REPORT

MODELLING DIFFERENT ARTIFICIAL REEFS IN THE COASTLINE OF PROBSTEI

DIFFERENT POSITIONS AND SHAPES OF ARTIFICIAL REEF, ITS IMPACTS ON SEDIMENT TRANSPORT, AFFECTS ON MARINE FAUNA. IMPACTS ANALYSIS ON INCREASE OF DIVING RECOURSES

Lina Kliucininkaite and Dr. Kai Ahrendt

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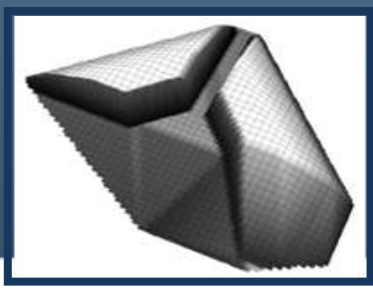

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Abstract

The coastal zones, dividing land and sea, have always played a significant role in human activities (Arnouil, 2006), but their economical importance has been significantly growing in the past few decades. Half of highly accelerating global human population lives in the coastal zone. Therefore, the interaction between humans and the environment often throws the natural coastal system out of equilibrium (Haslett, 2008) leading to coastal erosion. Many of the conventional coastal protection methods have the potential to adequately solve local erosion problems in some cases but can lead to some undesirable affects and disadvantages. One of the best ways to protect a beach is to emulate natural defense mechanism. Previous studies have shown that offshore submerged reefs can provide natural shoreline stabilization by wave breaking and dissipation. Such structures are potential tools protecting or restoring beaches, marine habitats, creating fishing grounds or even serving as facility to generate surfing waves for improving tourism. This paper gives short introduction to history and classification of such structures together with few examples worldwide.

This research is a part of series of investigations carried out and developed in the German Baltic Sea Coastal zone and the scope or a key-target of this Master Thesis was to come up with an integrated design and the most suitable submerged coastal engineering alternatives for the Probstei coastline, particularly for the Heidkate, Kalifornien and Brasilien beaches. These locations are favorable recreational spots, which are nowadays highly threatened by higher frequency of storms, higher wave heights attacking the coast and increasing water level due to climate change. A seek to preserve and maintain this coastal zone, ten different alternatives, including surfing reefs (Alternative 1 - 6), a shore-parallel breakwater (Alternative 7) and Reef Balls breakwaters (Alternative 8, 9 and 10), were proposed for this case study. The integrated design of submerged artificial reef-type structures, together with selection of reef placement locations, was based on multidisciplinary literature research and above mentioned requirements was integrated in the process of design.

DHI's MIKE 21 and LITPACK numerical models are employed to answer the key-question of this case study. Longshore sediment transport was modeled with LITPACK LITDRIFT module, while wave transmission coefficients through the structure were calculated from numerical modelling results, obtained with MIKE 21 Boussinesq Wave Module.

Two alternatives could be suggested for the Heidkate beach, such as: (1) the surfing reef with eastern arm extension and orientated 45° from North, marked as Alternative 2 in this case study or (2) submerged breakwater from Reef Balls, marked as Alternative 9. The toe shield or other protection or improvement measures in front of the structure are highly recommended for both breakwaters. Alternatives 4 and 6, both placed 45° from North, are the most effective reef-type structures from proposed ones for the Brasilien beach in this case study. Moreover, these structures don't induce high sediment transport in the vicinity of the breakwater. Alternative 4 is a surfing reef breakwater without extensions of arms, while Alternative 6 is surfing reef with a western arm extension. Alternative 10, breakwater from Reef Balls, can be also suggested for the Brasilien beach, if the main target would be the improvement or creation of the habitat. The toe protection and different size of the gap between structures should be considered then. The latter structure was not that effective in reduction of longshore sediment transport as Alternative 4 or 6.

Recommendations of further research are given in the final chapter of this research paper.

Key words: artificial reef, surfing, coastal protection, numerical modelling, MIKE 21, LITPACK, Reef Balls, geotextile.

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First of all I would like to thank to my supervisor, Dr. Kai Ahrendt, for giving me a chance to write my Master Thesis in the framework of RA:dOst Project, proposing me very interesting topic, providing with necessary data, literature, software and working place. Moreover, thanks for his guidance and support, and freedom to execute my ideas in this research work. I owe my deepest gratitude to him. I also would like to thank to my supervisor, Prof. Dr. Felix Müller, for his support, advices and encouragement, as well as recommendation through my thesis-writing period.

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Kiel, October 2011 Lina Kliucininkaite

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Notations

Symbol	Definition	Unit
SARB	Submerged Artificial Reef Breakwaters	N/A
ASR	Artificial Surfing Reef	N/A
SWL	Still Water Level	m
MWL	Mean Water Level	m
CEM	Coastal Engineering Manual	N/A
FINA	International Swimming Federation	N/A
FAD	Fish attracting device	N/A
α	Peel angle along breaker line	degree
V_s	Surfer velocity along the breaker line	m/s
L_s	Length of ride	m
ξ_b	Iribarren number along breaker line that provides an indication of the type of breaking	N/A
L_{prot}	Length of coast protected by the reed	m
H_b	Wave breaking height along the breaker line	m
L	Length of the breakwater along the coastline	m
X	Distance from coastline to the breakwater	m
h	Height of submerged breakwater	m
B	Crest width of submerged breakwater	m
F	Crest level or submergence	m
K_t	Transmission coefficient	N/A
H_t	Height of transmitted wave on the landside of the structure	m
H_i	Height of a incident wave on the seaward side of the structure	m
X_{off}	Distance between reef and salient	m
Y_{off}	Salient amplitude	m
D_{tot}	Length of salient	m
I_s	Beach response index	N/A

1 Introduction

1.1 General introduction

The coastal zones, dividing land and sea, have always played a significant role in human activities (Arnouil, 2006), but their economical importance has been significantly growing in the past few decades. Major factors are increase in the population, economic activities established near or on the coast such as construction of cities, ports and harbors, and high numbers of visitors wanting to enjoy sandy beaches and practice outdoor sports such as surfing, sailing, fishing etc. (ten Voorde at al., 2009). Haslet (2008) in his book highlights high acceleration of global human population, which passed the six billion mark before the end of the twentieth century. Moreover, more than half of these people live in coastal zones. This number can be illustrated telling that it is equal to the entire global population of the 1590s. Future predictions stated in the latter book are even more alarming. It refers that by 2025 more people will live in the coastal zone than were alive in 1990s. Unfortunately, the interaction between humans and the environment often throws the natural coastal system out of the equilibrium (Haslett, 2008) as natural coastal processes are impact efforts to maintain coastal development (Dean and Dalrymple, 2002), which typically results coastal erosion. The qualities, which provide and make coasts attractive holiday and living destinations, are under their gradual degradation. Increasing pressures on coasts and rising number of threads, such as resource exploitation, infrastructure, conservation, tourism and recreation (Kay and Alder, 2005), require increased and higher levels of management and protection. Moreover, the human use of the coast should meet the needs of the present population, without jeopardizing the opportunities of future generations, so that our descendents will be able to use the coast in much the same way as we do today (Haslett, 2008). In other words resources must be used in the sustainable way.

Our coasts are the resources which have to be protected and preserved for future, because their provided amenities play important direct or indirect roles. The coastal landscapes, which consist of beaches, cliffs, dunes, sand spits, barrier islands, tidal flats, deltas, tidal inlets, etc., are all the result of sediment transport generated by hydrodynamic forces. Hydrodynamics and beach materials are therefore two very basic ingredients in coastal morphology. Changes in coastal hydrodynamics can cause changes in coastal landscapes which are very vulnerable and sensitive. Some of the main factors which contribute to coastal erosion are (Silvester and Hsu, 1997; Pilarczyk and Zeilder, 1996):

- Storm events, extreme tides or currents, sea level rise
- Disrupting or changing sediment transport (natural or man-made)
- Elimination of sources of organic sediment as a results of water pollution
- Loss of sand from Aeolian (wind) transport of sediments.

But as these impacts on coastal ecosystems are hardly avoidable, but can be diminished and maintained. Various structures (Table 1.1), systems and methods have been developed and can be of use in coastal and shoreline protection or stabilization. It varies from traditional rubble and/or concrete systems to more novel ones, such as geotextile, reef balls and others.

Table 1.1: Alternative Solutions for coastal Erosion Protection.

Type of Structure	Objective	Principal function
Sea dike	Prevent/lessen flooding by the sea of low-lying land areas	Separation of shoreline from hinterland by a high impermeable structure
Seawall	Protect land/structures from flooding and overtopping	Reinforcement of part of the beach profile
Revetment	Protect the shoreline against erosion	Reinforcement of part of the beach profile
Bulkhead	Retain soil and prevent sliding of the land behind	Reinforcement of the soil bank
Groin	Prevent beach erosion	Reduction of longshore transport of sediment
Breakwater	Shelter harbor basins, harbor entrances, and water intakes against waves and currents	Dissipation of wave energy and/or reflection of wave energy back into the sea
Detached breakwater	Prevent beach erosion	Reduction of wave heights in the lee of the structure and reduction of longshore transport of sediment
Reef breakwater	Prevent beach erosion	Reduction of wave heights at the shore
Floating breakwater	Shelter harbor basins and mooring areas against short period waves	Reduction of wave heights by reflection and attenuation
Submerged sill	Prevent beach erosion	Retard offshore movement of Sediment
Beach drain	Prevent beach erosion	Accumulation of beach material on the drained portion of beach
Beach Nourishment and dune construction	Prevent beach erosion and protect against flooding	Artificial fill of beach and dune material to be eroded by waves and currents in lieu of natural supply
Jetty	Stabilize navigation channels at river mouths and tidal inlets	Confine streams and tidal flow. Protect against storm water and crosscurrents

Source: U.S. Army corps of Engineering, 2006a.

Many of the conventional coastal protection methods mentioned in Table 1.1 have the potential to adequately solve local erosion problems in some cases but can lead to some undesirable affects and disadvantages. Sand supply or nourishment, as well as dune construction can be used as additional but not as primary tool for coast stabilization. Emerged breakwaters, groins, seawalls and revetments are undesired of tourists and local people due to their high interference with aesthetics and visual amenity. Moreover, groins can cause large amounts of downdrift erosion (ten Voorde et al., 2009). Therefore, a novel and harmonical solution with surrounding environment is desired.

The responds of a beach to natural and seasonal erosion and accretion processes substantiate how the beach itself can support its own maintenance and protection. Therefore, one of the best ways to protect a beach is to emulate natural defense mechanism (Arnouil, 2008). Previous studies have shown that offshore submerged reefs can provide natural shoreline stabilization by wave breaking and dissipation. As a result submerged multi-purpose artificial reef-type breakwaters, in some literature simply Artificial Reefs (ARs), were proposed for the case studies of this Master Thesis. These structures can be potential tools in order to protect or restore beaches, marine habitats, creating fishing grounds or even serve as facility to generate surfing waves for improving tourism in certain locations. Submerged structures limit wave energy transmissions over the structure and thus can efficiently reduce wave induced currents and sediment transport gradients (Smit et al., 2007). Submerged structures are widely perceived to be capable of providing the necessary beach protection without any loss of beach amenity or negative aesthetical impact as they are designed to be submerged and exposure is counted to minimum cycles per year. In addition, these structures can improve the water quality and reduce the danger for swimmers while limiting wave energy transmission and sand trapping behind the structures.

This research is part of a series of investigations carried out and developed in the German Baltic Sea Coastal zone. Special concentration is dedicated to the Probstei coastline, particularly for the Heidkate, Kalifornien and Brasilien beaches (Figure 2.3). Human settlement, recreation spots, sea level rise and increasing erosion in the region brought concerns about the importance to save amenity of the region for future generations.

1.2 Aim and objectives of the research

The scope of this Master Thesis is, after the investigation of local shore and coast conditions, to come up with an integrated approach to design the most suitable coastal engineering alternatives for the Probstei coastline, and particularly for the Heidkate, Kalifornien and Brasilien beaches, to protect the coasts from loosing sand during stormy periods in winter. The provision of coastal protection during the summer together with tourism amenity enhancement by introducing surfing and diving resources are other important objectives which have to be achieved. Besides coastal protection and tourism aims, the habitat for marine biota, particularly to enhance fish populations, have to be taken into account while designing and selecting engineering structures and materials. The central question to be examined in this paper is how different shapes and sizes of artificial submerged reef-type breakwaters affect the shoreline and which of them act the most affectively as a costal protection tool. DHI's MIKE 21 and LITPACK numerical models are employed in order to answer this question. One of the main problems faced for the application of simultaneous processes in sediment dynamics derives from the fact, that this process is a complex multi-phase phenomenon. The research on sediment dynamics must be done taking into consideration complex non-linear interactions. Due to high rank of complexity, this process is modeled step-by-step, where hydrodynamics, wave, sediment dynamics modules are treated separately. The linkage between later mentioned modules is done later on through input and output data. It has to be kept in mind, in reality there is a tight interaction between these three modules and the separate treatment is only due to simplicity reasons.

1.3 Outline

The primary objective of this research is to suggest which of three proposed artificial reef types, surfing reef, shore parallel breakwater or breakwater formed from Reef balls, would be most suitable to the current research location and would meet the raised requirements such as:

- No destruction of the aesthetical view of beach

- Optimal functionality – sediment deposition in lee side of the reef
- Performance as storm wave dissipater
- Habitat provider for marine flora and fauna
- Support of tourism amenity for aspects such as:
    - Surfing
    - Sport fishing
    - Recreation (due to wider beaches)

This Master Thesis is composed of seventh main parts. First chapter give short introduction to the coastal problems and structural solutions for coastal protection. The second chapter is dedicated for description of the Baltic Sea and German coast. It also gives a brief look to two research locations of Heidkate and Brasilien beaches.

Planning and design of artificial multi-functional reef-type breakwaters are the core objectives of this Master Thesis. Design requirements and physical parameters as well as argumentation for certain design decisions and concepts are described in the third and fourth chapters, while suitable alternatives for two research locations in Heidkate and Brasilien beaches are covered in fourth chapter. The same chapters as well as the fifth one encompass an analysis of both Heidkate and Brasilien beaches research locations and available data, which are used as input data for further efficiency analysis of designed alternatives. The fifth segment of this Master Thesis describes software packages which were applied to perform numerical modelling and what outcome was expected. Results, methodology to analyze obtained results and the short description, as well as the evaluation of the results are covered in the sixth section. Finally, conclusions about all designed alternatives together with recommendations for further research are delineated in the final seventh chapter of this research paper. The literature list is presented in the end. Bathymetry, drawings of technical specifications and 3D models of designed breakwaters, aerial pictures with mapped locations of breakwaters, extracted profiles and points for data analysis, profiles with mapped annual sand drift are presented in Annexes in the end of this case study.

2 Baltic Sea and characteristics of Probstei coastline

2.1 Baltic Sea – background and review of literature

The Baltic Sea is one of the largest brackish seas in the world. It is a semi-closed sea with a total area (including Kattegat, Fig. 2.1) of 377.109 m^2 and a volume of 211.012 m3 (Meier et al., 2004). The Baltic Sea is highly dynamic and strongly influenced by hydrological and atmospheric processes and circulations (The Assessment of Climate Change for Baltic Sea (BACC) Author Team, 2008). The water exchange with the ocean is quite restricted due to its narrow entrance area. Due to this reason and freshwater excess, mainly from river discharge, salinity strongly varies from almost oceanic in the Northern Kattegat to freshwater conditions in the Northern Bay of Bothnia and the Gulf of Finland (Meier et al., 2004; The BACC Author Team, 2008).

Figure 2.1: Baltic Sea map (Source: Geographic Guide)

Water mixing and currents are strongly influenced by the complex bathymetry of the Baltic Sea. Moreover, the BACC Author Team describes the Baltic Sea “as the engine which drives the large-scale circulation" due to non-linear interactions between the estuarine circulation and the exchange with the North Sea. In addition there are big fluctuations because of changing winds and water level variations. These factors strongly effect water transport, exchange and mixing with the North Sea and the sub-basins and sub-regions of the Baltic Sea.

There is a pronounced annual cycle of the sea level with its maximum variance in late autumn to early winter (Samuelsson and Stigebrandt, 1996). The intensity of oscillations differs from north to south of the Baltic Sea. This factor has to be considered while designing coastal protection measures.

2.2 Climatic conditions

The Baltic Sea climate is located between 50th and 70th northern parallels in the coastal zone of the Eurasian continent (The BACC Author Team, 2008). Large scale atmosphere pressure systems such as the Icelandic Low, the Azores High, Winter high and Summer low, highly influence the Baltic Sea climate. In particular, the research interest of this Master thesis falls to the South West part of the Baltic Sea basin where the climate can be described as maritime west coast climate (referring to Köppen's climate classification scheme) (The BACC Author Team, 2008). In this part of the basin prevailing western winds bring moisture from the ocean. Due to the influence of the Ocean currents, winters in this region are mild with a high rate of moisture.

2.3 Sea level rise and climate change in Baltic Sea

The awareness of negative effects of Climate Change on environment and economy has steeply increased in the recent decades. Green house gases are the topmost factors of this change. Natural changes are highly interfered with anthropogenic human activities, which ones cause higher green house gases release to the atmosphere, thus more enhance natural effects and quicken the rise of global temperatures. The intensities of global temperature change differ highly in different parts of the world: slower in tropical, but faster in temperate and polar regions (Stonevičius et al., 2007).

The central consequence of rising global temperatures is the rise of the ocean water level. Investigations revealed that the water level raised 18,5 cm in the oceans during the last century. Depending on different green house gases emissions scenarios, future predictions for the XXI century are from 18 to 60 cm.

Predictions for the Baltic Sea water level rise include not only global green house gas emissions or global ocean water level rise, but include local factors such as post-glacier land uplift, wind direction and speed changes, runoff changes (Stonevičius et al., 2007). Three different maps for different cases, starting from the least and ending with the worst scenario, are presented in Figure 2.2. The South Western part of the Baltic Sea, the interest location of this Master thesis, indicates a water level rise of 1,0 m for the worst scenario (Figure 2.2 c)). These changes have to be taken into consideration while designing any coastal protection tools for the region.

a) b) c)

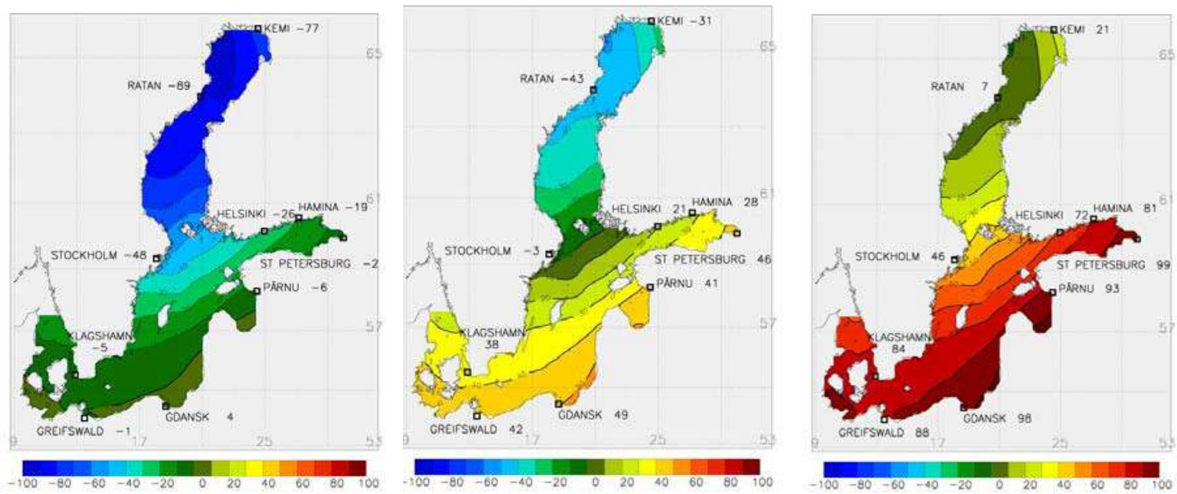


Figure 2.2: The Baltic Sea water level predictions for XXI century for the cold period of the year: a) the least changes; b) medium changes; c) the biggest changes (Meier et al., 2004).

2.4 Study area - introduction

Schleswig – Holstein is the northernmost federal state of Germany and 24% of its total land area is coastal lowlands. Therefore, this land is under natural thread to be flooded during extreme storm surges or facing sea water level rise as indicated in previous chapter. So applications of coastal protection tools are mandatory in these areas. In the past one of such tools, which was also applied in the research area of this Master Thesis, were dike constructions as the spatial focus was laid on the coastline and land protection behind the dike (Reese and Markau, 2002; Hofstede and Probst, 1999).

The Probstei coast is a part of Schleswig – Holstein at the Baltic Sea about 20 km in the North -East of the city of Kiel, Germany. It embraces Stein, Wendtorf, Heidkate, Kalifornien, Brasilien, Schönberger and Stakendorfer beaches. Heidkate and Brasilien beaches are two locations which have been chosen for this Master Thesis as a case study sites (see Figures 2.3 – 2.5).

Figure 2.3: Research locations (Source: Google Maps).

Figure 2.4: Research location Nr. 1 in the Heidkate Beach (Source: Google Maps).

Figure 2.5: Research locations Nr. 2 in Kalifornien and Brasilien Beaches (Source: Google Maps).

2.5 Analysis of the research sites

2.5.1 Existing coastal protection structures

As it was already mentioned above, the biggest part of the Probstei coast can be described as coastal lowlands; therefore, this location is vulnerable to sea level rise and extreme storm surges. In order to protect the land from flooding during extreme storms the dike of 14,3 km length, as part of the Probstei coastline protection system, was built. It stretches from Hafen Marina – Wendtorf to Stakendorfer beach. The construction of the dike was done in two steps. First of all, the 8,3 km long dike starting in Marina – Wendtorf was constructed during period of 1962 – 1985. Another 6,0 km long part of the dike was completed in 1990 together with maintenance and reinforcement works of the first part of the dike.

Following the needs to stabilize coastal erosion, maintain and widen the beaches after the installment of the dike (Schwarzer, 1991), a total amount of 48 groins were built along the Probstei Coastline, stretching from Heidkate, Kalifornien and Brasilien beaches down to Schönberger and Stakendorfer beaches (see Figures 2.6 – 2.7). The range of the groins starts near the vicinity of Große Schleuse channel and finishes in vicinity of the offshore emerged breakwater down of the Stakendorfer beach where tombolo (accumulated sand in the lee side of the structure reaches offshore breakwater) in the landward side of the breakwater started to form. In addition, three beach nourishments were carried out on 1987, 1989 and 1990 respectively, where one of them was in Heidkate beach and other two in Kalifornien/Brasilien beach. As it is described later on, higher erosion was observed in front of the Brasilien beach after the dike construction, which required more coast stabilization tools.

Figure 2.6: Aerial view of Brasilien beach (Source: http://www.ostsee-appartements-holm.de/images/luftbildschoenbergerstrand.jpg)

Figure 2.7: Aerial view ofl Brasilien beach (Source: http://www.ostseeblick-holm.de/images/schoenbergkueste.jpg)

2.5.2 Climate and Hydrodynamics

Schleswig-Holstein, thus Probstei coastline, is under strong North Atlantic Marine climate influence. Therefore, sudden weather changes as well as storms are common for the region (Duphorn at el., 1995). And as example it can be mentioned that the highest water level of 3,17 m in Kiel was registered in 1872 (Duphorn at el., 1995 cites Klug, 1986).

The western part of the Baltic Sea is a transition zone for water exchange between the Baltic Sea and the North Sea (Bobertz et al., 2005). Probstei coastline is exposed to the wave approach from West-Northwest (WNW) to East-Northeast (ENE) (see Figure 5.1) and fetch varies from 8 km (WNW) to 55 km (ENE) (Schwarzer and Diesing, 2001). It is also transition zone for salty water from Atlantic Ocean through Kattegat to enter eastern waters of the Baltic Sea.

2.5.3 Morphodynamics

Waves play an important role for the sediment transport in the Baltic Sea, because the Baltic Sea has almost no tides, which could influence morphological changes, therefore, it can be called tideless sea (Bobertz et al., 2005). Waves have capacity to stir up deposited material from sea bottom, which can be transported by currents (Bobertz et al., 2005).

The average gradient of the nearshore slope of Probstei is 1:200 (Figure 2.8). Such gradient is mostly present in front of Heidkate beach research location (see Figure 2.9), while the slope in front of Brasilien beach becomes a bit steeper (see Figure 2.10). The nearshore sand bar system, consisting from up to 4 bars (Schwarzer and Diesing, 2001), in some places can reach even up to 10 sand reefs (Duphorn at el., 1995) is highly developed in front of Heidkate beach and extends up to 700 m seawards. Main sediment transport direction here is from East to West. In front of Brasilien beach there is a slight different situation. Sand reefs are not permanent, meaning that erosion and accretion, as well as migration to West are more intense than in front of Heidkate beach (Duphorn at el., 1995). The presence of offshore sand bars can be easily observed in aerial pictures, which are presented in the Annex D.

Seasonal sediment mobility is typical for the Probstei coastline. Schwarzer and Diesing (2001) in their paper states that there is “less sediment mobility (erosion, accumulation, and turnover) at all stations during the summer months and maximum mobility during the winter period”. It is also important to state that inner sand bar slopes indicate higher sediment mobility during all seasons than in lower parts of the sea bed (further from coastline) (Schwarzer and Diesing, 2001).

The composition of sediment size of formed sand bars differ, while the bar crests are composed of medium sand while the seaward slopes are built up mainly of fine sand. These latter mentioned characteristics of sand has importance on preparing input files for further numerical modelling of sediment transport for this Master Thesis.

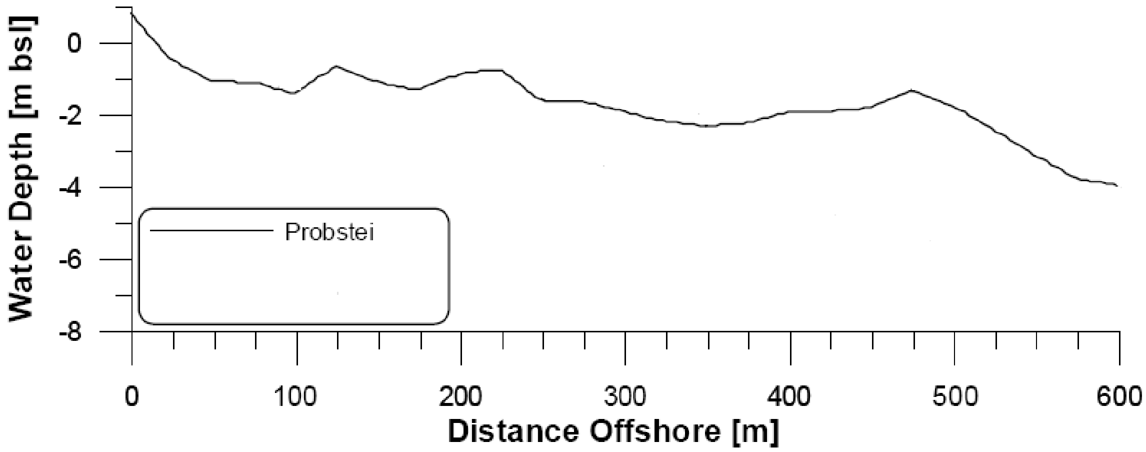


Figure 2.8: Morphological profile of the research area in Probstei Source: modified Schwarzer and Diesing, 2001).

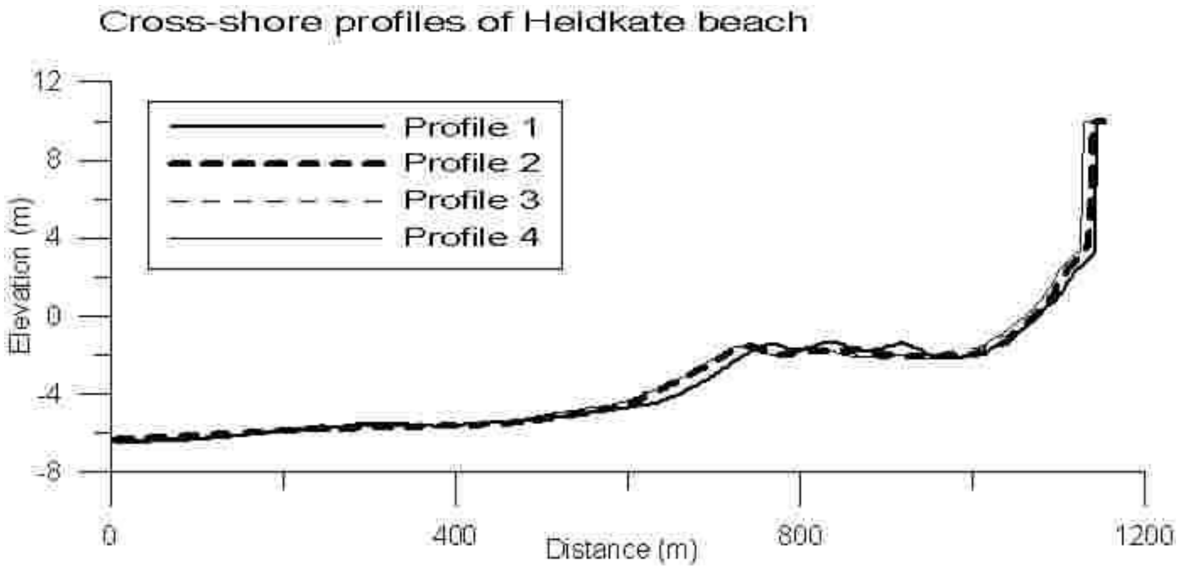


Figure 2.9: Cross-shore profiles of the research area in Heidkate beach.

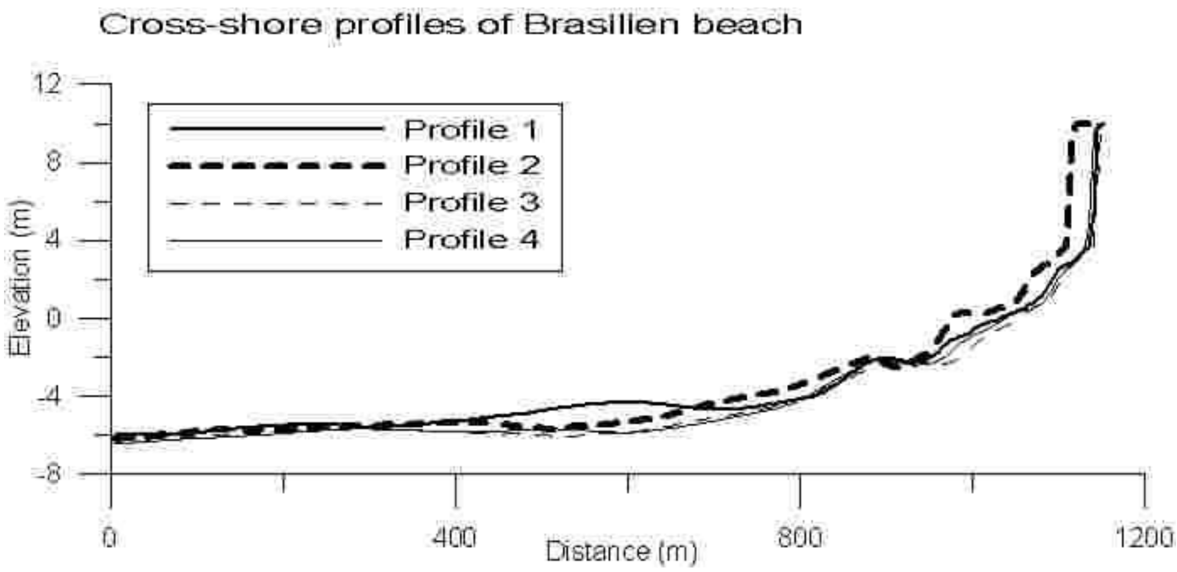


Figure 2.10: Cross-shore profiles of the research area in Brasilien beach.

3 Submerged Artificial Breakwaters – from term definition to design parameters

3.1 Introduction

Natural breakwaters such as coral reefs are known for providing positive affect on coastal protection. This feature emerged the need to build artificial breakwaters for coastal protection where natural ones are damaged or not present. Conventional ways of protecting coast can cause some disadvantages (ten Voorde at al., 2009), so submerged reef-type breakwaters could be used as innovative and interesting solutions. In recent years the use of submerged (in some literature it is named as low-crested) breakwaters for shore protection has increased as such structures have some positive side effects. The most important one, they can create desired beach protection without interfering with beach amenity or aesthetics. Correctly designed submerged artificial breakwaters have potential to create salient in the lee side of the structure by dissipating wave energy. This feature of low-crested breakwaters is thought to support sediment deposit at the shoreline and do not disrupt natural coastal processes (Ranasinghe and Turner, 2006). Sediment will build up in the lee side of artificial breakwater due to influence of longshore currents. Idealized shoreline response to the submerged breakwater is shown in Figure 3.1. Another important feature of structures is to offer touristic and economical benefits, as well as enhanced biodiversity.

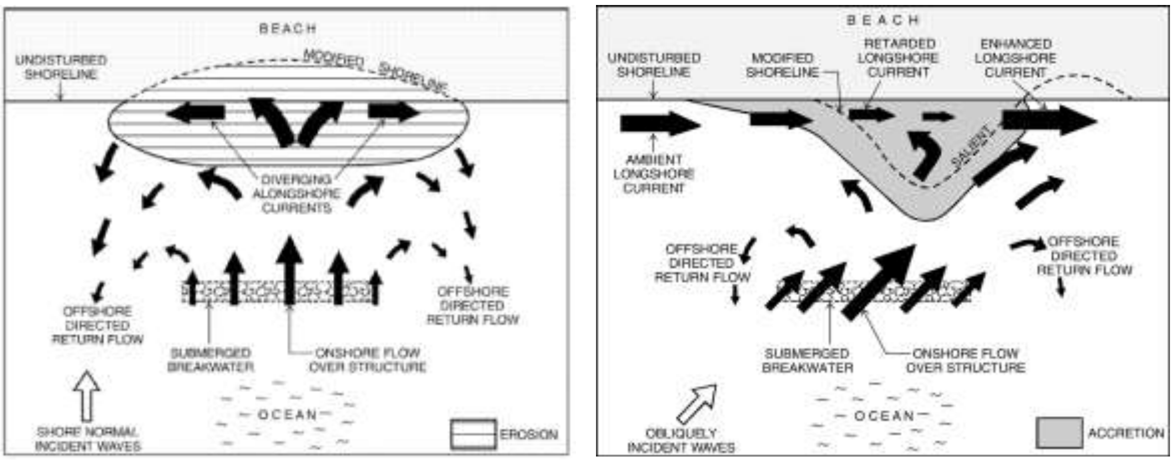


Figure 3.1: Nearshore circulations and accretion patterns in response to a submerged breakwater under incident waves (left) and oblique wave incidence (right) (Source: Ranasinghe and Turner, 2006).

3.2 Definition, description and design conditions of Submerged Artificial Multi-Purpose Reef-type Breakwaters

The term "artificial reef" has been widely used in the field of fisheries engineering, without clear definition (Thierry, 1988). Nowadays functionality of artificial reef structures has expanded as well as acceptance around the World. Growing installation rate of submerged artificial reef-type breakwaters, increasing number of shapes, constructional materials used for later mentioned constructions, demanded for the need to sort and define what is called Artificial reef. In 1988 Thierry in his article stated that international terminology defined artificial reefs as fish attracting devices (FAD). The same article also mention, based on evident analog with natural reefs, artificial reefs (AR) defined as artificially built structures, installed in a sea area, intended for fish productivity enhancement.

Nowadays, the range of functions, artificial reefs provide, have expanded, therefore they were begun to be called Multi-Purpose ones. In addition, design of artificial reefs emerged with coastal protection structures such as breakwaters or seawalls. Beside primary function to create or improve marine habitat, artificial reefs are used as coastal protection tool. Seaman and Jensen (2000) artificial reefs define as “one or more objects of natural or human origin deployed purposefully on the seafloor to influence physical, biological or socioeconomic processes related to living marine resources”. New “reef” type structures are called Submerged Multi-Purpose Artificial Reef-type Breakwaters and became the subject of extensive investigation in past years. Artificial Surfing Reef (ASR) Marine Consultant Company nowadays constructed Multi-Purpose reef breakwaters describes as an offshore, underwater coastal structures that can protect and stabilize the coastline, reduce erosion, to enhance recreational and tourism value (Corbet et al., 2005) by providing enhanced marine habitat as Multi-Purpose artificial reefs are designed in such way, that their form would mimic naturally found reefs. Furthermore, submerged structures can beneficially reduce wave induced currents and gradients in sediment transport, because they allow limited energy transmission over the structure (Smit et al., 2007). In addition, they have potential to diminish sand trapping behind the structure, minimize downdrift erosion (ten Voorde et al., 2009), improve safety for swimmers and enhance water quality. These structures are highly acceptable of coastal communities and coast users, as they don’t deploy aesthetical view. Potential amenity value of the multi-purpose reef breakwater to enhance surfing conditions is another significant advantage of submerged multi-purpose structures (Smit et al., 2007).

To avoid confusion and reduce complexity, in this paper such terms as Artificial Reef, Reef-type breakwater, submerged low-crested breakwater are used to exchange long name of Submerged Multi-Purpose Artificial Reef-type Breakwaters.

3.3 History of Submerged Artificial Reef Breakwaters

The concept of natural reefs is pretty well known not only between scientific communities but also between societies. The most famous natural reef is the Coral Barrier in Australia. And the shape or the size of the reef is not restricted; they can be of all possible shapes and spread over the world. Coastal reefs are undesired and constitute a problem for navigation but are of high importance for fisheries. Sunken wrecks have been proved to act as artificial reefs because are colonized by marine plants and animals, such as lobsters, rock fishes, octopus, mussels, oysters and etc. One of such examples were recorded already 300 years ago in Japan, when some fishermen in Awaji island near Kobe, on the Seto inner sea replaced highly productive wreck, which got destroyed during a typhoon, with gabions. It had very positive impacts as finishing grounds became even more productive (Thierry, 1988). This and many other such stories give base to confirm positive affects of artificial reefs on marine biota. So these structures were chosen for this Master thesis, including recent research on coastal protection and coast stabilization of later mentioned structures.

3.4 Classification and examples worldwide

3.4.1 Introduction

Thierry (1988) in his article tells that clear definitions and distinguish between unit reefs, reef groups and artificial reefs have to be done to avoid confusion. He sorts structures to Unit reefs which are divided to subgroups of Bottom and Floating structures, Groups of reefs which are divided to Group reef on the sea floor and Floating fish attracting devices, and Artificial reefs. Artificial reefs themselves can be divided to other subgroups, such as surfing reefs, reef balls and etc.

3.4.2 Nomenclature

Constructional material and shapes of modules, starting from old tires, ships to more novel ones as geotextile containers or tubes, concrete blocks or Reef Balls were or still are used to construct Artificial Reefs. The nomenclature were changing with time as more scientific research was carried out to find what impacts of constructed reef structures have on environment. Some of examples are presented in Figures 3.2 - 3.5.

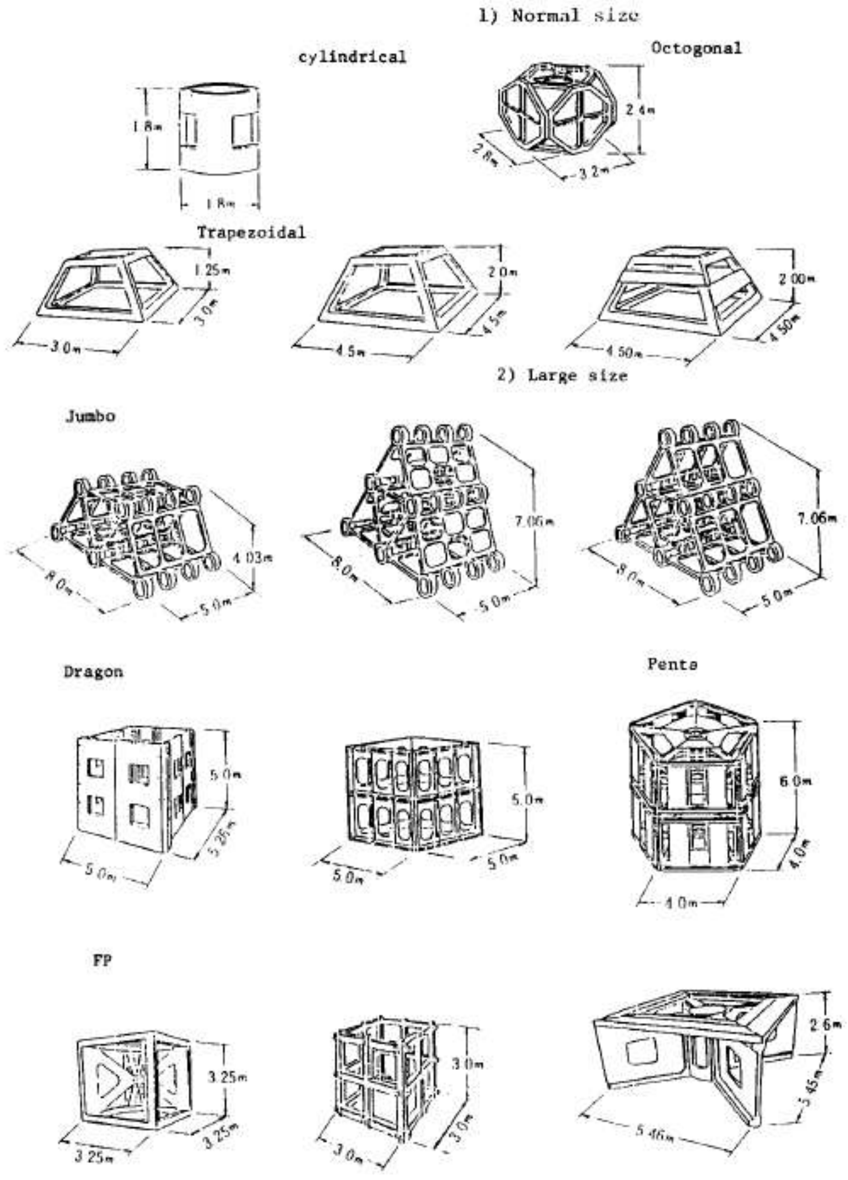


Figure 3.2: Example of normal and large reef unites (Source: Thierry, 1988).

Figure 3.3: Reef ball (Source: Harris, 2007).

Figure 3.4: Concrete block (Source: http://www2.rgzm.de/Navis2/Home/HarbourFullTextOutput.cfm?HarbourNR=Caesarea).

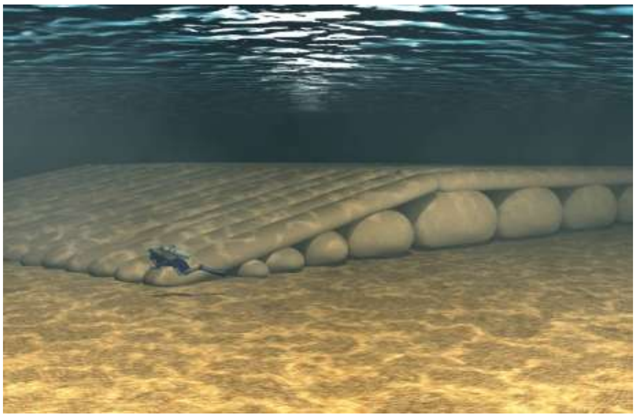


Figure 3.5: Geotextile bags, containers or tubes (Source: http://infranetlab.org/blog/2008/07/breaking-waves/).

3.4.3 Examples worldwide

There are quite wide ranges of constructed artificial reefs worldwide, started from submerged breakwaters, reefs balls or surfing reefs. The most recent example of Multi-Purpose Surfing reefs was constructed in India in the beginning of 2010 (Figure 3.6). Additionally to this latter one, surfing reefs were also constructed by New Zealand, Australian, English, Californian and other coasts. Examples with short description are presented in Figures 3.6 – 3.8.

Figure 3.6: Location: Kovalam, Kerala, India (Source: ARS Marine Research Consultants, 2010, http://www.asrltd.com/).

Figure 3.7: Location: Boscombe, Bournemouth, England. Completed: October, 2009 (Source: cooler.mpora.com).

Figure 3.8: Location: Gold Coast, Queensland, Australia. Completed: late 1999 (Source: ARS Marine Consultants, 2010, http://www.asrltd.com/).

3.5 Main features and functions of Multi-Purpose Artificial Reef-type Breakwaters

3.5.1 Overview

All coastal protection solutions are environmentally and socially sensitive issues. Multi-purpose reefs were developed to affectively address these two topics and coastal protection questions. In general, submerged coastal structures are not new topic in coastal engineering science. They have been applied around the world to address costal protection problems. It was and still is one of the main research topics. Nowadays, research for the better assessment and the most effective and efficient design of artificial reef includes numerical and physical modelling.

One of the key features resulting from the presence of a Multi-Purpose artificial reef is a salient formation. Salient is a wider, more stable part of the beach in the lee side of the reef. This phenomenon was well investigated and documented in many peer reviewed journals and coastal engineering manuals.

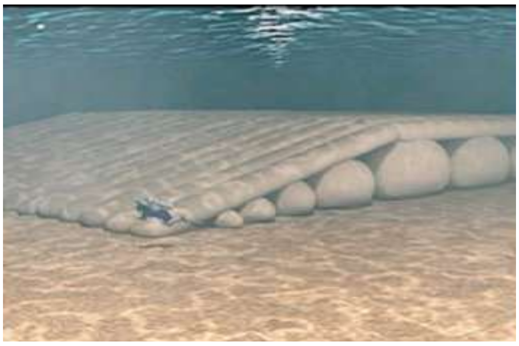
The best design of multi-purpose artificial reef is then, when all already investigated and proved concepts, such as salient formation, impact on marine systems, improvement of surfing conditions, stabilization of coastline, for optimal reef design are merged together.

The question of the best solution for coastline protection arises very often and arguments why artificial reefs are better than tradition solutions, like seawalls and groins, have to be answered. Design of multi-purpose reefs are developed in synergy of wide range disciplines and experts, which include engineers, biologists, coastal scientists, environmental managers, planners (ASR Marine Consultants). This allows creating the best environmentally friendly solution which would be able to fulfill industrial use of the beach, while taking into account marine environment, beach users and coastal communities. Most literature sources record four main distinct benefits of Multi-Purpose Reefs. ASR Marine Consultant company defined benefits are presented in Table 3.1 and illustrated in Figure 3.9.

Table 3.1: Benefits of Multi-Purpose Reefs.

Benefit		Explanation
1.	**Coastal protection**	Reefs reduce and redirect the wave energy affecting the coast, thereby reducing erosion stress on the shoreline
2.	**Beach stabilization**	In addition to producing a salient, reefs are submerged and located offshore, and therefore do not degrade or destroy the natural beauty of the beach.
3.	**Marine habitat creation**	Reefs provide a solid substrate which creates habitat for marine animals and promotes biodiversity and enhanced ecosystems.
4.	**Recreation enhancement**	Reefs create recreation for surfing, fishes, diving, and other water activities.

Beaches are valuable assets to coastal communities as they benefit from socio-economical, ecological, coastal protection standpoints so its protection is an essential issue. Seawalls and some other coastal protection structures protect only the land behind the structure and do not protect the beach. Multi-purpose reefs opposite to seawalls are designed to protect and stabilize the beach and this is another very import property of these structures.



(Source: ARS Marine Consultants, http://www.asrltd.com/) **(Source: portomarisports.com)**

Coastal Protection

Shoreline stabilization

Habitat Creation and Enhancement

Recreation Enhancement

(Source: goldcoast.qld.gov.au) **(Source: mauibeachguide.com)** **(Source: pbase.com)** **(Source: bayjournal.com.au)**

Socio-Economical Improvement

(Source: gilifastboats.com)

Figure 3.9: Artificial reef, its results and benefits

3.5.2 Marine Habitat Creation function

Enhanced or maintained marine habitats provided added value to the area where they exist by increased attraction for fishing, diving or snorkeling. The sites where the multi-purpose reefs are constructed can benefit of locally enhanced biodiversity. Artificial Surfing Reef (ASR) Marine Consultants give very simple explanation of this phenomenon in their report: a hard substrate, such as a reef, results in greater biodiversity and species abundance than mobile sandy substrate.

The biological enhancement consists of increased environmental value, which means improved bio-diversity and abundance, as well as increase in diving and snorkeling, leading to improved recreational amenity of the place. And the third feature is to create or maintain already existing fishing grounds, which is one of the main targets of the artificial reefs construction. Regarding Thierry (1988), fish grounds can be improved because:

- Artificial reefs can help to concentrate species and this allowing more efficient fishing, fuel reduction
- Nursery grounds for young or small animals
- Increase in natural productivity while providing new places for sessile organisms and providing new food availability

Regarding above mentioned functions, artificial reefs can be defined as Fishing, Spawning, Nursery and Rearing types.

3.5.3 Marine biota enhancement and impacts on fish population

A natural reef can be characterized as an elevated hard surface on which sedentary or encrusting animals live, such as sponges, hydroids, anemones, and bryozoans (Yip, 1998). Consequently, any new hard surface is assumed could be quickly occupied. For this reason, artificial reefs can be build as potential and positive management tool that allow the stressed natural site to recover, and to develop quality fishing grounds close to access points (Yip, 1998).

Many years ago it has been noticed, that such structures as sunken wrecked ships acted as attraction point to marine organisms. This characteristic was names as “fish swarming” in the paper of Thierry (1988). The same author gives three main factors, which could have influence on such fish behavior:

- Living place
- Hiding place
- Remote place, protecting from hydrodynamic turbulence.

The first research location in Heidkate beach has relatively small bed gradient, so it can be expected that the relatively shallow depths could have limitations on marine biota development over the reef. In other hand, world-wide examples of constructed submerged breakwaters, showed pretty positive effect on enhanced marine biodiversity. For example, during monitoring of Narrowneck Reef (Australia) a rapid development of a diverse marine ecosystem has been observed (Jackson et al., 2004). Similar development trends could be expected in both Heidkate and Brasilien beach locations in the Baltic Sea, but additional investigation in the field has to be carried out in order to confirm this assumption.

3.5.4 Recreation improvement

Design of artificial reefs is a complicated process based on holistic and comprehensive approach, applying extensive surveying, computer and physical modelling, knowledge of surfing, planning, marine biology sciences and etc. Due to wide variety of applied tools, artificial reefs can be designed to improve recreation, as for example by improving surfing conditions in location where the reef is constructed. In addition, multi-purpose reefs act as coastal protection structure, when one of the main installation targets is to protect or increase beach in the lee side of the reef. Moreover, multi-purpose reefs together with the increased marine habitats provide excellent location for enhanced or created favorable conditions for recreational activities (Corbet et al., 2005), including:

- Beach users
- Swimming
- Surfing
    - Body surfing
    - Body boarding
    - Short boarding
    - Long boarding
    - Kite surfing
    - Surf skiing / Kayaking
- Boating
- Canoeing
- Fishing
- Diving
    - Scuba Diving
    - Snorkeling
    - Spear fishing.

3.6 Negative impacts

Despite improving knowledge about efficiency of submerged breakwaters, more research for the shore response to introduced structures is needed. In other words, the shoreline response to submerged breakwaters is not fully understood. What is more, techniques used to predict shoreline response to emergent structures are not applicable for the submerged breakwater design. Another important aspect to mention, there are records in scientific literature about adverse affects of submerged breakwaters. Dean et al. (1997) after carried extensive monitoring study in West palm Beach, Florida stated that erosion in the lee side of the breakwater was twice as much as the background one. Reefs were removed and replaced with groins. Delaware Bay submerged breakwater case study, where salient was formed in the lee side of the constructed breakwater, is another example worth to mention. Fourth year after construction Douglass and Weggel's (1986) carried monitoring survey showed entire filled salient volume to be vanished. Oblique wave incidence is believed to be responsible for the erosion in this case. So, in order to achieve positive results, design of breakwater have to be based on existing scientific research outcomes and extensive monitoring programs have to be implemented in the sites of already constructed or planned submerged breakwaters.

3.7 Safety Aspects

Submerged Artificial Reef Breakwaters can create potentials for a range of recreational activities, habitats for marine biota, as well as coastal protection. Despite positive effects, potential safety hazards and litigation threads to potential users of the coast have to be taken into account, while designing the structures. Such parameters as specific site conditions, construction materials and the shape of the structure, depending on its usage, should be considered, because risks caused by these parameters are common for all submerged reef–type structures. Anyhow, specific investigation is needed for specific structure in certain location.

Water depth above crest (Corbet et al., 2005; Jackson at el., 2007), roughness of the slope, truncation of the tow are one of the main design parameters of submerged breakwaters to meet safety requirements (Corbet et al., 2005). Impact with the reef structure then surfers fall off their surfing boards is an important safety factor (Jackson at el., 2007). Therefore user-friendly materials, such as geotextile, earn sympathy as a constructional material of submerged reefs worldwide. It was chosen for reef design for the case study of this Master thesis. Description of geotextile can be found in following chapters. In addition, potential increase in conflict of coastal users has to be carefully considered and included in artificial reef planning process.

Another danger, which has to be considered while designing an artificial reef-type breakwater, is a wave breaking over the reef structure. Higher breaking wave heights results in more powerful turbulence, which is enhanced by shoaling, and cause high rate of risks in the location. Observations over Narrowneck reef in Australia helped to draw dependency of water level above crest with deep water wave height approaching reef structure (see Figure 3.10). Values presented in the graph can be taken as reference ones while designing reef breakwater, but have to be kept in mind, that observations were done for different water conditions and results in both case study locations in Baltic Sea can differ.

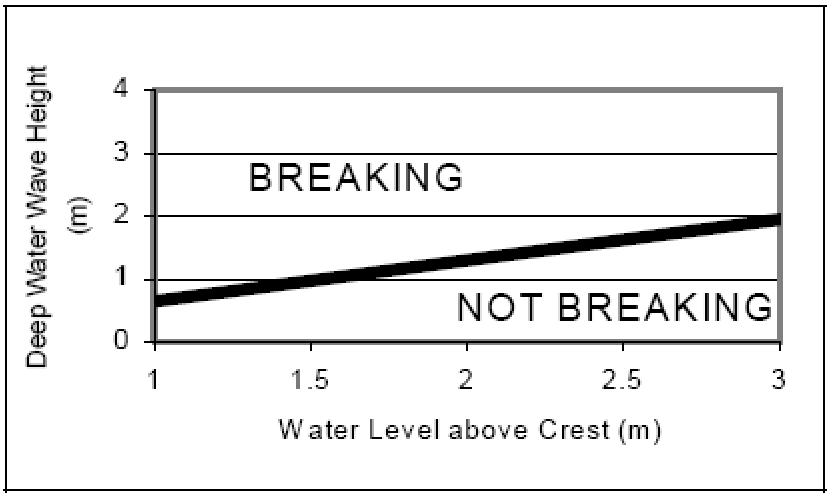


Figure 3.10: Inception of Breaking at Narrowneck (Source: Corbet et al., 2005)

Not only reef breakwater can create risks in the location, but people or vessels used for fishing can be potential thread to the reef construction. Reef breakwater zone should be marked as "no anchoring" zone to avoid damage to construction by anchors. The zone of the structure should be marked with boys and protection layer over the reef should be applied.

But this Master thesis is not to make comprehensive safety assessment of artificial submerged reef breakwaters. Additional research should be done before and after installation of the reef. In addition, the design of the reef breakwater should be modified if it is required in order diminish potential threads and to meet safety requirements.

3.8 Design considerations and reef breakwater positioning

The design of breakwater very depends on the site conditions and the purpose of the structure, so design characteristics also will vary depending on these objectives. Nevertheless, some characteristics are important and common for most submerged breakwaters. Shoreline response to an offshore breakwater is controlled by at least 14 variables (Pilarczyk, 2003 quoted Hanson and Kraus, 1989, 1990, 1991; Armono and Hall, 2003), of which 12 are considered primary ones:

- Length of the breakwater, Ls;
- Height, h, and the size of the breakwater;
- Crest width, B;
- Crest level, F, or degree of submergence ;
- Transmission characteristics of the structure;
- Gap between breakwaters (applicability for detached or duplicated breakwaters);
- Distance offshore, X, from the coastline;
- Orientation angle of structure to the coastline;
- Beach slope and/or depth of the structure;
- Mean wave height;
- Mean wave period;
- Predominant wave direction..

Simplified overview to main design parameters which have to be considered are presented in Figure 3.11.

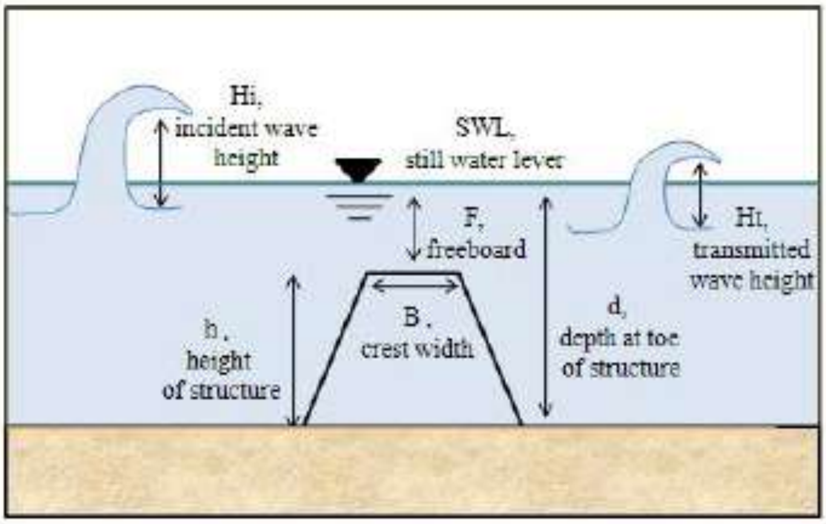


Figure 3.11: Main characteristics of submerged breakwater (Source: Arnouil, 2006).

The efficiency of submerged structures and the shoreline response mainly depend on transmission characteristics, the layout and orientation of the structure to the coast (Pilarczyk, 2003). One of the main design parameters of submerged artificial structures is wave transmission coefficient Kt. Such structures force waves to break while approaching the crest as the freeboard of the reef decreases and thus leads to dissipation of incoming wave energy (see Figure 3.12). A number of engineering procedures to estimate combined wave transmission through a breakwater and wave overtopping are available (Van der Meer, 1990, Seabrook et al, 1998, Wamsley & Ahrens, 2003 etc).

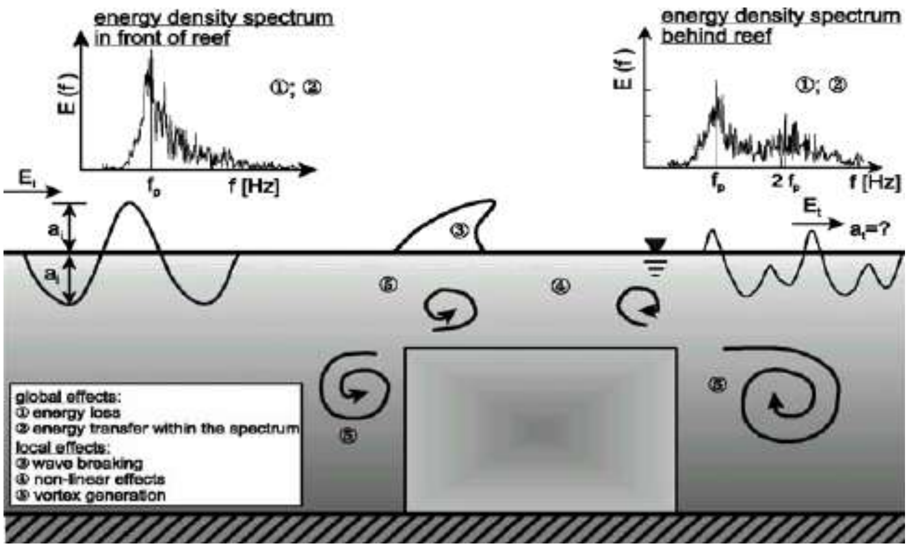


Figure 3.12: Global and Local Effects on Artificial Reefs (Source: Bleck and Oumeraci, 2001).

The height of structure is an important parameter for effective functioning of the designed submerged low-crested breakwater. Too small compared with the depth breakwater wont be effective as its interaction with approaching waves will be minimal, thus leading to ineffective wave attenuation (Armono and Hall, 2003). Harris (1996) refers to breakwater height of 60 – 80%, and Armono and Hall (2003) to 70% of water depth for submerged breakwater to be effective.

The low-crested breakwaters are designed to provide shoreline stabilization and protection so other notable parameters are the ration between length of the structure and its distance to the coastline, which indicates what type of formation, salient, tombolo or non deposition, will appear in the landside of the structure. Scientific literature determines various L_s / X ratio impacts on the type of formation, which is based on different tests and assessments. Aggregations of results found in literature are presented in Table 3.2.

Table 3.2: Type of shoreline formation for the ratio L_s / X .

Type of formation	Ratio	Notes	References
Tombolo	$L_s / X > 0,6$	Offshore reefs	(Black and Andrews, 2001)
	$L_s / X = 1,5 \; to \; 2,0$	Single breakwater	(Dally and Pope, 1986)
	$L_s / X = 1,5$	Multiple breakwaters $(L_s < G < B)$	(Dally and Pope, 1986)
	$L_s / X \geq 1,0$	Single breakwater	(Suh and Dalrymple, 1987)
	$G \cdot X / L_s^2 = 0,5$	Multiple breakwaters	(Suh and Dalrymple, 1987)
	$L_s / X \geq (1,0 \; to \; 1,5) / (1 - K_t)$	Submerged breakwaters	(Pilarczyk, 2003)
Salient	$L_s / X < 2,0$	Offshore reefs	(Black and Andrews, 2001)
	$L_s / X = 0,67 \; to \; 1,5$		(Dally and Pope, 1986)
	$L_s / X = 0,5 - 1,0$		(Shore Protection Manual, 1984)
	$L_s / X < 1,0 / (1 - K_t)$	Submerged breakwaters	(Pilarczyk, 2003)
	$G \cdot X / L_s^2 = 0,5 \cdot \; 1 - K_t$	Multiple submerged breakwaters	(Pilarczyk, 2003)
Non-depositional conditions	$L_s / X < 1,0$	Offshore reefs	(Black and Andrews, 2001)
	$L_s / X < 0,5$		(Nir, 1982)

Source: Arnouil, 2006.

The row in grey color indicates empirical relationship used to design reef-type breakwaters for this Master thesis.

Beside above mentioned design parameters, there are few other important ones, which should be taken into account while designing submerged breakwater, but are not covered in this Master Thesis. Stability, scour, settlement, overturning and sliding are some of them which are of high importance from the structural design point of view.

3.9 Methodology of salient formation predictions

Most of Artificial submerged reef-type breakwaters have coastal protection function as their primary design objective. Therefore, salient formation in the lee side of the structure is desired and favorable. Employing right constructional design methodology and parameters it can be achieved and predicted. But it has to be kept in mind that methodologies, used to predict salient formations in the lee side of the emerged structures, can't be employed for the submerged ones. Therefore, a careful literature study was carried out for this Master Thesis. The methodology presented further on is used to predict coastline response if submerged constructions would be present.

3.9.1 Black and Andrew (2001) salient prediction methodology

The main indicator allowing predicting the size of the salient is the ratio between distance offshore and breakwater width. This methodology was developed by Black and Andrew (2001) and illustrated by Hearin (2009) (see Figure 3.13).

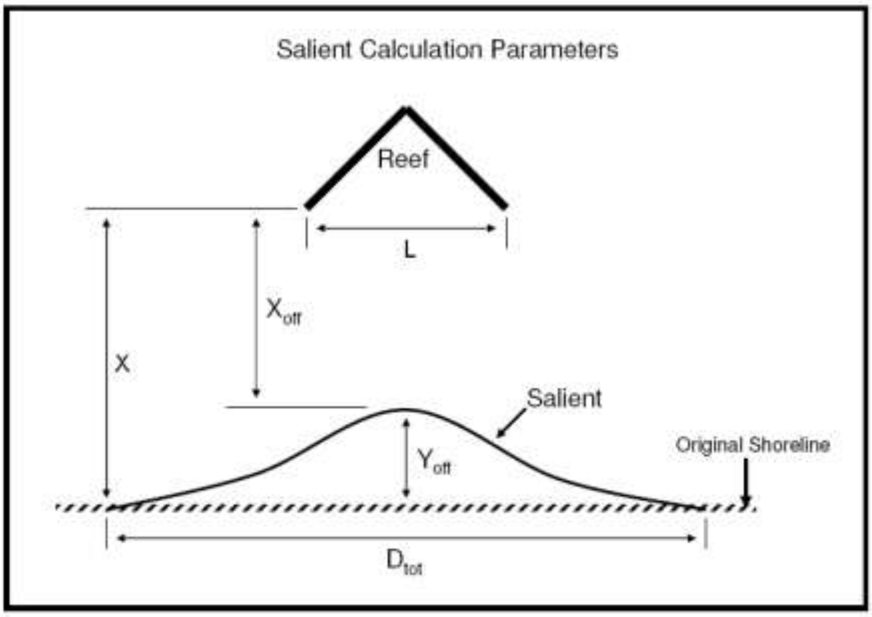


Figure 3.13: Salient calculation parameters (Souce: Hearin, 2009).

Main empirical relationships are:

- Salient may not form: $L/X \leq 0{,}1$ (1)
- Salient will form: $L/X > 0{,}1$ (2)
- Tombolo may form: $L/X > 0{,}6$ (3)

$$X_{off} / L = 0,498 \cdot (L / X)^{-1,268} \quad (4)$$

$$X_{off} = X - Y_{off} \quad (5)$$

$$Y_{off} / D_{tot} = 0,125 \pm 0,020 \quad (6)$$

3.9.2 Coastal Engineering Manual (CEM) salient prediction methodologies

There is a variety of theories how to predict shoreline response to the introduced offshore submerged structures and the Coastal Engineering Manuel (USACE, 2002) presents some of them. Each theory present wide range of ratios of breakwater width with distance offshore (L/X) to forecast salient or tombolo formation and aggregated information is presented in Table 3.3.

Table 3.3: Shoreline response in the lee side of offshore breakwater.

Type of Formation	L/X range	Average L/X values
Tombolo	$> 0,67 - 2,5$	>1,5
Salient	0,4 – 1,5	0,8
None	≤ 0,125 – 0,5	< 0,25

Source: USACE, 2002.

Ahrens and Cox (1990 – cited USACE, 2002) developed a Beach Response Index Is, which values are listen in Table 3.4.

$$I_s = \exp(1,72 - 0,41 \cdot L / X) \quad (7)$$

Table 3.4: Shoreline response predictions using Beach Response Index.

Type of Formation	Is
Permanent Tombolos	1
Periodic Tombolos	2
Well Developed Salients	3
Subdued Salient	4
No formation	5

Source: USACE, 2002.

Described methodology was applied for designed Alternatives of this Master Thesis, which are described in further chapters.

4 Artificial reef-type breakwaters - Heidkate and Brasilien beach case studies

4.1 Reef locations

Particular interest of this research is laid on two parts, Heidkate and Brasilien Beaches, of the whole Probstei coastal zone. Both research and potential construction locations of submerged reef breakwaters were chosen due to their importance to the local tourism. These locations are favorable recreational spots due to fine sand beaches, which are nowadays highly threatened by higher frequency of storms, higher wave heights attacking the coast and increasing water level due to climate change. Therefore, to preserve and maintain this coastal zone will require better coastal protection tools to be applied. Such structures as artificial surfing reef or Reef Balls for habitat enhancement could not only be employed to meet above mention threads, but be benefit to the local communities and tourism sector. Exact reef placement places were decided taking into account local geomorphologic features and existing sand bars. The structures were designed and located in such way, that they would have the most positive coastal protection and habitat creation affect. Moreover, submerged breakwaters compared with emerged coastal solutions were preferred due societal acceptance. As the structure is under water, it has no interference with aesthetical amenity of the beach. In addition, structures are planned to be constructed enough far from the coastline. Economical benefits for the region are predicted as a result of the wider beach strip, improved surfing conditions and created diving location.

4.2 Surfing reef

The popularity of artificial multi-functional surfing reef-tape breakwaters grew very fast, especially in the past decade. Numerous such kinds of reefs were designed and some of them actually were built or are under the construction. But to design surfing reef, physical background of waves and some other design parameters must be understood. Moreover, waves from surfer's point of view have to be considered, because reef should meet expectations of the surfers' community as well.

4.2.1 General characteristics

The main aim of the surf reefs is to reduce and dissipate energy of approaching waves, as well as driven currents in order to reduced sediment transport along the coast. Another important aspect is to enhance or create surfing conditions in the location of the constructed reef. In order to improve surfability conditions, a submerged artificial reef has to meet certain design requirements, where the most important are:

- Wave breaking height along the breaker line, H_b;
- Peel angle along the breaker line, α ;
- Surfer velocity along the breaker line, V_b;
- Length of the ride, L_b;
- Iribarren number along breaker line that provides an indication of the type of breaking, ξ_b;

- Length of the coast protected by the reed, L_{prot} .

Beside improved surfing conditions, other design parameters such as the crest height of the reef have to be considered. Corbet et al. (2005) in his article about safety aspects when designing artificial reef-type breakwaters defines water depth of 1,5 m above design crest level of the breakwater. He argues that design crest of 1,5 m reduces the potential for the reef to “suck dry” and surfers to impact with breakwater, as well as diminish potentially dangerous currents around and over the structure. Corbet et al. (2005) also states that performed physical modelling has indicated that the crest of 1,5 m bellow still water level is the most optimal one, when embracing safety and efficiency objectives. Nevertheless, the same physical modelling proved that such crest heights as -1,2 m and -0,9 m for 1,5 m waves can be sufficient and should be used as a minimum for the design of enough safe and efficient structure. Nevertheless, FINA (International Swimming Federation) regulations suggest 1,8 m depth of submergence due to safety reasons (Corbet at el., 2005). Following all recommendations, conducted numerical and physical modelling in previous researches, as well as taking into account local specific conditions, for both research locations of this Master Thesis, -1,2 m design crest height is chosen. Main arguments were:

- The Baltic Sea has small tide fluctuations and is only affected by seasonal storm surges. Therefore, the probability for long-term or frequent emersion is low.
- Closer as much as possible to the reference water level crest provides better wave dissipation during storm events (Hearin, 2009).
- Shallow crests maximize effectiveness of submerged surfing reef to provide surfing break (Hearin, 2009) (see Figure 4.1).
- “Surfers tend to fall off their boards rather than dive vertically” (ten Voorde et al., 2009) and this helps to reduce diving depth of surfers as well as probability of serious back injuries.
- First research – Heidkate – location is relatively shallow with small bed angle, so it was challenging to find right location to meet all requirements and still to provide the main objective - coastal protection function. The reef was designed approximately 300 m away from the coastline by following design requirements do not form a tombolo. The vicinity of constructional site falls in the shallow area, meaning the depth of sea bottom ranges between -2,5 and -3,1 m. The ideal solution, when considering only physical efficiency of the submerged structure, is to design the submerged reef breakwater with crest level as much as possible close to the Mean Lower Low Water Level without becoming exposed (Hearin, 2009). Conversely, safety aspects, as one of the main design criteria, allows to build just a little higher than 1,0 m height breakwater. Lower than 1 m height reef-type breakwater would loose its primary function – to provide coastal protection and to work as wave dissipater. Therefore, it would require deeper water levels, which start approx. 500 m away from coast in order to builder higher than 1,0 m submerged reef breakwater. In conclusion, farther than 300 m from the coastline constructed surfing reef would be harder accessible to the surfers and divers. For the sake of arguments, it was assumed that due to small crest level from water surface, which was designed with -1,2 m, the breakwater is going to be “sucked dry” on rare occasions only, typically associated with larger wave conditions during winter surges. This is not going affect surfers or construction itself as this time is usually during low-season of surfing. The same crest level was assumed to the second research location in the Brasilien beach.

- At a low tide and high waves the phenomena of sucking dry is probably hardly avoidable or prevented fully.

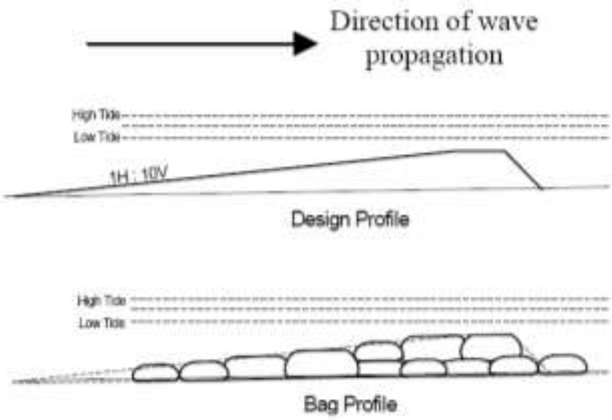


Figure 4.1: Crest level compared with reference water level and approaching wave (Source: Corbet et al., 2005)

The design of the submerged reef structure was led by aggregation of available information in literature. The shape of the reef differs from ones in Cable Station or Gold Coast at Narrowneck in Australia, or Pratte's Surfing Reef at Dockweiler Beach in California, or Kovalam Reef in Kerala, India, or Boscombe reef in Bournemouth, England. It is important to mention, even though multi-functional artificial reef-type breakwaters were successfully installed in some parts around the Globe and proved to be promising coast protection structures, the "design evolution of such breakwaters has not be adequately described" (ten Voorde et al., 2009). Step-by-step design manual embracing all key parameters are missing. The same can be said about the latter mentioned examples, because only limited information exists on the performance of these artificial surfing reefs. Although some level of physical and numerical modelling, surveys were carried out for the latter reef projects, there are no or very limited published records of the design evolution available. The design of the submerged artificial multi-functional reef-type breakwater for this research papers was achieved by submerging analyzed information from available topic-related scientific literature. Main properties taken into account were: side slopes, length of slides, height, reef orientation, nose angle etc.

4.2.2 Surfing conditions

Additional assessments of reef design have to be carried out based on numerical or physical model test results. Several parameters such as wave breaking height along the breaker line, H_b; peel angle along the break line, α; length of ride, L_s; Iribarren number, ξ_b; surfer velocity along the breaker line, v_s; length of coast protected by the reef, L_{prot} of designed reef-type breakwater have to be calculated and evaluated. Only very few of them are covered in this Master Thesis, so further research has to be carried out.

Most of latter mentioned parameters have very strong interaction between themselves; but the most important indicator on surfability is the peel angle (Fig. 2.1). It was considered as initial design parameter while designing the artificial surfing reef for this research paper.

The peel angle is the enclosed between the wave crest and the breaker line (van Ettinger, 2005 cite Walker, 1974) as it is illustrated in Figure 4.2. Peel angles vary between 0° and

90°. A zero peel angled waves are impossible to surf because they refer to so called “closed out” (Smit et al., 2007). Usually waves break simultaneously along the entire crest and this are common feature of most beaches around the world. Relationship between the peel angle, wave breaking speed and surfing speed is described in van Ettinger (2005).

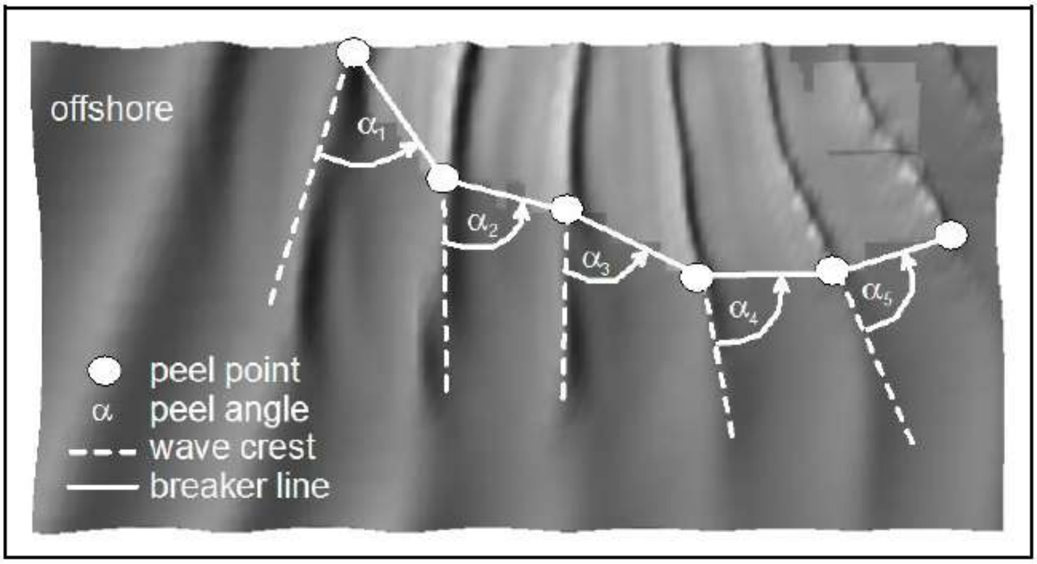


Figure 4.2: Peel angle definition (Source: Smit et al., 2007)

Rank 2-3 	Beginning surfers able to perform basic manoeuvres. Soft breaking waves (spilling breakers). No tube ratio.	Peel Angle 60-70°	Low gradient breaks
Rank 4 	Intermediate skilled surfers beginning to initate and execute standard surfing manoeuvers on occasion. Steep faced, but rarely tubing: vortex ratio 2.8-3.1	Peel angle 55°	Bells Beach, Indicators
Rank 5-6 	Competent surfer able to execute standard manoeuvres consecutively and advanced manoeuvres on occasion. Some tube sections: vortex ratio 2.2-2.8	Peel angle 40-50°	Kirra Point, Burleigh Heads
Rank 7 	Top amateur surfers able to perform consecutive advanced manoeuvres. Fast and hollow tubing) waves : vortex ratio 1.9-2.2	Peel angle 30°	Bingin, Padang Padang
Rank 8-9 	Top world surfers able to preform consecutive advanced manoeuvres under extreme and dangerous conditions. Very fast, square, spitting, waves: vortex ratio 1.6-1.9	Peel angle <27°	Pipeline, Shark Island

Figure 4.3: Artificial Surfing Reef’s degree of difficulty ranking for surfing reefs (Source: Black and Mead, 2009).

Based on peel angle and wave height Black and Mead (2009) published a classification of surfing skills which varies from 1 to 9 (see Figure 4.3). When peel angles increases, respectively α=30° to α=45°, leading to decrease of surfing speed which can be negotiated by experienced surfers only. The most optimal peel angles, which can be handled by most recreational surfers, is considered to be in the range of 45°-65° (Smit et al., 2007), which refers to surfer skills of 3 – 6 according to that classification. The definitions of surfers' skills and their relationship with peel angle and wave height are described in Hutt et al. (2001).

4.2.3 Design evolution

Design of artificial submerged surfing reef evolved after combining available research data and information in scientific literature. High importance was given to literature describing outcomes of physical and numerical modelling of surfing reefs. As a result, chevron-shaped reef with a delta-shape crest and a rip channel between two sleeves were designed. Three different shapes and two different orientations to the coast were designed for both Heidkate and Brasilien beach locations.

Parameters to meet surfing aims

To achieve surfing aims, design parameters of the surfing multi-purpose reef were based on the world-wide research and experience. F. Smit et al. (2007) states in order to reach a surfable range of 40° to 60°, reef nose has to be 30° or less. This fact also was confirmed by Black and Mead (2001) during design studies of the Narrowneck Artificial Surfing reef. Following this fact, 45° nose was chosen for this research, leading to 45° peel angle. As the results for small nose angle, narrower and elongated reef has to be designed and located in deeper water to meet the same properties as wider reefs do in order to provide the same coastal protection and surfing functionality. As one of solutions to small nose angles, duplication of installed reefs, i.e. similar second reef installed alongshore at certain distance from the first reef, were proposed in Smit et al. (2007). Possible higher economical costs of installment of duplicated reefs have to be considered.

Conventional V shape of Narrowneck surfing reef in Australia was split to two as it caused high seaward velocities over the crest of the reef and was considered as unsafe conditions for surfers and swimmers (Jackson et al., 2007). In addition, this solution helped to provide longer shoreline protection. Following this example, surfing reefs, designed for Heidkate and Brasilien case studies are of divided "V", or in other terms it is called chevron shape (see Annex C). Shoreward extensions of the Surfing Reef arms were also proposed for the case study of this Master Thesis, which are the part of integrated designs. The latter solution came out following the same implemented Narrowneck Surfing Reef design, where the extension of reef arm had the purpose to improve the submerged groin effect (Jackson at el., 2007). Therefore, design solutions with arm extensions are considered having higher potentials to improve coastal conditions than solutions without arm extensions. This assumption is checked by numerical modelling and described in further chapters of this research.

Design assumptions to reduce rip currents

Black et al. (2001) designed doubled reef structure with rip channel in between both parts of the structure on Gold Coast of Australia seeking: (1) to eliminate wave interference on the surfing conditions; (2) to provide the space needed at the take-off; (3) to give surfers access for surfing during moderate and large wave conditions. Van Ettinger (2005) introduced rip channel in designed reef modelling in order to minimize the rip currents at the sides of the reef. The channel is created in the middle of the structure where surfers do not surf (van Ettinger, 2001). Therefore, as it was already mentioned in previous paragraph, duplicated reef design is preferred and was chosen in this Master Thesis case study in order to meet surfing and safety requirements.

Proposed Surfing Reef alternatives for this research are with internal reef angle of 45° (see Annex C). Ettinger (2001) in his study confirmed that reducing reef width in x and y – direction (through increasing internal reef angle (see Annex C-Engineering drawings)) helps to decrease rip currents through the channel. The same study also states that internal reef slopes close to 1:1 and the width of the rip channel in the range of 10 to 15 m are the best design parameters in order to reduced rip currents. This was taken into account while designing surfing reefs for this case study (see Annex C). Therefore, 10 m width rip channels were implemented in the design of all Surfing Reef alternatives in this research.

Crest level

Both designed alternatives have crests similar to the delta-shape, and which are with a constant crest elevation of –1,2 m relative to SWL. The reef is designed with gradient sloping cross-section, giving the reef a convex profile shape as it is assumed to produce better waves for surfing with the longer ride (Hearin, 2009). In addition, as it was already mentioned, closer crest provides better wave dissipation during storm events (Hearin, 2009).

Slope of the reef structure

Designed slopes of the reef have to be verified with the numerical and, when possible, with physical simulations for each set of reef geometry and wave conditions. It is necessary to design reef with such profile sloping angles that breaker would lie in the surf zone. Some additional changes have to be made in reef-type breakwater if necessary in order to meet latter mentioned requirements. Chosen profile slopes of different reef sections were chosen according ten Voorden at el. (2009) paper but additional or further research is not covered in this paper.

Positioning of the reef and salient predictions for Heidkate beach research site

As it was already mentioned in previous chapters the first research site in front of Heidkate beach is relatively shallow with a small bed angle (see Figure 2.9). Shallow conditions in the site don't allow to build breakwater higher than 1,3 m height in the highest point because crest level of 1,2 m have to be preserved in order to meet low rate of exposure and safety requirements. Lower than 1 m height reef-type breakwater would have little impact on wave dissipation and would loose its primary design objective to protect coast from storm surges. The construction of higher reef breakwater respectively would require deeper water depths, which start approx. 500 m from the shoreline. Another argument supporting reef construction in deeper water is predicted salient amplitude and width (see Figures 4.4 and 4.5). Following methodology of Chapter 3.8 maximal salient was predicted to form if breakwater would be constructed 1 km away from the shoreline. Nevertheless, since the reef is used for surfing and diving, it was desirable to place it as close to the coast as possible. Consequently, a breakwater was designed approximately 300 m away from the coastline.

The empirical relationships developed by Black and Andrews (2001) (see formulas from 1 to 6) shows that the ratio of Heidkate reef-type breakwater width with its distance of placement from the coast is more than 0,6 indicating that a tombolo might form, when CEM suggest that a salient could be expected. The CEM suggested Beach Response Index is equal to 3,9 and regarding Table 3.3 it indicate that well developed salient should form. In conclusion, 300 m away from the shoreline placed artificial submerged reef-type breakwater of 182,6 m width would be the optimal solution (see Annex A). Such distance reduces the probability that the structure could interfere with longshore sediment flow and form a tombolo or tombolos.

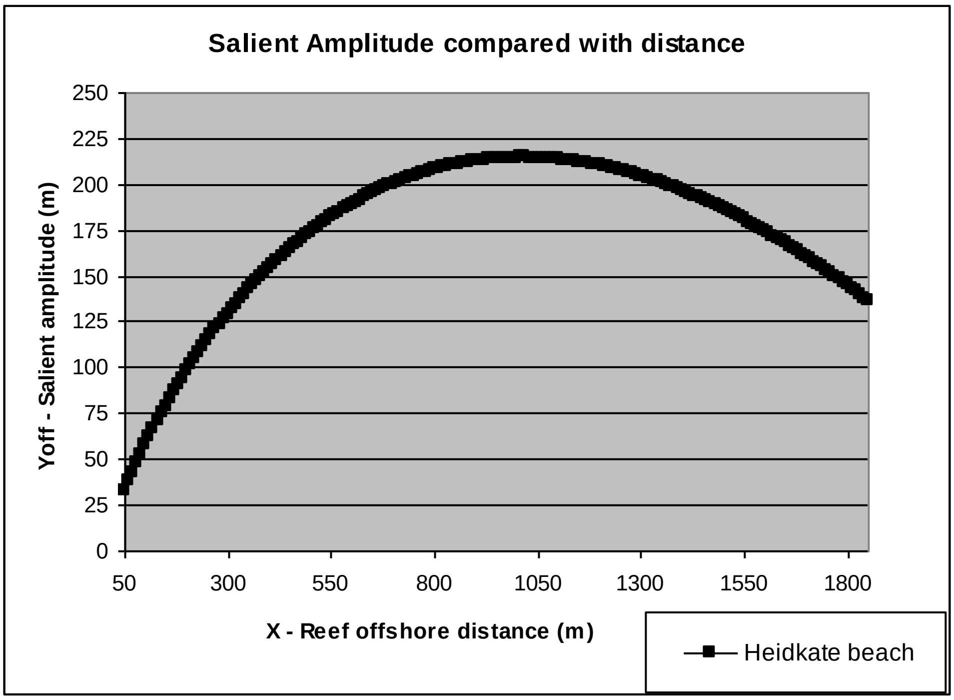


Figure 4.4: Salient Amplitude

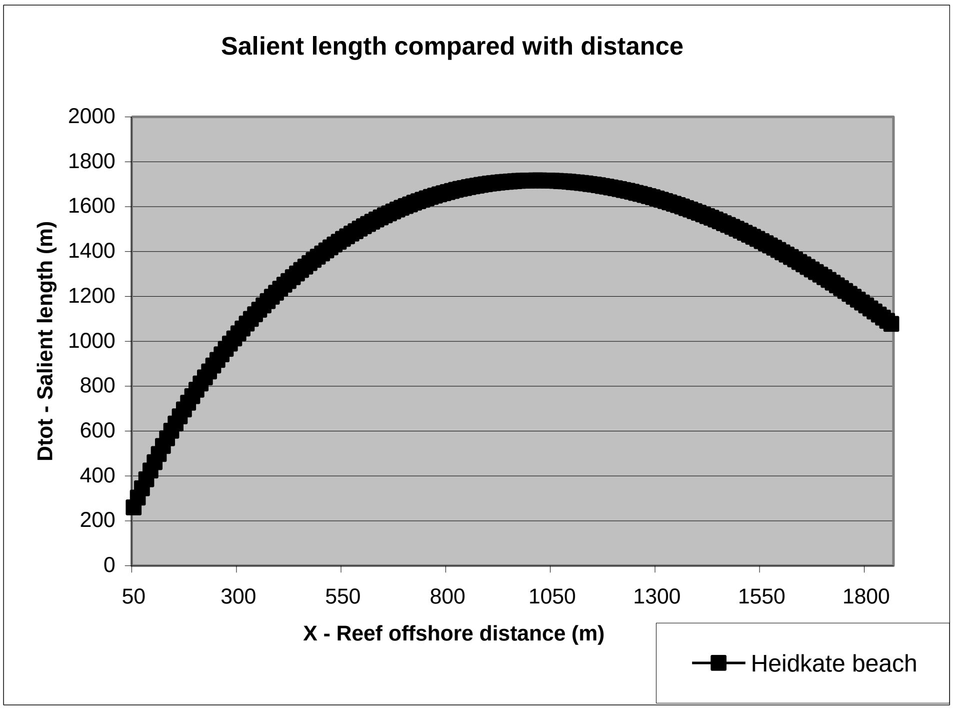


Figure 4.5: Salient Length

Positioning of the reef and salient predictions for Brasilien beach research site

The Brasilien beach research location can be described as having bed slope of more rapid gradient (see Figure 2.10), with some sand bars and higher erosion rates than in Heidkate beach.

The crest level of the surfing reef is -1,2 m bellow Still Water Level which is the same as it was designed for the Heidkate beach reef, and the reef itself is approximately 4,1 m height in the highest point. The surfing reef is designed to be installed in the end of the sand bar 300 m away from the coastline with expectation of longer sand bar would form after installation of the breakwater (see Annex D). Predicted salient amplitude and width are plotted in Figures 4.6 and 4.7, which indicates that maximal salient would form if breakwater would be constructed 1050 m away from the shoreline. Nevertheless, the same conclusions as for the Heidkate breakwater are made. This means that 300 m distance for reefs construction is optimal solution, since reef is used for surfing and diving.

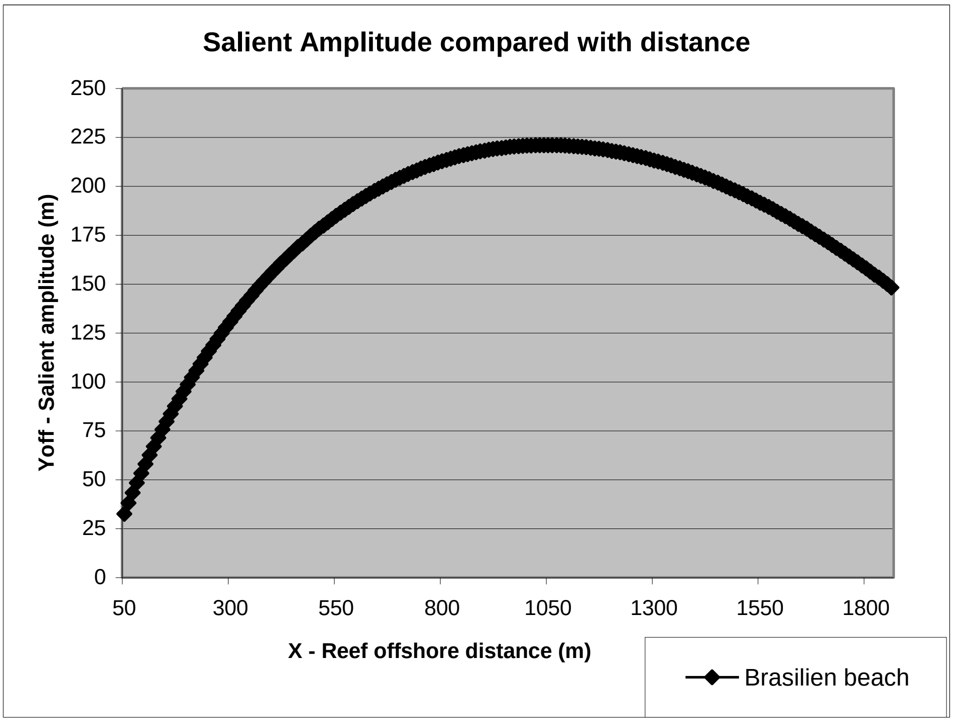


Figure 4.6: Salient Amplitude

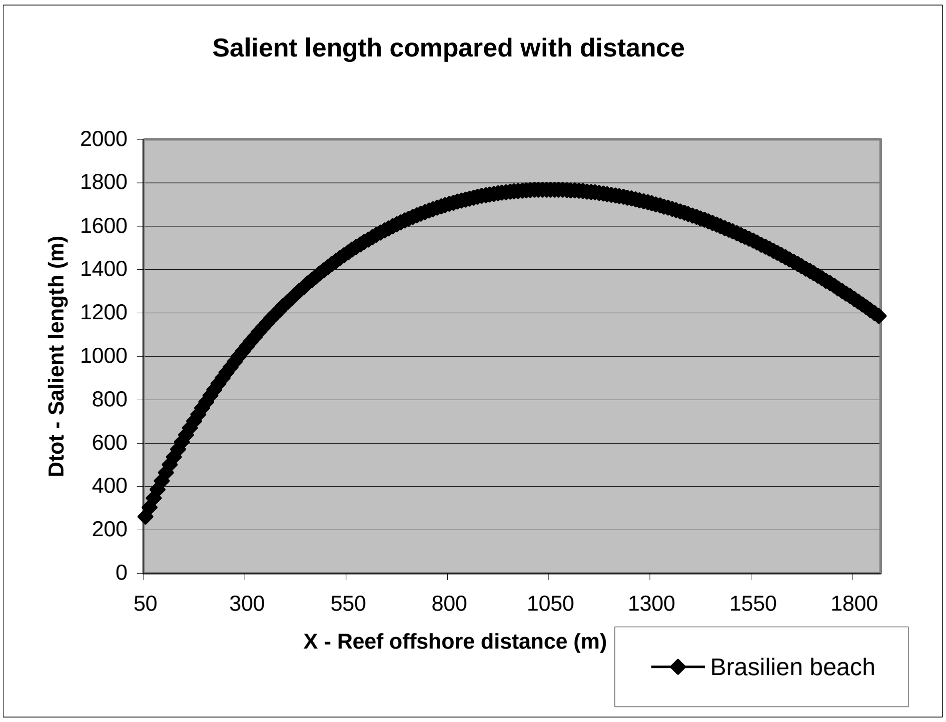


Figure 4.7: Salient Length

Prediction of a possible sand formation in the lee side is done following the same methodology described in 3.8 chapter. The ratio of the breakwater width with its distance of placement from coast is more than 0,63 indicating that tombolo might form. CEM suggested Beach Response Index is equal to 3,9 and regarding Table 3.1 it indicates that well developed salient should form. In conclusion, 300 m away from the shoreline placed artificial submerged reef-type breakwater of 188,1 m width would be the optimal solution (see Annex A).

Summarized design parameters and concluding remarks

Final parameters of designed Surfing Reefs in front of Heidkate and Brasilien beaches are presented in Annex C. Shortly summarized design is described in Table 4.1 for the Heidkate beach and in Table 4.2 for the Brasilien Beach.

Table 4.1: Parameter of designed reef for Alternatives 1, 2 and 3 in front of the Heidkate beach.

Alternative	Alternative 1	Alternative 2	Alternative 3
Description	Surfing reef without arm extensions	Surfing reef with Eastern arm extension	Surfing reef with Western arm extension
Purpose	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement
Distance from coastline, X (m)	300 m	~300 m	~300 m
Orientation to the coast	1. parallel 2. reef normal orientated 45° from north	1. parallel 2. reef normal orientated 45° from north	1. parallel 2. reef normal orientated 45° from north
Constructional material	Geotextile tubes and containers filled with sand	Geotextile tubes and containers filled with sand	Geotextile tubes and containers filled with sand
Length of breakwater, L (m)	182,6 m	182,6 m	182,6 m
Width of breakwater, W (m)	86,3 m without arm extension	86,3 m without arm extension; 143,4 m with extension	86,3 m without arm extension; 143,4 m with extension

Table 4.2: Parameter of designed reef for Alternatives 4, 5 and 6 in front of the Brasilien beach.

Alternative	Alternative 1	Alternative 2	Alternative 3
Description	Surfing reef without arm extensions	Surfing reef with Eastern arm extension	Surfing reef with Western arm extension
Purpose	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement	Coastal protection, surfing and diving conditions improvement, marine habitat enhancement
Distance from coastline, X (m)	300 m	300 m	300 m
Orientation to the coast	1. parallel 2. reef normal orientated 45° from north	1. parallel 2. reef normal orientated 45° from north	1. parallel 2. reef normal orientated 45° from north
Constructional material	Geotextile tubes and containers filled with sand	Geotextile tubes and containers filled with sand	Geotextile tubes and containers filled with sand
Length of breakwater, L (m)	188,1 m	188,1 m	188,1 m
Width of breakwater, W (m)	89,1 m without arm extension	89,1 m without arm extension; 143,4 m with extension	89,1 m without arm extension; 143,4 m with extension

Beach nourishment should be performed in conjunction with the breakwater construction, in order to pre-fill the salient (Harris, 2007), which is expected to form and thus to prevent from erosion cause of introduction of the new structure. In this case no sediment from the existing shoreline will be required to create stabilized salient (Hearin, 2009).

4.3 Offshore Reef- and Bar-type shore-parallel breakwater from geotextile

A variant of submerged offshore shore parallel breakwaters evolved from conventional emerged shore parallel breakwaters as emerged breakwaters were and still are used for beach protection. But submerged structures become more advantageous as they don't interfere with aesthetical amenity of beaches and thus are more favorable of coastal users than usual conventional solutions. The most important disadvantage of submerged structures in general is that the shore response to such structures is not fully understood and number of constructed submerged breakwaters caused erosion on the adjacent coast where accretion was expected. Therefore, high attention has to be given to the correct design of such structures and their investigation.

The aim of this Master Thesis is to suggest the most effective submerged offshore solution for coastal protection and habitat enhancement. Therefore other alternatives were considered as well. One of them is offshore shore-parallel breakwater from geotextile. Further sub-chapters of this paper describe design requirements of such construction. Geotextile as constructional material and its advantages are delineated in the following chapters.

4.3.1 Positioning of the reef breakwater

After analyzing both Heidkate and Brasilien beach research locations, it was decided to design shore parallel breakwater only in front of Brasilien Beach. In this Master Thesis this solution is indicated as Alternative 7. Decision was influenced due to better morphological and geological conditions of the site. This location can be distinct due to more rapid gradient bed slope, some sand bars and higher erosion rates are present at the site leading to higher needs to maintain sandy beaches of this location. The start of the reef breakwater is designed to be installed just in the end and in the lee side of an already present sand bar. The purpose of this placement is that positive coast reaction to the installed structure and formation of the sand bar elongation down-side of the beach in the lee side of the structure would be expected (see Figure 4.8). Therefore, the breakwater was designed approximately 170 m from the coastline.

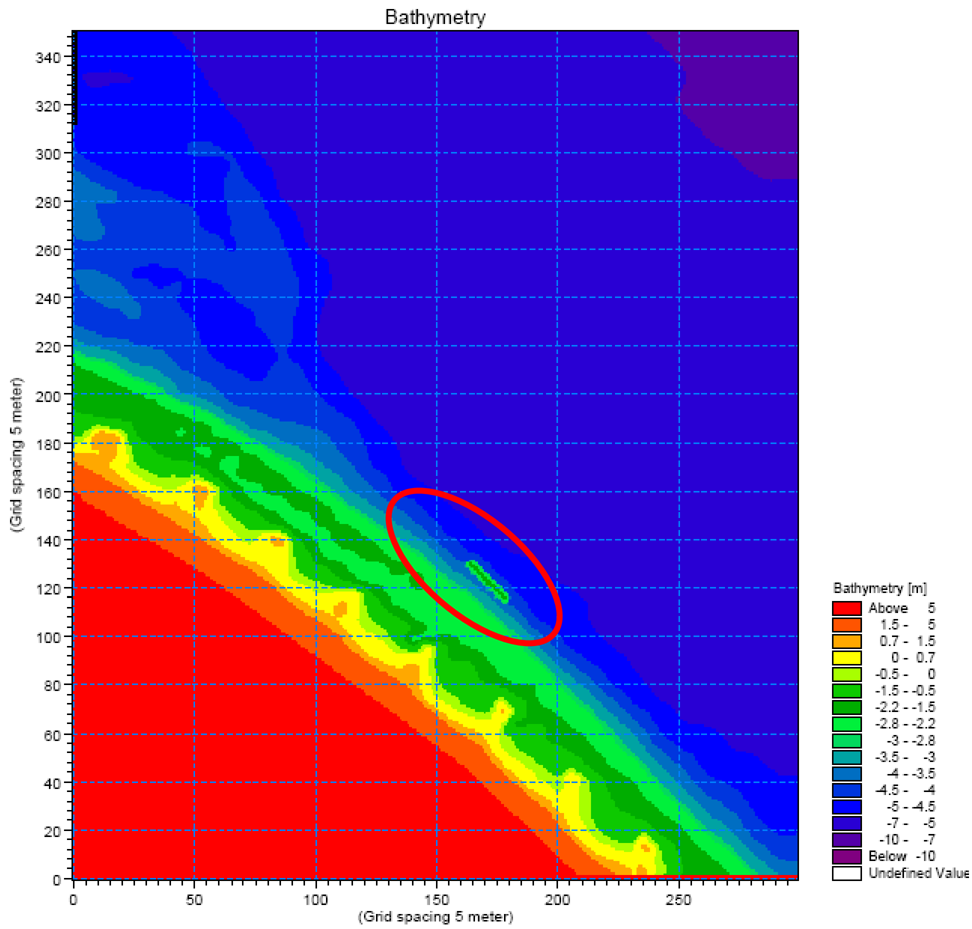


Figure 4.8: Alternative 7. Bathymetry of Brasilien Beach with shore parallel breakwater.

4.3.2 Design evolution

Design of the shore-parallel reef was done based on analysis of available scientific literature, where physical and numerical modelling results were described. One type of breakwater for Brasilien Beach was suggested and design was evaluated using various components of MIKE 21 numerical modelling suite, as well as LITPACK (DHI Water and Environment, 2005) to determine sediment transport changes.

The main objective of designed submerged breakwater for this case study is to stabilize the shoreline by trapping sand in the lee side of the structure. As well, the structure should dissipate waves and thus protect the coast from storm surges. Main design parameters of the submerged shore parallel breakwater are (van der Hout, 2008):

- Crest width;
- Slope of structure;
- Water depth;
- Length;
- Width of structure;
- Distance from shoreline.

Most of these parameters can be illustrated with the Figure 3.11, which was described in third chapter.

The previous third and first sub-chapters of the fourth chapter cover many design requirements of submerged reef breakwaters. The same considerations are applied while designing shore-parallel submerged breakwater for this case study.

4.3.3 Crest level and shape of the breakwater

A breakwater is designed as one continuous structure, which is constructed from geotextile tubes and containers (description in Chapter 4.4) in such way that cross-profile would form trapezoid. When looking to the profile of such structure, two tubes as the base and one above can be seen. The better view as well as other engineering geometrical design parameters can be seen in drawings and presented in Annex C. The structure is 100 m long and 12 m width at the toe and with approximately 4 m crest width. The crest level of -1,6 m was designed. It was a compromising solution between safety requirements and efficiency of the structure to attenuate approaching waves. Designed slopes of the reef have to be additionally verified with the numerical and, when possible, with physical simulations for each set of geometry and wave conditions. This is not covered in this Master Thesis.

4.3.4 Salient predictions for the Brasilien Beach research site

Predicted salient size and length for the Brasilien Beach is presented in Figures 4.9 and 4.10 respectively. They indicate that maximal salient would form if breakwater would be constructed 550 m away from shoreline. Since breakwater is designed to form sand bar elongation and the reef should be used by divers it is desirable to place structures as close to the coast as possible. Therefore 170 m distance from shore was chosen. Summarized design parameters of the shore-parallel breakwater are presented in Table 4.3.

The prediction of possible sand formation in the lee side is done following the same methodology described in Chapter 3.8. The ratio of breakwater width with its distance of placement from coast is more than 0,59. Both Black and Andrew (2001) CEM (2002) methodologies indicating that salient might form. The beach Response Index (USACE, 2002) suggests (regarding Table 3.1) that subdued salient could form as Index is equal to 4,3. In conclusion, 170 m away from the shoreline placed artificial submerged reef-type breakwater of 100 m width would be the optimal solution.

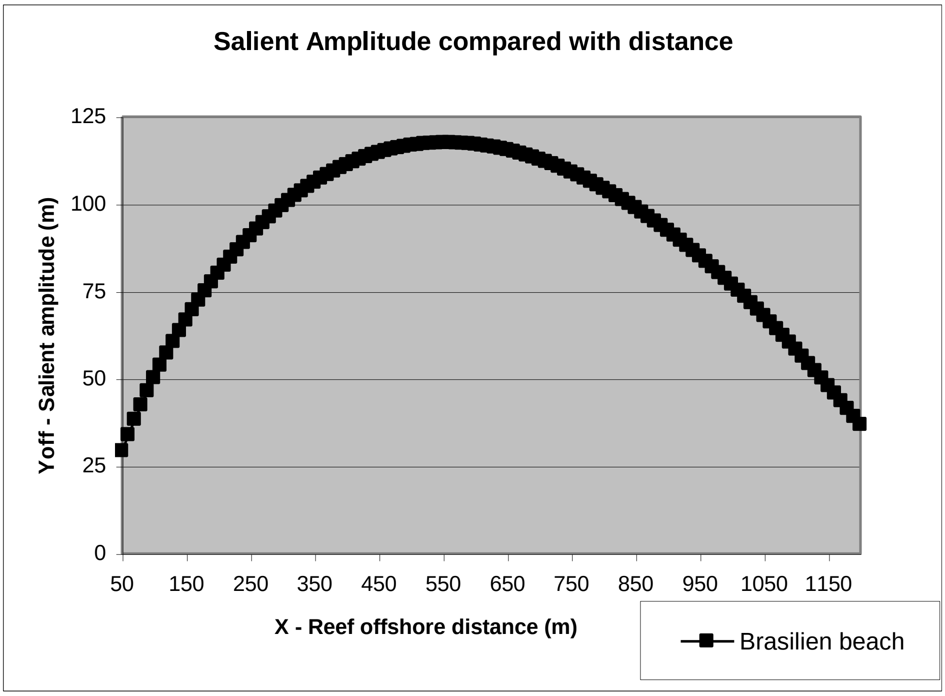


Figure 4.9: Salient Amplitude

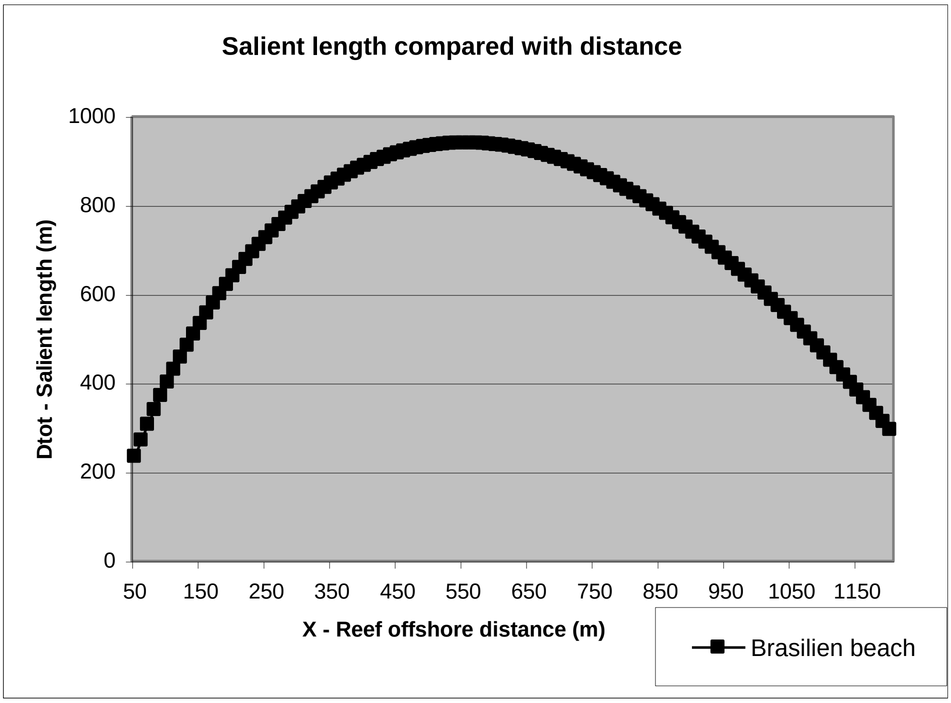


Figure 4.10: Salient Length

Table 4.3: Parameter of designed reefs for Alternative 7 in Brasilien Beach.

Alternative	Alternative 7
Location	Brasilien Beach
Purpose	Coastal protection, diving conditions improvement, marine habitat enhancement
Distance from coastline, X (m)	170 m
Constructional material	Geotextile tubes and containers, filled with sand
Length of breakwater, L (m)	100
Height of breakwater, H (m)	2,5 m
Width of breakwater, W (m)	12 m
Crest level or Freeboard, F (m)	-1,6 m
Crest wide, B (m)	Approximate 4 m

Beach nourishment should be performed in conjunction with the breakwater construction, in order to pre-fill the salient (Harris, 2007), which is expected to form and thus to prevent from erosion cause of the introduction of new structure.

4.4 Constructional materials and its impact on biodiversity. Installation of the breakwater

Rubble mound is the most often used material to build coastal structures. Such kinds of structures are very expensive due to shortage of natural rock. In addition, rubble mound coastal structures are potentially more dangerous to the coastal users such as swimmers or divers. As a result to raised arguments, another cost-effective constructional material was desired for constructing artificial reefs in this case study.

4.4.1 Geotextile

Geotextile have been used worldwide in wide variety marine and hydraulic applications and is desired constructional material due to soft contact with environment. Nowadays, geotextile containers, tubes and bags find their application as construction elements for bottom scour protection, scour fill, erosion control, artificial reefs and breakwaters, groins, dams, seawalls, revetments or dune reinforcements (Saathoff at el., 2007). From constructional perspective, this material can be described as permeable fabric, which has the ability to separate, filter, reinforce, protect, or drain. Typically made from polypropylene or polyester; geotextile fabrics come in three basic forms: woven (looks like mail bag sacking), needle punched (looks like felt), or heat bonded (looks like ironed felt) (Wikipedia) (see Figure 4.11).

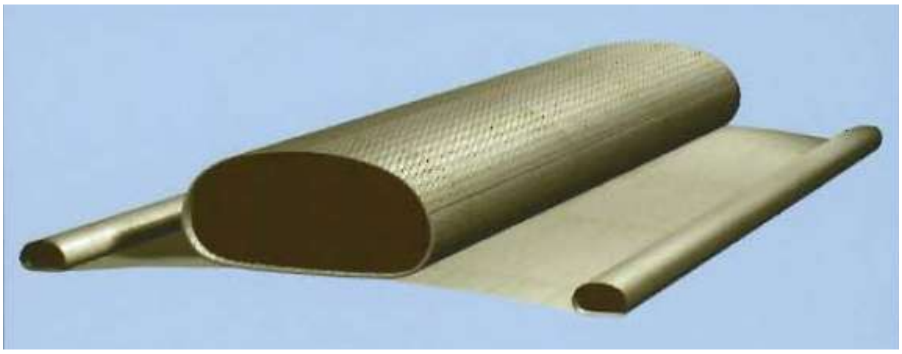


Figure 4.11: Geotextile (Source: MIRATECH®)

Geosystems are geotextile encapsulated with soils and tend to be more stable hydraulically and geotechnically. This is due to larger weight and height ratio. Moreover, units are heavier and have better boundary contacts with adjacent units (MIRATECH®).

Depending on constructional and client requirements, three different geosystem types are available: tubes, containers and bags (see Figure 4.12).

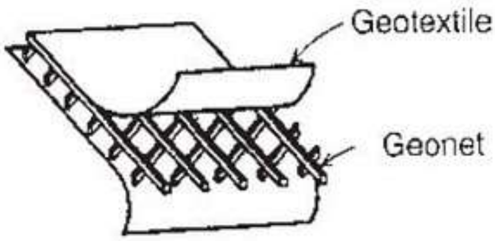
Figure 4.12: Geosystem types (Source: MIRATECH®).

Geotextile was chosen as constructional material for the surfing and bar-type breakwaters (Alternative 1 - 7) of this research study. The intention of design of first six alternatives (surfing reefs) was to construct the delta-shape with the rip channel in between from sand-filled tubes and containers. The purpose of the seventh (bar-type) submerged breakwater alternative was to use sand-filled geotextile tubes and containers to form one shore parallel structure. Surfers and swimmers safety concerns were one of the main objectives choosing constructional materials for the first seven alternatives because fabric is softer and without sharper borders. Second and not least important reason of geotextile application was potential increase in marine biodiversity. Latter mentioned parameter was successfully recorded and monitored at the Narrowneck reef on the Gold Coast, Australia (Jackson et al. 2004, Jackson, 2007 and Edwards, 2003). Jackson et al. (2007) stated that "geotextile has provided a surprisingly good substrate for development of a diverse marine community". Moreover, usage of geotextile systems gives flexibility to the constructional design as each tube, container or bag can be produced by individual project requirements.

From geotextile elements constructed structures have withstand different climatic and anthropogenic conditions such as impacts with boats or constant abrasion of sand and gravel, which are carried by currents and waves. Therefore, geotextile must have high elongation and puncture resistance to limit damage (Saathoff at el., 2007). Geotextile of higher technical properties are used to meet above mentioned requirements in coastal and hydraulic applications. What is more, geogrids as additional tool to diminish possible damage and increase durability of constructional elements are applied (see Figure 4.13).

(Source: http://www.fiberglassmesh.cc/)

(Source: www.sinofuwang.com)



(Source: http://soiltestingequipment.blogspot.com/2010/02/geotextiles-geogrids-and.html)

Figure 4.13: Geogrids.

Geotextile tubes

Geotextile tubes are factory fabricated closed-ended ellipse cross-shape and factory fabricated modules, which are flexible in design regarding required objectives of the project. Tubes are designed with one or two filling ports which enable to fill modules hydraulically with sand. Sand as a fill material allows ensuring long-term stability and shape of tubes. The designed tube diameter varies from 1 to 10 m and typical length is from 20 to 30 m, although 100 m length tubes are available and can be used with restriction that they are not installed in deeper than 5 m water depths (Smith, unpublished).

Geotextile containers

Geotextile containers from tubes are distinguished by smaller length and the technique of delivery to the site – once filled containers can be brought to installation site and placed by split bottom barge. Depending on application, site conditions and size containers are manufactured from nonwoven or woven geotextile and can be mechanically or hydraulically filled. Typical length is 25 m. The greatest advantage of geotextile containers (Figure 4.14) is that they can replace expensive material for coastal structures. In addition, modules can be used in deeper water engineering works.

Figure 4.14: Sand containers at demonstration site (Source: Heerten et al., unpublished).

Geotextile bags

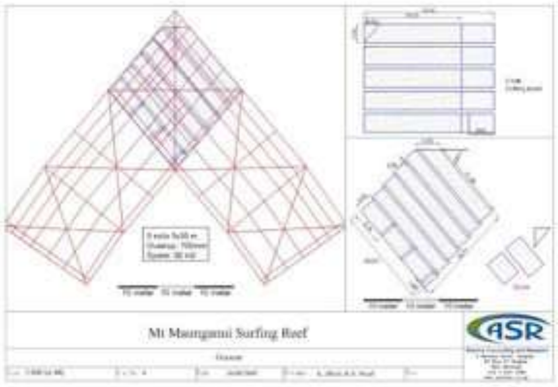
Geotextile bags are the smallest structures from available geosystem types. They are designed to be filled with soil and used for coastal, marine and hydraulic installations. Containers can be custom designed depending on the project requirements. The installation possibilities vary from dry land to water of any depth.

4.4.2 Geotextile breakwater installation

Containers and tubes are positioned empty and filled in place, and this way of construction is called in-situ method. An example of Artificial Breakwater made of geotextile containers and tubes constructional sequence is illustrated in Figure 4.15.

Breakwaters, made of geotextile tubes and containers, are modular constructions which can be delivered on special rollers, which ones themselves can be mounted on to the stern of the vessel used to bring model to their installation locations (Hearin, 2009). In such way model can be easily rolled off the vessel. Construction is secured by anchors to the seabed by divers. Before modules are filled with sand final survey has to be done to verify that dimensions and depths are within design tolerance (Hearin, 2009) and reef is correctly positioned. The location of installed breakwater has to be marked with buoys.

(a)



(b)

(c)

(d)

Figure 4.15: Construction of Multi-Purpose reef (Source: ARS Marine Consultants). (a) Design of the Reef, (b) Attaching geotextile containers to the web, (c) winching reef to the seabed, (d) filling geotextile containers with sand.

4.4.3 Geotextile impact on marine biodiversity

Geotextile as constructional material is preferred due to its "soft" interaction with environment. Moreover, recognition to its positive impact to the marine biodiversity is rising up. Smit et al. (2007) in his paper describes the testing site with three different commercially available – a non woven, a composite dual layer non woven and a split film high strength woven – samples by Dubai coast. He seeks to compare these results with ones already obtained from long-run monitoring at Narrowneck reef at the Gold Coast, Australia, which showed positive response to the installation of the reef. Only four months later, when the samples were deployed, considerable enhancement of marine biota on and in the vicinity of the geotextile samples were observed. Outcome results of the testing site confirmed that geosynthetics can be used as affective substrata to increase biomass (Smit et al., 2007). This was important argument to choose geotextile as constructional material for the surfing reef and the shore-parallel breakwater solutions.

4.5 Reef balls

4.5.1 General description and specifications

Reef BallTM is relatively new and innovative solution to build submerged breakwaters. The usage of Reef Balls had increased recently and modules can be described as permeable, hollow cement hemisphere structures, which mimic natural coral heads. Reef Balls, shown in Figures 4.16 - 4.18, originally were designed to enhance biodiversity, then constructed as artificial reefs. The spectrum of usage has expanded to many applications, to such as coast stabilization, marina protection, oyster growth, mangrove rehabilitation (Reef Beach Company, Ltd., 2007). Reef Balls are available in different shapes and sizes which makes construction and design of a breakwater flexible. Moreover, units are easy to install. Molds are pre-fabricated to form desired size of Reef Balls. Halls are formed with installed and fixed balls inside the molds. To improve concrete workability and durability in marine conditions some additives such as micosilica are added in the mixture of the concrete (Harris, 2003).

Due to novel design, Reef Balls can provide both habitat for marine biota and coastal protection function. Exclusive feature of latter mentioned constructions are holes which create nature-close conditions for marine organisms. In addition, from reef ball modules formed breakwater can be effective wave attenuation tool which would dissipate a large parts of wave energy before it reaches the beach.

Figure 4.16: Reef Balls as habitat and diving resort (Source: Reef Ball Foundation, http://www.reefball.org/)

Figure 4.17: Reef Balls before deployment (Source: Reef Ball Foundation, http://www.reefball.org/)

Figure 4.18: Reef Ball breakwater and a diver (Source: Reef Ball Foundation, http://www.reefball.org/)

Already mentioned novel design of reef balls and thus designed breakwater, would still stay permeable allowing easy water flow through it and over it, so that formation of tombolos is prevented. In addition, it helps to secure good quality and avoid standing water. Such porous structures can prevent from ponding effect which can cause erosion at the ends of breakwater (Harris, 2007).

Several advantages of Reef ball units can be distinguished over traditional breakwater materials, including:

- Fabrication is easy and cost-effective as it can be done directly on-site by using a patented mold systems
- Easy and economical deployment which can be handled with lift bags. Unites can be floated to the deployment site without usage of barges and cranes.
- To increase stability of the formed breakwater, unites can be anchored to the sea bottom
- Unites can be custom designed, depending on required or selected habitat. In addition, Reef Balls can be applied for transplanting or propagation of corals or used for aquaculture purposes (Harris, 2007).

4.5.2 Technical details of Reef Ball breakwaters for Heidkate and Brasilien beaches

Description of technical specifications and parameters of artificial Reef Balls available today are presented in Table 4.4 Rows in grey mark types of reef balls, which are suitable for this research case.

Table 4.4: Technical specification of artificial reefs.

Style	Width	Height	Weight	Concrete Volume	Surface Area	# Holes
Goliath Booster Ring	2 m	1 m	1,818-2,727 kg	1.19 m^3		15-25
Goliath	1.83 m	1.52 m	1,818-2,727 kg	1.19 m^3	21.4 m^2	25-40
Super Ball	1.83 m	1.37 m	1,818-2,727 kg	1.19 m^3	17.6 m^2	22-34
Ultra Ball	1.68 m	1.31 m	1,591-2,045 kg	0.76 m^3	13.9 m^2	22-34
Reef Ball	1.83 m	1.16 m	1364-1,909 kg	0.57 m^3	12.1 m^2	22-34
Pallet Ball	1.22 m	0.88 m	682-1,000 kg	0.25 m^3	7.0 m^2	17-24
Bay Ball	0.91 m	0.61 m	170-341 kg	0.08 m^3	11-16 m^2	
Mini-Bay Ball	0.76 m	0.53 m	68-91 kg			8-12
Lo-Pro	0.61 m	0.46 m	36-59 kg			6-10
Oyster	0.30 m	14-20 kg	less than 1 50 lb. bag		6-8	

Source: modified from http://www.reefball.org.

4.5.3 Design evolution

Accordingly to arguments already described in previous chapters, especially ones in Chapter 3, three different Reef Ball breakwater alternatives were designed, where two of them are tested for the Heidkate and other one for the Brasilien research sites. To increase effectiveness of breakwaters, doubled shore parallel and the same length structures were designed for each of alternatives. Objectives of designed breakwaters are presented in Table 4.5.

Successful installation of submerged artificial reef breakwaters, constructed from Reef Balls, in some locations as well as physical modelling and wave tank studies, which were performed by the US Army Corps of Engineers Coastal Hydraulics Laboratory, have shown 0,5 m crest or less bellow the low tide elevation and an 8 to 10m wide breakwater performs sufficient wave attenuation to stabilize beaches, but does not create tombolos (Harris, 2007). Decreased effectiveness of the structure can occur during higher submergence level or storm surges. In order to provide effective coastal protection, the structure has to be wide enough to provide sufficient wave attenuation. Nevertheless structures have to be safe for swimmers and divers. Embracing latter mentioned arguments, approximate -1,2 m for Alternative 8 and -2,0 m for Alternative 9 crest levels of submerged Reef Ball breakwaters in Heidkate research site are adopted. Alternative 10 is designed in front of Brasilien beach and crest level of this breakwater is assumed to be more than -2,0 m bellow Still Water Level (SWL). The designed levels of crests are double compared with ones recommended by the scientific literature. This has to be countered by increased breakwater width in order to reach the same breakwater efficiency (Harris, 2007) and to provide sufficient wave attenuation and stable marine habitat.

Table 4.5: Parameters of designed reefs for Alternatives 8, 9 and 10.

Alternative	Alternative 8	Alternative 9	Alternative 10
Location	Heidkate Beach	Heidkate Beach	Brasilien Beach
Purpose	Coastal protection and habitat enhancement	Habitat enhancement	Coastal protection and habitat enhancement
Distance from coastline, X (m)	170	490	170
Reef ball types	Pallet Ball	Goliath and Goliath Booster Ring	Goliath and Goliath Booster Ring
Length of breakwater, L (m)	2 x 122 (with 60 m gab in between)	2 x 80 (with 40 m gab in between)	2 x 100 (with 50 m gab in between)
Height of breakwater, H (m)	0,88	2,52	2,52
Width of breakwater, W (m)	~ 20	20	20
Crest level or Freeboard, F (m)	~ 1,2	~ 2,0	~ 2,0

4.5.4 Positioning of structure and salient predictions for Heidkate and Brasilien beach research sites

The capacity and efficiency of Submerged Reef Ball Breakwaters to provide coastal protection function are also analyzed applying already described methodology which was applied for other discussed Alternatives of this Master Thesis.

Alternative 8 (see Figure 4.25, location is marked with red ellipse) is designed for shallow waters in front of Heidkate beach 170m from the coast. The distance was chosen following already described in Chapter 3 arguments about geological, safety, efficiency of the structure. Crest level of the breakwater is around 1,2m bellow Still Water Level (SWL). The ratio of the breakwater length and its distance to the coastline is $L_s / X = 122m / 170m = 0,71$. This falls in the range of 0,5 – 1,0 (see 3.2 table), meaning that salient should be formed in the hinter-side of the breakwater. CEM (Table 3.3) also confirms possible salient formation, while Black and Andrew (2001) suggested empirical relationships (see formula (6)) states that tombolo might form. Beach Response Index (USACE, 2002) suggests (regarding Table 3.1) that subdued salient could form as it is equal to 4,16. In conclusion, 170 m away from the shoreline placed artificial submerged reef-type breakwater of 122 m long would be the optimal solution. Predicted Salient amplitude and length is presented in Figure 4.19 and Figure 4.20 respectively.

Breakwater is formed from Pallet Balls which are relative smaller in size and hence smaller weight, so anchoring of each unit to the bottom is extremely important in order to ensure stability of the structure.

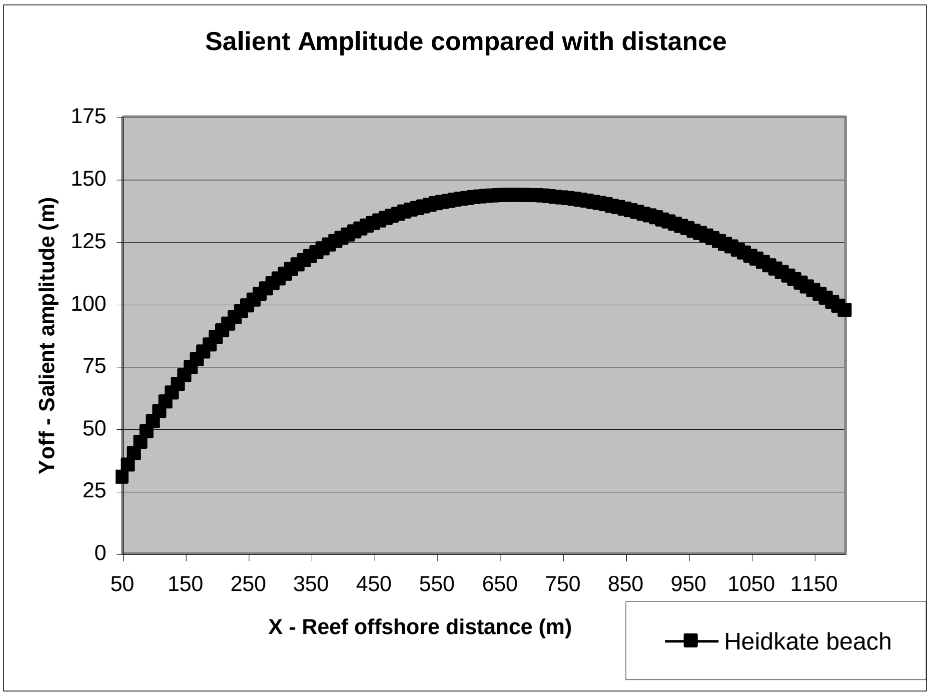


Figure 4.19: Salient Amplitude for Alternative 8 (coastal protection and habitat enhancement)

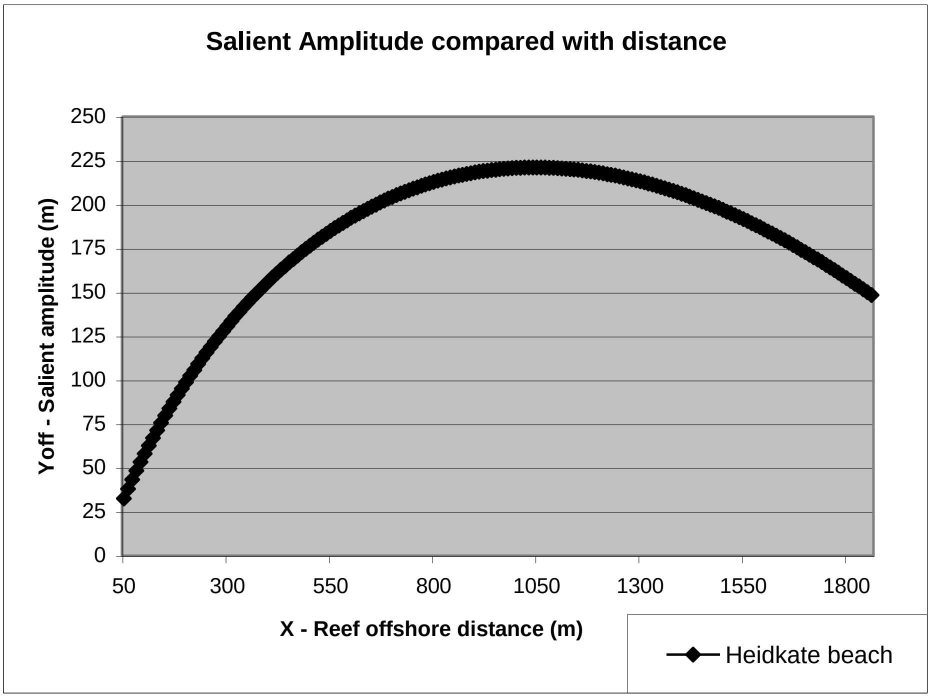


Figure 4.20: Salient Length for Alternative 8 (coastal protection and habitat enhancement)

Alternative 9 (see Figure 4.26, location is marked with red ellipse) is also designed for Heidkate beach more than 500m from the coast where deeper seabed starts, which refer to 4,0m depth and more from the SWL. This raised the question whether it is feasible to construct such breakwater which would meet both coastal protection and habitat enhancement conditions. Due to technical and economical reasons, it was decided to design

Reef ball breakwater only for the habitat improvement objectives. The biggest available Goliath Reef Balls with Booster extensional ring to raise the height of the breakwater were chosen for this alternative. The crest level in this location reached more than 2,0m bellow Still Water Level (SWL). The Reef breakwater would be places around 490 m away from the coastline. Even though that structure is designed only due to habitat improvement reasons, salient formation can be predicted if methodology described in Chapter 3 is applied. Results are presented in Figure 4.21 and Figure 4.22. These graphs indicate that decided constructional location should form maximal amplitude and length of salient, but this has to be verified with numerical or physical modelling.

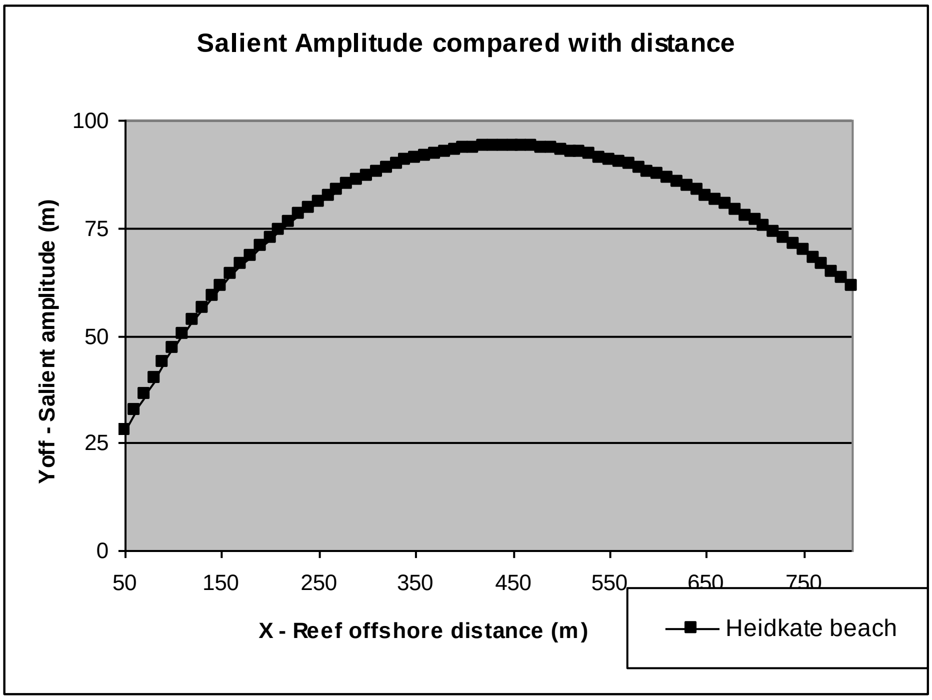


Figure 4.21: Salient Amplitude for Alternative 9 (habitat enhancement)

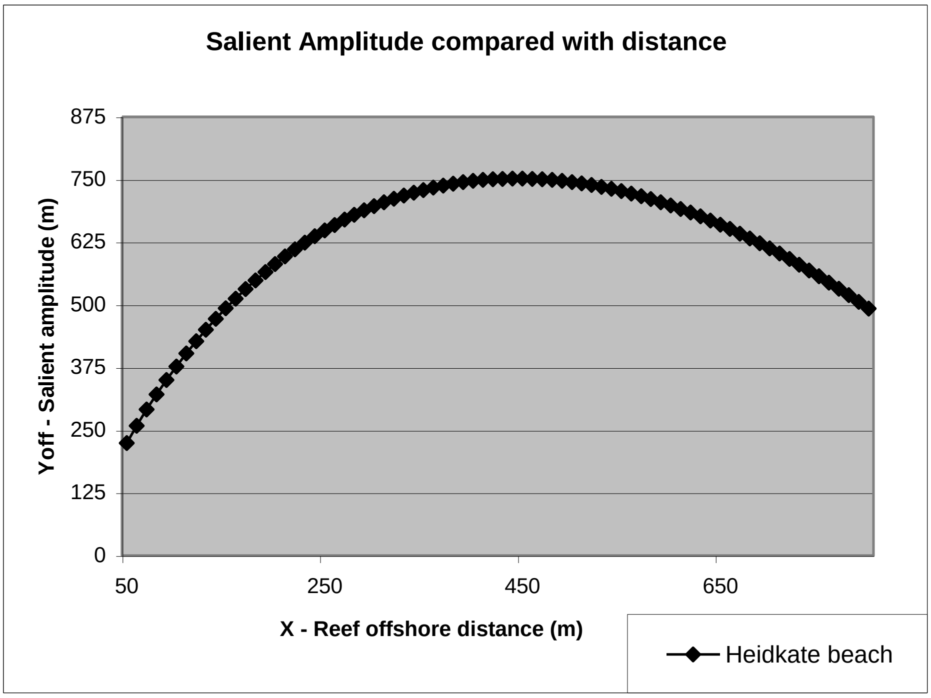


Figure 4.22: Salient Length for Alternative 9 (habitat enhancement)

Brasilien beach, the second research location, has steeper gradually sloping seabed, so it allows exploiting location in more effective way. It follows that breakwater can meet both coastal protection and habitat improvement requirements. Goliath Reef Balls and Booster extension are chosen for Alternative 10 (see Figure 4.27, location is marked with red ellipse) and located around 170 m from the coast. The crest of the breakwater is in more than 2,1m depth and the ratio of length with distance is 0,58. The same as for Alternative 8, salient formation is expected in the lee side of the structure. Beach Response Index (USACE, 2002) suggests (regarding Table 3.1) that subdued salient could form as Index is equal to 4,38. In conclusion, 170 m away from the shoreline placed artificial submerged reef-type breakwater of length of 100 m would be the optimal solution. Predicted salient amplitude and length is presented in Figure 4.23 and Figure 4.24 respectively.

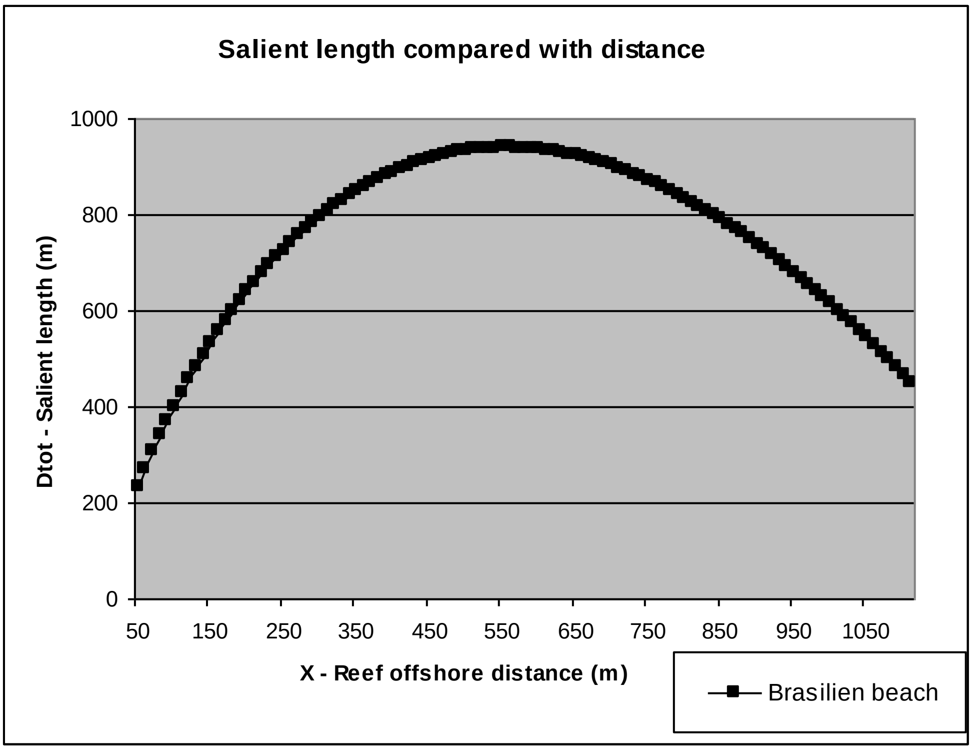


Figure 4.23: Salient Amplitude for Alternative 10 (coastal protection and habitat enhancement)

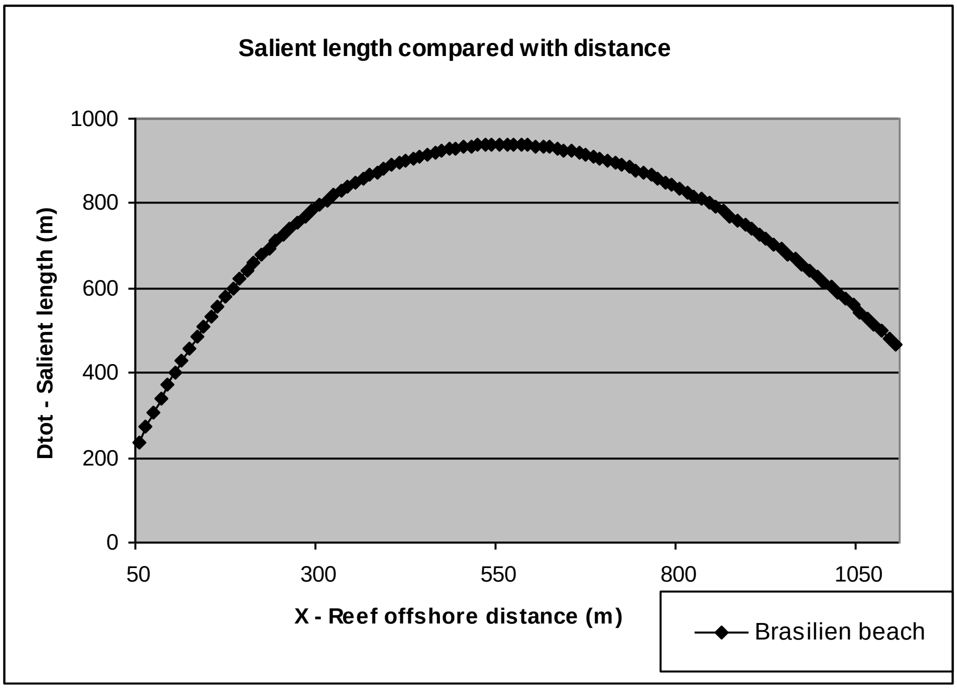


Figure 4.24: Salient Length for Alternative 10 (coastal protection and habitat enhancement)

Each unit of installed Reef Ball breakwater is anchored securely to the seabottom. The method used to do this depends on the bottom type. It can be done by using rods drilled in the existing hardbottom, or by pilings jetted into sand bottom.

Beach nourishment should be performed in conjunction with the breakwater construction, in order to pre-fill the salient (Harris, 2007), which is expected to form and thus to prevent from erosion cause of introduction of new structure.

Design parameters of all three proposed alternatives are presented in Annex C and Annex D.

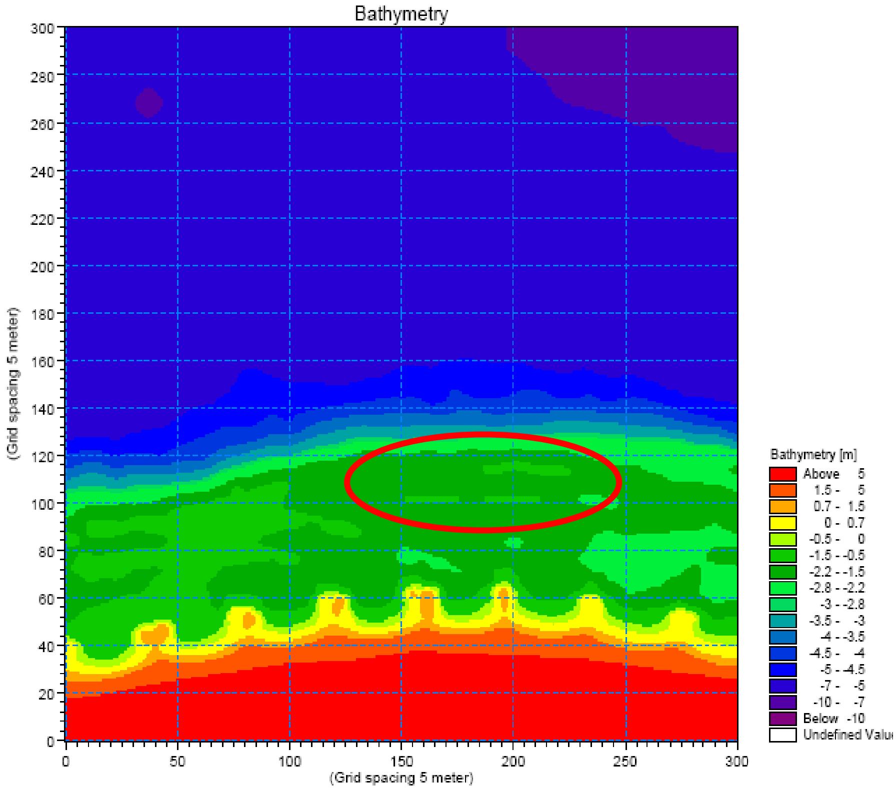


Figure 4.25: Alternative 8. Reef Ball breakwater in Heidkate Beach.

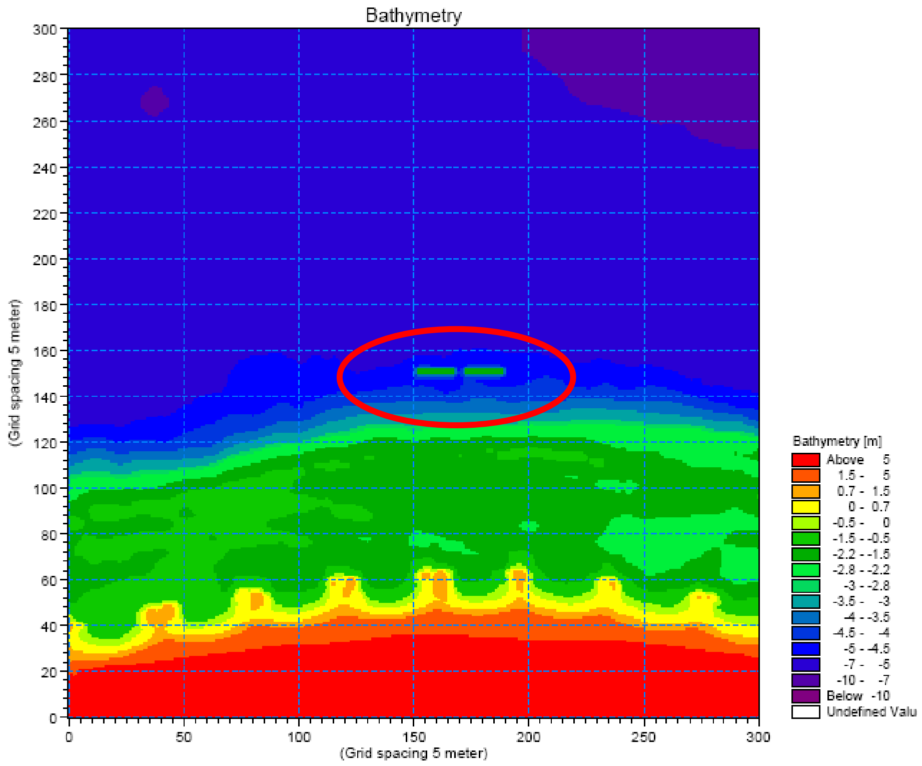


Figure 4.26: Alternative 9. Reef Ball breakwater in Heidkate Beach.

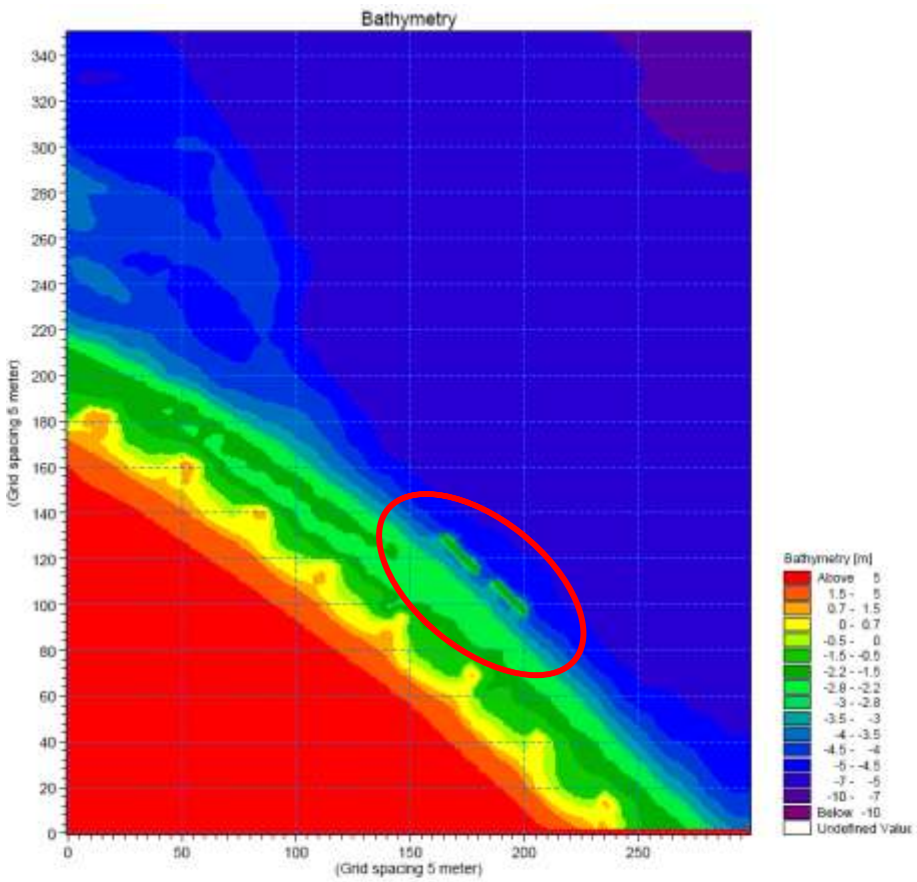


Figure 4.27: Alternative 10. Reef Ball breakwater in Brasilien Beach.

5 Numerical modelling

5.1 Introduction

Numerical modeling is a powerful tool if it is applied in correct way. Numerical models help to simplify complex environment, but it have to be taken into account that actual conditions are variable and numerical models provide information for limited number of specific conditions (Jackson at el., 2007). Nevertheless, models should represent actual conditions and results have to be interpreted accurately and appropriately based on independent data and experience (Jackson at el., 2007).

The aim of present research is to compare proposed designed submerged reef-tape breakwaters for the coastal protection and habitat enhancement and suggest the most suitable one for the research locations. The most important objective is to model possible sediment transport before and after installation of the coastal protection structure. For the numerical modelling three computer-aided MIKE software models, developed by DHI Water and Environment, were applied:

1. MIKE 21 Flow Hydrodynamic Model (HD) to evaluate hydrodynamic processes
2. MIKE 21 Boussinesq Wave Model (BW) to evaluate efficiency of reef structure to dissipate waves and create surfing conditions
3. LITPACK LITDRIFT modules to evaluate sediment transport in the lee side of the breakwater.

5.2 Input data

5.2.1 Bathymetry

Accurate bathymetry is a base for numerical modelling. The input bathymetry files are created with DHI's software package tool MIKE Zero Bathymetry Editor, as well as Surfer Program from Golden Software (2009) group. Input data in order to produce bathymetry has to be in XYZ format, meaning that XY refer to geographical coordinates and Z to elevation. This data is obtained from Bundesamt für Seeschifffahrt und Hydrographie (Federal Authority for Maritime and Hydropgraphy, http://www.bsh.de/en/index.jsp). The working area for each research site was defined according to the local conditions, meaning that area kept small to reduce simulation time of the program run, but big enough to diminish boundary impacts on results. Therefore 1500 m x 1500 m area was chosen for the first location in front of the Heidkate beach and 1500 m x 1750 m area was defined for the Brasilien beach research location. Bathymetries of both locations have three open boundaries – in East, North and West, where additional data such as wave climate and wind have to be defined. Prepared Bathymetries with designed ten alternatives, as well as for reference conditions without any submerged structure, are presented in Figures 4.8, 4.19, 4.20, 4.21 and Annex A.

5.2.2 XYZ grid input data files of Artificial Submerged Reef-type Breakwaters

AutoCAD computer aided design software (Autodesk, 2010) was used to draw 2D sketches of Artificial Reef Breakwaters. The grid of 10 x 10 m was placed over the produced sketch. Three-dimensional values at each grid point overlapping with the reef contours were recorded and XYZ file was created. Another computer aided software Surfer (Golden Software, 2009) was applied to map and verify XYZ reef grid files, as well as to produce 3D reef views which are presented in Annex C. Only then initial reef design was superimposed with the bathymetry of Heidkate and Brasilien beaches. Produced bathymetries for both research locations and all alternatives are presented in Figures 4.8, 4.19, 4.20, 4.21 and Annex A.

5.2.3 Wave input data

Wave data was obtained from Rostock University. Wave values (height, direction, period and other parameters) were extracted with BASEAST Model, in order to obtain values for the Probstei Coastline. Available data for this Master Thesis is for the period between 01.01.2010 to 08.06.2010 (Figure 5.1). This date is also used as input file for DHI's software package LITCONV Utility (DHI Water and Environment, 2005) to obtain one year wave climate for both research locations, that it can be used for further modelling applications. In this data North-East and North-West wave directions as a large percentage of presence can be observed and could be called as one of the main driving wave conditions for the sediment transport. The highest wave of 2,15 m is also recorded from the North-East direction. However, sediment transport is dependent on the total sum of all wave conditions and not only on these two directions.

The wave data of Daisy storm was used to model Hydrodynamic conditions for both, Heidkate and Brasilien, research locations, which was obtained from Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel (IFM – Geomar Research Institute in Kiel, Germany). It embraces time period between 01.01.2010 to 14.01.2010. Highest water level for this period is 1,2 m.

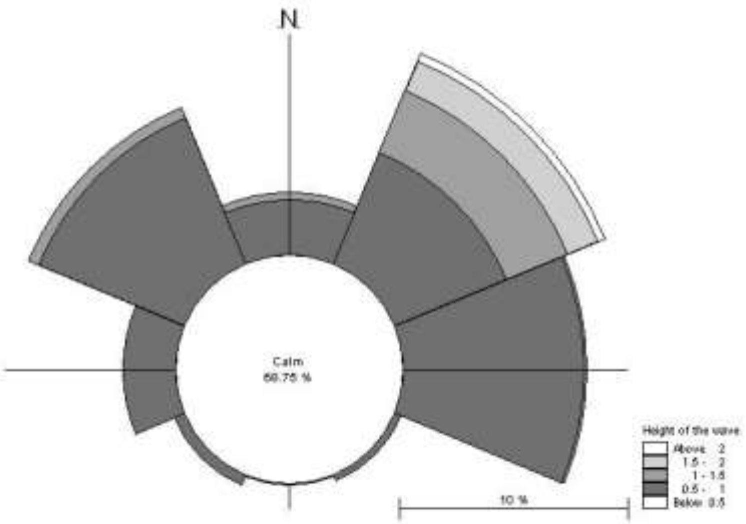


Figure 5.1:. Wave rose graph for Probstei Coastline for the period between 01.01.2010 to 08.06.2010 (data source: IFM – Geomar Research Institute).

5.2.4 Wind

The graph of long term (for 1937-1967 period) wind speed observations (Figure 5.2) are used in order to indicate prevailing winds and their speed as it has tight correlation with hydrodynamic processes in the region. However, input date for numerical modelling, mostly for Hydrodynamic simulations, was obtained from Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel (IFM – Geomar, Kiel, Germany). Data measurement location is at the Lighthouse of Kiel (Kiel Leuchturm). Latter mentioned data is available for 14 days and is measured during Daisy Storm from 01.01.2010 to 14.01.2010 (Figure 5.3).

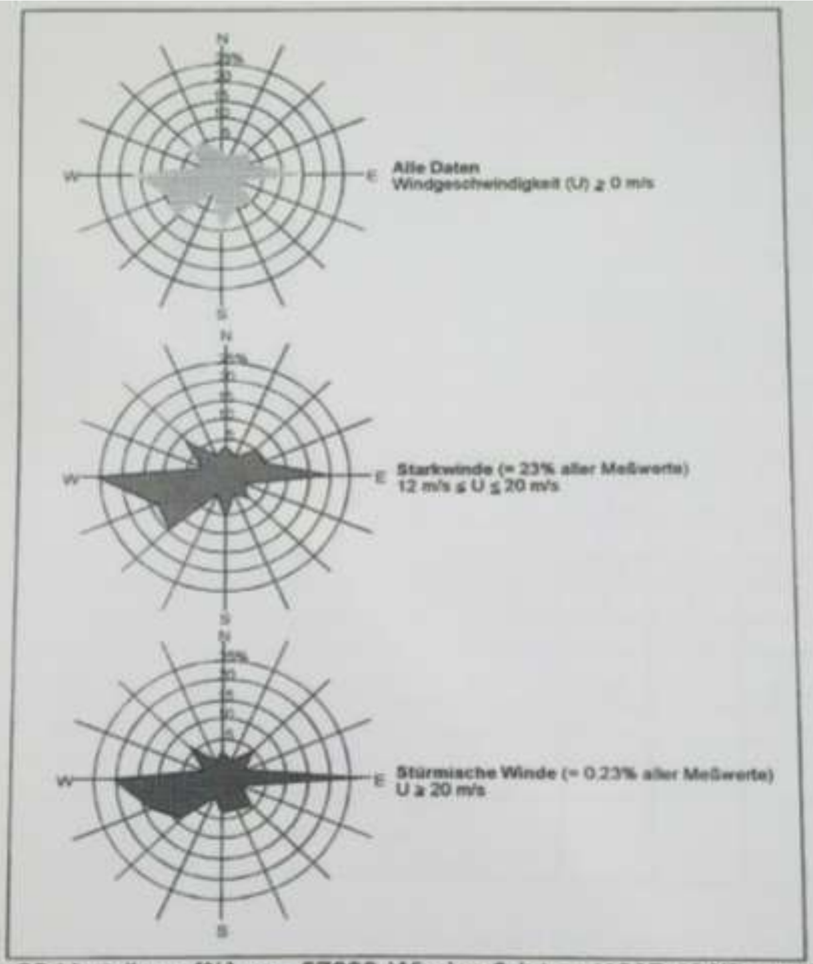


Abb. 22: Verteilung [%] von 57000 Windmeßdaten (1937-1967) am Feuerschiff Kiel differenziert nach Windrichtung und -stärke
Quelle: leicht verändert nach DETTE & STEPHAN (1979)

Figure 5.2: Wind data for period of 1937-1967, measure in lightship of Kiel. (1) all data graph; (2) strong wind graph; (3) storm wind graph (Source: Dette and Stephan, 1979).

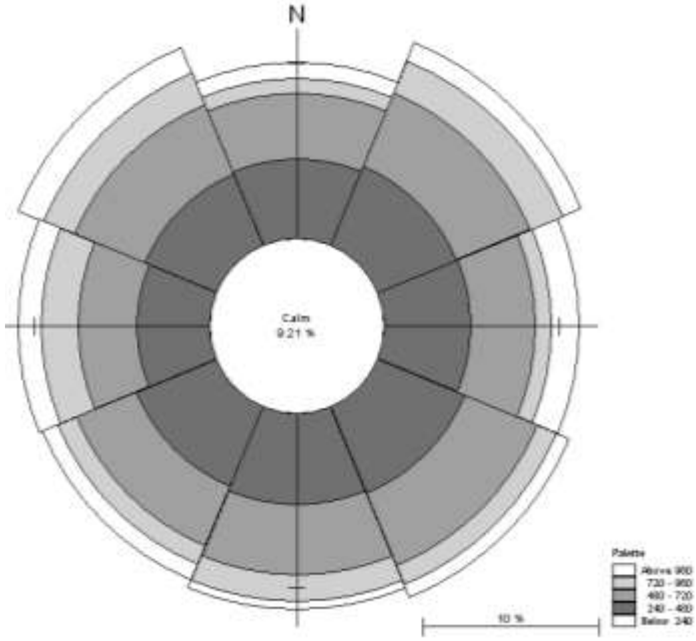


Figure 5.3: Wind rose for Probstei Coastline for the Daisy storm period (01.01.2010 to 14.01.2010) (data source: IFM – Geomar Research Institute, 2010).

5.2.5 Sediment

The description of sediment properties is required in order to model annual sediment drift in DHI's LITDRIFT model. Bobertz et al. (2005) research results were used a a reference ones. Therefore, four sediment types such as (1) silt, clay, mud; (2) fine sand; (3) medium sand; (4) coarse sand, gravel, hardrock were indicated as common types for the German Baltic Sea coast and were considered as input data in this case study. Sand properties (see Table 5.1), including mean grain size for respective sediment type, are presented in Bobertz et al. (2005) paper.

A map, presented by Bobertz et al. (2005) was analyzed in order to define sediment types for case study. It indicates that fine and medium sand is present in front of Heidkate and Brasilien beaches, so it should be considered as input data for the numerical modelling.

Table 5.1: Sediment types and their properties. The mean grain size is denoted by md, z0 is the roughness length (adopted from Bobertz et al., 2005).

Sediment type	m_d (µm)	z_0 (cm)
Silt	20	0,005
Fine sand	130	0,033
Medium sand	250	0,063
Hard rock	-	0,125

Source: adopted from Bobertz et al., 2005.

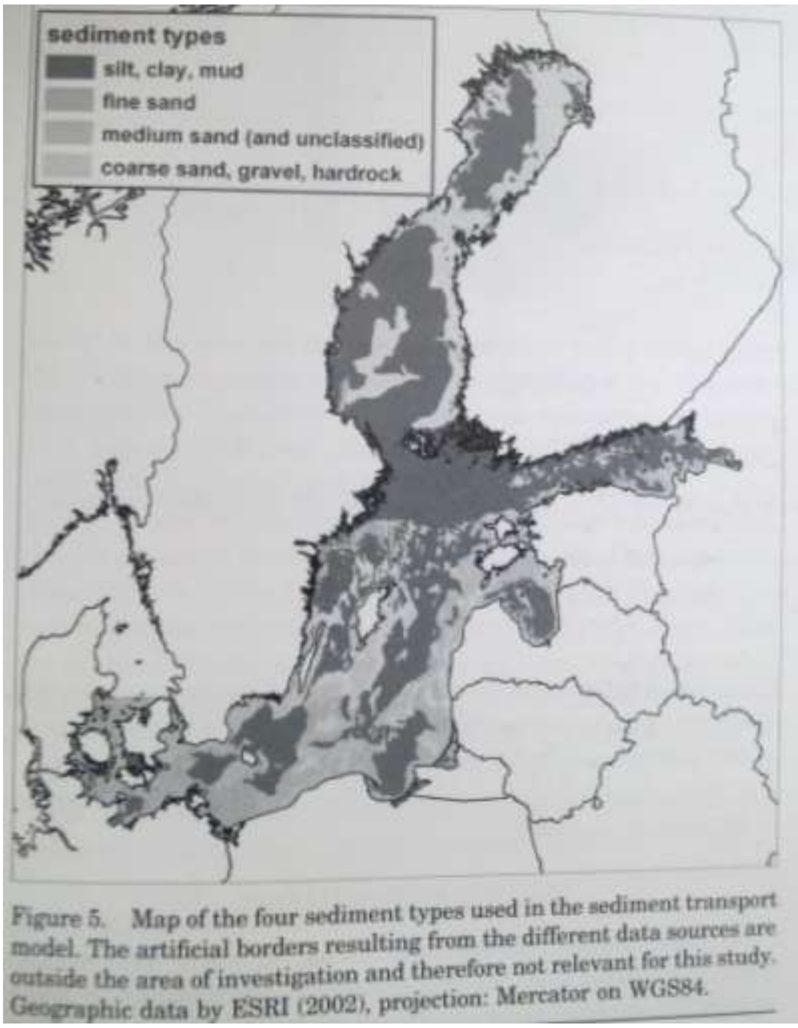


Figure 5.4: Map of the four sediment types in Baltic Sea (Source: Bobertz et al., 2005).

5.3 Numerical modelling application

5.3.1 DHI's Mike 21 Flow Model and its application for case study

MIKE 21 Flow Model is a modeling system for 2D free-surface flows (DHI Water and Environment, 2005). It consist of few modules such as hydrodynamic (HD), the Advection-Dispersion (AD), the ecological process (ECOLab) and the mud transport (MT). MIKE 21 Flow Model has wide applicability range; therefore, it can be applied to simulate hydraulic and environmental phenomena in lakes, estuaries, bays, coastal areas and seas (DHI Water and Environment, 2005). Nevertheless, it has to be kept in mind that modelling system may be applied wherever stratification can be neglected.

For this Master Thesis Hydrodynamic module of MIKE 21 Flow Model is used to test designed Artificial submerged reef-type breakwaters and their impacts on water circulation in the test sites. In the previous chapter described input files such as Bathymetry, Wave and Wind conditions are used to run the model, while other parameters are defined as constant values. Model bathymetry is setup to run with three open boundaries - East, North and West. The time step of 3,6 s was chosen to keep Courant number as small as possible (for MIKE 21 Flow Model Courant number has to be smaller than 8 and it can be adjusted changing grid spacing of bathymetry or time step). Outcome results of this simulation are analyzed to clear out the general performance of the designed alternatives. Detailed description of outcomes results is not presented in this Master Thesis.

5.3.2 DHI's Boussinesq Wave Module (MIKE 21 BW) and its application for case study

The Boussinesq Wave model (MIKE 21 BW) is used to analyze short- and long- period directional and unidirectional waves and their impacts to ports, harbors or coastal areas (DHI Water and Environment, 2005). Moreover, this model also is applied to model wave-induced current fields, surf zone dynamics and swash zone oscillations (DHI Water and Environment, 2005). It is preferable of users due to enhanced Boussinesq equation on which the MIKE 21 Boussinesq Wave Model is based on. The model has been extended into the surf zone by inclusion of wave breaking and moving shoreline as described in Madsen et al. (1997a,b), Sørensen et al. (1998), and Sørensen et al, (2004) (DHI Water and Environmental, 2005).

For this Master Thesis 2DH Boussinesq Wave Module (MIKE 21 BW) is used to verify efficiency of designed Artificial submerged reef-type breakwaters to dissipate waves and perform as coastal protection measure. „The 2DH module (two horizontal space co-ordinates) solves the enhanced Boussinesq equations by an implicit finite difference technique with variables defined on a space-staggered rectangular grid“ (DHI Water and Environmental, 2005).

In order to setup the MIKE 21 BW model slight modifications in bathymetry has to be done. All open boundaries have to be closed and land values replaced with assigned artificial land values. The spatial grid is the same as for Hydrodynamic model, this leading to 5 x 5 m. Therefore, grid spacing has to be combined with time step in order to meet Courant number (CFL) requirements, which has to be less than 1 (DHI Software, 2005) for MIKE 21 BW 2DH model. For this reason 0,16 s time step was agreed and 53 min (including star-up and time to resolve minimum wave period) simulation period was chosen. Prevailing North-East wave direction is observed from available wave data for this Master Thesis for the 01.01.2010 – 09.06.2010 period, and which includes storm of Daisy on the German Baltic Coast. This observed wave direction was used for the simulation. In order to come up with the most suitable coastal protection solution, other prevailing wave directions and their interaction with reef-type submerged structures should be modeled and tested. This is not covered in this Master Thesis.

Two wave generation lines are required to simulate North-East waves. One is place in front of the North, other one in front of the Eastern boundaries with a certain distance from the edge of the absorbing layer. The incident directional wave interaction with submerged structure is analyzed and input file of water level for model setup is generated with MIKE 21 Toolbox program "Random Wave Generation". The JONSWAP (Joint North Sea Wave Project) spectra, which is recommended by DHI's manual, is applied. It defines an empirical relationship between the distribution of wave energy with frequency within the ocean. Simulations are run with maximal wave height value of 2,15 m and maximal period of 5,81 s, obtained from available data for this Master Thesis (Chapter 5.1.2).

Absorbing, or Sponge, layers are set up along the model boundaries and artificial land to avoid wave energy propagation out of the model area, wave reflection from artificial land and thus wave interference with each other. In such way conditions close to the physical ones are created because a sponge layer helps to prevent from serious wave distortion inside the model area. Sponge layer is generated with MIKE 21 Toolbox program "Generate Sponge and Porosity Layer Maps". Regarding MIKE 21 BW User Guide (DHI Software, 2005) recommendations, sponge layer of 20 grid lines is required. Wave breaking and moving shoreline is also included to the model. Outcomes of the MIKE 21 BW model are used to predict efficiency of the reef-type submerged structure to dissipate waves and its impacts to the coast on the lee side of the structure. Results are presented in the Chapter 6.

5.3.3 Basics of sediment modelling. Numerical modelling application and LITPACK model

Most engineering applications, among them submerged structures, alter shoreline evolutions, therefore, adequate shoreline analysis and its variability is an important objective. This is not an easy task as nearshore is a dynamic environment and its sediment transport is highly complex. Changes in beach morphology are caused by cross-shore as well as long-shore sediment transport. In order to fulfill requirements of various coastal engineering projects, predictions of morphological changes of the beach play very important role. Numerical modelling and numerical models gradually accomplished success between scientific and industrial communities as a powerful tool to meet latter expectations (Shamji at el., 2010).

LITPACK is based on the concept of MIKE Zero and also belongs to DHI software family, which has integrated Windows Graphical User Interface (DHI Water and Environment, 2005). The software is used to model noncohesive sediment transport in waves and currents, littoral drift, coastal evolution and profile development along quasi-uniform beaches. LITPACK model consist of few modules which apply fully deterministic approach, which allow solving complex situations such as multi-barrier profiles or varying grain size conditions. LITPACK model consist of five main modules which can be grouped to two groups. To the first group belongs two, LITSTP and LITDRIFT, modules which describe noncohesive sediment transport (LITSTP) and longshore current and littoral drift (LITDRIFT). The second group consists of the add-on modules, describing coastline evolution (LITLINE), cross-shore profile evolution (LITPROF) and sedimentation in trenches (LITTREN) (DHI Water and Environment, 2005).

LITDRIFT module is used to calculate annual longshore sediment distribution if any of the 10 designed submerged reef-type structure would be build in the research site. Outcomes are compared with results from reference locations without artificial offshore structures. LITDRIFT module was chosen because it can simulate the cross-shore distribution of wave height, setup and longshore current and longshore sediment transport for an arbitrary coastal profile. It also can calculate the net/gross littoral transport over a specific design period. Moreover, “important factors, such as linking of the water level and the profile to the incident sea state, are included” (DHI Water and Environment, 2005).

5.3.4 DHI’s LITPACK model application for case study

One of the main aims of this Master Thesis is to evaluate efficiency of designed reef-type submerged breakwaters to aggregate sediments in the lee side of the structure. Therefore, two-dimensional LITDRIFT module is applied for. LITPACK Graphical Setup tool is used to define working area. Bathymetry pictures generated with Surfer Program from Golden Software (2009) and exported referring to coordinate system, as well as aerial pictures (GeoBasis-DE/LVermGeo SH) are applied as background material to draw existing and planned coastal protection structures in order to reflect conditions of the research sites and thus to obtain the most accurate simulation results, when LITDRIFT module is run.

Successful run of LITDRIFT module requires some additional in advance prepared input files. Profile files are one of such ones, which are produced with “Extraction” function of MIKE Zero Toolbox. Values are extracted from Bathymetry files. Number of profiles depends on the research location and the shape of the structure. Places of profiles are mapped on aerial pictures, which, together with graphs of breakwater shapes are presented in Annex D. Number of profiles for each Alternative is defined in Table 5.1.

The annual longshore transport module requires one year wave statistical time series file. As date of only half year period, from 01.01.2010 to 08.06.2010, is available for this Master Thesis LITCONV Utility of LITPACK software package has to be applied in order to obtain Annual Wave Climate. This Utility allows times series of half year to transform to times series of one or more years. The mean grain size has to be specified, while preparing profile filed for LITDRIFT module and input files for LITCONV Utility. Bobertz et al. (2005) published results about sediment properties in the Western Baltic Sea were taken as a reference one, so the mean grain size of 200 μm is applied for numerical modelling, indicating sediment particles between fine and medium sand. The fall velocity of particles depends on water temperature and a grain size and is chosen from Figure 5.5.

Table 5.2: Number of profiles and their location for each designed Alternative 1 – 10 of this Master Thesis.

Label	Profile 1 Aprox. 100m from structure	Profile 2 Through structure	Profile 3 Between structures	Profile 4 Through structure	Profile 5 Aprox. 100m from structure
Alternative 1 **Surfing Reef without arm extension in Heidkate beach**	X	X		X	X
Alternative 2 **Surfing Reef with Eastern arm extension in Heidkate beach**	X	X		X	X
Alternative 3 **Surfing Reef with Western arm extension in Heidkate beach**	X	X		X	X
Alternative 4 **Surfing Reef without arm extension in Brasilien beach**	X	X		X	X
Alternative 5 **Surfing Reef with Eastern arm extension in Kalifornien beach**	X	X		X	X
Alternative 6 **Surfing Reef with Western arm extension in Brasilien beach**	X	X		X	X
Alternative 7 **Reef- and Bar-type submerged breakwater Brasilien beach**	X	X	X	X	X
Alternative 8 **Reef Balls in Heidkate beach**	X	X	X	X	X
Alternative 9 **Reef Balls in Heidkate beach**	X	X	X	X	X
Alternative 10 **Reef Balls in Brasilien beach**	X	X	X		

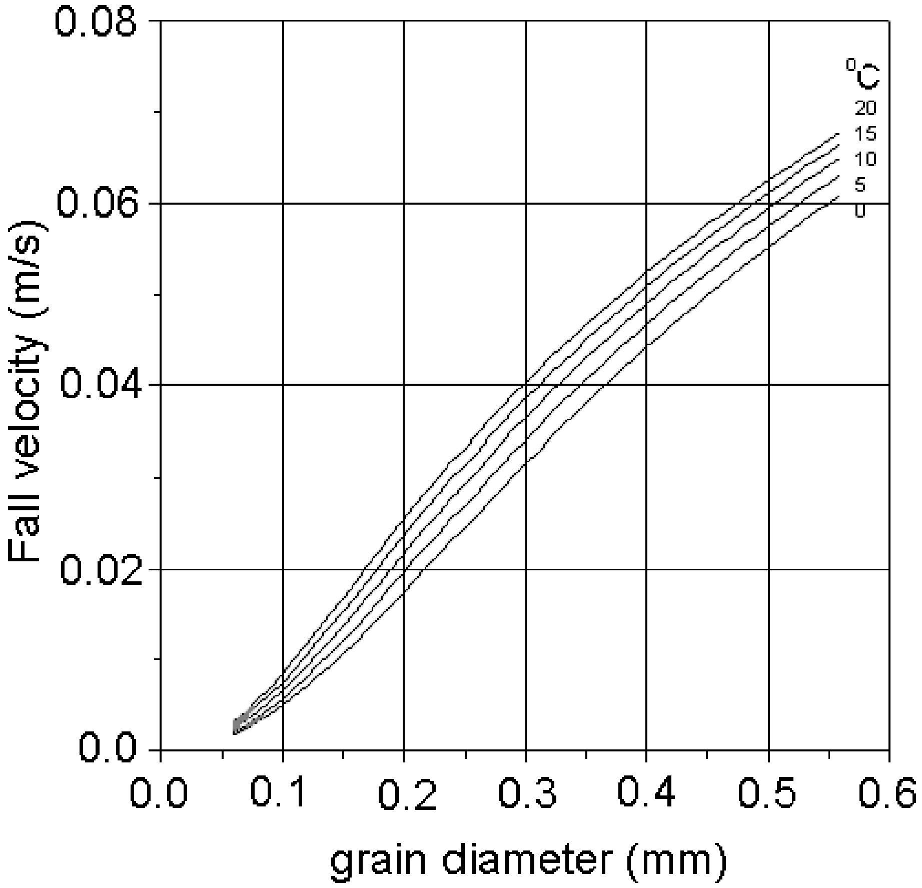


Figure 5.5: Calculator of sediment fall velocity (Source: DHI Water and Environment, 2005).

A grid spacing of 5 m was chosen across the profile. The bed roughness is assumed to be constant across the profile. No external currents or wind are assumed to be present. The sediment transport was calculated by Stoke's 1st order theory with a single grain diameter approach.

6 Results and discussion

6.1 Breakwater efficiency to attenuate waves

6.1.1 Methodology

Breakwaters are designed to dissipate wave energy. It is known that higher submergence level of the low-crested breakwater, the less the wave impacts with the structure, which leads to the lower waver attenuation. Transmission coefficient, Kt, is a measure, which is used to describe effectiveness of a breakwater in terms of wave attenuation,

$$K_t = H_t / H_i; \qquad (8)$$

Where Kt is the wave transmission coefficient, Ht is the height of transmitted wave on the landside of the structure; Hi is the height of an incident wave on the seaward side of the structure (U.S. Army Corps of Engineers, 1984). When transmission coefficient is equal to 1, it indicates that transmitting waves are not dissipated at all, while 0 indicates 100% dissipation of waves. This leads to conclusion that as lower calculated transmission coefficient, the better waves are dissipated by structure. Nevertheless, obtained results have to be treated with critics, as compared results are obtained from numerical modelling only and can't be collated with physical or field data in this case study.

Above described methodology was applied analyzing all ten designed alternatives for this case study and results presented in next chapter in Tables 6.1 – 6.16. The outcome results of run of the DHI's MIKE 21 BW module were used to calculate efficiency of structures. First of all four points for the extraction of results had to be defined, where two of them are in front of the structure (Point 1 and 2 in Tables 6.1 – 6.16), and other two in the lee side of the structure (Point 3 and 4 in Tables 6.1 – 6.16). Locations of extracted points are drawn in aerial pictures presented in Annex D.

MIKE 21 BW model was run for 53 minutes in order to obtain reliable results when even short waves are dissolved. Following the recommendations of DHI's manual for MIKE 21 BW module. Four times steps for 18th, 27th, 36th and 45th minutes were extracted to calculate transmission coefficient.

6.1.2 Results

Following the methodology of the previous chapter transmission coefficients were calculated for all 10 alternatives. All results are presented in Tables 6.1 – 6.16.

Pictures of MIKE 21BW modelling results for the 36th time step can be found in Annex E. It gives better visual overview how structures affect wave transition.

Table 6.1: Dissipation coefficient for Alternative 1. Surfing Reef without arm extension in Heidkate beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,091	1,099	0,526	1,993	1,080	0,542
27	1.2.2010	00:27:04	2,091	1,217	0,582	1,993	1,080	0,542
36	1.2.2010	00:36:06	2,093	1,292	0,617	2,130	1,080	0,507
45	1.2.2010	00:45:07	2,093	1,340	0,640	2,155	1,080	0,501

Table 6.2: Dissipation coefficient for Alternative 1. Surfing Reef without arm extension in Heidkate beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,097	1,219	0,581	1,702	0,998	0,586
27	1.2.2010	00:27:04	2,097	1,219	0,581	1,889	0,998	0,528
36	1.2.2010	00:36:06	2,362	1,219	0,516	1,889	0,998	0,528
45	1.2.2010	00:45:07	2,362	1,219	0,516	1,889	0,998	0,528

Table 6.3: Dissipation coefficient for Alternative 2. Surfing Reef with Eastern arm extension in Heidkate beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,092	1,073	0,513	1,990	1,086	0,546
27	1.2.2010	00:27:04	2,092	1,162	0,555	1,990	1,086	0,546
36	1.2.2010	00:36:06	2,095	1,215	0,580	2,128	1,086	0,510
45	1.2.2010	00:45:07	2,095	1,242	0,593	2,153	1,086	0,504

Table 6.4: Dissipation coefficient for Alternative 2. Surfing Reef with Eastern arm extension in Heidkate beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,098	1,144	0,545	1,701	1,097	0,645
27	1.2.2010	00:27:04	2,098	1,155	0,550	1,891	1,097	0,580
36	1.2.2010	00:36:06	2,360	1,168	0,495	1,891	1,097	0,580
45	1.2.2010	00:45:07	2,360	1,168	0,495	1,891	1,097	0,580

Table 6.5: Dissipation coefficient for Alternative 3. Surfing Reef with Western arm extension in Heidkate beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,088	1,043	0,499	1,993	1,097	0,550
27	1.2.2010	00:27:04	2,088	1,140	0,546	1,993	1,097	0,550
36	1.2.2010	00:36:06	2,088	1,169	0,560	2,129	1,097	0,515
45	1.2.2010	00:45:07	2,088	1,169	0,560	2,154	1,097	0,509

Table 6.6: Dissipation coefficient for Alternative 3. Surfing Reef with Western arm extension in Heidkate beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,098	1,207	0,575	1,702	1,013	0,595
27	1.2.2010	00:27:04	2,098	1,207	0,575	1,889	1,013	0,536
36	1.2.2010	00:36:06	2,360	1,207	0,511	1,889	1,013	0,536
45	1.2.2010	00:45:07	2,360	1,219	0,517	1,889	1,022	0,541

Table 6.7: Dissipation coefficient for Alternative 4. Surfing Reef without arm extension in Brasilien beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,020	1,495	0,740	1,983	1,407	0,710
27	1.2.2010	00:27:04	2,020	1,509	0,747	1,983	1,407	0,710
36	1.2.2010	00:36:06	2,020	1,578	0,781	1,983	1,407	0,710
45	1.2.2010	00:45:07	2,020	1,615	0,799	1,983	1,407	0,710

Table 6.8: Dissipation coefficient for Alternative 4. Surfing Reef without arm extension in Brasilien beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	1,768	1,548	0,875	1,937	1,345	0,694
27	1.2.2010	00:27:04	1,768	1,548	0,875	2,034	1,487	0,731
36	1.2.2010	00:36:06	1,778	1,548	0,871	2,034	1,717	0,844
45	1.2.2010	00:45:07	1,838	1,548	0,842	2,034	1,717	0,844

Table 6.9: Dissipation coefficient for Alternative 5. Surfing Reef with Eastern arm extension in Brasilien beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,013	1,515	0,752	1,974	1,520	0,770
27	1.2.2010	00:27:04	2,013	1,515	0,752	1,974	1,520	0,770
36	1.2.2010	00:36:06	2,013	1,659	0,824	1,974	1,520	0,770
45	1.2.2010	00:45:07	2,013	1,659	0,824	1,974	1,530	0,775

Table 6.10: Dissipation coefficient for Alternative 5. Surfing Reef with Eastern arm extension in Brasilien beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	1,732	1,642	0,948	1,912	1,603	0,839
27	1.2.2010	00:27:04	1,732	1,642	0,948	1,988	1,691	0,850
36	1.2.2010	00:36:06	1,781	1,642	0,922	1,988	1,691	0,850
45	1.2.2010	00:45:07	1,814	1,642	0,905	1,988	1,742	0,876

Table 6.11: Dissipation coefficient for Alternative 6. Surfing Reef with Western arm extension in Brasilien beach (45° from north)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,020	1,562	0,773	1,978	1,382	0,699
27	1.2.2010	00:27:04	2,020	1,562	0,773	1,978	1,382	0,699
36	1.2.2010	00:36:06	2,020	1,562	0,773	1,978	1,382	0,699
45	1.2.2010	00:45:07	2,020	1,569	0,777	1,978	1,382	0,699

Table 6.12: Dissipation coefficient for Alternative 6. Surfing Reef with Western arm extension in Brasilien beach (perpendicular to the coast)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	1,750	1,284	0,734	1,937	1,542	0,796
27	1.2.2010	00:27:04	1,750	1,284	0,734	2,036	1,616	0,794
36	1.2.2010	00:36:06	1,779	1,284	0,722	2,036	1,806	0,887
45	1.2.2010	00:45:07	1,839	1,319	0,717	2,036	1,806	0,887

Table 6.13: Dissipation coefficient for Alternative 7. Shore-parallel breakwater in Brasilien beach

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt
18	1.2.2010	00:18:03	1,785	1,534	0,859
27	1.2.2010	00:27:04	1,785	1,534	0,859
36	1.2.2010	00:36:06	1,785	1,534	0,859
45	1.2.2010	00:45:07	1,785	1,534	0,859

Table 6.14: Dissipation coefficient for Alternative 8. Reef Balls Breakwater in Heidkate beach (costal protection and habitat enhancement)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	1,226	0,962	0,785	1,428	1,296	0,908
27	1.2.2010	00:27:04	1,226	1,009	0,823	1,428	1,357	0,951
36	1.2.2010	00:36:06	1,240	1,047	0,844	1,428	1,378	0,965
45	1.2.2010	00:45:07	1,247	1,063	0,852	1,428	1,378	0,965

Table 6.15: Dissipation coefficient for Alternative 9. Reef Balls Breakwater in Heidkate beach (habitat enhancement)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	2,258	1,535	0,680	1,920	1,595	0,831
27	1.2.2010	00:27:04	2,258	1,619	0,717	1,960	1,638	0,836
36	1.2.2010	00:36:06	2,258	1,665	0,737	1,960	1,639	0,836
45	1.2.2010	00:45:07	2,258	1,665	0,737	1,960	1,783	0,810

Table 6.16: Dissipation coefficient for Alternative 10. Reef Balls Breakwater in Brasilien beach (costal protection and habitat enhancement)

Time step	Date	Time	Point 1: wave height [m]	Point 2: wave height [m]	Kt	Point 3: wave height [m]	Point 4: wave height [m]	Kt
18	1.2.2010	00:18:03	1,827	1,519	0,831	1,802	1,497	0,831
27	1.2.2010	00:27:04	1,827	1,519	0,831	1,859	1,580	0,850
36	1.2.2010	00:36:06	1,827	1,519	0,831	1,962	1,598	0,814
45	1.2.2010	00:45:07	1,827	1,519	0,831	2,013	1,629	0,809

6.1.3 Discussion

Results revealed that Alternatives 1, 2 and 3 (surfing reefs) designed for Heidkate beach for both coast perpendicular and rotated of 45° degree from North should work well as wave dissipaters and their transmission coefficient varies between 0,5 to 0,65.

Surfing reefs designed for Brasilien beach, referring to Alternatives 4, 5 and 6, showed higher transmission coefficients than observed for alternatives of Heidkate beach. Regarding the described methodology, these structures should be less effective for the wave dissipation. The least effective from latter mentioned alternatives is Alternative 5 – surfing reef with eastern arm extension, when orientated perpendicular to the coast. Its transmission coefficient is higher than 0,9 through arm without extension (western part of the breakwater), and with a coefficient of approx. 0,85 through the arm with extension. It means that nearly all waves are transmitted through the structure. Moreover, these numbers suggest that extension of the arm slightly increase wave dissipation but cause higher waves for the arm without an extension. The lowest transmission coefficients are observed for Alternative 6 orientated 45° from the North. Its transmission coefficient falls in the range of 0,69 – 0,77 and could be called as the most effective surfing reef solution from three designed to this location and for tested conditions. While coefficients of the rest alternatives of surfing reefs for Brasilien beach are between 0,70 to 0,88.

The last four alternatives (Alternatives 7, 8, 9 and 10), two Reef Ball breakwaters for Heidkate beach and one Reef Ball and one a shore-parallel breakwater from geotextile for Brasilien beach, showed similar results between each other. Nevertheless, Alternatives 9 and 10 with transmission coefficient range of 0,68 – 0,83, both constructed from Reef Balls, showed the best results, while Alternative 7 with coefficient equal to 0,86 are following them. Alternative 8 are the least effective from these four alternatives. Its transmission coefficient varies between 0,78 to 0,96. Western part of doubled structure performs better than an eastern part for wave dissipation. It's interesting to mention, that the main design purpose of Alternative 9 for Heidkate beach was to improve the habitat, but results allow to state that this structure would have positive affects on coast and would work as coastal protection tool too.

As concluding remark, it can be said that Alternatives 1, 2 and 3 have the lowest transmission coefficients from all 10 designed solutions and could be the most effective wave dissipaters. Nevertheless, the shallow bathymetry of this areas should be taken into consideration making final conclusion.

6.2 Morphodynamics

The definition of sediment transport can be explained as movement of sediment particles through a plane over a certain time period. Characteristics of sediments and movement inducing forces are the main drivers of the sediment transport. The longshore transport means sediment redistributions along the coast and suspended load is the dominant mode in the longshore sediment transport. The main driving forces in such transport are wind, tides, waves, currents, Coriolis force. When waves approach break-zone, they become steeper and higher until they break. Sediments along the shoreline are carried by the longshore current, which has maximum near this wave breaking line (Mangor, 2004). This theory, beside evaluation of morphodynamics in the area, can be used to evaluate efficiency of submerged structures to dissipate waves, as well as predict surfing wave production when surfing reefs are planned.

For this Master Thesis DHI's LITPACK DRIFT module was applied and annual longshore sediment drift was calculated for reference conditions for existing bathymetry and for all ten designed breakwater alternatives.

6.2.1 Results and discussion

Obtained results of sediment transport were analyzed and results presented in both charts (Figures 6.1 – 6.36), which present final sediment accumulation per year for the each profile. In addition to this, annual longshore sediment drift together with the directional sediment transport through each point of cross-shore profiles are presented in graphs of Annex F. These results give better representation of sediment transport per year through the profiles and how designed alternatives affect this phenomenon.

The comparison with reference conditions allows suggesting, which of alternatives could be the most efficient in trapping sediments in the lee side of the structure. However, the final conclusion has to be done after collation with results presented in Annex F. This is necessary in order to avoid misevaluation of efficiency of structures, because, on one hand, some structures could be efficiently slowing sediment movement and trapping them in the lee side, but on the other hand could cause higher sediment transport in the vicinity of the structure.

Results are presented in the form of accumulated Net and Gross sediment drift in cubic meters per year. Depending on structure results are drawn for 3 – 5 profiles, which was extracted and used for numerical modeling as input data. This allows to attain joint overview how designed submerged breakwaters impacts coastlines and areas aside of them. In four-profile conditions, the first and the fourth profiles indicates areas aside the structure, while second and third ones cross submerged structures in a cross-shore direction. In three-profile conditions, the first and the third profiles are aside the structure and the second one is through the structure. In locations, where Alternatives 8, 9 and 10 have been planned, five profiles were extracted. First and fifth profiles fall in the area beside the breakwater, second and fourth ones cross the structures. The third cross-shore profile is between doubled structures.

The efficiency of structures is determined depending on the accumulated sediment transport per year. LITPACK, thus LITDRIFT, is two-dimensional numerical modeling program. Therefore, it calculates wave energy and wave energy dissipation at each grid point of the profile. It is known that sediment movement is mainly caused by waves, so, assuming this, wave energy dissipation would affect coastal parallel sediment transport. The submerged breakwaters are designed to dissipate wave energy end reduce sediment transport in the lee side of them and thus increase sediment trapping and forming desired salient. But as it was mentioned in previous chapters, sometimes submerged structures can cause totally opposite processes, leading to erosion while accretion was expected.

Outcome results of numerical modelling of morphological processes are analyzed individually and are not associated with external research outcome data. First of all, in different locations of the Baltic Sea these processes can differ so interrelation would not give desired conclusions. To validate and verify obtained results, the data from field measurements, pilot project or physical modelling are necessary, but which is not available to this Master Thesis. Outcome results are connected with constructional characteristics of the structure in order to give suggestions for the improvements of the designed alternatives.

Reference conditions for Heidkate and Brasilien beaches

Results obtained with DHI's LITPACK module for Heidkate and Brasilien beaches are presented in Figures 6.1 - 6.4, which indicates that accumulated sediment drift per year varies between 5500 to 6100 cubic meters for the Heidkate, and between 4200 to 6000 cubic meters for the Brasilien beach.

The variation between profiles is insignificant in front of Heidkate beach. The only third profile showed lightly smaller sediment transport which can be explained by reduced bed gradient (Annex F). Base conditions indicate approx. 100 m3/yr/m sediment transport to the West in the area of sudden bed gradient change and in front of the areas where sand bars are present (Annex F).

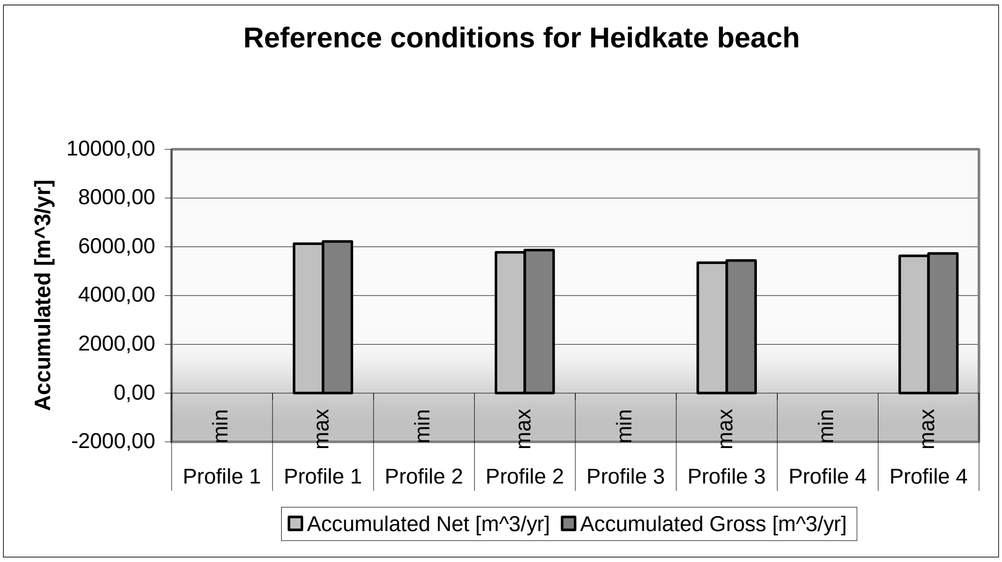


Figure 6.1: Accumulated sediment for Heidkate beach (reference location).

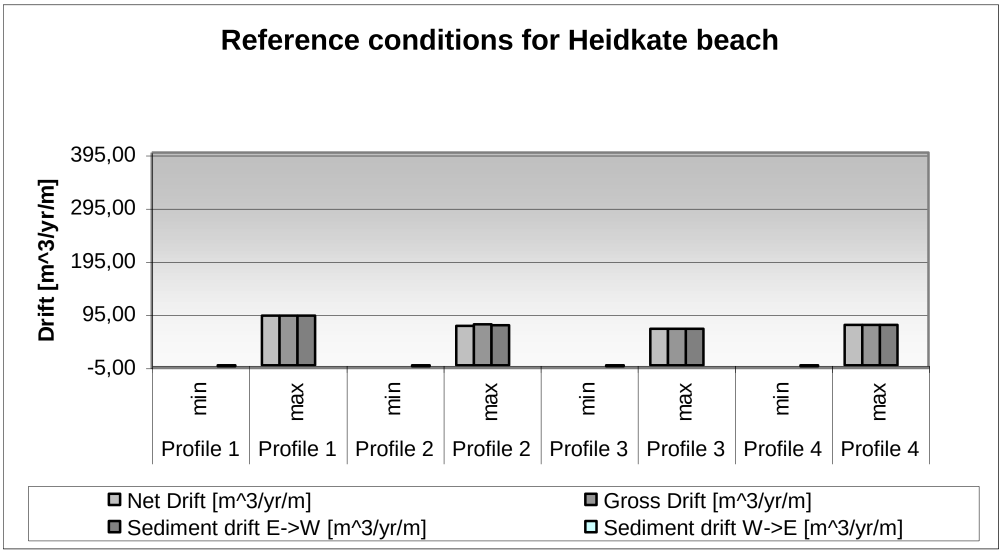


Figure 6.2: Sediment drift for Heidkate beach (reference location).

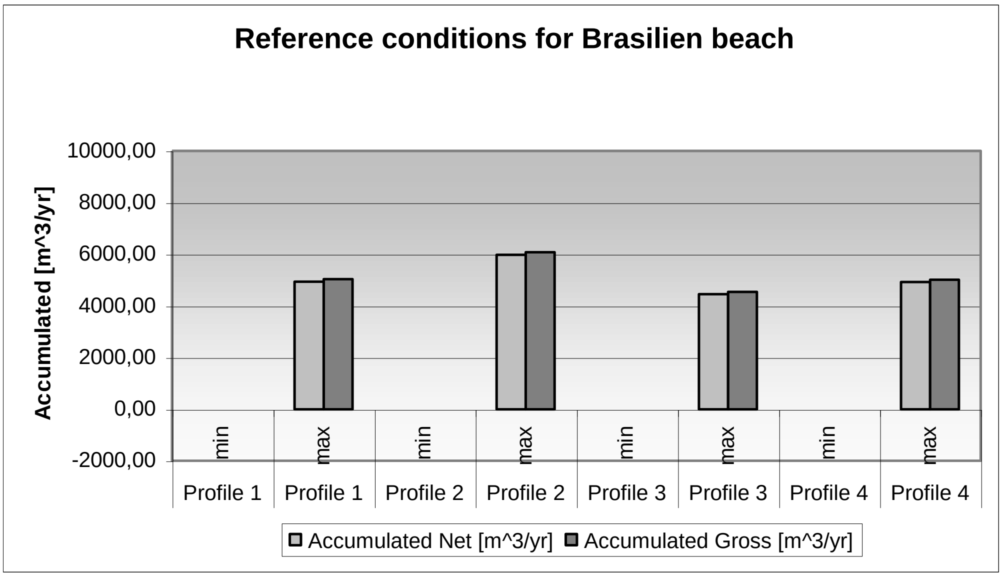


Figure 6.3: Accumulated sediment for Brasilien beach (reference location).

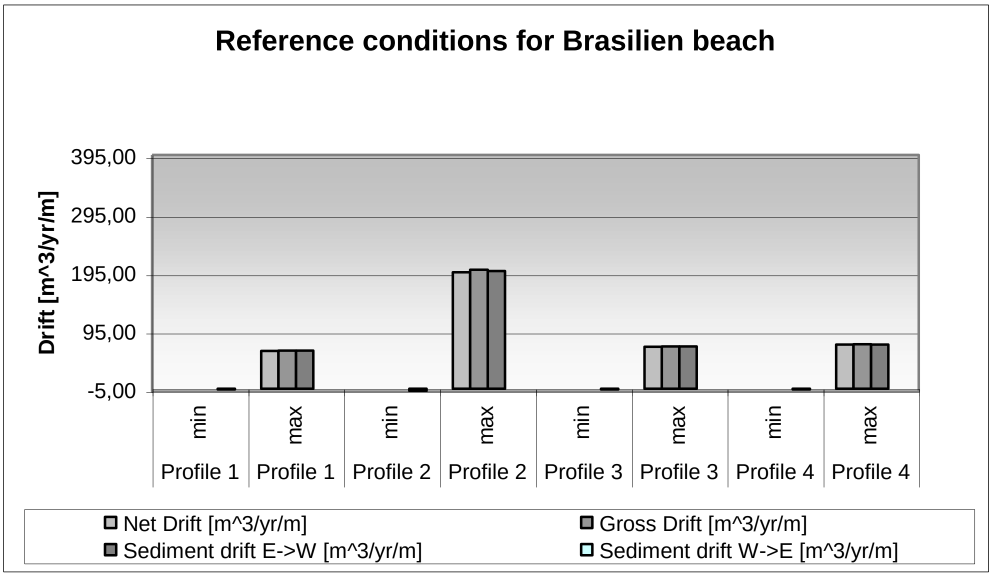


Figure 6.4: Sediment drift for Brasilien beach (reference location).

The little variation in yearly sediment transport can be better seen in the first, third and fourth profiles in front of Brasilien beach. The second profile showed the highest yearly sediment accumulation, while Annex F indicates high sediment drift to West close to the coast of the same profile. The groin falling in the cross-shore profile cause this higher numbers and the peak point on directional sediment drift graph confirms this.

Alternative 1 – surfing reef without arms extensions for the Heidkate beach

Alternative 1 orientated to the coast with 45° from North shows increased accumulated sediment drift in all four profiles (Figure 6.5), if compared with reference conditions, meaning that the high impact on the coastline could be expected and therefore erosion in the lee side of the structure could occur. The highest increase is observed in the third profile, which is equal to approx. 9000 m3 per year. Moreover, the structure induce high sediment transport of nearly 400 m3/yr/m to West in front of the breakwater (Annex F), meaning that the toe protection would be required if such structure would be constructed.

The same alternative, but perpendicularly orientated to the coast, has shown sediment drift reduction in the lee side of the structure (Figure 6.7), as well as in profiles beside the breakwater. Therefore, the salient formation could be expected. Nevertheless, structure induces less than 100 m3/yr/m sediment transport in front of it (Annex F), which is close to the base conditions. Although, it is four times less than 45° orientated structure, toe protection should be considered.

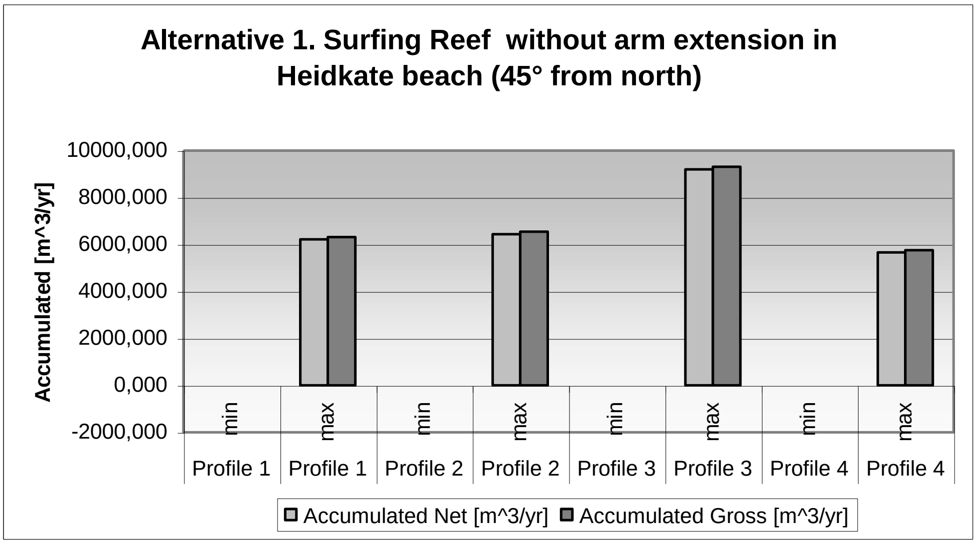


Figure 6.5: Accumulated sediment for Alternative 1 (45° from North).

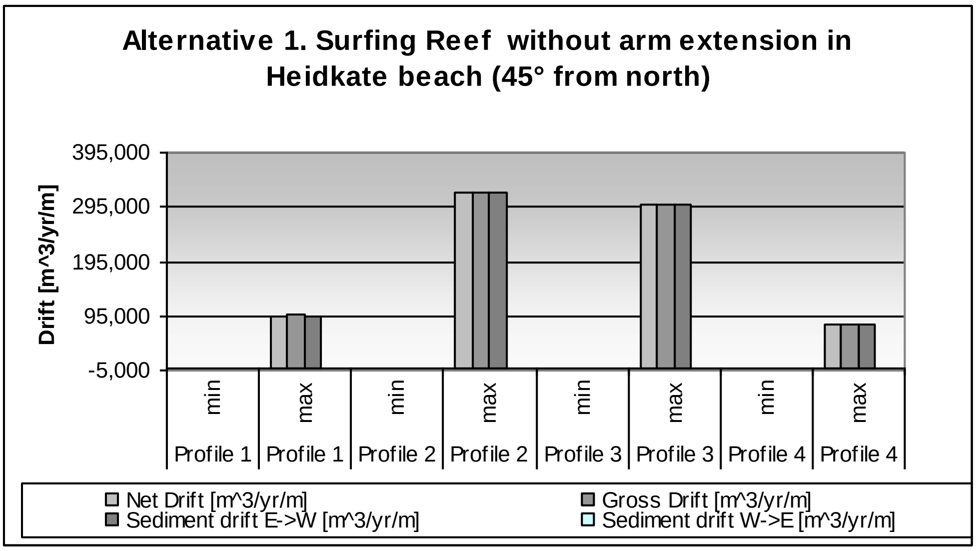


Figure 6.6: Sediment drift for Alternative 1 (45° from North).

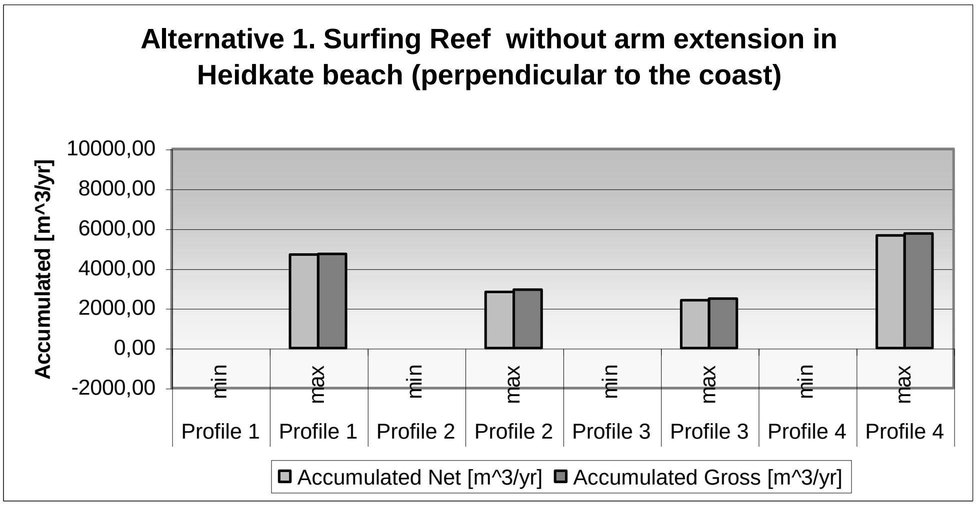


Figure 6.7: Accumulated sediment for Alternative 1 (perpendicular to the coast).

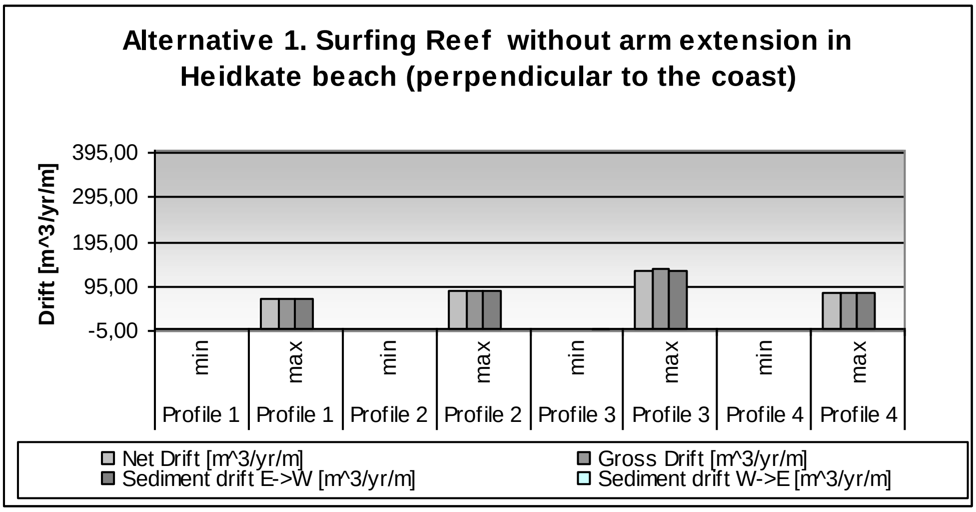


Figure 6.8: Sediment drift for Alternative 1 (perpendicular to the coast).

Alternative 2 – surfing reef with the eastern arm extension for Heidkate beach

When alternative is orientated to the coast with 45° from North, the same sediment transport as in reference conditions is expected in first, second and fourth profiles, while a reduction in the lee side of extended arm of the structure (third profile) is observed in the modelling results (Figure 6.9). Moreover, the structure induce relatively high sediment transport falling in the range between 220 to 370 m3/yr/m in front of the breakwater (Annex F), indicating that high attention to the toe protection should be given.

The same alternative, but perpendicularly orientated to the coast, has shown sediment drift reduction in the lee side of the structure (Figure 6.11) for both second and third profiles, leading to conclusion that salient formation could be expected. Slight reduction of sediment drift is also observed in the first profile, while the rate stays the same for the fourth profile. Nevertheless, structure provokes high sediment transport of approx 380 m3/yr/m in front of the breakwater (Annex F). The toe protection measures should accompany the construction of this alternative.

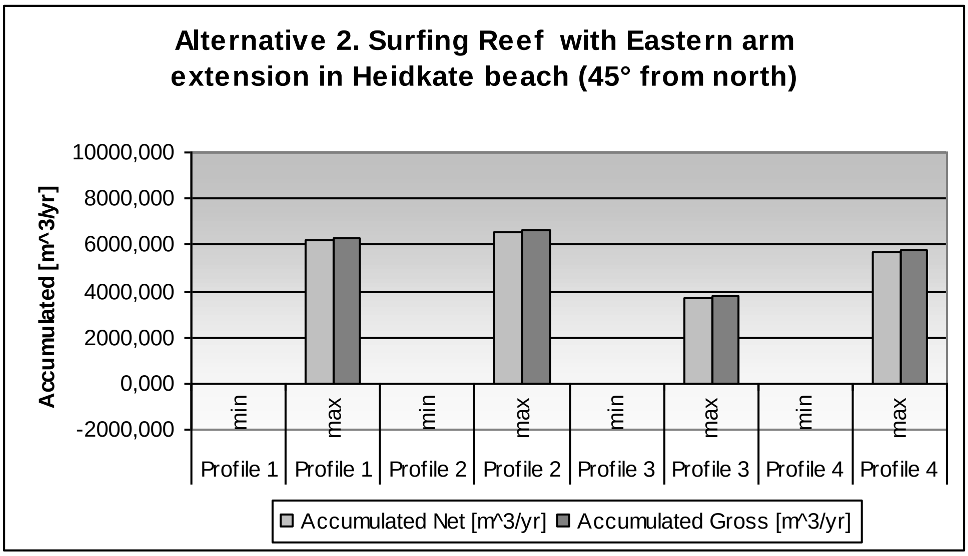


Figure 6.9: Accumulated sediment for Alternative 2 (45° from North).

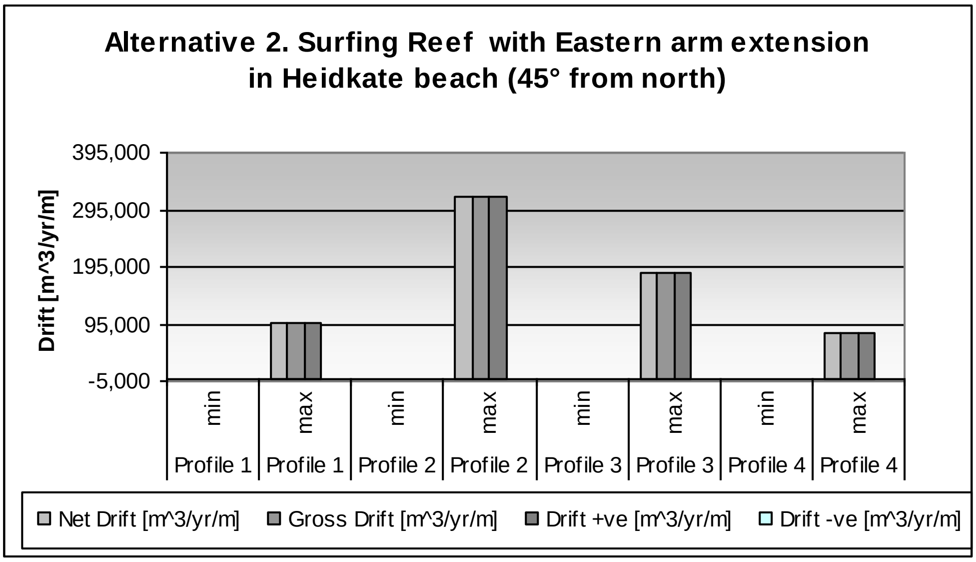


Figure 6.10: Sediment drift for Alternative 2 (45° from North).

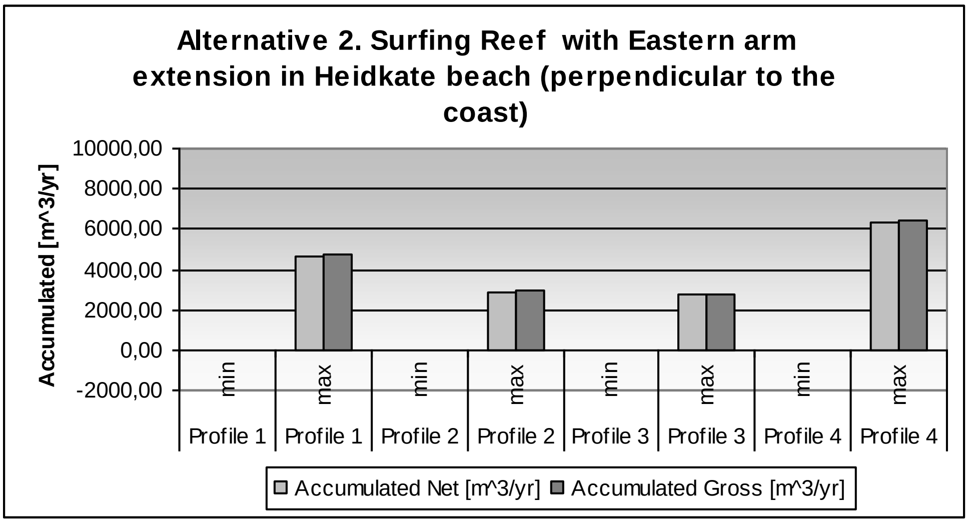


Figure 6.11: Accumulated sediment for Alternative 2 (perpendicular to the coast).

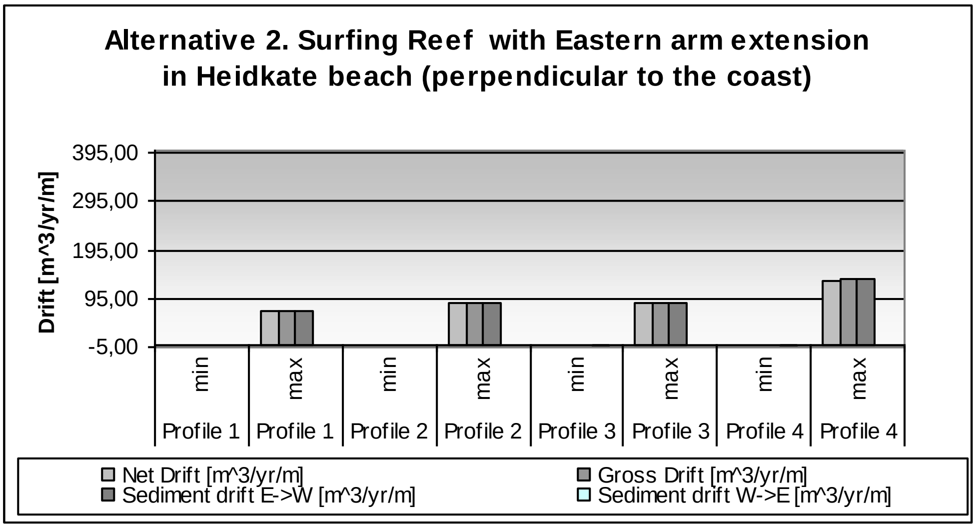


Figure 6.12: Sediment drift for Alternative 2 (perpendicular to the coast).

Alternative 3 – surfing reef with the western arm extension for Heidkate beach

When alternative is orientated to the coast with 45° from North, the same sediment transport as in reference conditions is expected in first, second and fourth profiles, while the increase of drift in the lee side of extended western arm of the structure is observed in modelling results (Figure 6.13). Moreover, the structure induce relatively high sediment transport falling in the range between 300 to 320 m3/yr/m in front of the breakwater (Annex F), indicating that high attention to the toe protection should be given.

The same alternative, but perpendicularly orientated to the coast, has shown sediment drift reduction in the lee side of the structure (Figure 6.15) for both second and third profiles, leading to conclusion that salient formation could be expected. The reduction of sediment drift is also observed in the first profile, while the rate slightly increases for the fourth profile. The structure induces less than 100 m3/yr/m sediment transport in front of it, which is close to the base conditions (Annex F). Although, it is four times less than 45° orientated structure, toe protection should be considered, but positive affect on the coastline could be expected.

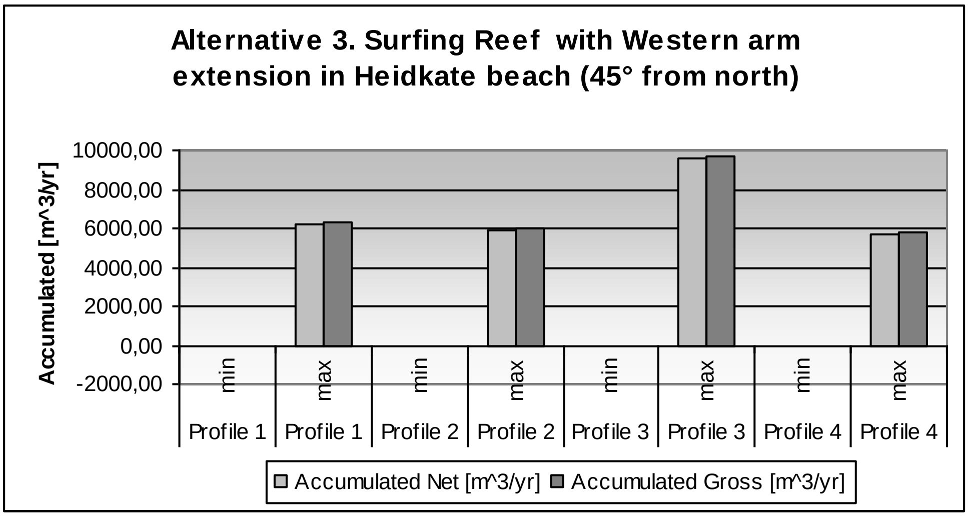


Figure 6.13: Accumulated sediment for Alternative 3 (45° from North).

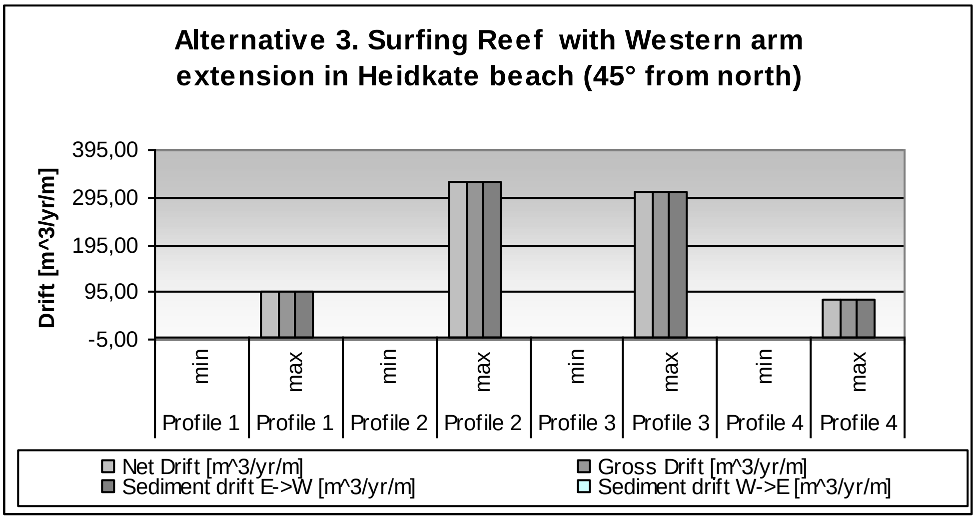


Figure 6.14: Sediment drift for Alternative 3 (45° from North).

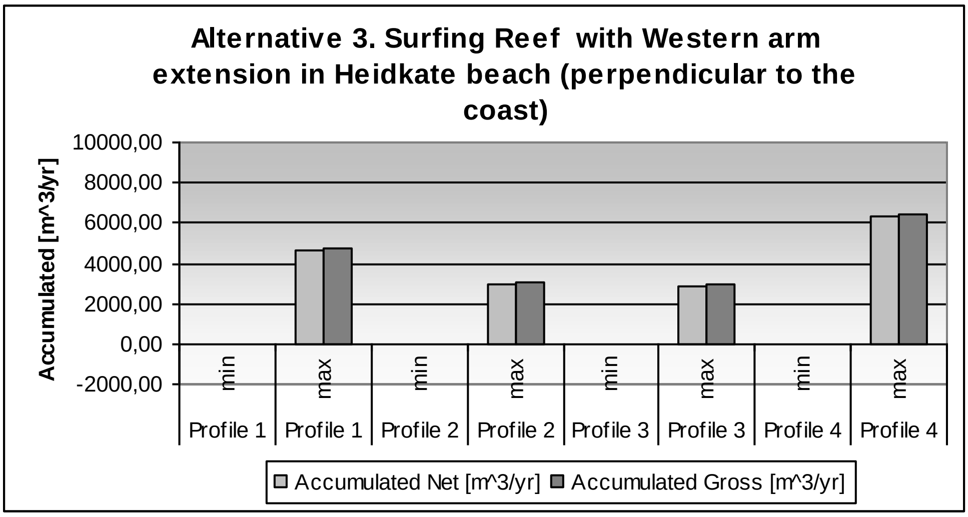


Figure 6.15: Accumulated sediment for Alternative 3 (perpendicular to the coast).

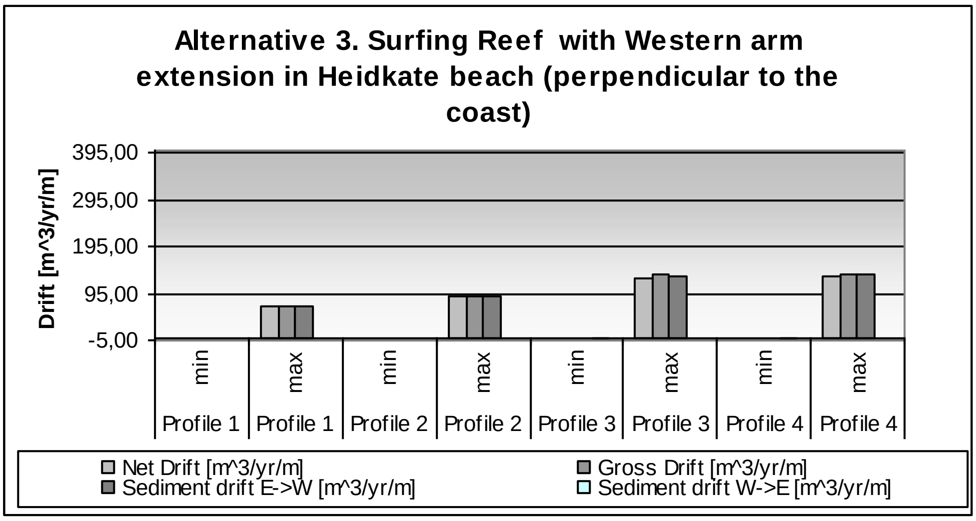


Figure 6.16: Sediment drift for Alternative 3 (perpendicular to the coast).

Alternative 4 – Surfing reef without arms extensions for Brasilien beach

A high reduction of sediment transport is observed through the second and third profiles, when structure is orientated 45° from North. The first and the fourth profiles indicate nearly the same sediment transport as in reference conditions (Figure 6.17). Moreover, the structure doesn't induce high sediment transport in front of the breakwater (Annex F) and reducing peak point of longshore sediment drift in the lee side of the structure.

The same alternative, but perpendicularly orientated to the coast, has shown sediment drift reduction in the lee side of the structure (Figure 6.19) for both second and third profiles. Slight reduction of the sediment drift is observed in the first profile, and stays the same for the fourth profile. There is almost non directional sediment transport in front of the breakwater. The drift is also diminished in the landward side (Annex F) meaning that positive effect on the coastline can be expected.

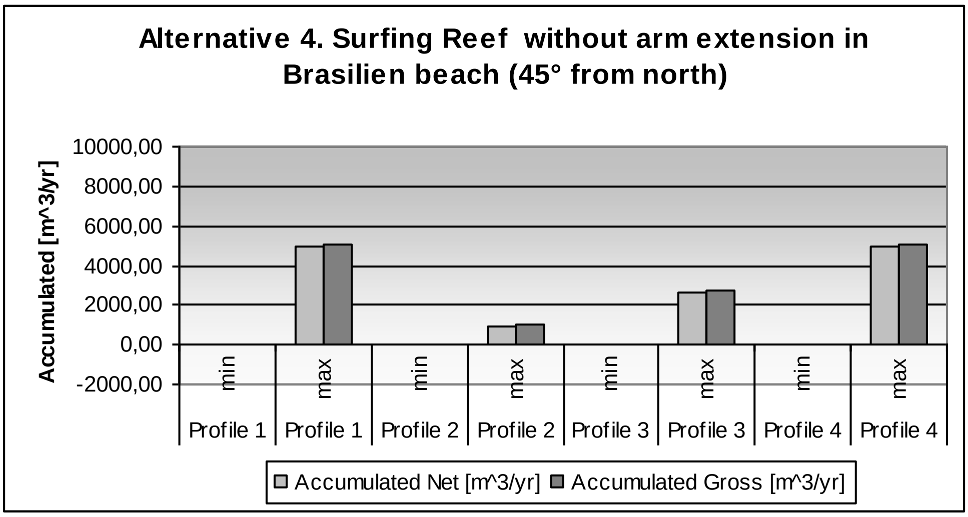


Figure 6.17: Accumulated sediment for Alternative 4 (45° from North).

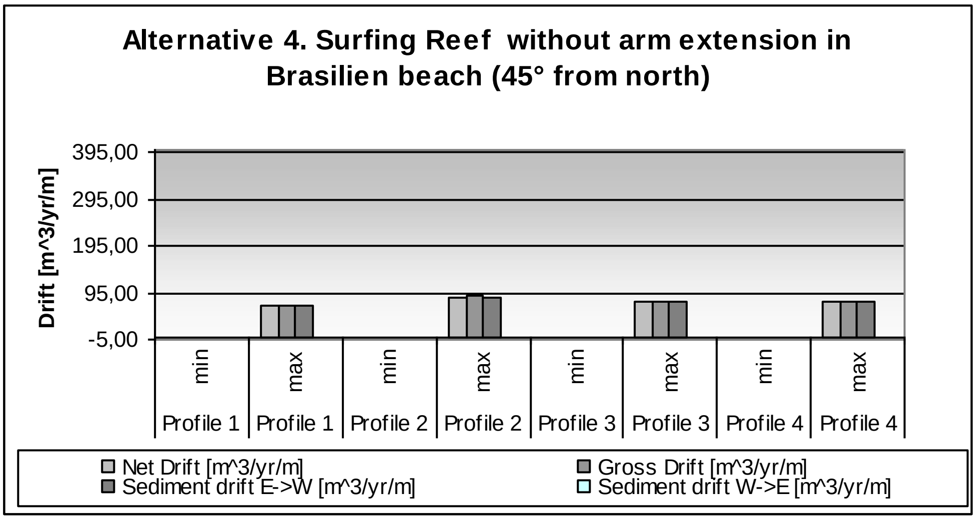


Figure 6.18: Sediment drift for Alternative 4 (45° from North).

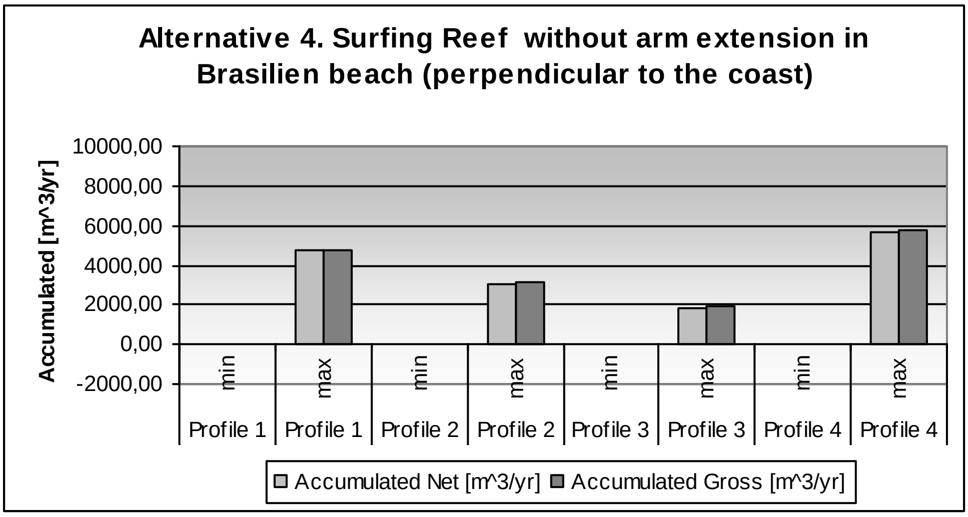


Figure 6.19: Accumulated sediment for Alternative 4 (perpendicular to the coast).

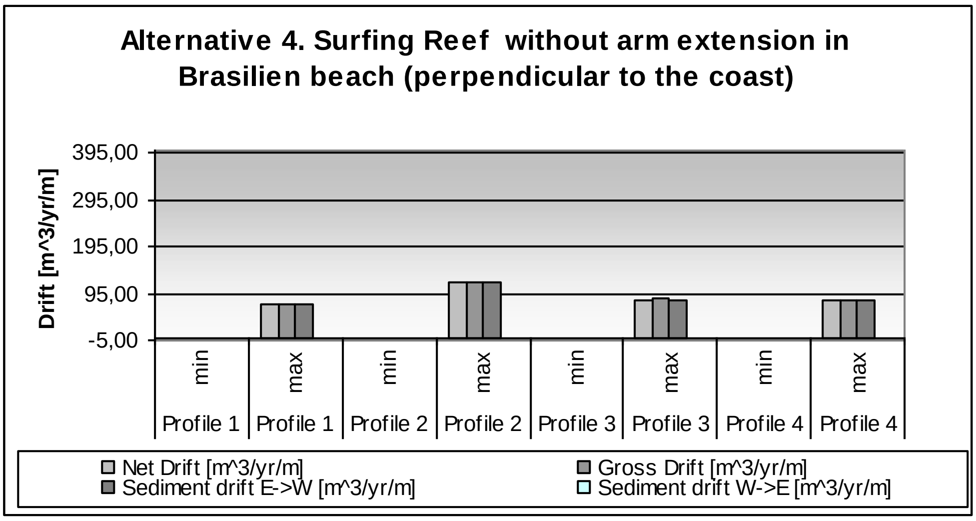


Figure 6.20: Sediment drift for Alternative 4 (perpendicular to the coast).

Alternative 5 – surfing reef with the eastern arm extension for Brasilien beach

A reduction of sediment transport is observed in the second and third profiles, when structure is orientated to the coast of 45° from North. Sediment drift is also reduced for the third profile, while first and fourth profiles beside the structure indicate nearly the same sediment transport as in reference conditions (Figure 6.21). The sediment drift in the vicinity of the breakwater is minimal and nearly not observable (Annex F).

When alternative is orientated perpendicularly to the coast, sediment drift reduction in second and third profile can be expected (Figure 6.23), but it is not that effective as structure with 45° orientation from North. Slight reduction of sediment drift is observed in the first and fourth profiles. There is almost non sediment transport in front or behind the designed breakwater. The drift is also diminished in the landward side of it (Annex F).

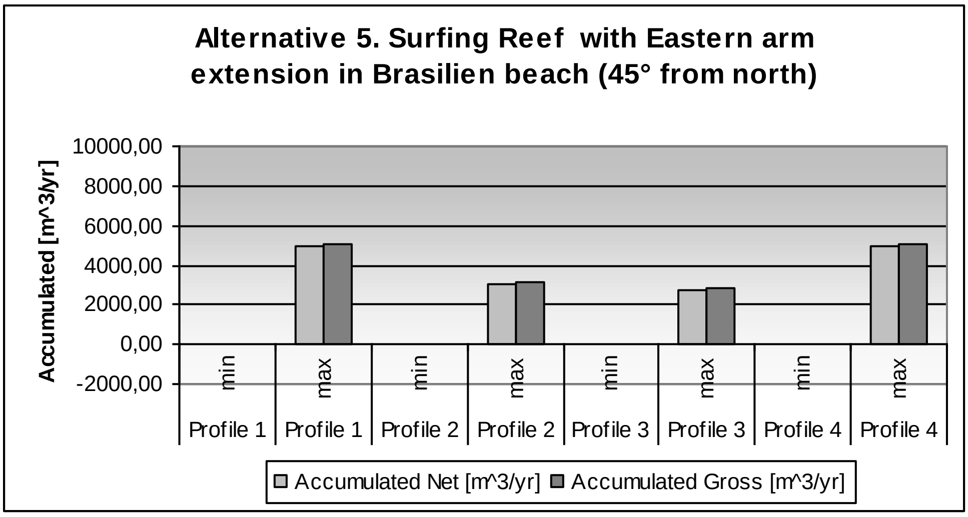


Figure 6.21: Accumulated sediment for Alternative 5 (45° from North).

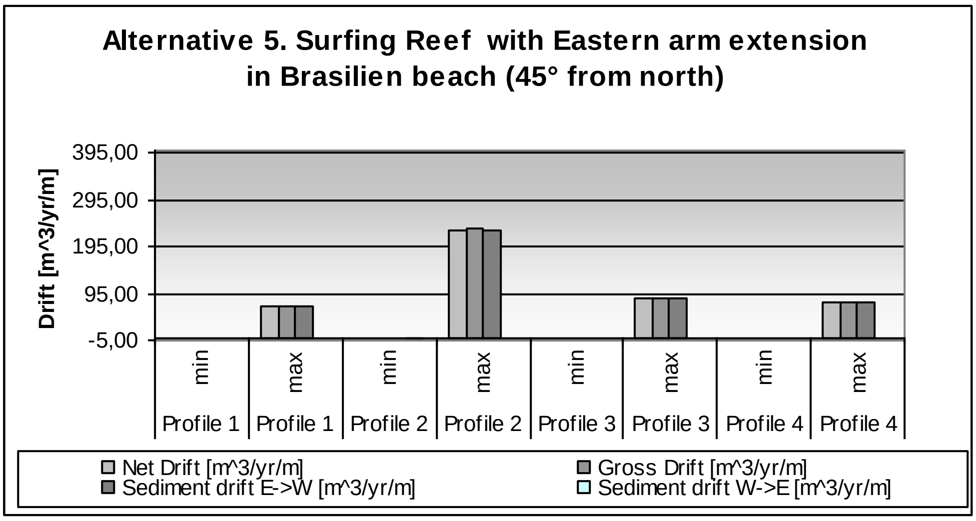


Figure 6.22: Sediment drift for Alternative 5 (45° from North).

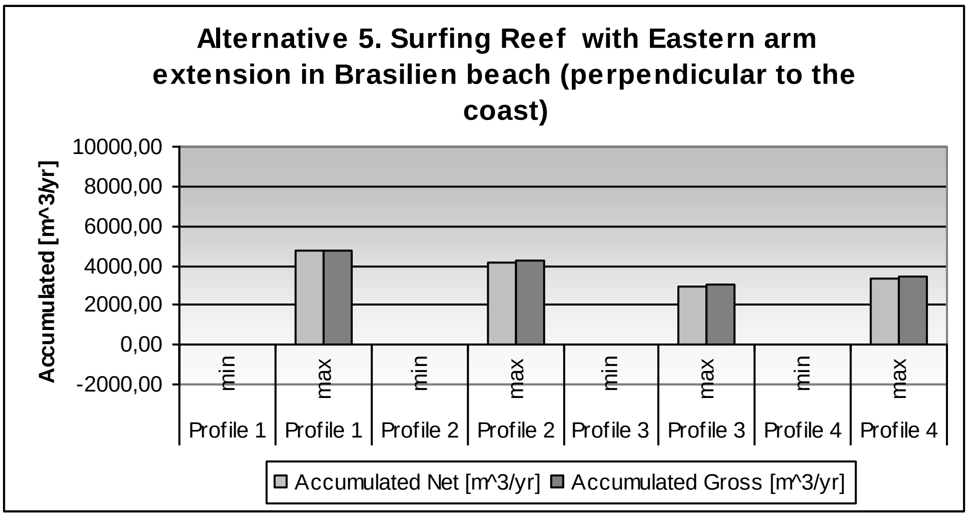


Figure 6.23: Accumulated sediment for Alternative 5 (perpendicular to the coast).

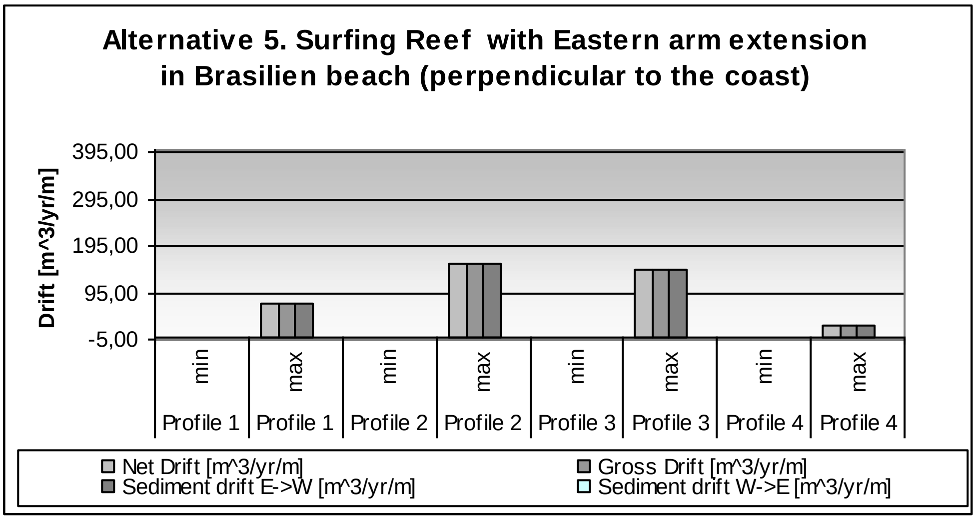


Figure 6.24: Sediment drift for Alternative 5 (perpendicular to the coast).

Alternative 6 – surfing reef with the western arm extension for Brasilien beach

A high reduction of sediment transport is observed through the second and third profiles, when structure is orientated the 45° from North. Sediment drift stays the same through the third and fourth profiles compared with the reference conditions (Figure 6.25). The structure doesn't induce high sediment transport in the vicinity of the breakwater (Annex F) and reduces longshore sediment drift in the lee side of it.

The same alternative, but perpendicularly orientated to the coast, has shown sediment drift reduction in the lee side of the structure (Figure 6.27) for both second and third profiles. The same as in reference conditions sediment drift is observed in the first profile, while the transport rate decreases through the fourth profile. There is almost non sediment transport in front of the breakwater. Only third profile indicates little longshore drift in the landward side of the structure (Annex F), but induced sediment transport is insignificant and doesn't require toe protection.

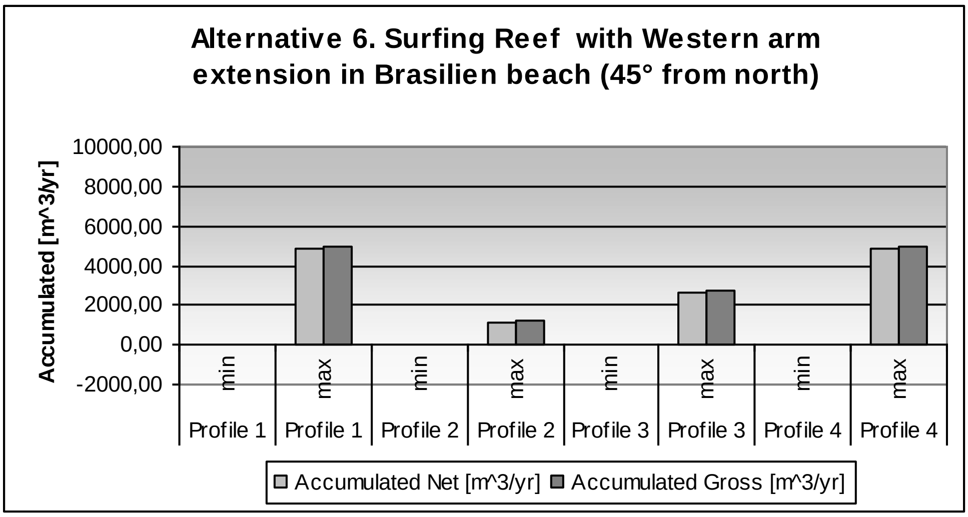


Figure 6.25: Accumulated sediment for Alternative 6 (45° from North).

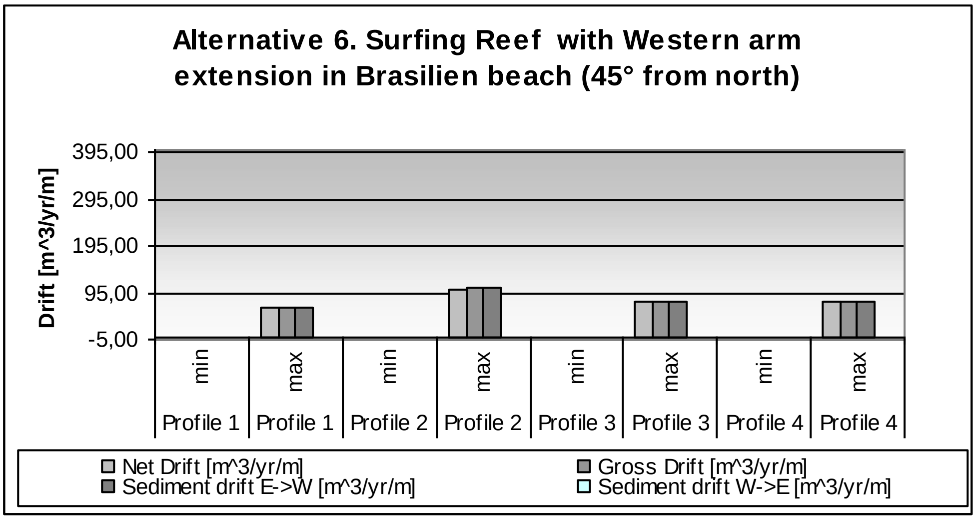


Figure 6.26: Sediment drift for Alternative 6 (45° from North).

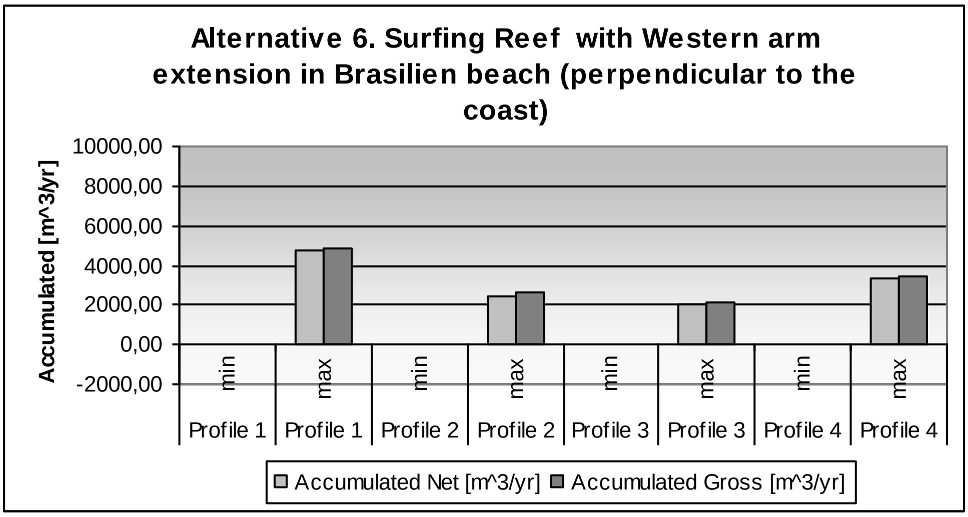


Figure 6.27: Accumulated sediment for Alternative 6 (perpendicular to the coast).

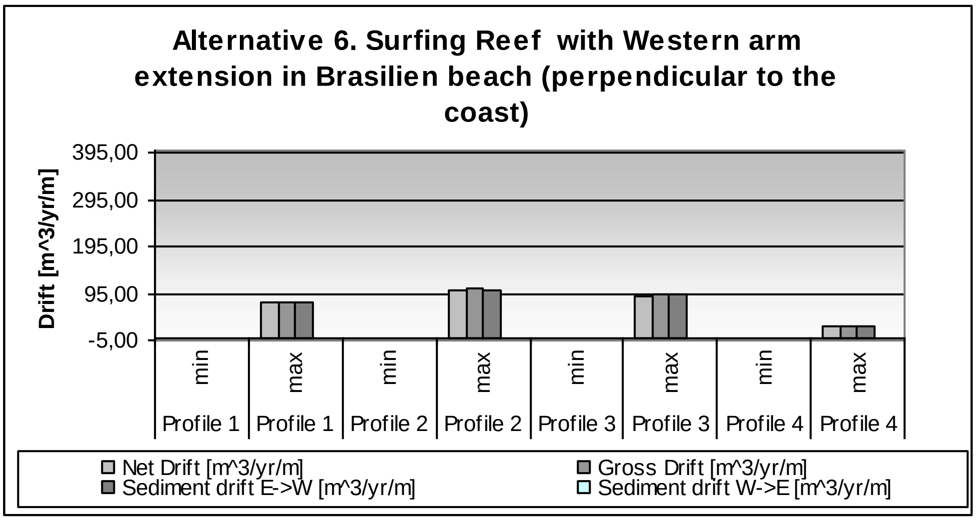


Figure 6.28: Sediment drift for Alternative 6 (perpendicular to the coast).

Alternative 7 – shore-parallel submerged breakwater from geotextile for the Brasilien beach

Numerical LITDRIFT modelling results for coast-parallel breakwater in Brasilien beach suggest that increase in sediment accumulation beside the structure can be expected, while rate of sediment transport in the lee side (profile 2) stays the same when compared with results of reference location (Figure 3.29). Moreover, sediment drift of approx 90 m3/yr/m to West is observed in both front and hinter side of the structure and shows no influence on the sediment transport in the lee side (Annex F) keeping the rates of drift in the same numbers as in a base conditions. Concluding it can be said, that structure induces sediment drift in the vicinity of the breakwater, which was not present in at the same distance from shore before the introduction of the construction.

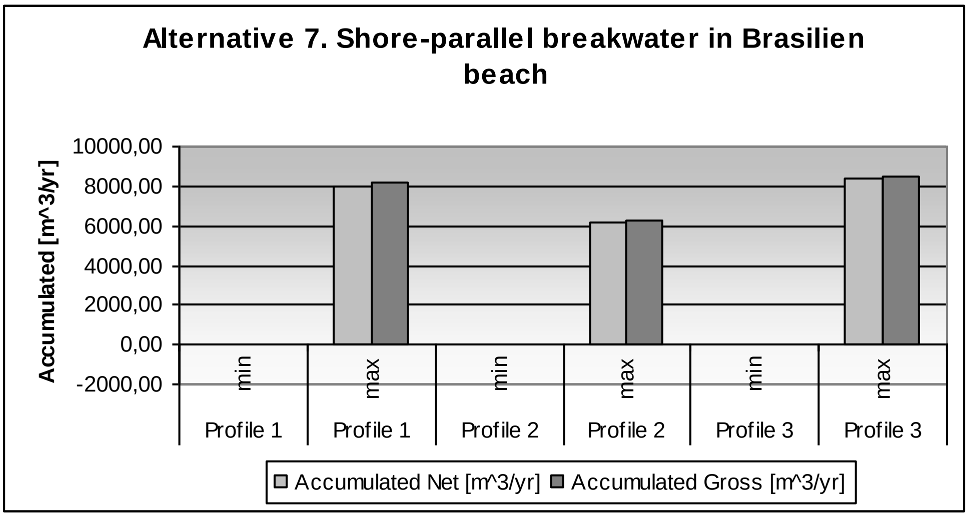


Figure 6.29: Accumulated sediment for Alternative 7.

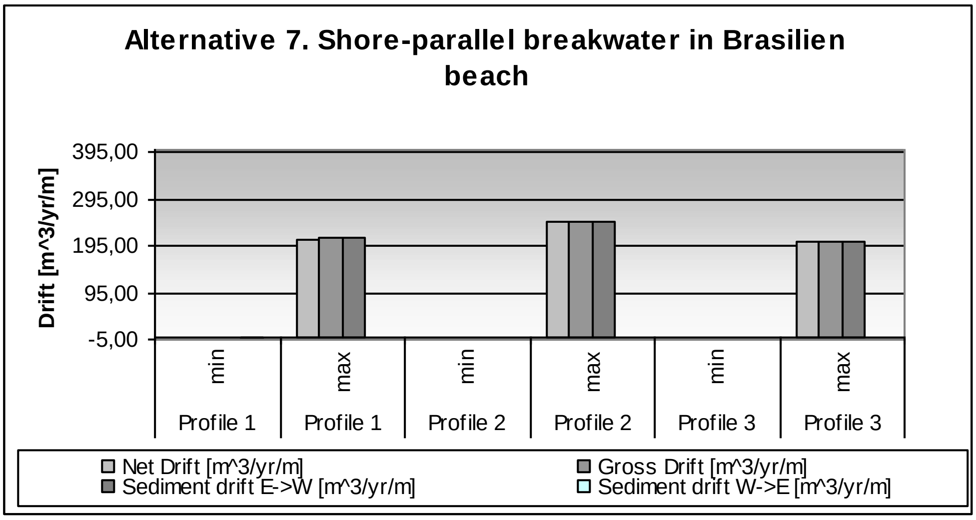


Figure 6.30: Sediment drift for Alternative 7.

Alternative 8 – Reef Balls submerged breakwater (coastal protection and habitat enhancement) for Heidkate beach

This alternative was designed for coastal protection and habitat enhancement and numerical modelling results indicate higher sediment transport rates in all 5 profiles (Figure 6.31) compared to reference conditions.

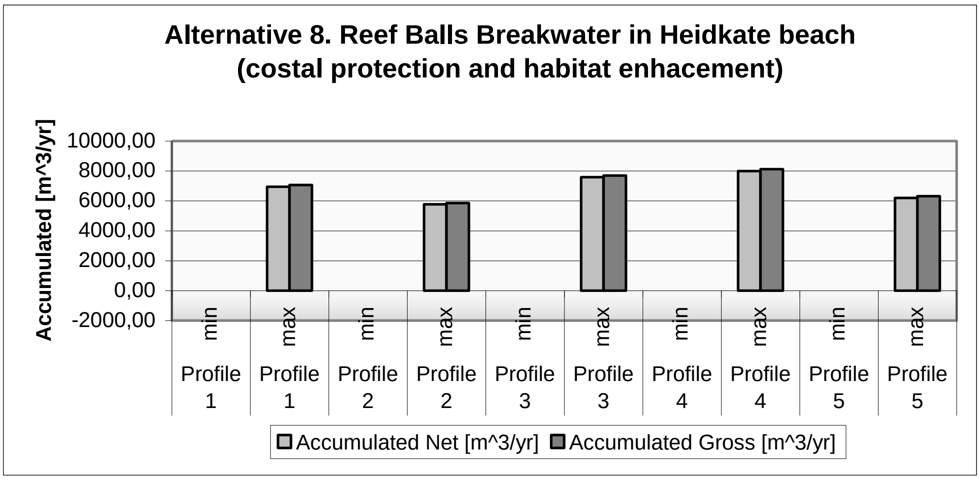


Figure 6.31: Accumulated sediment for Alternative 8.

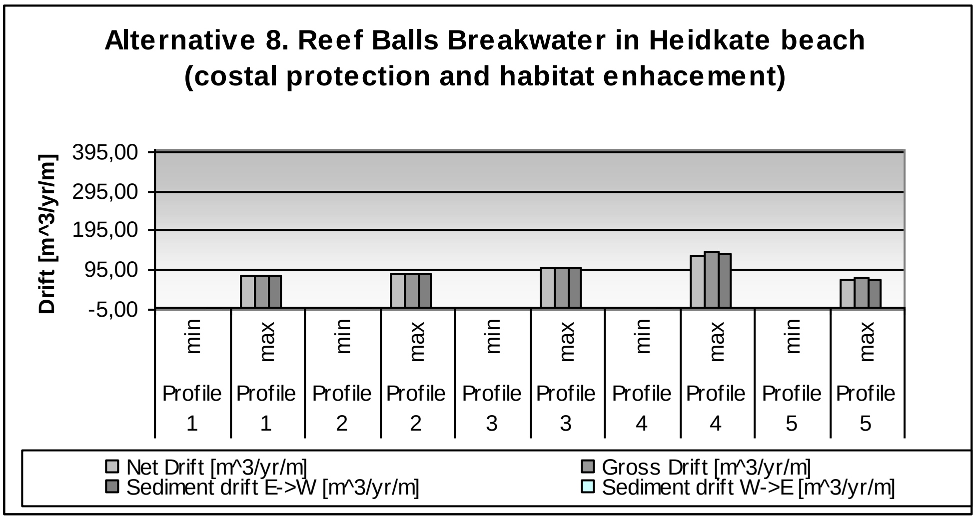


Figure 6.32: Sediment drift for Alternative 8.

Alternative 9 – Reef Balls submerged breakwater (habitat enhancement) for Heidkate beach

The reduction of sediment accumulation was observed in the second and fourth profiles crossing the breakwater (Figure 33), but in the same time, the profiles aside the structure showed higher sediment transport rates than in reference conditions. The third profile goes through the gap between the doubled structures, and modelling results indicates high sediment transport rates.

The sediment drift of approx 90 m3/yr/m is observed in front side of the structure and shows reduction on the sediment transport in the lee side (Annex F), especially over the present sand bars. The highest reduction of sediment transport is observed in fourth profile. The structure induces sediment drift in the vicinity of the breakwater, which was not present in at the same distance from shore before the introduction of the construction. Although transport rate there isn't very high, toe protection should be considered.

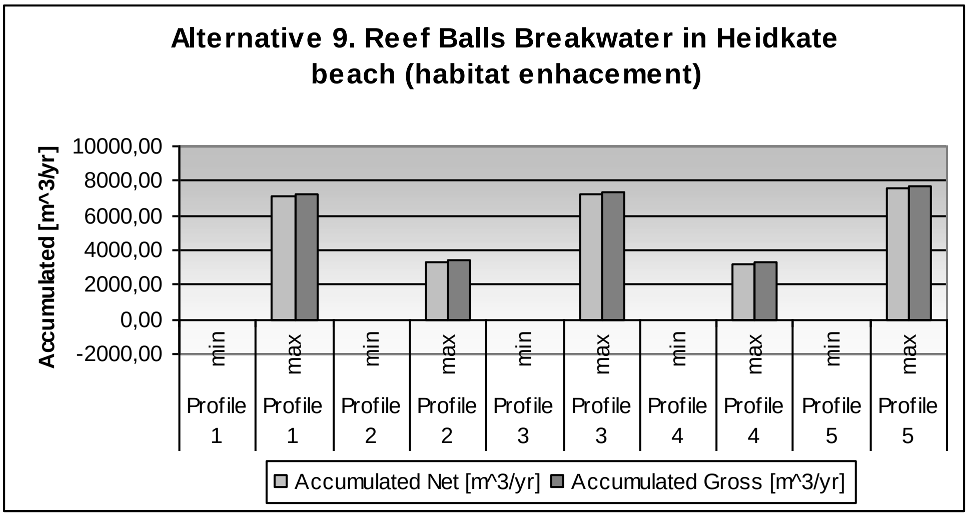


Figure 6.33: Accumulated sediment for Alternative 9.

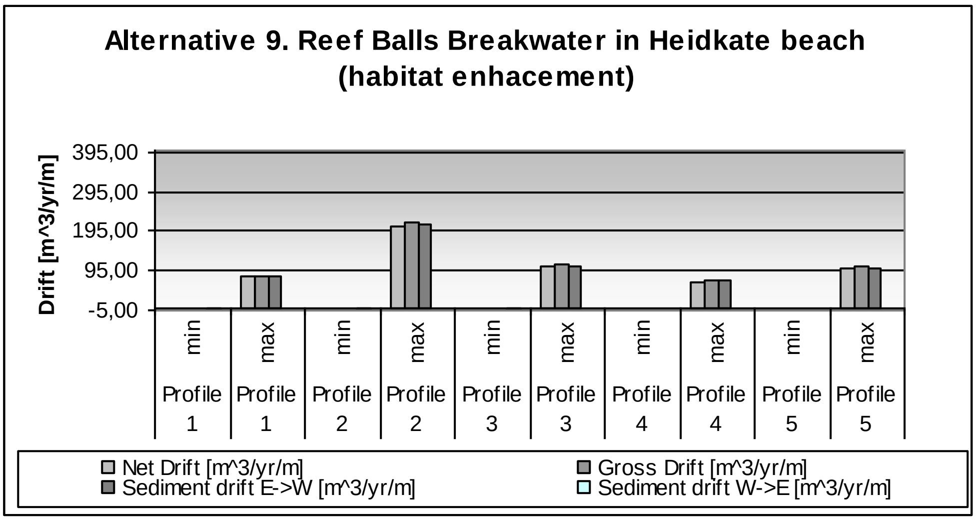


Figure 6.34: Sediment drift for Alternative 9.

Alternative 10 – Reef Balls submerged breakwater (habitat enhancement) for Brasilien beach

The first and the third profiles of the Alternative 10 (Figure 6.35) predict higher sediment transport than in reference conditions, while both second and fifth profiles predict the same rates of sediment transport as in reference conditions. The slight reduction of sediment accumulation was observed only in the fourth profile.

When analyzing results of Annex F, the sediment drift of approx 300 m3/yr/m to West was observed in the gap area of the designed breakwater (third profile). Therefore, toe protection or change in the size of the gap has to be tested and applied.

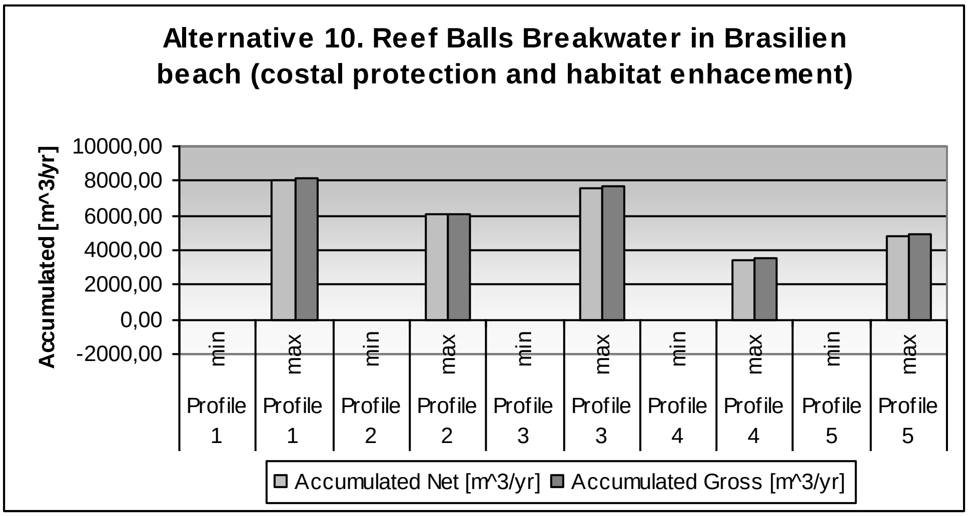


Figure 6.35: Accumulated sediment for Alternative 10.

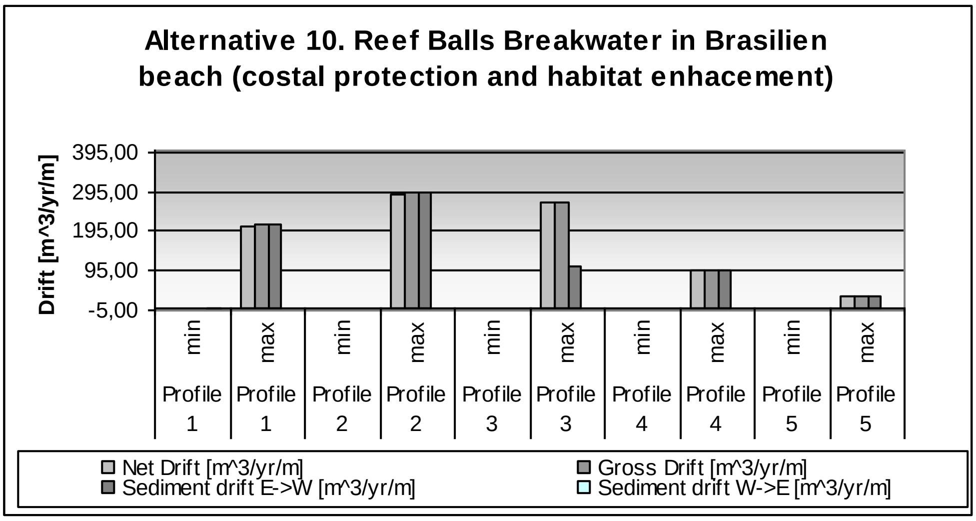


Figure 6.36: Sediment drift for Alternative 10.

7 Conclusion and Recommendations

7.1 Conclusion

The primary objective of this research was to suggest such type of artificial reef-type breakwater, that it would be the most suitable one to research locations of the Heidkate and Brasilien beaches. In additional, the answer had to be based on how the structure would meet requirements such as:

- No destruction of the aesthetical view of beach
- Sediment deposition in the lee side of the reef
- Performance as storm wave dissipater
- Habitat provider for marine flora and fauna
- Support of tourism amenity.

Ten different alternatives, including surfing reefs (Alternative 1 - 6), shore-parallel breakwater (Alternative 7) and Reef Balls breakwaters (Alternative 8, 9 and 10), were proposed for this case study. The integrated design of submerged artificial reef-type breakwaters, together with selection of reef placement locations, was based on multidisciplinary literature research and above mentioned requirements was integrated in the process of design. It is important to mention, although some level of physical and numerical modelling, surveys were carried out for constructed reef projects worldwide, there are no or very limited published records of the design evolution or performance of reefs available. The design of the submerged artificial multi-functional reef-type breakwater for this research paper was achieved by submerging analyzed information from available topic-related scientific literature. The final conclusion about potentials of different breakwaters to meet coastal protection objectives is made referring to numerical modelling results, obtained with DHI's MIKE 21 and LITPACK models.

As Pilarczyk's (2003) conclusion in one of his papers stated that the efficiency of submerged structures and the shoreline response mainly depends on transmission characteristics, the layout and orientation of the structure to the coast. The layout and orientation of the structure was covered in pre-modelling phase, while transmission characteristics were analyzed from results of numerical modelling, done with DHI's MIKE 21 Boussinesq Wave Module, while results to evaluate morphodynamical processes, obtained with LITDRIFT Module (DHI Water and Environment), were sifted. It is important to keep in mind that calculated transmission coefficients give only general overview about efficiency of structures, because the applied formula doesn't include structure parameters or sea-bottom characteristics. Beside this, only North-East wave direction was modeled for this Master Thesis, so judgments about transmission coefficients of structures should be treated reservedly.

Results revealed that Alternatives 1, 2 and 3 (surfing reefs) designed for Heidkate beach for both coast perpendicular and rotated of 45° degree from North should work well as wave dissipaters. After analysis of bathymetry profiles of the Heidkate beach (Annex F), the conclusion of the influence of the bathymetry gradient change to the transmission coefficient is wooing. Wave physics tells that waves start breaking, when depth of the bathymetry in the coastal area decreases. It allows assuming that the change in the bottom elevation as the surfing reef alternatives are placed on the edge of the bathymetry bottom elevation change would have influence of the modelling results, meaning that lower waves in the landward side of the breakwater could be due to both, the presence of the structure and shallower seabottom. Sediment modelling confirmed conclusions done after analysis of transmission coefficients of first three alternatives for Heidkate beach. Longshore sediment transport is observed in the lee side of Alternative 1, 2 and 3, when structures are rotated 45° to the coast from North, but only Alternative 2 induce lower longshore sediment drift in the vicinity of the breakwater. The toe shield or other protection or improvement measures are highly recommended.

Surfing reefs designed for Brasilien beach, referring to Alternatives 4, 5 and 6, showed higher transmission coefficients than observed for alternatives for the Heidkate beach. The least effective from latter mentioned alternatives is Alternative 5 – surfing reef with eastern arm extension, when orientated perpendicular to the coast. Its transmission coefficient is higher (low wave dissipation) through arm without extension (western part of the breakwater). The lowest transmission coefficients are observed for Alternative 6, especially when it is orientated 45° from the North and could be called as the most effective surfing reef solution of three designed to this location from the perspective of transmission coefficient. Numerical modelling of sediment transport revealed that all three alternatives with both orientations to the coast should diminish longshore sediment transport in the lee side of the structure. Anyhow, structures with 45° orientation from North showed the highest sediment reduction compared with base conditions. Alternative 4 and 6, both placed 45° from North, could be called as the most effective surfing reef structures from designed ones for Brasilien beach. Moreover, these structures don't induce high sediment transport in the vicinity of the breakwater (Annex F).

The last four alternatives (Alternatives 7, 8, 9 and 10), two Reef Ball breakwaters for Heidkate beach and one Reef Ball and one shore-parallel breakwater from geotextile for Brasilien beach, showed similar results between each other. Nevertheless, Alternatives 9 and 10 constructed from Reef Balls, showed the best results, while Alternative 7 is following them. Alternative 8 are the least effective for wave dissipation from these four alternatives. Western part of doubled structure performs better than an eastern part for wave dissipation. It's interesting to mention, that the main design purpose of Alternative 9 for Heidkate beach was to improve the habitat, but results allow to state that this structure should have positive affects on coast and would work as coastal protection tool too. Morphological modelling indicates the best performance of Alternative 9 for the Heidkate beach and Alternative 10 for the Brasilien beach, confirming conclusions of transmission coefficients analysis. Another two alternatives cause higher sediment transport in the vicinity of the breakwater or in the gap between doubled structures, which was not present at the same distance from the shore before the introduction of the construction. Nevertheless, Alternative 9 also causes little drift in the front side of the structure. Although transport rate there isn't very high, the toe protection should be considered. The toe shield, as well different size of the gap between the structure have to be highly considered for Alternative 10 as structure induce high rates of longshore drift in the gap area. Modelling results for latter four breakwaters confirmed the statement, that when submergence level is pretty high (equal or more than 2,0 m), the width of the structure should be increased in order to fulfill coastal protection function and do not induce sediment transport in places such as in a front part of the planned structure, where it is undesirable.

Described outcomes of the numerical modelling helped to answer main question of this Master Thesis. Nevertheless, it has to be kept in mind, that alternatives were analyzed only for specific and relatively short-term conditions, so additional research, described in the following chapter of this paper, should be carried out, before the last and the final word could be said about designed breakwaters and their impact on the shoreline.

Two alternatives could be suggested for the Heidkate beach, such as: (1) the surfing reef with eastern arm extension and orientated 45° from North, marked as Alternative 2 in this case study or (2) submerged breakwater from Reef Balls, marked as Alternative 9. The latter structure was planned only as a habitat provider, but numerical modelling revealed its positive effects on coastline. The toe shield or other protection or improvement measures in front of the structure are highly recommended for both breakwaters.

Alternatives 4 and 6, both placed 45° from North, are the most effective reef-type structures from designed ones for the Brasilien beach. Moreover, these structures don't induce high sediment transport in the vicinity of the breakwater. Alternative 4 is a surfing reef breakwater without extensions of arms, while Alternative 6 is with a western arm extension. Alternative 10, breakwater from Reef Balls, can be also suggested for the Brasilien beach, if the main target would be the improvement or creation of the habitat, but the toe protection and different size of the gap should be considered then.

7.2 Recommendations

Conclusions were lined only referring to the numerical modelling results and literature research. Moreover, only short-term and limited input data, such as wave climate, wind, are available for this Master Thesis; therefore, additional research is necessary and recommended in order to give final answer to the key-question of this research. The main recommendations are:

- In order to achieve positive results, design of breakwater have to be based on existing scientific research outcomes and extensive monitoring programs have to be implemented in the sites of already constructed or planned submerged breakwaters as specific investigation is needed for specific structure in certain location.
- In addition, the design of the reef breakwater should be modified if it is required in order diminish potential threads and to meet safety requirements. Changes should be again tested at least in the same modelling loop, which was applied for this research.
- Designed slopes of the reef structures have to be verified with the numerical and, when possible, with physical simulations for each set of reef geometry and wave conditions, because chosen profile slopes of different reef sections were chosen according ten Voorden at el. (2009) paper but additional or further research is not covered in this paper.
- In order to come up with the most suitable coastal protection solution, other than North-East prevailing wave directions and their interaction with reef-type submerged structures should be modeled and tested (for Boussinesq Wave application). This is not covered in this Master Thesis.
- Hydraulic studies to determine wave actions and effects on reef construction have to be carried out in order to prevent models to be moved from the installation location, destroyed, turned, sliding, scour formation (Düzbastılar at el., 2009).
- Outcome results of numerical modelling of morphological processes are analyzed individually and not associated with external research outcome data. Therefore, physical modelling or field studies should be carried out in order to validate numerical modelling results.
- Numerical modelling should also be performed for the submerged artificial reef-type Breakwaters (Alternatives 1 - 6) rotated with 45° from coastline (reef normal looking to

the North-West, or in other words, with rotation of 45° counterclockwise from North) to test surfing conditions, as well as reef efficiency to cope with waves from Western and North-Western directions.

- Numerical modelling should also be performed for the Reef Balls breakwaters (Alternative 8, 9 and 10) rotated 45° from coastline that Western and North-Western waves would be less disturbed and storm waves from Eastern and North-eastern would be the most effectively captures and wise versa.
- Additional surveys of detailed water depths, offshore distances, jet probes to determine sand cover and bottom type is required. This is a question of especially high importance for submerged artificial reef breakwaters that correct size of units for structure body and foundation would be designed.
- Pre-filling of the beach in the landward side of the constructed submerged reef-type breakwater is highly recommended. The volume of sand should be as predicted to accrete and form the salient where numerical modelling and mathematical tools described in scientific literature can be used to the prediction of the volume.
- In order to assess the effectiveness of the offshore breakwaters periodical monitoring surveys have to be carried on.

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Reef Ball Foundation: http://www.reefball.org/

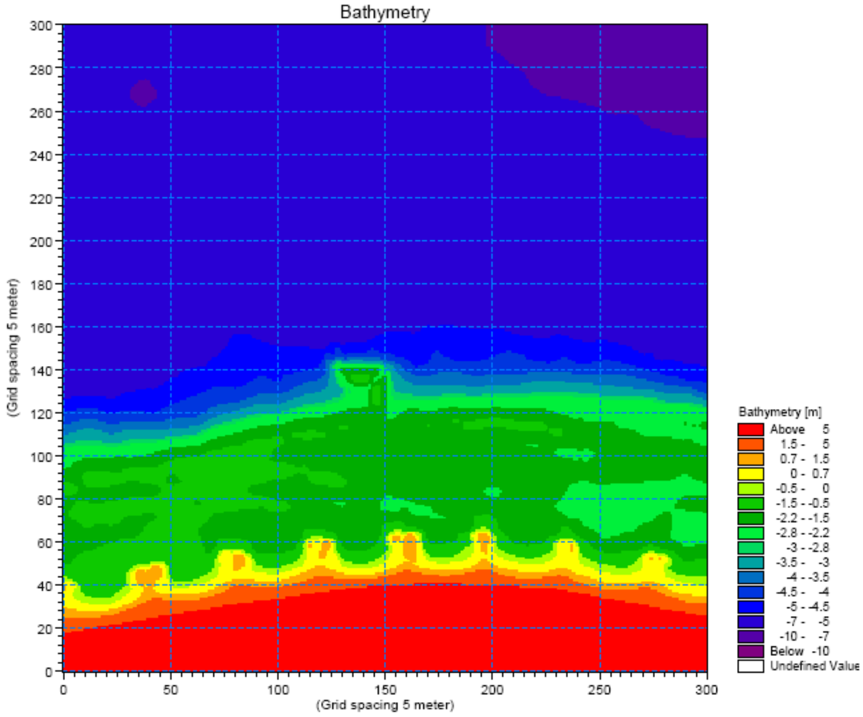
Bundesamt für Seeschifffahrt und Hydrographie (Federal Authority for Maritime and Hydrography): http://www.bsh.de/en/index.jsp

Leibniz Institute of Marine Sciences at the Christian-Albrechts Universität zu Kiel (IFM-GEOMAR): http://www.ifm-geomar.de/index.php?id=home&L=1

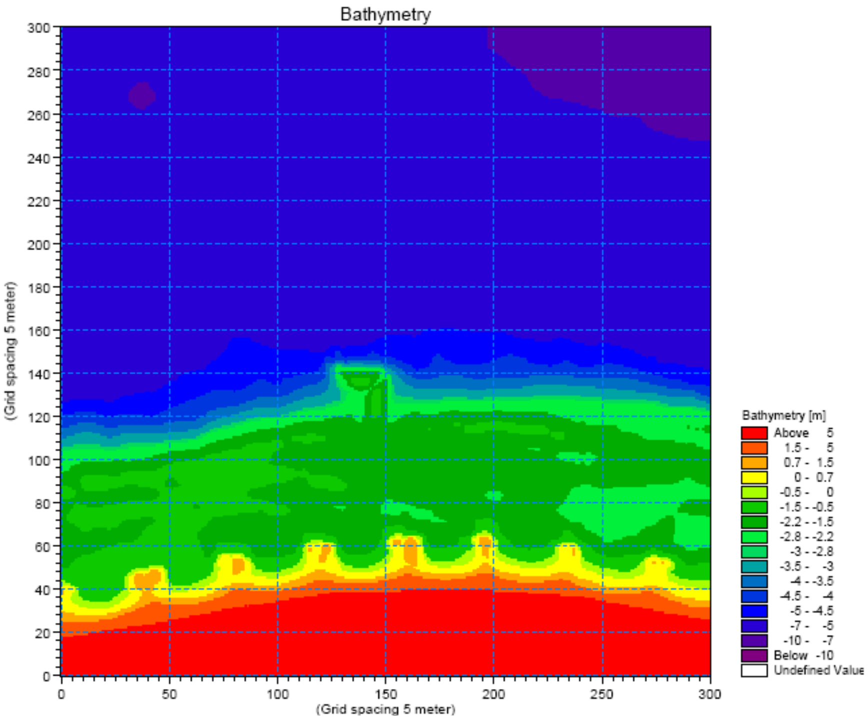
Annex A – Bathymetry views of artificial surfing reef-type breakwaters

Research location in Heidkate

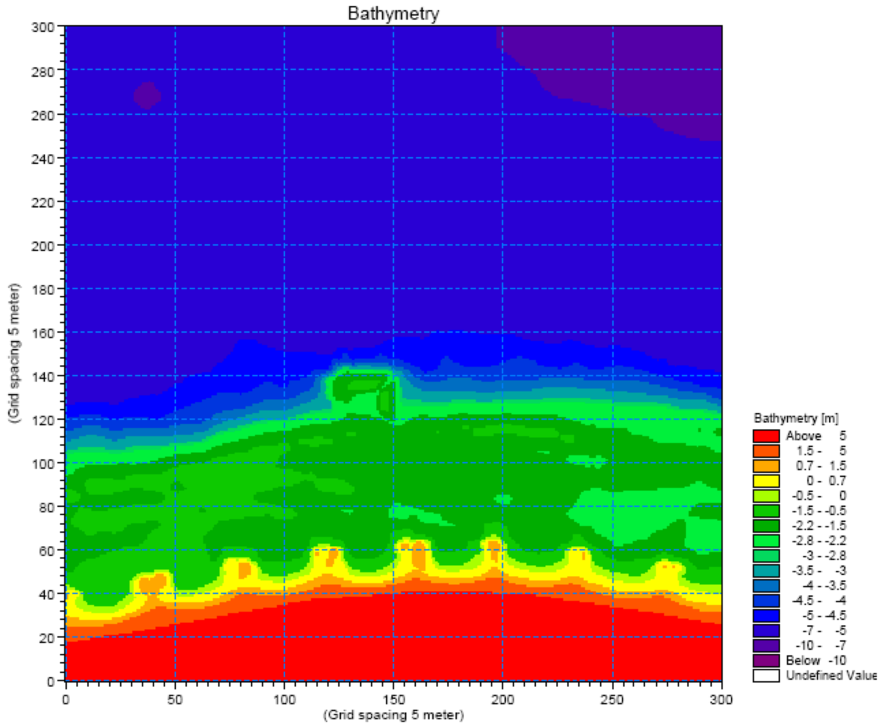
1. Artificial Reef with 45° rotation from North and without Sleeve extension (Alternative 1)



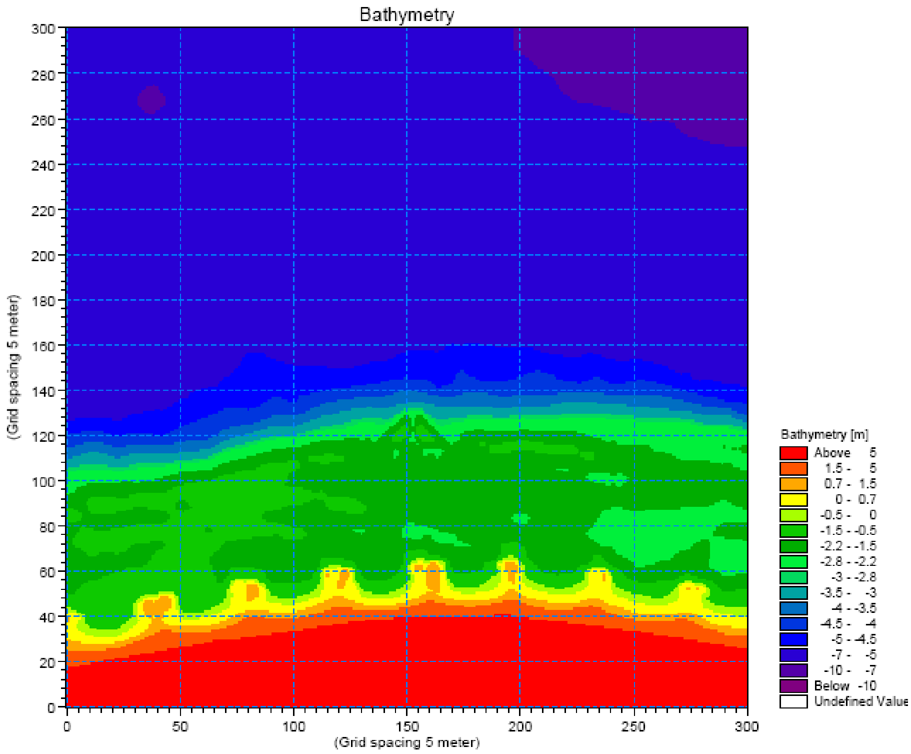
2. Artificial Reef with 45° rotation from North and Eastern Sleeve extension (Alternative 2)



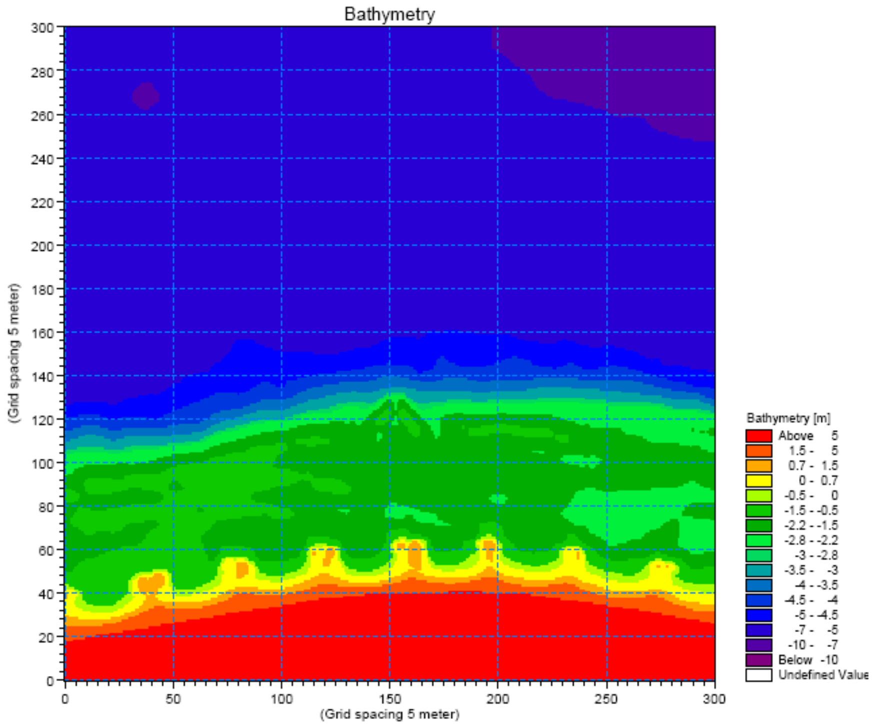
3. Artificial Reef with 45° rotation from North and Western Sleeve extension (Alternative 3)



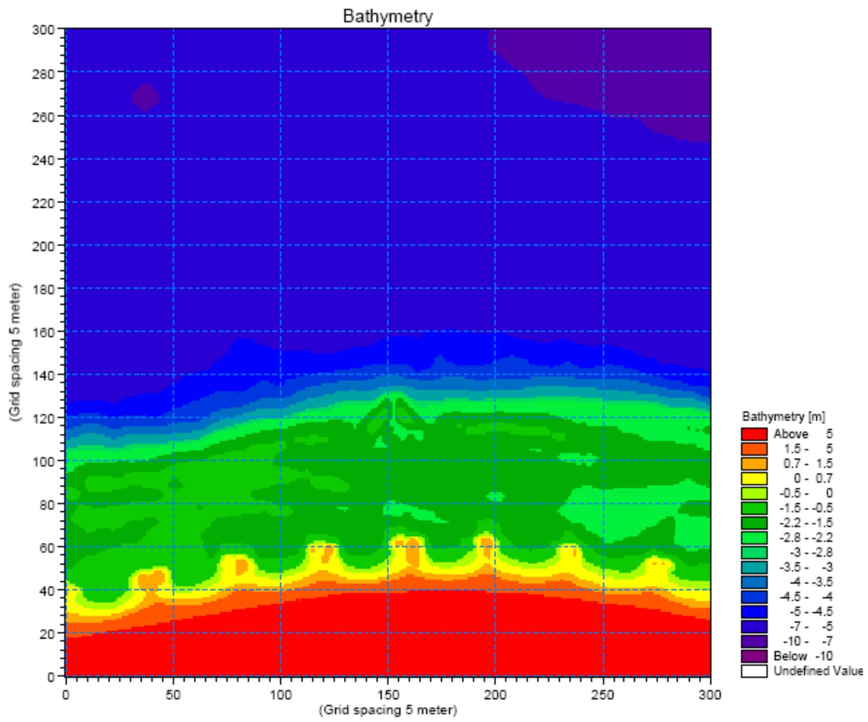
4. Artificial Reef, parallel to North and without Sleeve extension (Alternative 1)



5. Artificial Reef, parallel to North and with Eastern Sleeve extension (Alternative 2)

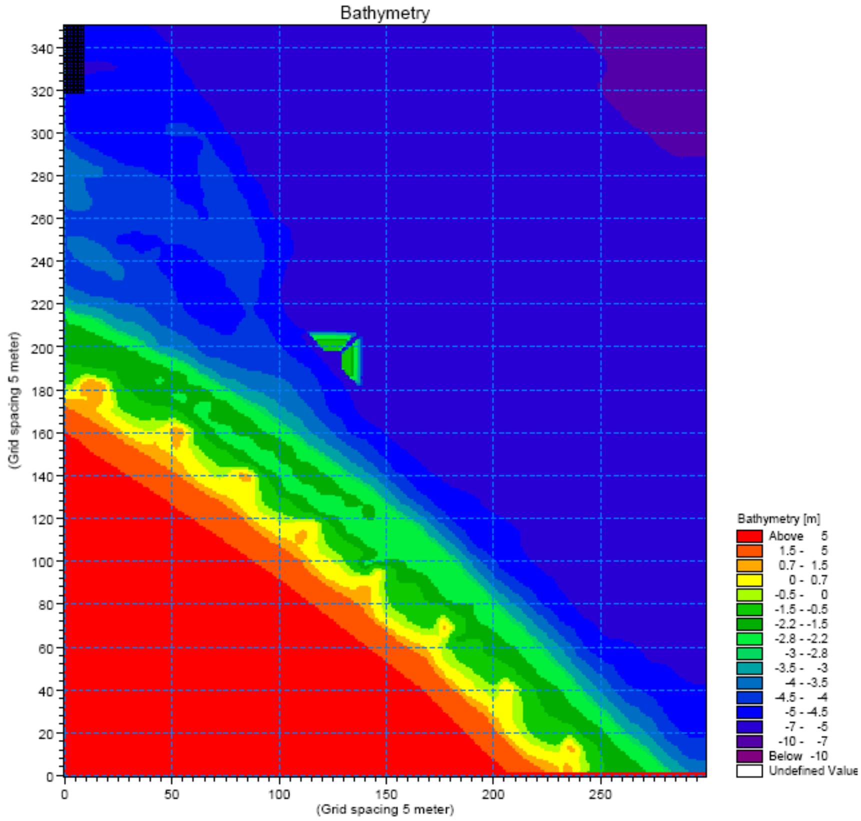


6. Artificial Reef, parallel to North and with Western Sleeve extension (Alternative 3)

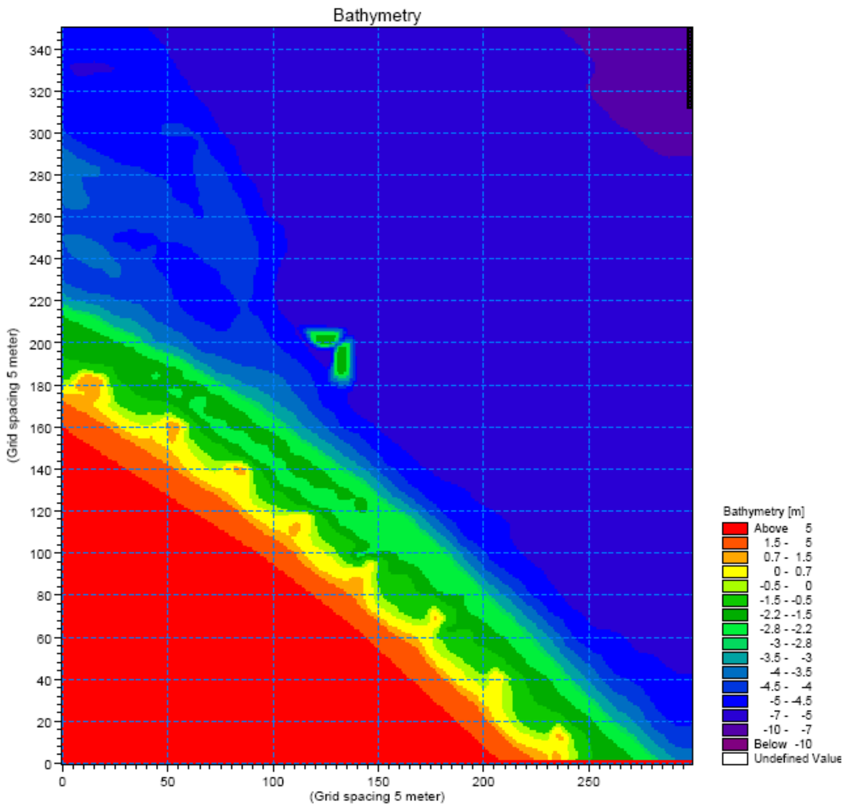


Research Location in Kalifornien and Brasilien beaches

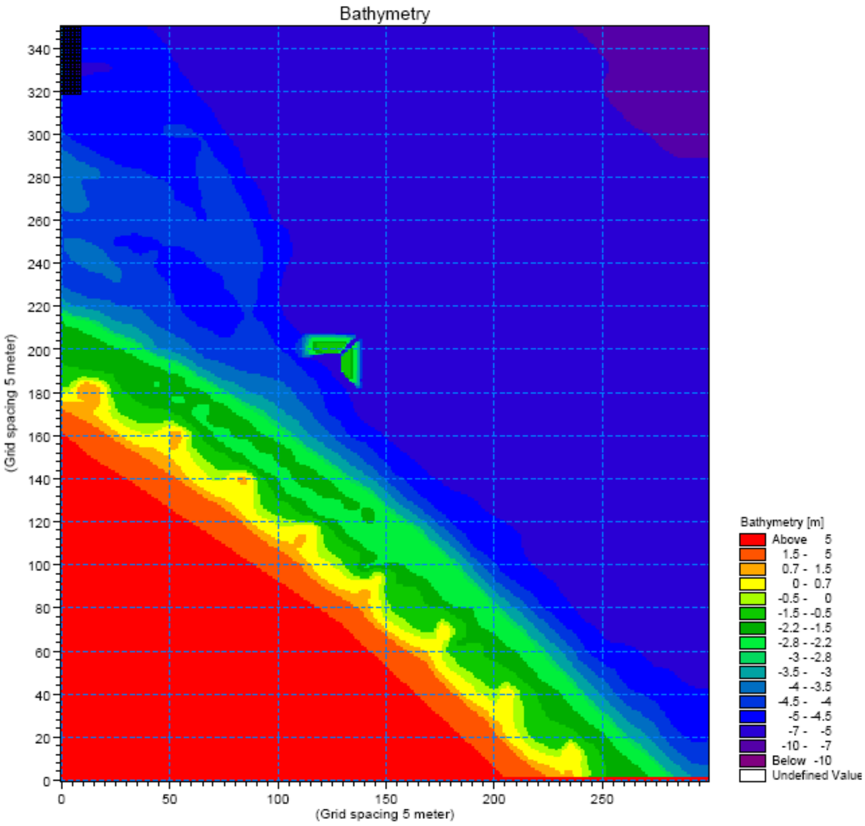
7. Artificial Reef with 45° rotation from North without Sleeve extension (Alternative 4)



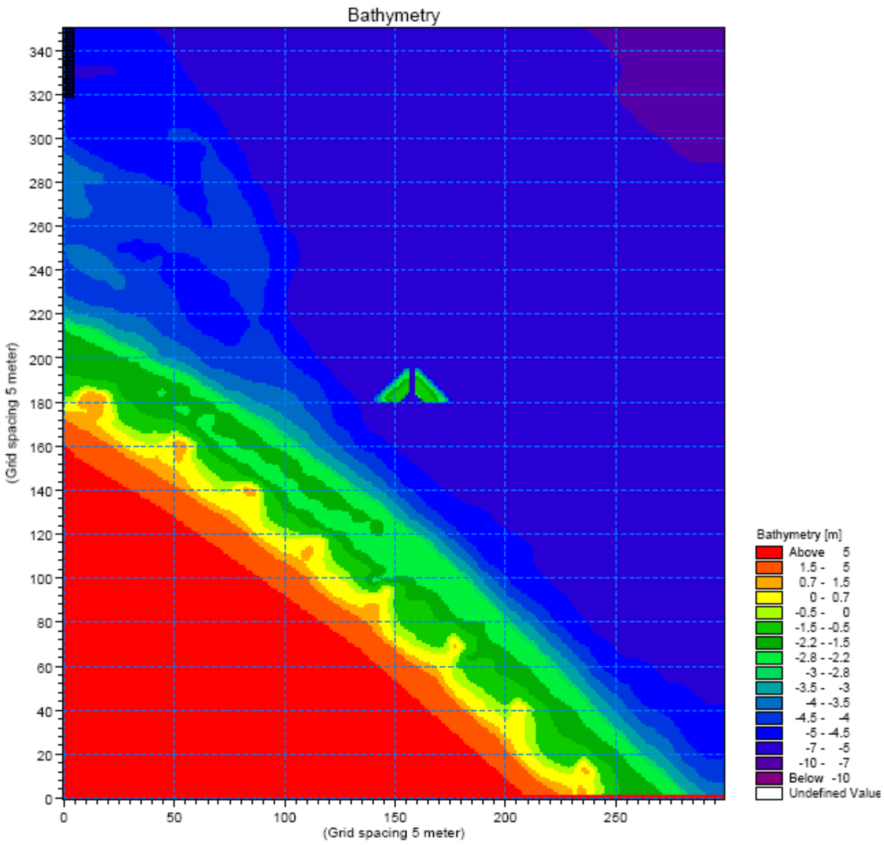
8. Artificial Reef with 45° rotation from North and Eastern Sleeve extension (Alternative 5)



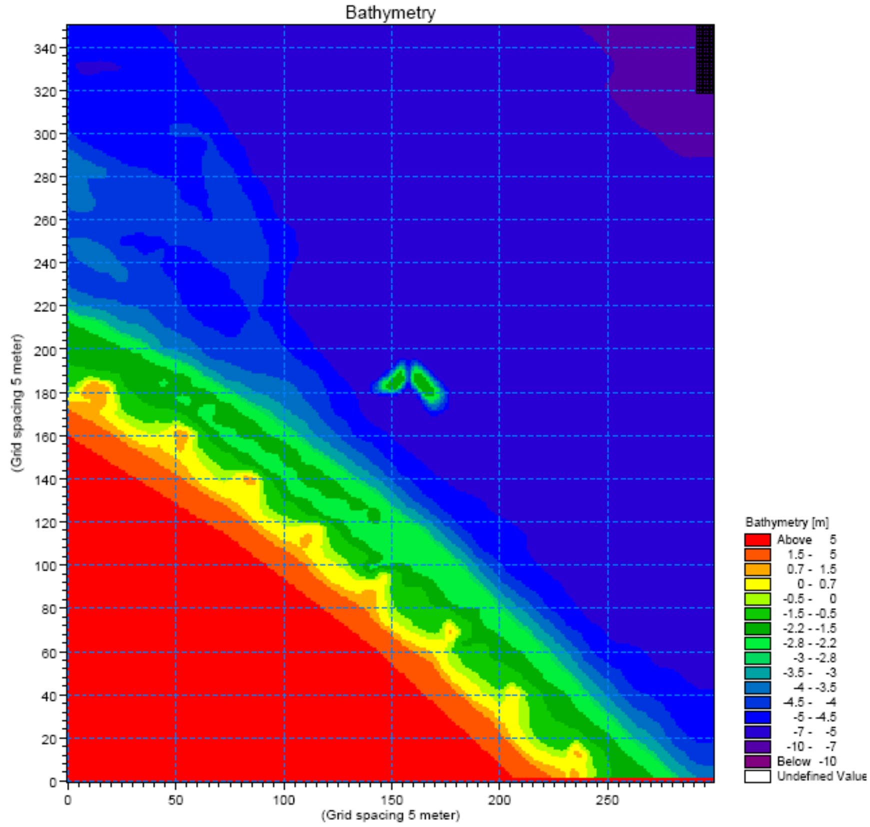
9. Artificial Reef with 45° rotation from North and Western Sleeve extension (Alternative 6)



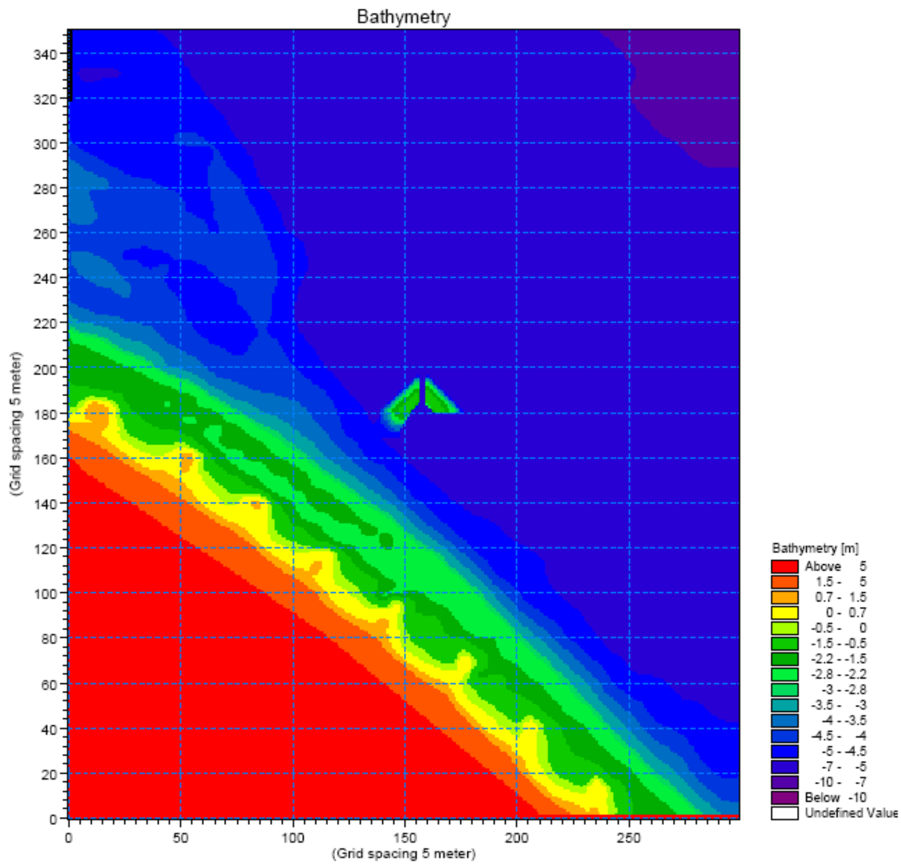
10. Artificial Reef, parallel to North and without Sleeve extension (Alternative 5)



11. Artificial Reef, parallel to North and with Eastern Sleeve extension (Alternative 5)

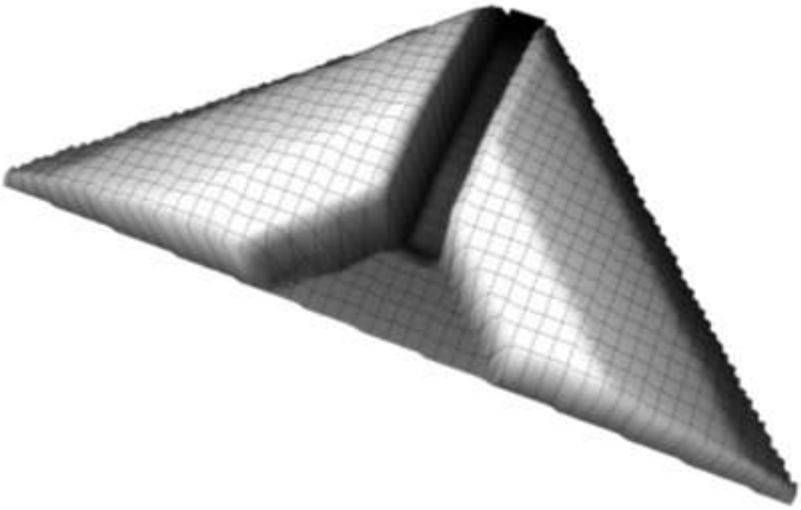


12. Artificial Reef, parallel to North and with Western Sleeve extension (Alternative 6)

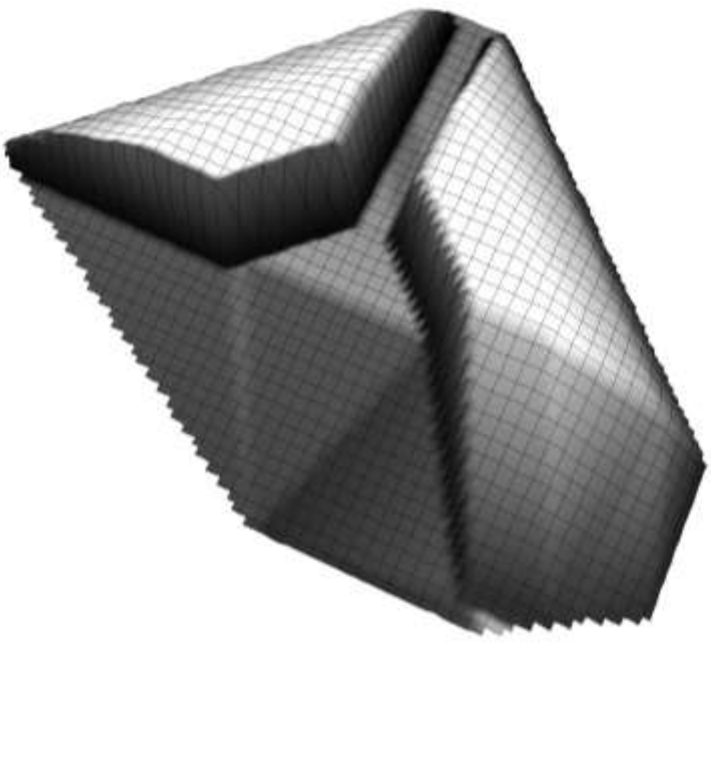


Annex B - 3D models of Artificial Surfing Reef

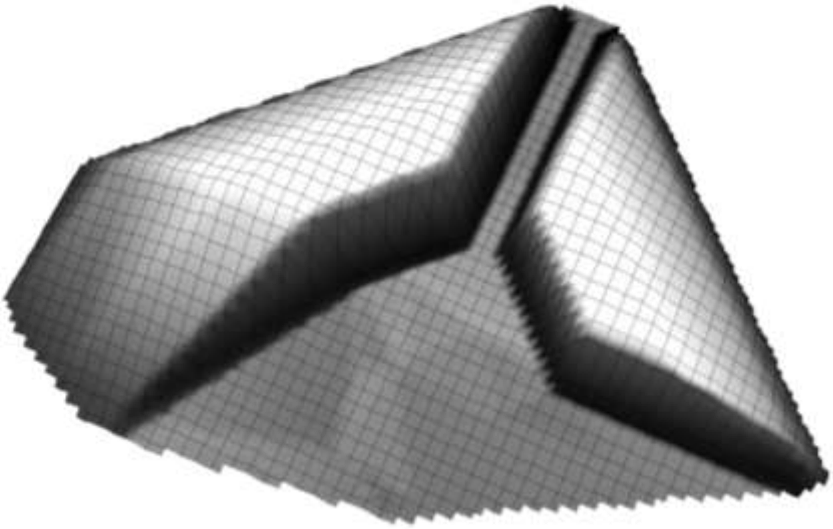
1. Surfing reef without Sleeve extensions (Alternatives 1 and 4)



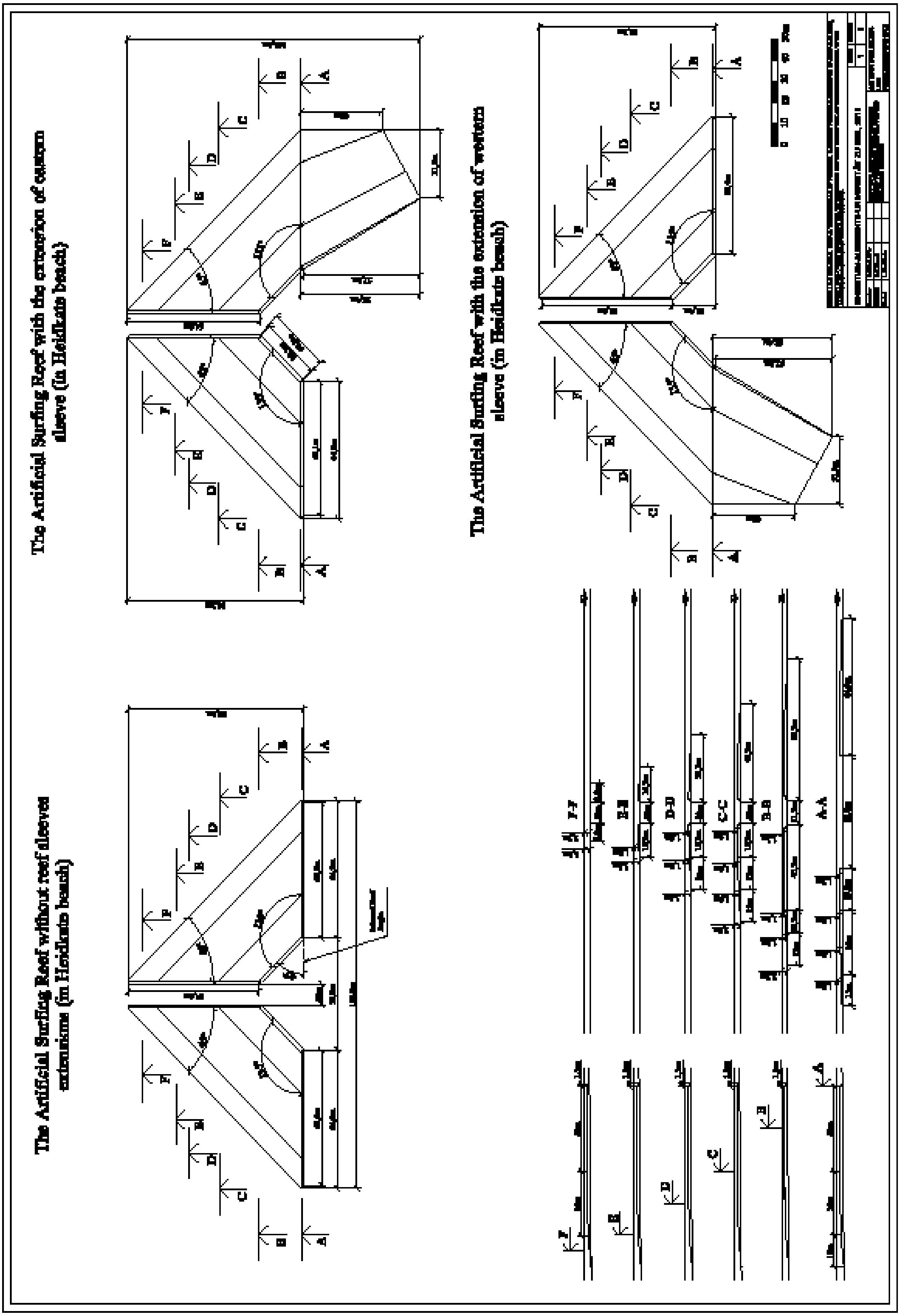
2. Surfing reef with Eastern Sleeve extensions (Alternatives 2 and 5)

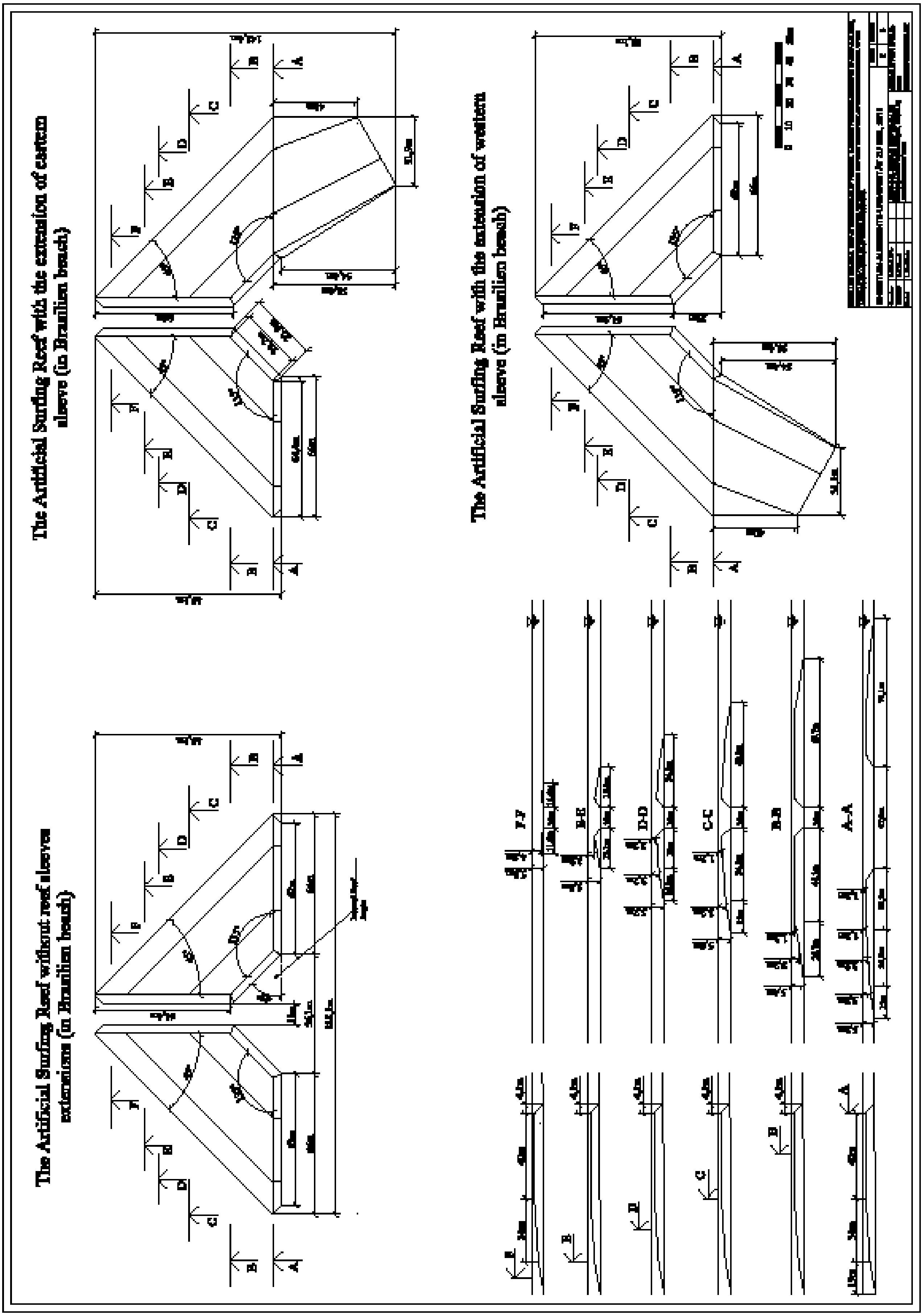


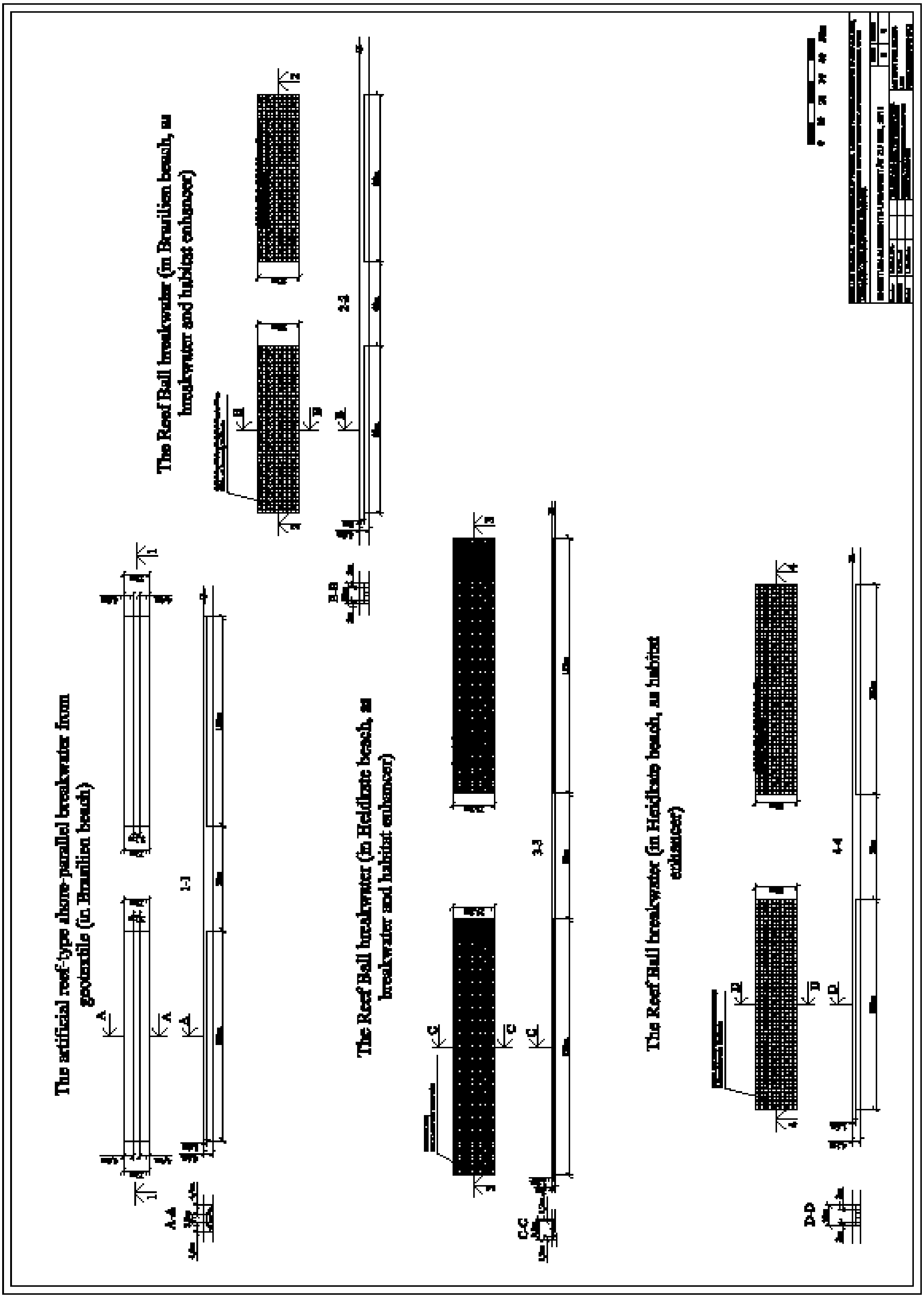
3. Surfing reef with Western Sleeve extensions (Alternatives 3 and 6)



Annex C – Engineering drawings and technical, geometrical specifications of designed reef-type breakwaters


The Artificial Surfing Reef with the extension of eastern sleeve (in Heidkate beach)
The Artificial Surfing Reef with the extension of western sleeve (in Heidkate beach)
The Artificial Surfing Reef without reef sleeves extensions (in Heidkate beach)
F-F
E-E
D-D
C-C
B-B
A-A

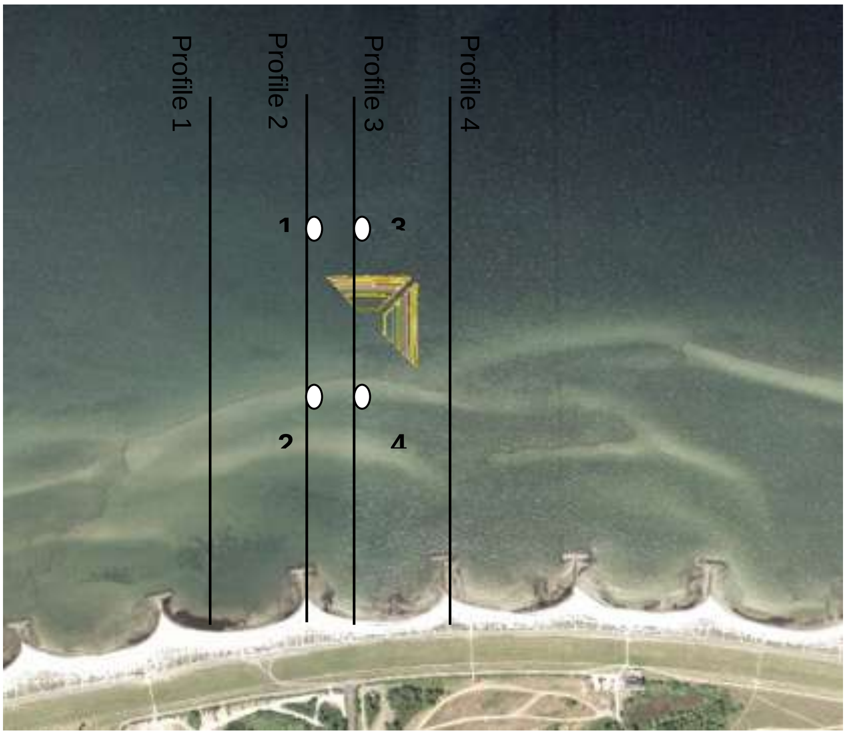

The Artificial Surfing Reef with the extension of eastern sleeve (in Brasilien beach)
The Artificial Surfing Reef without reef sleeves extensions (in Brasilien beach)
The Artificial Surfing Reef with the extension of western sleeve (in Brasilien beach)


The artificial reef-type shore-parallel breakwater from geotextile (in Brasilien beach)
The Reef Ball breakwater (in Brasilien beach, as breakwater and habitat enhancer)
The Reef Ball breakwater (in Heidkate beach, as breakwater and habitat enhancer)
The Reef Ball breakwater (in Heidkate beach, as habitat enhancer)

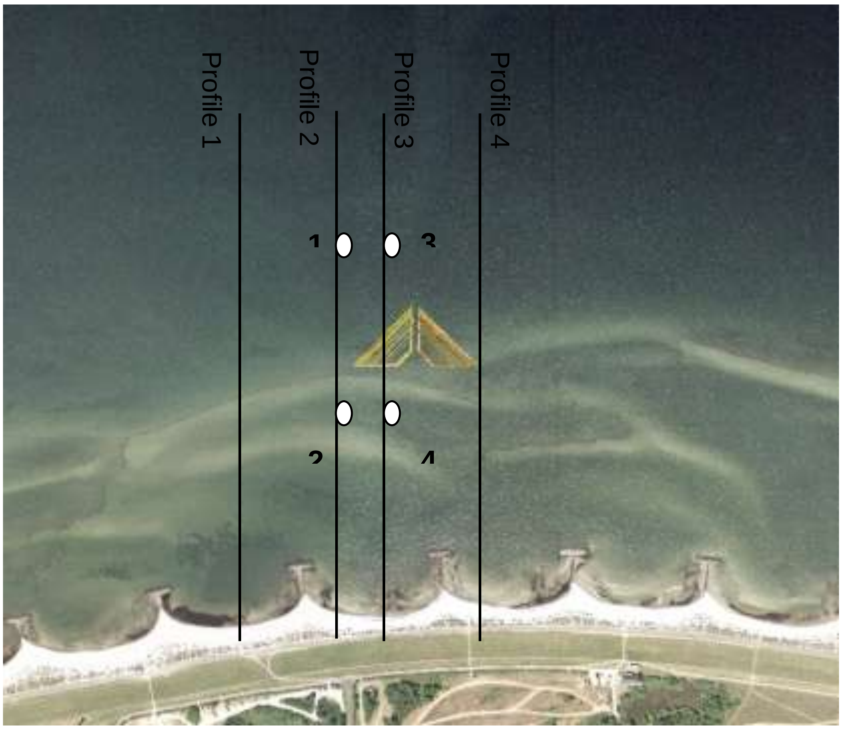
Annex D – Aerial pictures with mapped designed breakwater alternatives for the Heidkate and Brasilien beaches. Locations of profiles and points for results extraction

Aerial pictures are from GeoBasis-DE/LVermGeo SH (www.LVermGEoSH.schleswig hostein.de)

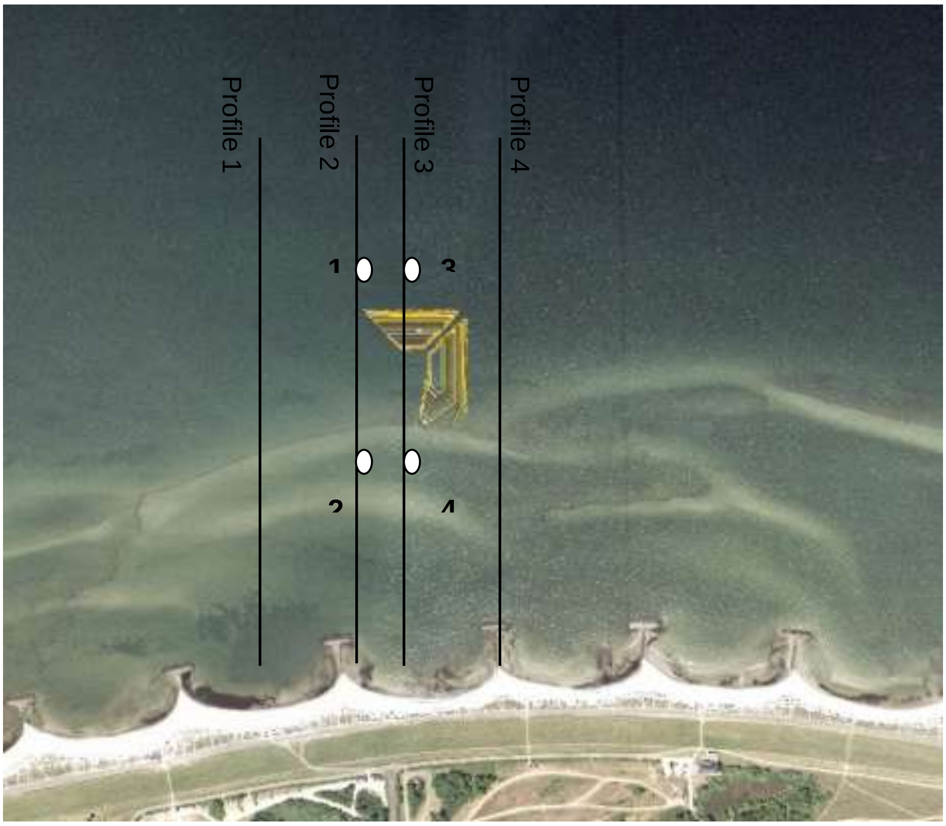
Alternative 1. Surfing Reef without arm extension in Heidkate beach (45° from north)



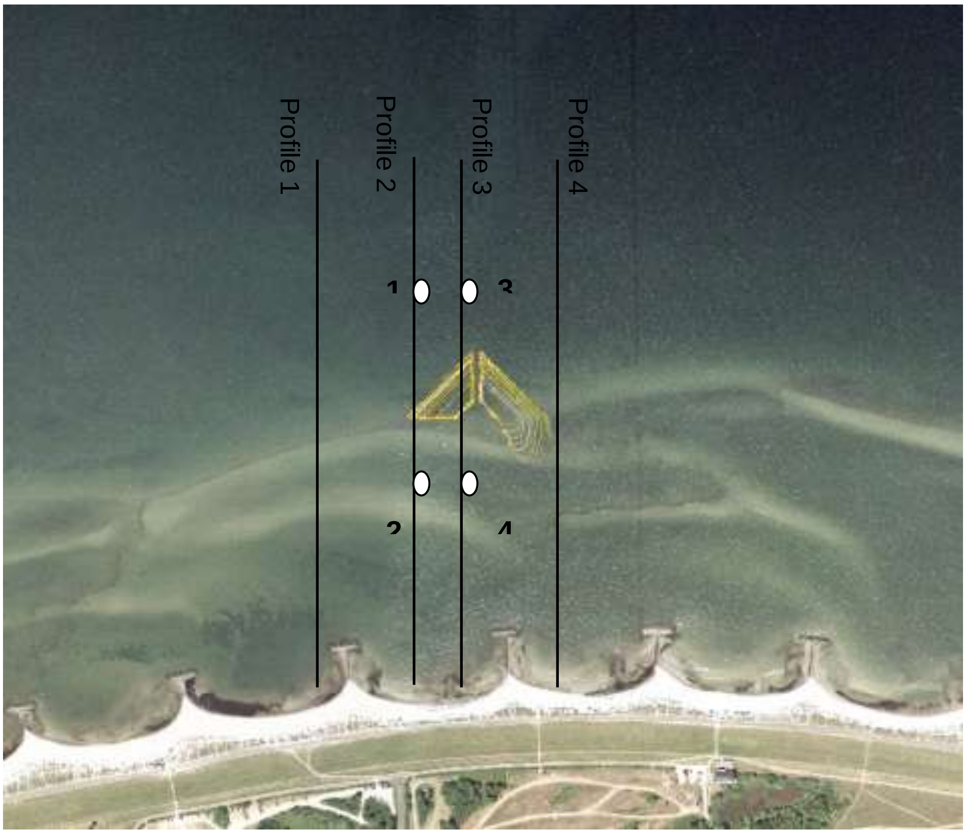
Alternative 1. Surfing Reef without arm extension in Heidkate beach (parallel to the coast)



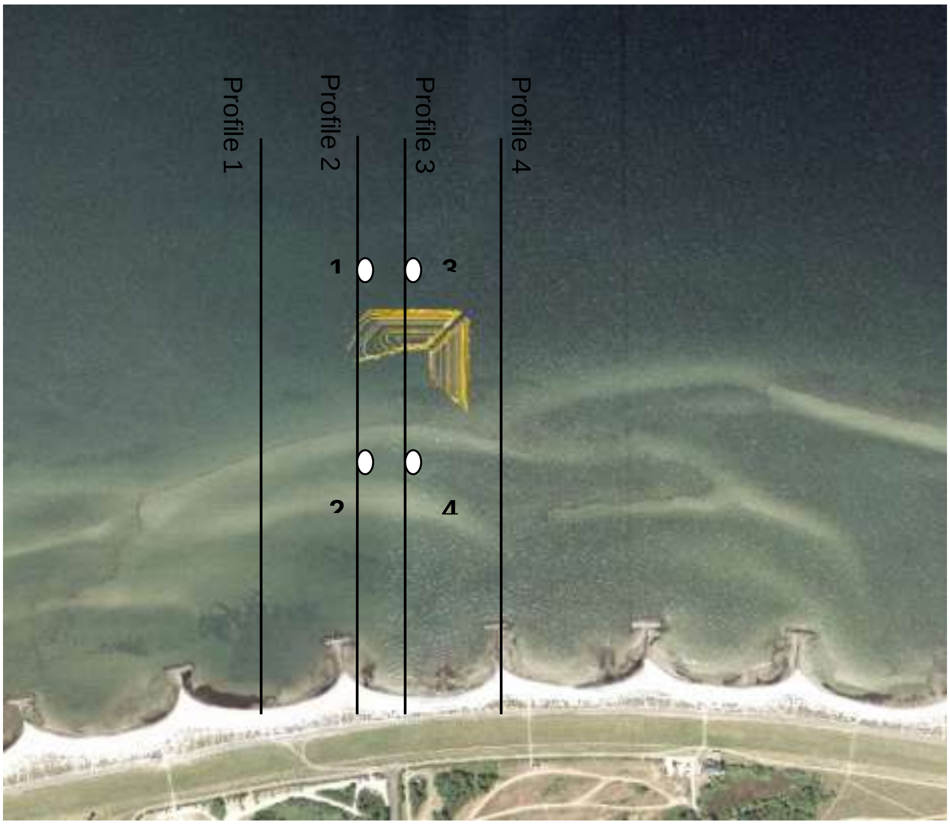
Alternative 2. Surfing Reef with Eastern arm extension in Heidkate beach (45° from north)



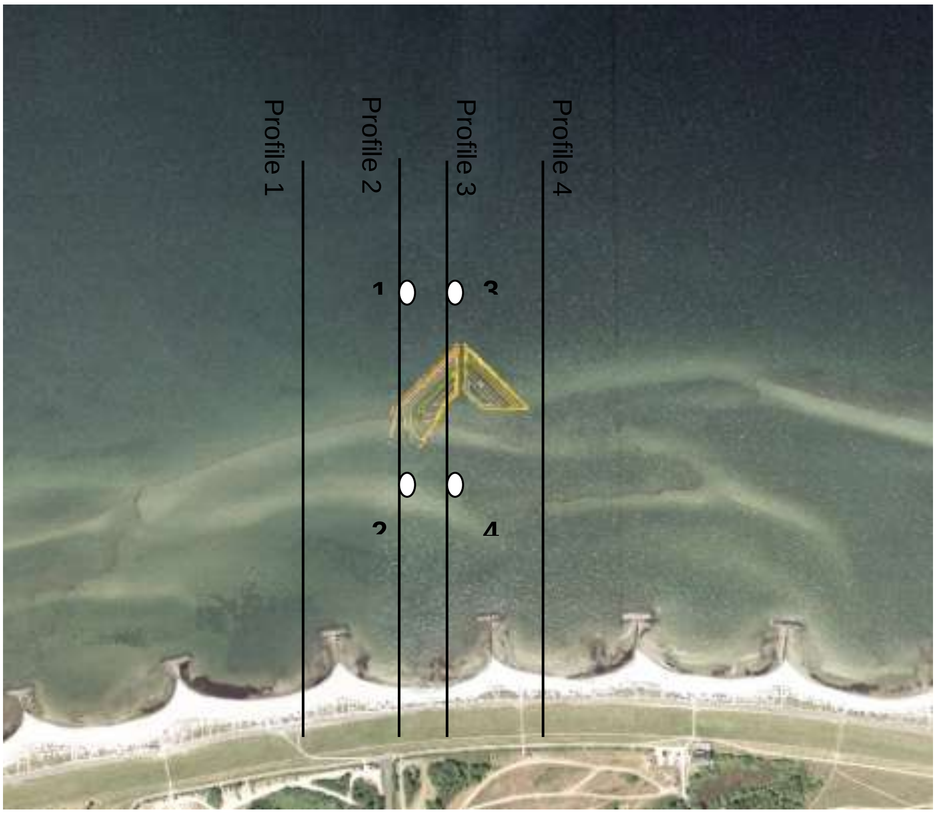
lternative 2. Surfing Reef with Eastern arm extension in Heidkate beach (parallel to the coast)



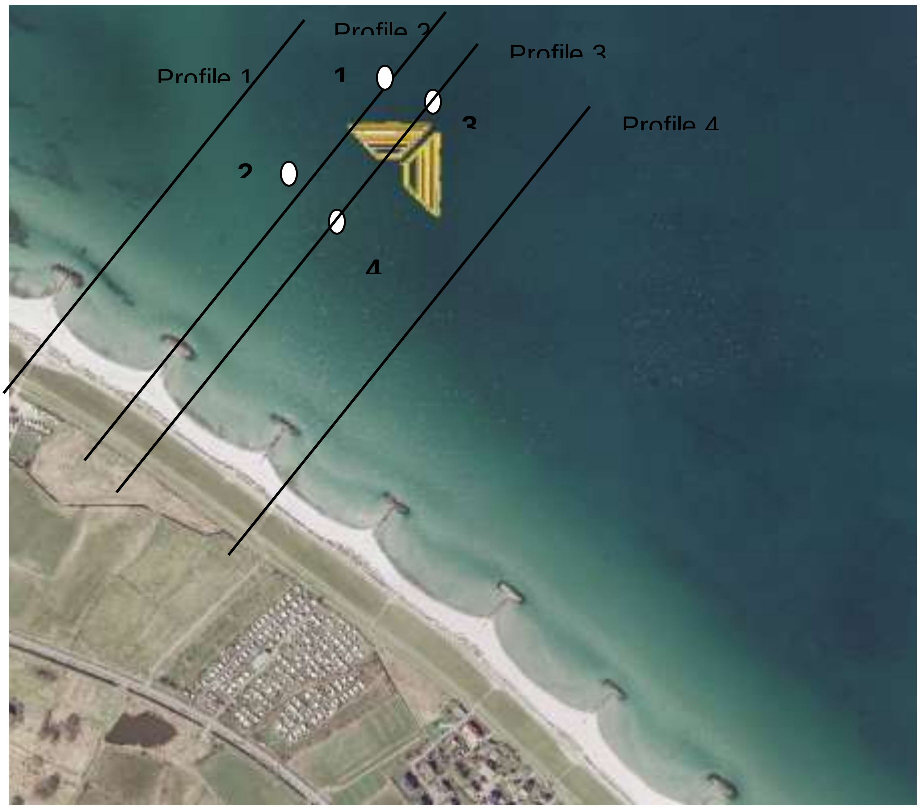
Alternative 3. Surfing Reef with Western arm extension in Heidkate beach (45° from north)



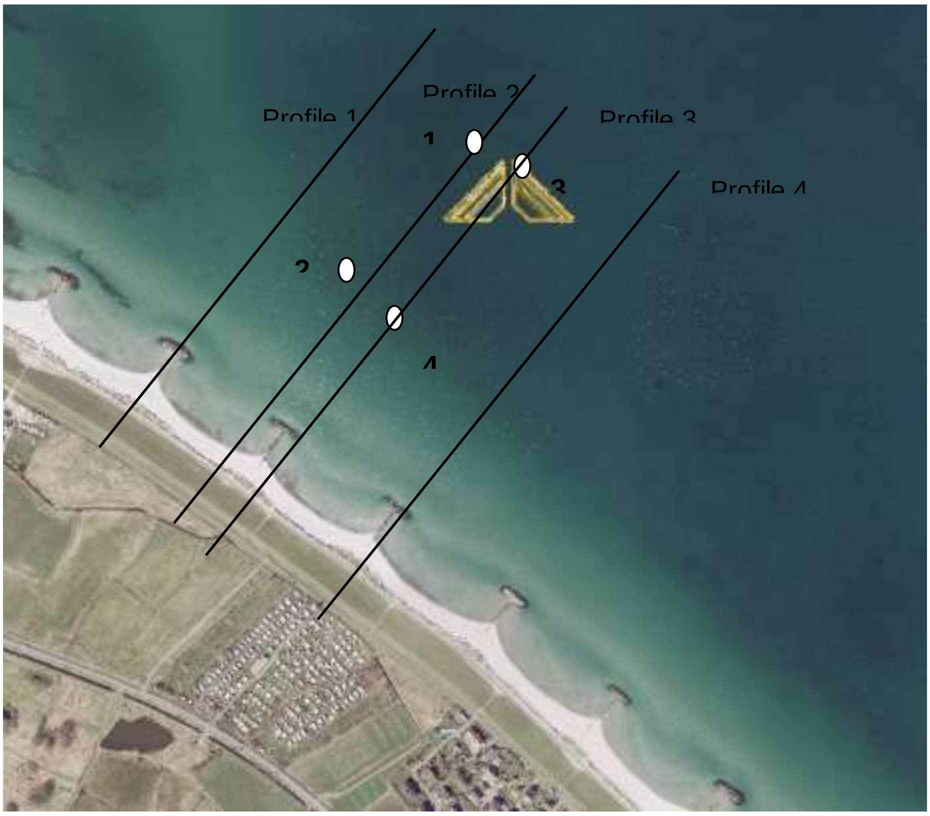
Alternative 3. Surfing Reef with Western arm extension in Heidkate beach (parallel to the coast)



Alternative 4. Surfing Reef without arm extension in Brasilien beach (45° from north)

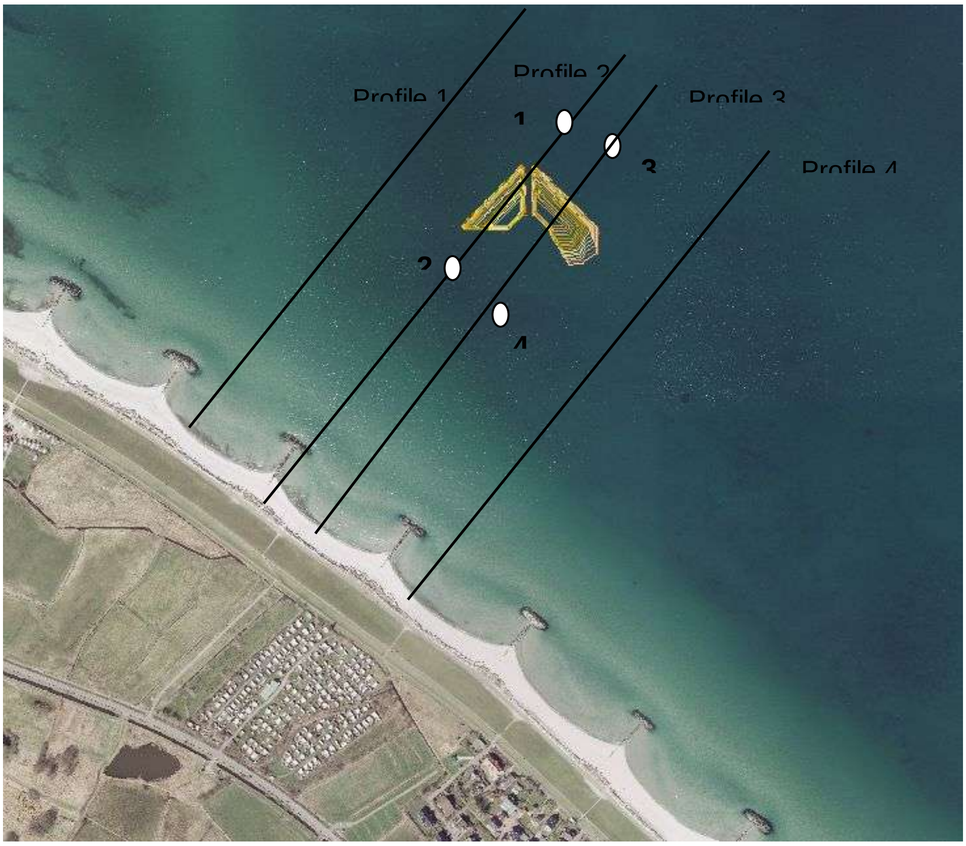


Alternative 4. Surfing Reef without arm extension in Brasilien beach (parallel to the coast)

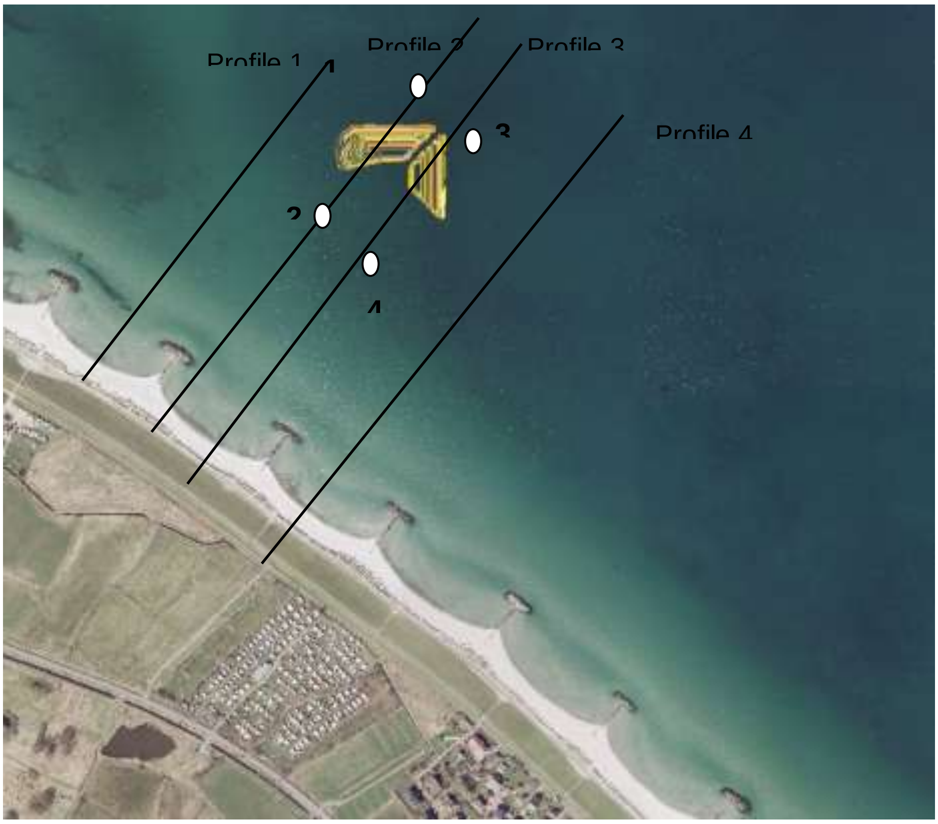


Alternative 5. Surfing Reef with Eastern arm extension in Brasilien beach (45° from north)

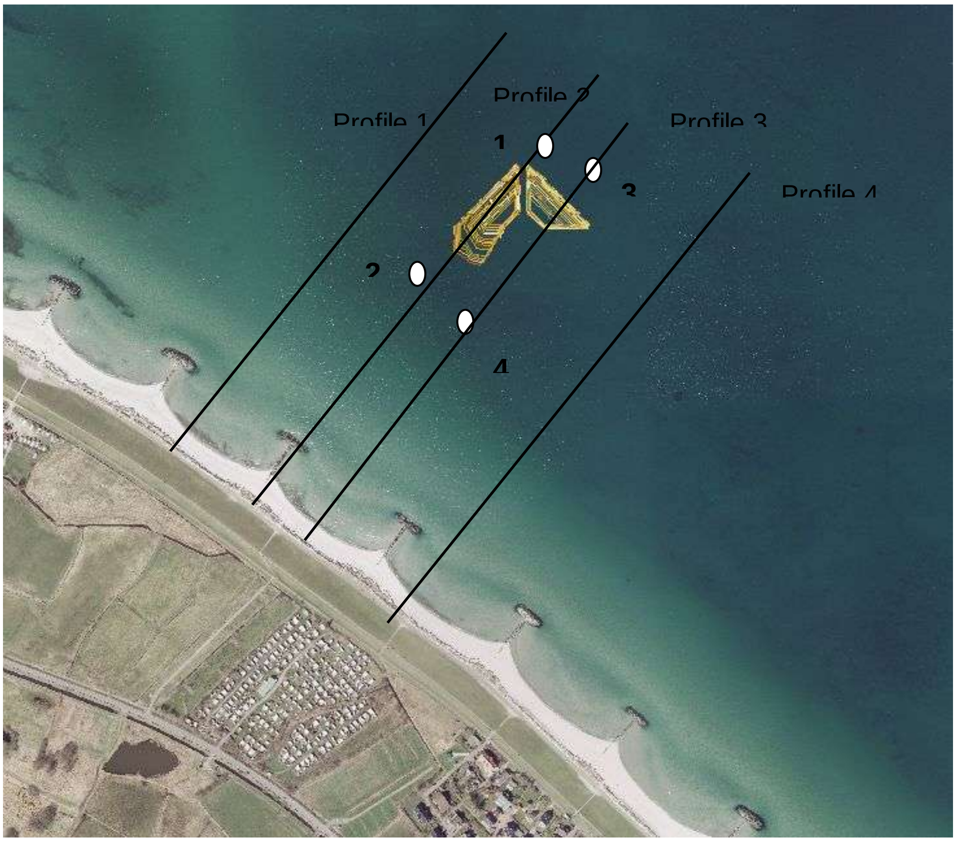
Alternative 5. Surfing Reef with Eastern arm extension in Brasilien beach (parallel to the coast)



Alternative 6. Surfing Reef with Western arm extension in Brasilien beach (45° from north)

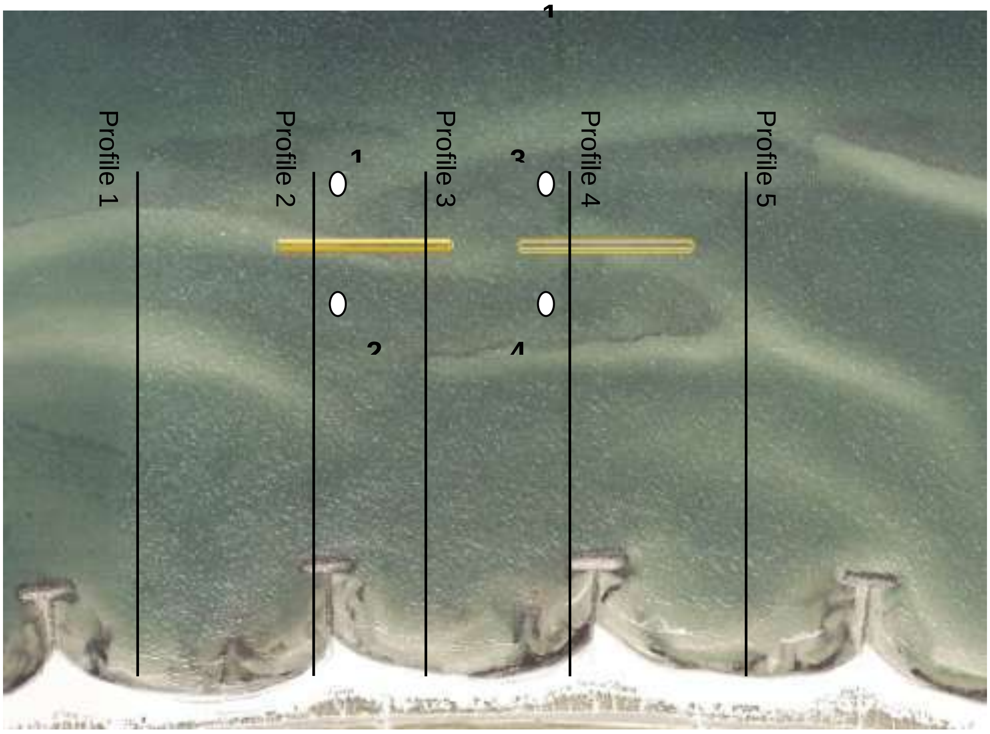


Alternative 6. Surfing Reef with Western arm extension in Brasilien beach (parallel to the coast)

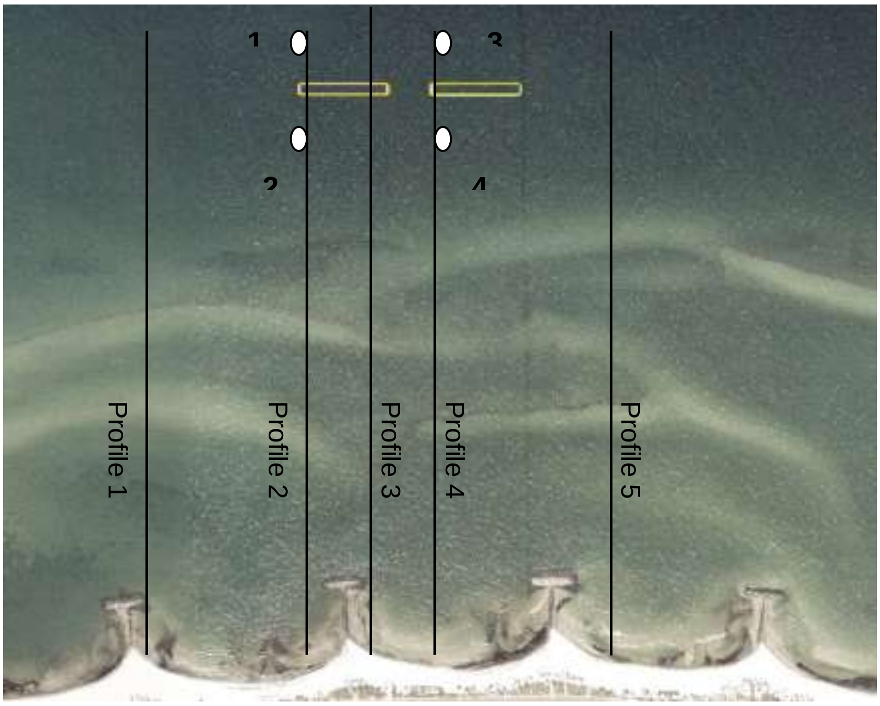


Alternative 7. Shore-parallel breakwater in Brasilien beach

Alternative 8. Reef Balls Breakwater in Heidkate beach (costal protection and habitat enhancement)

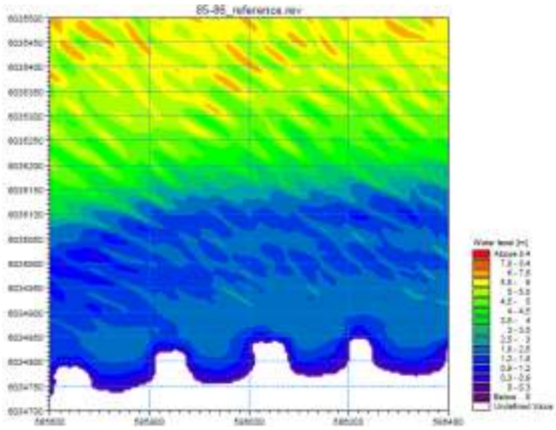
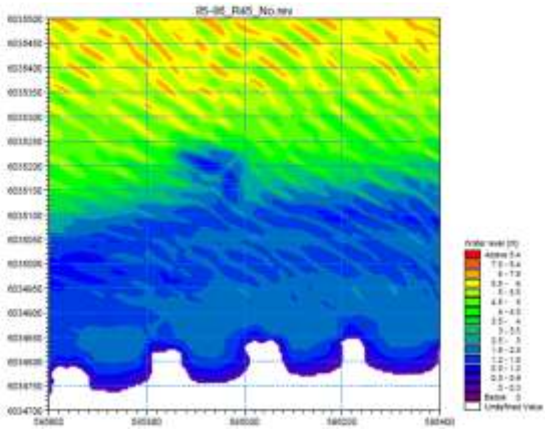
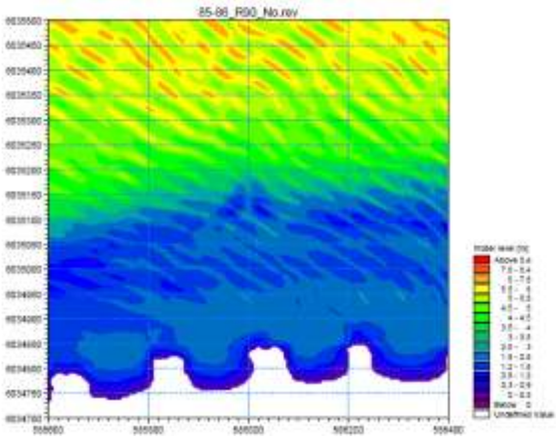
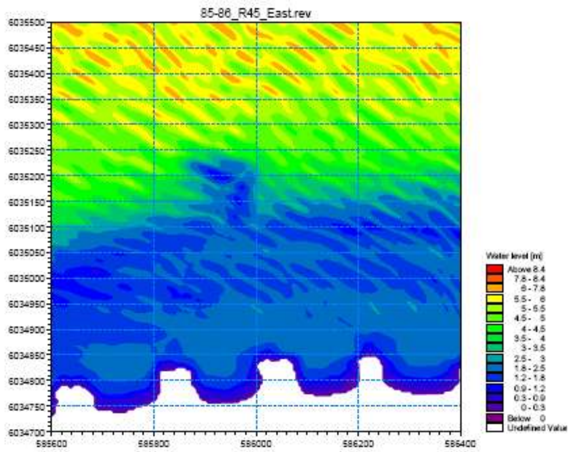


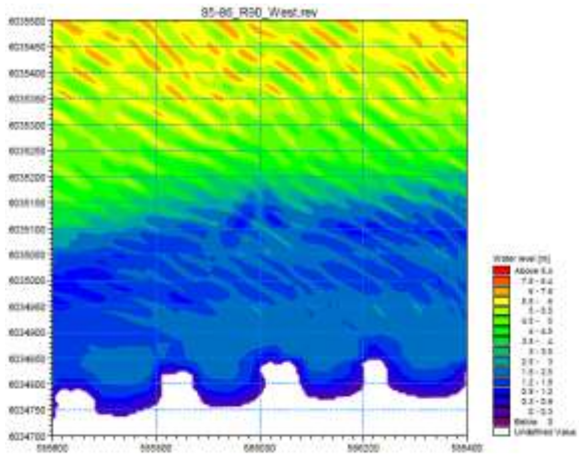
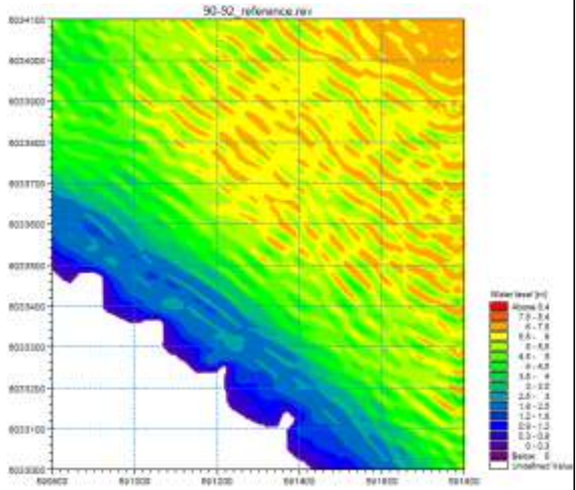
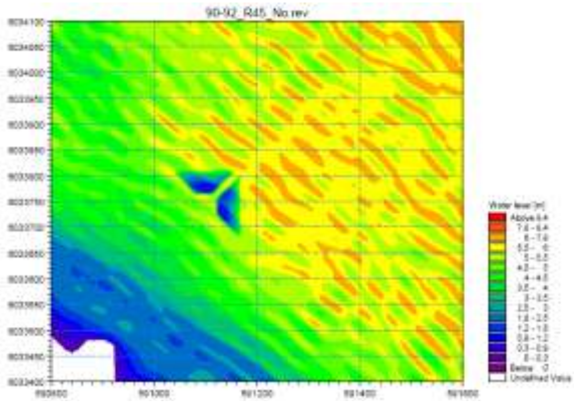
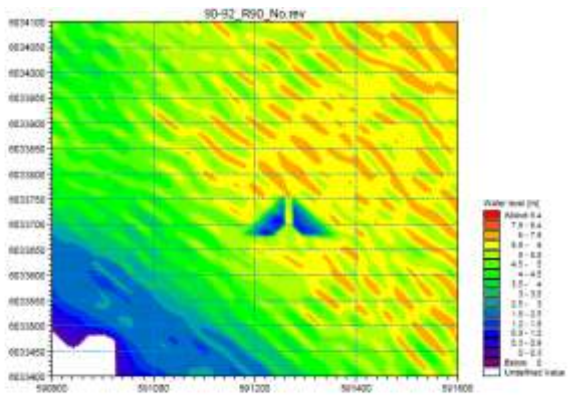
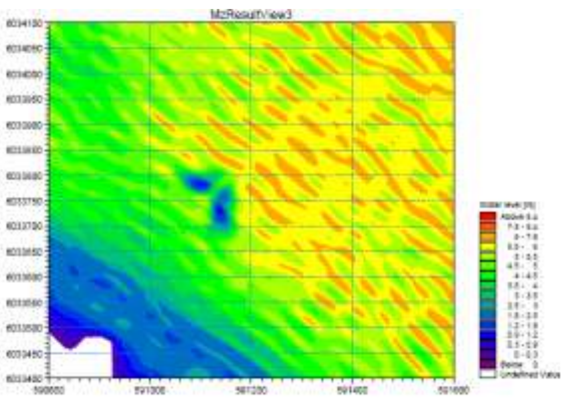
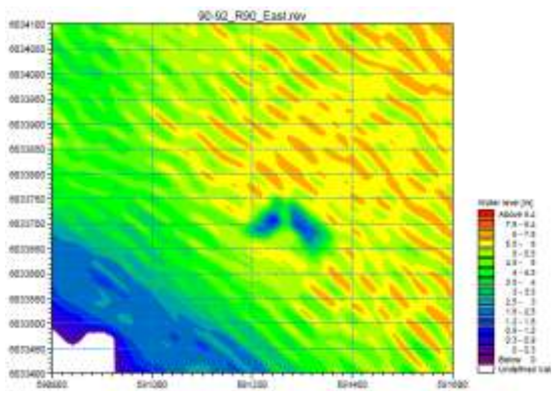
Alternative 9. Reef Balls Breakwater in Heidkate beach (habitat enhancement)

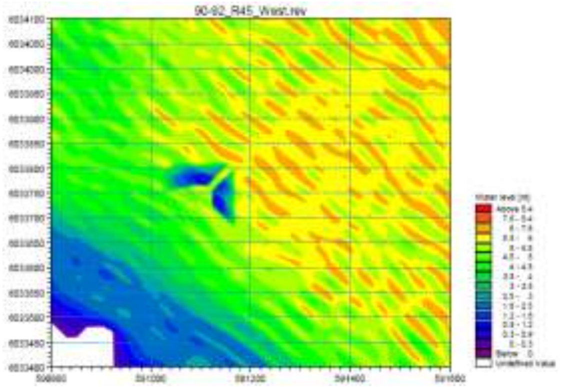
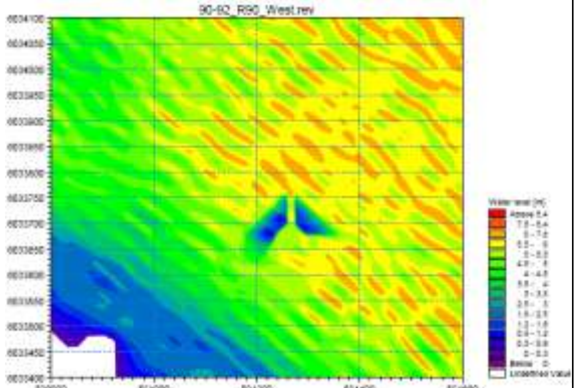
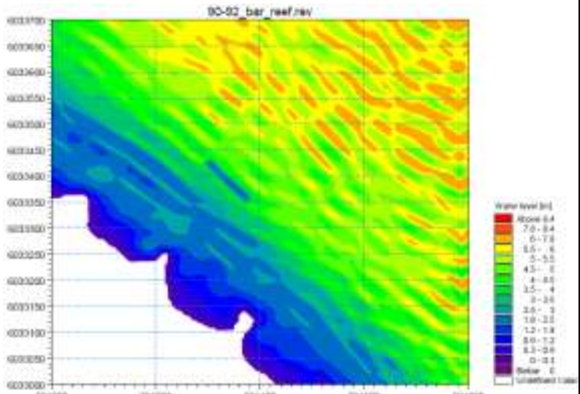
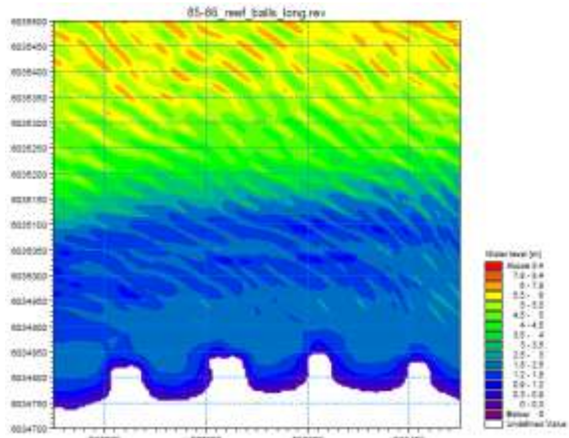
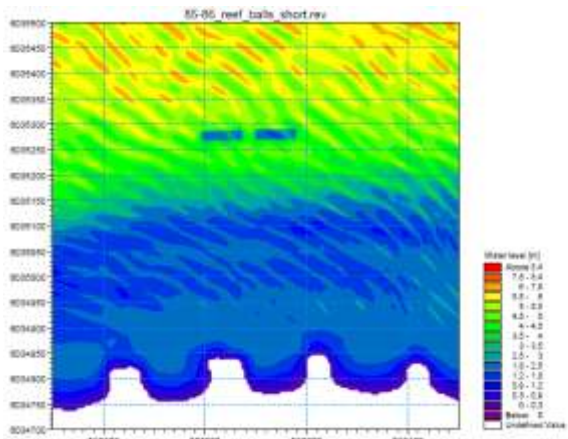
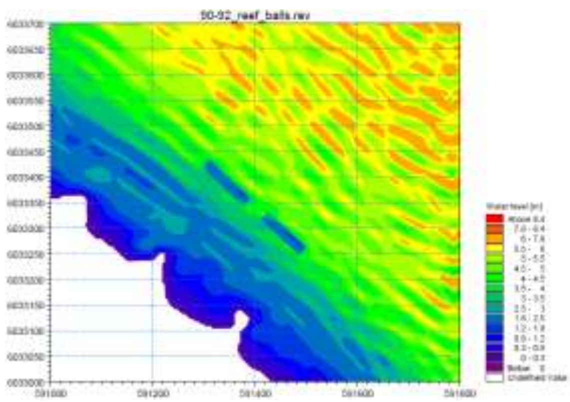


Alternative 10. Reef Balls Breakwater in Brasilien beach (coastal protection and habitat enhancement)

Annex E – MIKE 21 Boussinesq wave modelling results (graphs)

The Heidkate beach. Reference conditions	Alternative 1. Surfing Reef without arms extensions in Heidkate beach (45° from north)
	
Alternative 1. Surfing Reef without arms extensions in Heidkate beach (parallel to the coast)	**Alternative 2. Surfing Reef with Eastern arm extension in Heidkate beach (45° from north)**
	

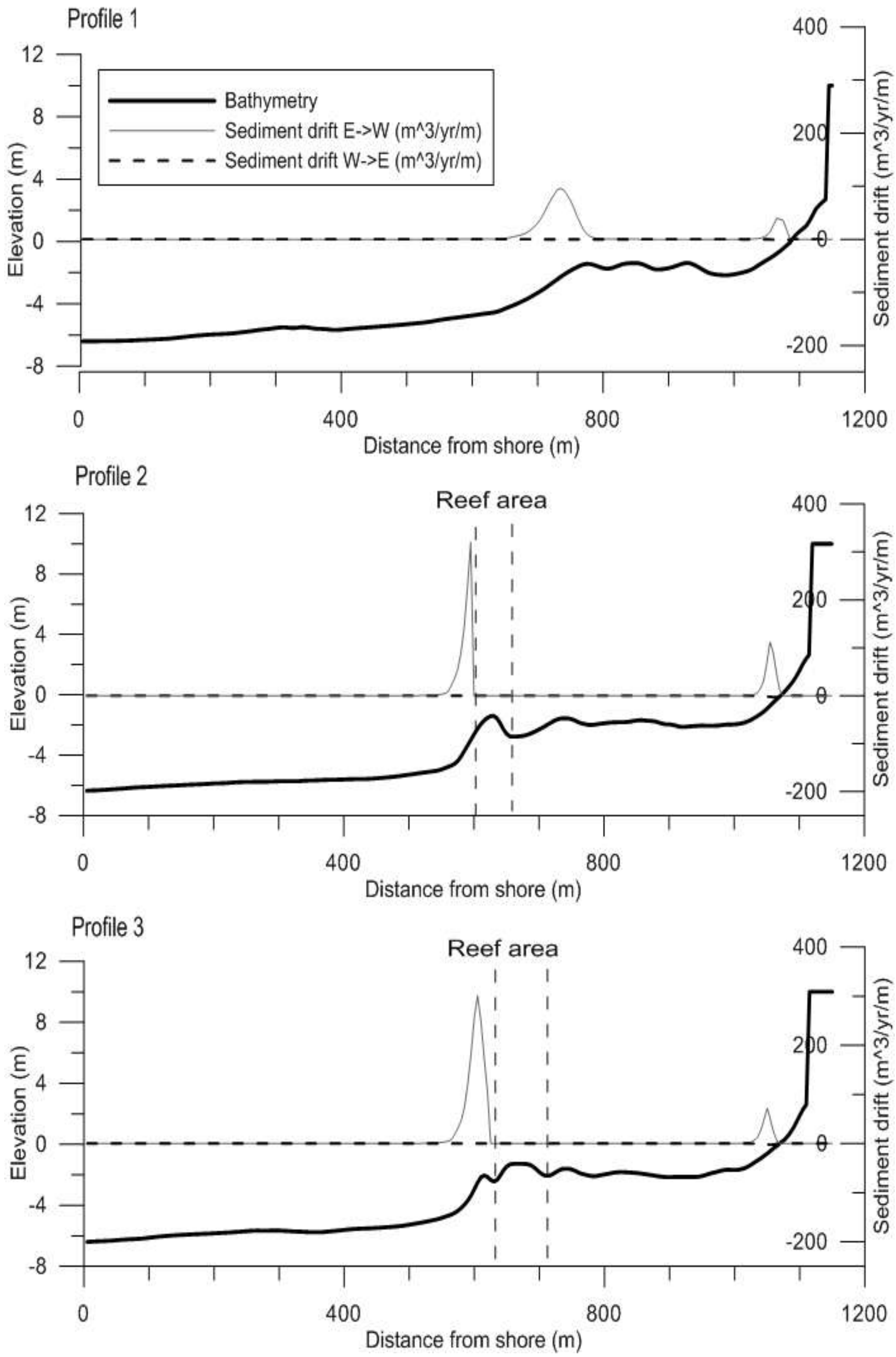
Alternative 3. Surfing Reef with Western arm extension in the Heidkate beach (parallel to the coast)	The Brasilien beach. Reference conditions
	
Alternative 4. Surfing Reef without arms extensions in the Brasilien beach (45° from north)	**Alternative 4. Surfing Reef without arms extensions in the Brasilien beach (parallel to the coast)**
	
Alternative 5. Surfing Reef with Eastern arm extension in the Brasilien beach (45° from north)	**Alternative 5. Surfing Reef with Eastern arm extension in the Brasilien beach (parallel to the coast)**
	

Alternative 6. Surfing Reef with Western arm extension in the Brasilien beach (45° from north)	**Alternative 6. Surfing Reef with Western arm extension in the Brasilien beach (parallel to the coast)**
	
Alternative 7. Shore-parallel breakwater in the Brasilien beach	**Alternative 8. Reef Balls Breakwater in the Heidkate beach (coastal protection and habitat enhancement)**
	
Alternative 9. Reef Balls Breakwater in the Heidkate beach (habitat enhancement)	**Alternative 10. Reef Balls Breakwater in the Brasilien beach (coastal protection and habitat enhancement)**
	

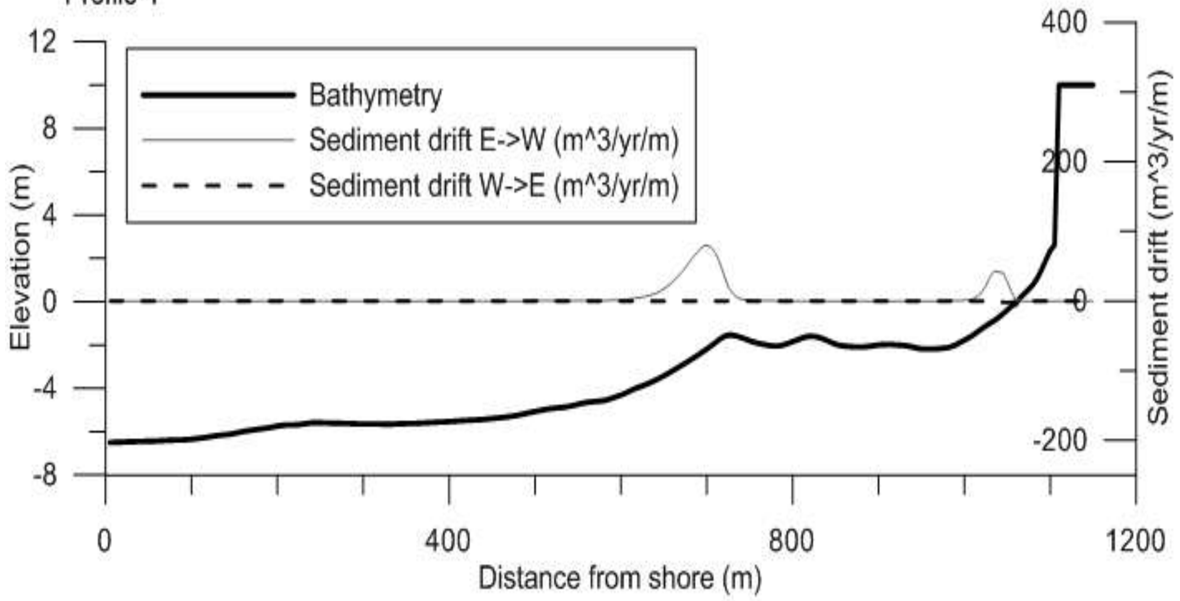
Annex F – Graphs of sediment drift

Sediment drift (m3/yr/m)

Alternative 1 - Surfing Reef without arm extensions in Heidkate beach (45° from North)

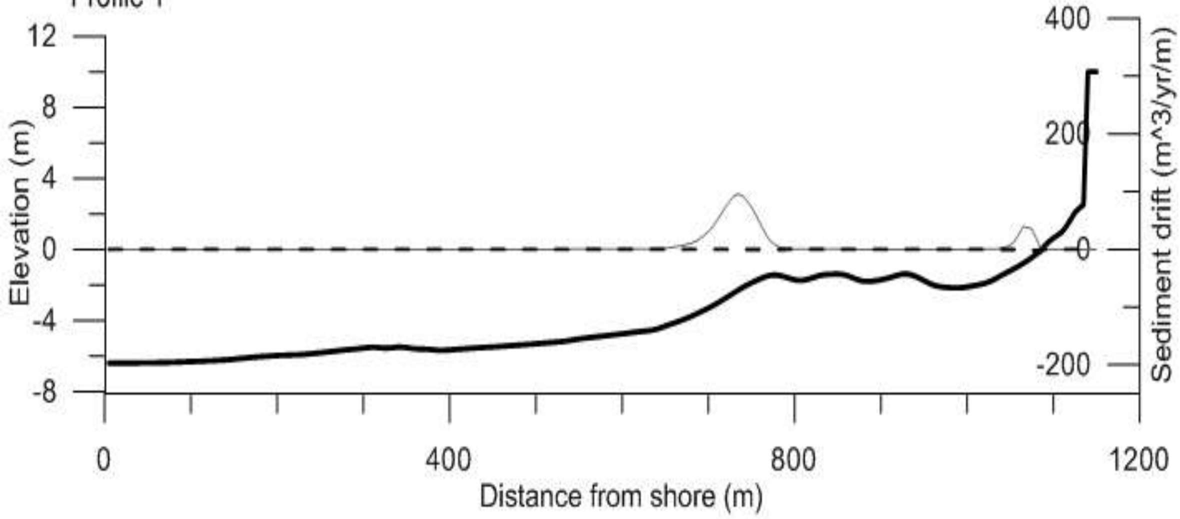


Profile 4

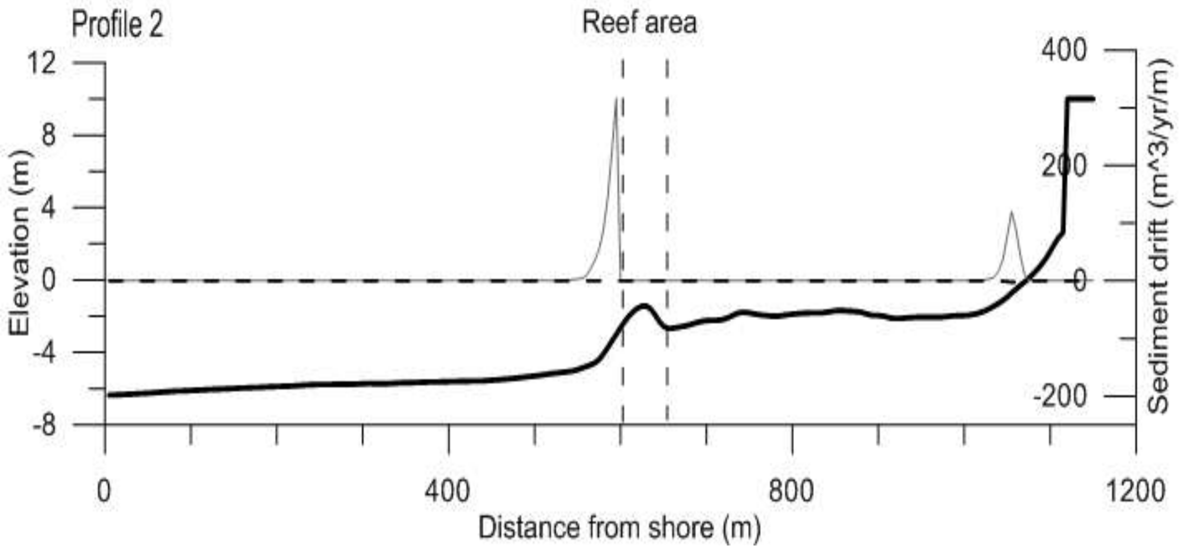


Alternative 2 - Surfing Reef with Eastern arm extension in Heidkate beach (45° from North)

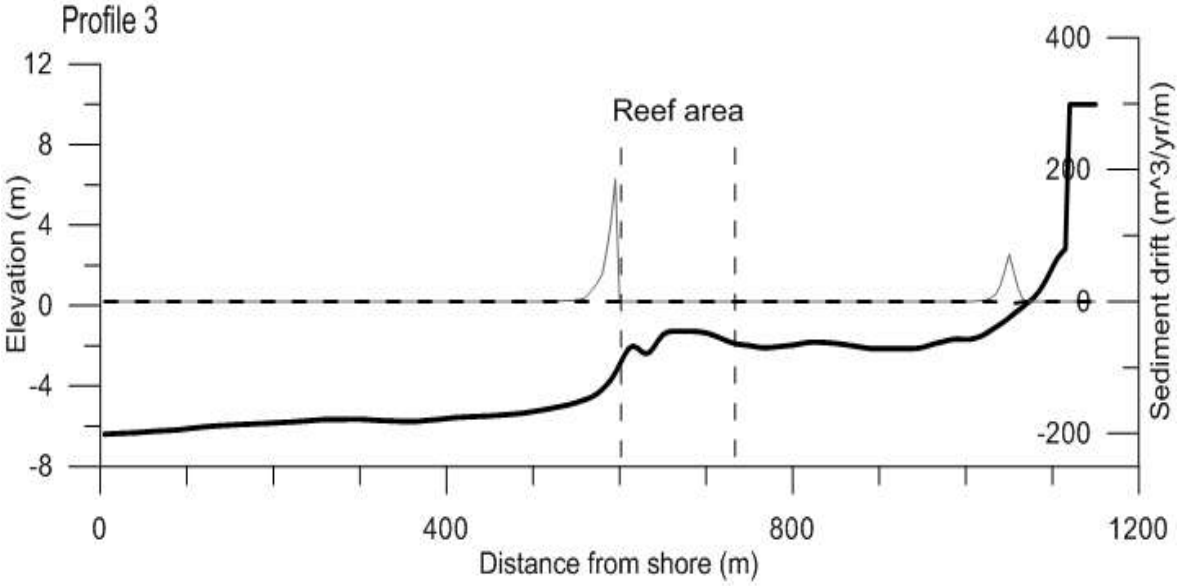
Profile 1



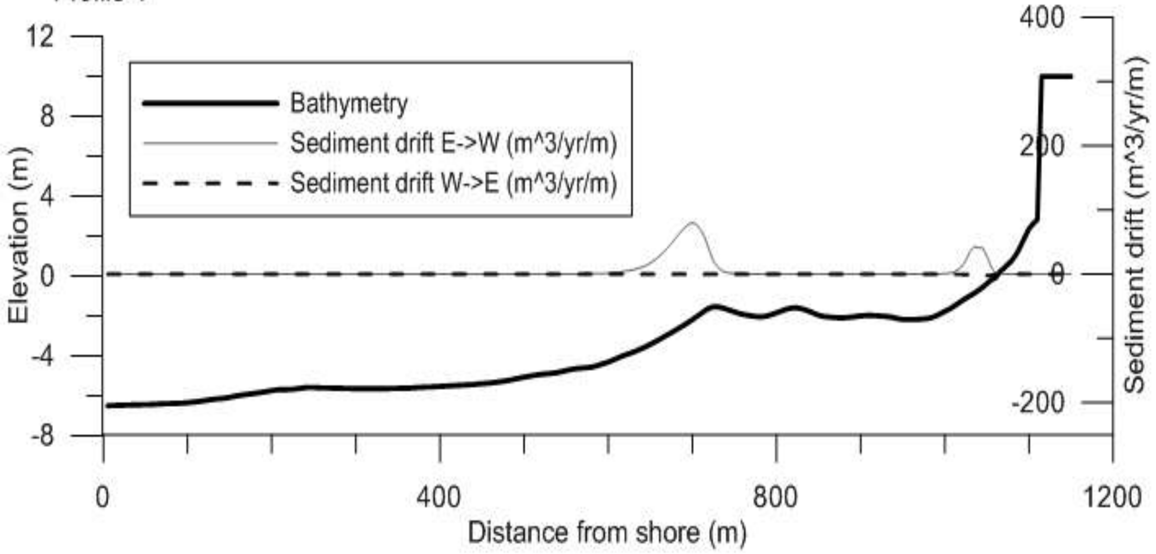
Profile 2



Profile 3

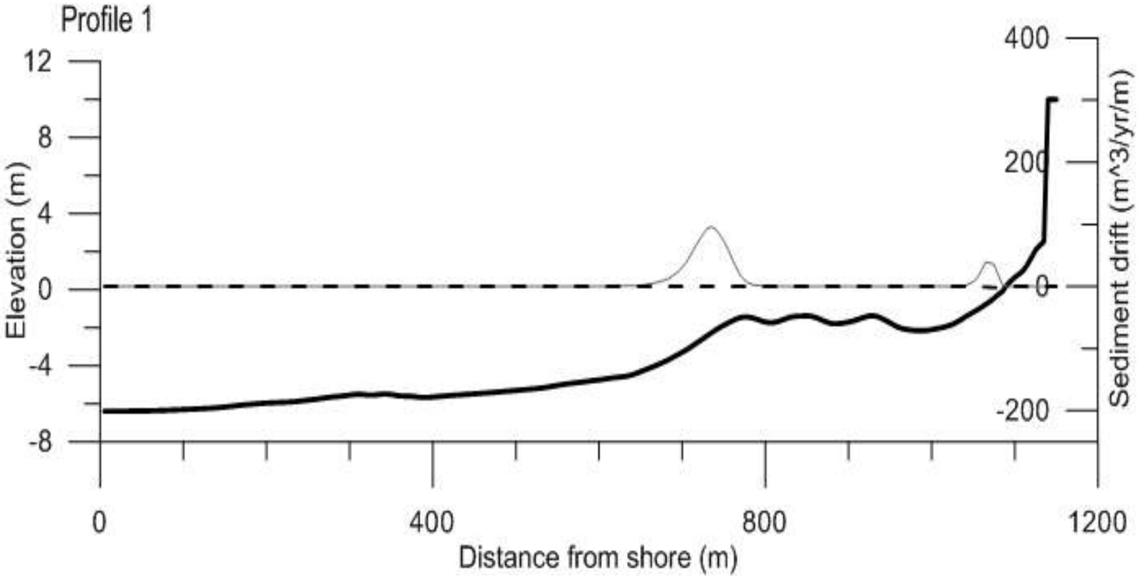


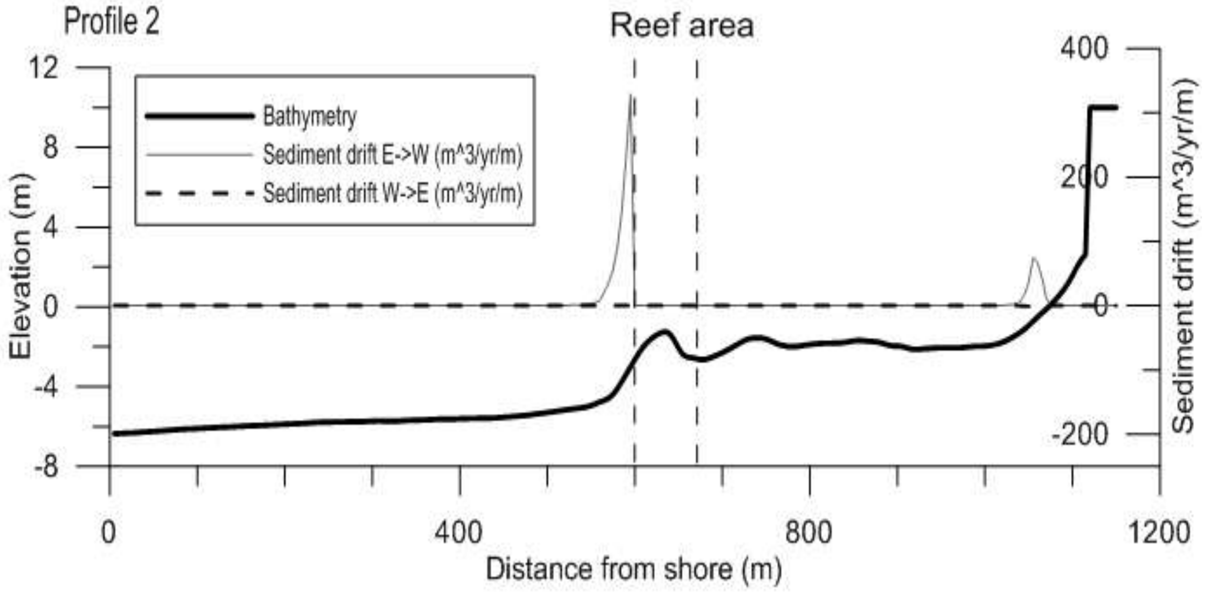
Profile 4

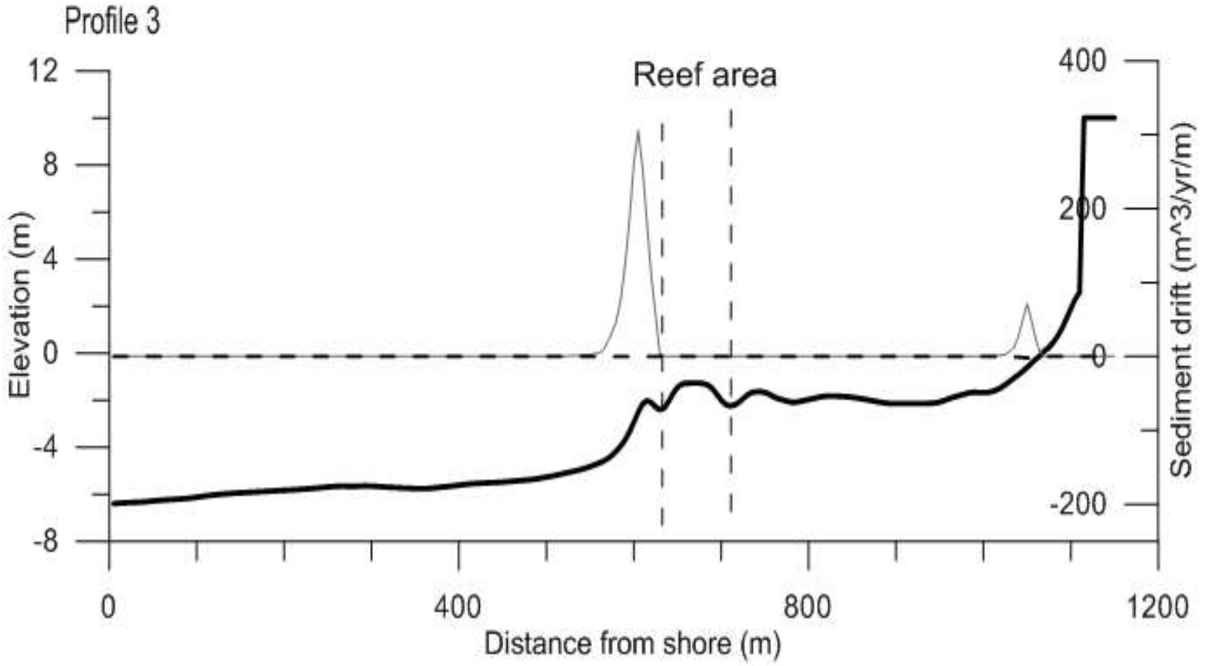


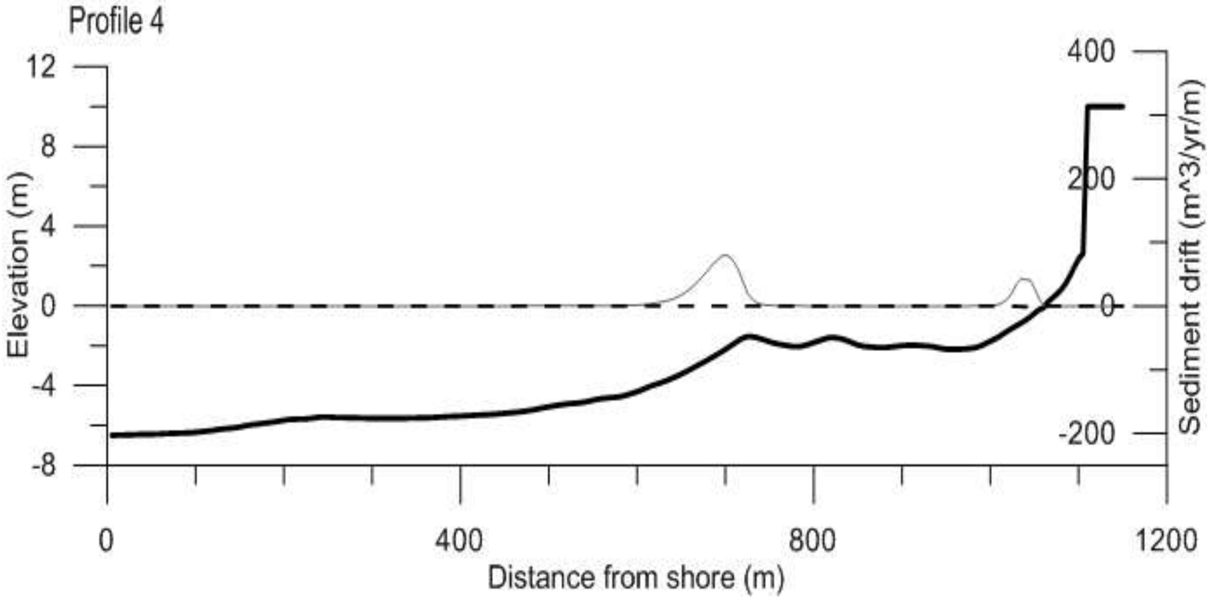
Alternative 3 - Surfing Reef with Western arm extension in Heidkate beach (45° from North)

Profile 1

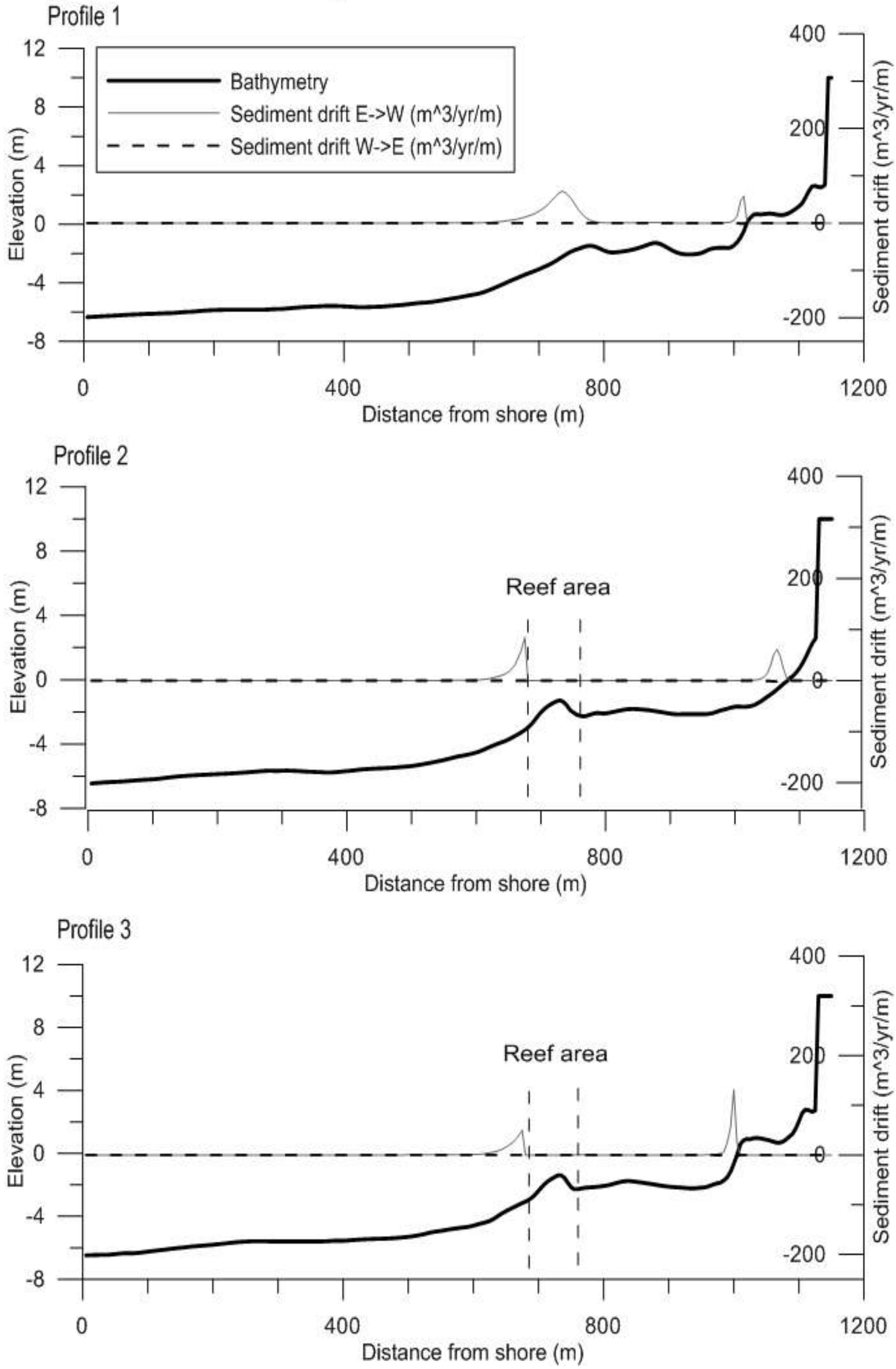



Profile 2
Reef area
Bathymetry
Sediment drift E->W (m^3/yr/m)
Sediment drift W->E (m^3/yr/m)
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

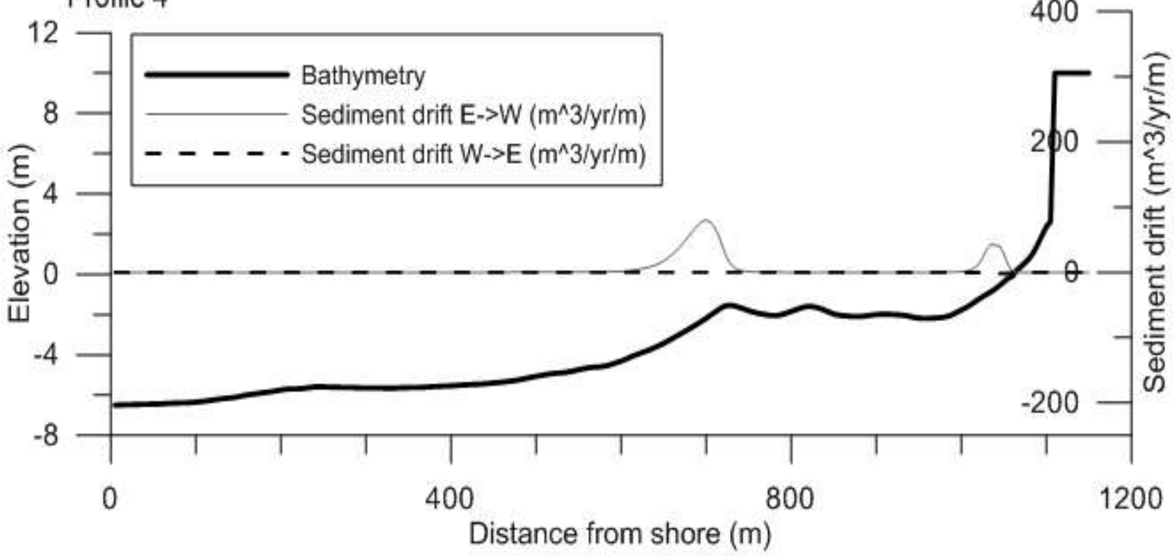

Profile 3
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200


Profile 4
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

Alternative 1 - Surfing Reef without arm extensions in Heidkate beach (perpendicular to the coast)

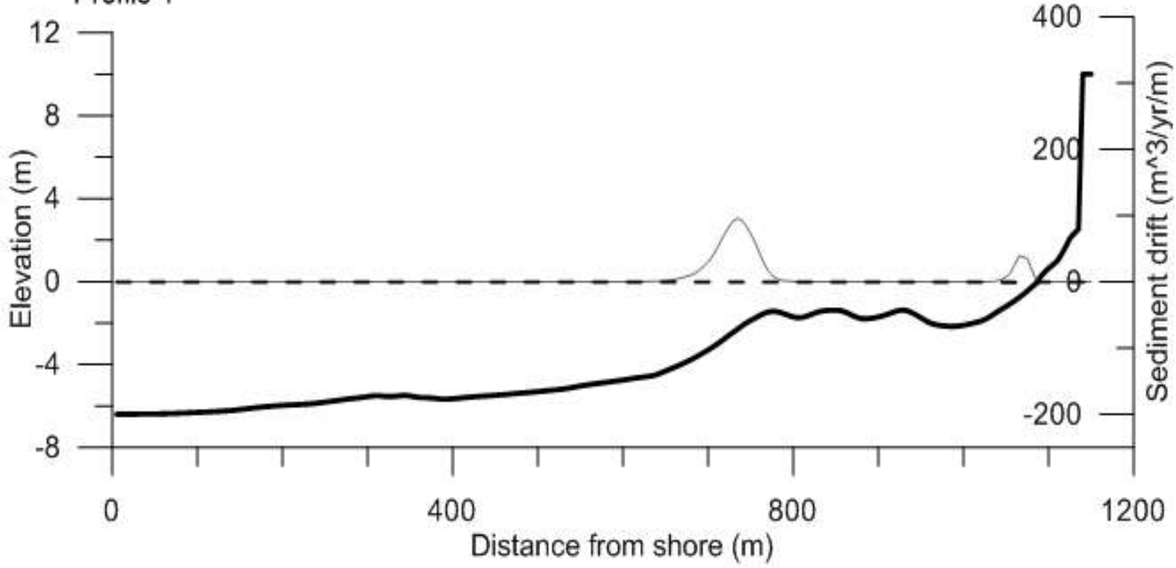


Profile 4

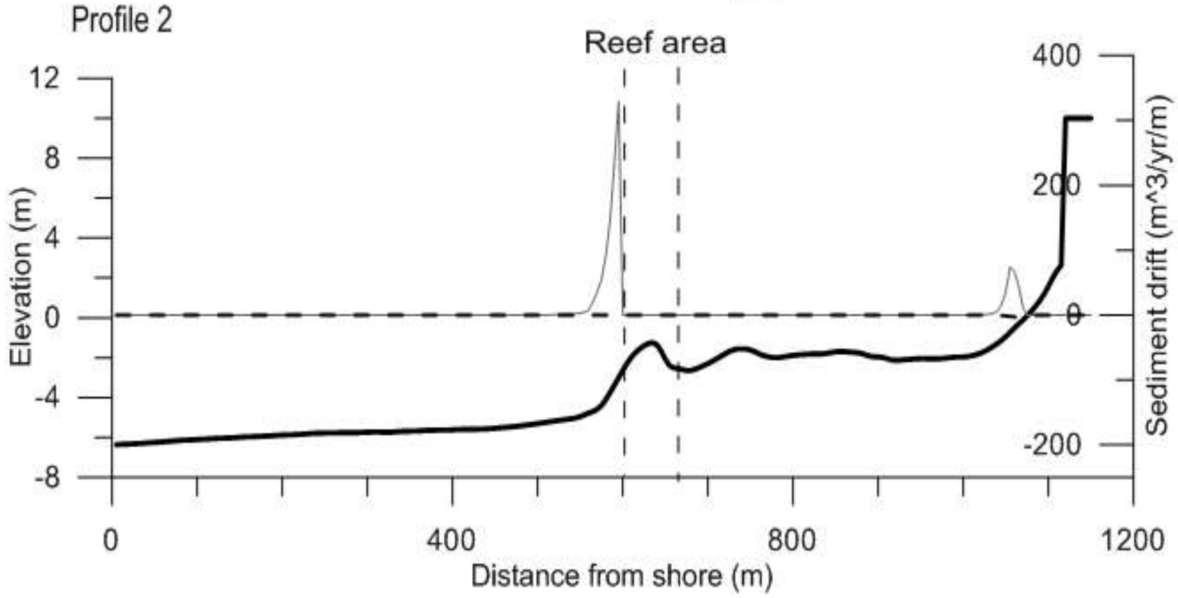


Alternative 2 - Surfing Reef with Eastern arm extension in Heidkate beach (perpendicular to the coast)

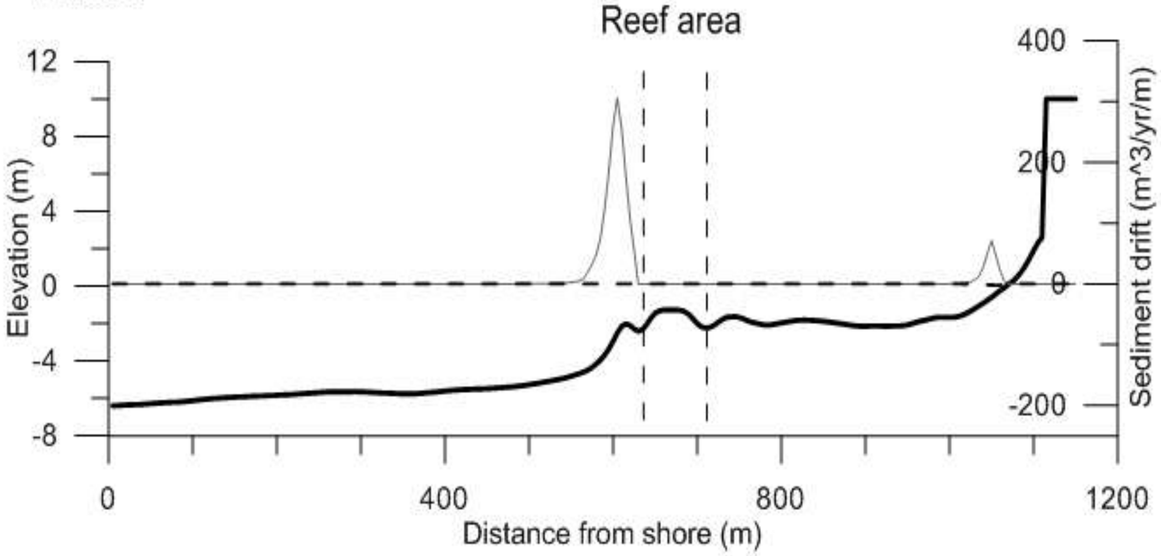
Profile 1



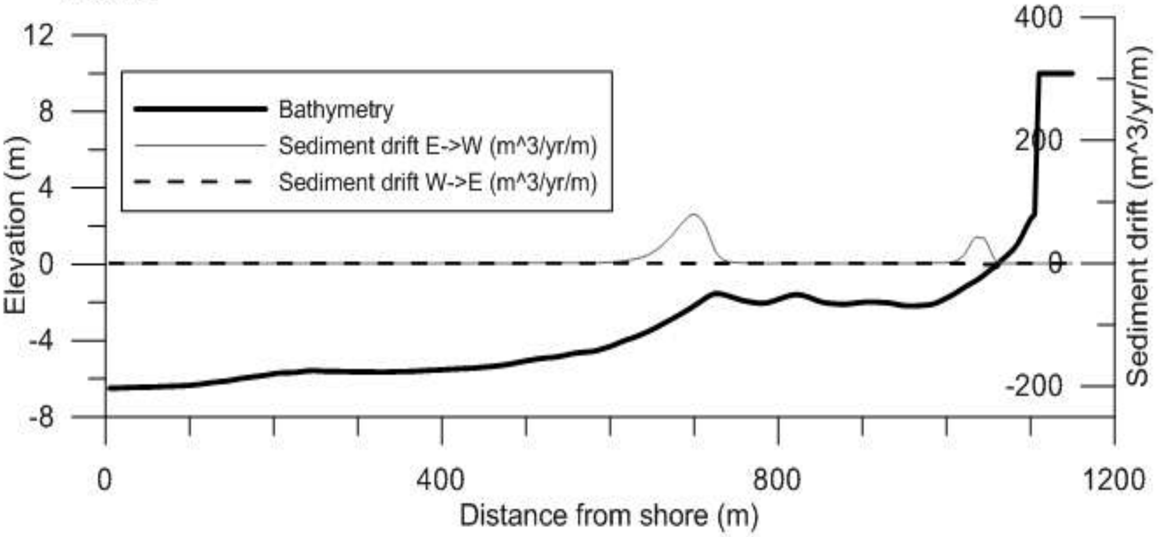
Profile 2



Profile 3

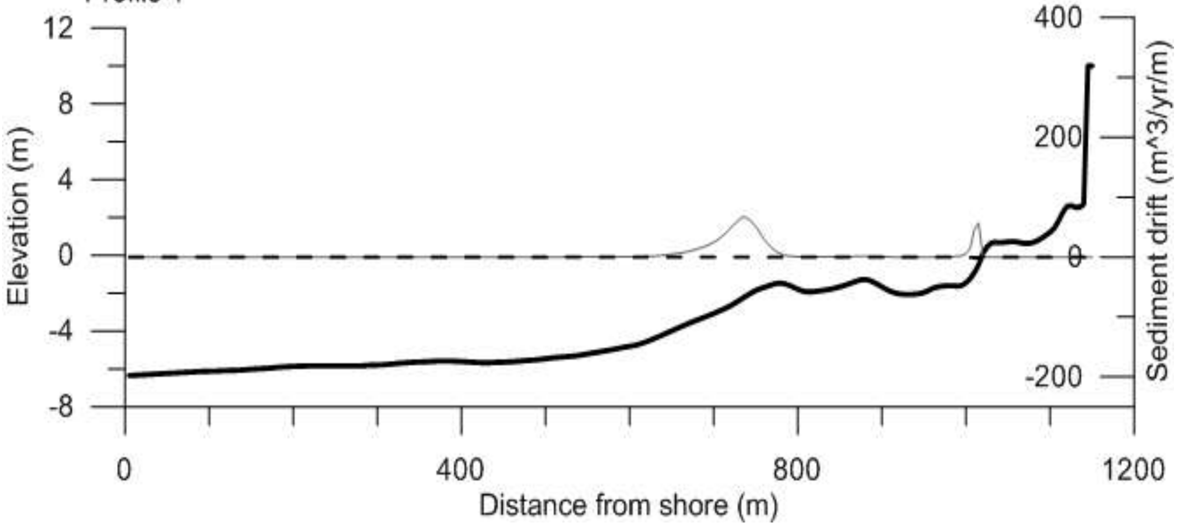


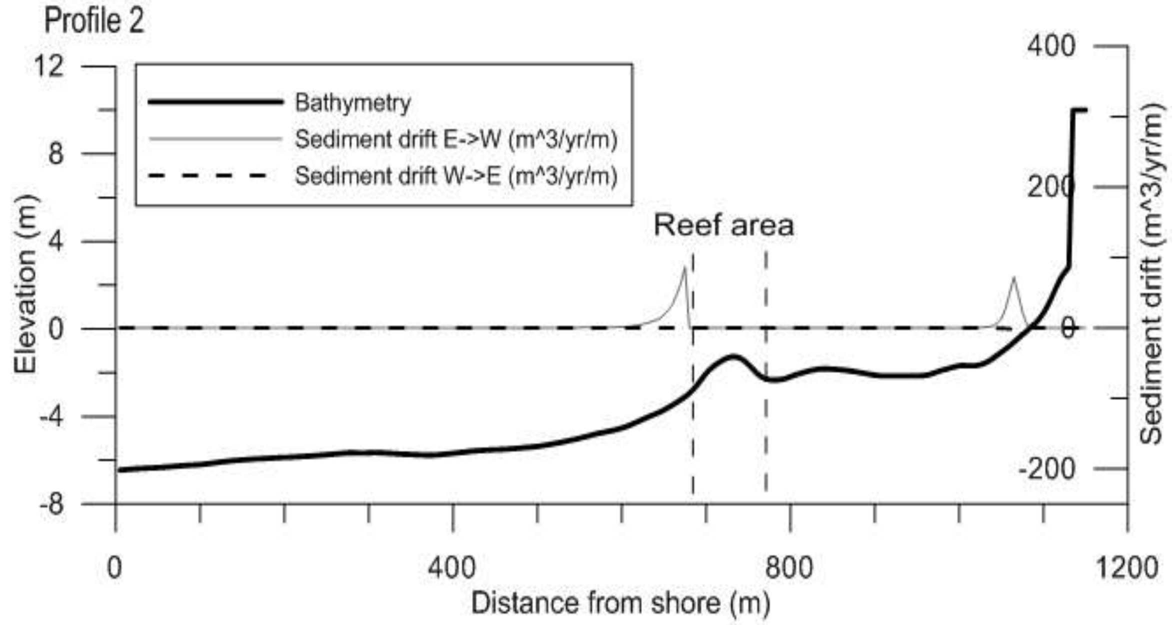
Profile 4

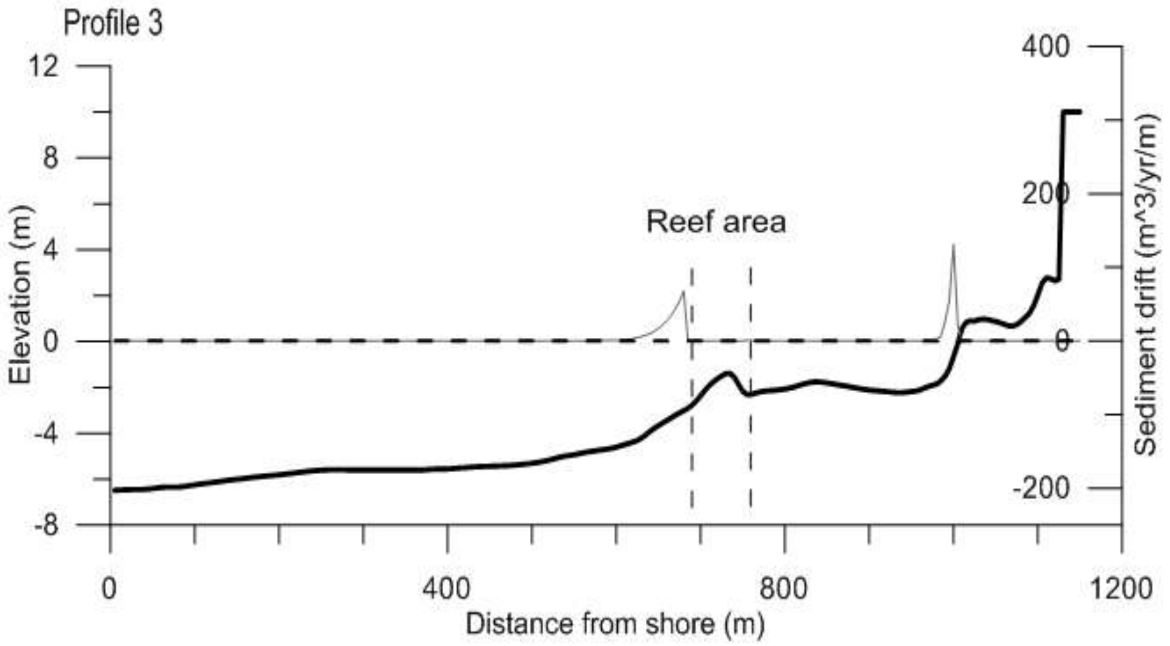


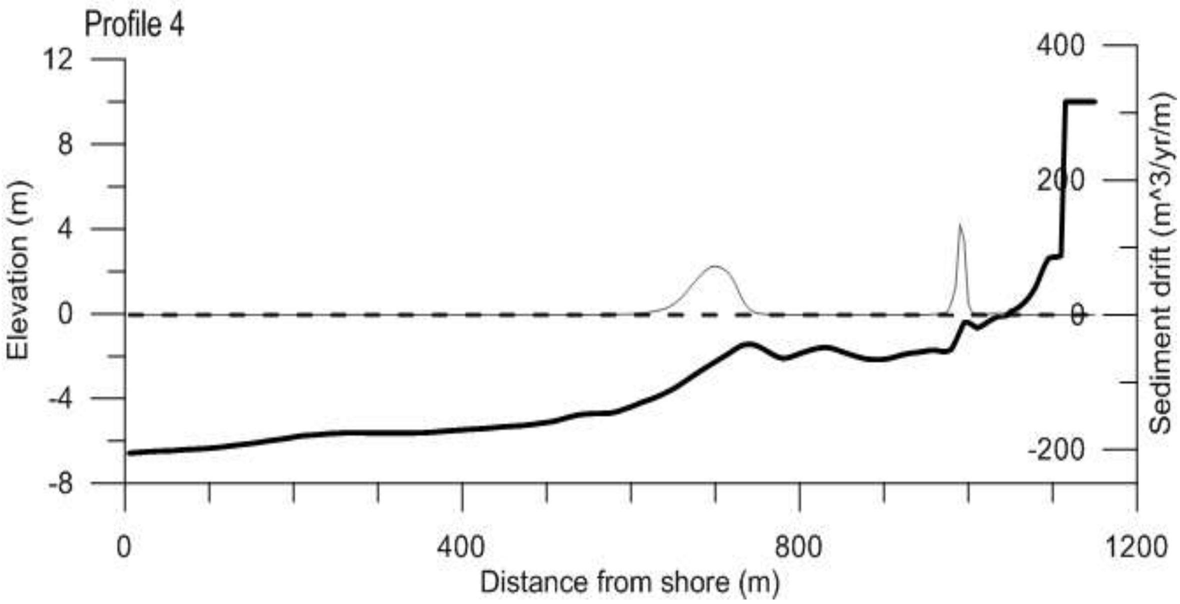
Alternative 3 - Surfing Reef with Western arm extension in Heidkate beach (perpendicular to the coast)

Profile 1



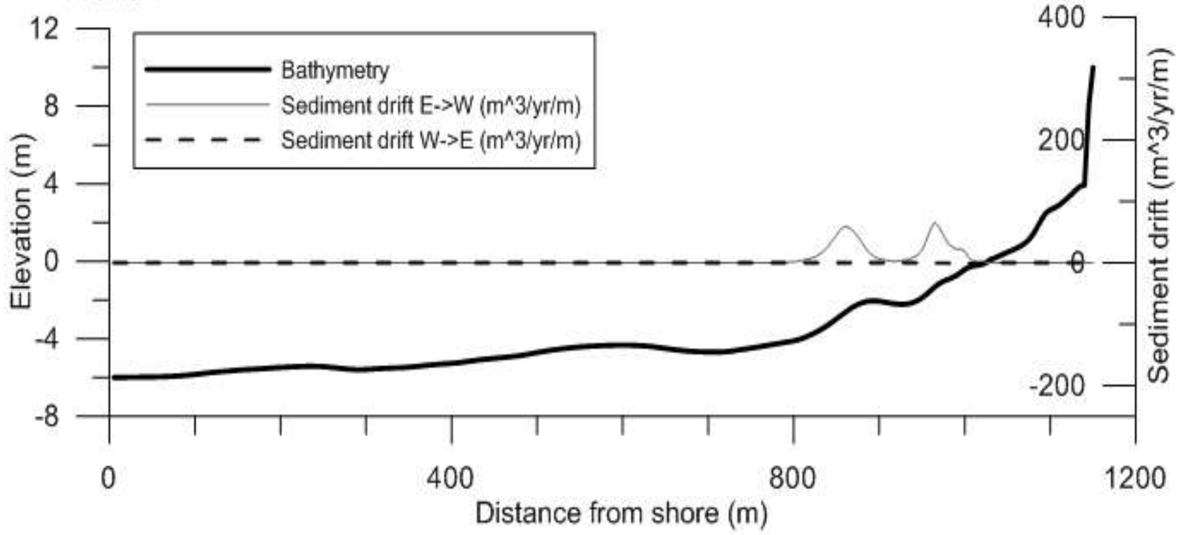

Profile 2
Bathymetry
Sediment drift E->W (m^3/yr/m)
Sediment drift W->E (m^3/yr/m)
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200


Profile 3
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

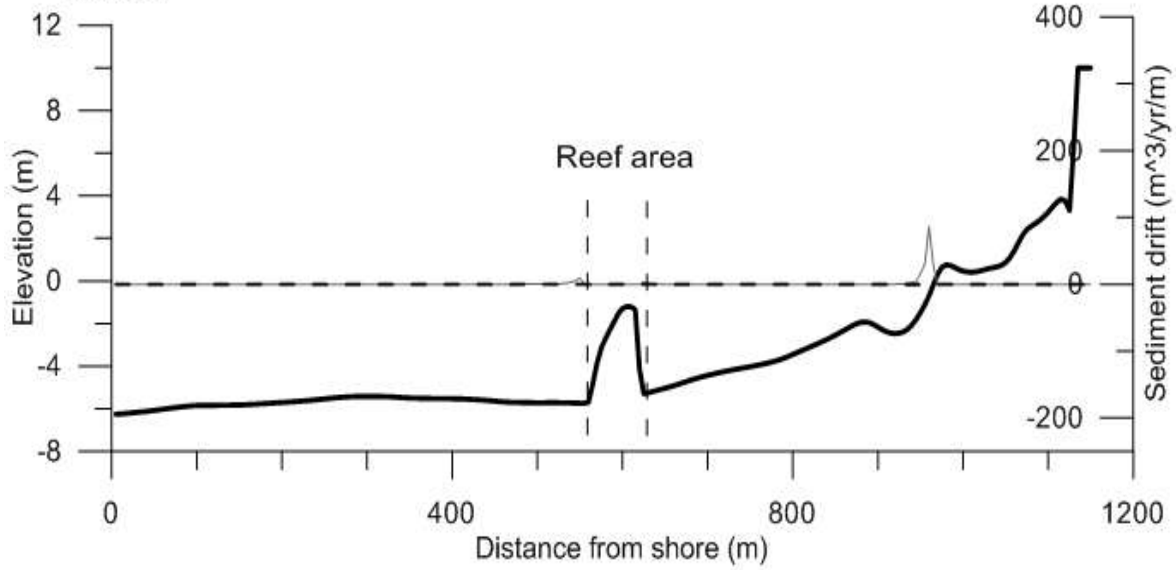

Profile 4
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

Alternative 4 - Surfing Reef without arm extensions in Brasilien beach (45° from North)

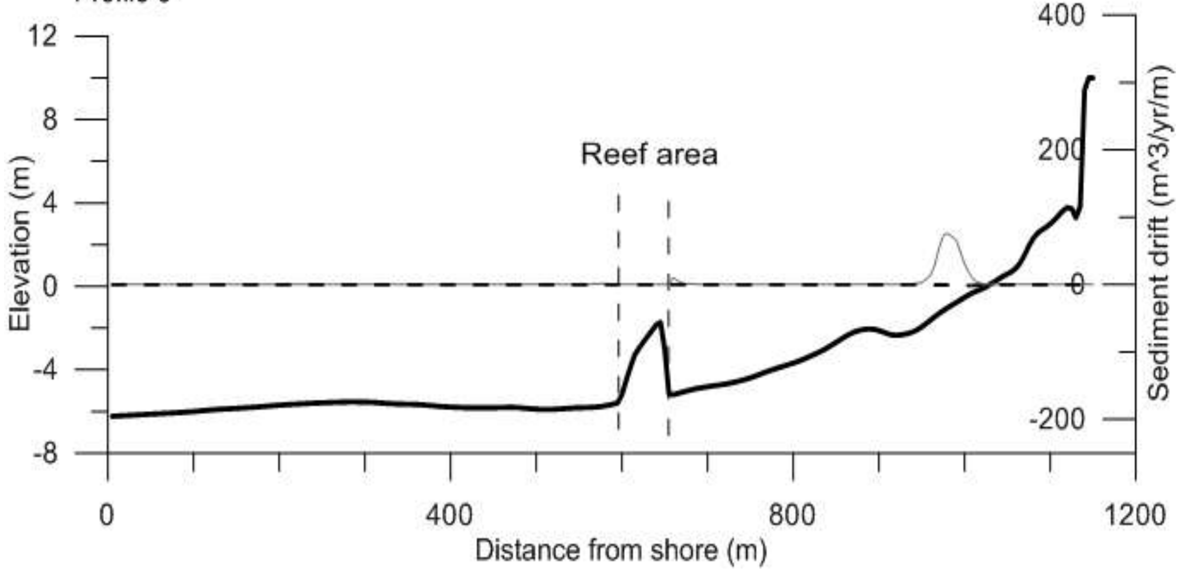
Profile 1



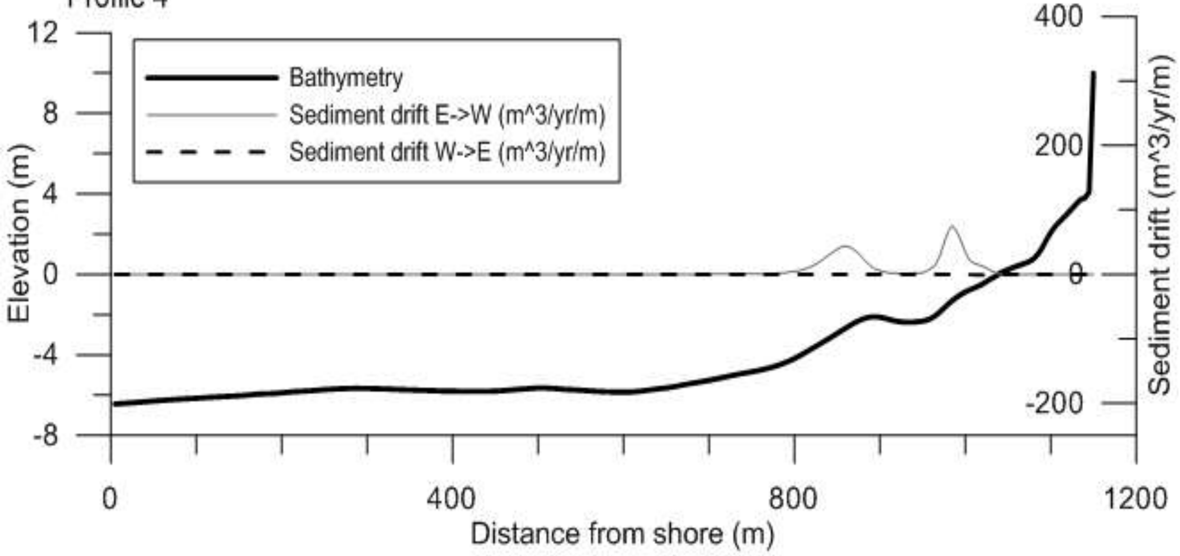
Profile 2



Profile 3

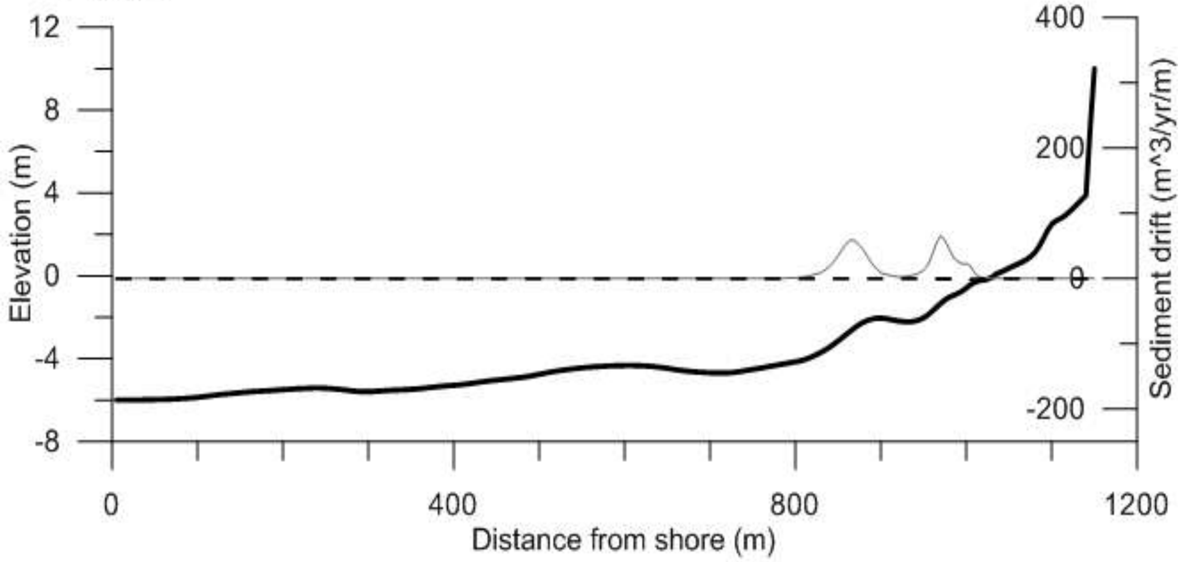


Profile 4

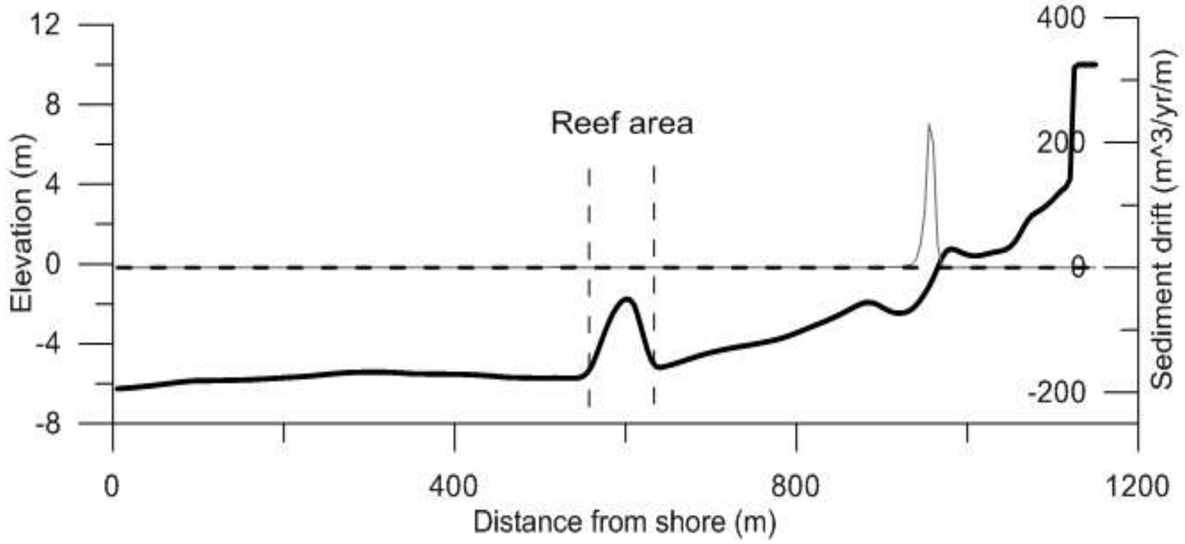


Alternative 5 - Surfing Reef with Eastern arm extension in Brasilien beach (45° from North)

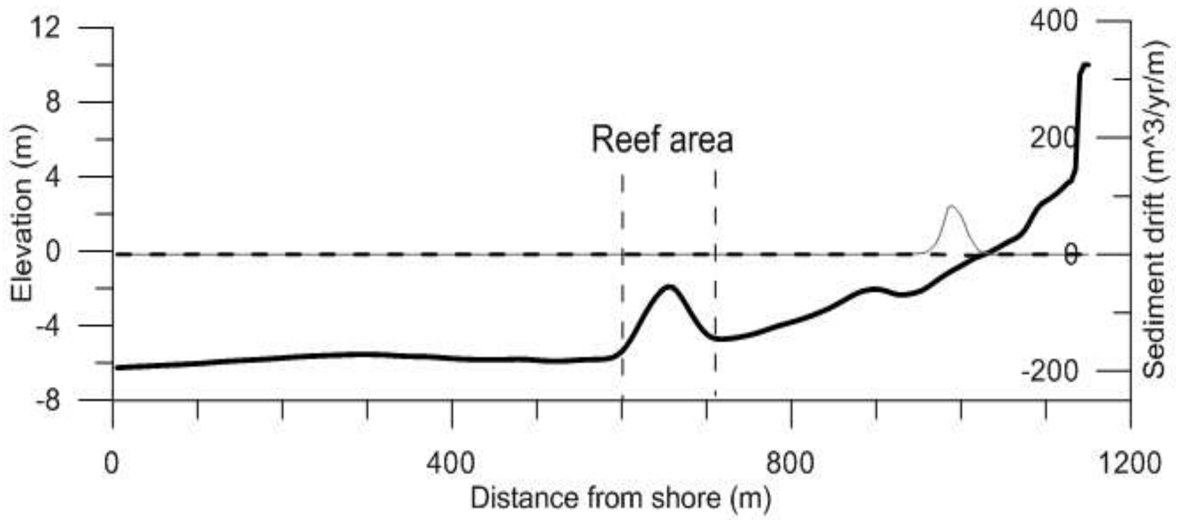
Profile 1



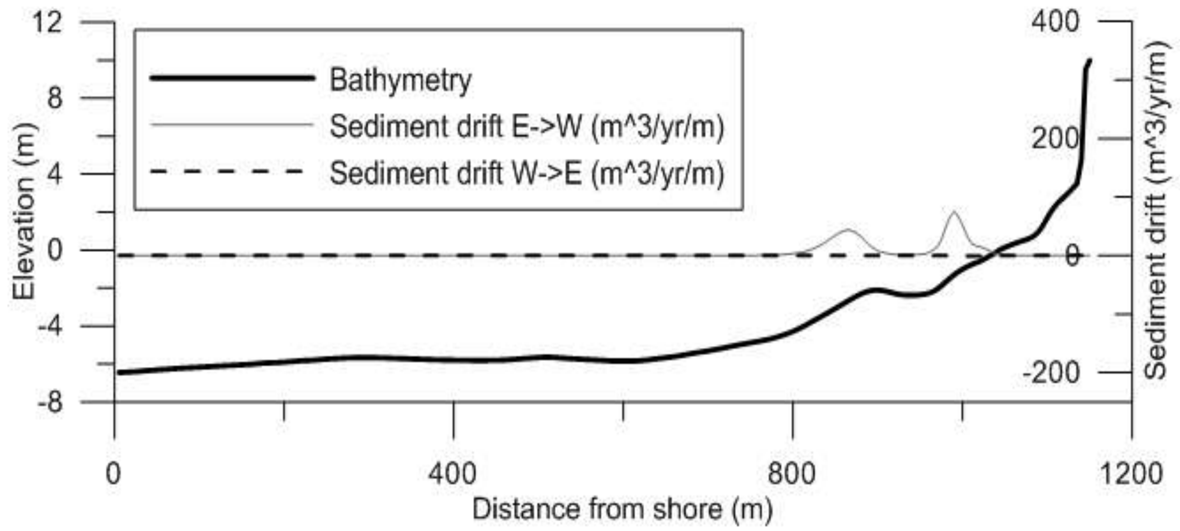
Profile 2



Profile 3

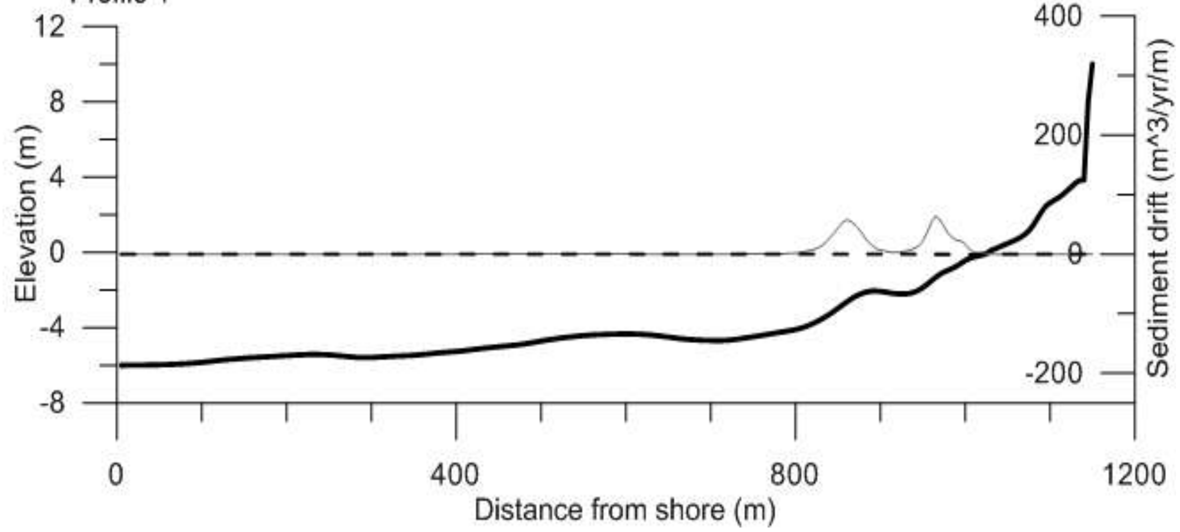


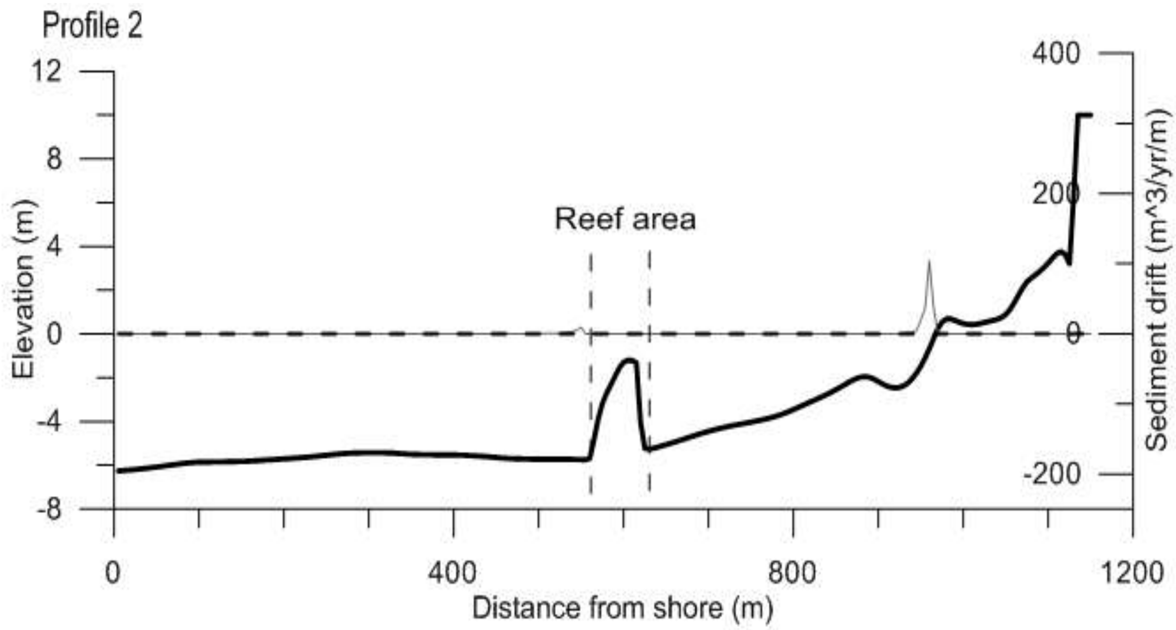
Profile 4

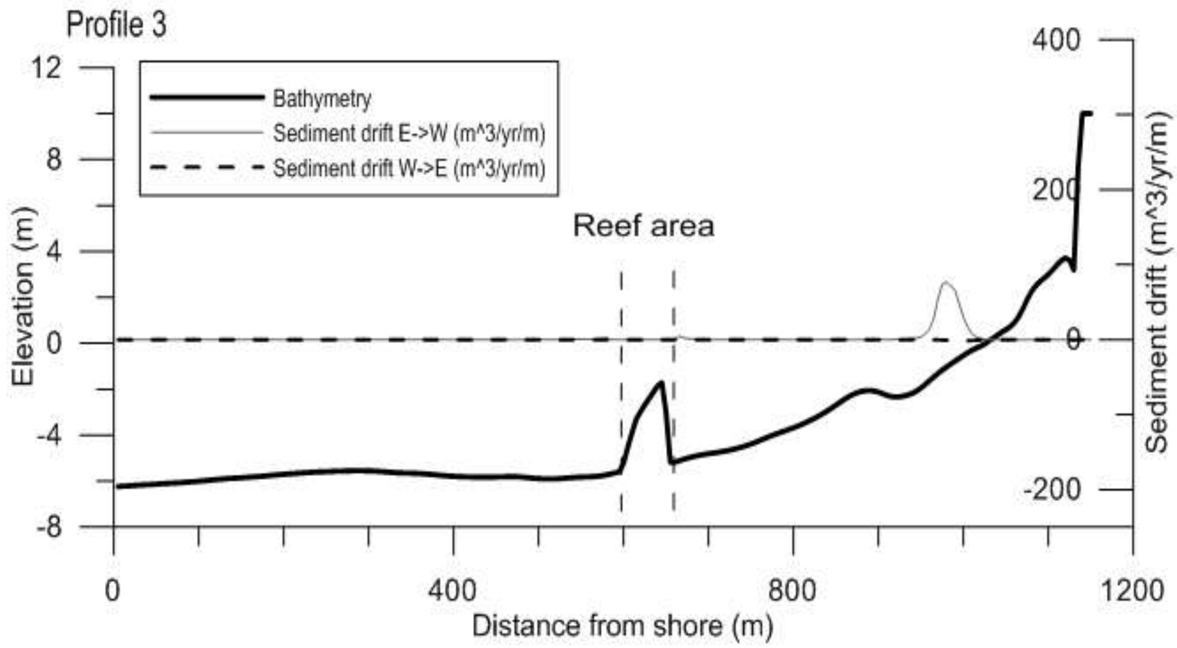


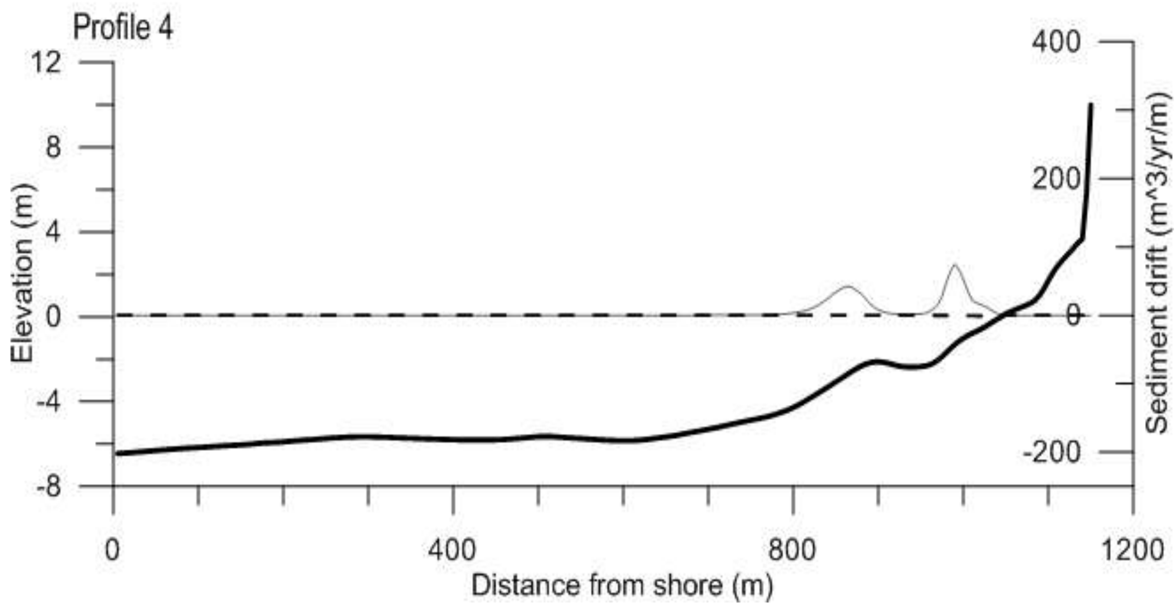
Alternative 6 - Surfing Reef with Western arm extension in Brasilien beach (45° from North)

Profile 1

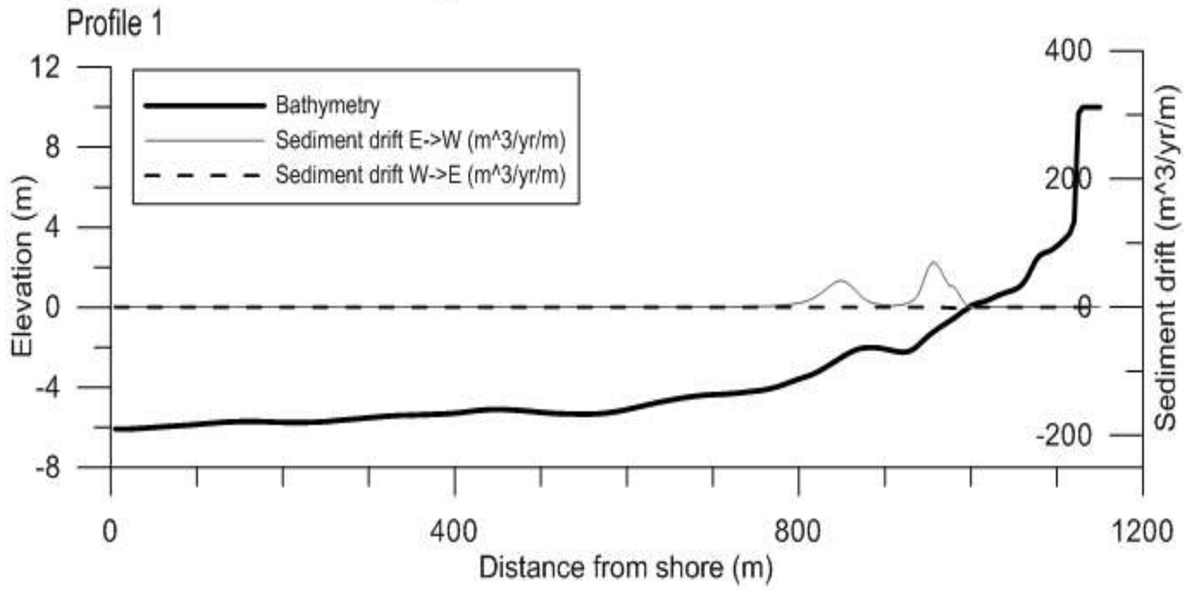


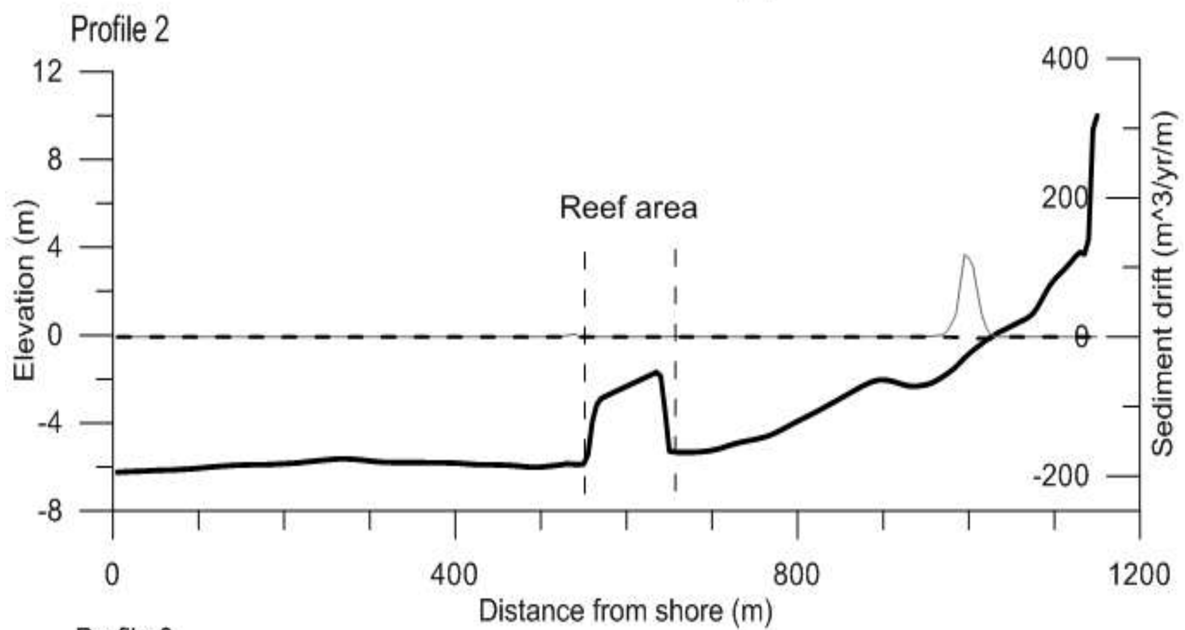

Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

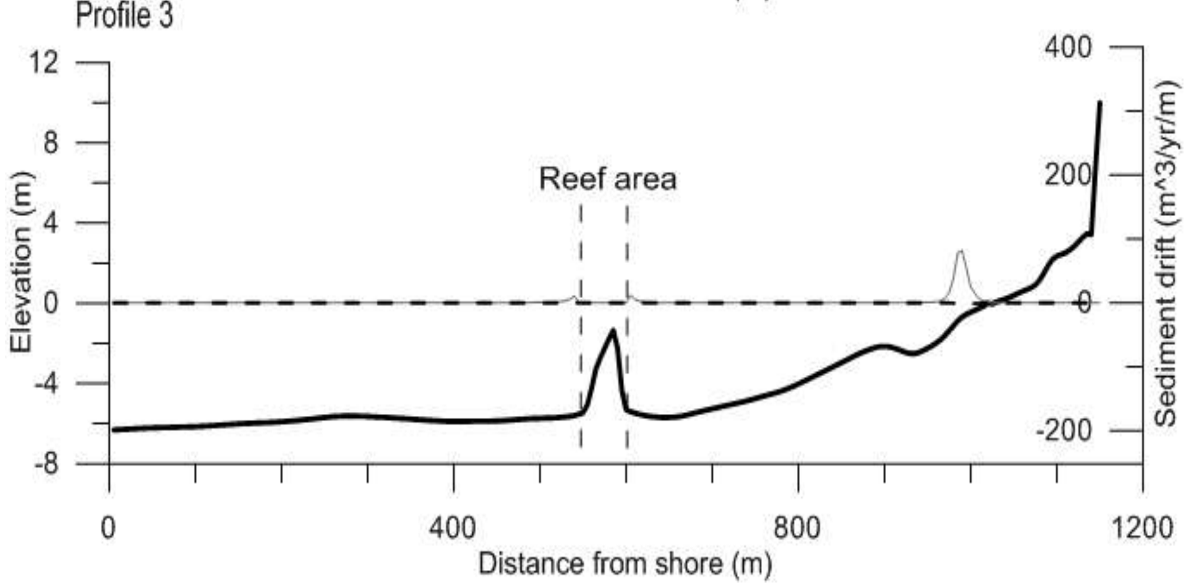

Profile 3
Bathymetry
Sediment drift E->W (m^3/yr/m)
Sediment drift W->E (m^3/yr/m)
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200


Profile 4
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

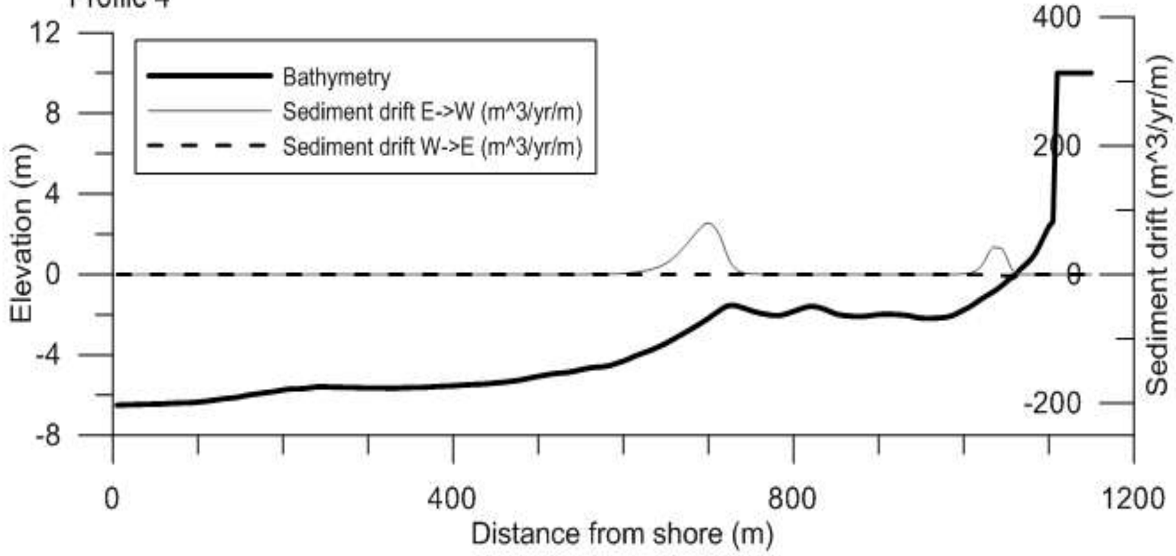
Alternative 4 - Surfing Reef without arm extensions in Brasilien beach (perpendicular to the coast)





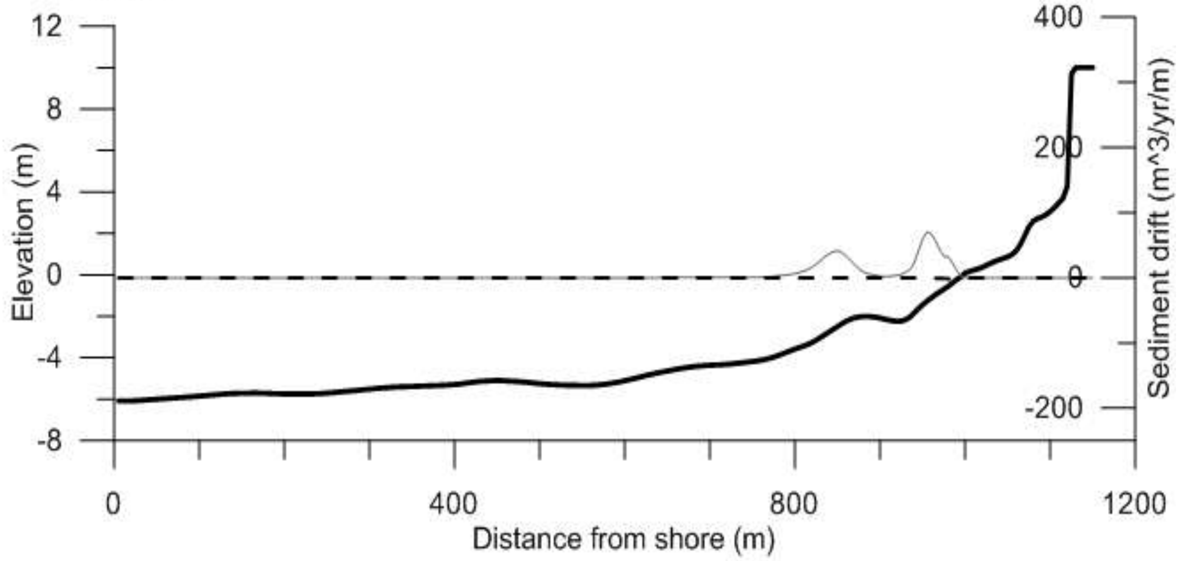


Profile 4

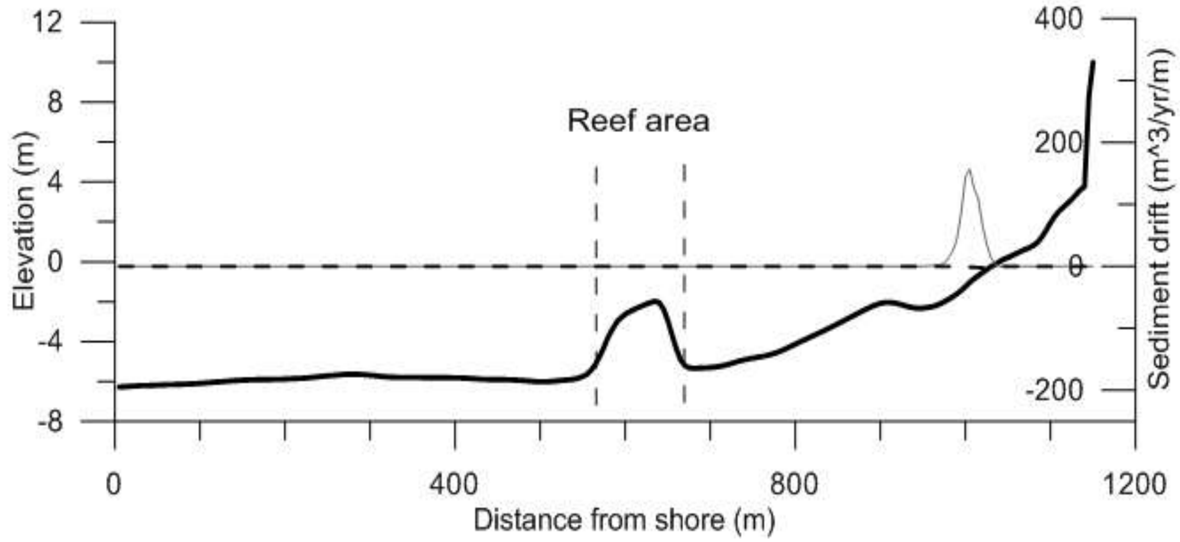


Alternative 5 - Surfing Reef with Eastern arm extension in Brasilien beach (perpendicular to the coast)

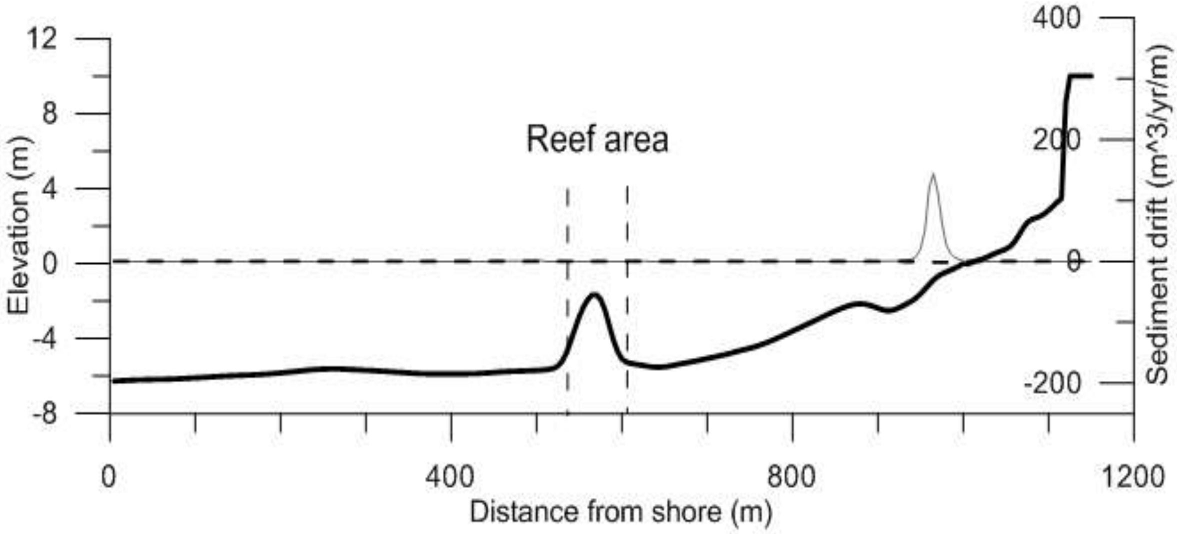
Profile 1



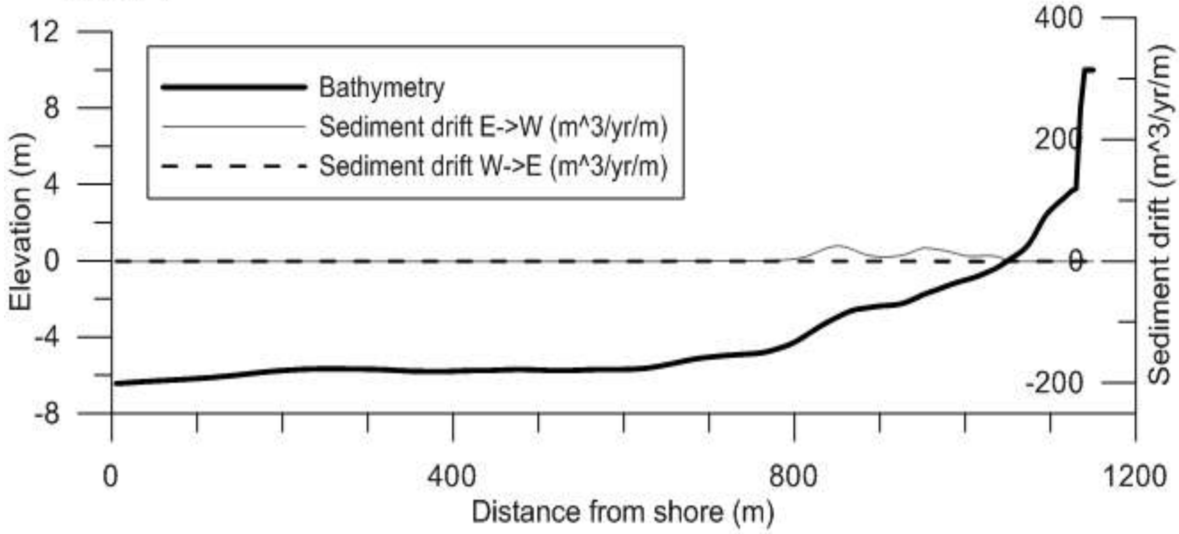
Profile 2



Profile 3

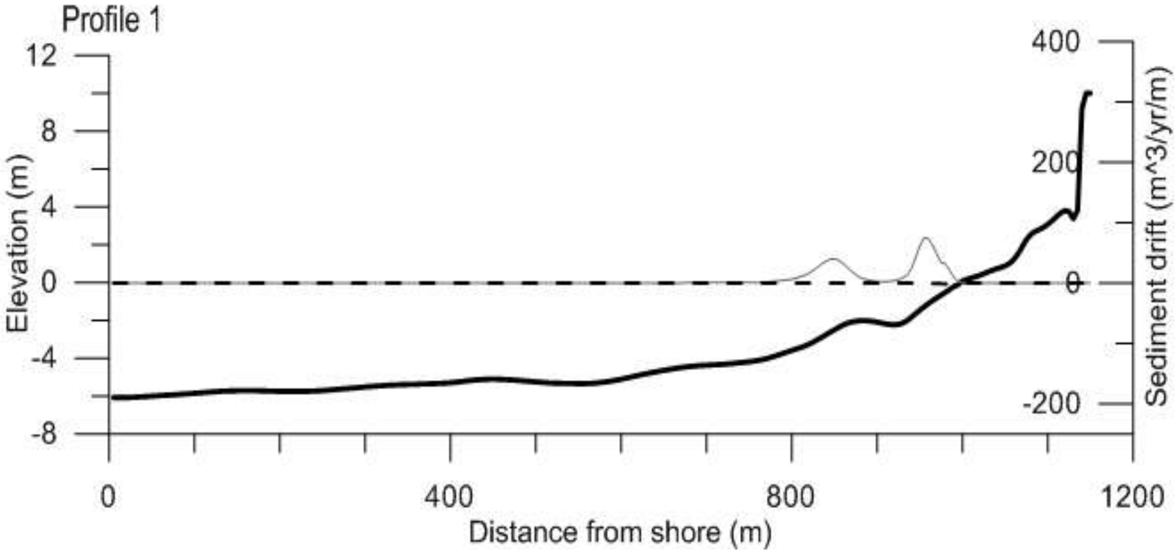


Profile 4

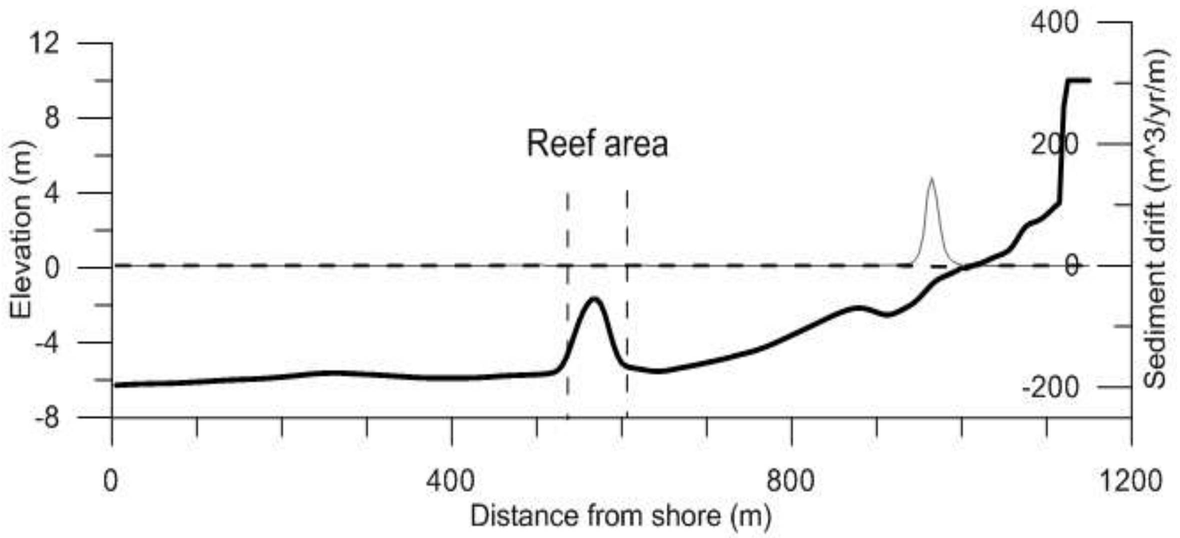


Alternative 6 - Surfing Reef with Western arm extension in Brasilien beach (perpendicular to the coast)

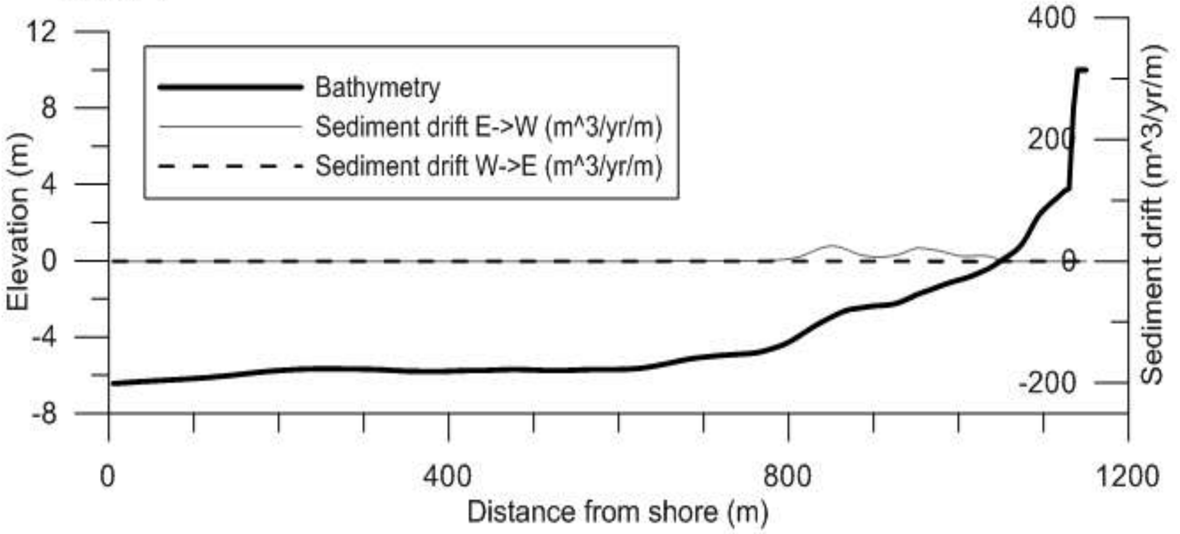
Profile 1



Profile 3

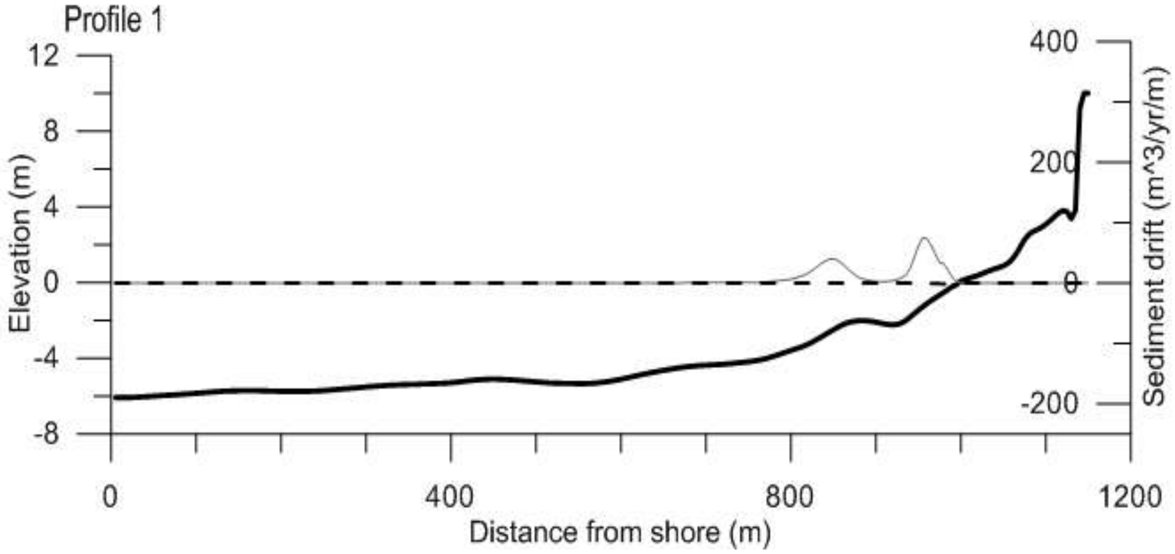


Profile 4

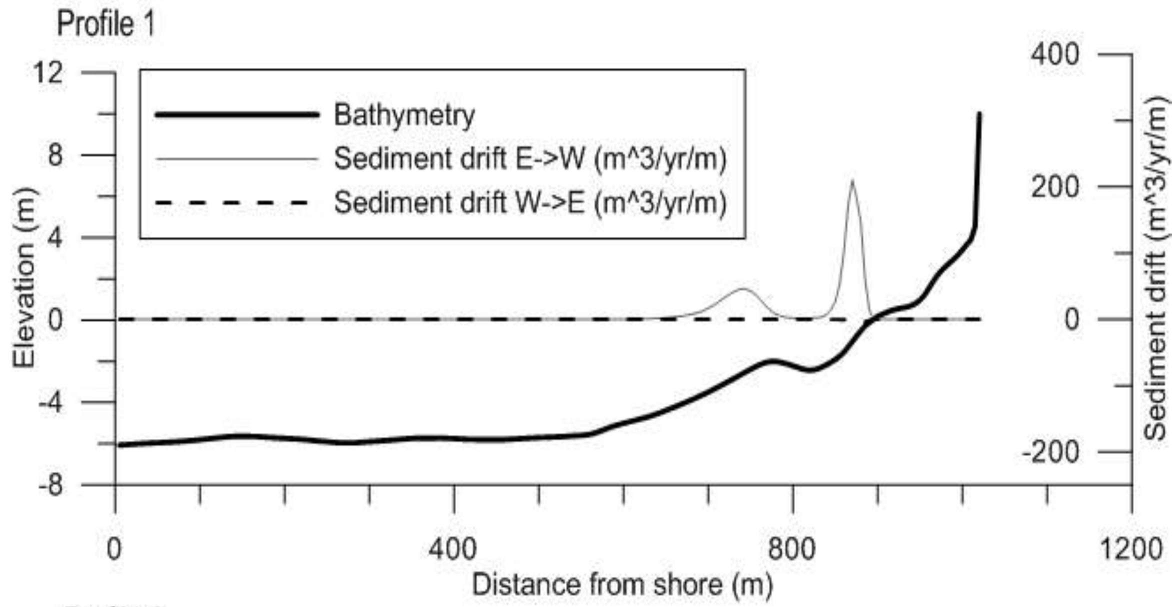


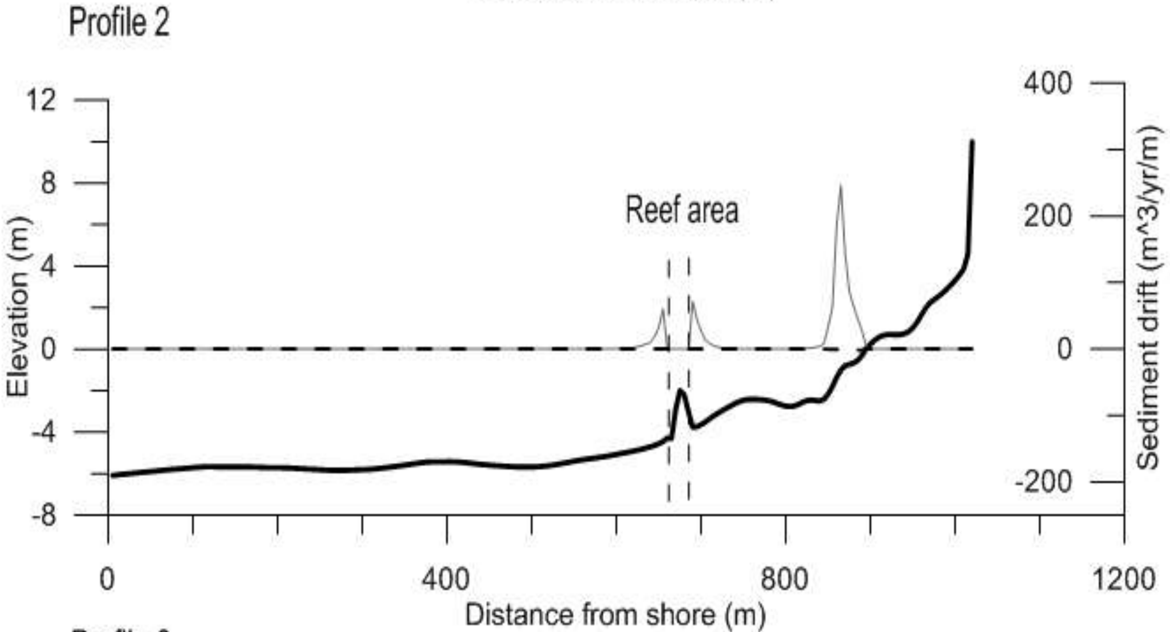
Alternative 6 - Surfing Reef with Western arm extension in Brasilien beach (perpendicular to the coast)

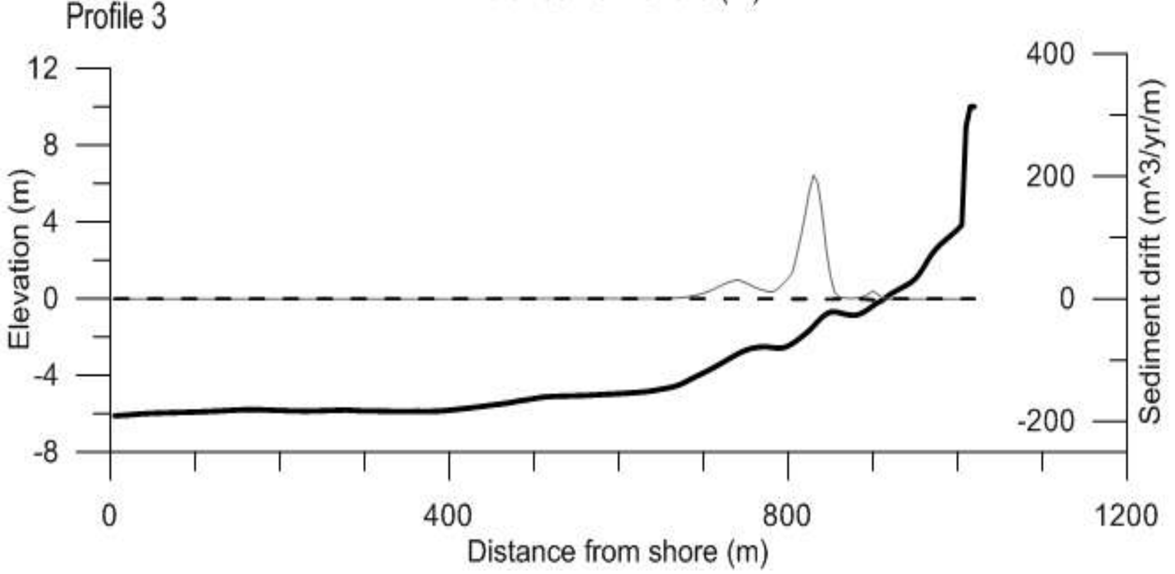
Profile 1



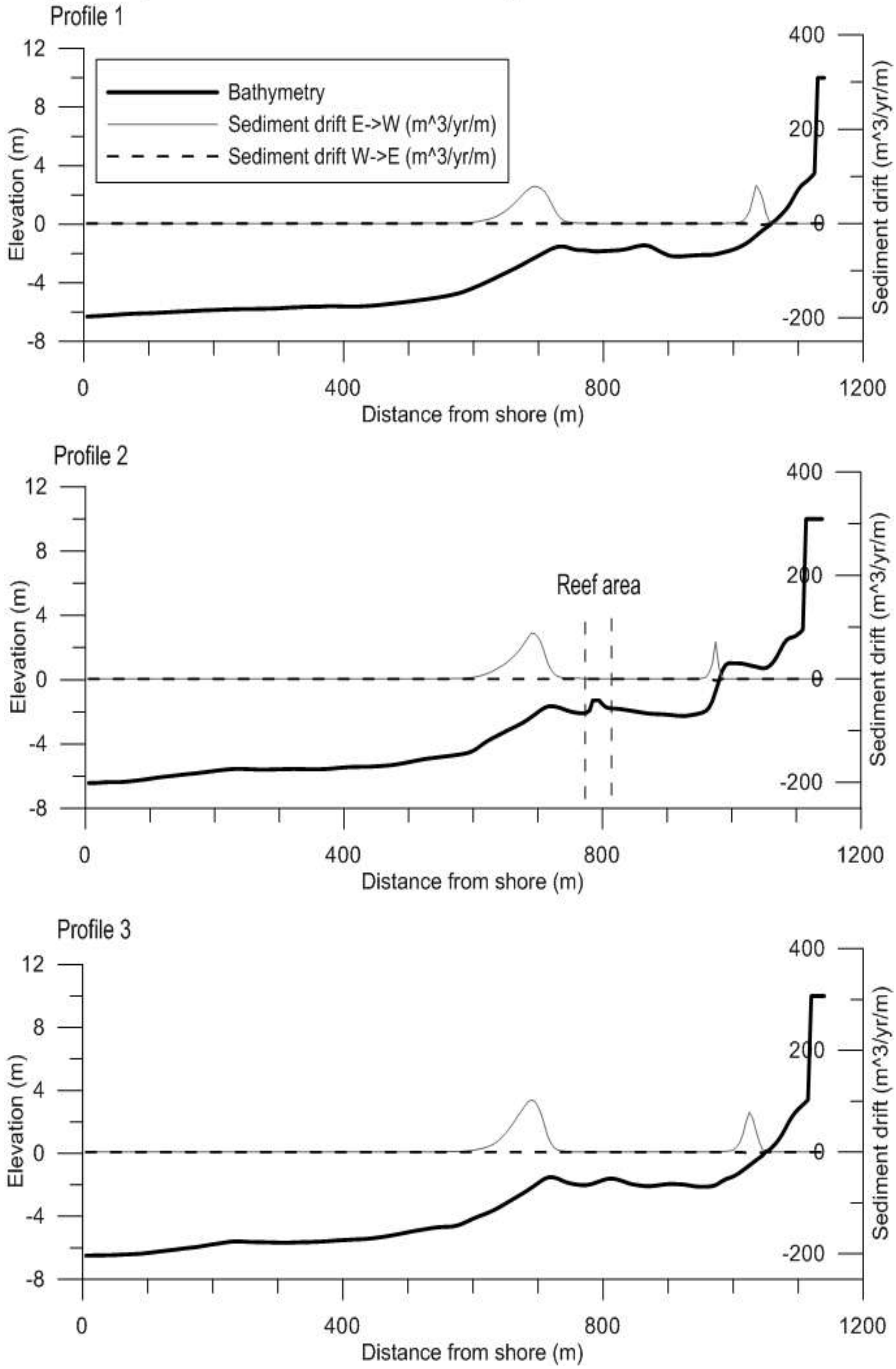
Alternative 7 - Shore-parallel breakwater in Brasilien Beach

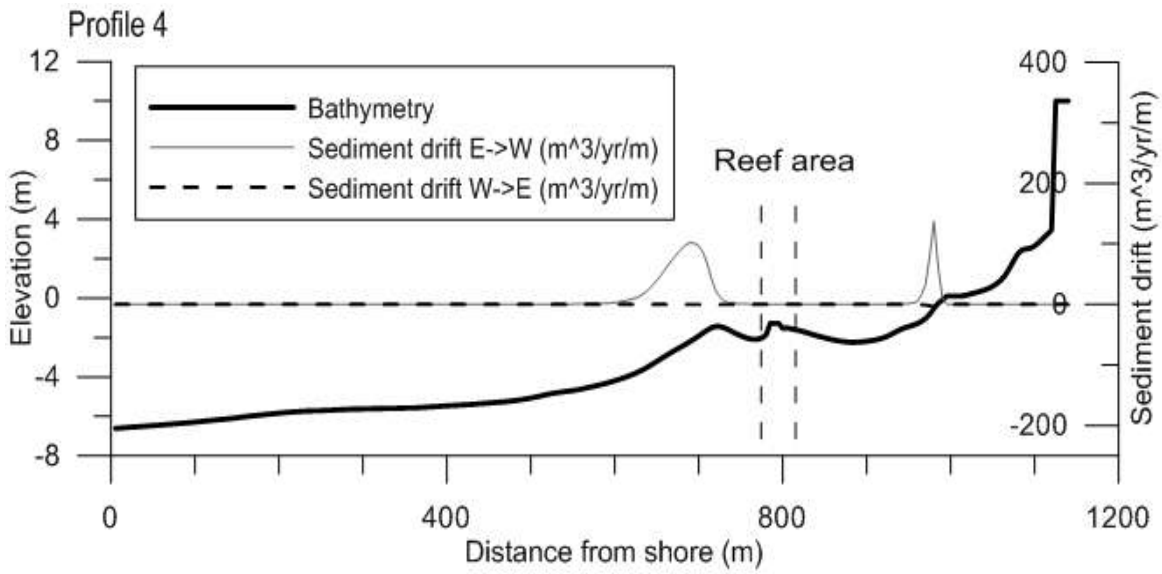


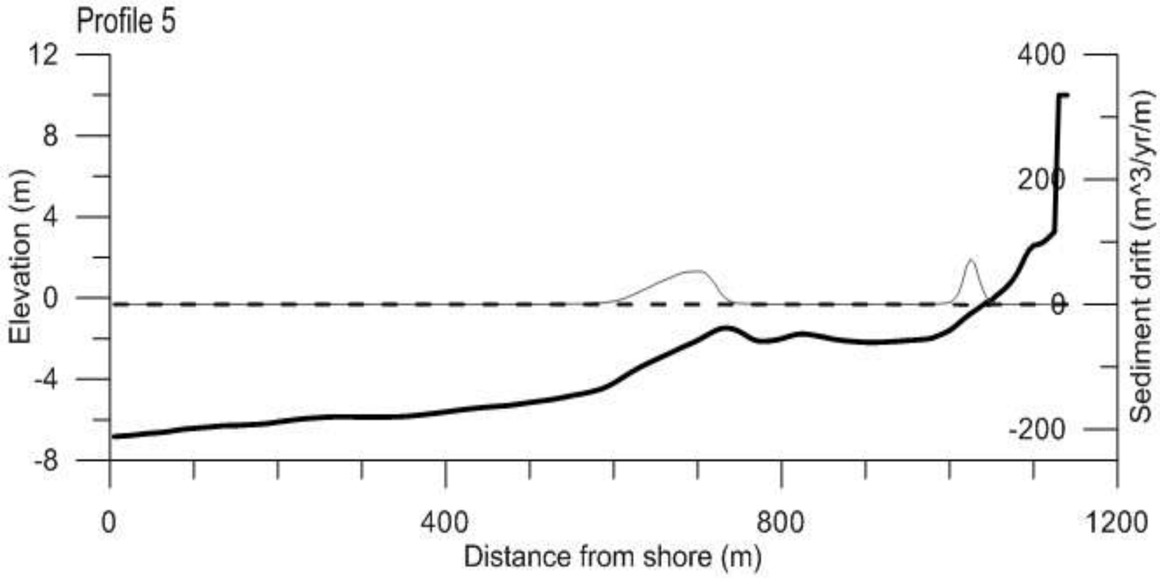




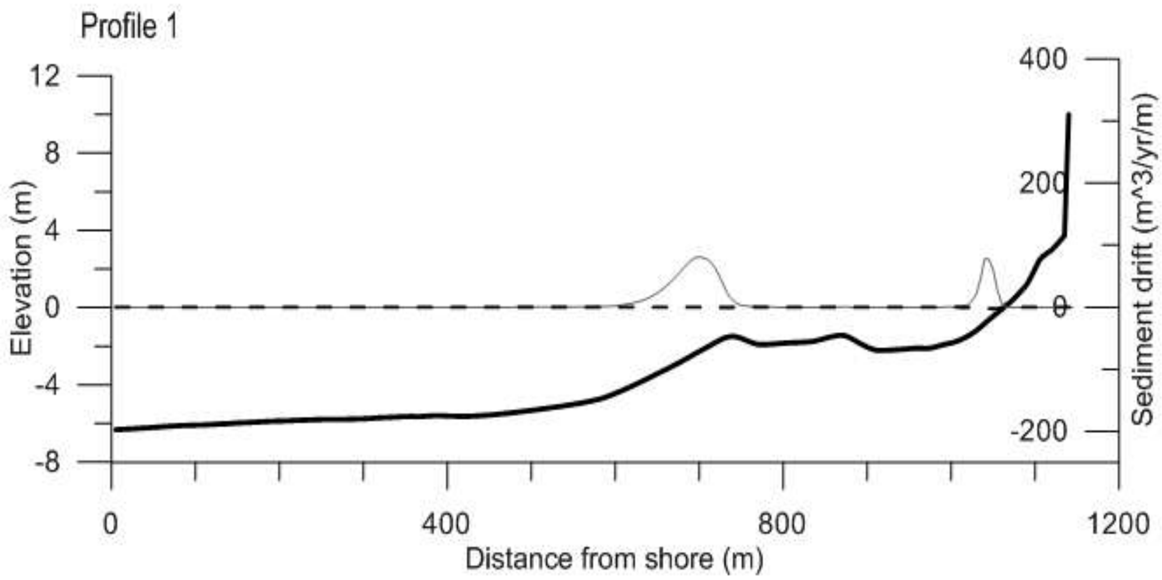
Alternative 8 - Reef Balls Breakwater in Heidkate beach
(coastal protection and habitat enhancment)

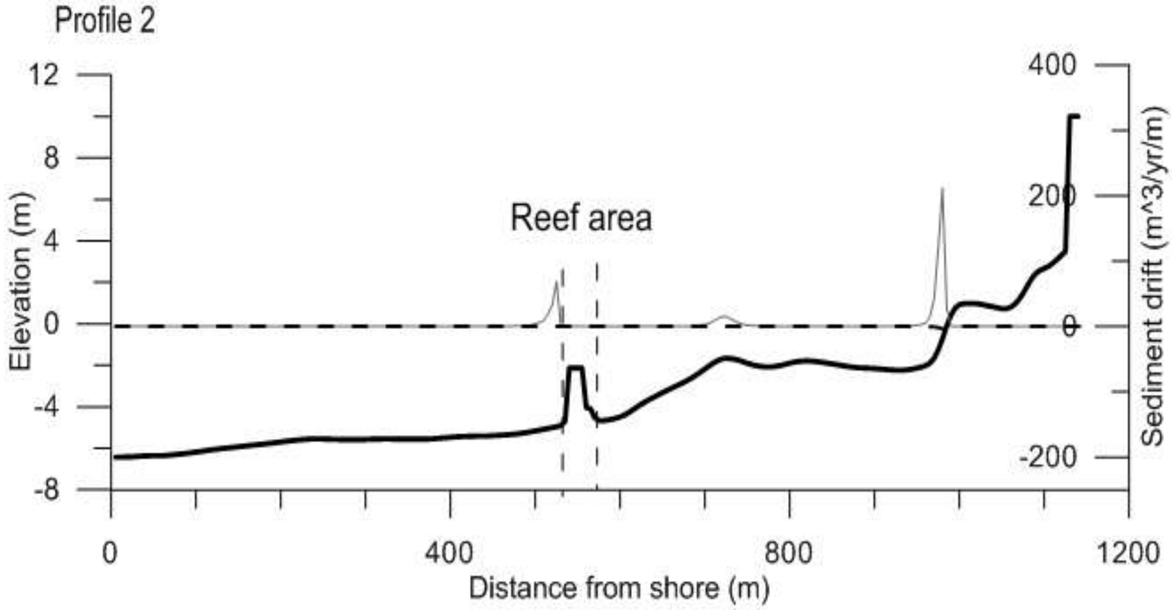


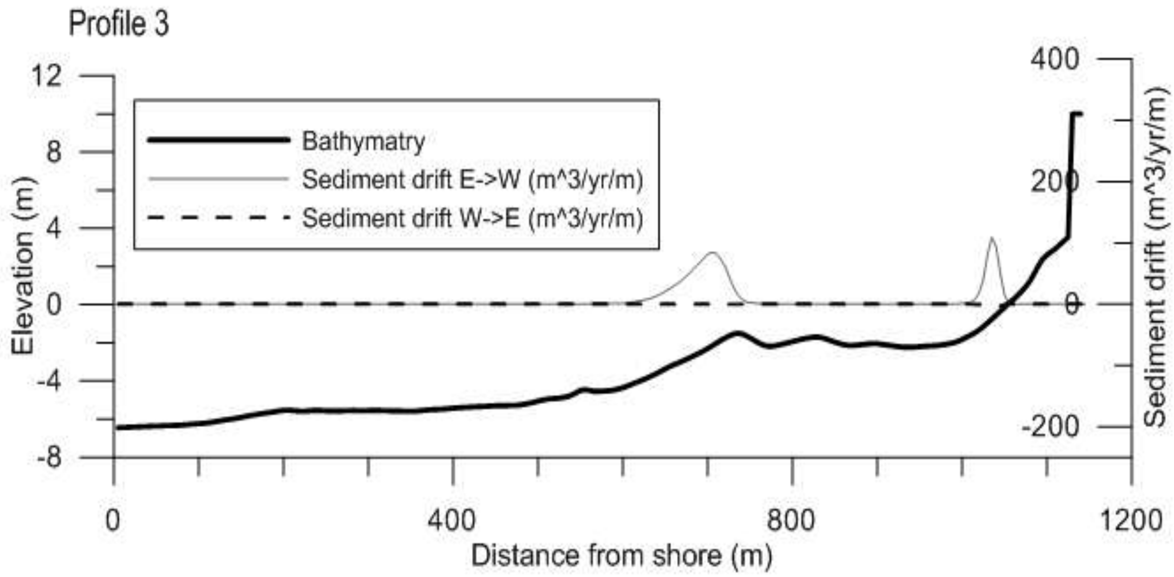


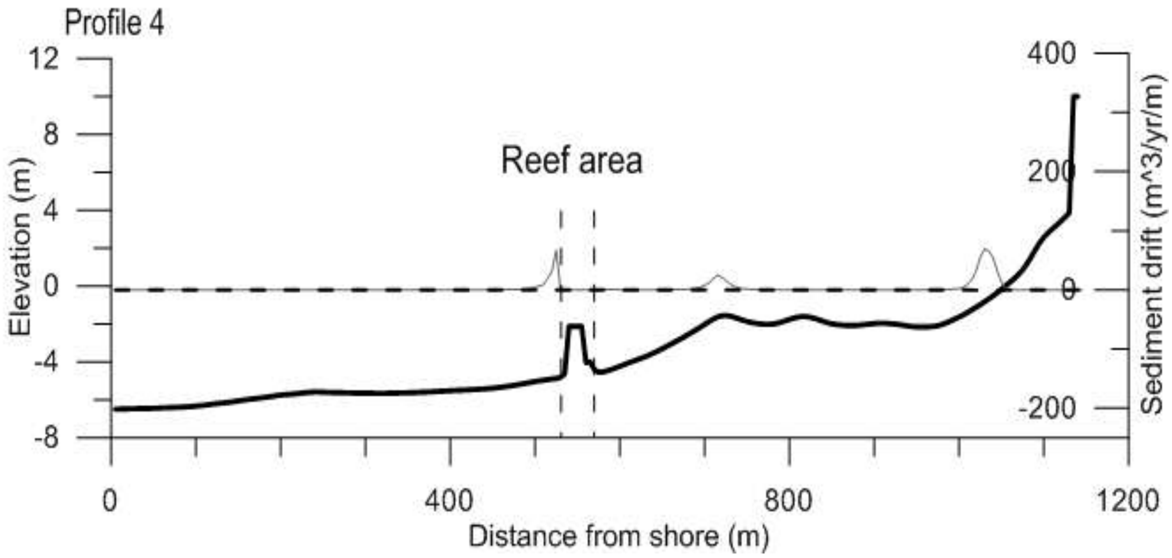


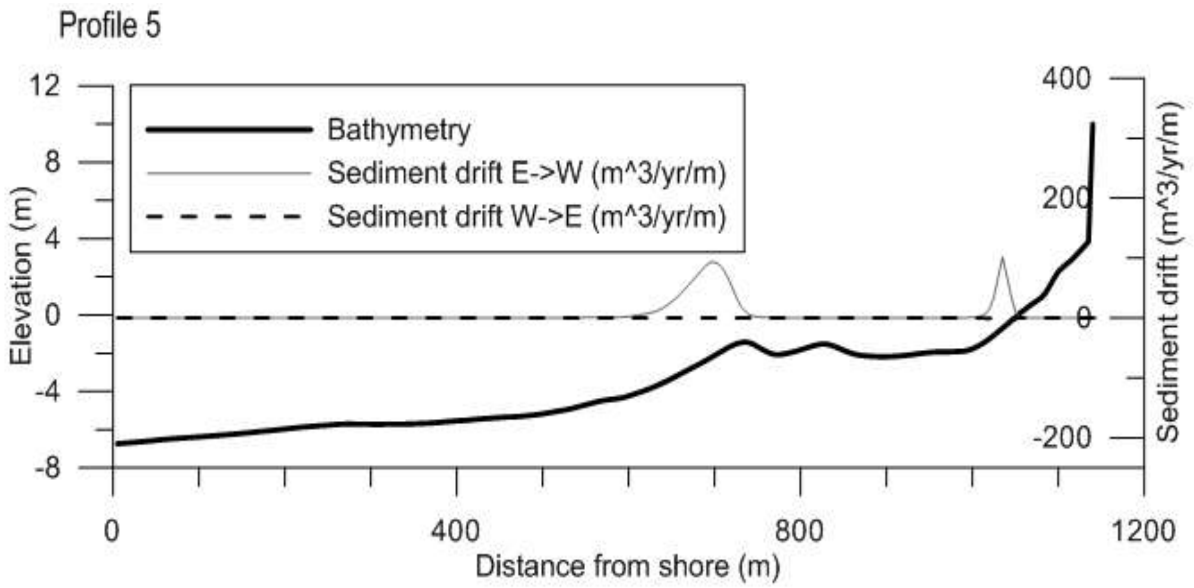
Alternative 9 - Reef Ball Breakwater in Heidkate beach (habitat enhancement)



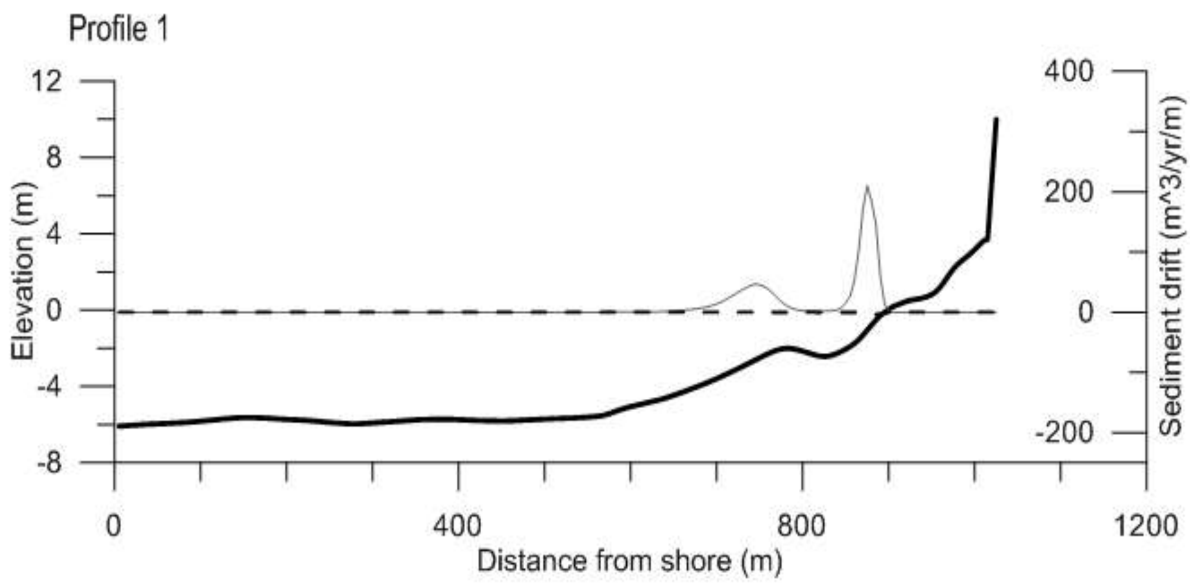

Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

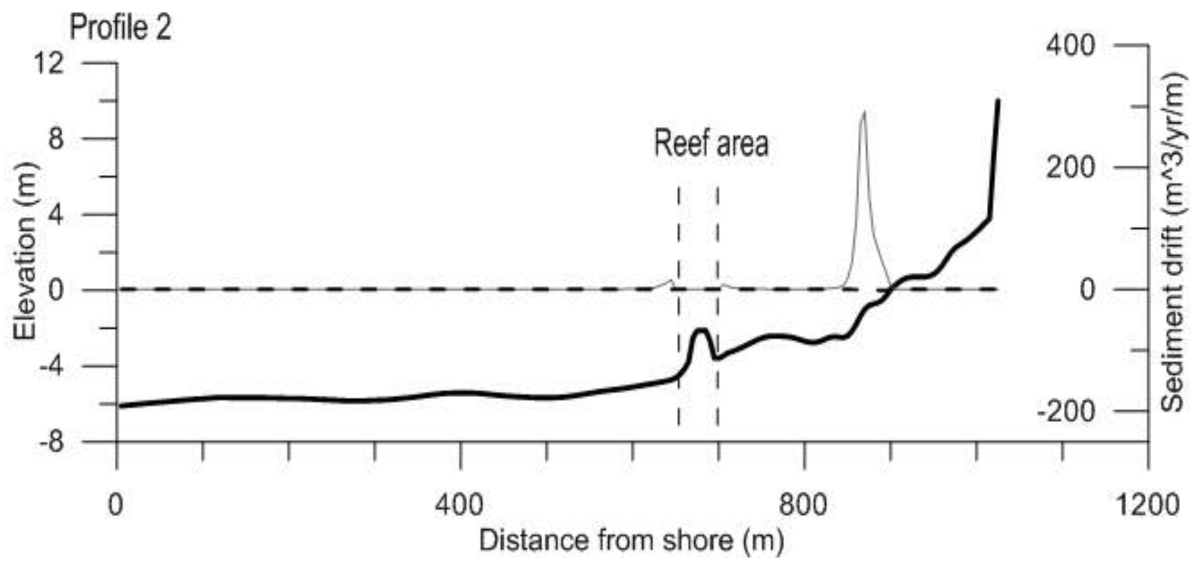

Profile 3
Bathymatry
Sediment drift E->W (m^3/yr/m)
Sediment drift W->E (m^3/yr/m)
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200


Profile 4
Reef area
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

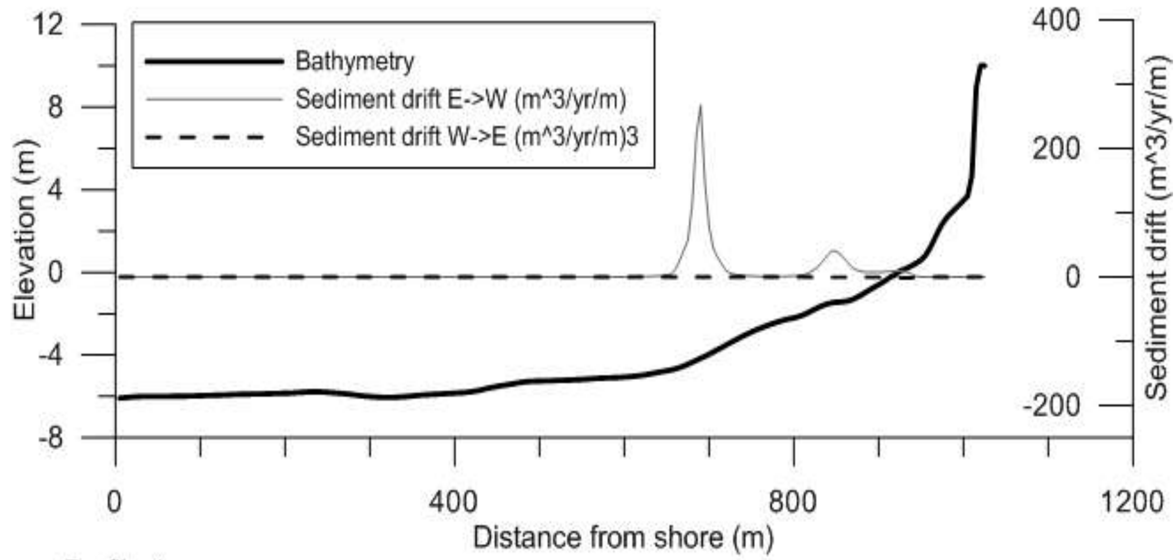


Alternative 10 - Reef Balls Breakwater in brasilien Beach
(coastal protection and habitat enhacement)

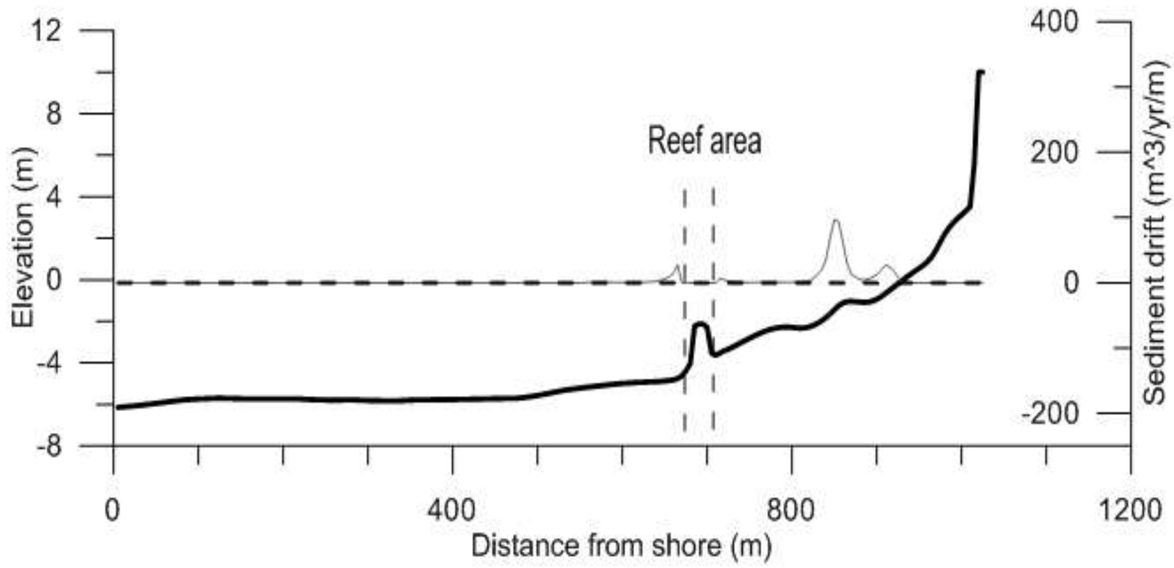




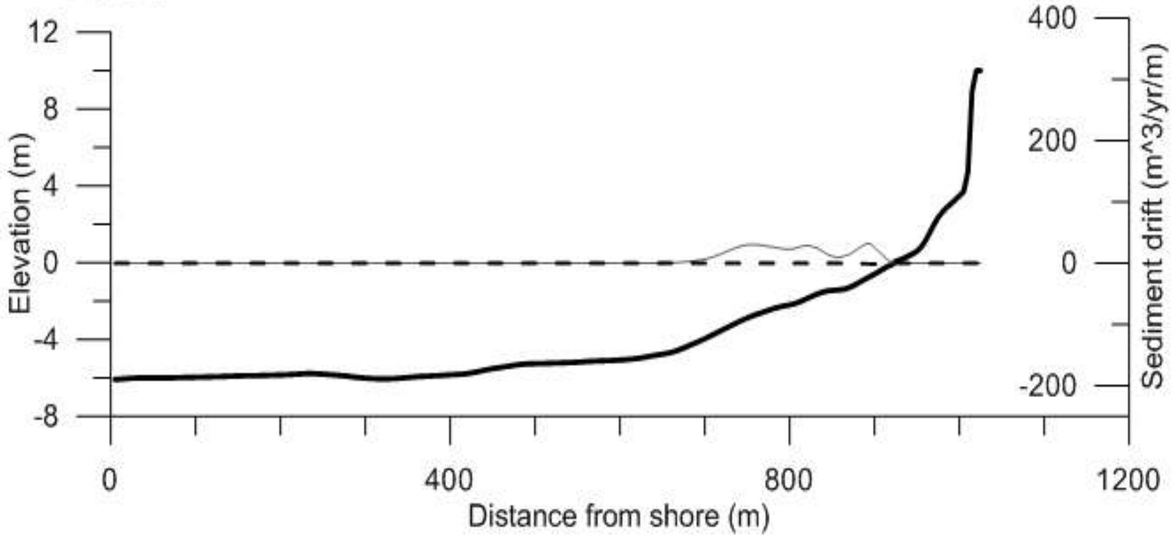
Profile 3



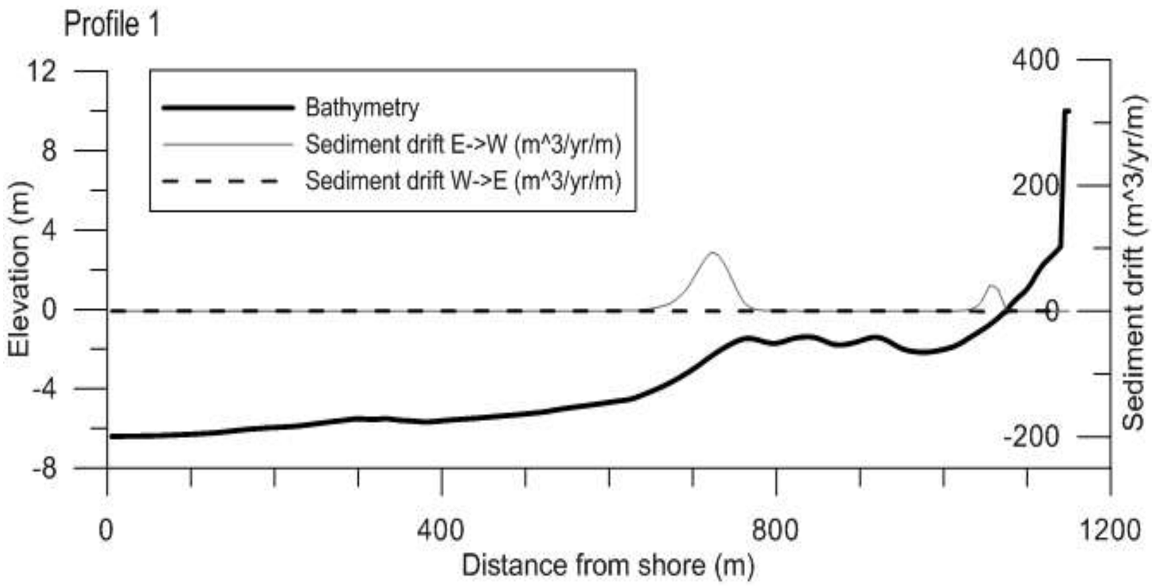
Profile 4

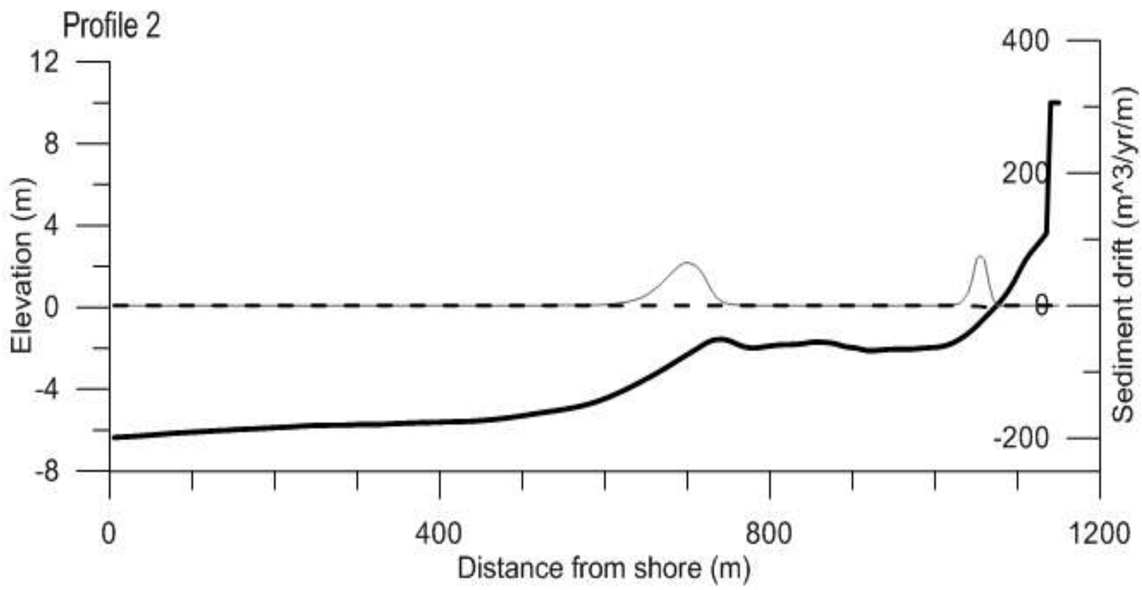


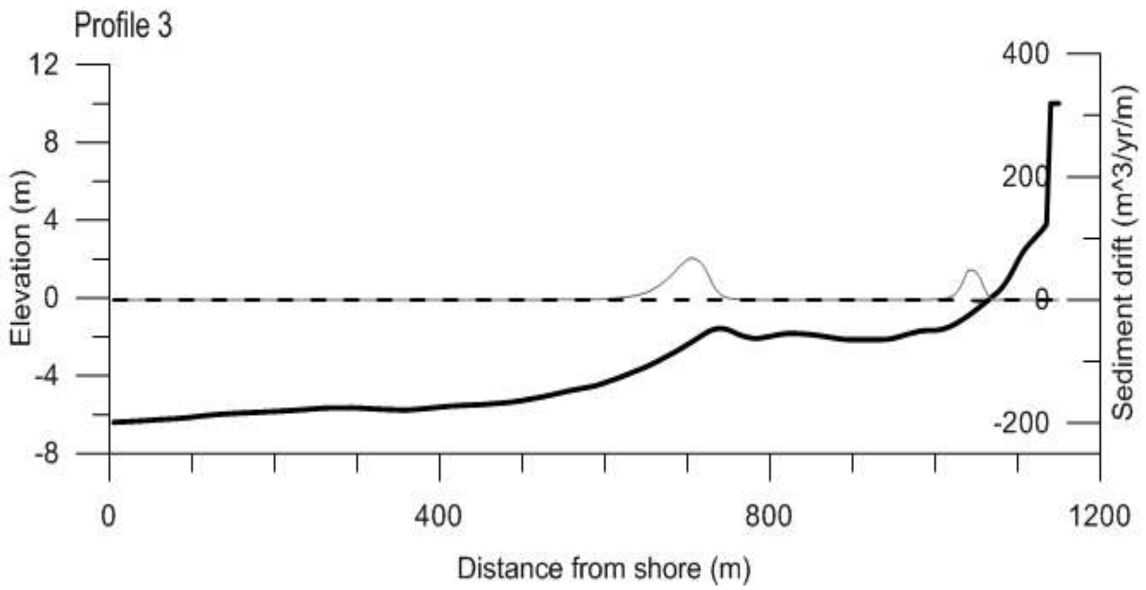
Profile 5

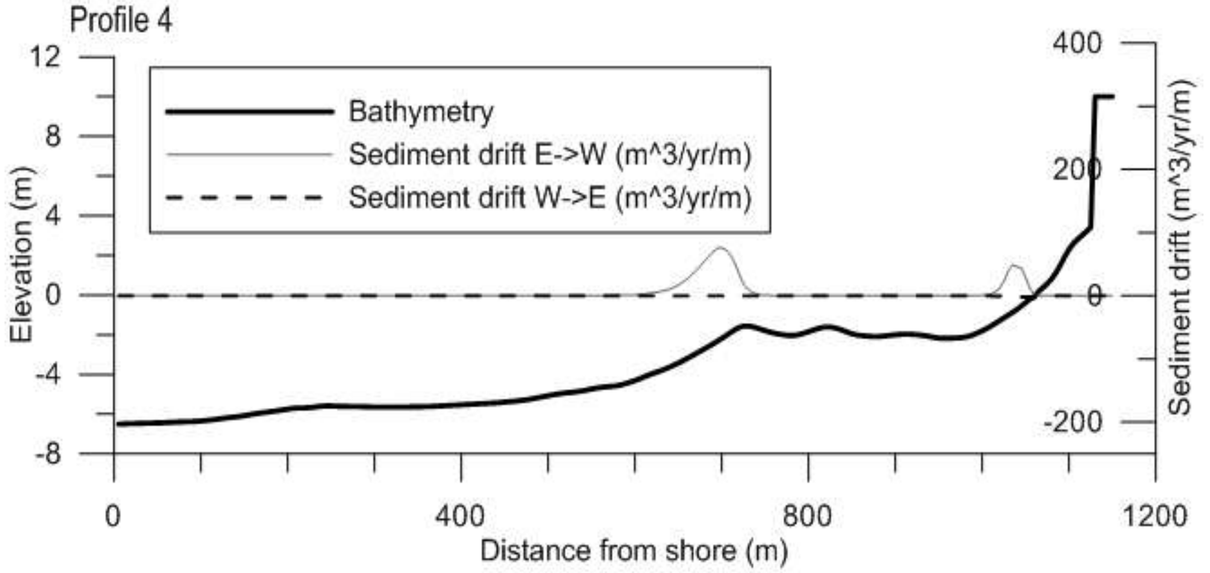


Reference conditions - no breakwater. Heidkate Beach

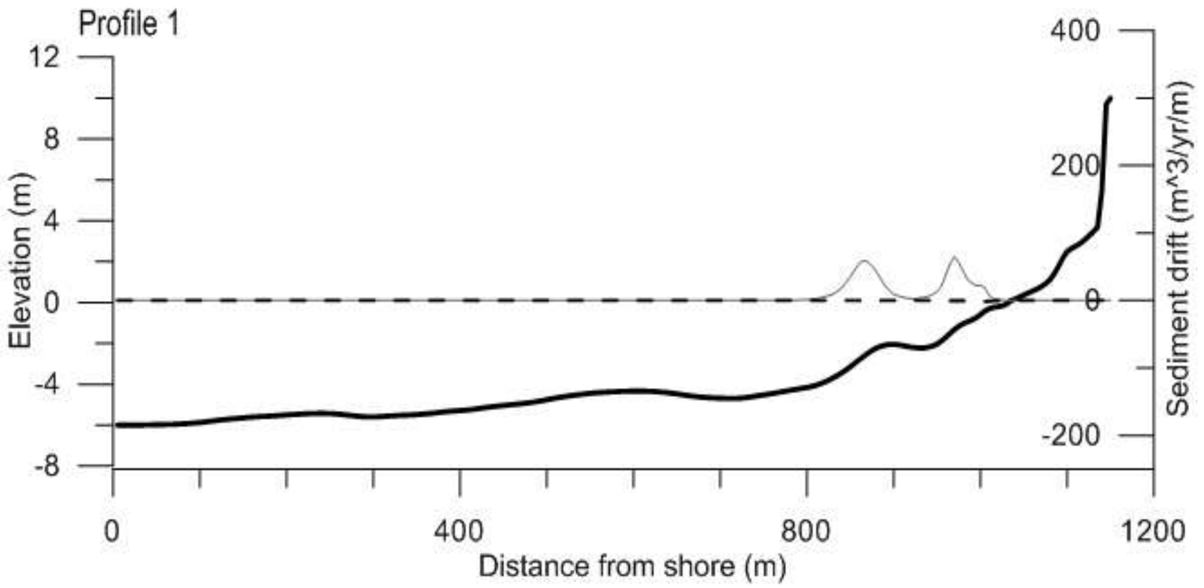


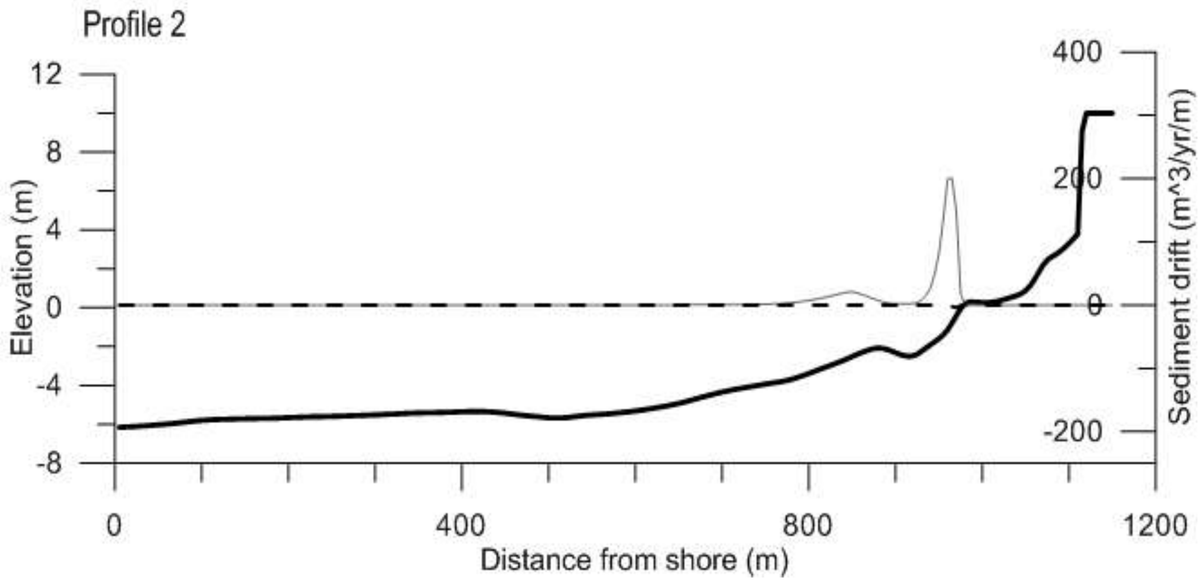


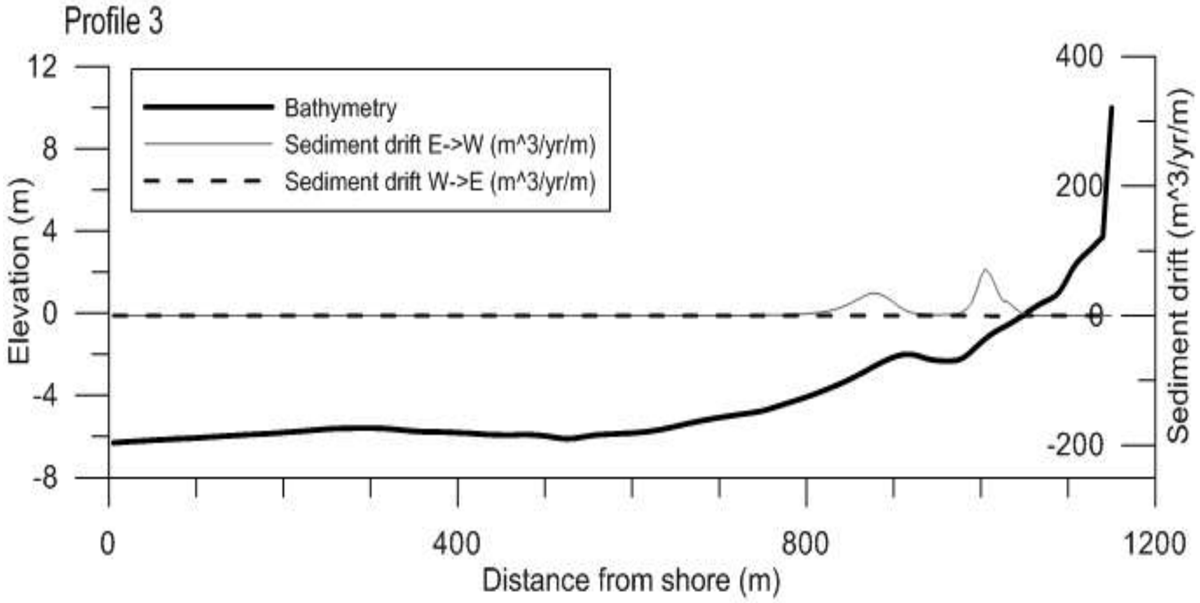


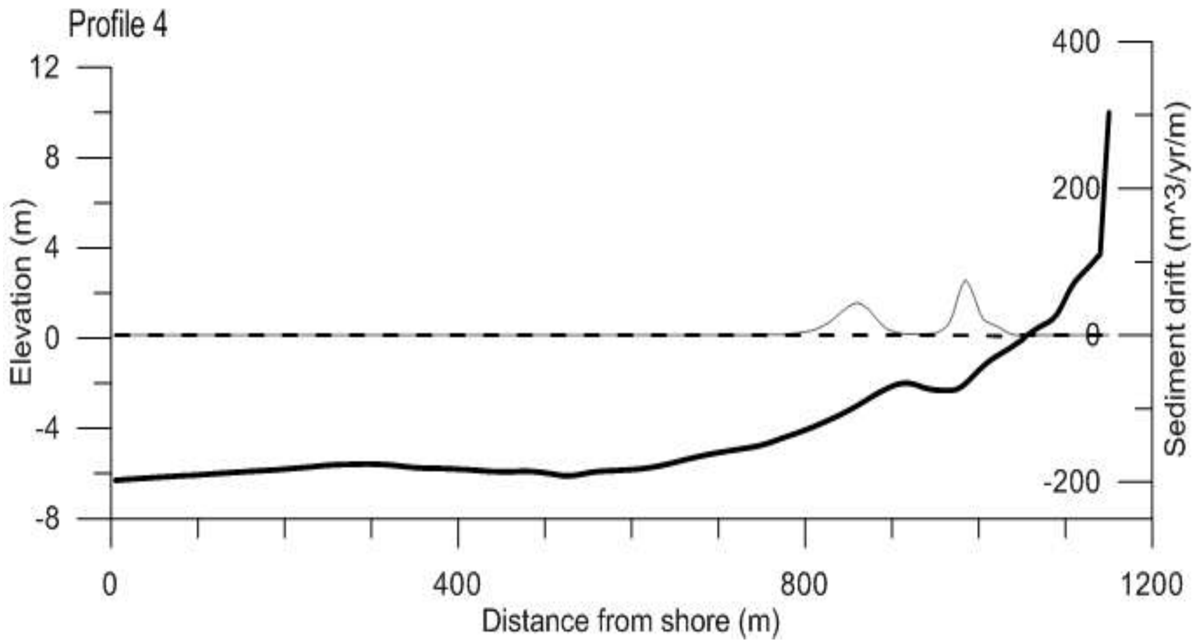


Reference conditions - no breakwater. Brasilien Beach

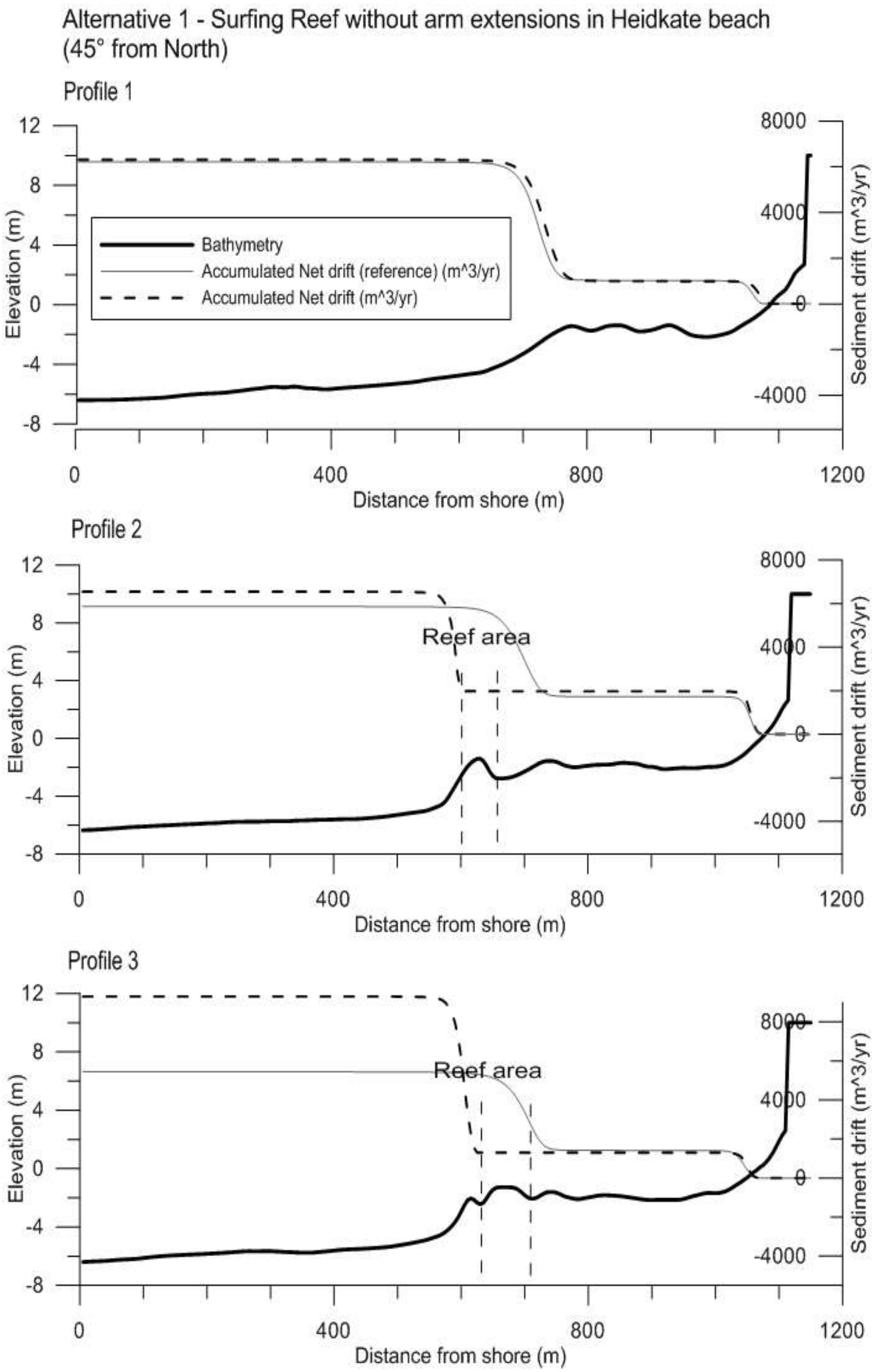


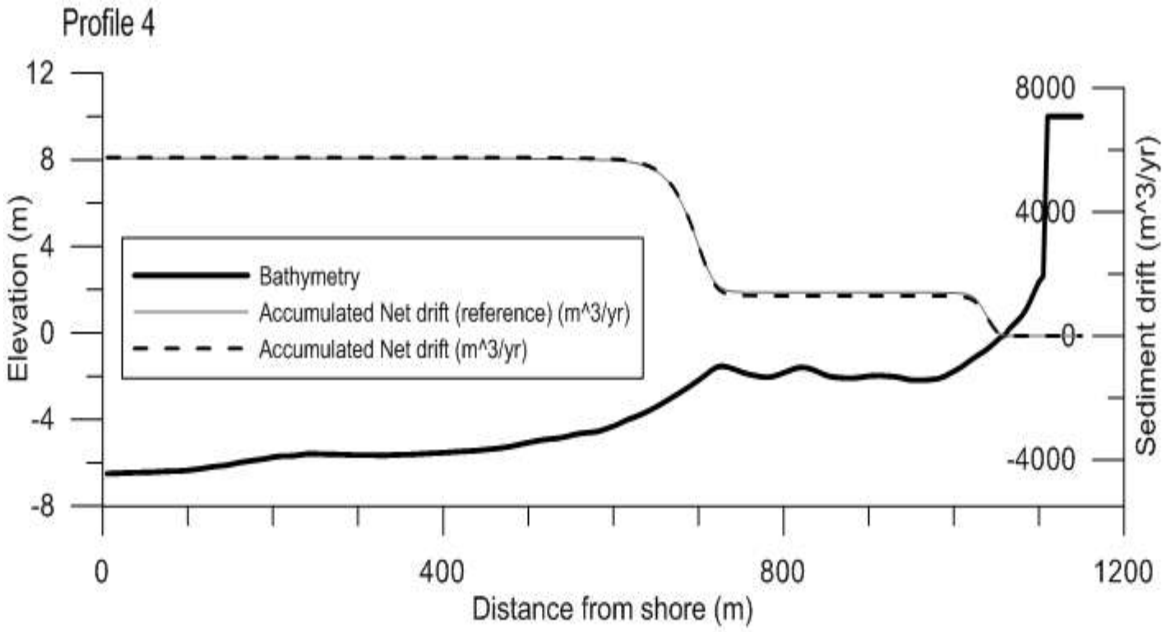



Profile 3
Bathymetry
Sediment drift E->W (m^3/yr/m)
Sediment drift W->E (m^3/yr/m)
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

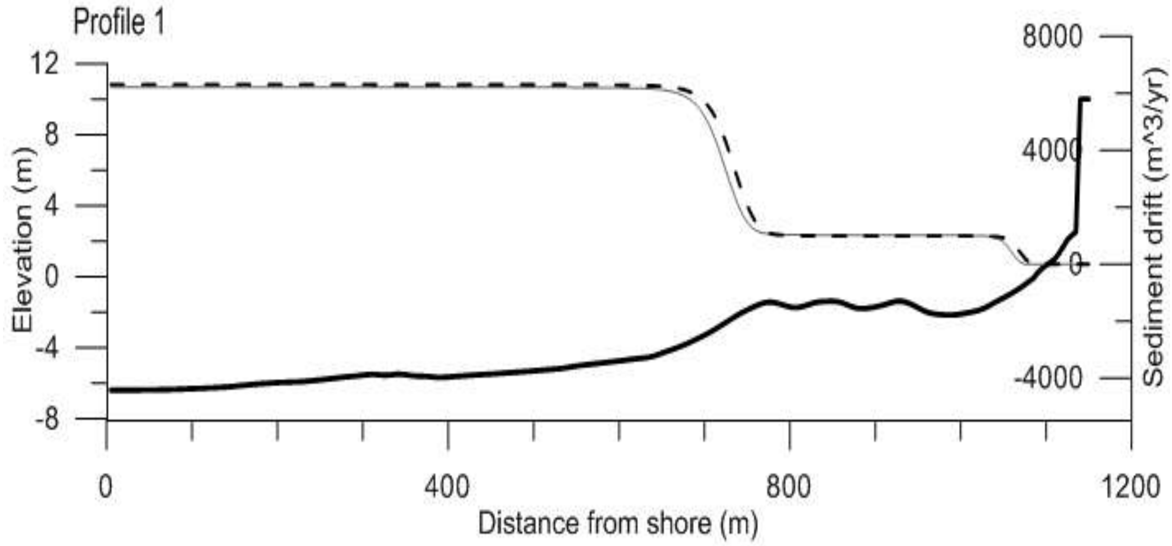

Profile 4
Elevation (m)
Sediment drift (m^3/yr/m)
Distance from shore (m)
12
8
4
0
-4
-8
400
200
0
-200
0
400
800
1200

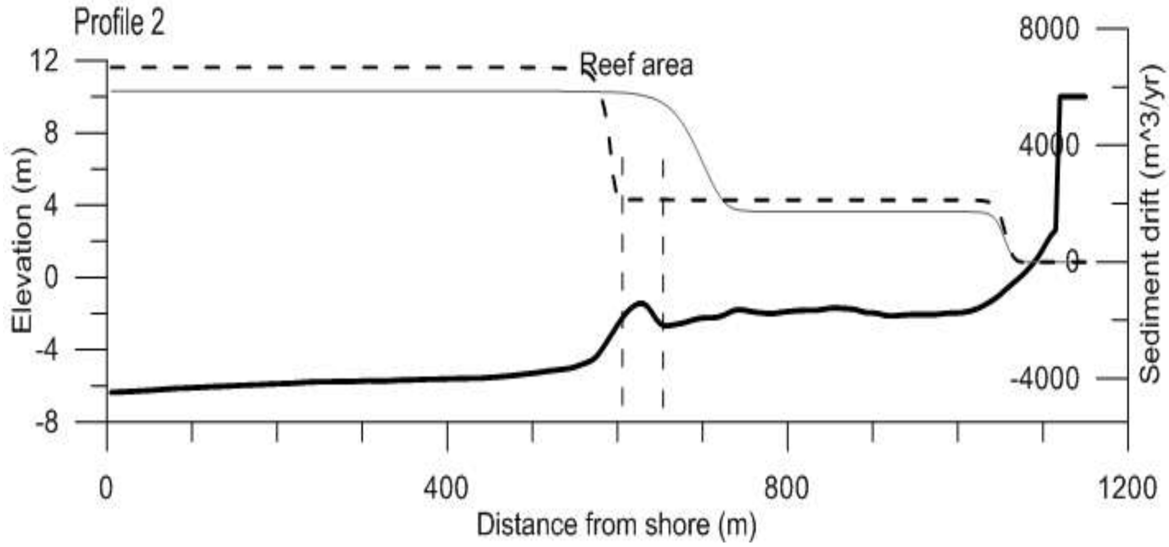
Accumulated sediment drift (m3/yr)



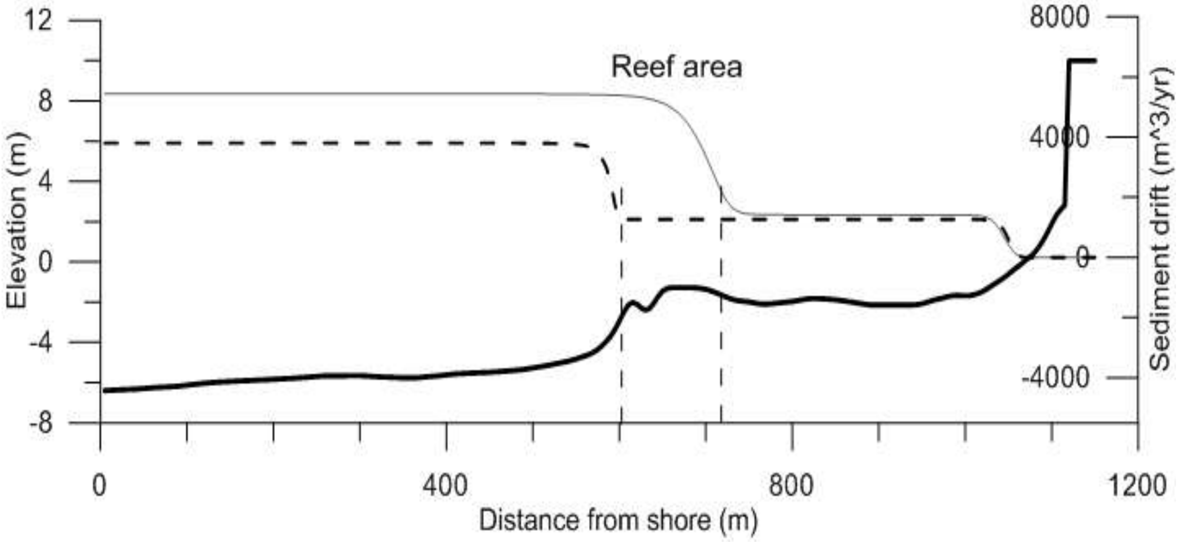


Alternative 2 - Surfing Reef with Eastern arm extension in Heidkate beach (45° from North)

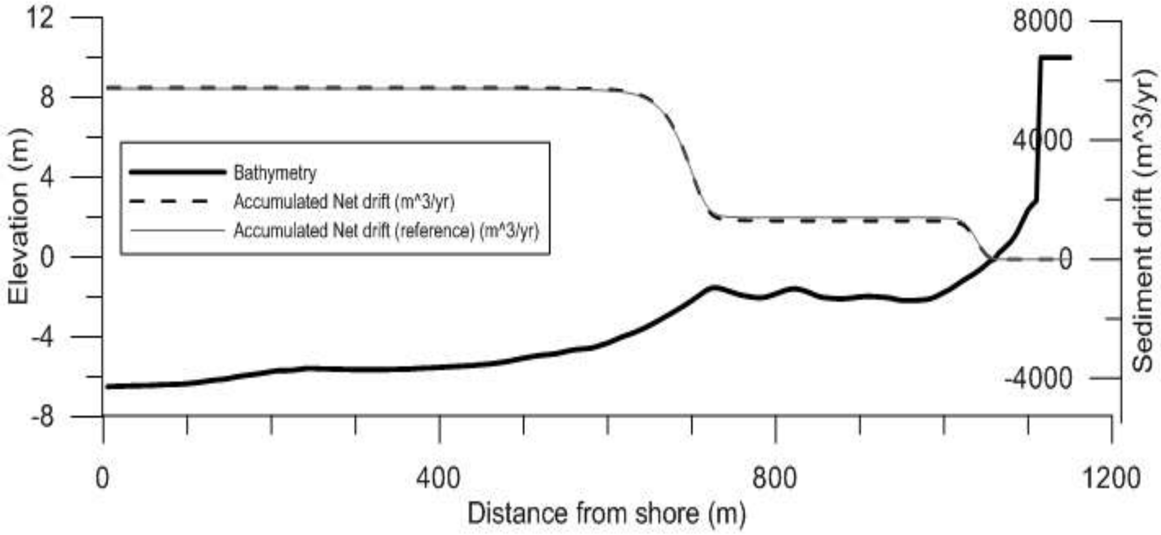




Profile 3

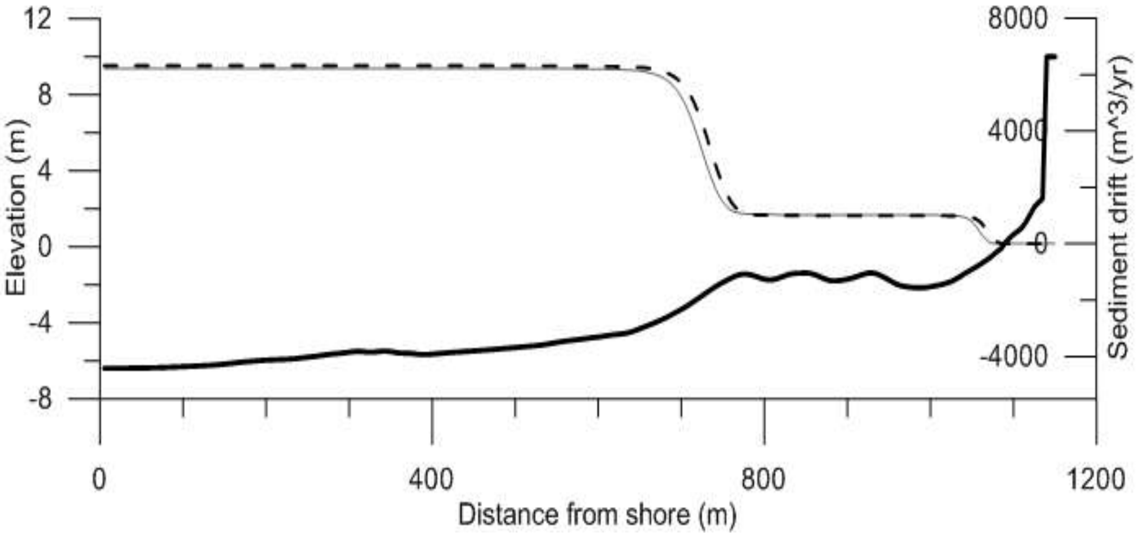


Profile 4

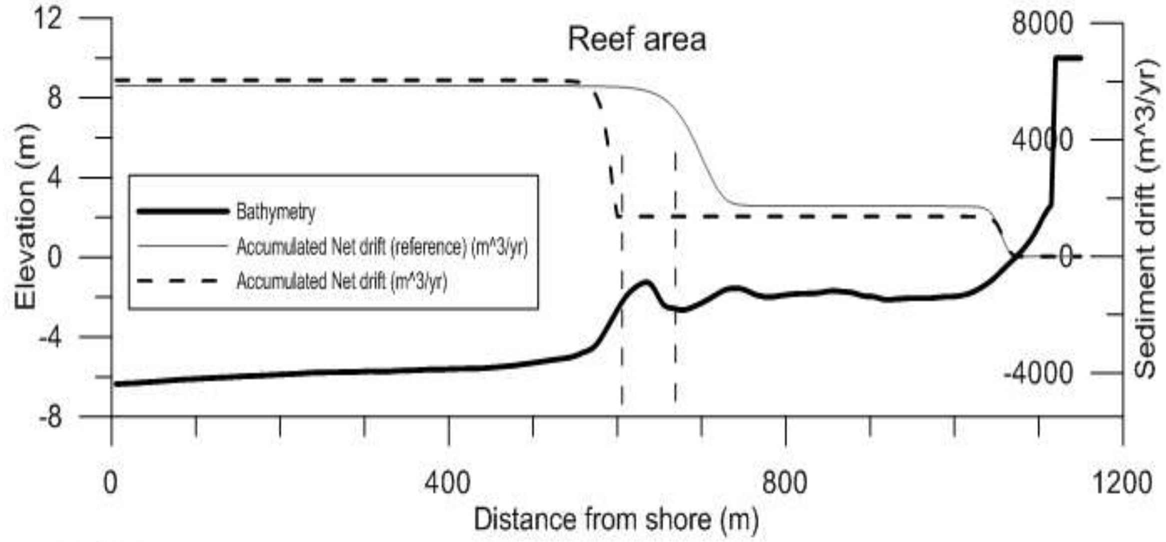


Alternative 3 - Surfing Reef with Western arm extension in Heidkate beach (45° from North)

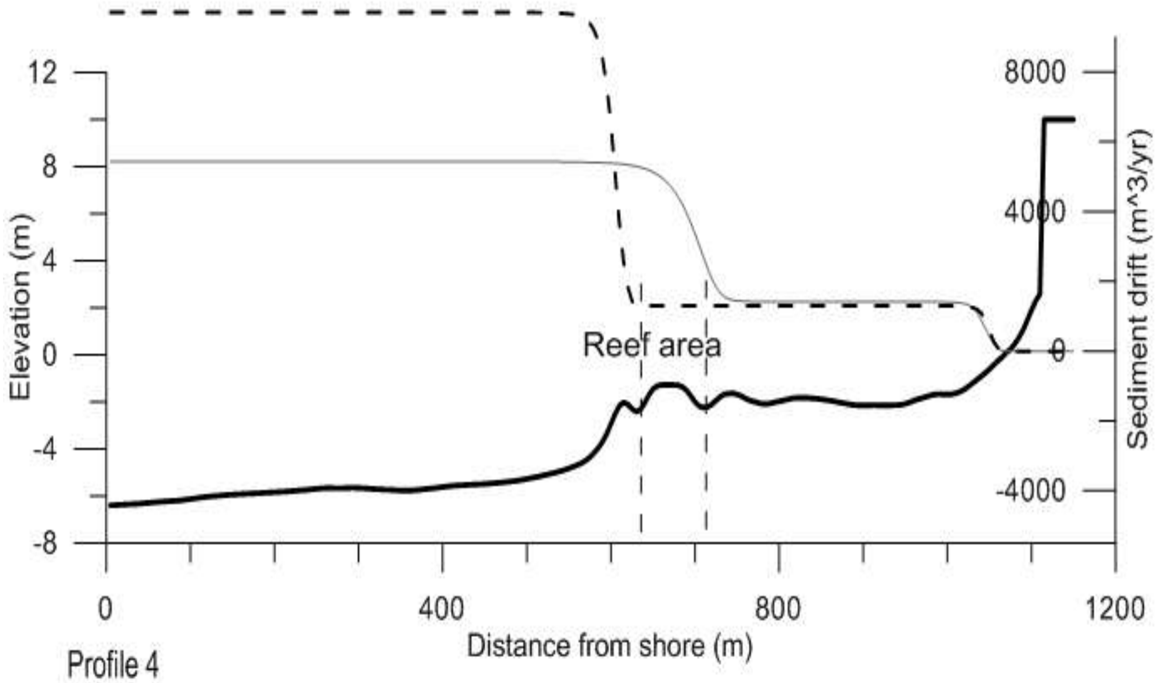
Profile 1



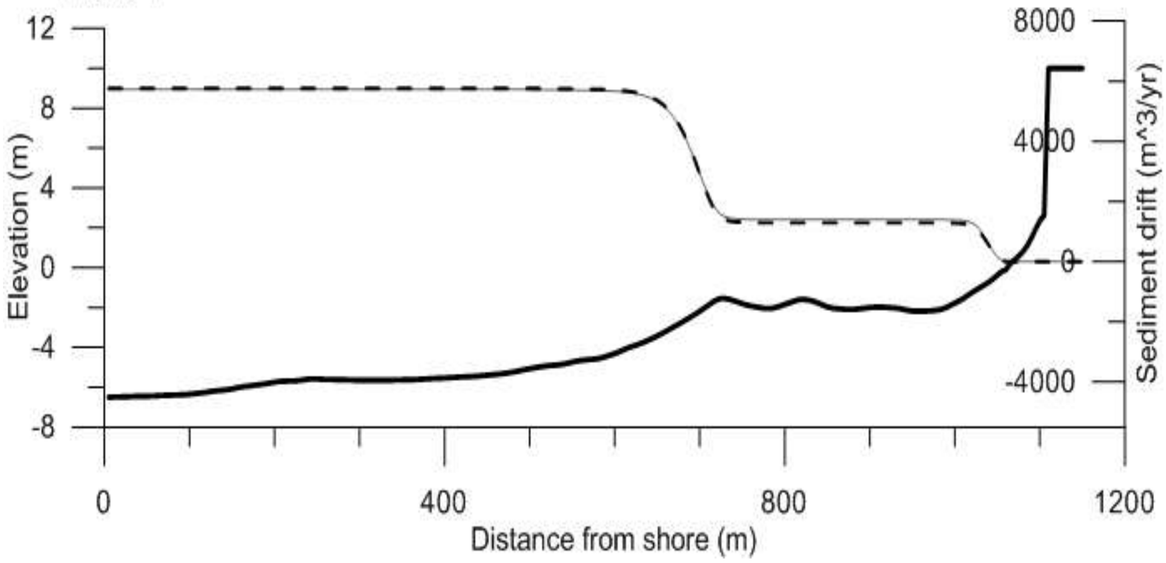
Profile 2



Profile 3

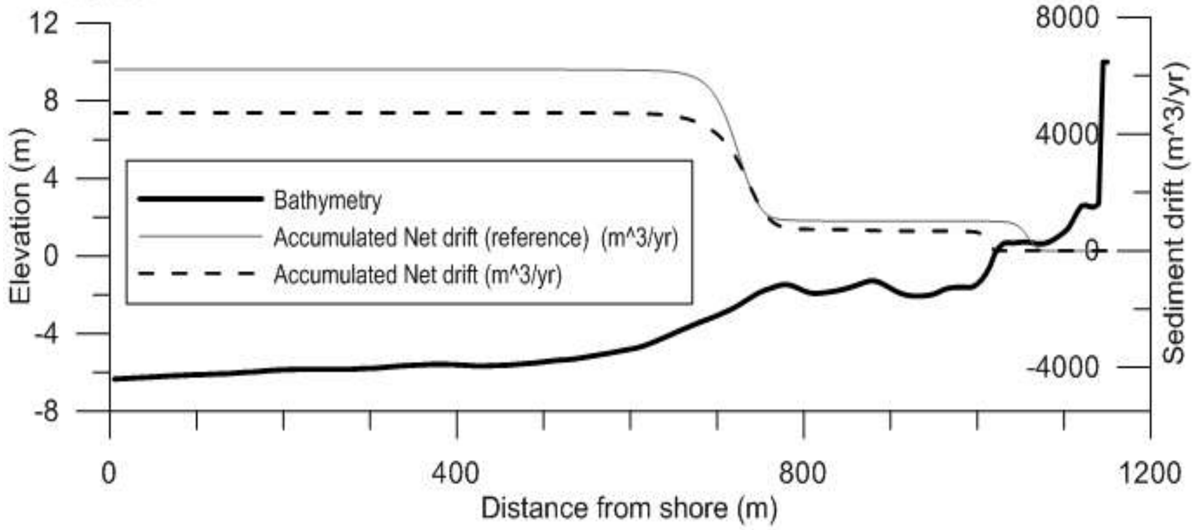


Profile 4

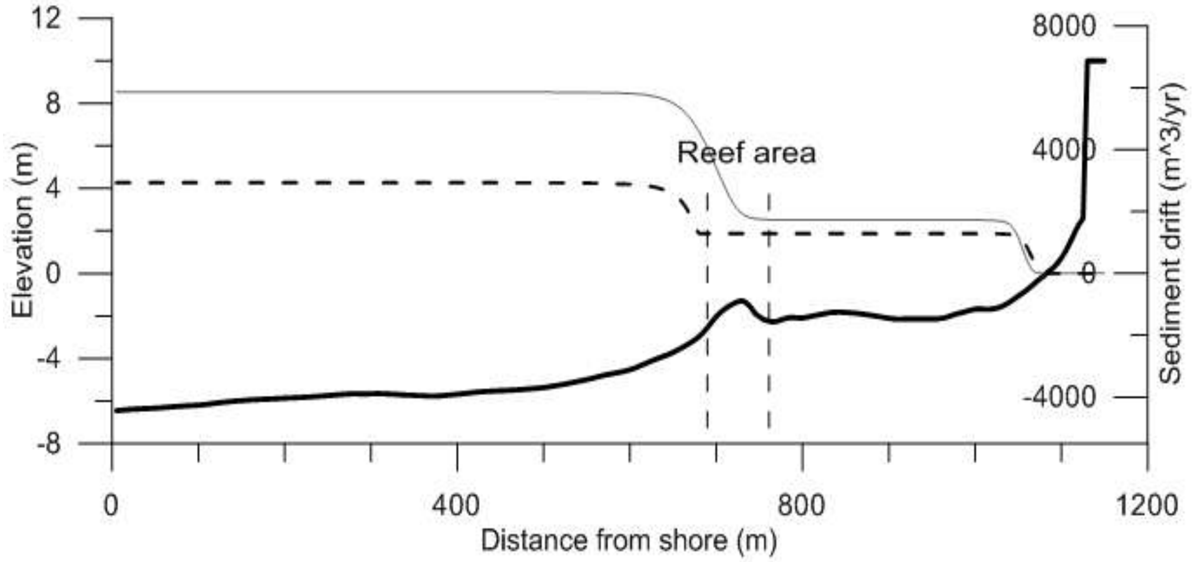


Alternative 1 - Surfing Reef without arm extensions in Heidkate beach (perpendicular to the coast)

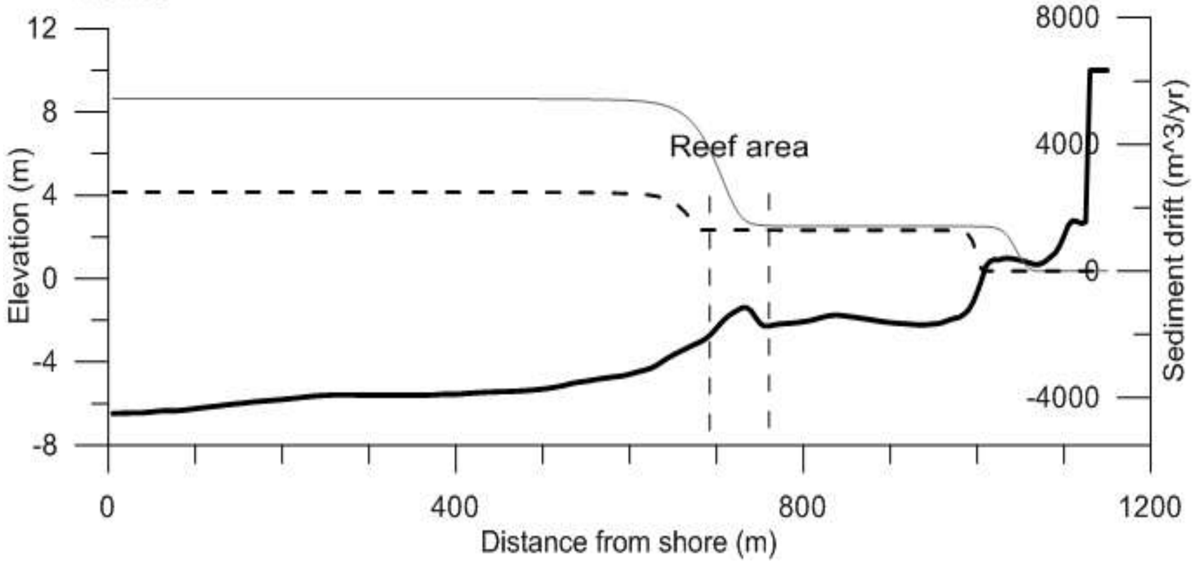
Profile 1

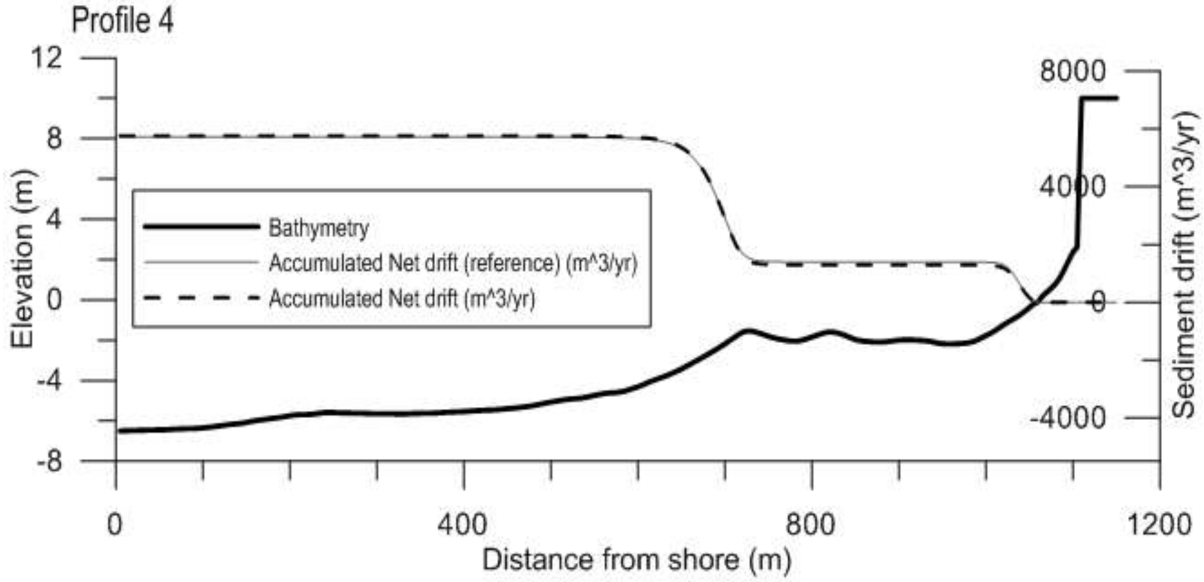


Profile 2

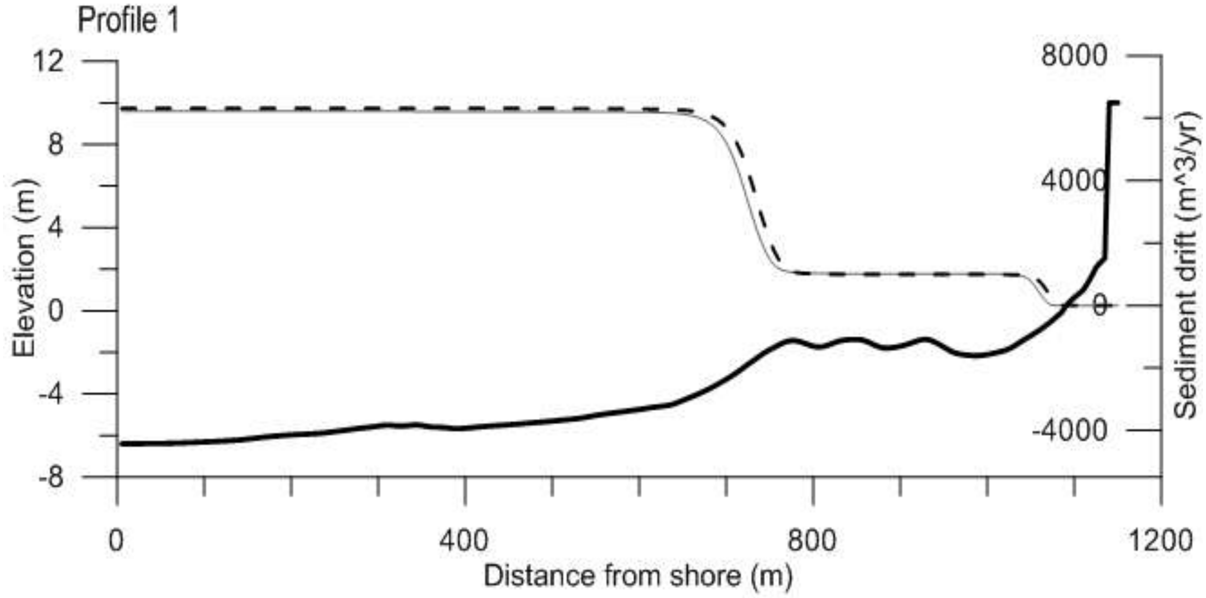


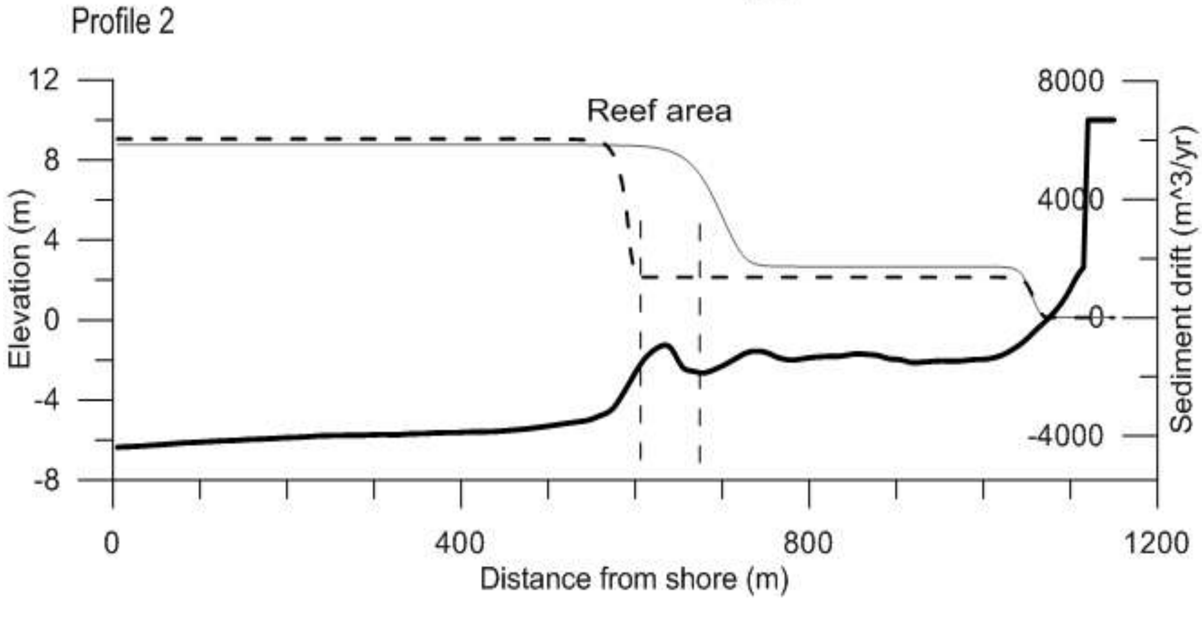
Profile 3



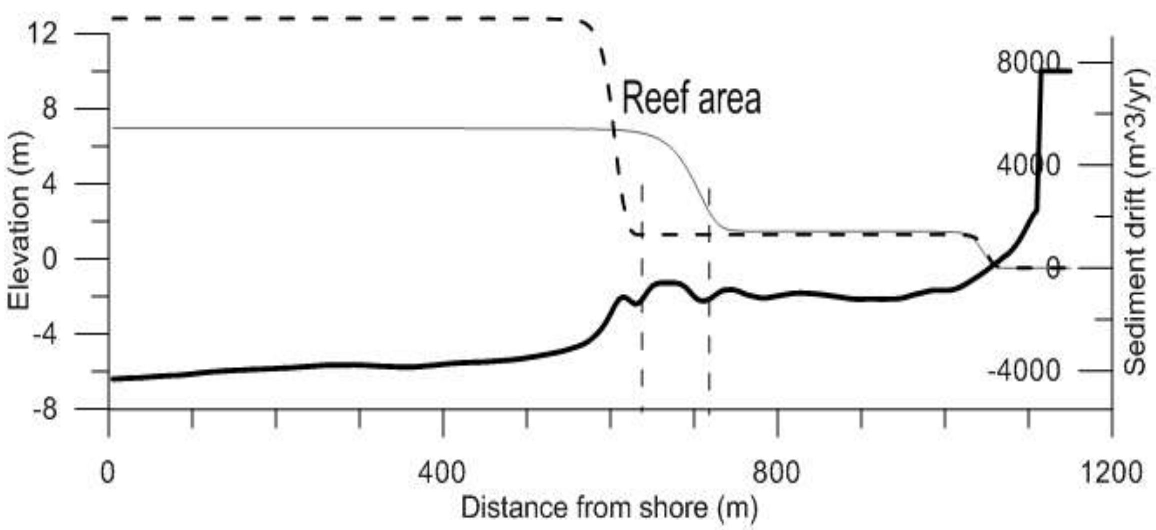


Alternative 2 - Surfing Reef with Eastern arm extension in Heidkate beach (perpendicular to the coast)

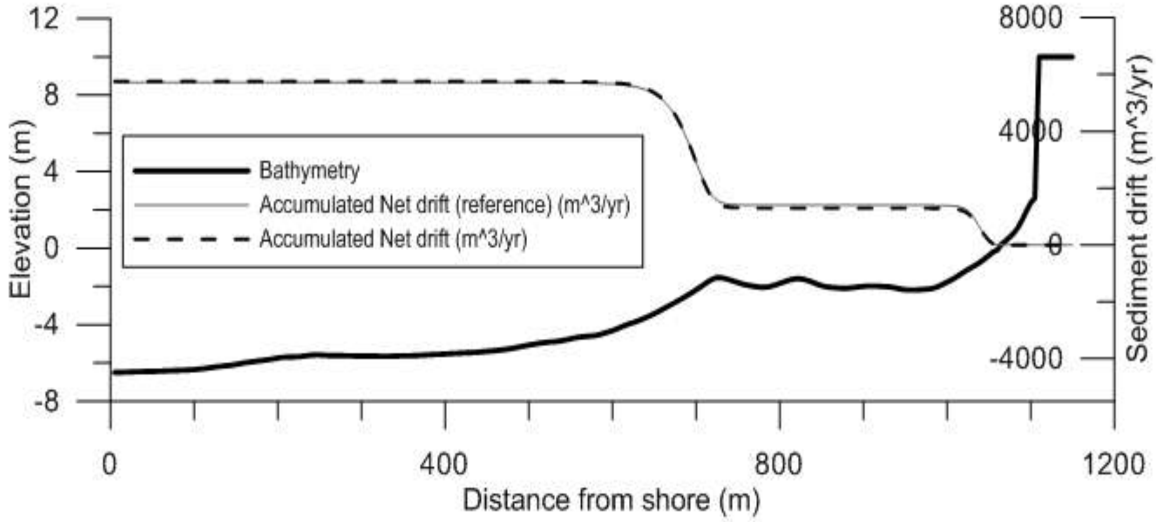




Profile 3

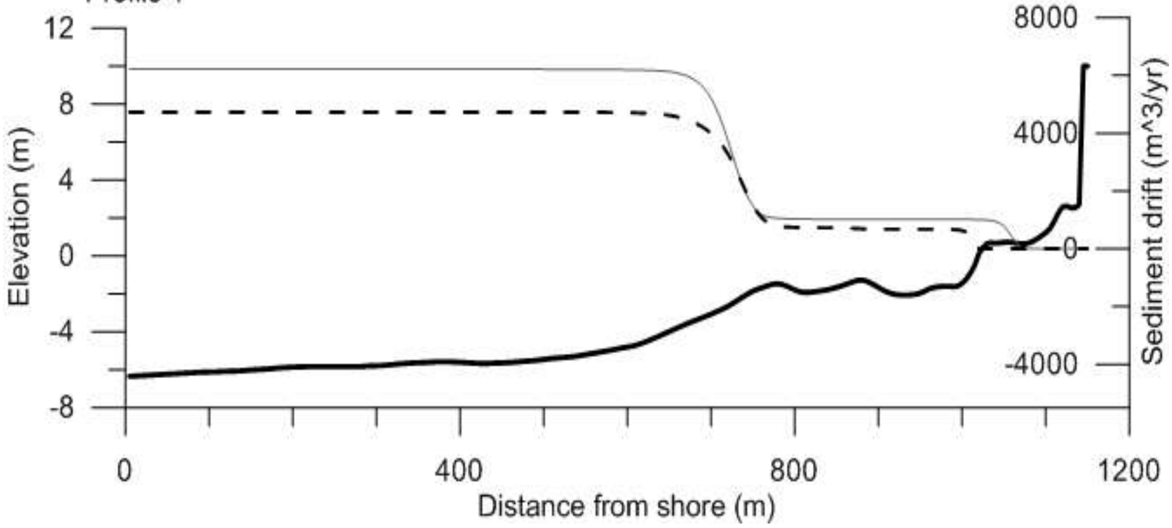


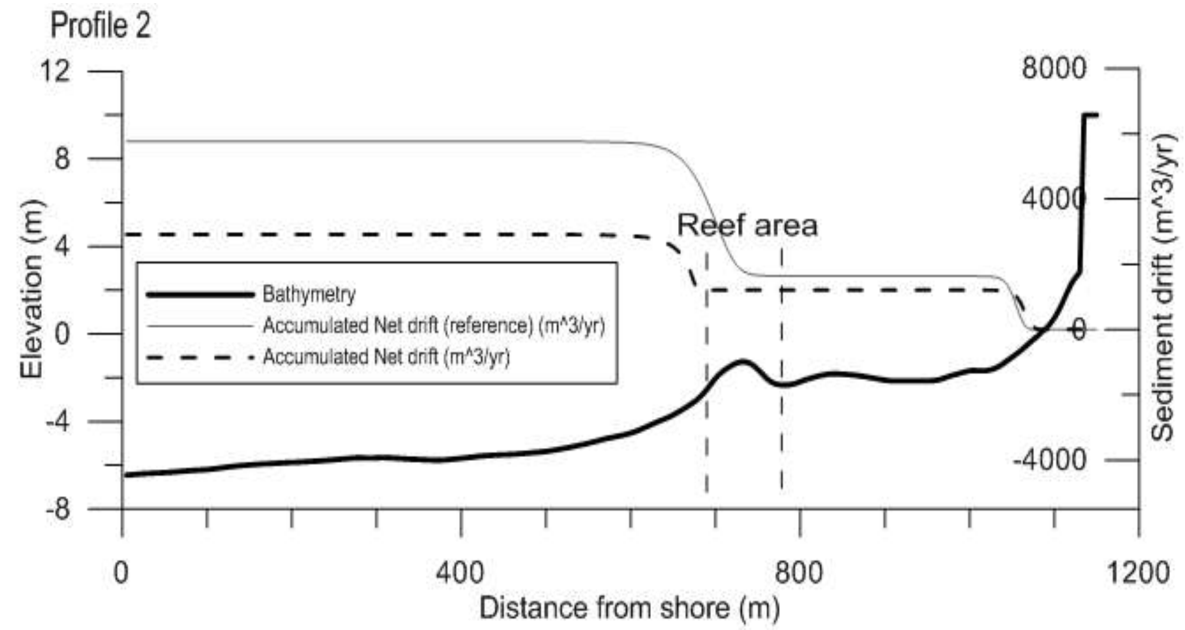
Profile 4

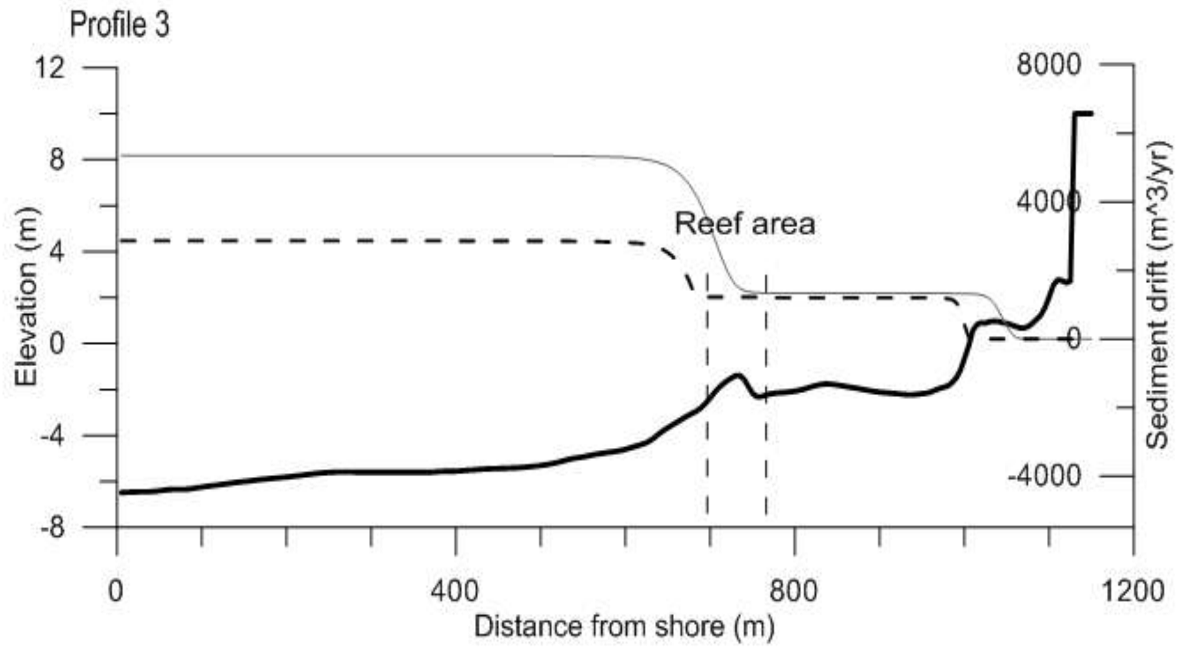


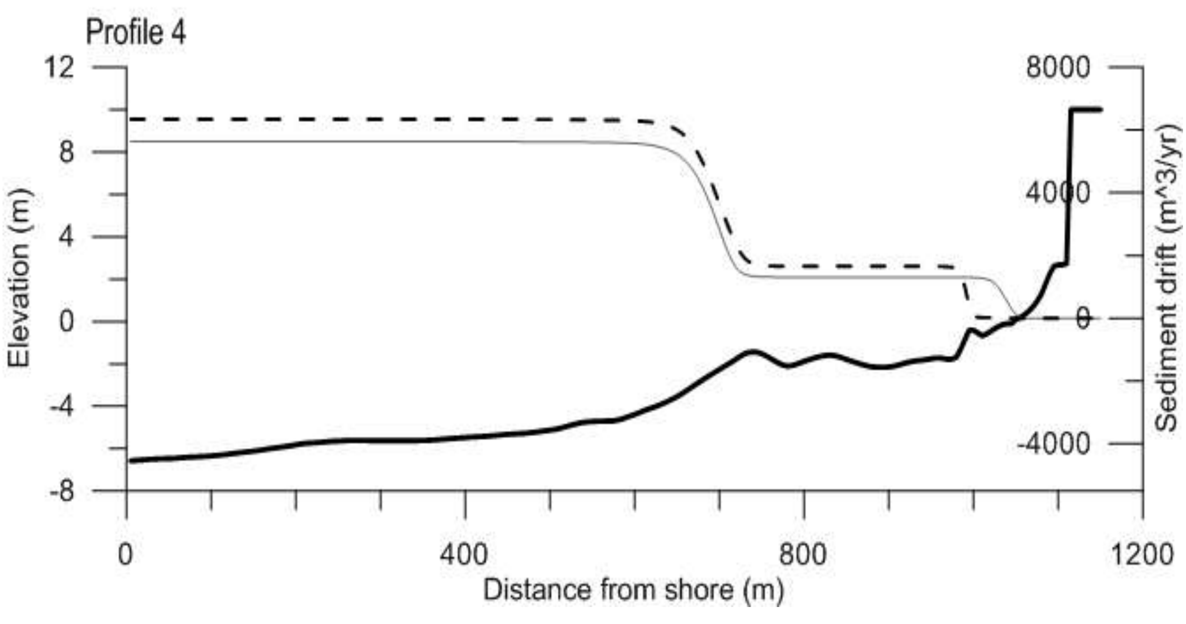
Alternative 3 - Surfing Reef with Western arm extension in Heidkate beach (perpendicular to the coast)

Profile 1



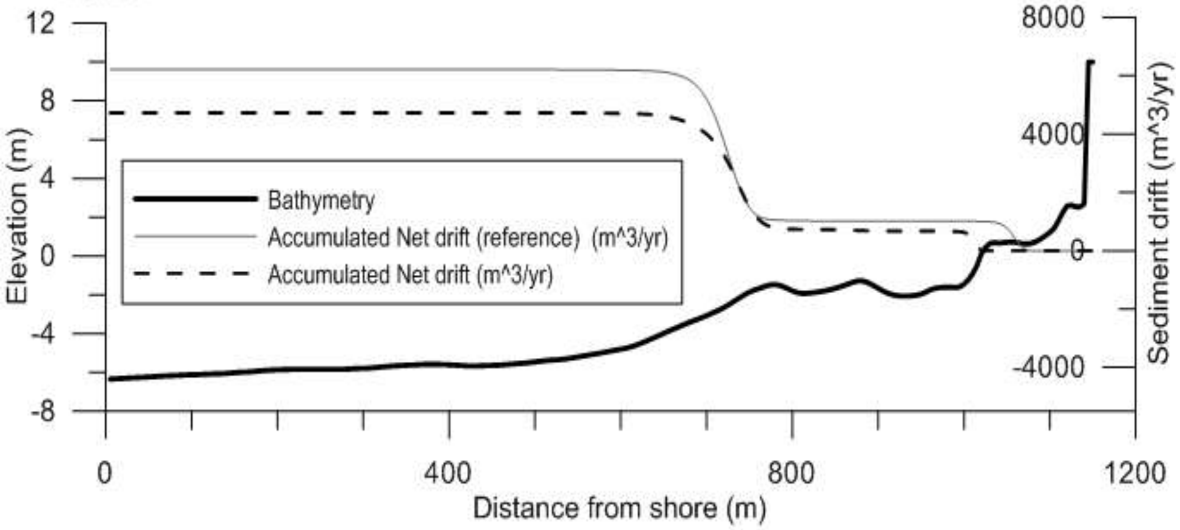

Profile 2
Reef area
Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Net drift (m^3/yr)
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200


Profile 3
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

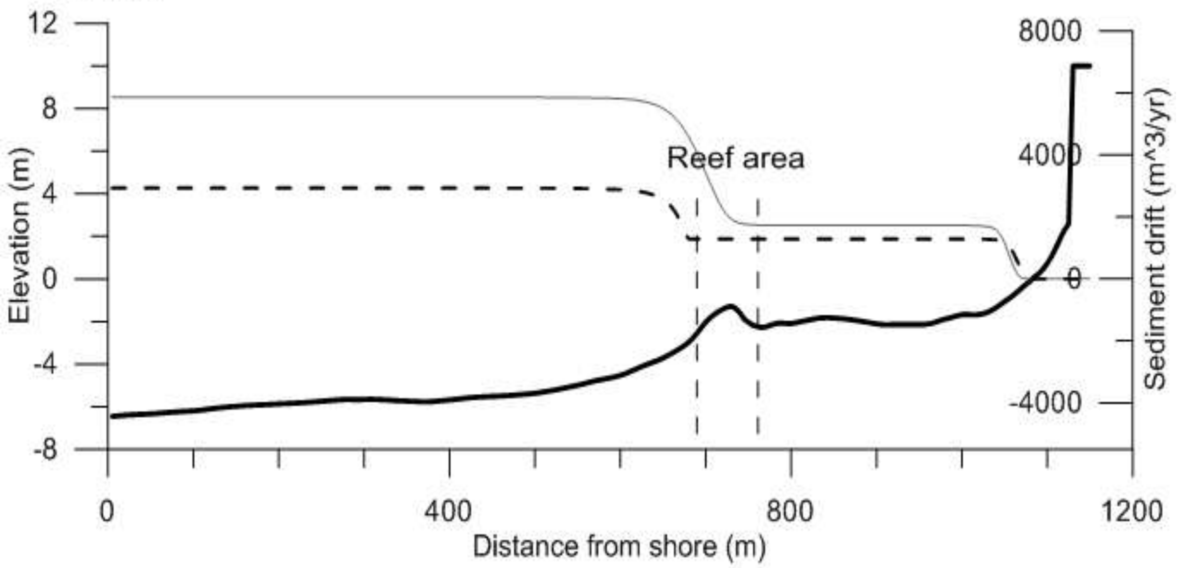

Profile 4
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

Alternative 1 - Surfing Reef without arm extensions in Heidkate beach (perpendicular to the coast)

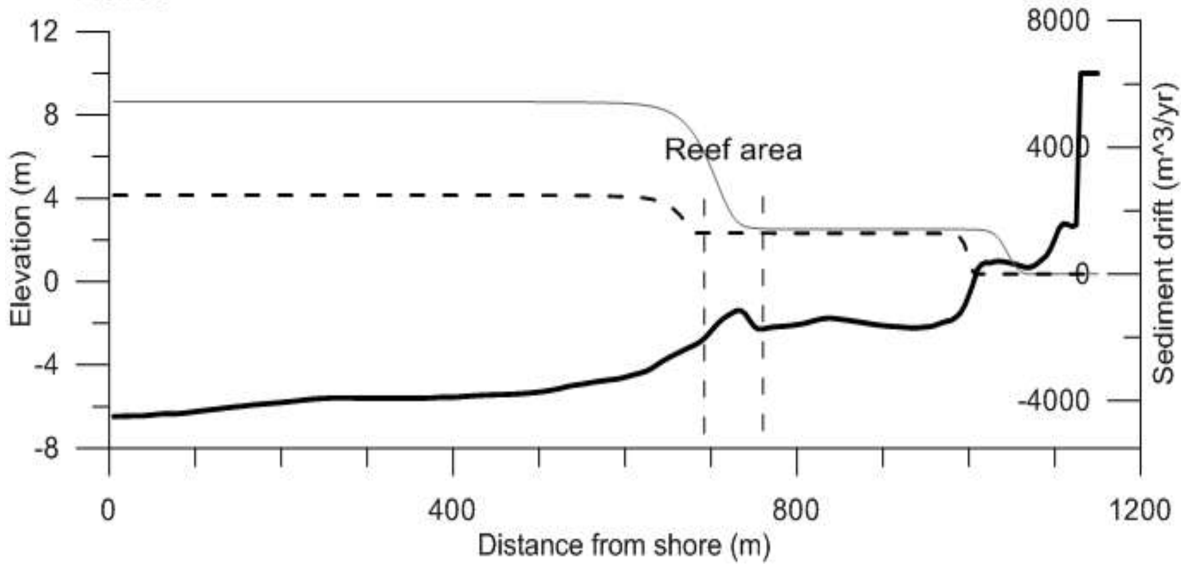
Profile 1



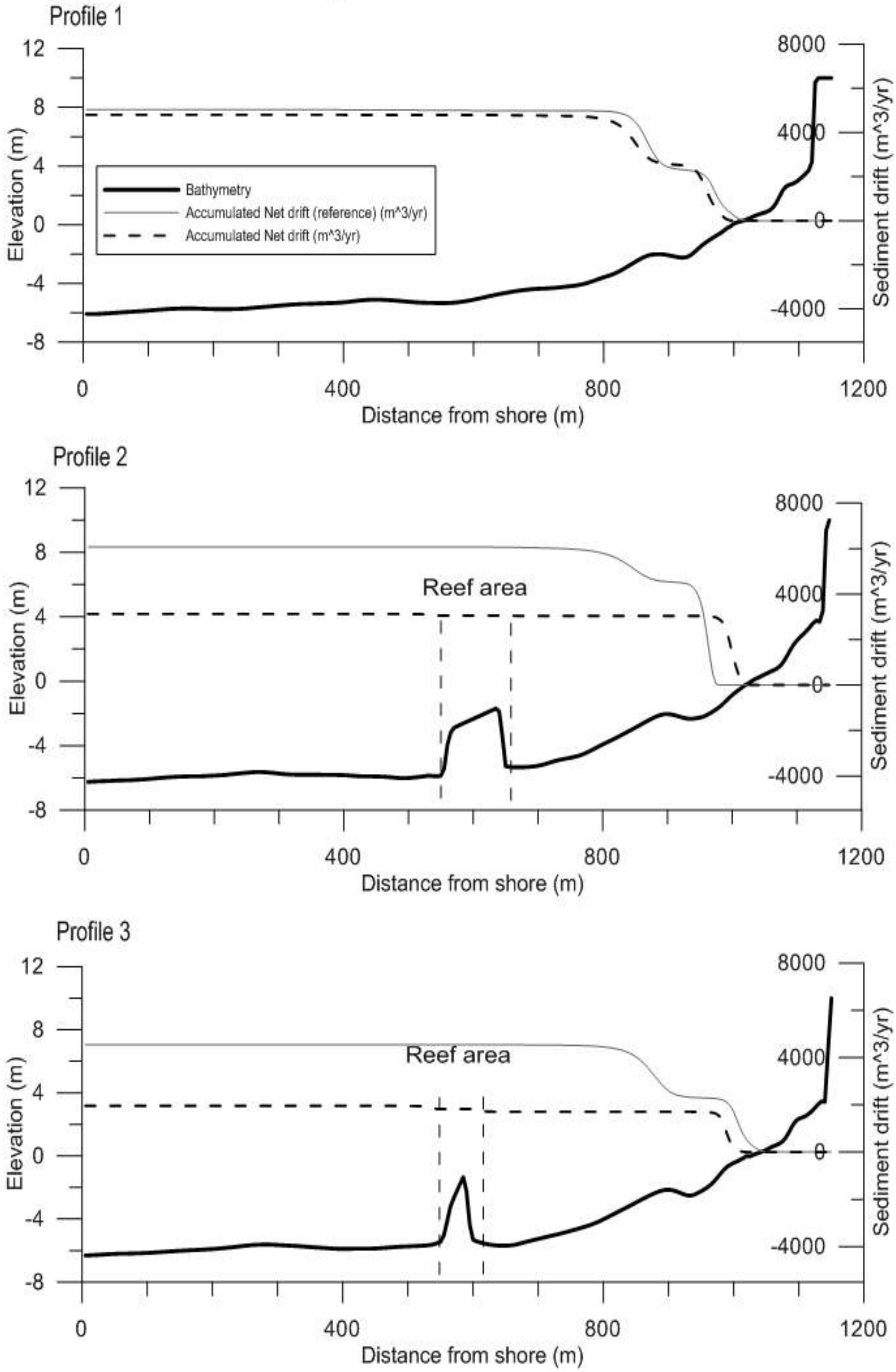
Profile 2



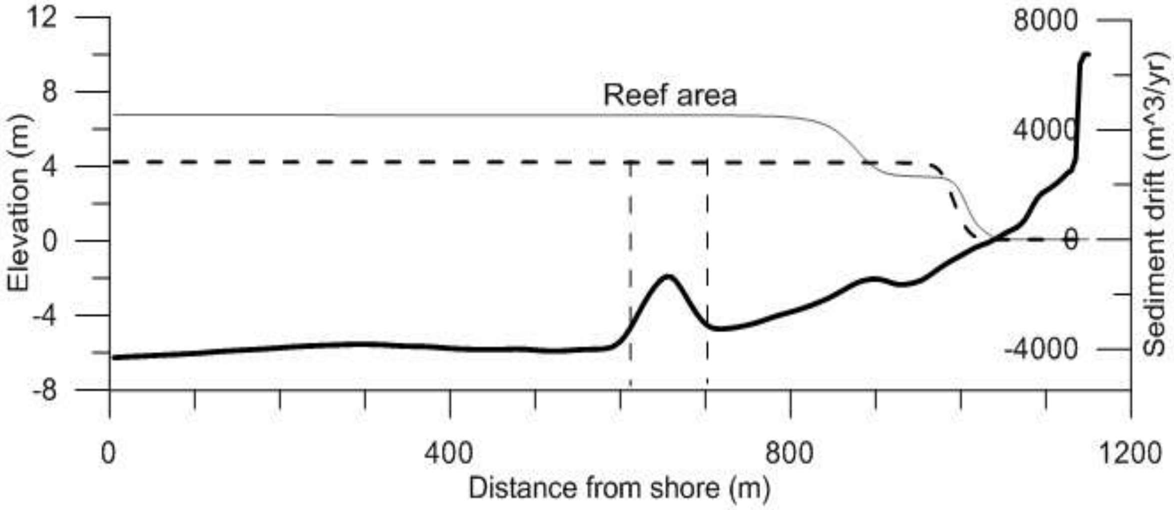
Profile 3



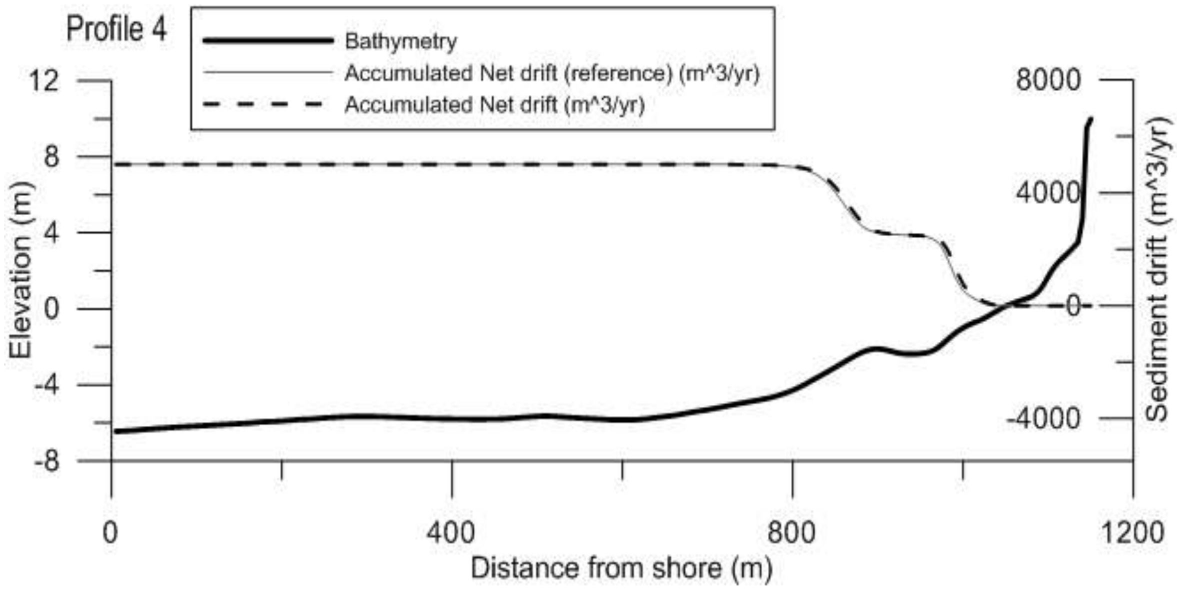
Alternative 4 - Surfing Reef without arm extensions in Brasilien beach (perpendicular to the coast)



Profile 3

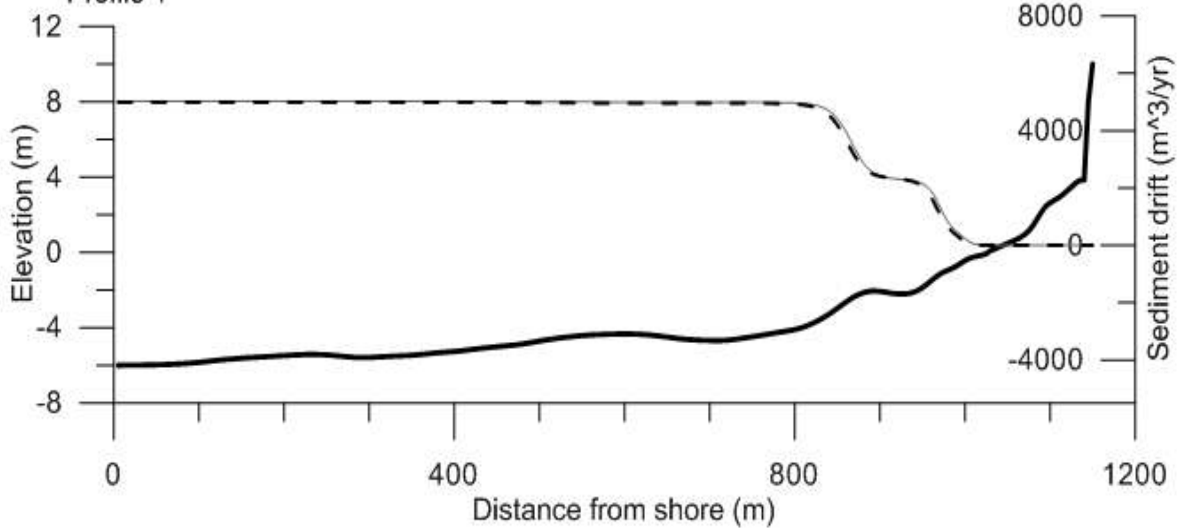


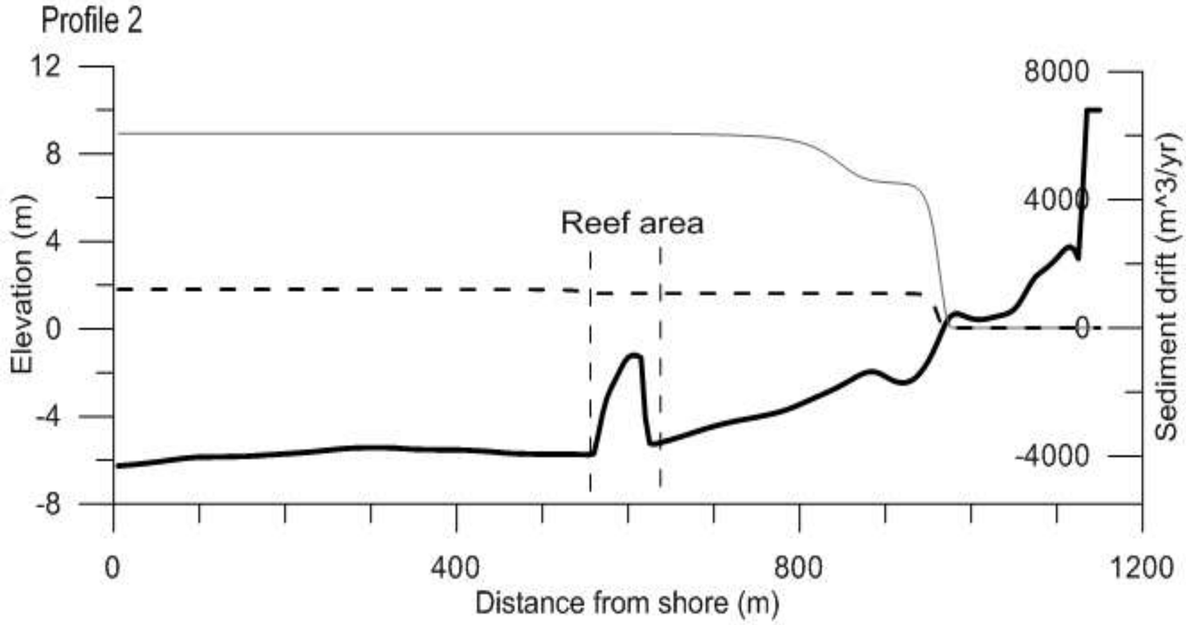
Profile 4

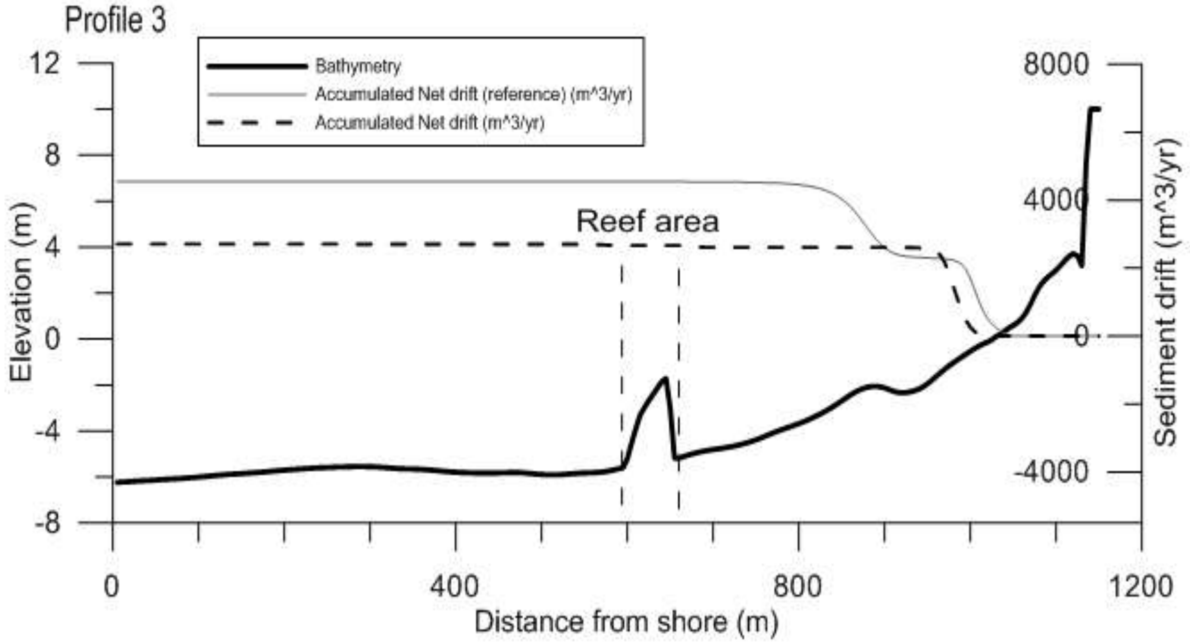


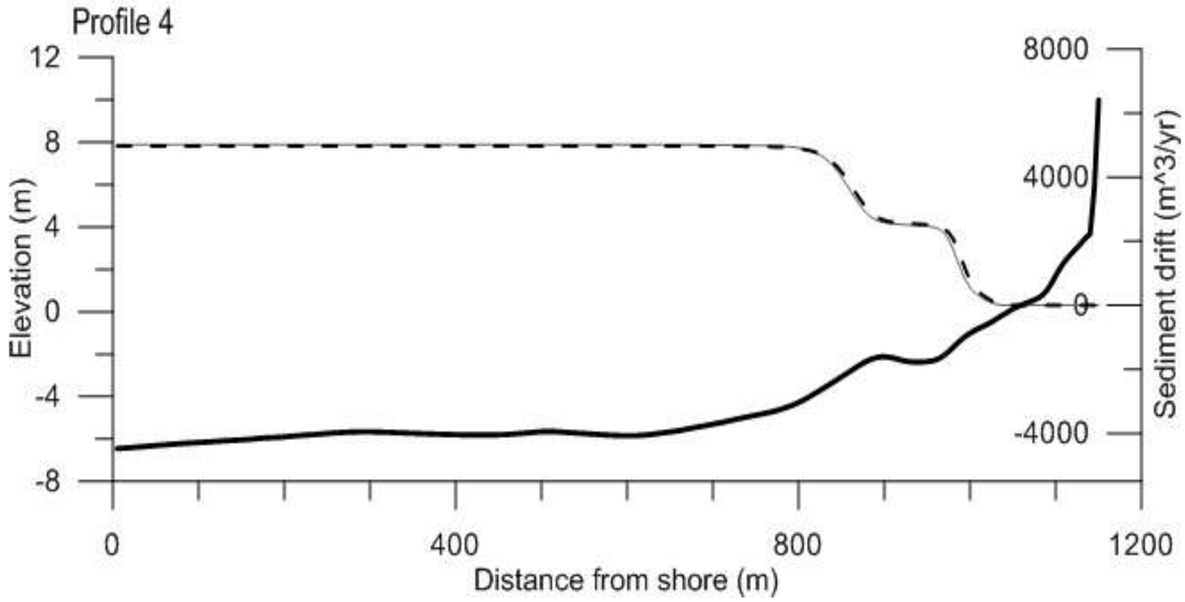
Alternative 6 - Surfing Reef with Western arm extension in Brasilien beach (45° from North)

Profile 1

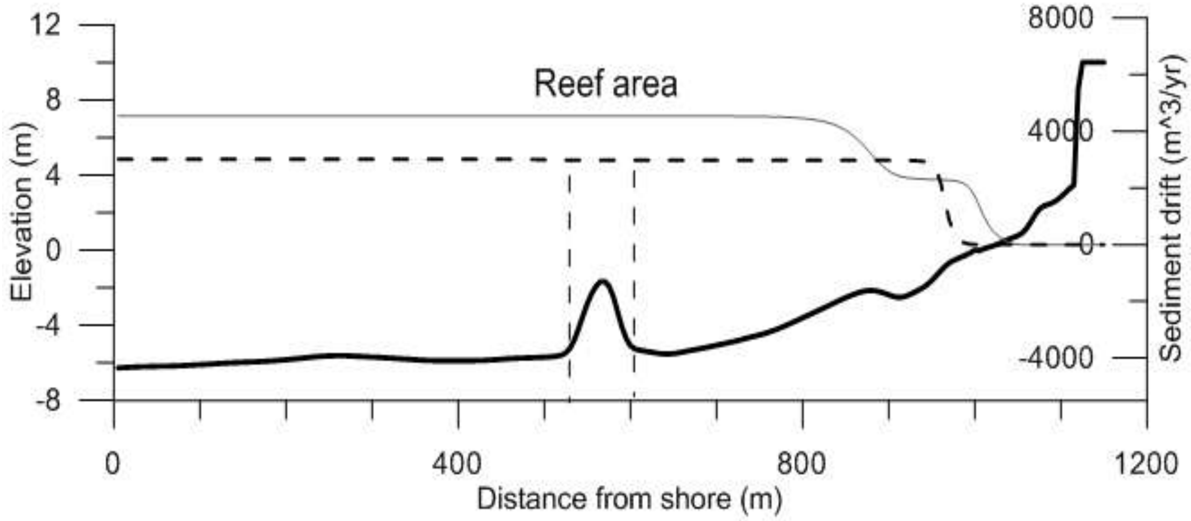



Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
400
800
1200

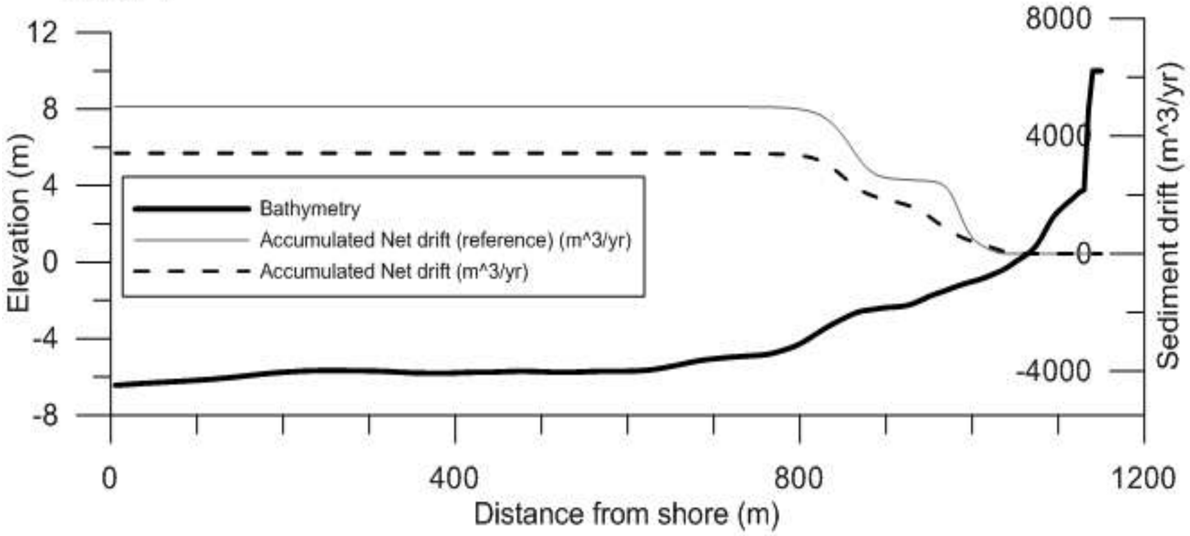

Profile 3
Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Net drift (m^3/yr)
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
400
800
1200


Profile 4
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
400
800
1200

Profile 3

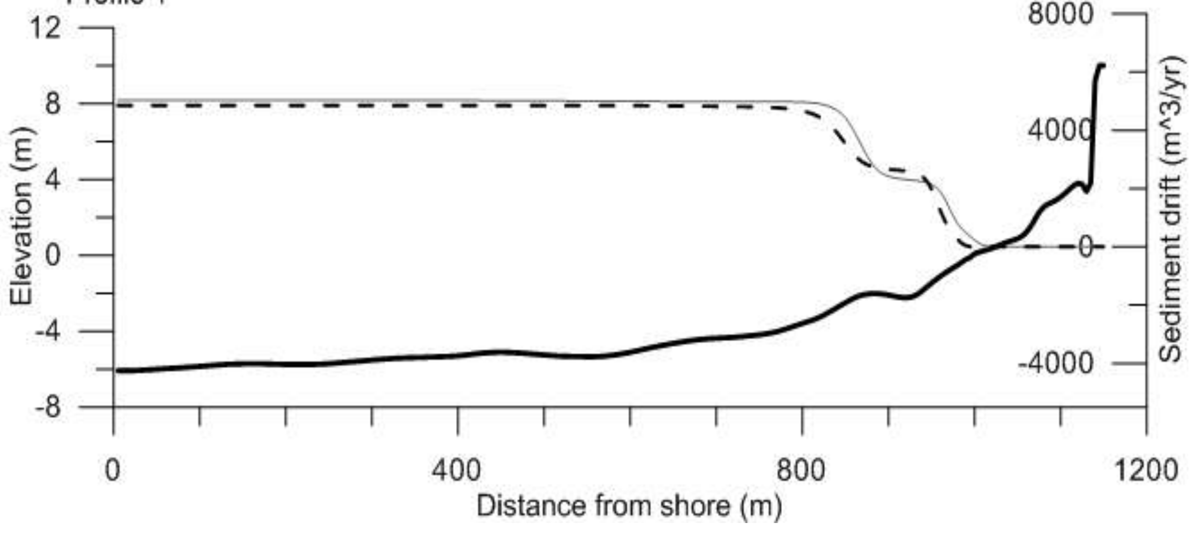


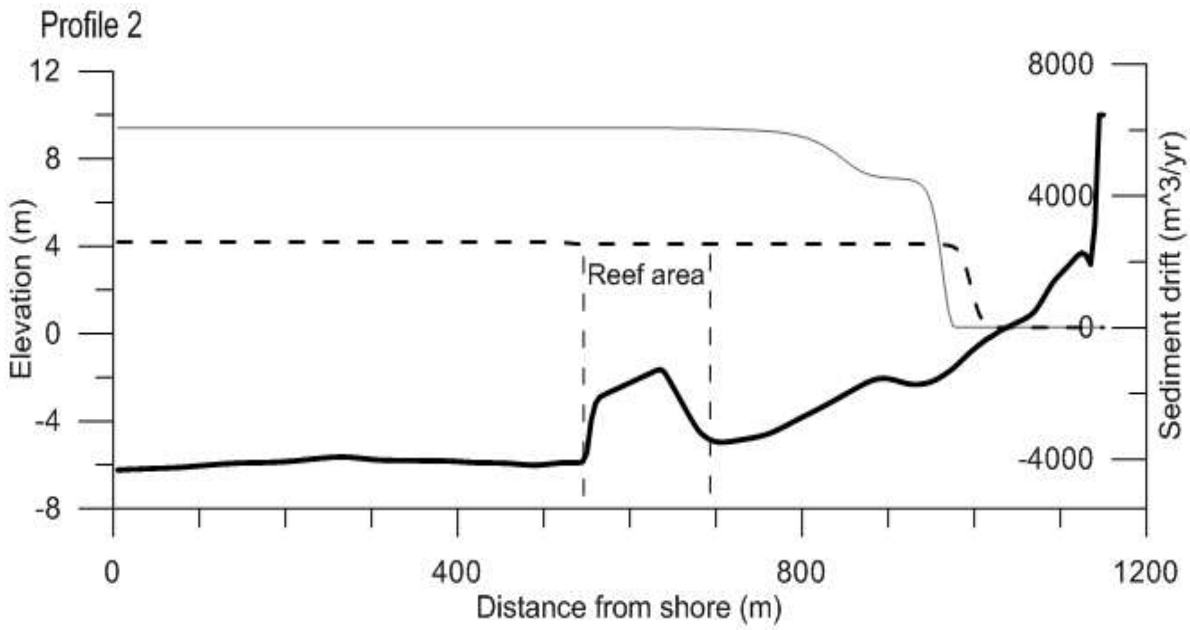
Profile 4

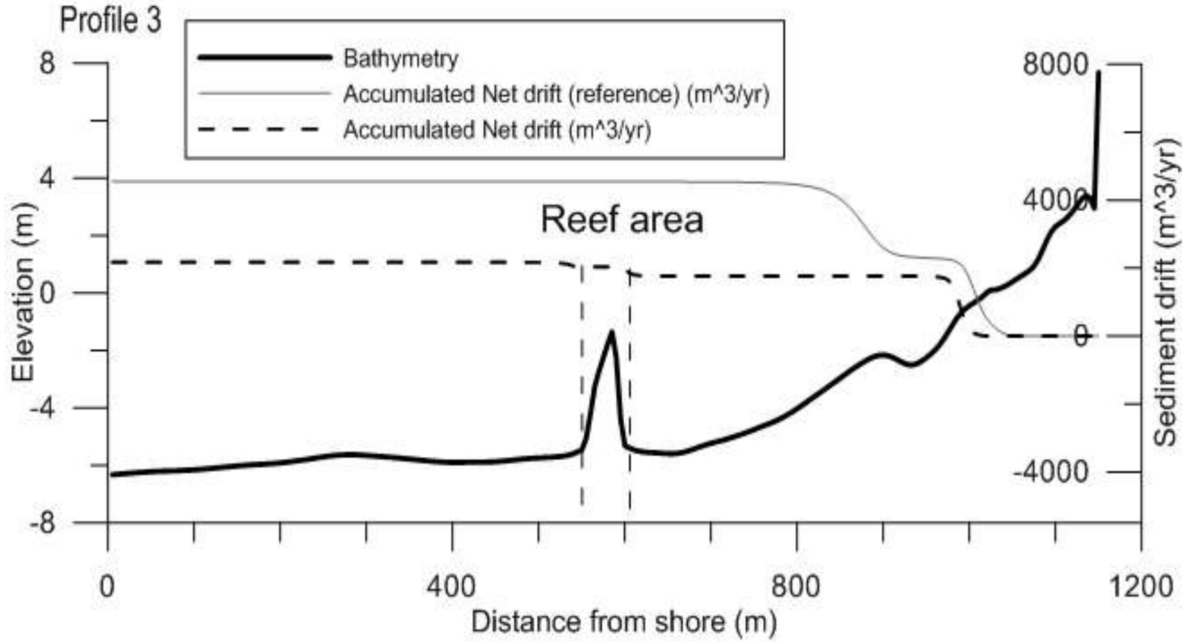


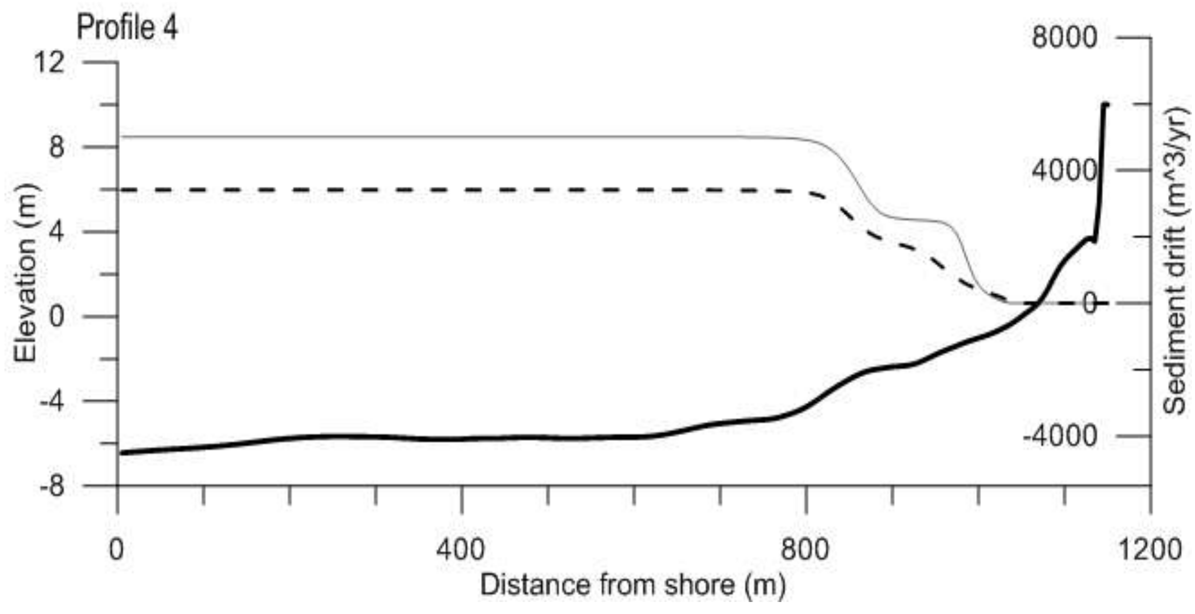
Alternative 6 - Surfing Reef with Western arm extension in Brasilien Beach (perpendicular to the coast)

Profile 1



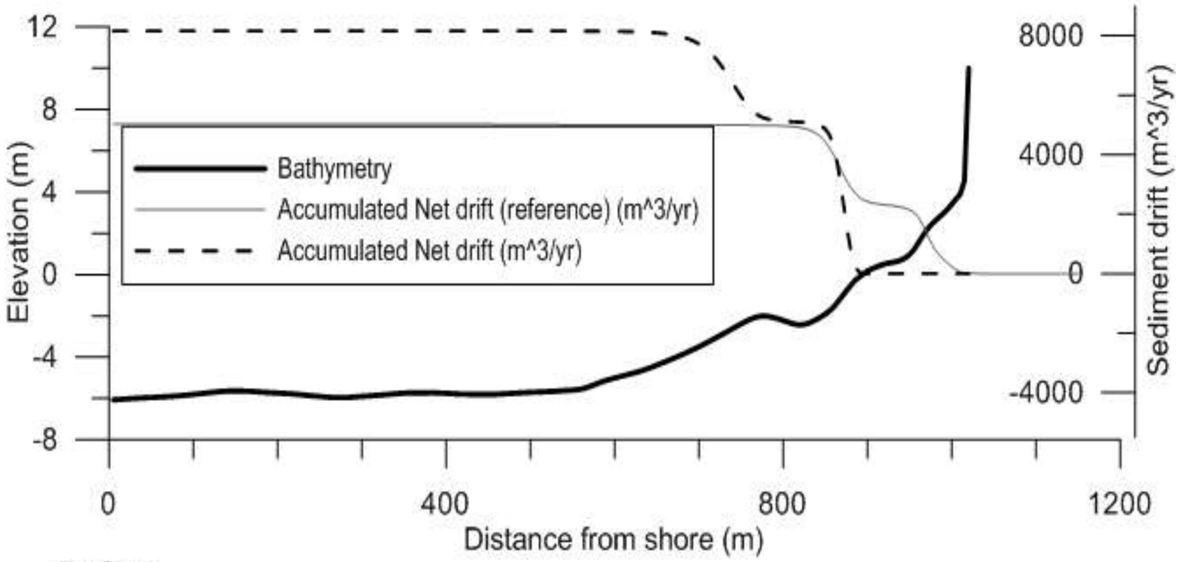

Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200


Profile 3
Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Net drift (m^3/yr)
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

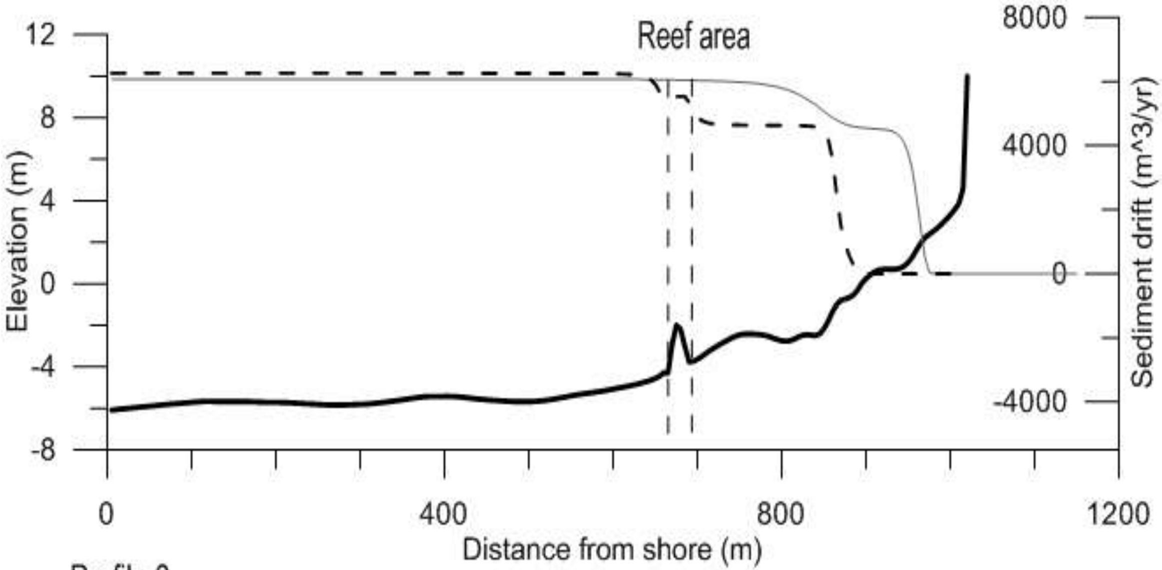

Profile 4
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

Alternative 7 - Parallel to coast breakwater in Brasilien Beach

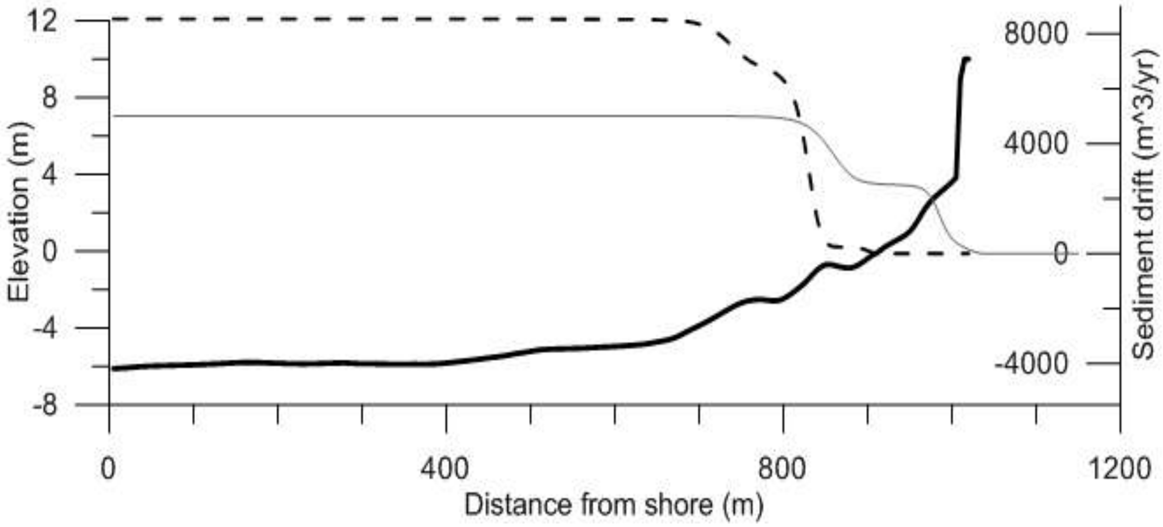
Profile 1

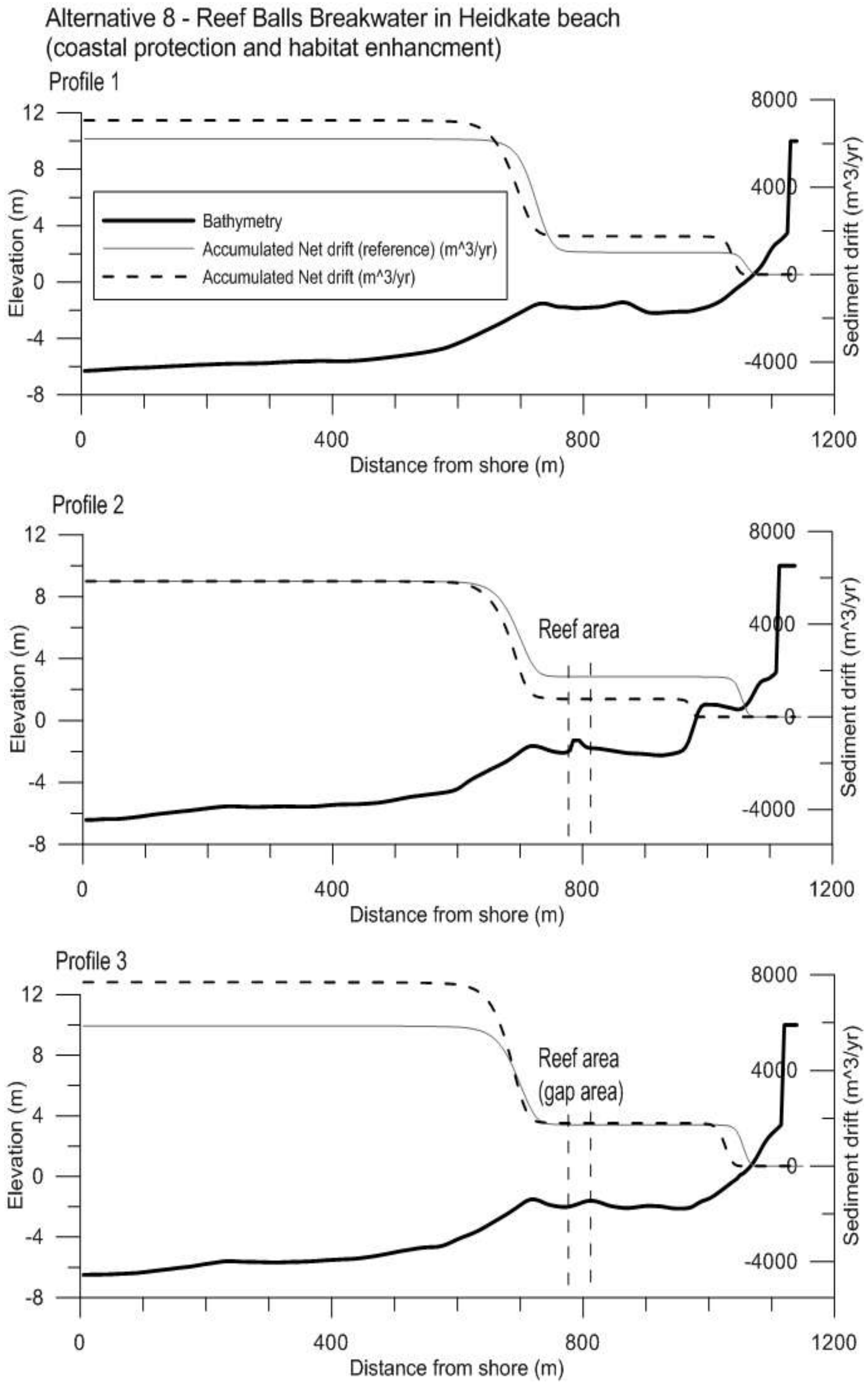


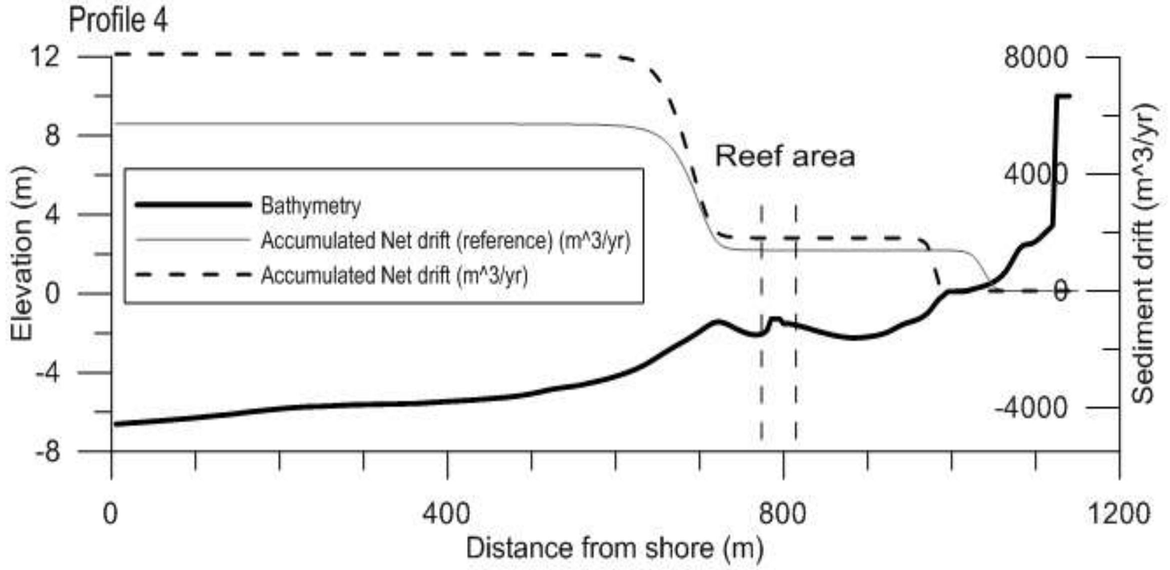
Profile 2

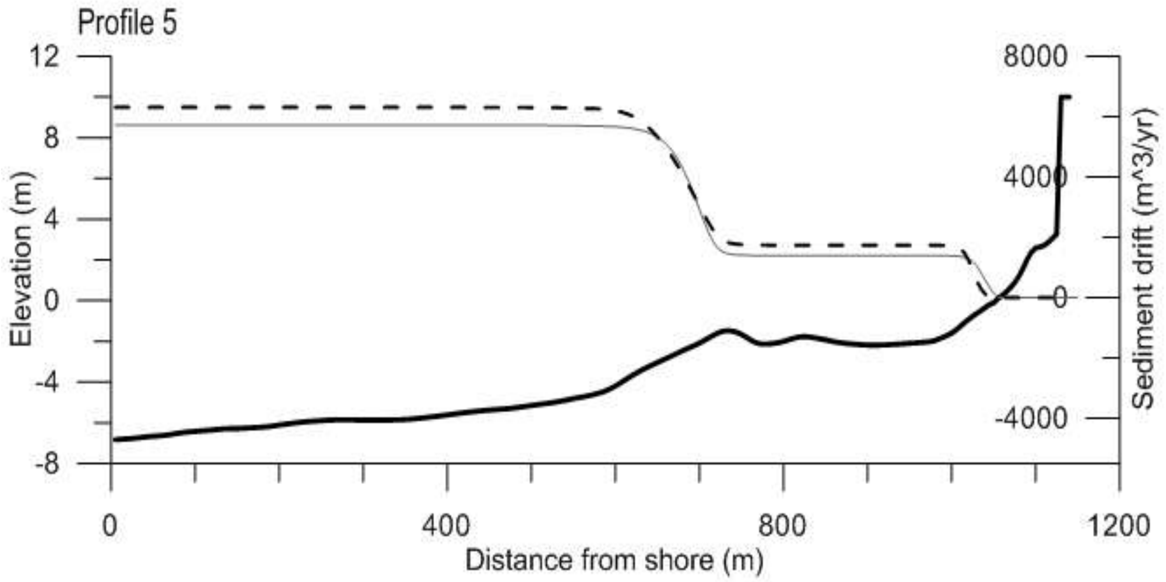


Profile 3

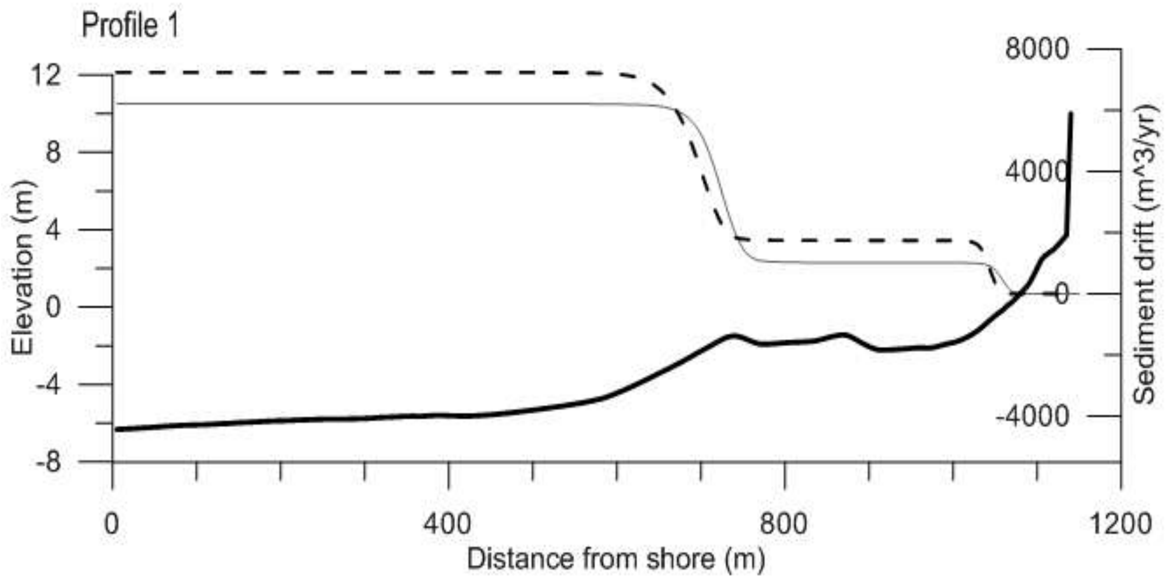


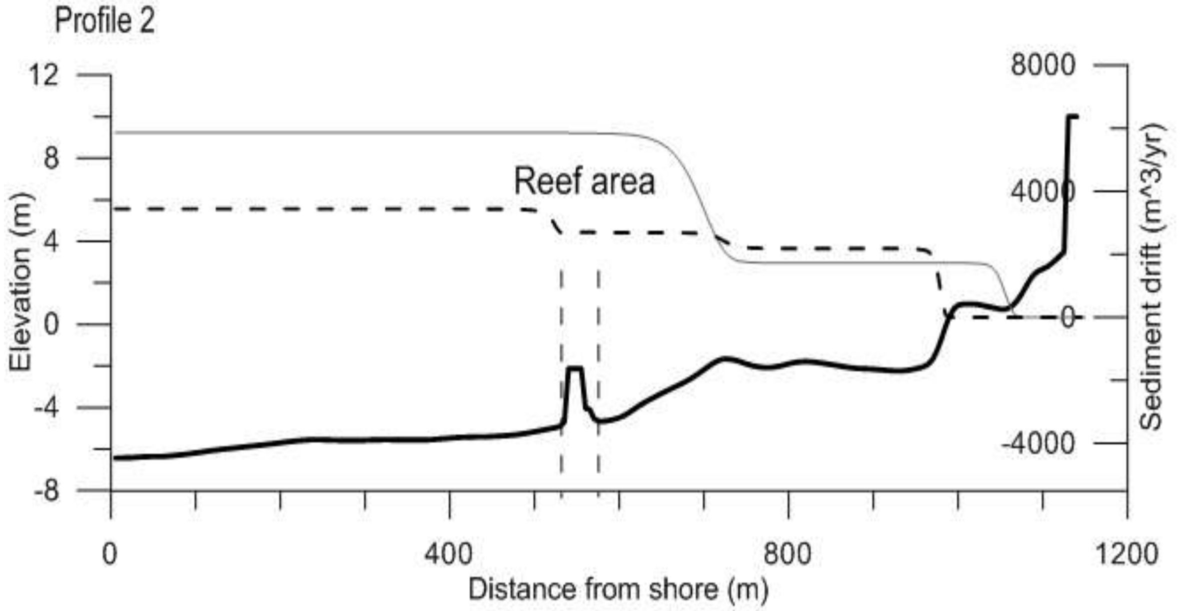

Alternative 8 - Reef Balls Breakwater in Heidkate beach
(coastal protection and habitat enhancment)
Profile 1
Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Net drift (m^3/yr)
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200
Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
Profile 3
Reef area
(gap area)
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)

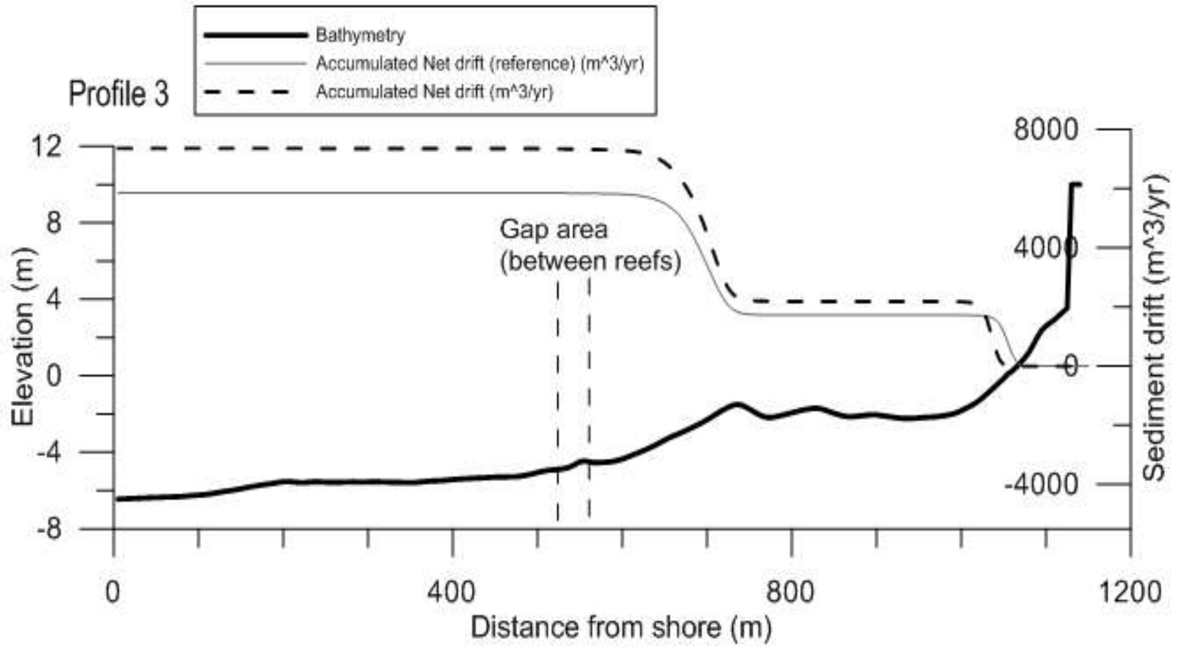


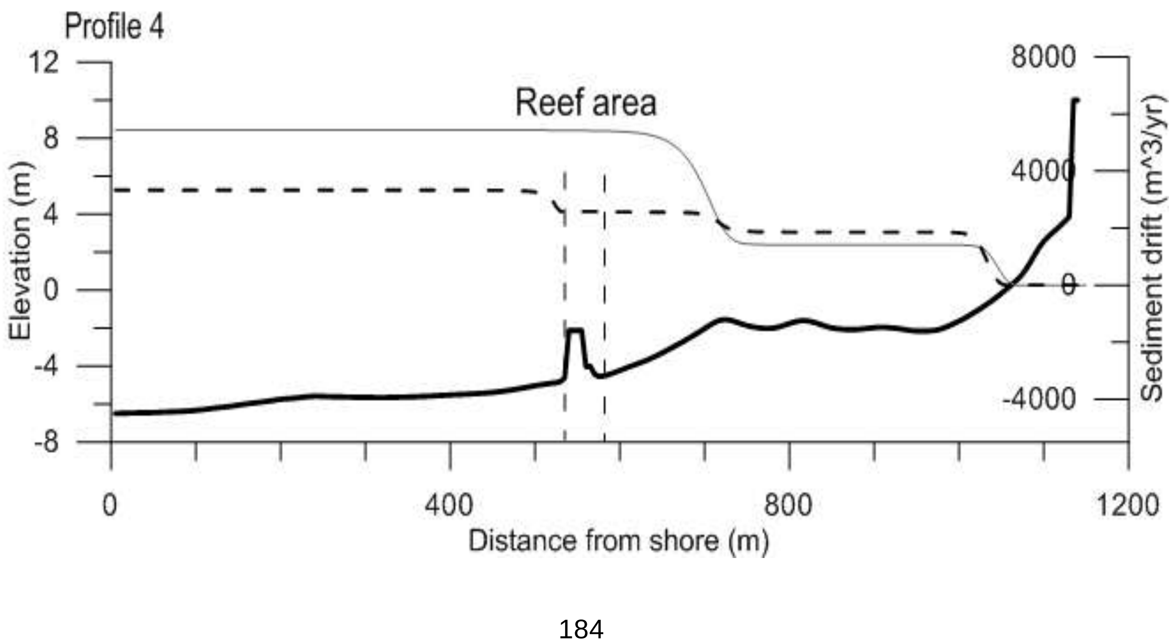


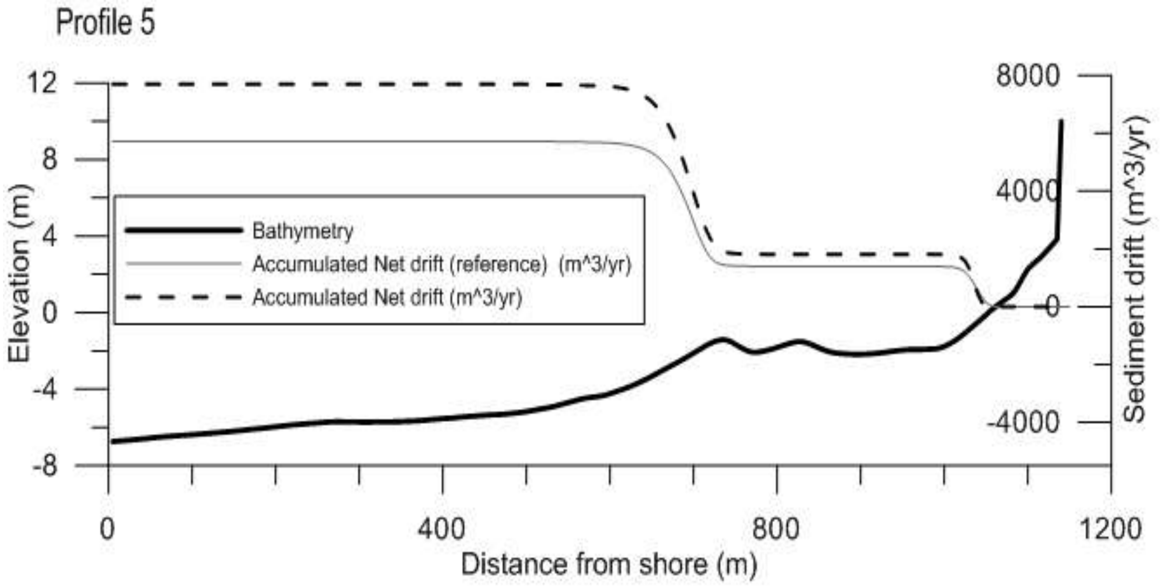
Alternative 9 - Reef Ball Breakwater in Heidkate Beach (habitat enhancement)



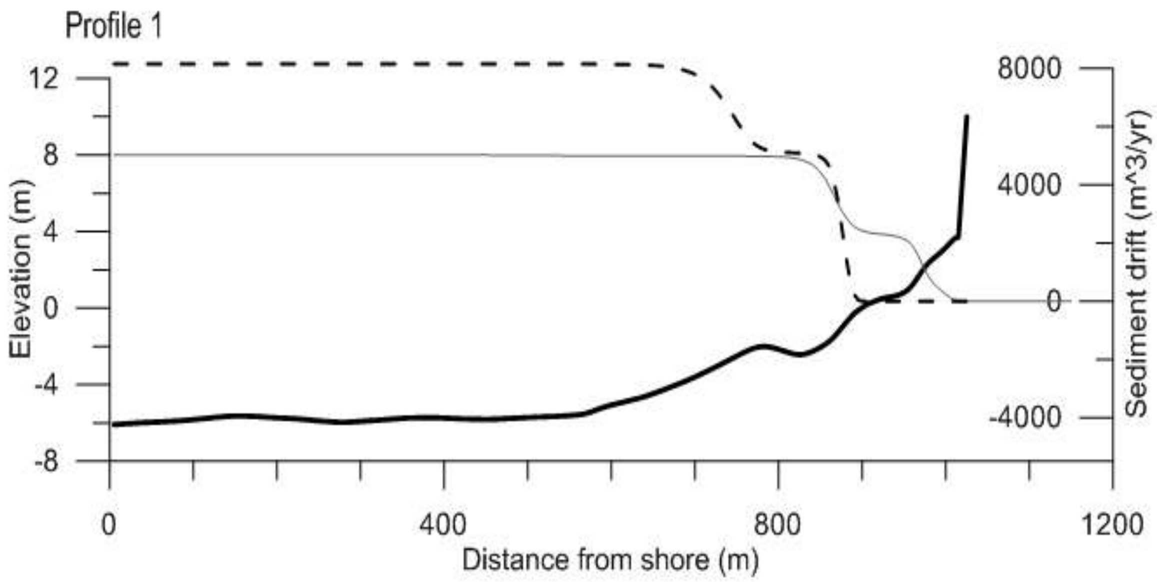

Profile 2
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

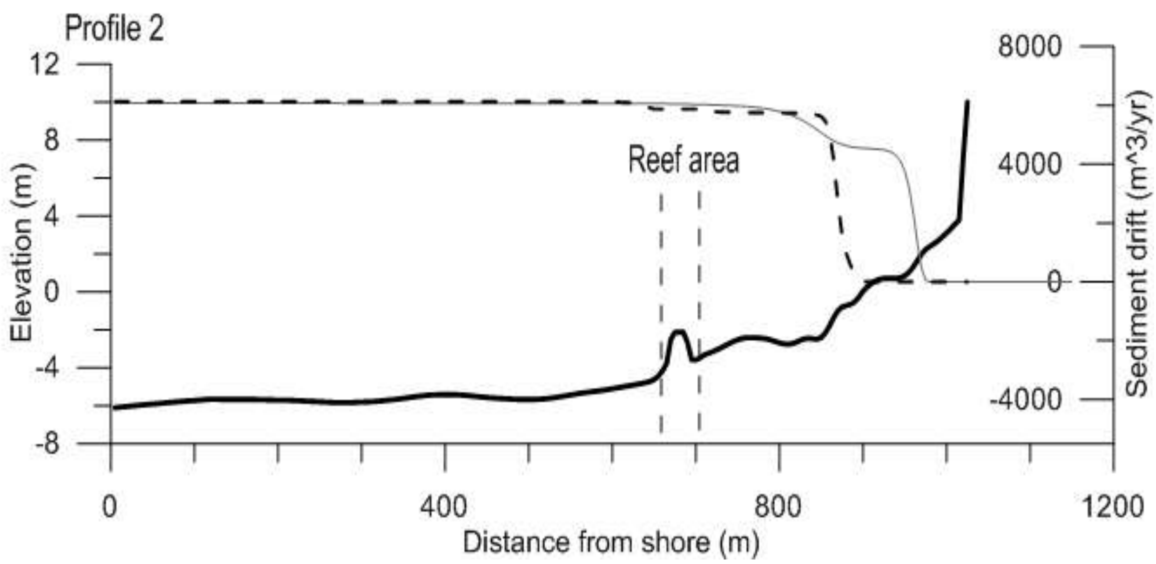

Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Net drift (m^3/yr)
Profile 3
Gap area
(between reefs)
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200


Profile 4
Reef area
Elevation (m)
Sediment drift (m^3/yr)
Distance from shore (m)
12
8
4
0
-4
-8
8000
4000
0
-4000
0
400
800
1200

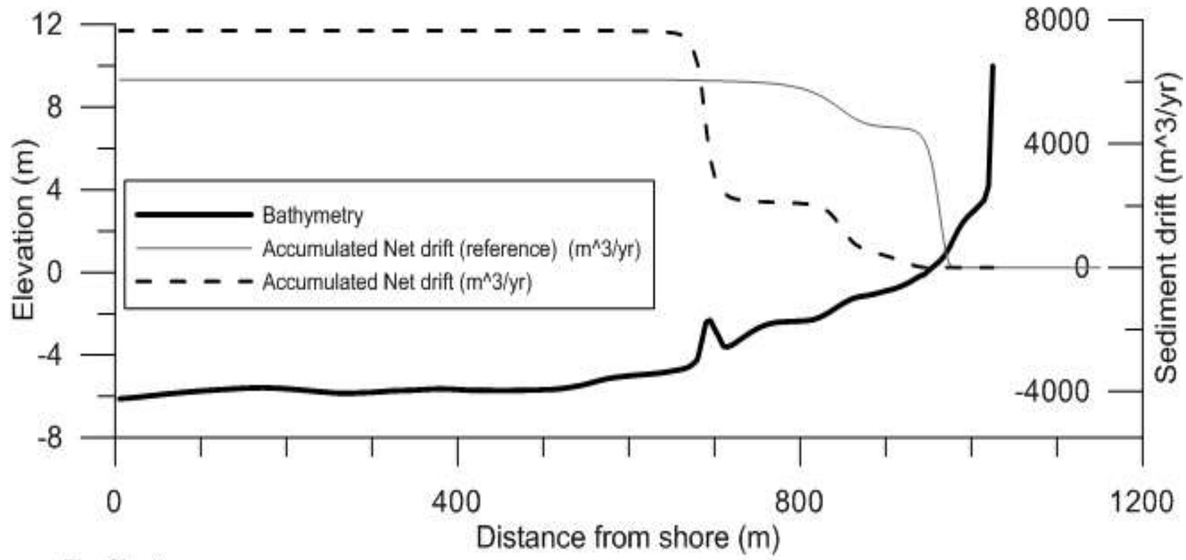


Alternative 10 - Reef Balls Breakwater in Brasilien beach (coastal protection and habitat enhacement)

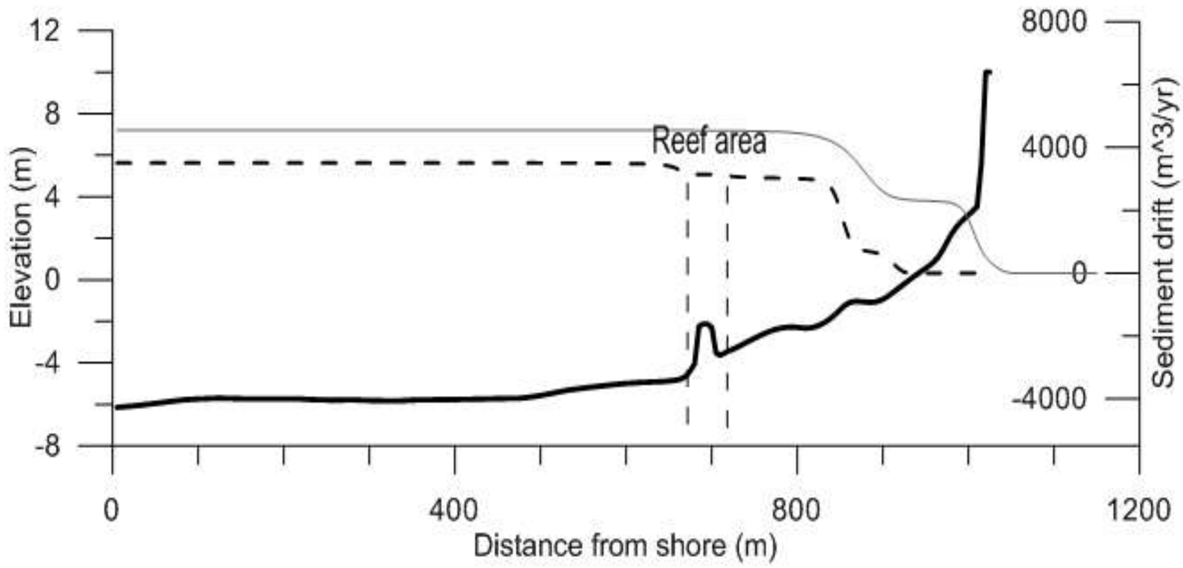




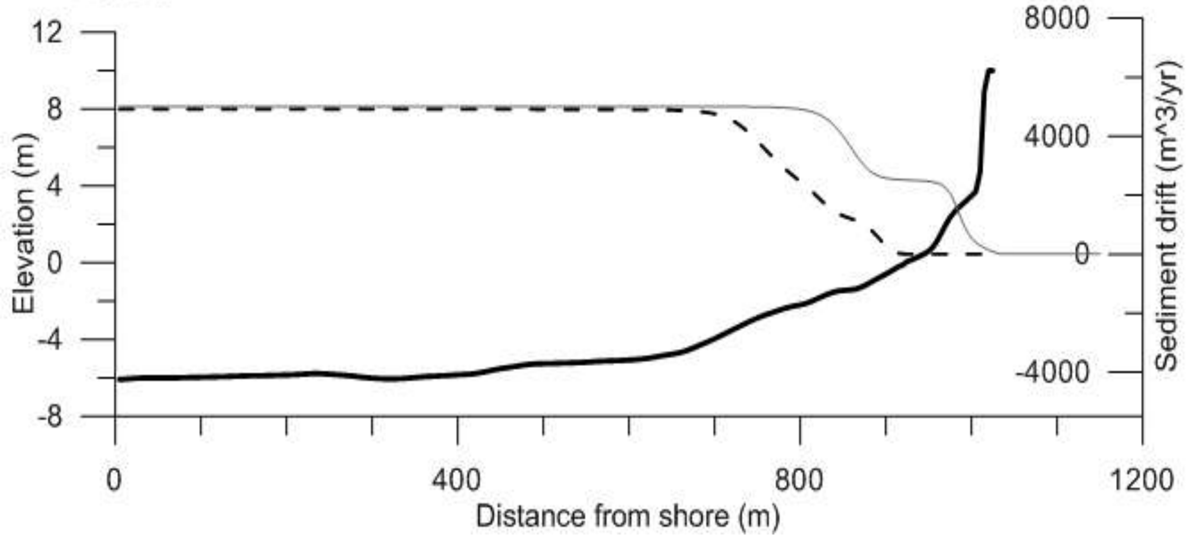
Profile 3



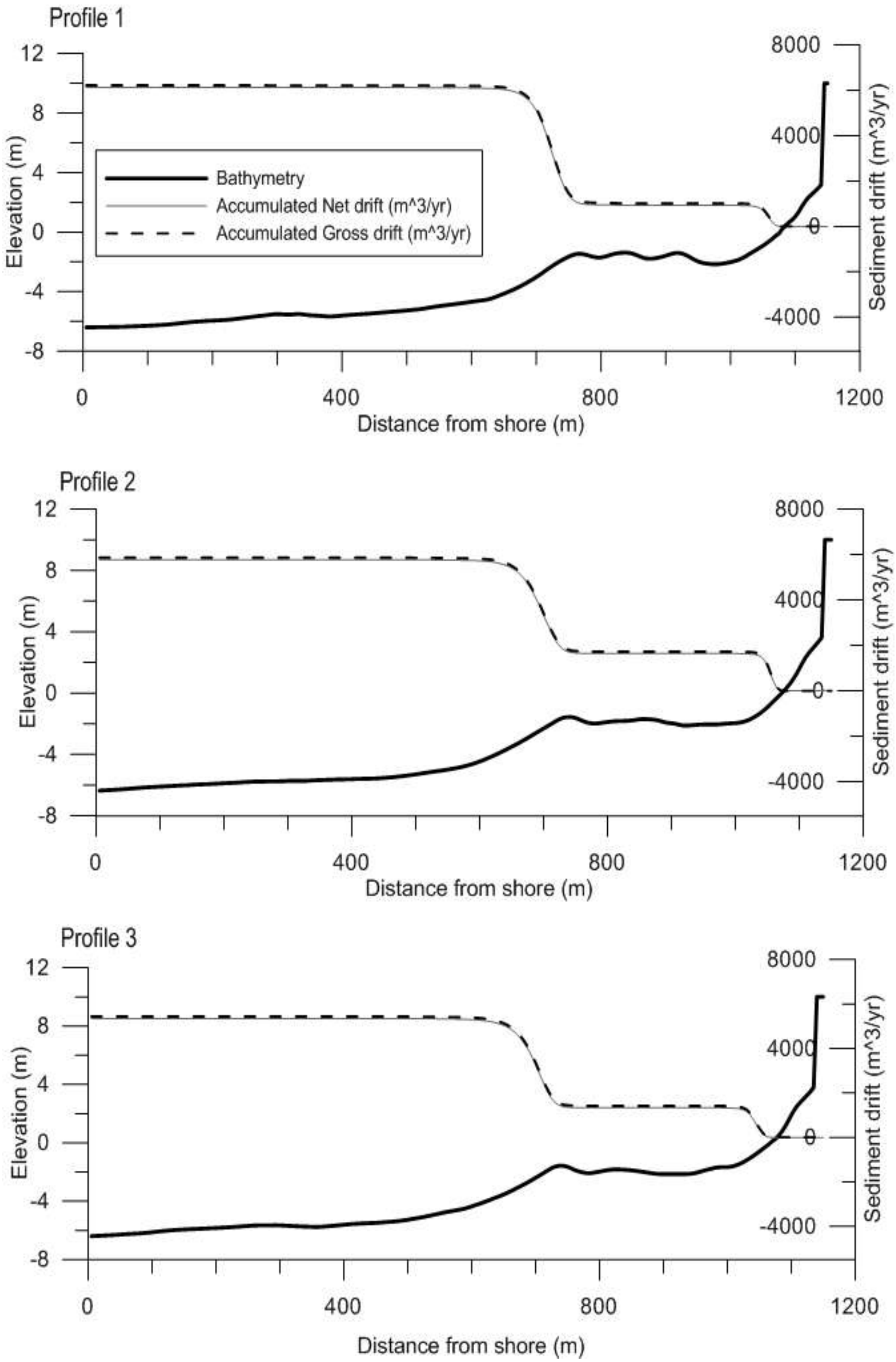
Profile 4

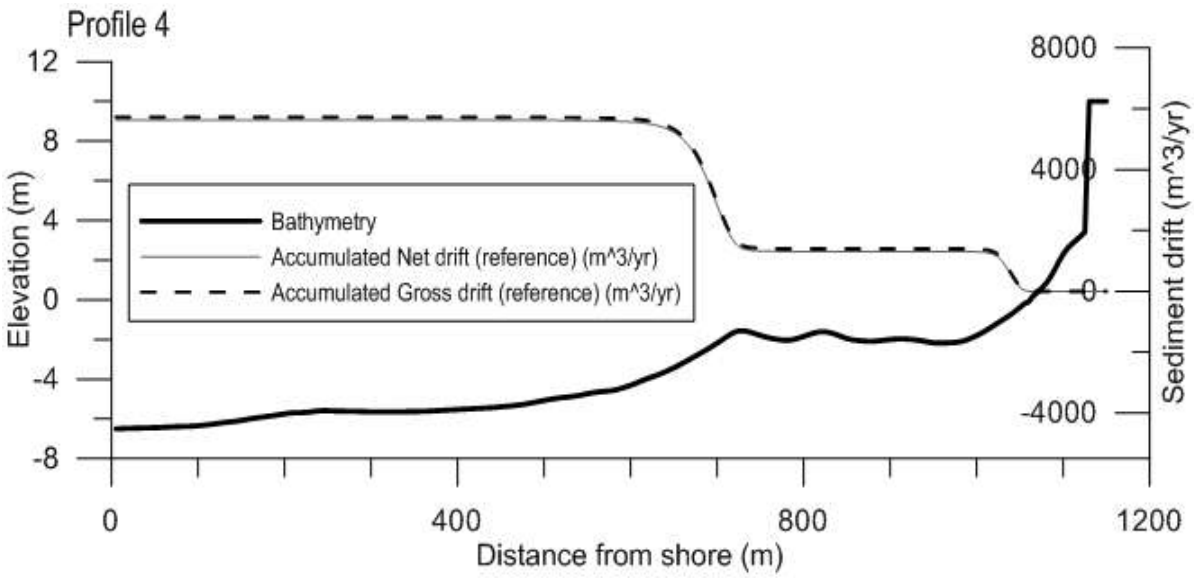


Profile 5

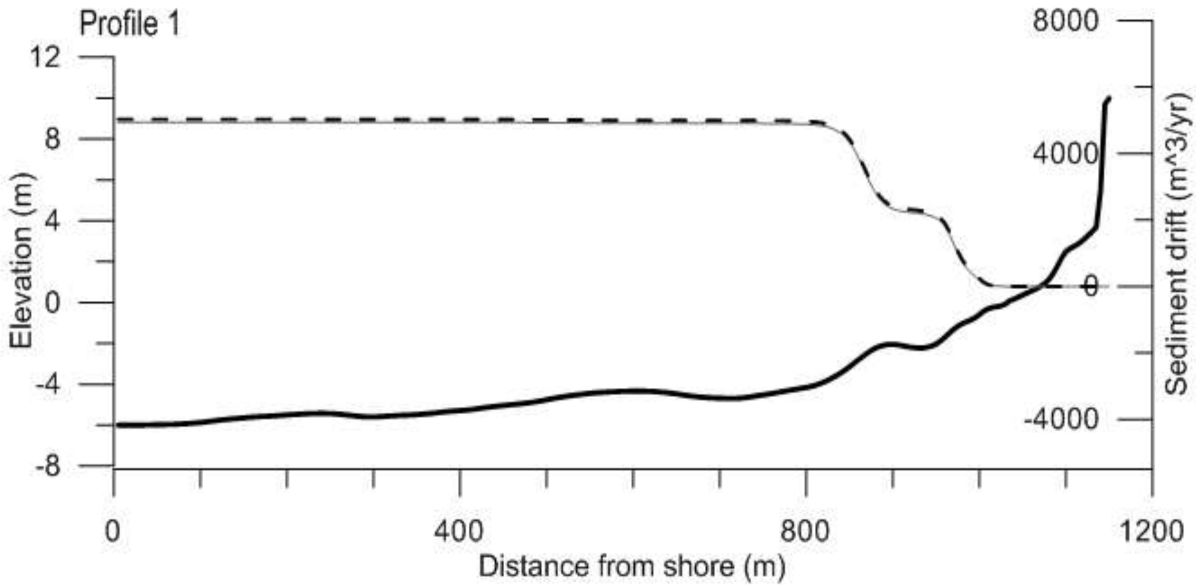


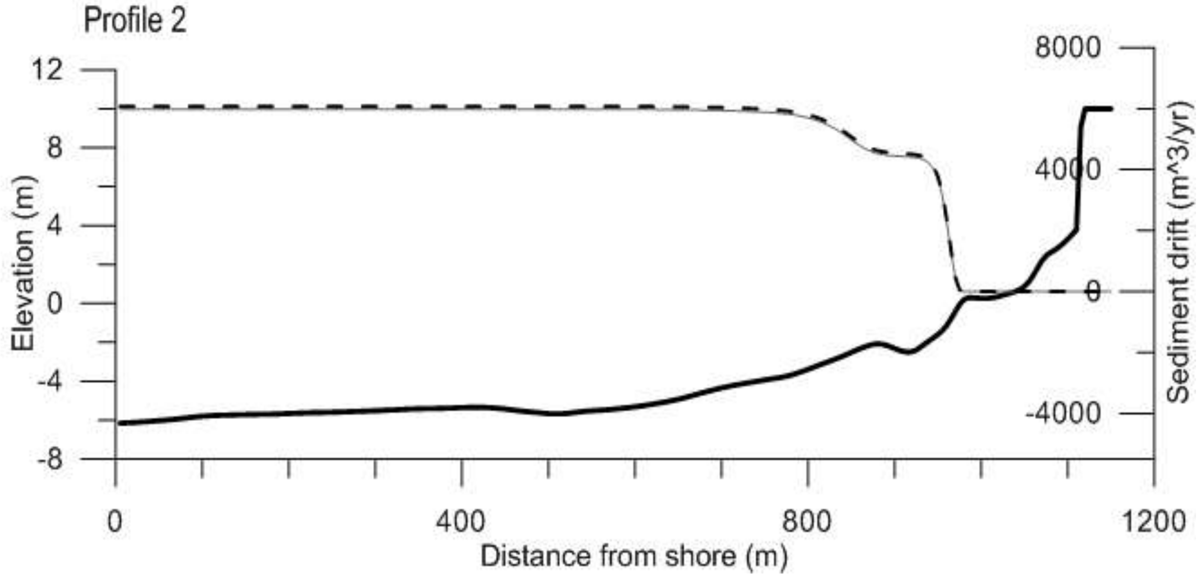
Reference conditions - no breakwater. Heidkate Beach

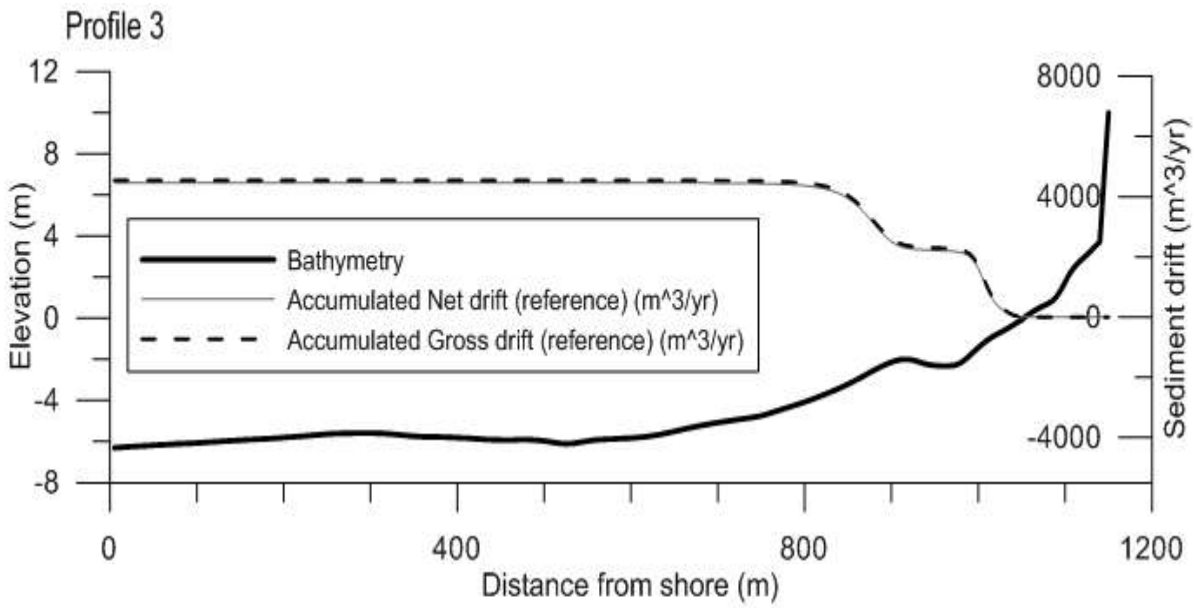


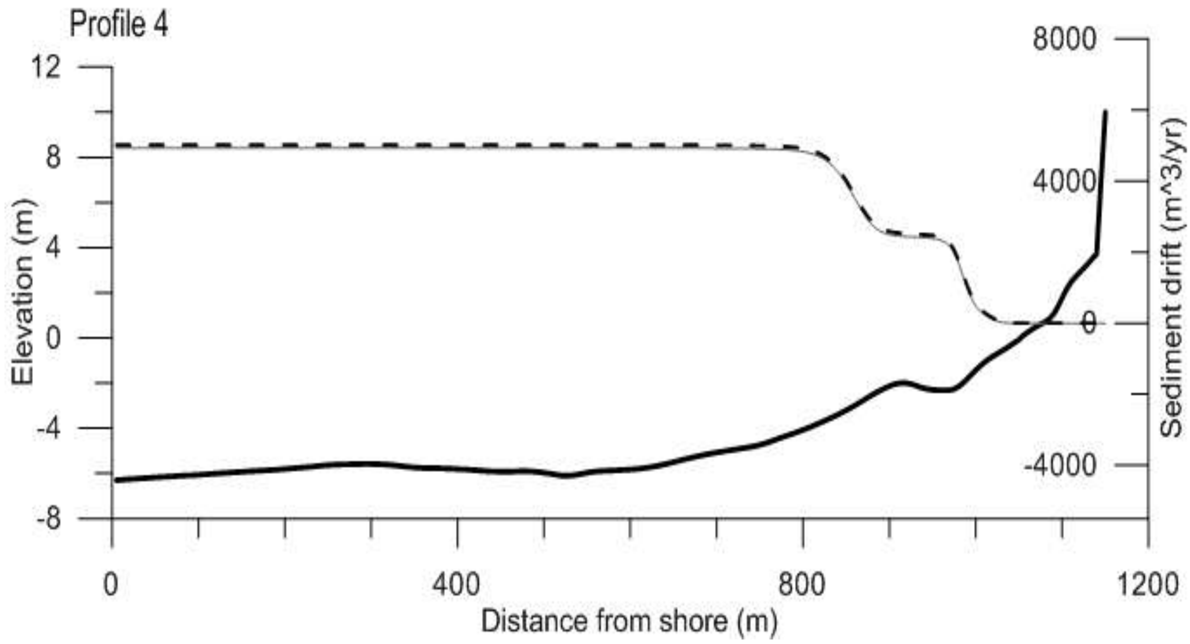


Reference conditions - no breakwater. Brasilien Beach






Profile 3
12
8
4
0
-4
-8
Elevation (m)
8000
4000
0
-4000
Sediment drift (m^3/yr)
Bathymetry
Accumulated Net drift (reference) (m^3/yr)
Accumulated Gross drift (reference) (m^3/yr)
0
400
800
1200
Distance from shore (m)


Profile 4
12
8
4
0
-4
-8
Elevation (m)
8000
4000
0
-4000
Sediment drift (m^3/yr)
0
400
800
1200
Distance from shore (m)

RA:dOst
Regionale Anpassungsstrategien
für die deutsche Ostseeküste

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Bundesministerium
für Bildung
und Forschung

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Klimawandel in Regionen