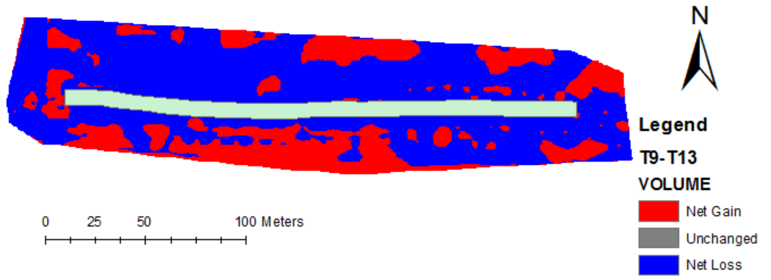






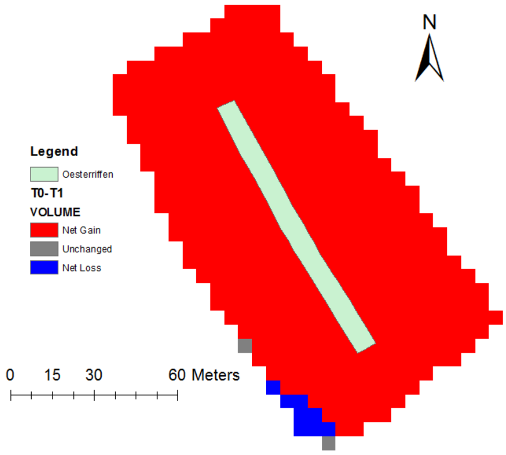
Short term analysis

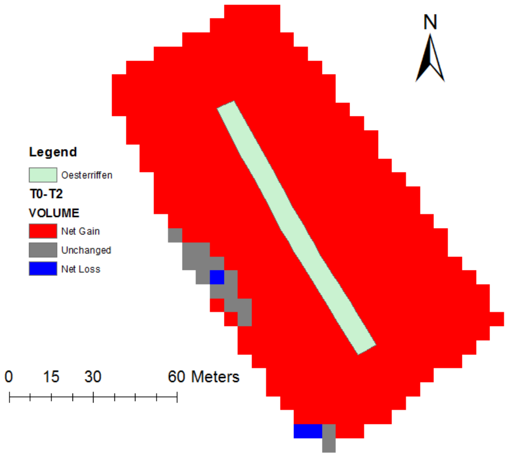

N
Legend
T9-T12
VOLUME
Net Gain
Unchanged
Net Loss
0 25 50 100 Meters

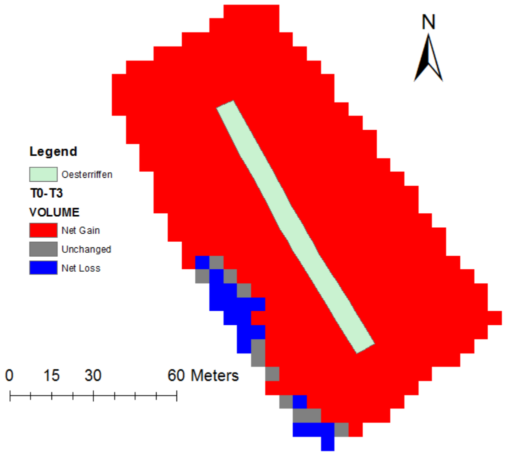

N
Legend
T9-T13
VOLUME
Net Gain
Unchanged
Net Loss
0 25 50 100 Meters

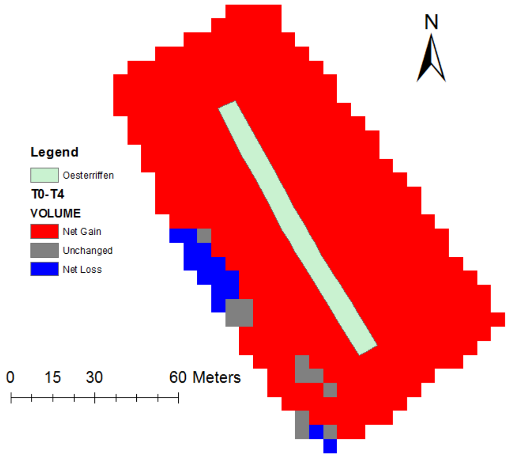
Reef C

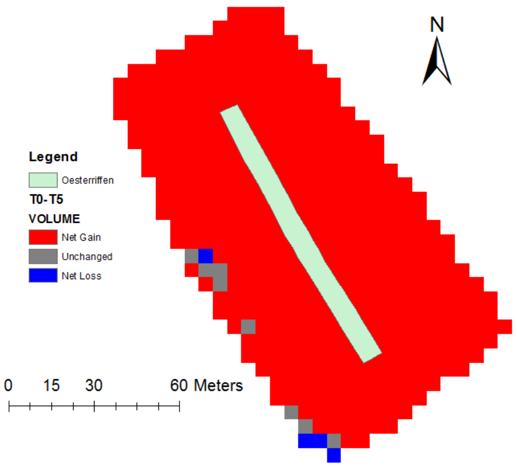
Long term analysis



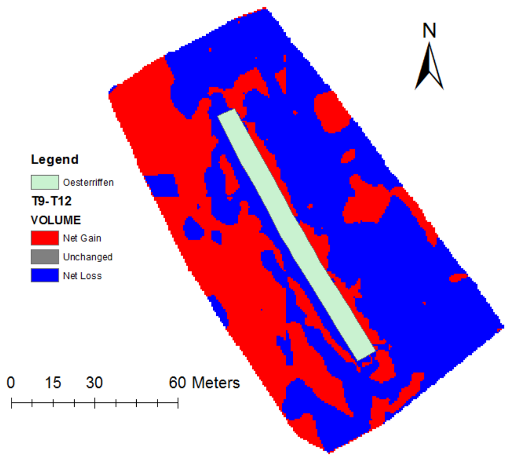


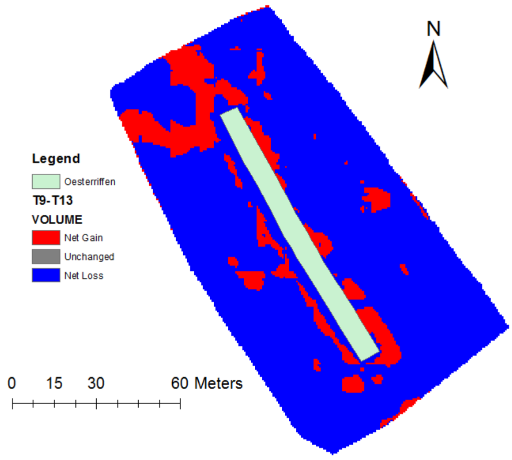






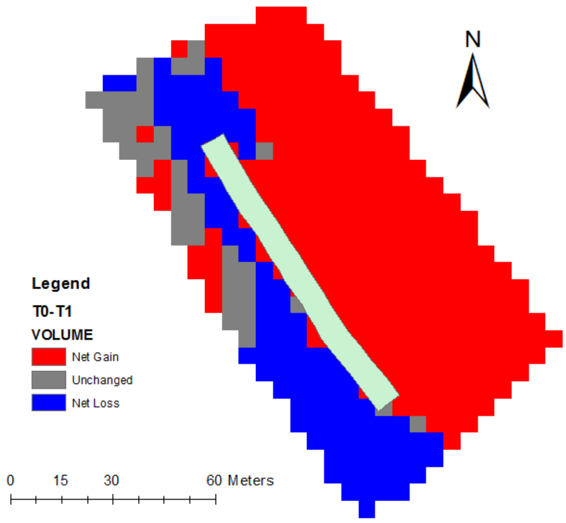
Short term analysis

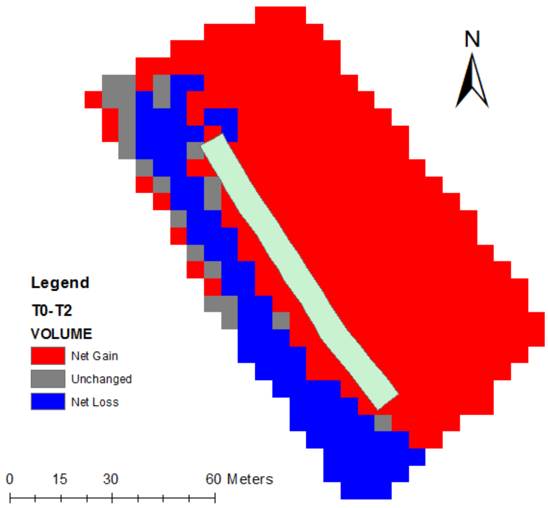


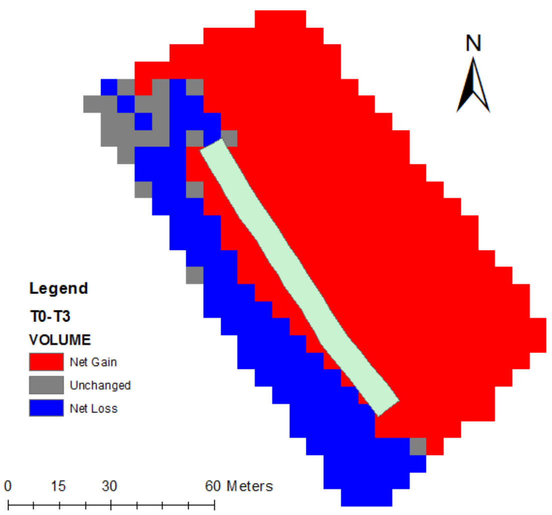


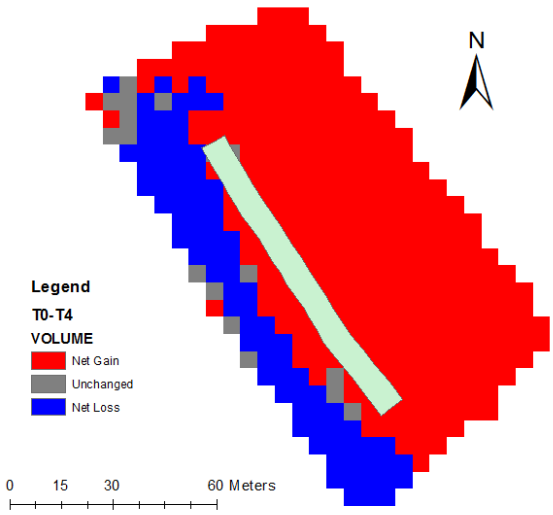
Reef D

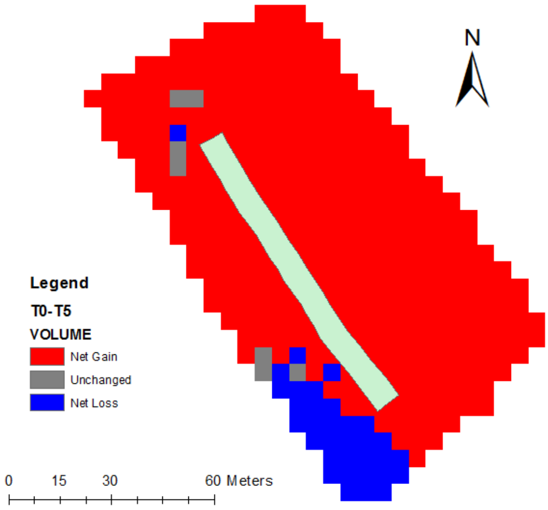
Long term analysis



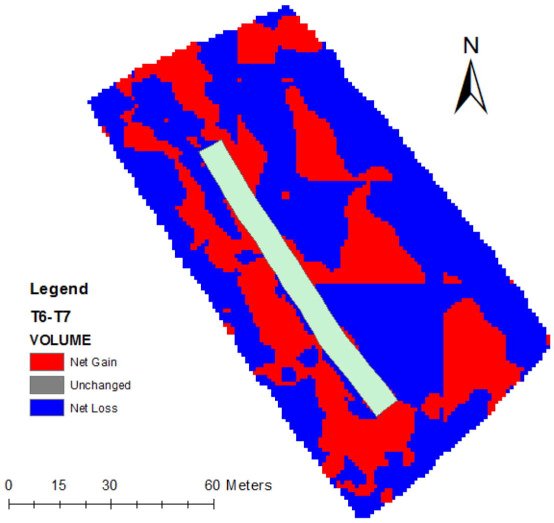


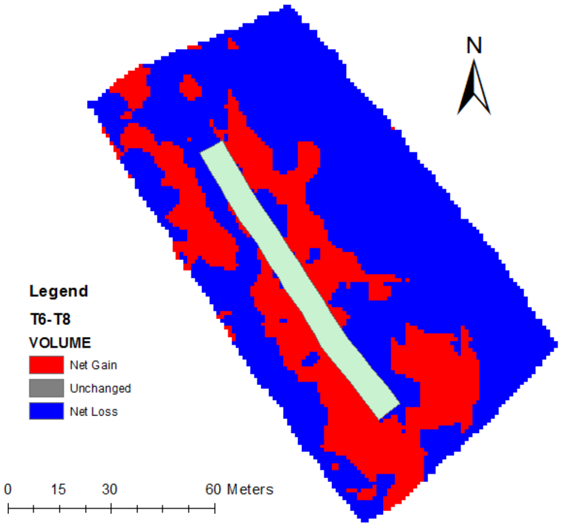


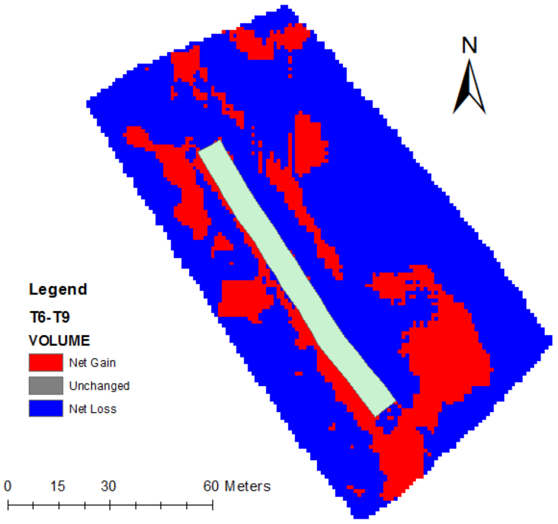


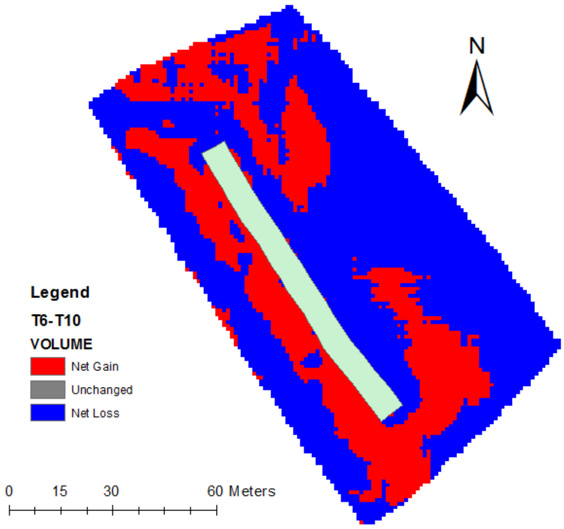


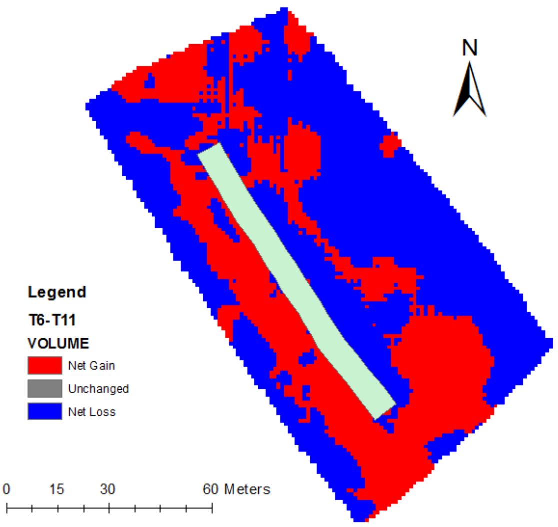
Short term analysis

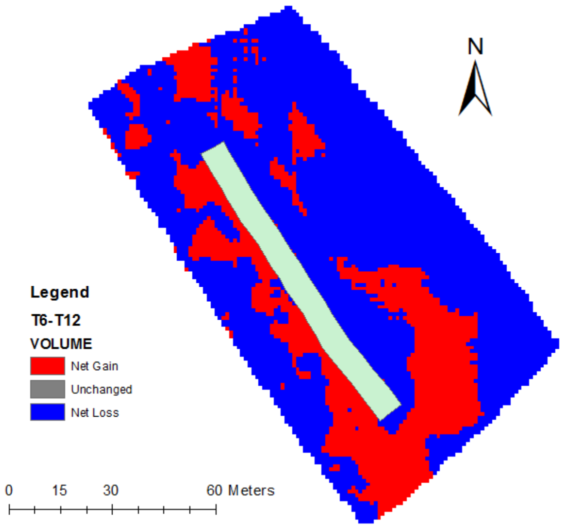


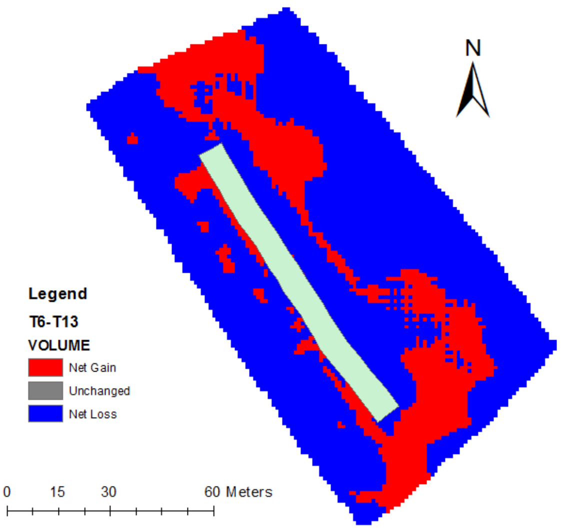


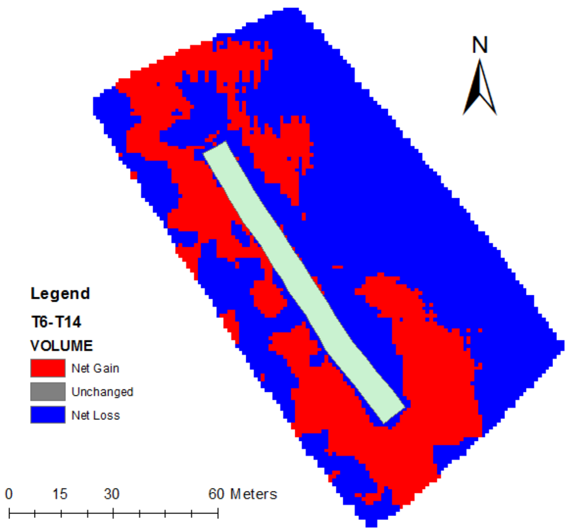

N
Legend
T6-T9
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

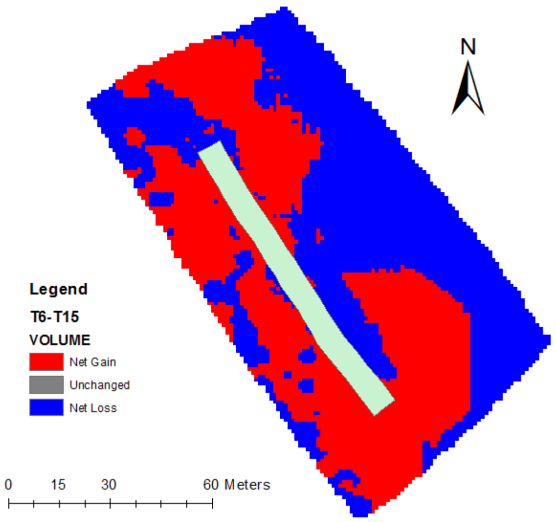

N
Legend
T6-T10
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

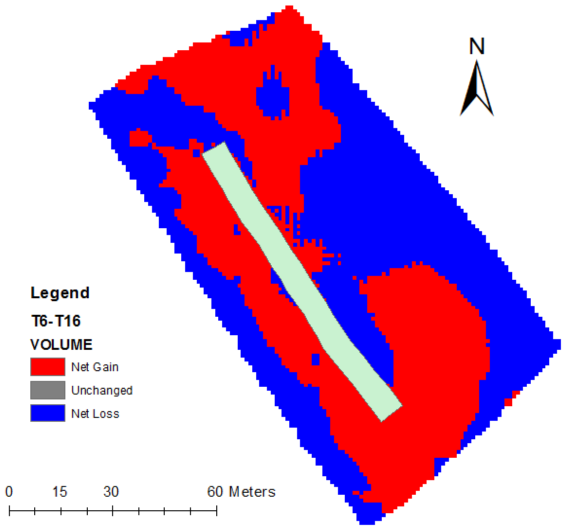

N
Legend
T6-T11
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

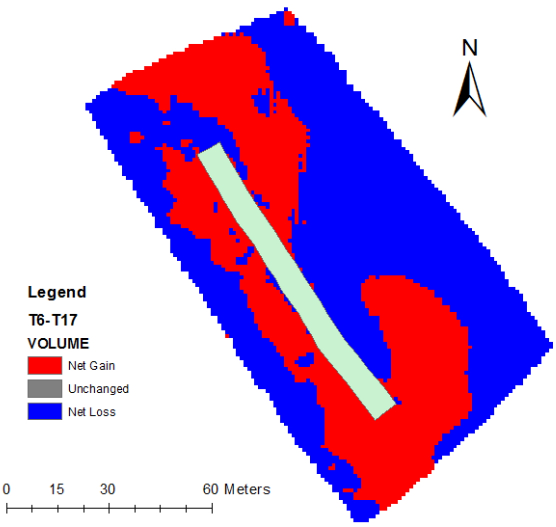

N
Legend
T6-T12
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

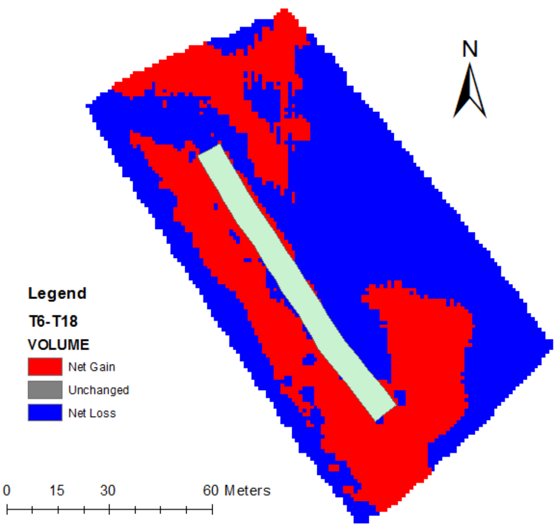

N
Legend
T6-T13
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

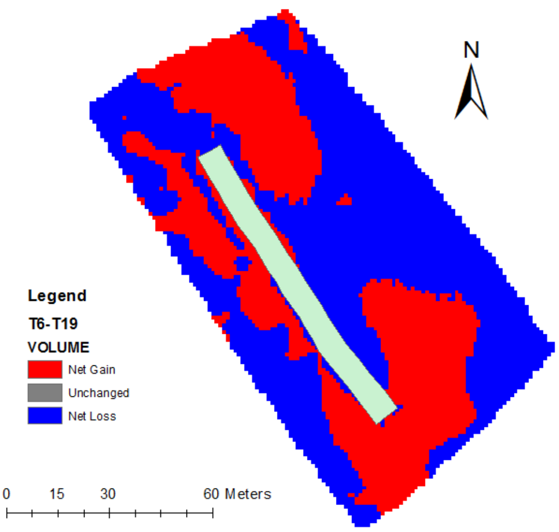

N
Legend
T6-T14
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters


N
Legend
T6-T15
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters


N
Legend
T6-T16
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

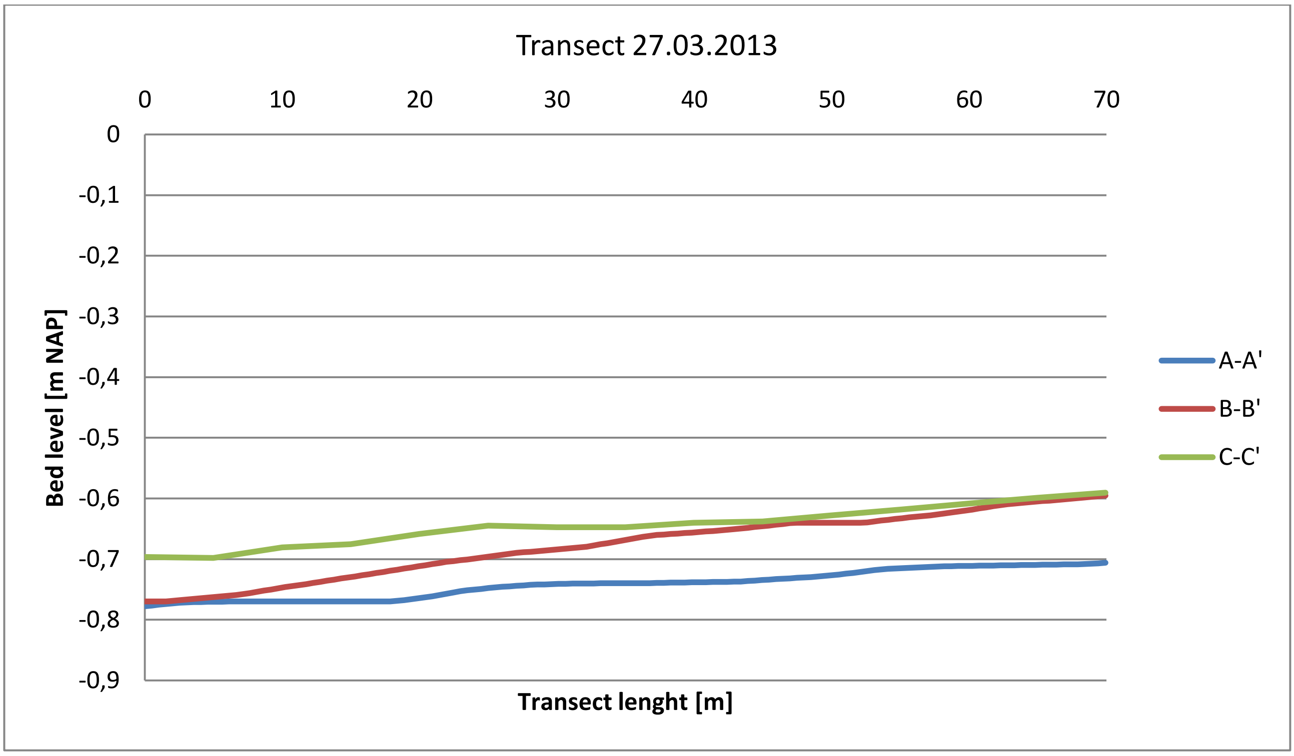

N
Legend
T6-T17
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

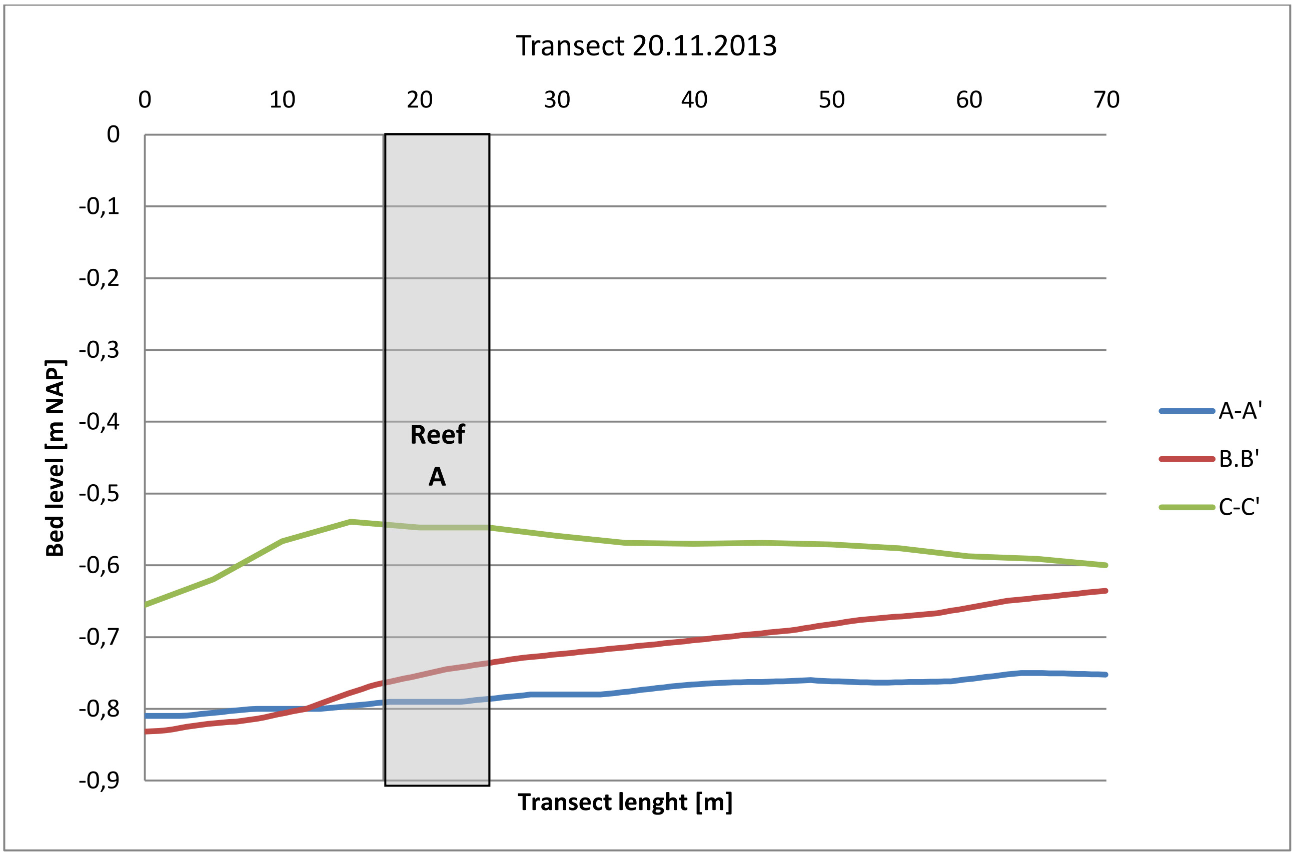

N
Legend
T6-T18
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

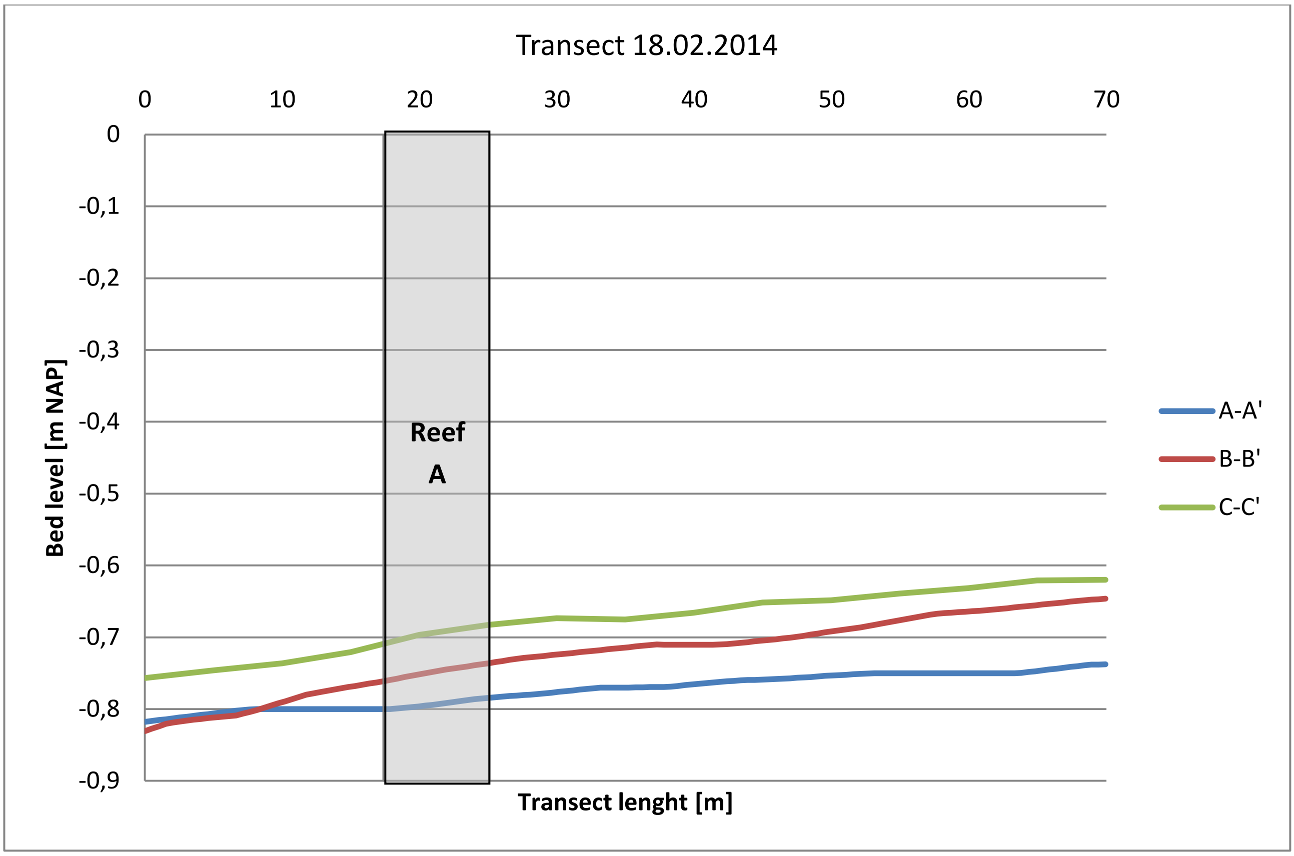

N
Legend
T6-T19
VOLUME
Net Gain
Unchanged
Net Loss
0 15 30 60 Meters

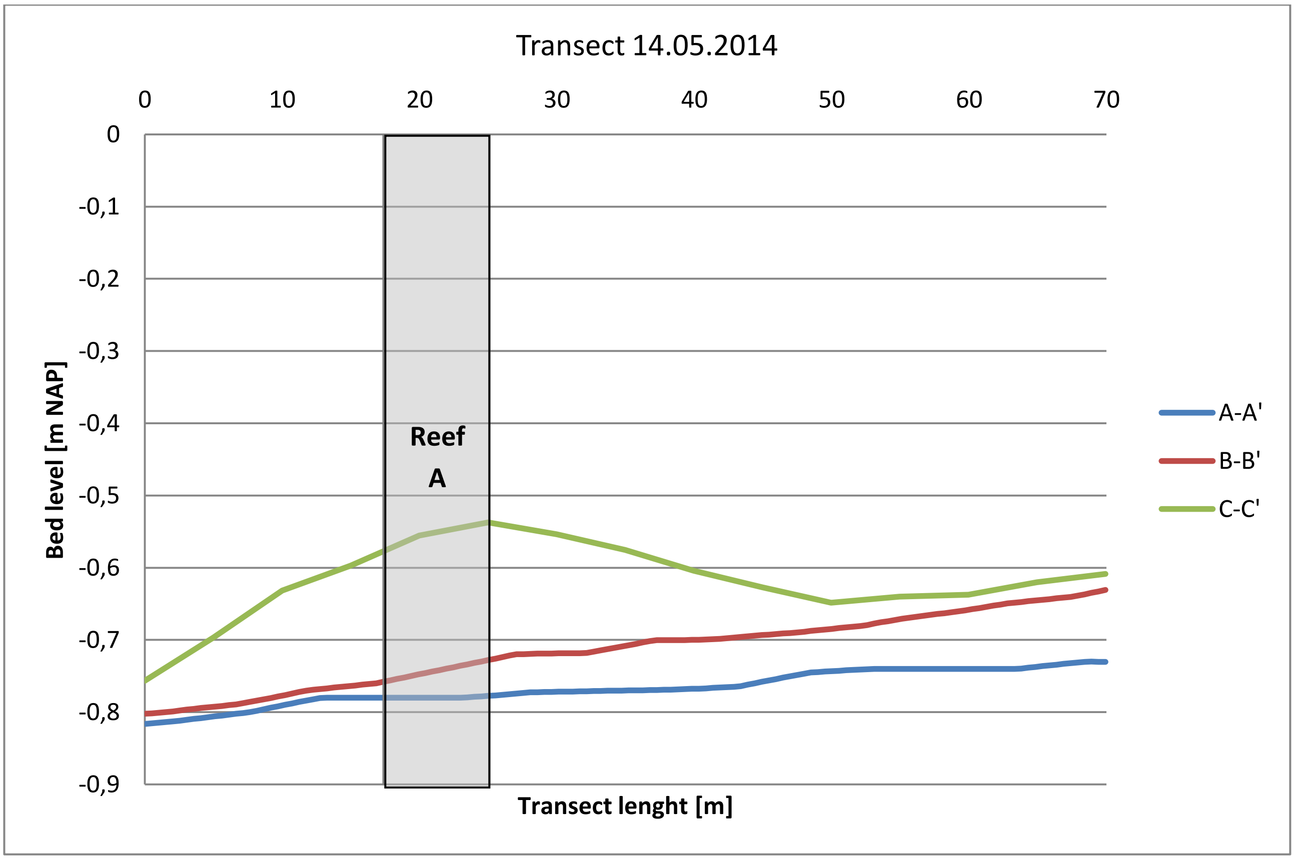
Appendix F : Elevation profiles for the long term analysis

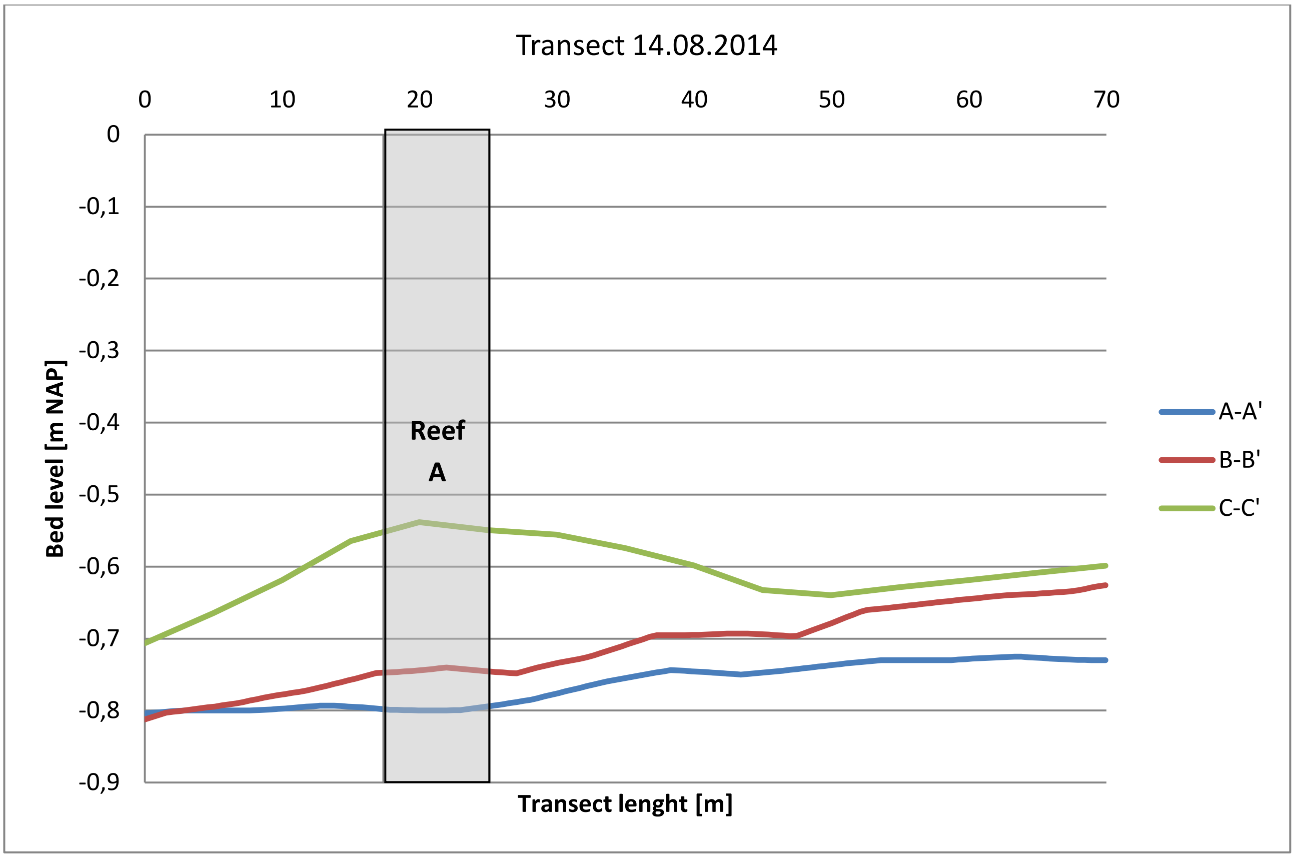
Reef A

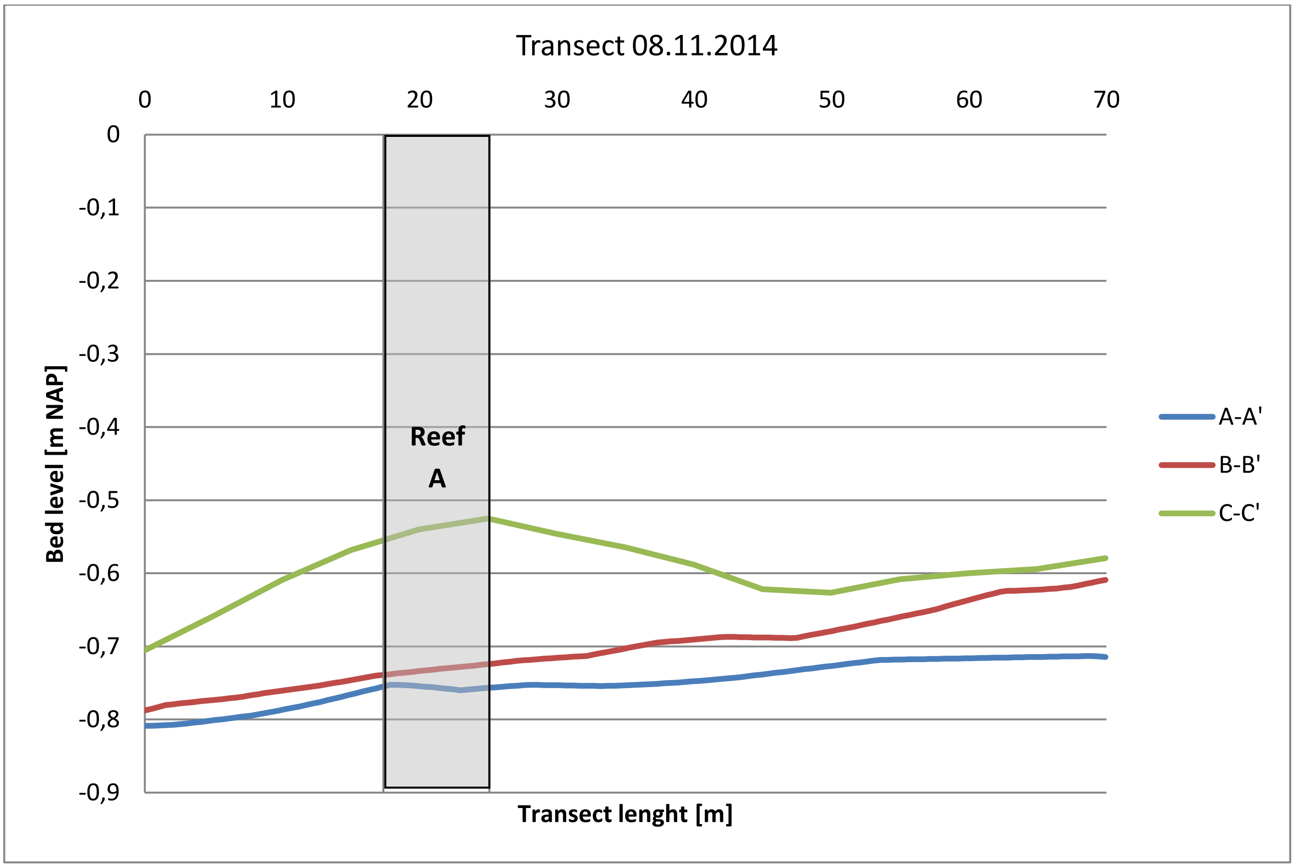




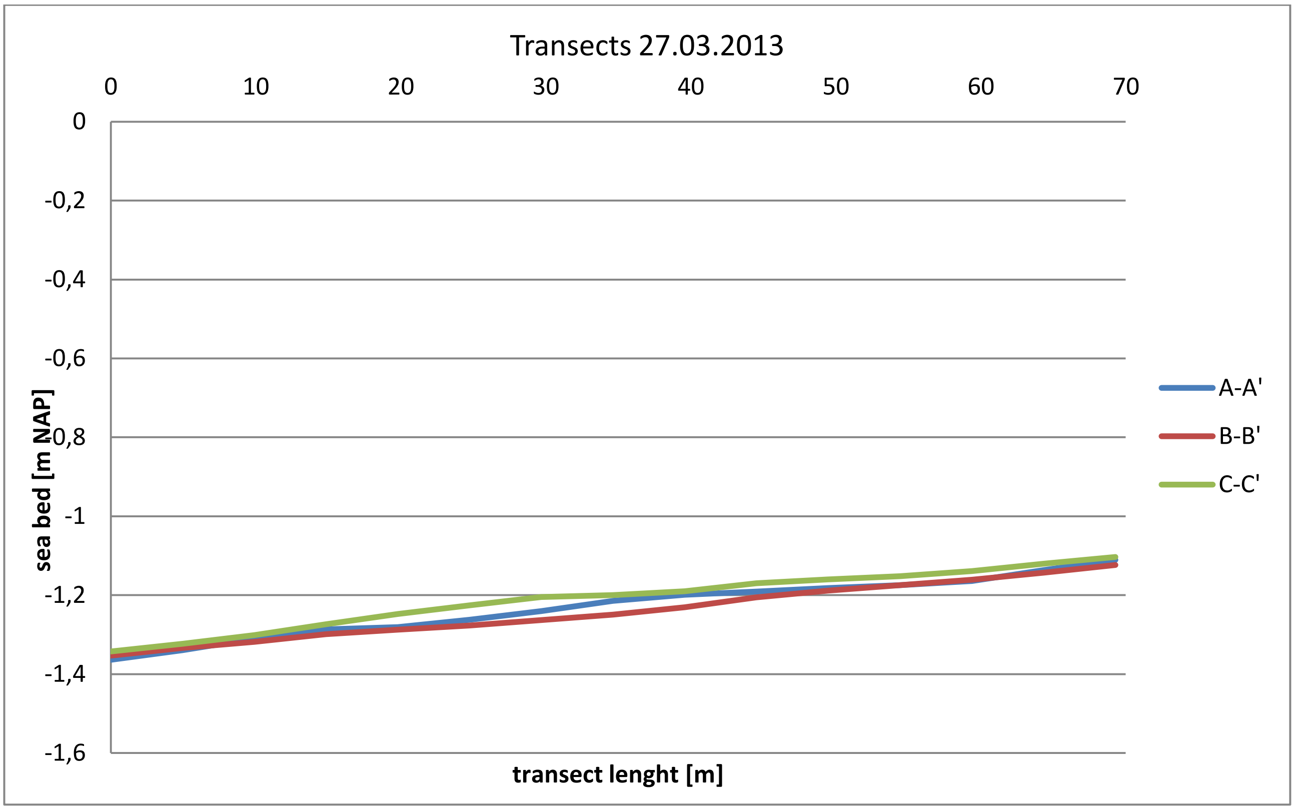

Transect 18.02.2014
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
A-A'
B-B'
C-C'

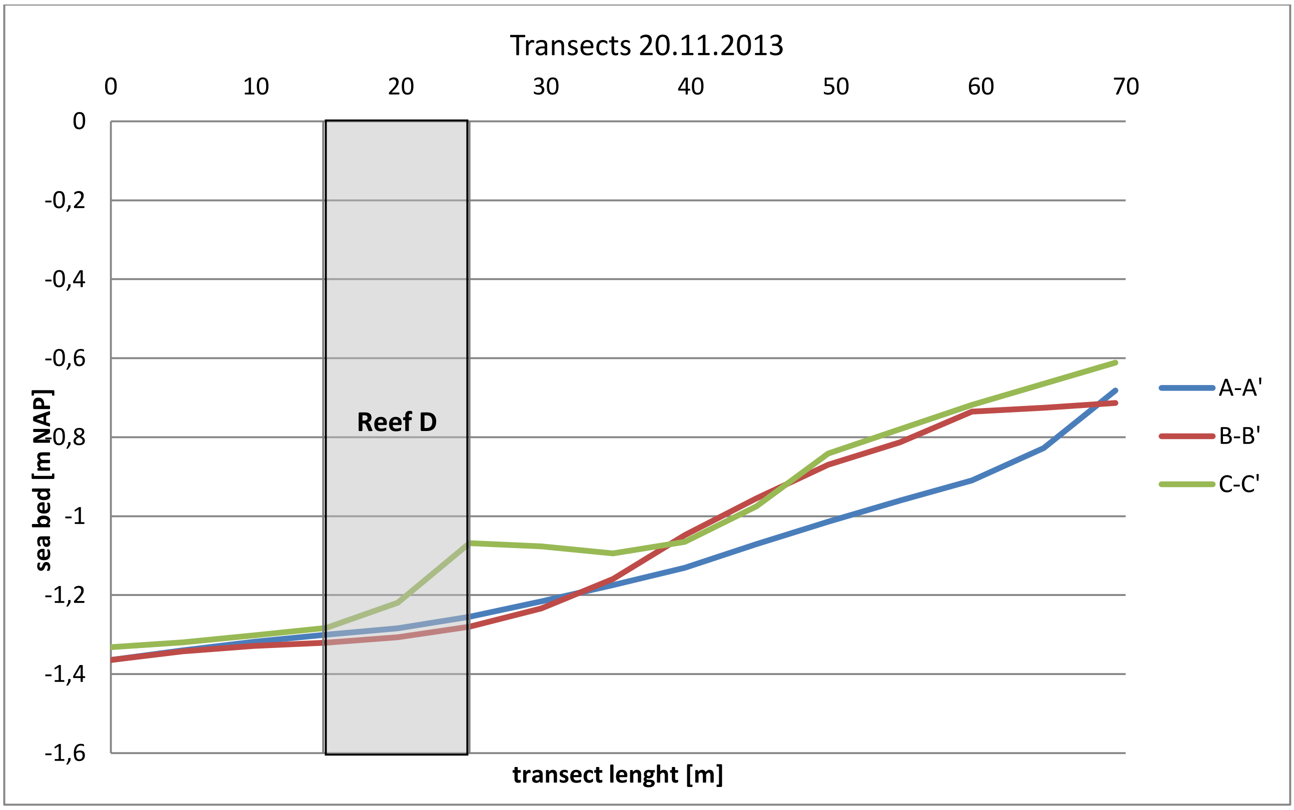

Transect 14.05.2014
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
A-A'
B-B'
C-C'

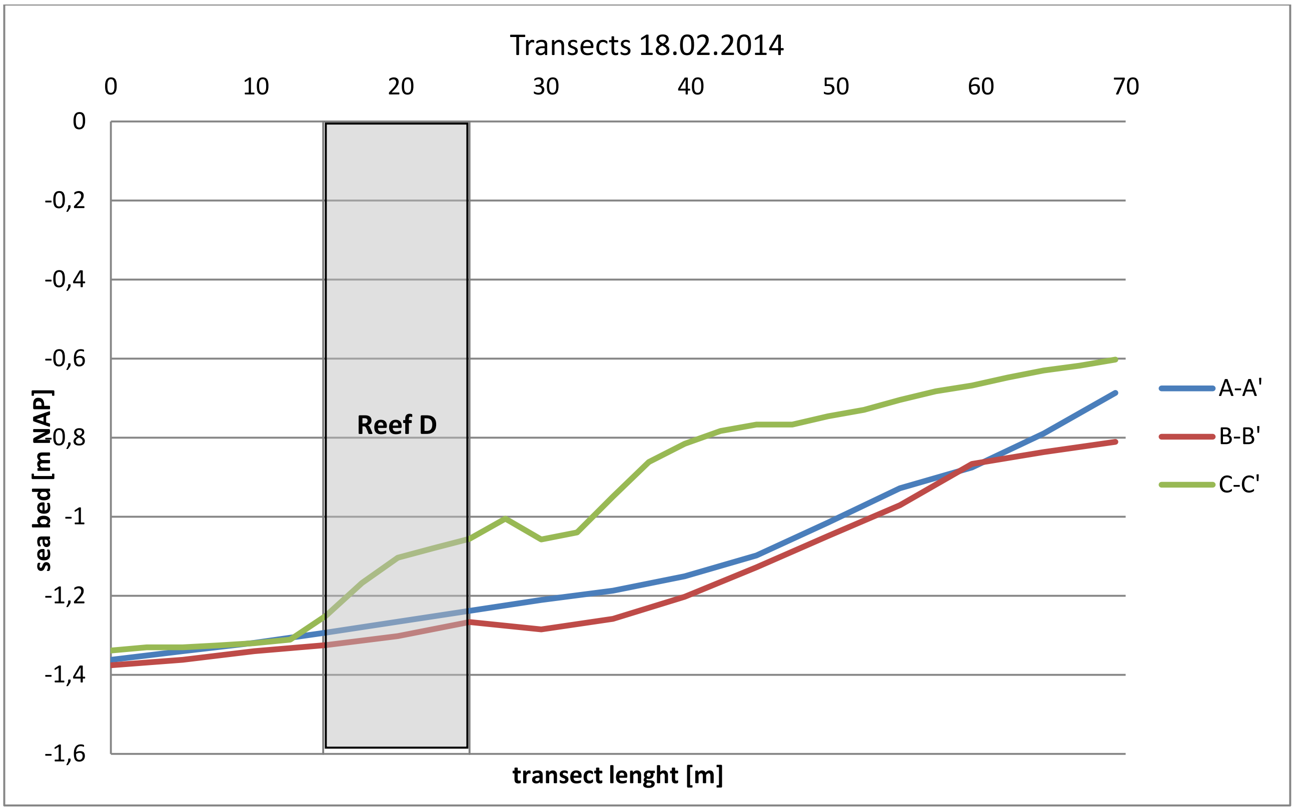

Transect 14.08.2014
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
A-A'
B-B'
C-C'

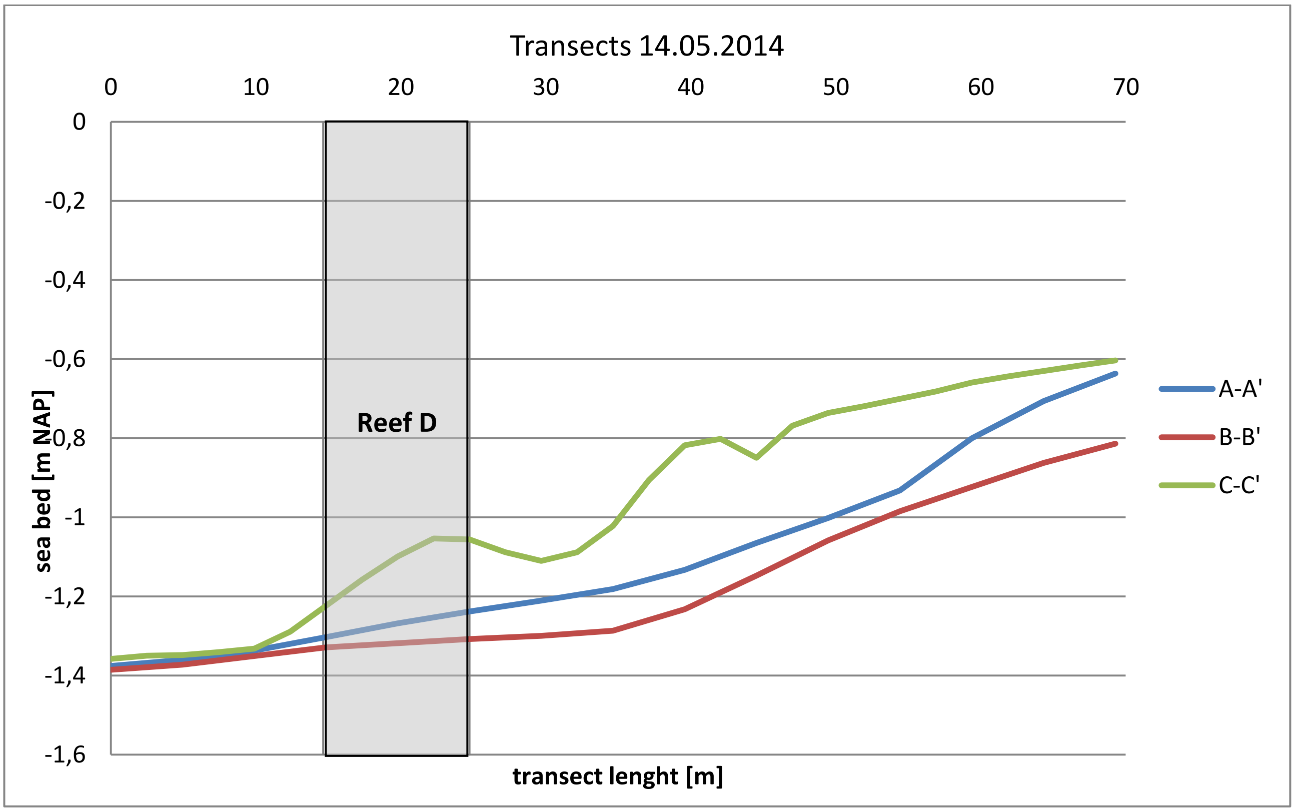

Transect 08.11.2014
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
A-A'
B-B'
C-C'

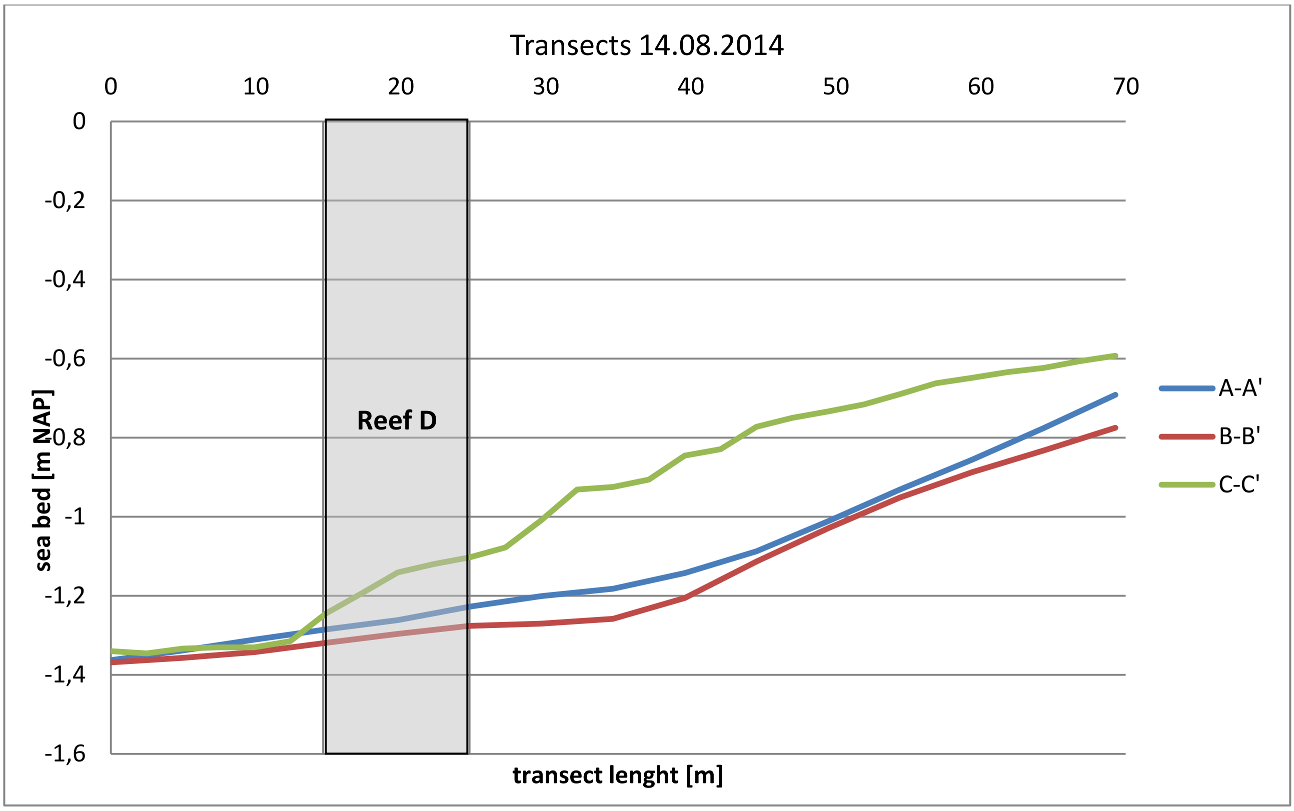
Reef D

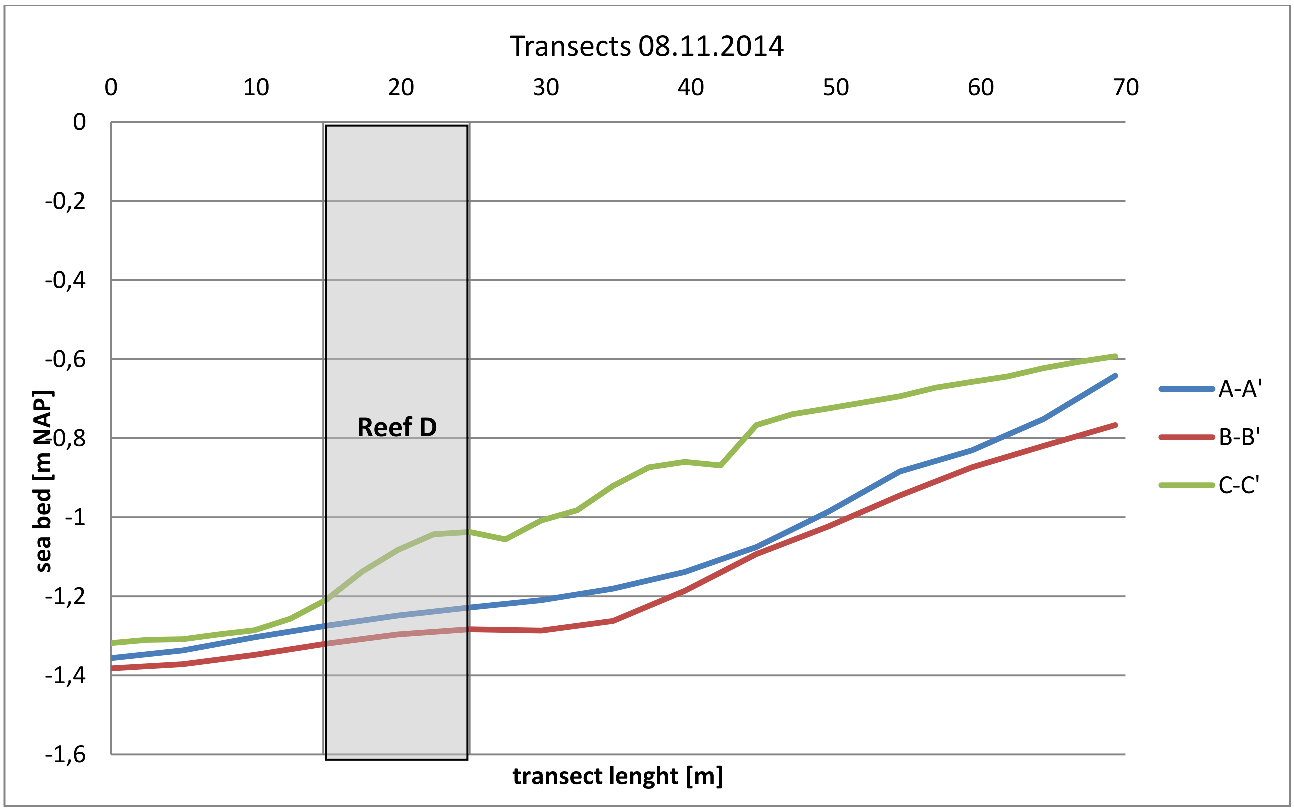

Transects 27.03.2013
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
transect lenght [m]
A-A'
B-B'
C-C'


Transects 20.11.2013
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
Reef D
transect lenght [m]
A-A'
B-B'
C-C'


Transects 18.02.2014
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
Reef D
transect lenght [m]
A-A'
B-B'
C-C'

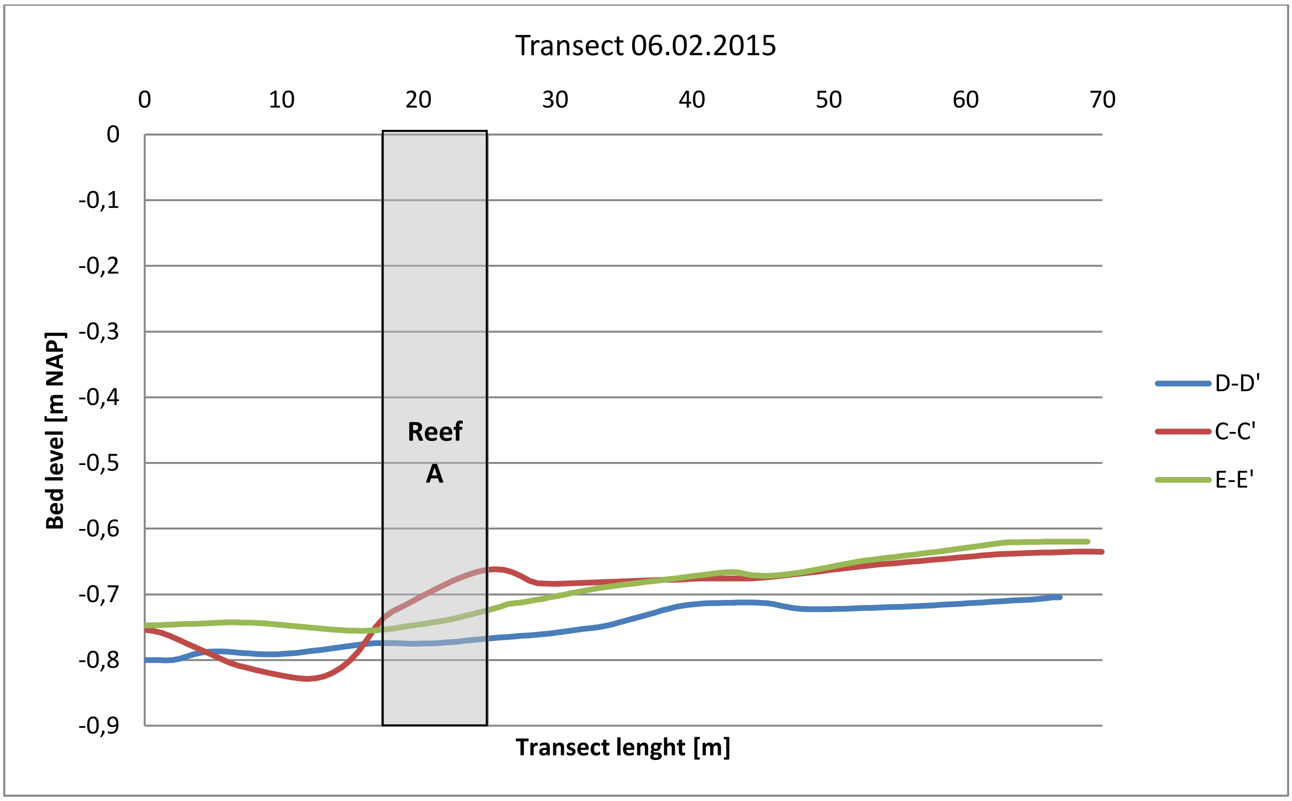

Transects 14.05.2014
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
Reef D
transect lenght [m]
A-A'
B-B'
C-C'

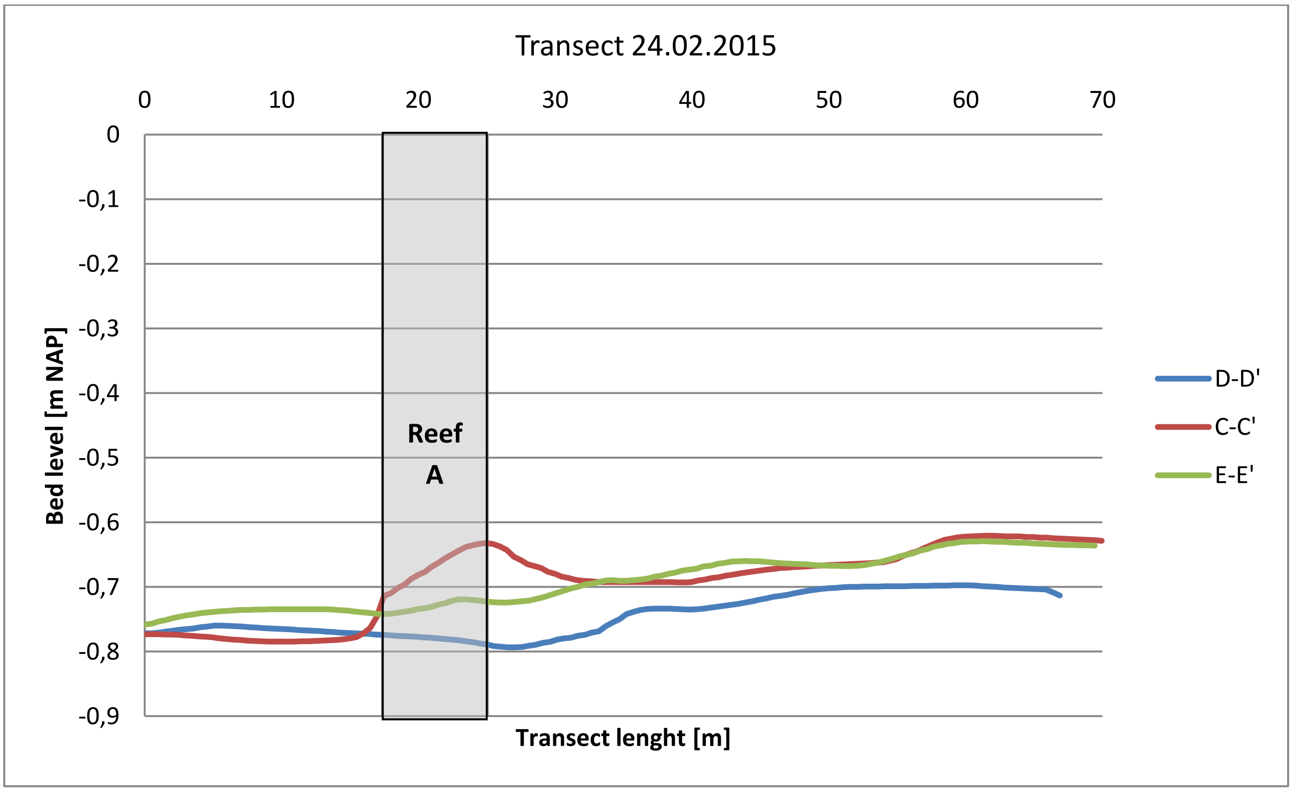

Transects 14.08.2014
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
Reef D
transect lenght [m]
A-A'
B-B'
C-C'

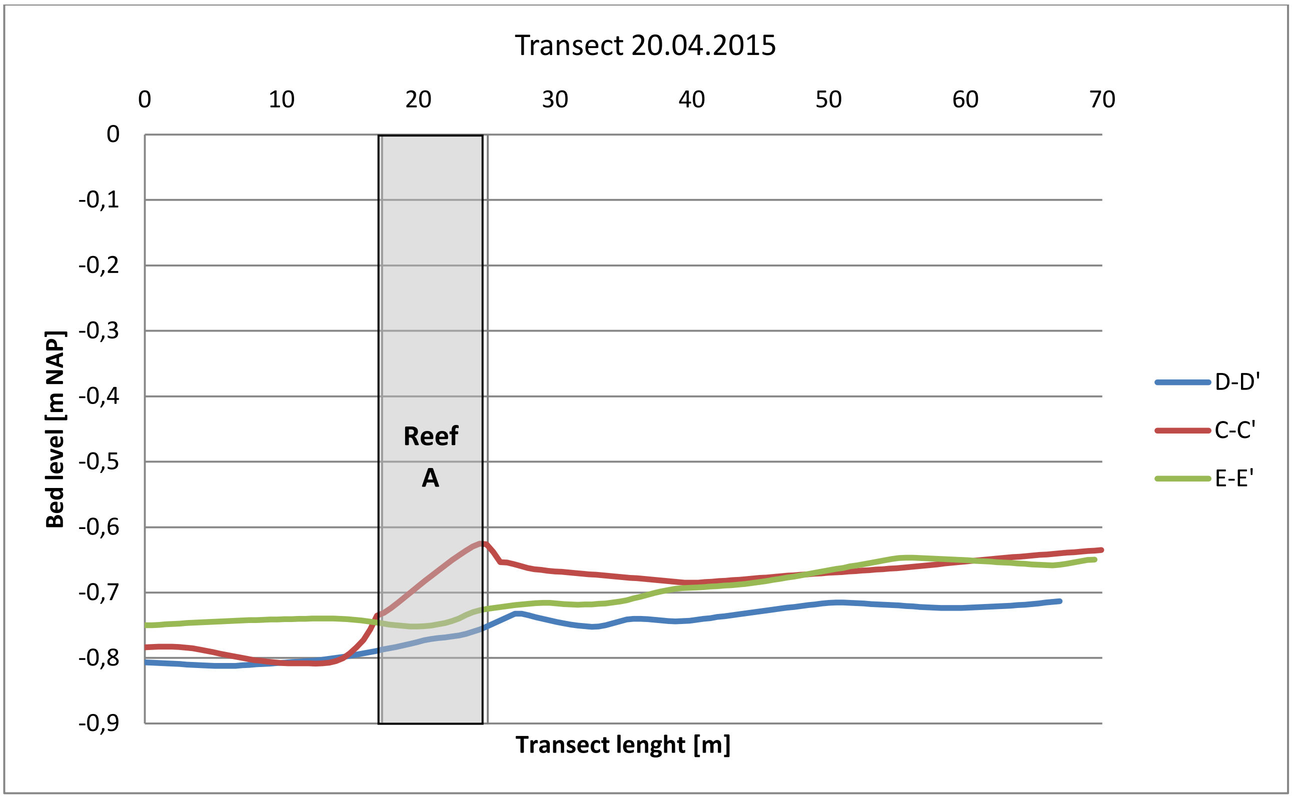

Transects 08.11.2014
0
10
20
30
40
50
60
70
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
sea bed [m NAP]
Reef D
transect lenght [m]
A-A'
B-B'
C-C'

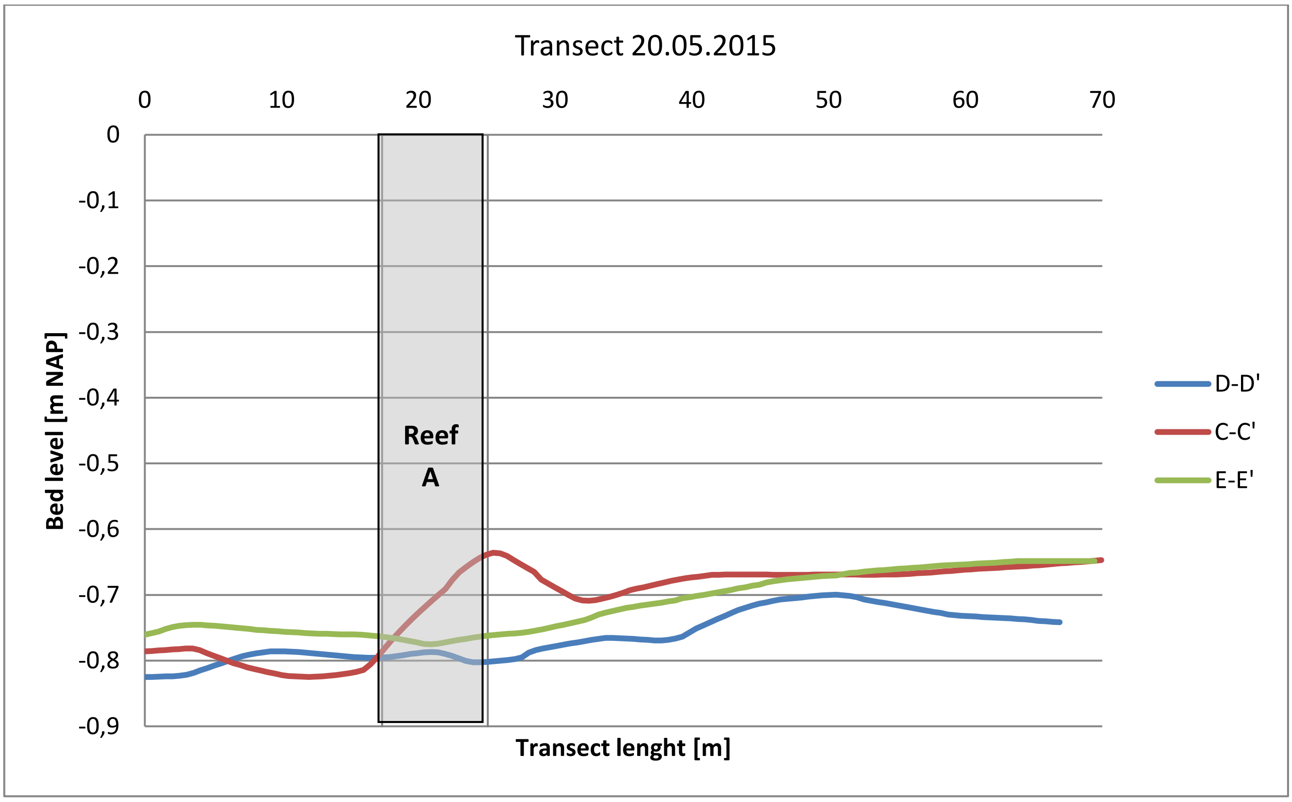
Appendix G : Elevation profiles for the short term analysis

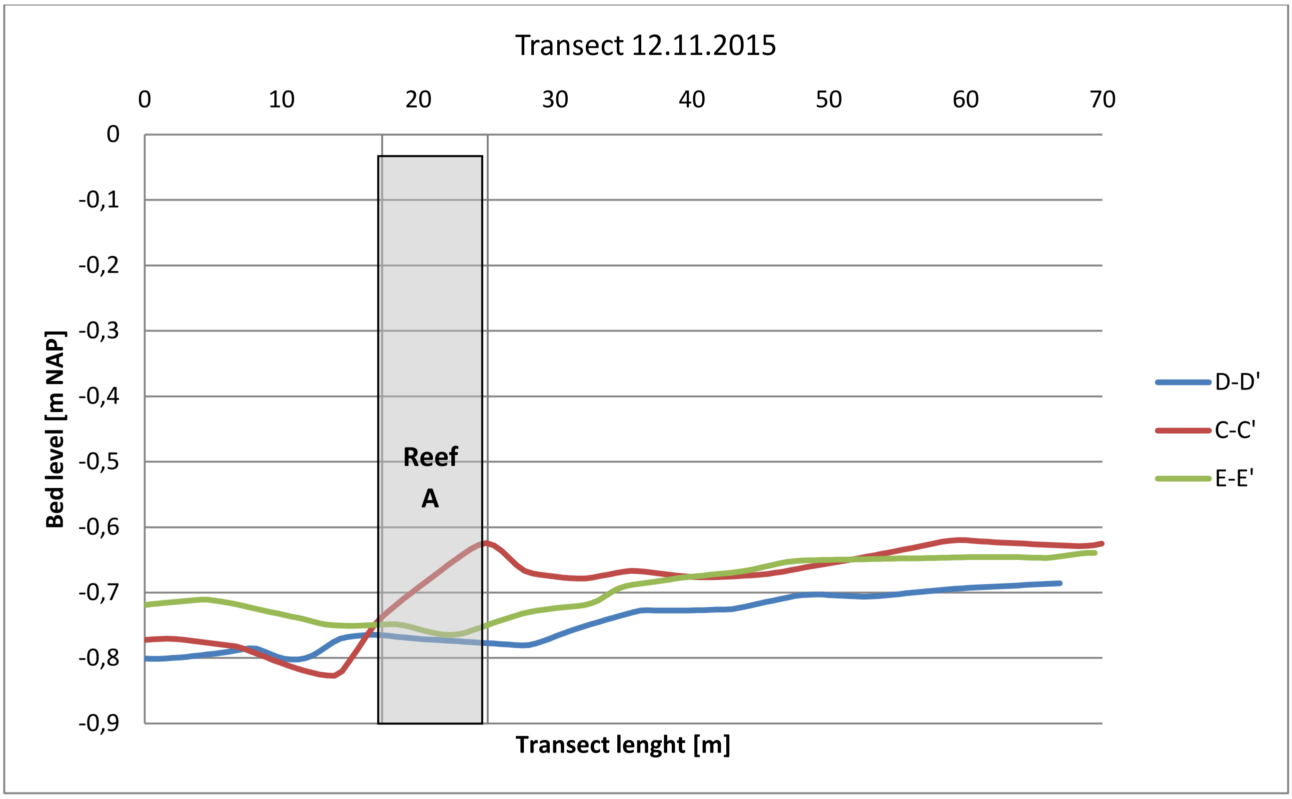
Reef A

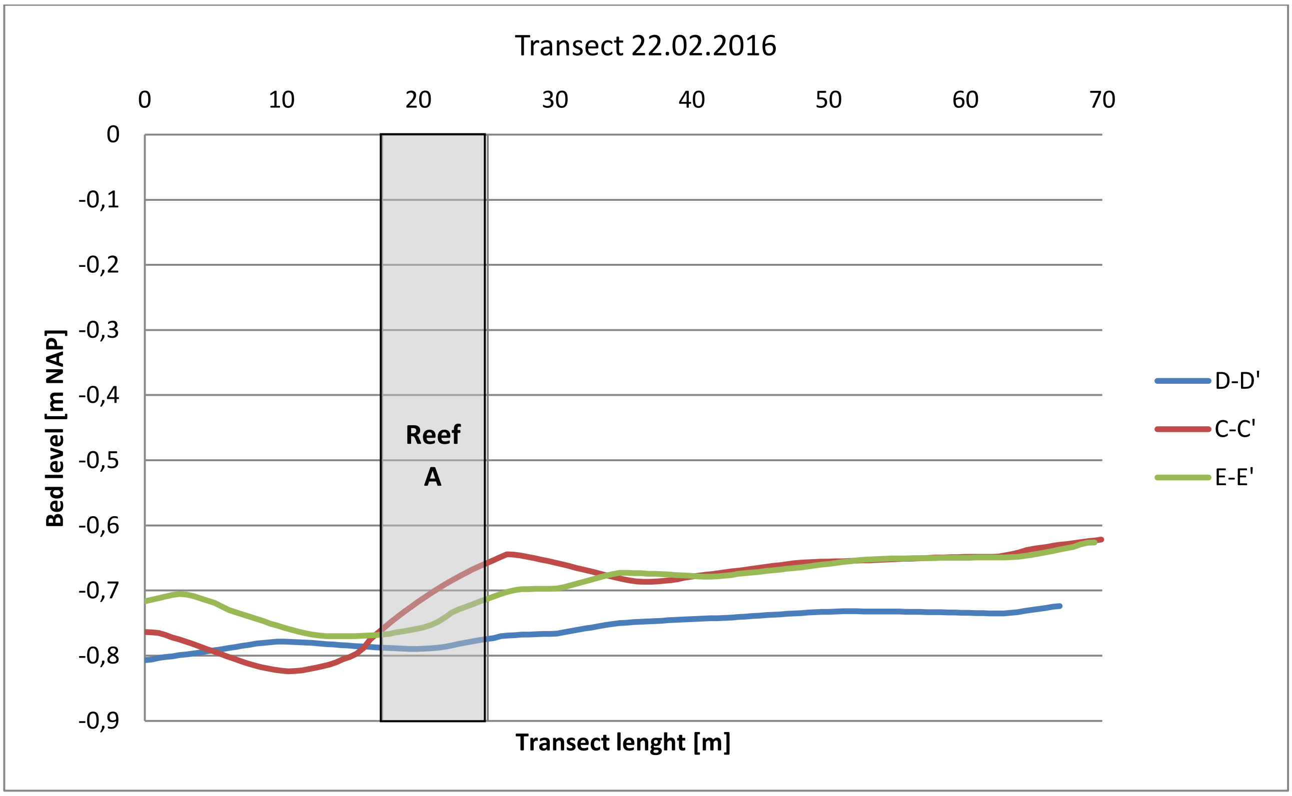


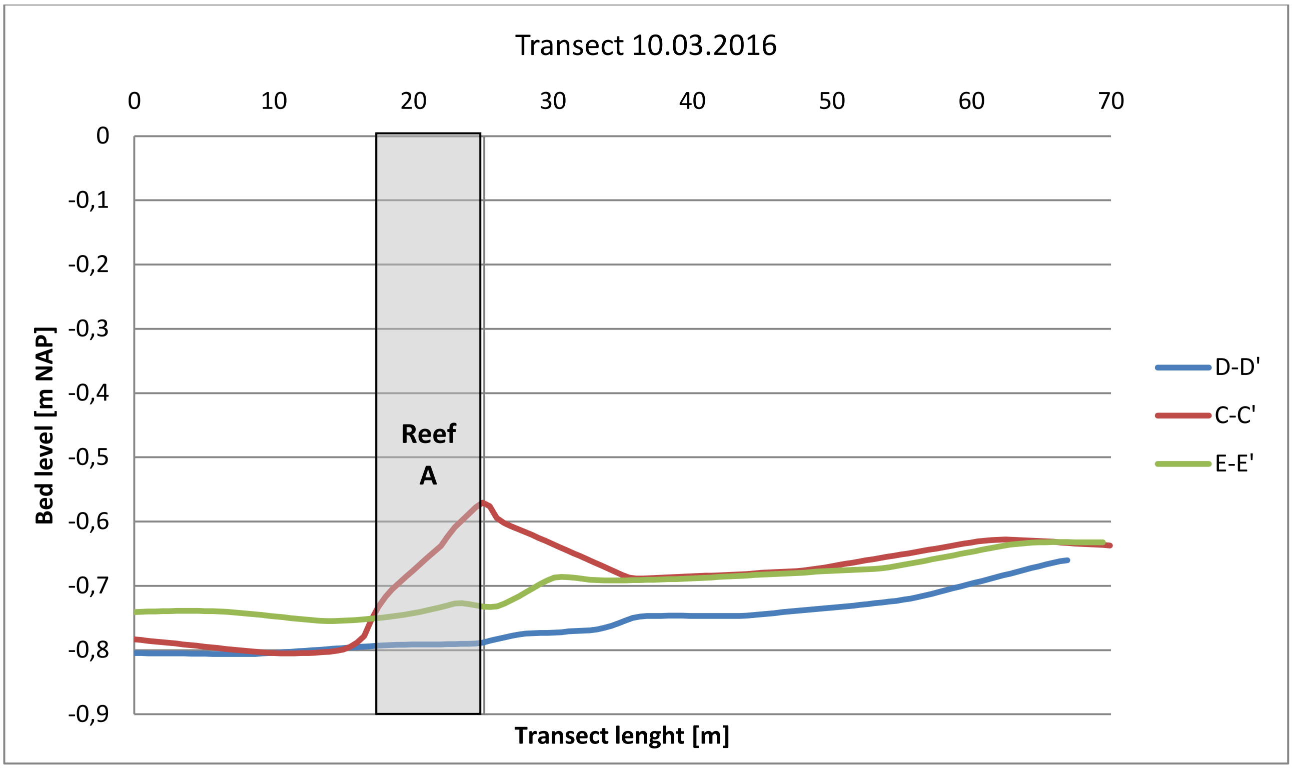


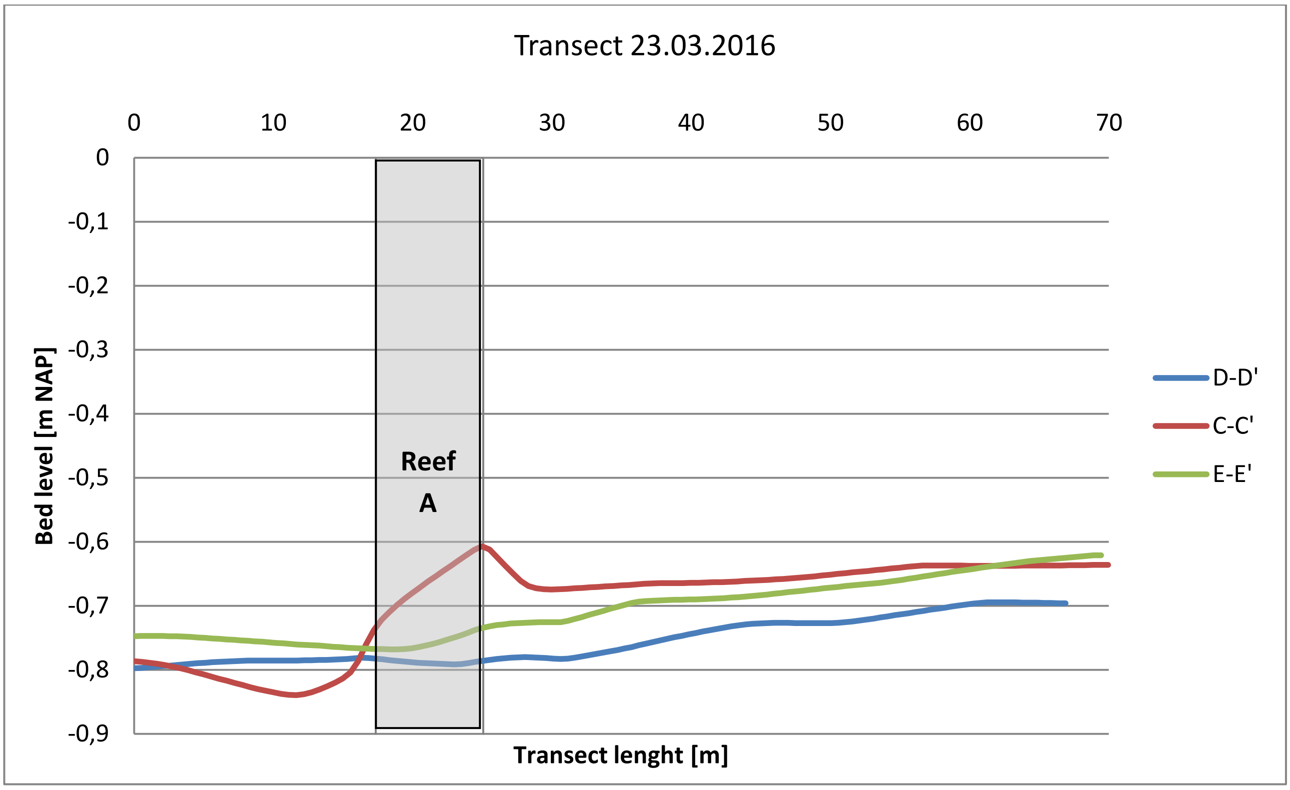

Transect 20.04.2015
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
D-D'
C-C'
E-E'

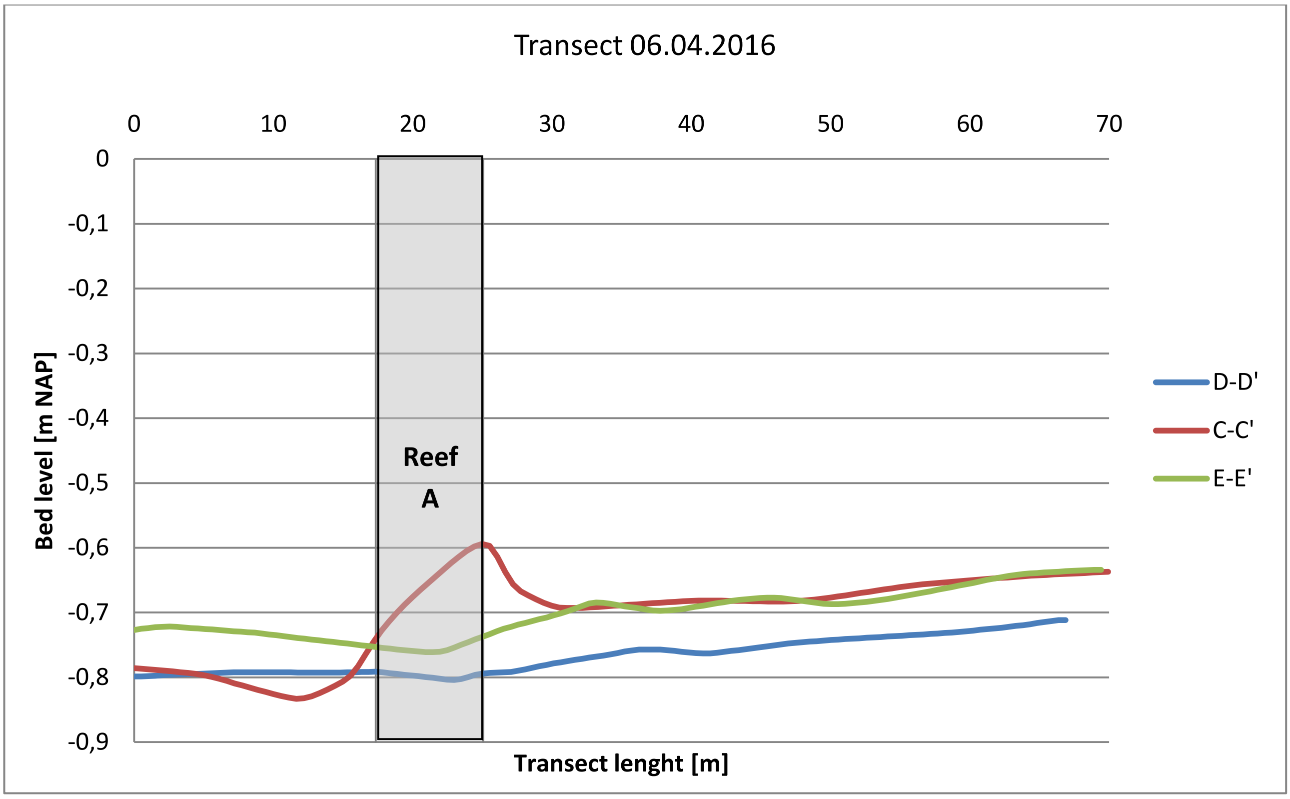

Transect 20.05.2015
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 12.11.2015
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
D-D'
C-C'
E-E'

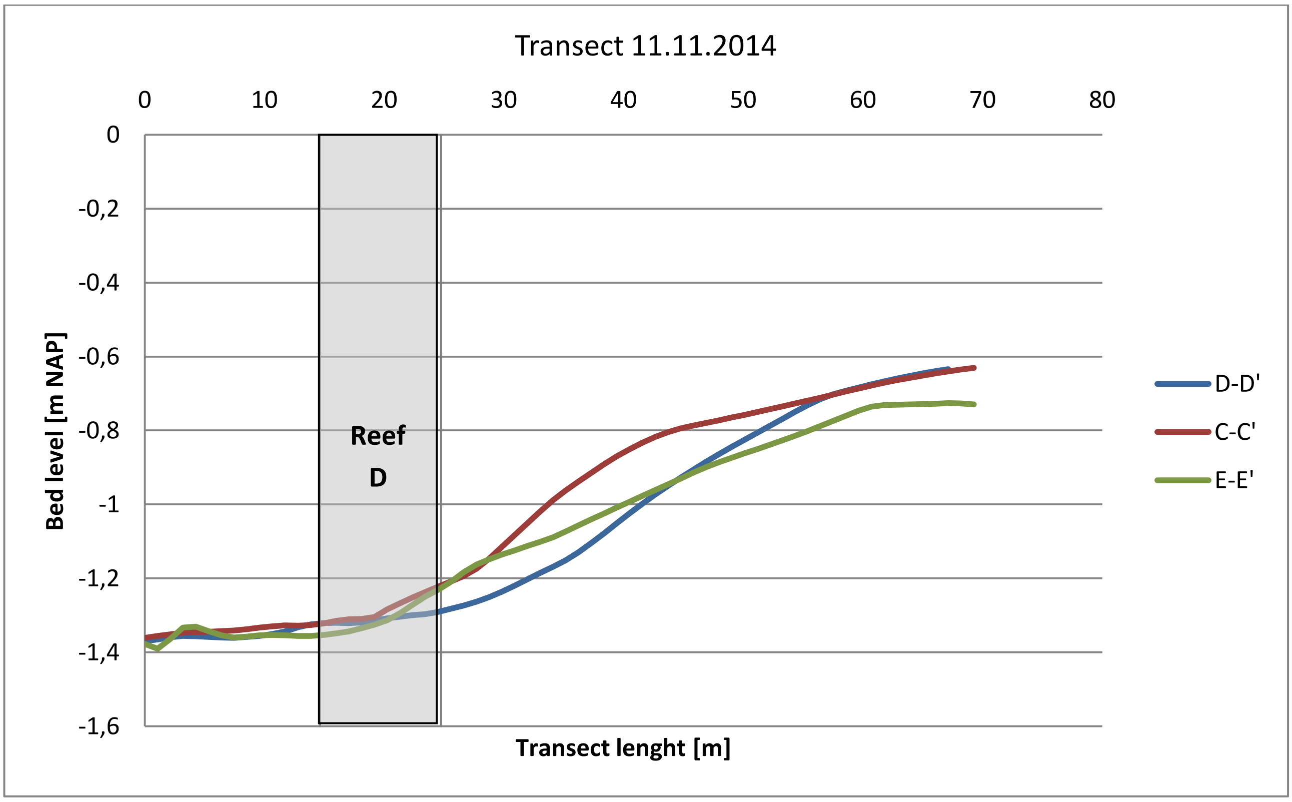

Transect 22.02.2016
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
D-D'
C-C'
E-E'

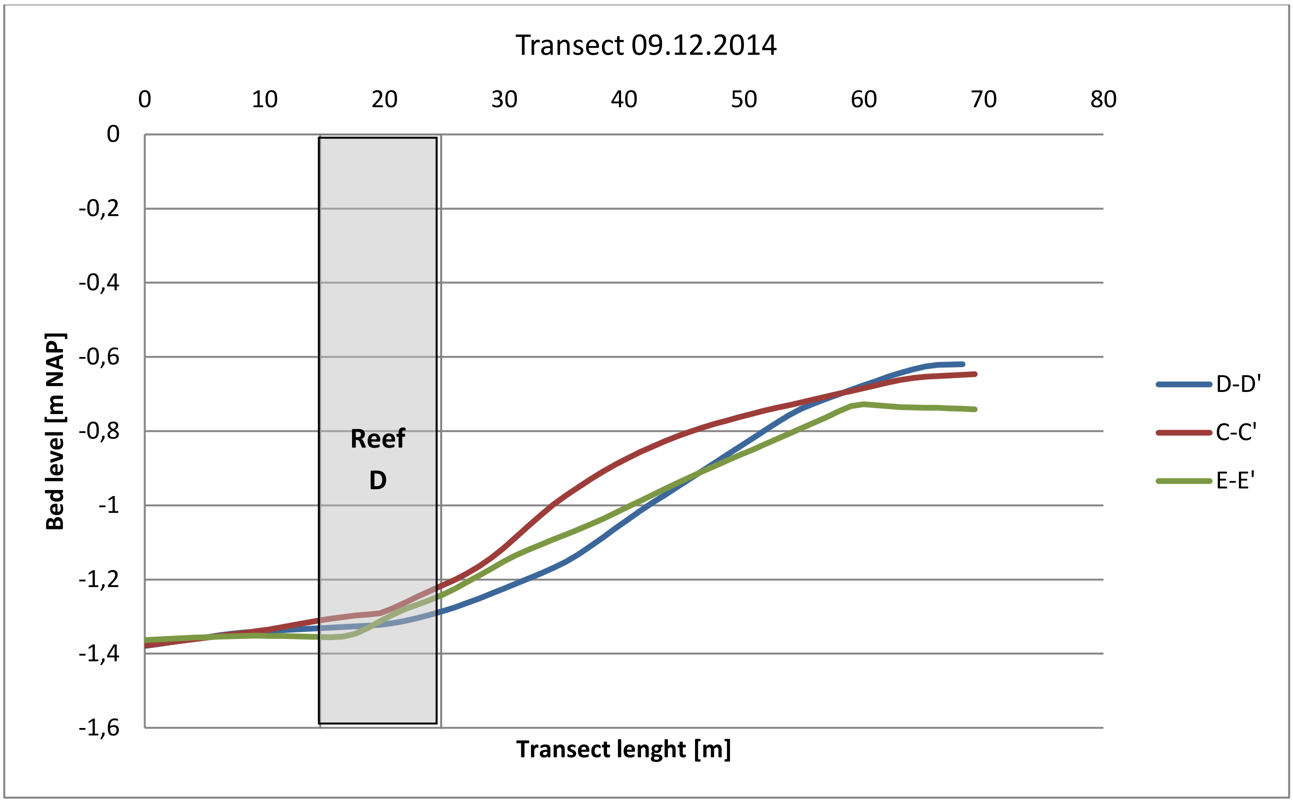

Transect 10.03.2016
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
D-D'
C-C'
E-E'
Transect lenght [m]

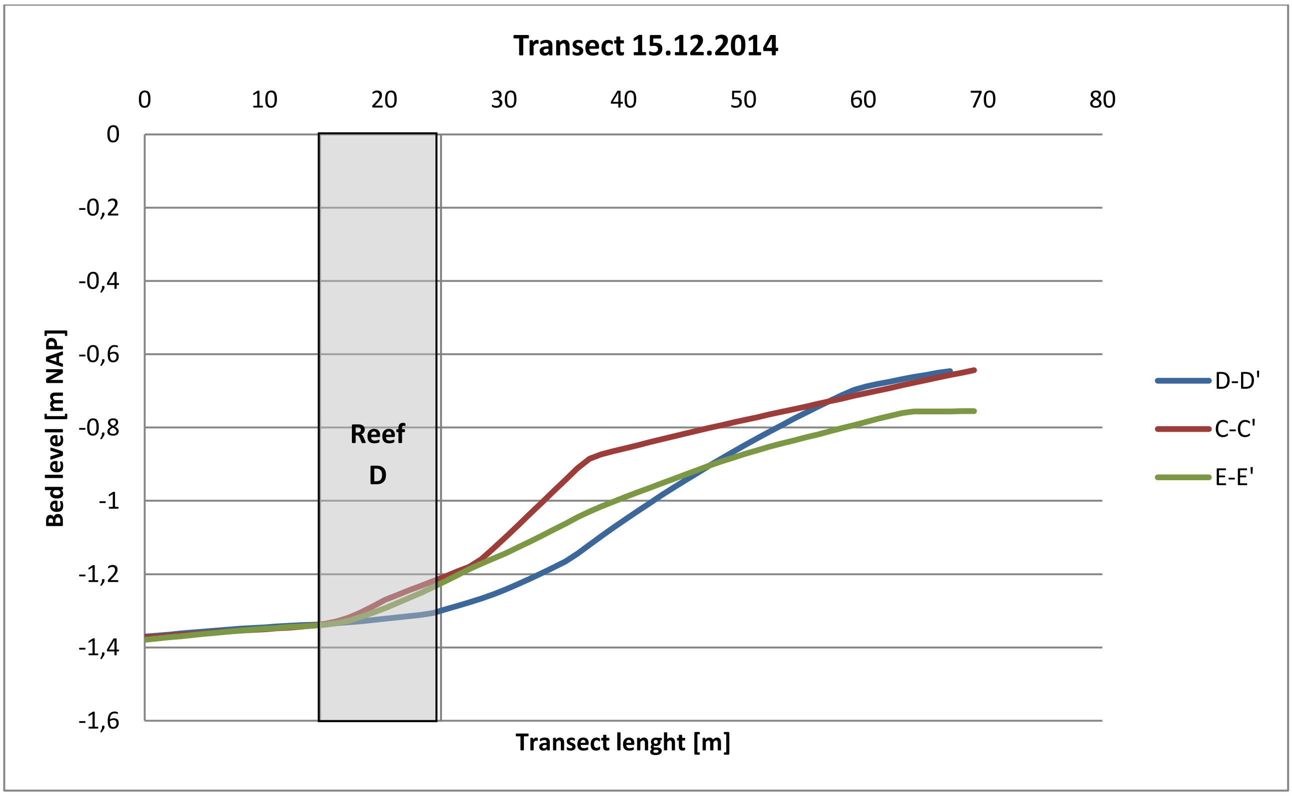

Transect 23.03.2016
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
D-D'
C-C'
E-E'
Transect lenght [m]

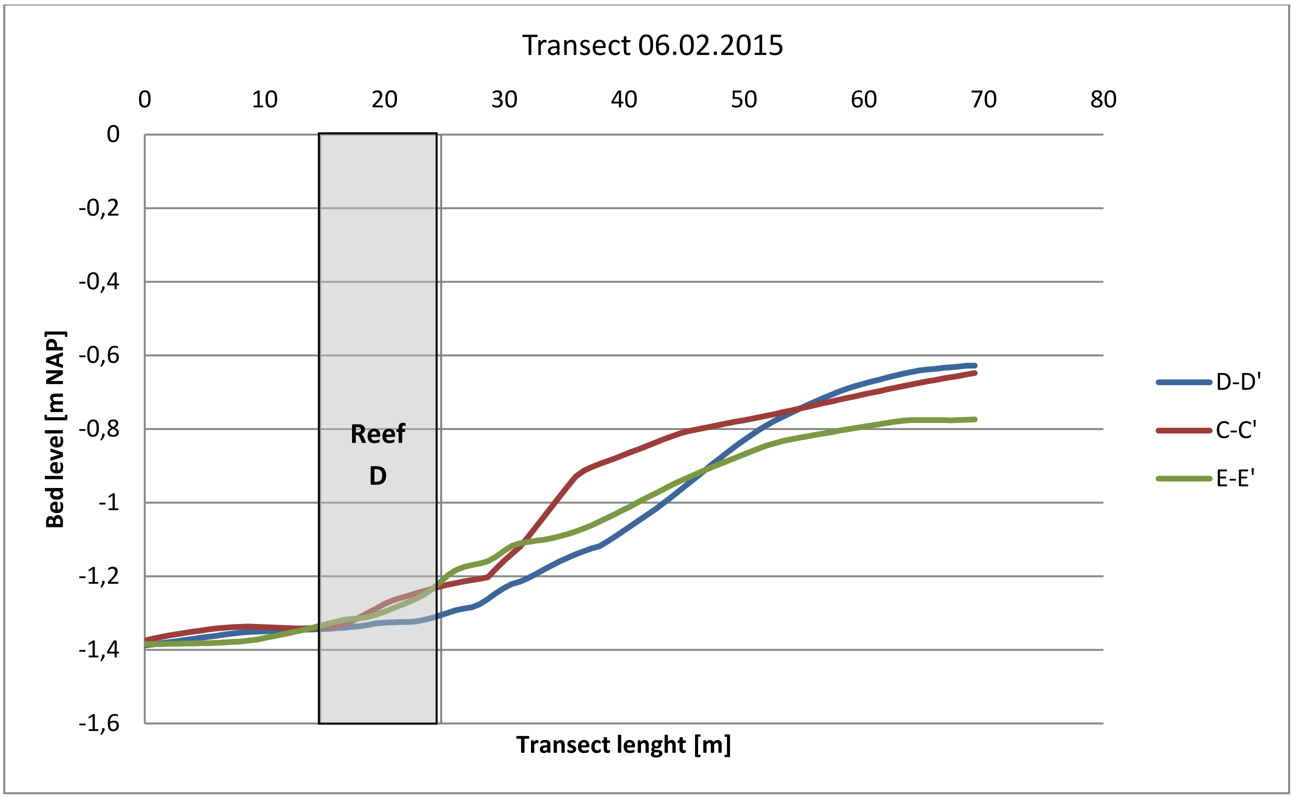

Transect 06.04.2016
0
10
20
30
40
50
60
70
0
-0,1
-0,2
-0,3
-0,4
-0,5
-0,6
-0,7
-0,8
-0,9
Bed level [m NAP]
Reef
A
Transect lenght [m]
D-D'
C-C'
E-E'

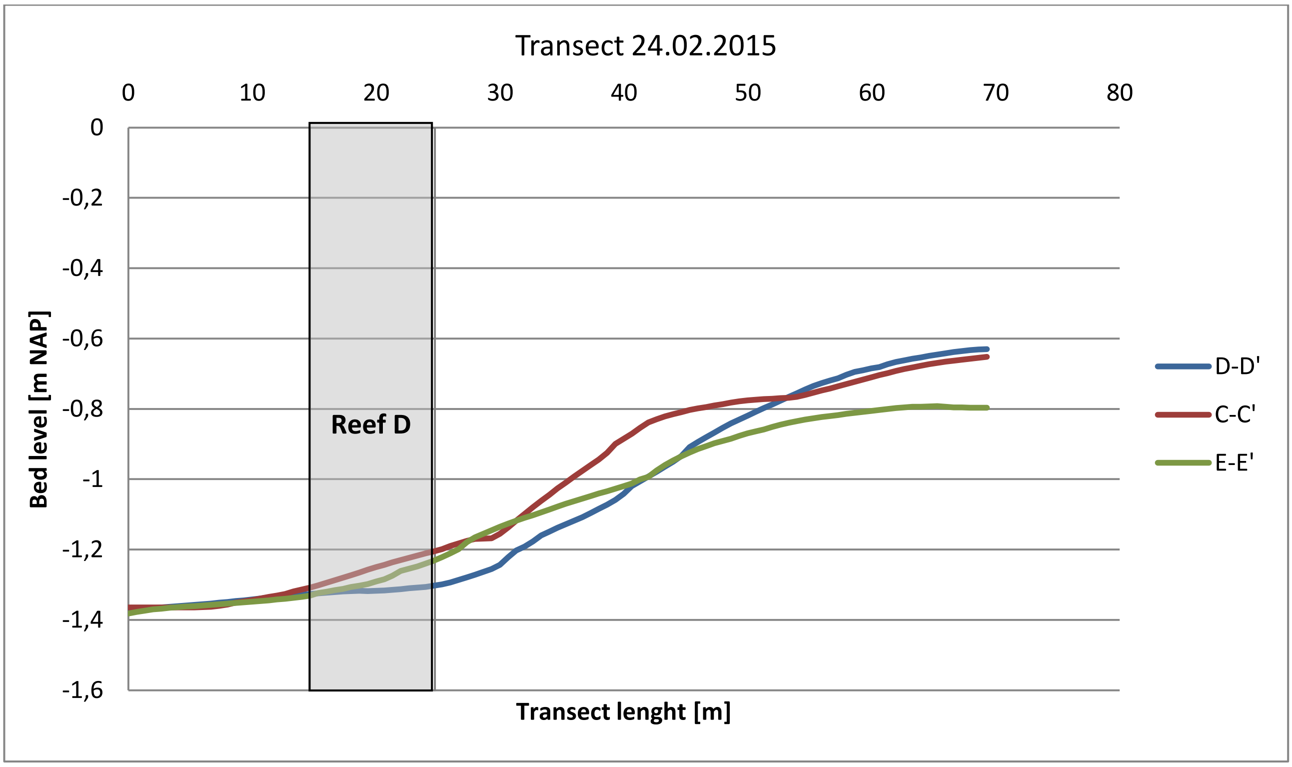
Reef D

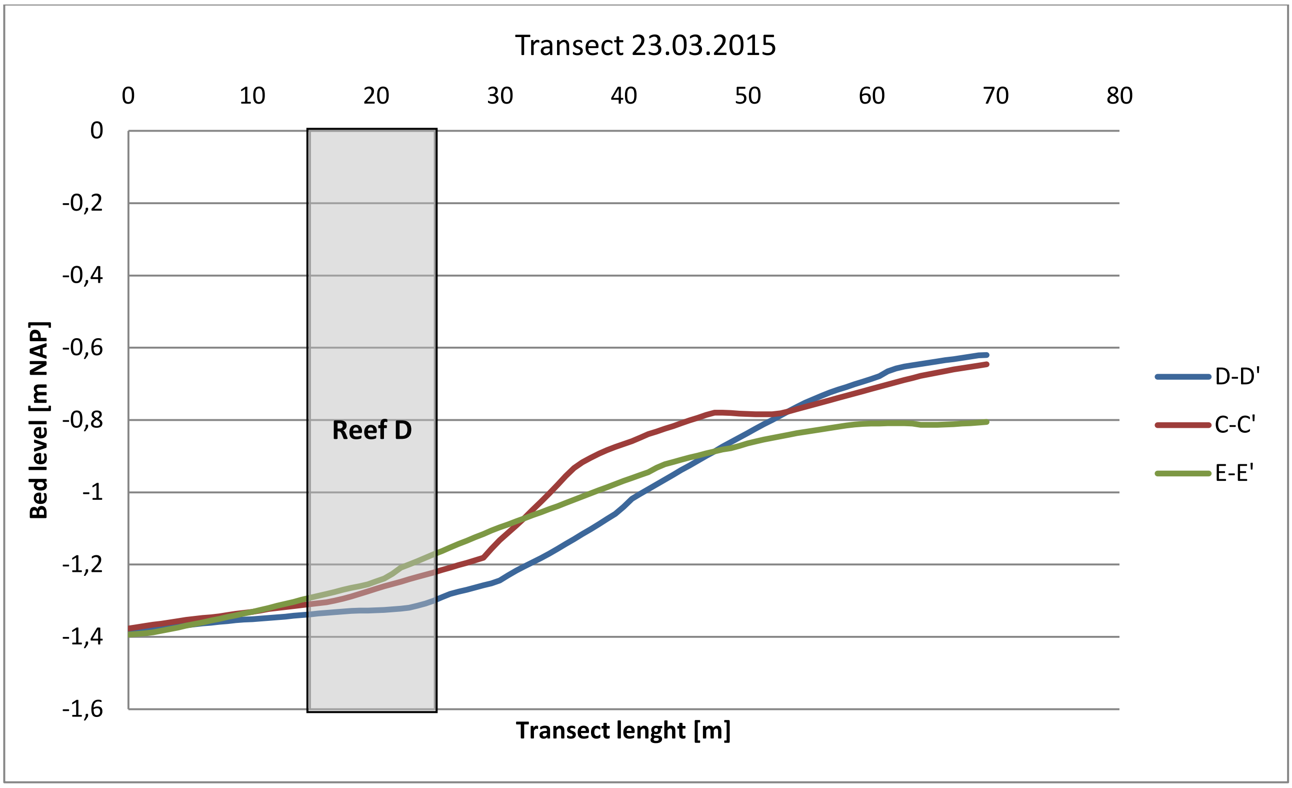

Transect 11.11.2014
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'

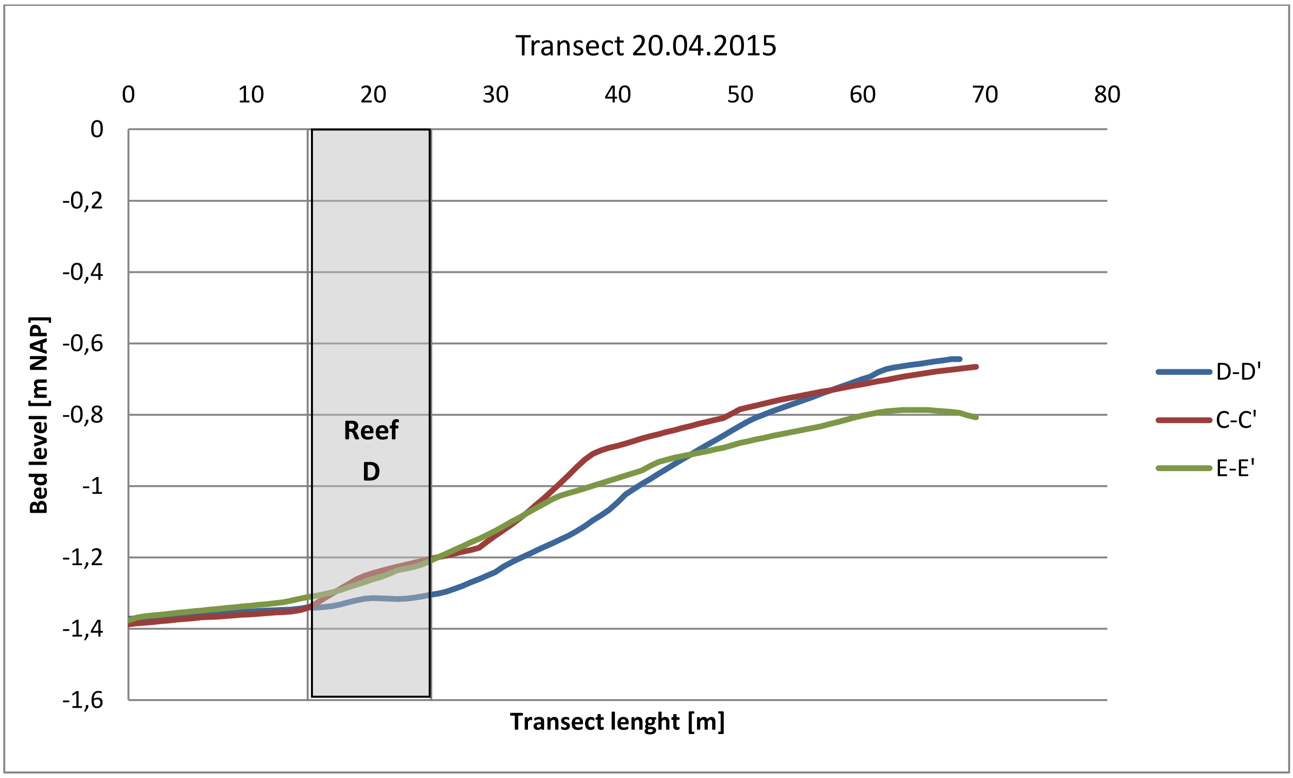

Transect 09.12.2014
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 15.12.2014
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 06.02.2015
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 24.02.2015
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 23.03.2015
0
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 20.04.2015
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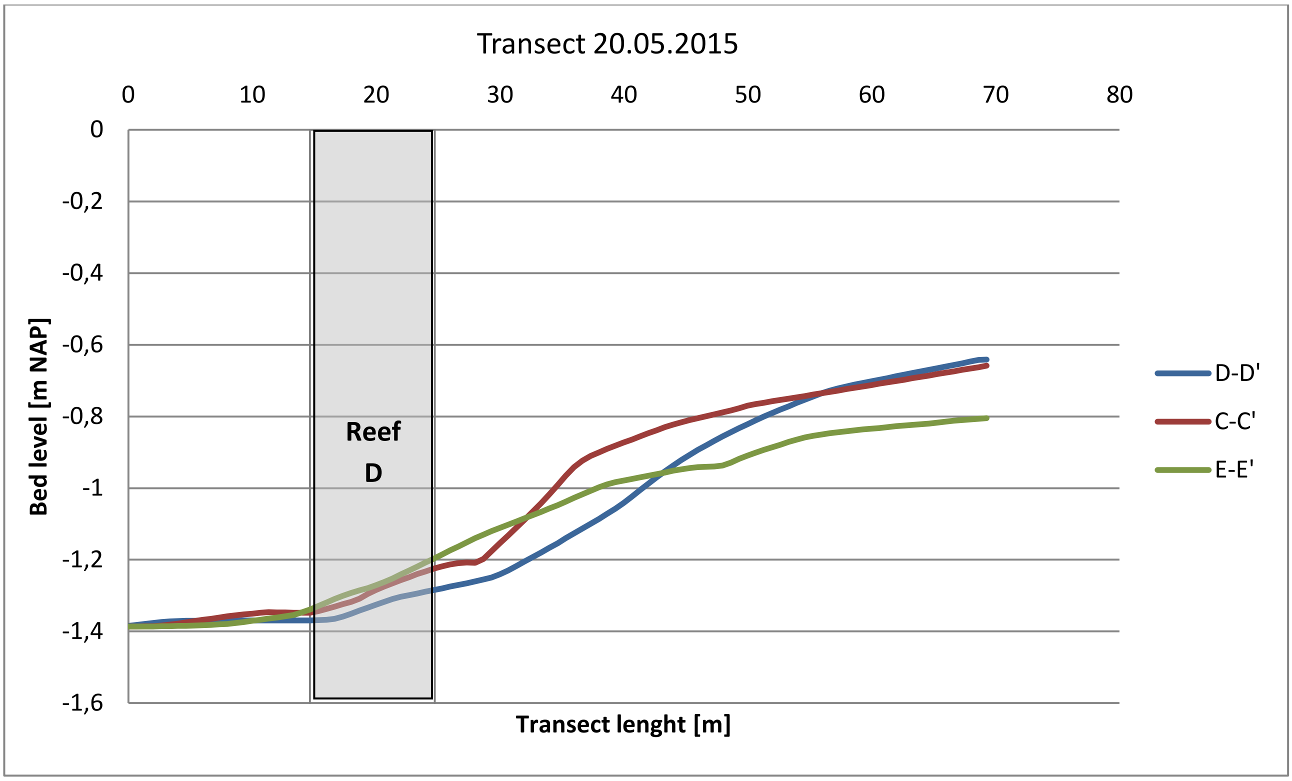
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 20.05.2015
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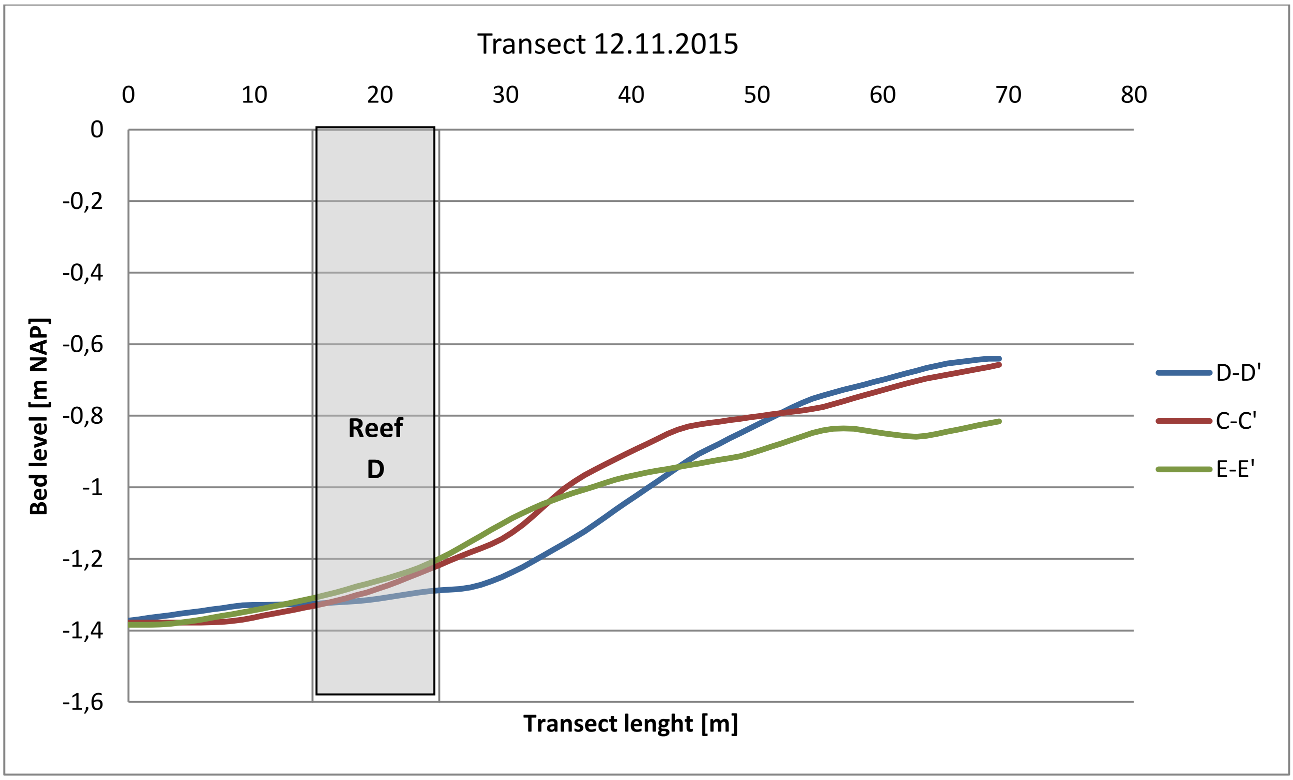
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 12.11.2015
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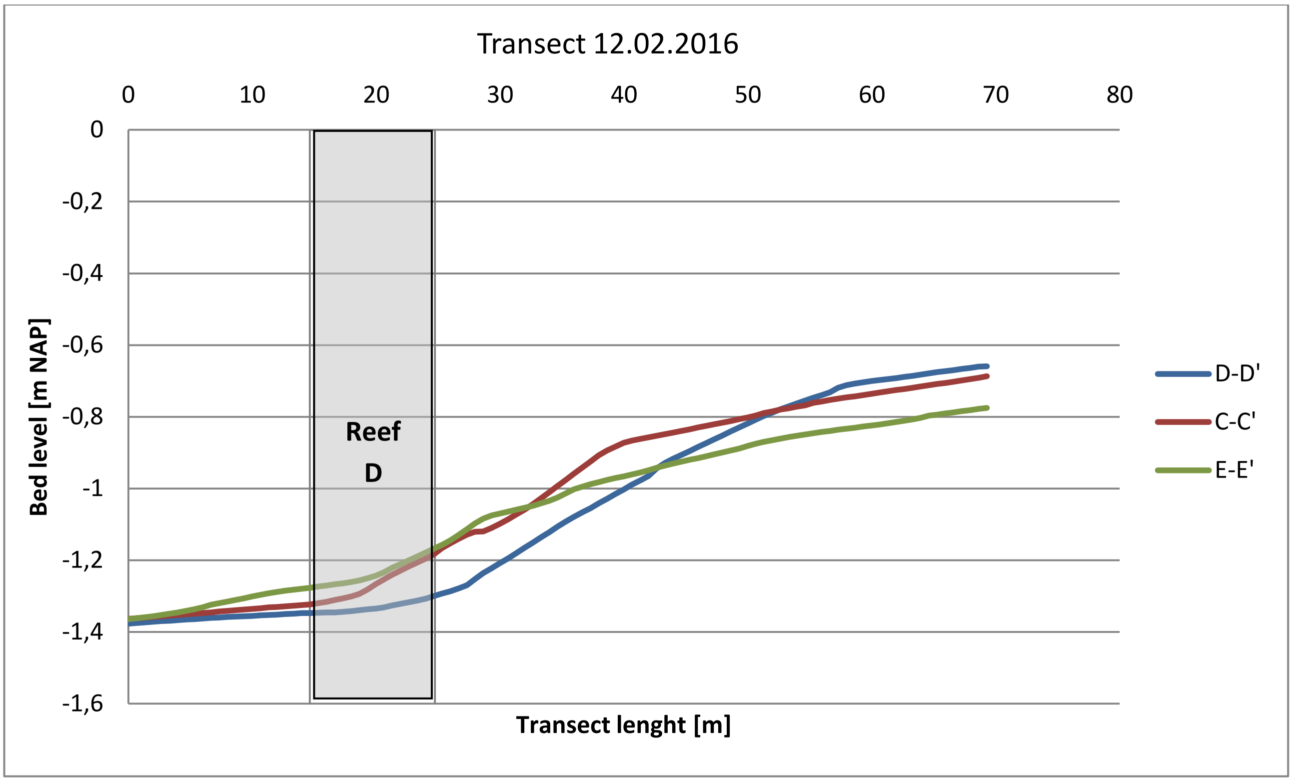
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 12.02.2016
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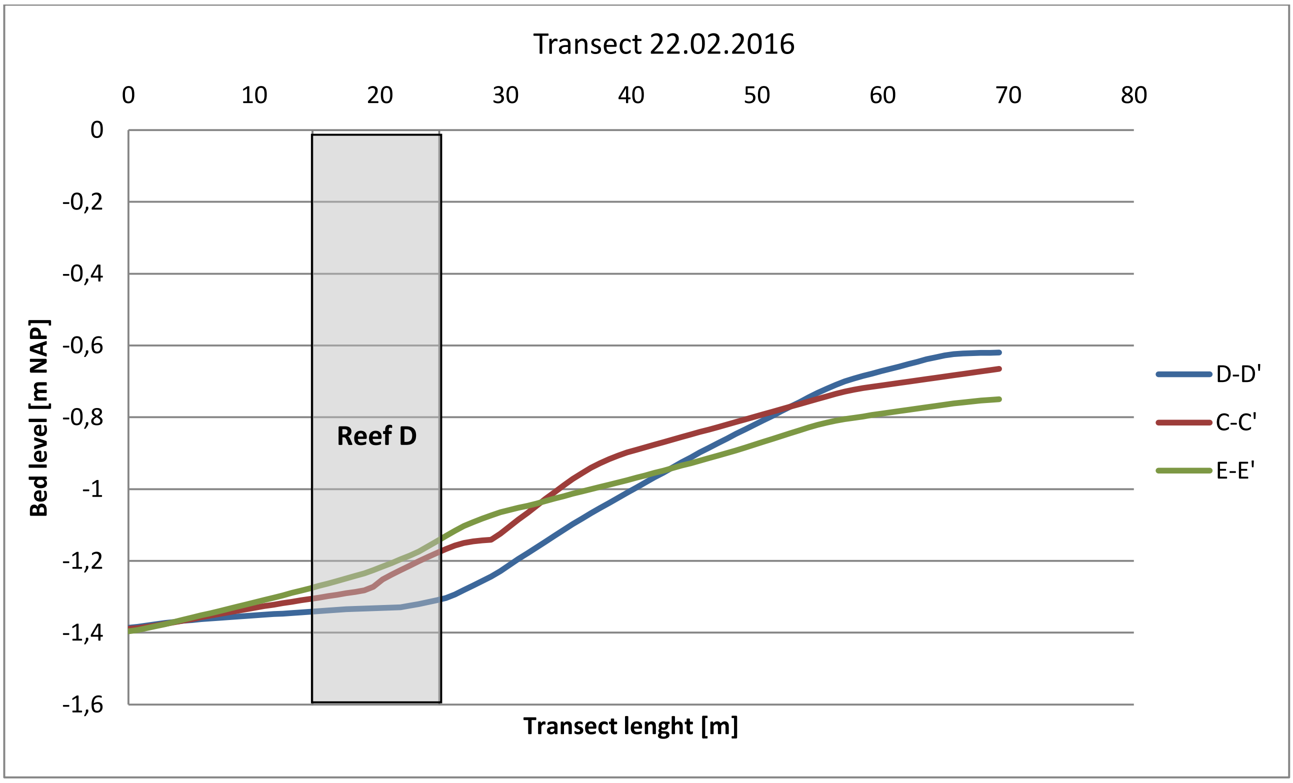
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 22.02.2016
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30
40
50
60
70
80
0
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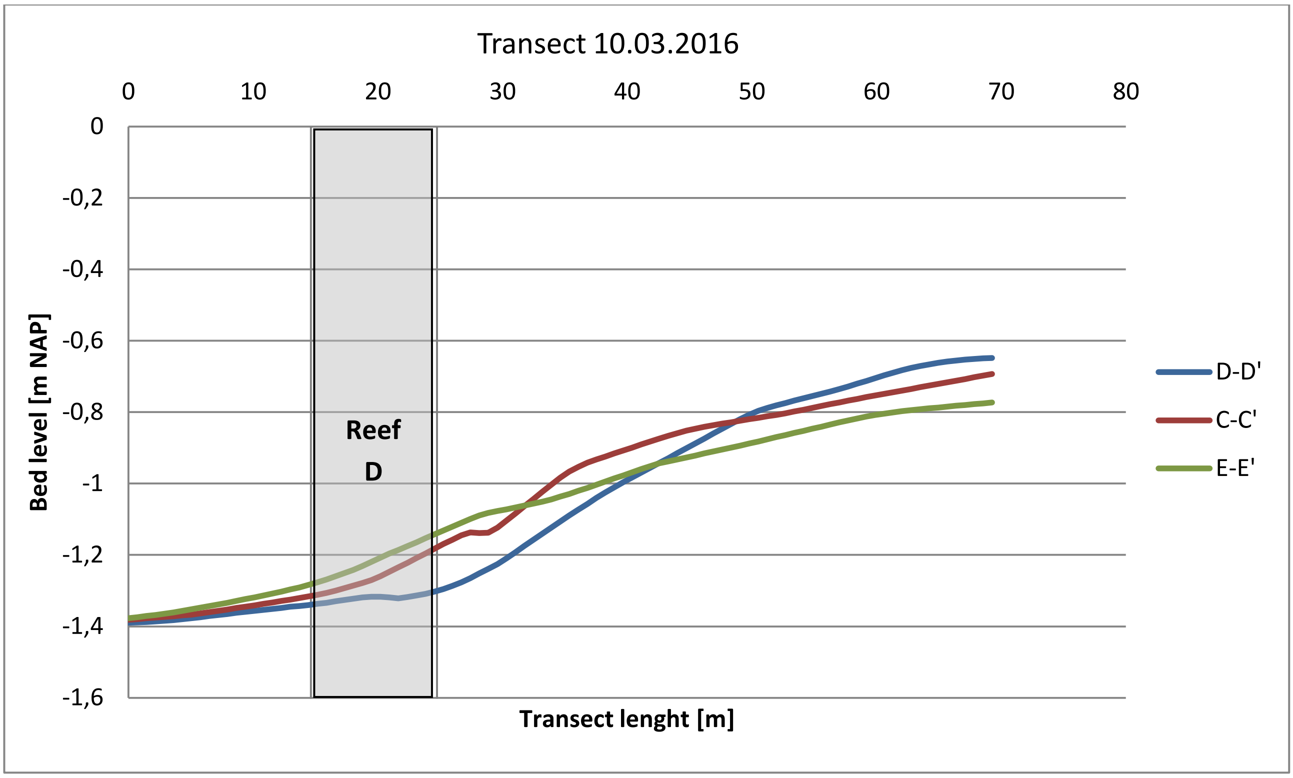
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 10.03.2016
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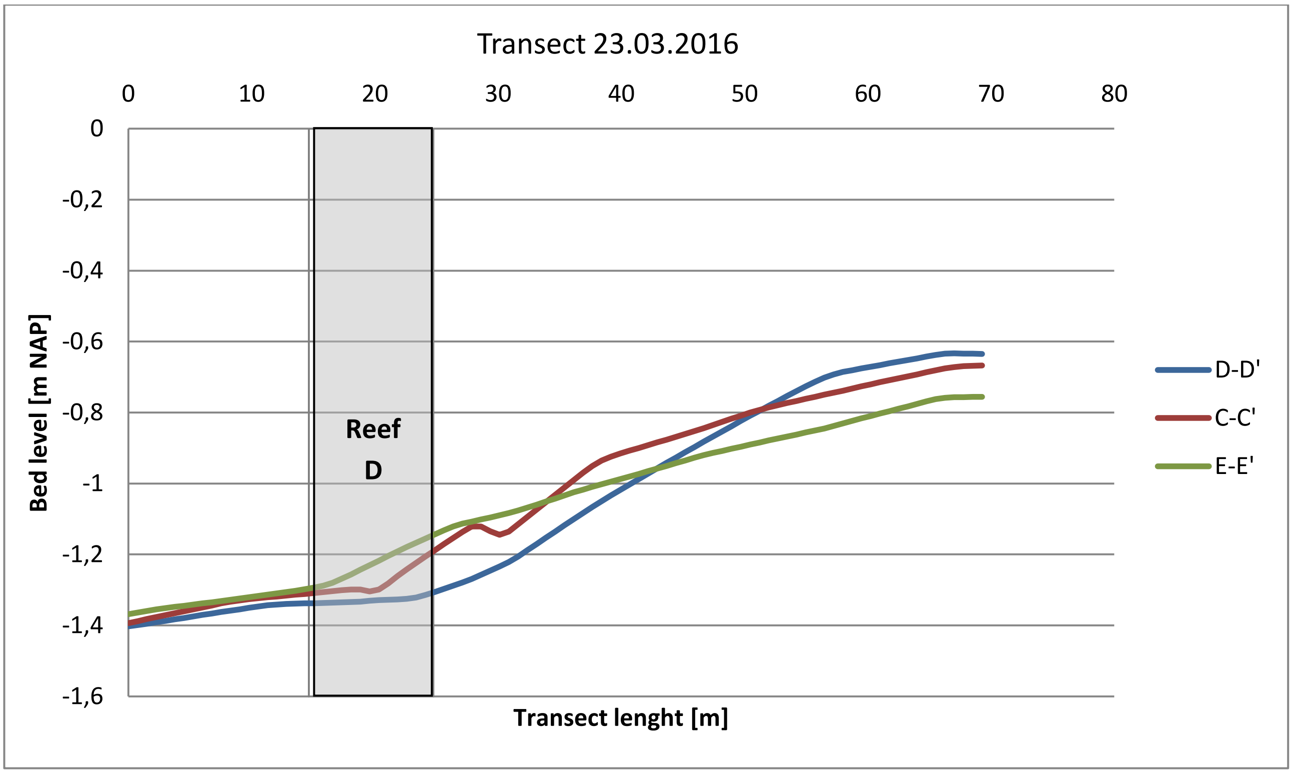
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 23.03.2016
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30
40
50
60
70
80
0
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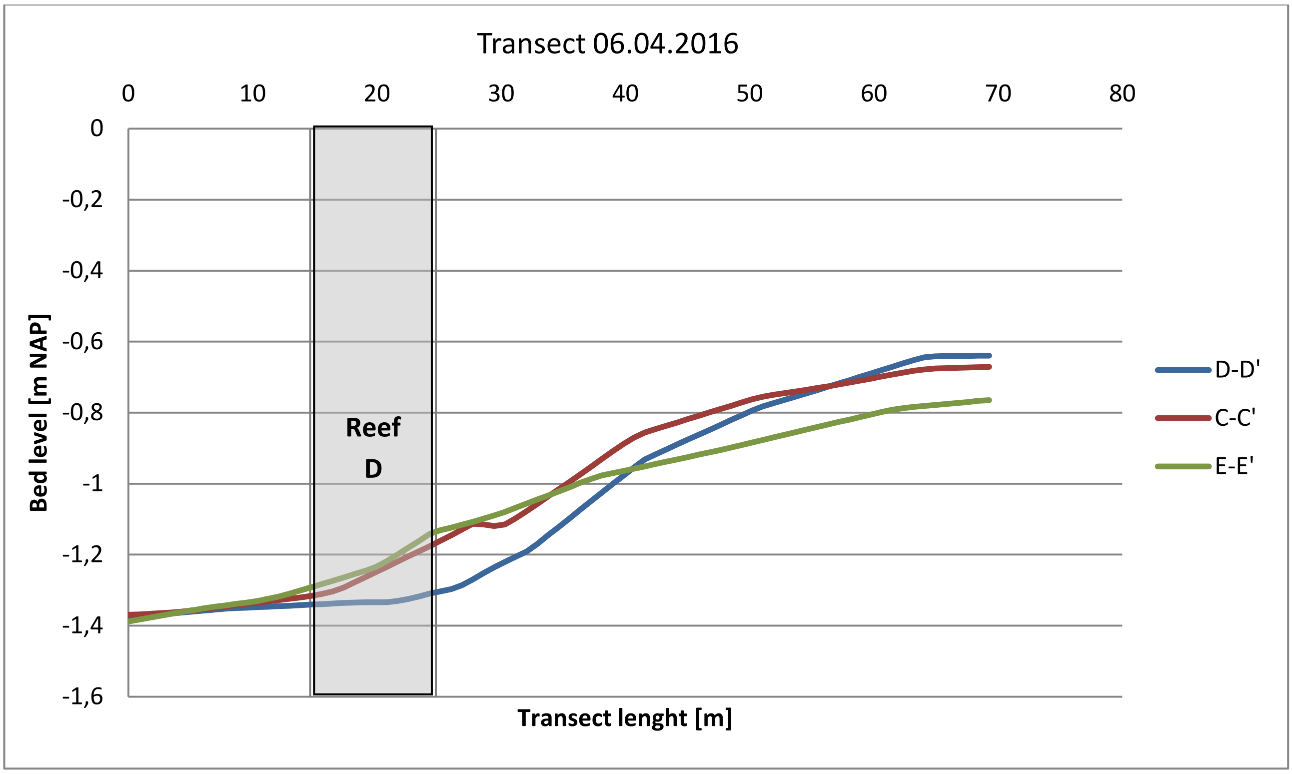
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'


Transect 06.04.2016
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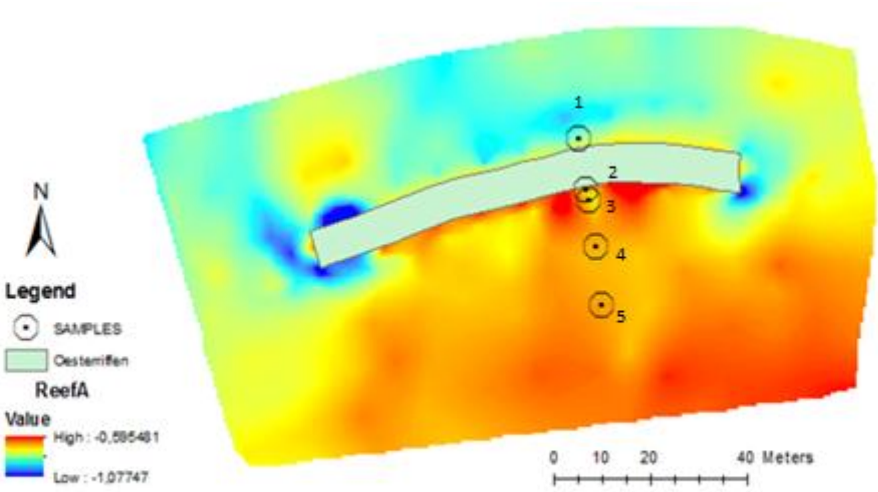
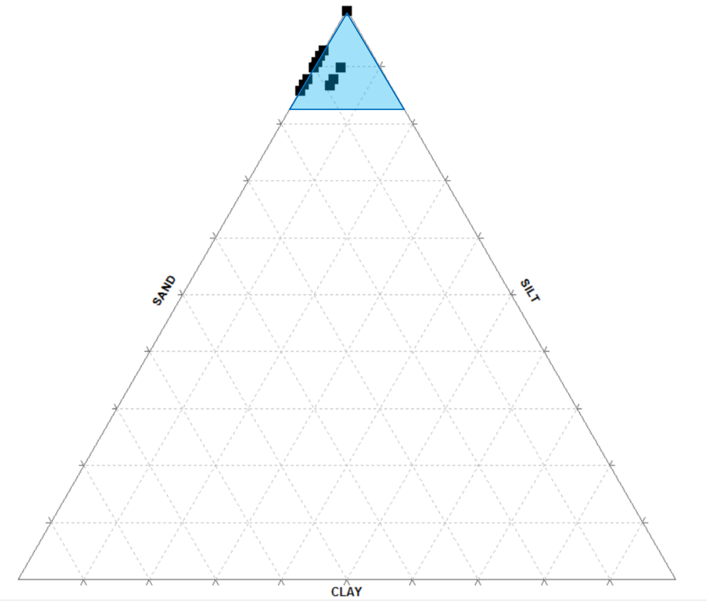
10
20
30
40
50
60
70
80
0
-0,2
-0,4
-0,6
-0,8
-1
-1,2
-1,4
-1,6
Bed level [m NAP]
Reef
D
Transect lenght [m]
D-D'
C-C'
E-E'

Appendix H: Tri-plot diagram of the samples

Reef A

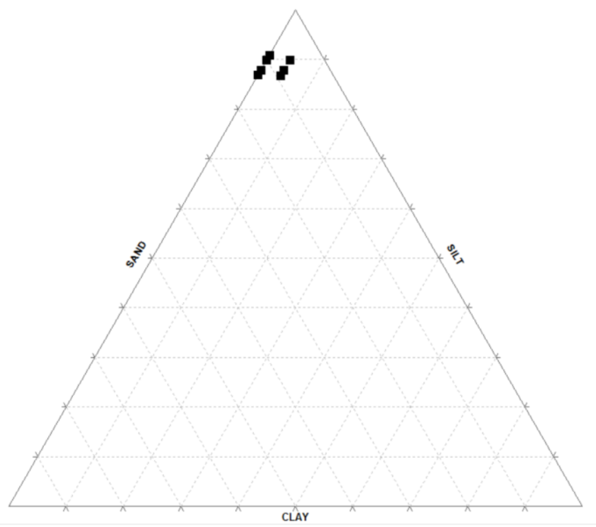




Results from the global analysis

Sample 1

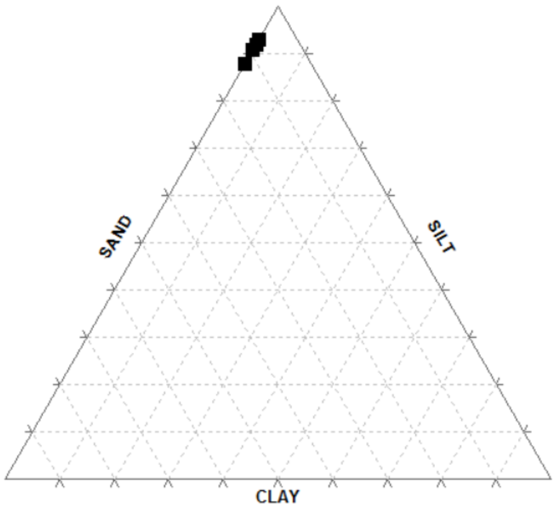
	sample	% sand	% silt	% clay
27.03.2015	**A1**	85.74	4.53	9.73
11.05.2015	**A1**	89.14	4.22	6.65
12.02.2016	**A1**	90.85	0	9.16
22.02.2016	**A1**	89.72	0	10.28
10.03.2016	**A1**	87.11	0	12.89
23.03.2016	**A1**	87.36	4.18	8.47
06.04.2016	**A1**	86.14	0	13.86



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**A1**	0	12.44	73.3	4.53	9.73
11.05.2015	**A1**	0	18.02	71.12	4.22	6.65
12.02.2016	**A1**	0	19.18	71.67	0	9.16
22.02.2016	**A1**	0	17.11	72.61	0	10.28
10.03.2016	**A1**	0	18.43	68.68	0	12.89
23.03.2016	**A1**	0	14.76	72.6	4.18	8.47
06.04.2016	**A1**	0	17.62	68.52	0	13.86
AVERAGE:		0	16.79	71.21	1.85	10.15

Sample 2

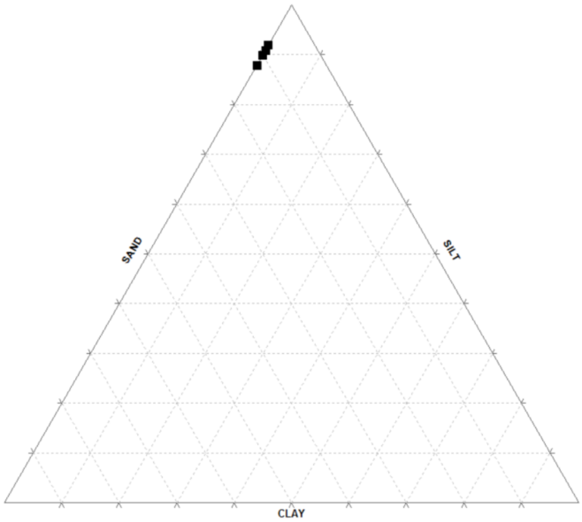
	sample	% sand	% silt	% clay
27.03.2015	A2	92.75	0	7.24
11.05.2015	A2	89.93	0.67	9.4
12.02.2016	A2	87.31	0	12.69
22.02.2016	A2	92.41	0	7.6
10.03.2016	A2	92.28	0	7.72
23.03.2016	A2	91	0	8.99
06.04.2016	A2	92.22	0	7.78



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	A2	0	20.58	72.17	0	7.24
11.05.2015	A2	0.86	19.8	69.27	0.67	9.4
12.02.2016	A2	0	18.6	68.71	0	12.69
22.02.2016	A2	0	21.99	70.42	0	7.6
10.03.2016	A2	0	21.91	70.37	0	7.72
23.03.2016	A2	0	19.31	71.69	0	8.99
06.04.2016	A2	0	21.94	70.28	0	7.78
AVERAGE:		0.12	20.59	70.42	0.10	8.77

Sample 3

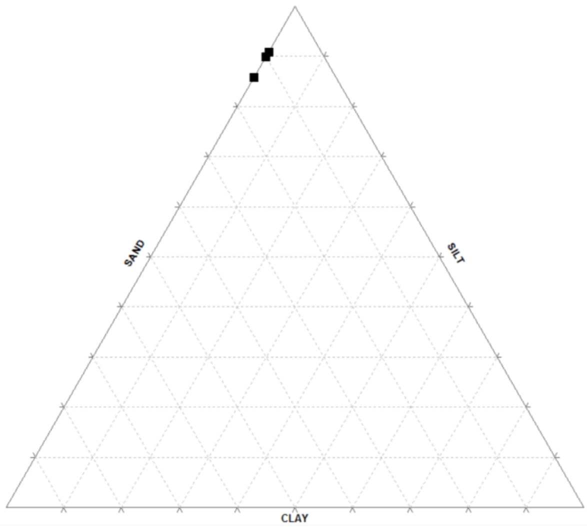
	sample	% sand	% silt	% clay
27.03.2015	**A3**	89.56	0	10.43
11.05.2015	**A3**	91.29	0	8.71
12.02.2016	**A3**	90.82	0	9.18
22.02.2016	**A3**	89.23	0	10.77
10.03.2016	**A3**	90.5	0	9.5
23.03.2016	**A3**	89.17	0	10.83
06.04.2016	**A3**	87.27	0	12.73



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**A3**	0	16.96	72.6	0	10.43
11.05.2015	**A3**	0	19.45	71.84	0	8.71
12.02.2016	**A3**	0	19.35	71.47	0	9.18
22.02.2016	**A3**	0	16.65	72.58	0	10.77
10.03.2016	**A3**	0	18.64	71.86	0	9.5
23.03.2016	**A3**	0	16.67	72.5	0	10.83
06.04.2016	**A3**	0	18.53	68.74	0	12.73
AVERAGE:		0	18.04	71.66	0.00	10.31

Sample 4

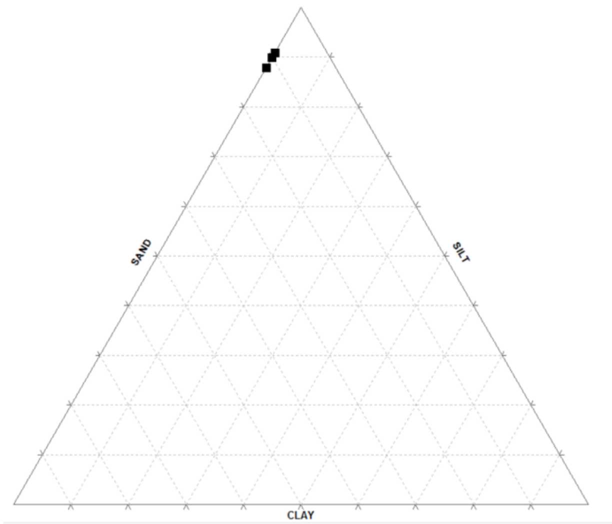
	sample	% sand	% silt	% clay
27.03.2015	**A4**	85.2	0	14.8
11.05.2015	**A4**	89.21	0	10.78
12.02.2016	**A4**	89.77	0	10.23
22.02.2016	**A4**	90.71	0	9.29
10.03.2016	**A4**	90.27	0	9.73
23.03.2016	**A4**	89.46	0	10.54
06.04.2016	**A4**	89.45	0	10.55



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**A4**	0	15.97	69.23	0	14.8
11.05.2015	**A4**	0	21.05	68.16	0	10.78
12.02.2016	**A4**	0	17.61	72.16	0	10.23
22.02.2016	**A4**	0	18.98	71.73	0	9.29
10.03.2016	**A4**	0	18.18	72.09	0	9.73
23.03.2016	**A4**	0	17.08	72.38	0	10.54
06.04.2016	**A4**	0	17.19	72.26	0	10.55
AVERAGE:		0	18.01	71.14	0.00	10.85

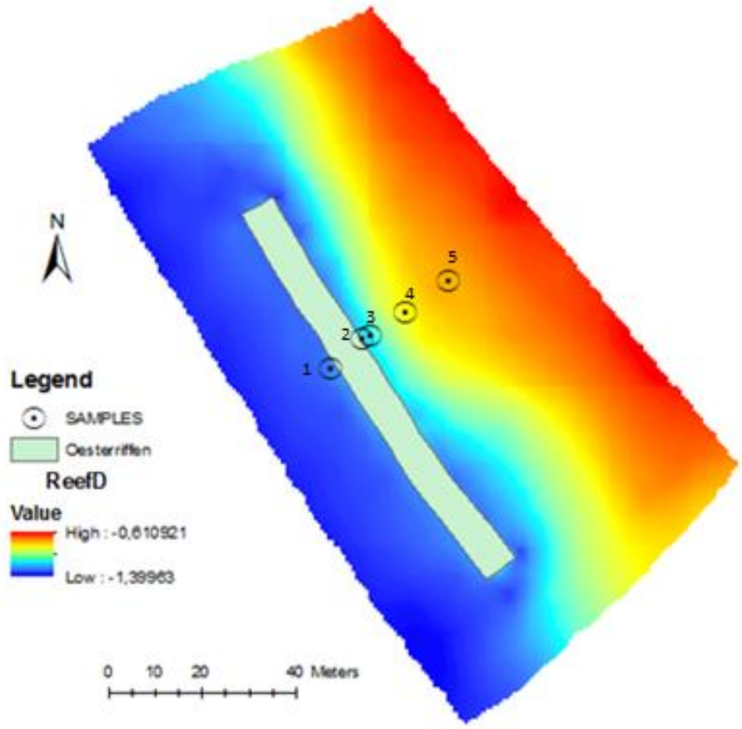
Sample 5

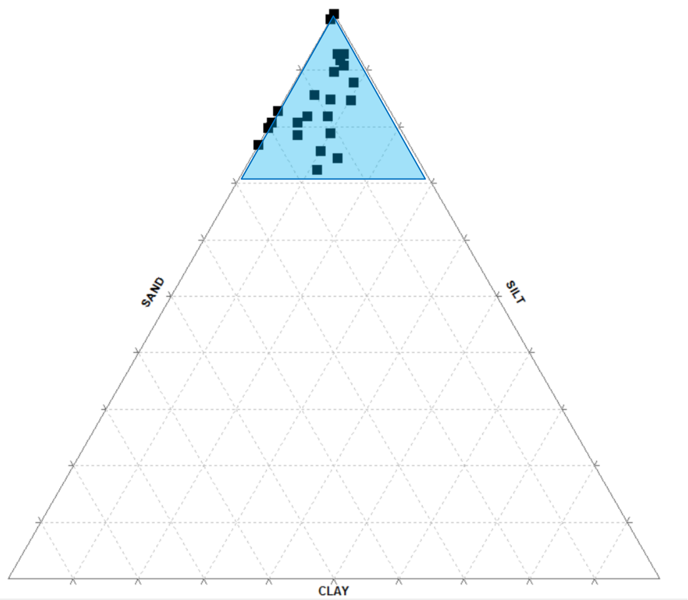
	sample	% sand	% silt	% clay
27.03.2015	**A5**	89.43	0	10.57
11.05.2015	**A5**	90.1	0	9.91
12.02.2016	**A5**	90.33	0	9.67
22.02.2016	**A5**	89.91	0	10.09
10.03.2016	**A5**	90.08	0	9.92
23.03.2016	**A5**	87.77	0	12.23
06.04.2016	**A5**	90.11	0	9.9



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**A5**	0	18.42	71.01	0	10.57
11.05.2015	**A5**	0	17.57	72.53	0	9.91
12.02.2016	**A5**	0	18.53	71.8	0	9.67
22.02.2016	**A5**	0	17.7	72.21	0	10.09
10.03.2016	**A5**	0	17.97	72.11	0	9.92
23.03.2016	**A5**	0	19.23	68.54	0	12.23
06.04.2016	**A5**	0	18.01	72.1	0	9.9
AVERAGE:		0	18.20	71.47	0.00	10.33

Reef D

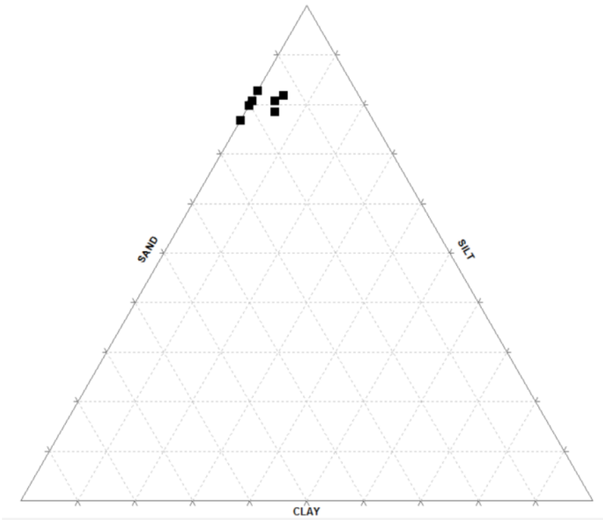




Results from the global analysis

Sample 1

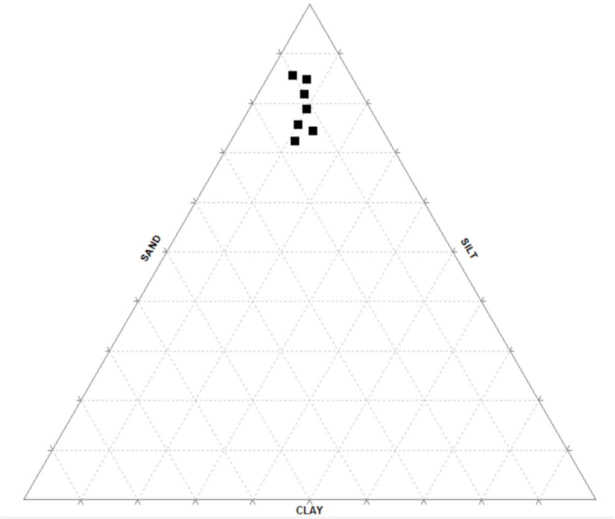
	sample	% sand	% silt	% clay
27.03.2015	**D1**	81.46	5.24	13.31
11.05.2015	**D1**	77.7	5.58	16.71
12.02.2016	**D1**	82.21	0	17.79
22.02.2016	**D1**	80.32	0	19.68
10.03.2016	**D1**	79.48	0	20.52
23.03.2016	**D1**	76.77	0.01	23.24
06.04.2016	**D1**	80.67	4.13	15.20



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**D1**	**0**	9.72	71.74	5.24	13.31
11.05.2015	**D1**	**0**	13.34	64.36	5.58	16.71
12.02.2016	**D1**	**0**	14.27	67.94	0	17.79
22.02.2016	**D1**	**0**	12.26	68.06	0	19.68
10.03.2016	**D1**	**0**	11.52	67.96	0	20.52
23.03.2016	**D1**	**0**	9.82	66.95	0.01	23.24
06.04.2016	**D1**	**0**	9.85	70.82	4.13	15.20
AVERAGE:		0.00	11.54	68.26	2.14	18.06

Sample 2

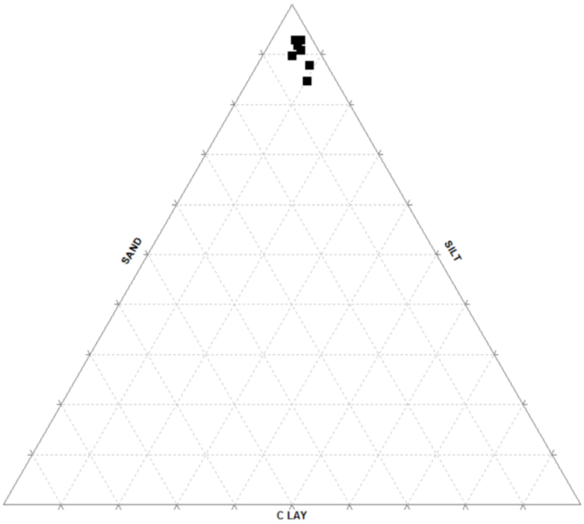
	sample	% sand	% silt	% clay
27.03.2015	**D2**	75.19	10.56	14.31
11.05.2015	**D2**	84.95	4.69	10.39
12.02.2016	**D2**	81.84	8.09	10.09
22.02.2016	**D2**	84.89	7.04	8.10
10.03.2016	**D2**	78.21	10.25	11.59
23.03.2016	**D2**	73.92	13.20	12.94
06.04.2016	**D2**	71.88	11.61	16.57



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**D2**	**5.58**	31.13	38.48	10.56	14.31
11.05.2015	**D2**	**9.12**	40.7	35.13	4.69	10.39
12.02.2016	**D2**	**8.67**	39.85	33.32	8.09	10.09
22.02.2016	**D2**	**10.29**	43.57	31.03	7.04	8.10
10.03.2016	**D2**	**8.95**	37.46	31.80	10.25	11.59
23.03.2016	**D2**	**6.68**	33.45	33.79	13.2	12.94
06.04.2016	**D2**	**5.45**	29.61	36.82	11.61	16.57
AVERAGE:		7.82	36.54	34.34	9.35	12.00

Sample 3

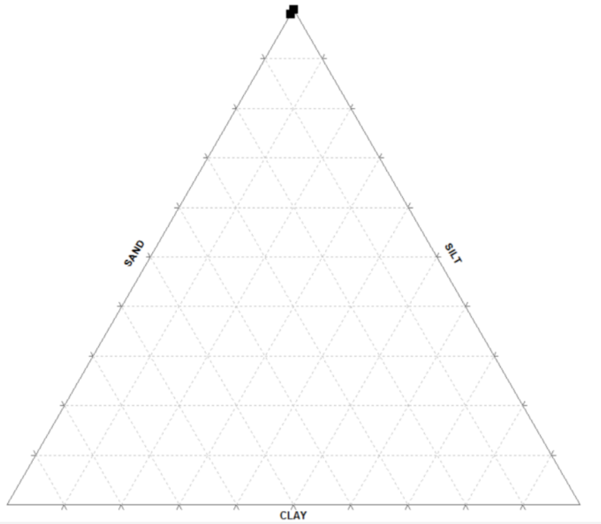
	sample	% sand	% silt	% clay
27.03.2015	**D3**	83.91	10.62	5.48
11.05.2015	**D3**	90.58	5.5	3.93
12.02.2016	**D3**	91.58	4.44	3.99
22.02.2016	**D3**	88.39	5.79	5.84
10.03.2016	**D3**	89.47	6.68	3.87
23.03.2016	**D3**	87.71	9.30	3.02
06.04.2016	**D3**	91.98	5.32	2.71



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**D3**	**10.04**	44.57	29.3	10.62	5.48
11.05.2015	**D3**	**10.82**	50.11	29.65	5.5	3.93
12.02.2016	**D3**	**11.14**	49.55	30.89	4.44	3.99
22.02.2016	**D3**	**11.32**	47.14	29.93	5.79	5.84
10.03.2016	**D3**	**12.89**	50.29	26.29	6.68	3.87
23.03.2016	**D3**	**11.81**	49.58	26.32	9.3	3.02
06.04.2016	**D3**	**12.49**	52.24	27.25	5.32	2.71
AVERAGE:		11.50	49.07	28.52	6.81	4.12

Sample 4

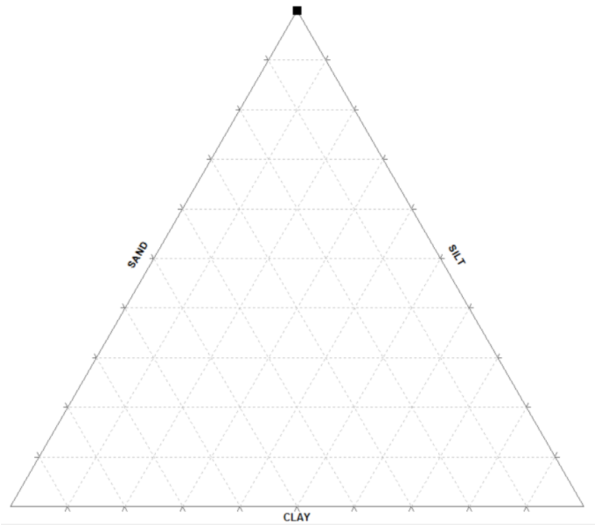
	sample	% sand	% silt	% clay
27.03.2015	**D4**	99.94	0	0.05
11.05.2015	**D4**	99.94	0	0.07
12.02.2016	**D4**	99.6	0	0.41
22.02.2016	**D4**	99.86	0	0.14
10.03.2016	**D4**	99.75	0	0.25
23.03.2016	**D4**	99.97	0	0.04
06.04.2016	**D4**	98.18	0	1.81



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**D4**	**8.56**	65.34	26.04	0	0.05
11.05.2015	**D4**	**7.11**	64.79	28.04	0	0.07
12.02.2016	**D4**	**6.97**	58.71	33.92	0	0.41
22.02.2016	**D4**	**6.39**	62.52	30.95	0	0.14
10.03.2016	**D4**	**7.65**	60.17	31.93	0	0.25
23.03.2016	**D4**	**9.65**	62.69	27.63	0	0.04
06.04.2016	**D4**	**5.04**	52.15	40.99	0	1.81
AVERAGE:		7.34	60.91	31.36	0.00	0.40

Sample 5

	sample	% sand	% silt	% clay
27.03.2015	**D5**	100	0	0
11.05.2015	**D5**	99.34	0.48	0.18
12.02.2016	**D5**	99.88	0	0.12
22.02.2016	**D5**	99.94	0	0.06
10.03.2016	**D5**	99.96	0	0.04
23.03.2016	**D5**	99.84	0	0.15
06.04.2016	**D5**	99.65	0	0.35



	sample	% coarse sand	% medium sand	% fine sand	% silt	% clay
27.03.2015	**D5**	**8.84**	68.77	22.39	0	0
11.05.2015	**D5**	**6.35**	61.28	31.71	0.48	0.18
12.02.2016	**D5**	**5.51**	62.17	32.2	0	0.12
22.02.2016	**D5**	**7.69**	64.61	27.64	0	0.06
10.03.2016	**D5**	**8.36**	64.22	27.38	0	0.04
23.03.2016	**D5**	**7.64**	60.51	31.69	0	0.15
06.04.2016	**D5**	**7.58**	59.11	32.96	0	0.35
AVERAGE:		7.42	62.95	29.42	0.07	0.13