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COMEM

Sustainable long term coastal protection and development based on sand nourishments

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Sustainable long term coastal protection and development based on sand nourishments

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Table of Content

List of Figures

Abstract

This study aims to define and apply long term sustainable sand nourishment strategies for coastal protection and development. Three sites have been chosen as study cases representing multi-characteristic coasts: Sylt, Germany; S'Abanell, Spain; Ghana. After a comprehensive literature review, key aspects have been identified in order to achieve successful results together with technical constrains. Among these aspects, political, social, economic and environmental features are the main subjects to be considered. From the interaction of those characteristics with coastal typologies and planned functions to be achieved, a simple but useful summary of good nourishment practices has been made. Regarding coastal typologies, most coastal areas can be grouped into two main classes based on sediment budget: open and closed coastal cells. In addition three main coastal functions – enclosing protection, environment and recreation – further refined sound sand nourishment strategies for specific cases. The application of such concepts at Sylt shows that following the currently strong management and experience in soft solutions an optimized nourishment strategy can further enhance strategy while lowering costs and environmental impacts. There, a mega nourishment (like the Dutch 'Sand Engine') on the Center protects the high risk area while benefiting other sites along the coast by the natural spreading of sand. On the other hand, for S'Abanell the combination of restoration of the Tordera River sand supply, a set-back measure, and reduction of material requirements and losses by perching the beach, coupled with ARGUS monitoring to trigger smaller emergency nourishments, shows better benefits for tourism and protection. This strategy enhances protection and lowers the risk in addition to creating an optimum beach area for tourism. For this site, large deposits of sand were not successful in the past, leading to complete loss of sediment in a region where sand reservoirs are scarce. For Ghana, the lack of information and management in the coastal protection industry are evident from unsuccessful deployment of structures that, due to unknown erosion causes and weak policy and management, cannot counteract erosion in the global context. There, the assessment needs to start from a plan of approach, with data acquisition, local interviews and identification of goals and key stakeholders, together with education involving soft solutions.

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1 Introduction

Several coasts around the world consist of sand which has its functions as natural ecosystem but also protection and human leisure. Numerous of those areas are under erosion characterized by shoreline retreat. Erosion processes are induced by natural forces (*e.g.* storms and sea level change) nonetheless in many places human intervention increases marine transgression by reducing the sediment supply, accelerating sea level rise and also by causing local land subsidence.

Erosion can show different behaviors and time scales, *e.g.* storm induced and structural erosion. The former occurs in shorter time scale (*i.e.* few hours to months) and usually represents only the redistribution of sand from the dry beach and dunes to the surf zone. In this case, by means of waves this sand comes back to the beach in few months. This process makes the so called winter and summer profile that usually does not cause changes in the sediment balance. On the other hand, structural erosion is caused by the long term negative budget of sediment within the coastal cell. Therefore it constantly withdraws material leading to shoreline retreat in a scale of years to decades.

Since coastal areas are of high interest with growing human occupation, in the last century raised the need of protecting the shorefront (Figure 1).

Figure 1: Example of coastal erosion threatening houses.

Early engineering works to mitigate coastal erosion had the focus on holding the sand or protecting the shore with the so called hard structures. It comprises: revetments, groins, jetties, breakwaters and so on. They act by means of changing the local hydrodynamic and sediment transport in order to diminish erosion or sedimentation. Those methods were largely applied in Europe until the middle of 1900's to control structural and storm induced erosion (Hamm *et al.*, 2002; Hanson *et al.*, 2002; Dean & Dalrymple, 2004). Although, by blocking or interfering on the sediment transport those methods can enlarge gradients, enhancing even more downstream erosion as in Figure 2 (Dean, 2002; Bosboom & Stive, 2012). Van Rijn (2010) advices their construction in places where longshore shore transport gradient is close to zero. From economical point of view they are relatively more expensive for the initial investment since it usually encompass large deployment of rocks and concrete blocks however maintenance costs are rather low. On the other hand such constructions can result in unattractive landscape besides representing possible harm for swimmers and boats.

Figure 2: Example of updrift drift accretion and downdrift erosion caused by the introduction of structures at Mataró, Spain.

Since the 1950's there has been a trend in protecting the seaside by means of introducing more sediment into the coastal system. This method works based on sediment budget within a delimited coastal cell. The coastal cell balance is controlled by the result of input, storage and output of sediments. From this simple evaluation a surplus on inputs over outputs results in coastal progradation, while the opposite leads to coastal retreat. In this middle, the balance or absence or both inputs and outputs results in shoreline stability. This principle characterizes open and coastal cells, in which the former has open boundaries while the latter is closed.

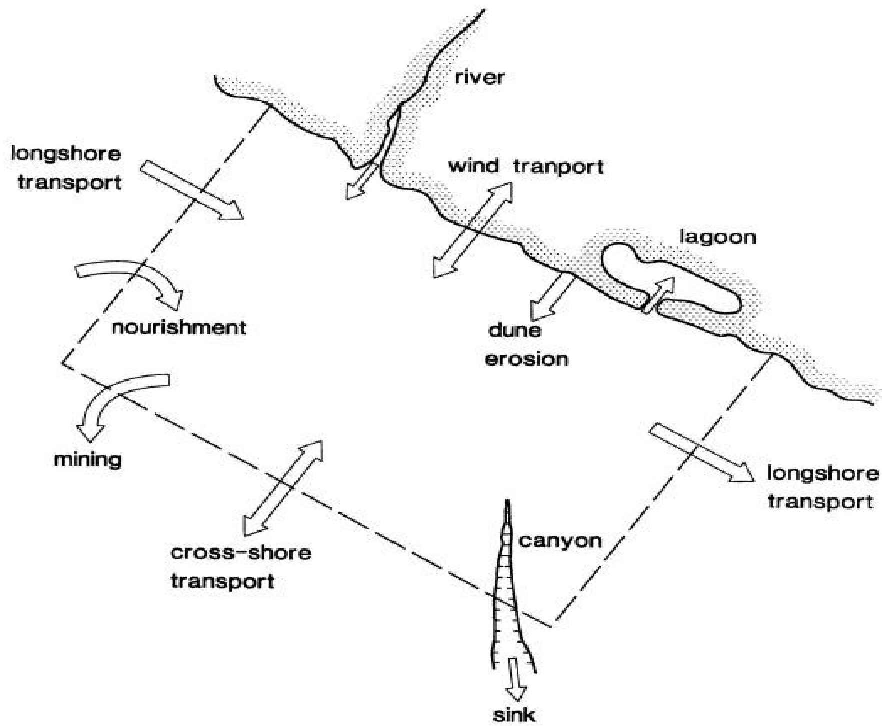

Figure 3: Schematic coastal cell with examples of sources and sinks (Van Rijn, 2010).

In a schematic coastal cell represented in Figure 3 the longshore transport balance is very important when considering possible alongshore gradients. Other major contributions come from several factors among: cross-shore transport (*i.e.* onshore and offshore directed), submerged canyons, river inputs, lagoon and inlet interaction, dune and cliff erosion, wind transport, sand mining among others.

Hence soft protection methods allow free transport of material and also the improvement of the natural function of sandy coasts before deprived or changed as consequence of erosion or introduced structures (Figure 4). Nowadays nourishment works are advised for beach enlargement, storm protection, littoral drift controlled and sediment starved coasts (structural erosion) by the most recent guidelines. Those methods have been successfully applied worldwide in addition to its lower environment impacts (Dean, 2002; European-Comission, 2004; Marchand (Ed.), 2010; Marchand *et al.*, 2011; Mulder *et al.*, 2011). The drawback of sand nourishments is the constant need of maintenance and also uncertainties regarding project life-time and its behavior.

Figure 4: Example of beach nourishment at Copacabana beach in Brazil before the nourishment (left) in the 1920's and nowadays (right).

Several techniques can be employed in nourishment projects throughout the whole process. They differ from acquiring sand, transporting and finally placing and spreading the material onto the shore (Dean, 2002; Dean & Dalrymple, 2004). The choice among procedures and equipments does not have a successful standard guideline. It will highly depend upon technical constrains such as project size and type, hydrodynamic, soil conditions, available equipments but also relies on the local policy, environmental requirements, public activities, human health, safety and the social usage of the area (Sánchez-Arcilla *et al.*, 2011). All those facts interact in a synergic way making choice between one and other method very complex. Feasible technical solutions can lead to non-acceptable impacts on the environment or on the public usage and vice-verse; as well as successful strategies applied somewhere sometimes cannot be extended to other areas.

Sediment placement can be performed within four zones regarding the cross-shore profile, as demonstrate in Figure 5 .

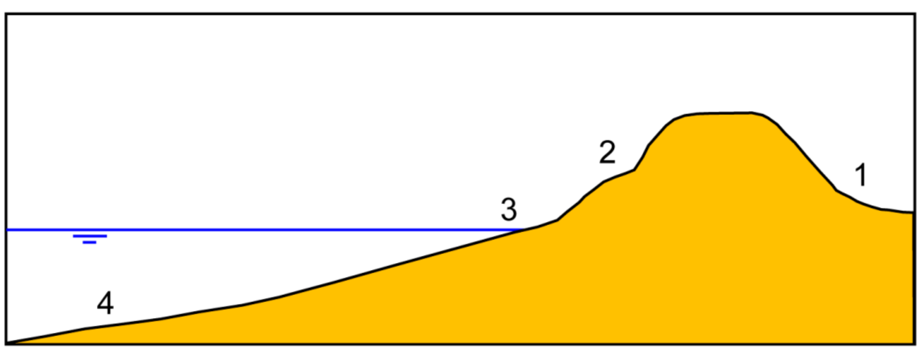

Figure 5: Cross-shore placement schemes for nourishing the shore.

Dune deposits (1 and 2) show immediate response and are suitable for high risk areas where the exposition of hinterland to wave attack and floods represents harm. Beach or berm nourishments (3) also present instantaneous response by enlarging the shore. Such schemes are suitable for both protection and tourism development. Shoreface or foreshore nourishments (4) protect the coast by means of wave dissipation and slower natural beach enlargement[1]. It has a long term effect however its result on the dry beach enlargement is rather unpredictable as well as its efficiency as energy buffer especially in case of large storm surges. Nonetheless those methods lead to less environmental impacts since the surfzone is already highly disturbed by waves and turbidity where the organisms are well adapted to such conditions.

In a broad panorama nourishment works started in Europe around the 1950's in Germany as a practice to counteract erosion and promote coastal development. Those projects differ from place to place regarding size, frequency, policy and funding as described extensively by Hamm *et al.* (2002) and Hanson *et al.* (2002), summarized in Table I. A closer analysis from those figures revels the diversity among countries in which some important aspects regarding coastal protection strategies can be drawn. For example, despite the difference in long term strategy between The Netherlands (*i.e.* with strategy) and Spain (*i.e.* without strategy) both countries show similar volume magnitudes nourished through time. Spain applied several small fills (*i.e.* 11.000 m³/y per site) while The Netherlands fewer but larger (*i.e.* 91.000 m³/y per site). This investigation reveals interesting points once the Mediterranean area has limited reservoirs of sediment available while the shallow North Sea does not experience this limiting factor. Though, Spain has benefited with similar amount of material. This fact is in part supported by the different nature of their shore since the Dutch coast is rather straight and uninterrupted when compared to the Spanish coast formed by several pocket beaches and short straight sections which limits the volume requirement for replenishment per site.

The presence or absence of long term strategy and monitoring programs are other key parameters for a successful coastal development plan. In this European overview only Germany, The Netherlands and Denmark have such planning embedded in their policy. On the other hand France, Italy and Spain face problems with sediment reservoir management, funding sources and integrated solutions where several interventions with hard structures actually only translated the erosion towards downstream.

Table I: Summary of nourishment works in Europe from approximately 1950's until the 2010's (Hamm *et al.*, 2002).

Country	First Recorded Project	Nº of nourished sites	Total fill volume [Mm³]	Long-term strategy	Funding
France	1962	26	12	No	Local
Italy	1969	36	15	No	National/Regional
Germany	1951	60	50	Yes	Federal/National
The Netherlands	1970	30	110	Yes	National
Spain	1985	400	110	No	National
Denmark	1974	13	31	Yes	National/Local
United Kingdom	1950's	32	20	No	National/Local

This rather quick evaluation points out the difference in basic background and boundary conditions that need to be evaluated and considered while planning coastal development in site specific situations.

[1] Caused by onshore sediment transport due to wave asymmetry, mainly.

Nourishment works are usually designed for lifetimes up to 10 years however in practice this is reduced to around 3 to 5 years due to uncertainties regarding sediment diffusion (Hamm *et al.*, 2002; Hanson *et al.*, 2002; Van Rijn, 2010; Van Rijn, 2011). In the last decades the endeavor of finding longer nourishment strategies enclosing environmental friendly, better cost & benefit and social acceptance designs raised studies of new methodologies. From this, a new concept called *building with nature*[2] encourages the development of innovative solutions using natural processes and forces in favor of engineering (Ecoshape-BwN, 2012; De Vriend & Van Koningsveld, 2012). The successful implementation of the pilot *ZandMotor* (Sand Engine) in The Netherlands was the benchmark of such strategies. The project aimed coastal protection but also the environment and social interaction (Mulder & Tonnon, 2010; Zandmotor, 2012). It consists of a mega nourishment in which 21Mm³ of sand were placed in a hook shaped beach deposit onto Delftland coast. The primary goal is to protect the shore by means of the natural spreading of sand by currents and wind, strengthening the beach and front dunes (Figure 6). Despite of having its longevity estimated in 20 years, the design meant to be environmental friendly by creating new intertidal areas for ecosystem development. In addition, it also made recreational areas where kite surf and surf are the main activities.

Figure 6: Aerial photo from the pilot Zand Motor in The Netherlands (Zandmotor, 2012).

Other solution for littoral drift controlled coasts consists of bypass systems such the ones applied in the USA (*e.g.* Delaware) and Australia (*e.g.* Tweed and Nerang Rivers, Figure 7). This method works by transporting sediments through blockages towards the downdrift coast. By transposing jetties or harbors it restores the natural sediment transport. Those systems have been maintaining coasts for decades in those places with relative lower impact when comparing with traditional replenishments performed before (Boswood & Murray, 2001; Castelle *et al.*, 2009; Cooke *et al.*, 2012).

[2] Available at <www.ecoshape.nl>

Figure 7: Sediment bypass on Tweed River, Australia. On the left the benefited beaches downdrift; on the right the bypass pier and the river entrance.

This review of coastal protection methods and examples around the world shows that sometimes hard structures are not a sustainable solution for dealing with erosion. Although sand nourishments strategies if not well designed and implemented, may also show its weakness. Due to the large variety of techniques and backgrounds, the design of sand nourishments can turn out to be very complex. The endeavor of finding more sustainable long term solutions has raised the endeavor of identifying potential attractive innovative strategies.

In this context the present project ventures to first identify key general and more specific parameters important for designing sustainable long term nourishments (chapter 3). Such design aspires to enclose technical, environmental, social, economical and political aspects. These theoretical concepts are then applied into three case specific designs: Sylt in Germany (chapter 4), S'Abanell in Spain (chapter 5) and on the Ghanaian Coast (chapter 6).

2 Objective

To define and apply long term sustainable sand nourishment strategies for costal protection and development.

To do so the following steps will be taken:

- Evaluation of general sustainable practices for the execution of sand nourishment enclosing political, environmental, economical and social aspects;
- Proposal of sand nourishment strategies based on main coastal typologies and beaches functions to be achieved;
- Application of those previous concepts and practices at three sites: Sylt, Germany; S'Abanell, Spain and Ghana.

3 Designing Sustainable Sand Nourishments

As observed, several methods can be applied in coastal protection within hard and soft methods. The choice within sand nourishment techniques can largely differ from each other. In order to compile numerous applications and guidelines an extensive evaluation of practices were previously compiled in Albernaz (2012). The goal in this study was to evaluate worldwide projects and guidelines in order to define sustainable practices. The compiled assessment is the starting point for planning long term and sustainable solutions involving sand nourishments for coastal protection and development.

The project accounts the interaction of technical, social, political and environmental aspects. Important to mention that long term in this project is defined in the scale of decades. Important to keep in mind that case-by-case applications can differ from this frame. This happens due to very complex synergy within variables from where there is no standard guideline to be followed (Sánchez-Arcilla *et al.*, 2011).

3.1 General Characteristics

This section describes general subjects to be previously evaluated when designing nourishments. It consists of an important step in order to identify the problem, the background and the public desire towards the shore.

To better explain those results the next sections explores the basic political (3.1.1), environmental (3.1.2), economical (3.1.3) and social (3.1.4) aspects enclosing nourishment works assessed in Albernaz (2012) from a generic perspective.

3.1.1 Political aspects

For defining coastal protection strategies it is essential to have solid and clear policies. It encloses who is responsible for monitoring and funding erosion related issues.

Other import point is the definition of triggers for actions since projects can take long to be approved, planned and applied. Therefore it is necessary to know the necessity of action before critical situations. Emergency interventions are rather expensive and most of the time does not consist as a long term solution.

Prevention is advised rather than remediation procedures nonetheless the latter should also be ready in case of emergency, *e.g.* after severe storms.

Knowing in advance the sediment reservoir characteristics and managing its use is strongly advised.

Projects such CONSCIENCE and EUROSION are important tools for developing strong management towards sand nourishments. They define key strategies and concepts starting with the definition of coastal cell and monitoring programs until political aspects enclosing coastal erosion issues. (EUROSION, 2004; Marchand (Ed.), 2010; Marchand *et al.*, 2011).

3.1.2 Environmental aspects

Endeavoring to reduce environment impacts the intervention should be done with sediments clean of pollution, with similar granulometric characteristics compared to *in situ* material. It is also advised to avoid fine fractions since they are usually associated with turbidity, pollution and also larger loss of material.

A compromise between the total area impacted versus deposit thickness should also be evaluated. Thicker layers impact most of the benthic fauna while extensive areas also affect more biota. In addition, works performed in the surfzone (*i.e.* foreshore nourishment) shows less impact as when executed during winter season since the natural conditions of high turbulence already select more tolerant species that are already adapted to severe conditions. Works on the beach or dunes shows larger impacts and lower recovery of the macro and interstitial fauna (Nordstrom, 2005; Speybroeck *et al.*, 2006; Schlacher *et al.*, 2012).

New concepts as *bed landscaping* on the borrow area and alternation of the fill placement in location and time are pointed as successful tactics enhancing the biota recovery since they improve re-colonization capacity of impacted borrow and settling areas (Ecoshape-BwN, 2012).

In most cases it is important to keep the natural function of the ecosystem for ecological matters but also considering physical (*e.g.* protection, energy buffer) and social functions (*e.g.* leisure and wealth), as described by Costanza *et al.* (1997).

3.1.3 Economical aspects

The application of coarser material reduces the total volume to be used due to equilibrium profile characteristics and sediment diffusion. Finer sand produces gentler slope that needs more volume to achieve certain beach width. In addition, finer sediment enhances transport which can lead to higher and quicker material loss.

Doing combined schemes such as beach with foreshore nourishment can enlarge the project life time and reduce costs. Foreshore methods are cheaper to be executed and last longer when compared with beach and dune methods.

Constructions during high season should be avoided in touristic places. In such places the minimum beach width must be ready at the beginning of the season (Lent *et al.*, 1999; Raybould & Mules, 1999; Parsons & Powell, 2001; Dean, 2002; Dean & Dalrymple, 2004; Parsons & Noailly, 2004; Van Rijn, 2010; Van Rijn, 2011).

Nourishment works in exposed areas are usually executed by **T**railing **S**uction **H**opper **D**redgers acquiring sand from the borrow area, sailing and placing the material on site by: bottom doors, rainbowing or pipeline discharge. The price and operational time increases from the bottom doors towards pipeline methods. Any job involves mobilization of crew, equipments and sailing vessels towards the site which presents large initial costs. In this sense, large operations can reduce the total cost per cubic meter. In addition, closer and easily accessible borrow area lowers the cost. Fixed installed system, such as bypass systems or only discharge lines can possibly reduce costs due to avoiding several installations. However maintenance can be expensive in bypass systems enclosing pumps and also electricity costs.

Studies assessing cost and benefit analysis in the United States of America and Australia agreed that urbanized areas usually presents positive results in doing coastal protection. Evaluating damage costs, decrease of property value and also tourism activities the general conclusion is to apply and maintain sand nourishments or bypass systems (Beachler & Mann, 1996; Lent *et al.*, 1999; Raybould & Mules, 1999; Parsons & Powell, 2001; Parsons & Noailly, 2004). Soft methods have been largely applied at Florida, *e.g.* Delray Beach which received the award of best restored beach of 2013 by The American Shore and Beach Preservation Association (ASBPA)[3].

3.1.4 Social aspects

From the social point of view, the project should enclose all relevant stakeholders and users, together with public information, looking for an integrated solution. The inclusion of social aspects makes the strategy very subjective upon the usage and culture. Although swimmer safety, comfort and avoiding beach closure are usually common sense aspects (Short, 1999; Klein *et al.*, 2003; Benedet *et al.*, 2004; Bosh, 2008).

3.2 Summary of Good Practices

From this broad review it becomes clear that there is no standard solution in dealing with erosion. However by considering the importance of key parameters in case-to-case assessments the project can increase its chance of being successful. The main parameters enclose political, environmental, economical and social aspects. Those, together with the goal to be achieved and technical constrains indicates among several methods the most suitable strategy.

Table II summarizes the important aspects described in this section.

[3] Available on <www.asbpa.org.>.

Table II: Definition of sustainable practices doing long-term sand nourishment strategies for coastal development compiled in Albernaz (2012).

Political	Environmental	Economical	Social
Strong and well defined policy	Sediment as close as possible to natural, clean from pollution, debris and invading species	Similar or coarser sediments reduces transport/loss	Inclusion of stakeholders and user towards 'integrated solution'
Monitoring program	Shoreface showed lower impacts and better recovery	Larger operations reduces costs per m^3	Swimmer safety and user's comfort.
Definition of 'triggers'	Trade-off between deposit thickness versus total surface impacted area	Combination of schemes to enhance longevity	Minimize beach closure during construction (when relevant upon the usage)
Who is in charge? The decision maker	Bed landscaping in borrow area	Close and easy accessible borrow area	Suitable/Successful strategy very subjective upon the usage
CONSCIENCE/EUROSION principles	Maintenance of "natural function"	Construction during low touristic season	Public information and user's education
Prevention *versus* Remediation	Alternation of placement in time/space	Shoreface is cheaper and requires less maintenance	
Who pays?	Less impact during winter	Cost-benefit analysis	

Generically, dune schemes are made for short term protection and are expensive despite of heavily impacting the environment. Beach nourishments have an intermediate duration effect and can benefit tourism as well. Shoreface replenishment shows lower direct protection but longer longevity and reduced implementation costs and impacts on the natural system.

Sometimes small and frequent maintenance strategy can be more attractive instead of large and less frequent works. Meanwhile more flexibility and longer contracts can lower the price. Although in any case the development of sustainable long term strategy for fighting coastal erosion without a strong and consolidate policy and management will hardly be achieved. Most of sand nourishments need maintenance through time and planning is the key for winner solutions.

3.3 Interaction with Coastal Typologies and Functions

Complementing this generic assessment, some coastal typologies target of sand nourishment schemes have been reviewed in site specific level considering coastal functions to be achieved in order to provide more specific and reliable applications. This evaluation is based on the principle that site-to-site applications may not always be valid from one place to the other depending upon the background problem, *e.g.*: cause of erosion, type of coast and beach function to be achieved. The result is a more generally applicable guideline as a function of main coastal typologies and beach functions (Table III).

Table III Nourishment techniques advised from Albernaz (2012) considering different coastal typologies and function.

	Recreation	Protection	Environment
Close cell (Headland bay)	-Redistribution of sediment -Beach nourishment	-Redistribution of sediment -Beach or dune nourishment	-Redistribution of sediment
Open cell (Littoral drift and Starved coasts)	-Restore sediment supply -Beach (shoreface?) nourishment	-Restore sediment supply -Shoreface, beach or dune nourishment	-Restore sediment supply -Shoreface nourishment

C*lose* and *open* cells typologies groups most types of coasts under beach nourishment works together with the function to be achieved: *recreation, protection and environment*. Evaluating the underlying erosion problem, function and goals to be achieved some methods are advised.

In *closed cells* there is no input or output of sediment, meaning no change in volume. The main issue in this case is extreme shoreline orientation caused by seasonal wave climate when some portions of the beach can be too narrow. This phenomenon exposes the hinterland or deprives beach use due to the lack of available space. In those cases, the *redistribution of sand*[4] is a suitable solution avoiding large operations and large environment impacts. In cases when protection or recreation is the functions to be achieved, sand nourishments can also be an option. In this case the total width and strength of the cell is enlarged. The design of pocket beaches is well described in literature, for example by the parabolic fit theory (Hsu & Evans, 1989; Gonzáles & Medina, 2001; Gonzáles *et al.*, 2010; Raabe *et al.*, 2010). Those techniques are suitable for the average long term equilibrium shape of such coasts.

For *open cells* where the littoral drift or other sinks of sediment are dominant, regular sand nourishments are advised in order to balance the sediment loss. When the cause of erosion is well know, it is strongly advised to restore the sediment source. It can be made directly or by simulating its natural behavior through sand replenishments. In case of littoral drift blockage sand bypass systems are strongly recommended. Such practices restore the natural system behavior.

Beach nourishment is usually recommended for recreation, while shoreface schemes are suitable in more natural systems due to reduced impacts. In case of safety all schemes are suitable, especially dune reinforcement.

In sum, the interaction of all factors makes decision very complex. Although, by evaluating the political, environmental, economical and social aspects together with physical characteristics among closed of open sediment cell and the functions to be achieved, suitable successful solutions can be drawn. The synergy among all features will highly depend upon the weight of each variable on the final decision.

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[4] is the practice of moving sand from one side to the other in order, for example, to prevent extreme coastline alignment in pocket beaches. It can be executed by excavators and bulldozers.

In this context the next phase of this project aims to look for the development of innovative solutions towards long term sand nourishment strategies for specific sites, applying the previous knowledge acquired in this chapter. The choice of sites strives to represent multi-characteristic coasts, making this evaluation very comprehensive with technical and management aspects.

4 The Island of Sylt

As the first study case, Germany consists of a well experimented country protecting its coast. It is recognized to have a long term management and planning enclosing sand nourishments. The strong monitoring, problem identification and defined goals makes this example very comprehensive.

Germany has 1900 km of coastline in which one third is made of sandy beaches (Hanson *et al.*, 2002; Dette, 2003). The continental part of Germany is protected by off-shore natural barrier islands and sea dikes. Part of those islands and other sandy coasts are eroding. Until the 1950's shore protection in Germany was focused on hard structures and the first nourishment was executed in 1951 at Norderney. After, the country experienced a gradual change of preference towards soft measures in sandy areas since hard protection methods were not solving the problem. Herein, Sylt is known by its long history of coastal protection where groins and tetrapods actually enhanced downdrift erosion in several places along the island. As a consequence since 1972 the island started applying sand nourishments to counteract this trend. The long monitoring and extensive experience in such projects makes this place a benchmark for evaluating nourishment strategies.

This chapter presents the basic morphology, coastal evolution and sand nourishment history of Sylt. This part is follows the definition of problem, numerical modeling hindcast and forecast of the Island evolution in the absence of intervention and with nourishment schemes, respectively. The goal is the assessment of innovative sustainable sand nourishments schemes for Sylt.

4.1 Coast Morphology and Underlying Processes

The island of Sylt is located in the North Sea on the northernmost portion of the German Wadden Sea, part of the sandy barriers islands of the North Frisian Islands chain. Sylt was formed by glacial deposits that have been eroded and transported forming two spits, southward and northward oriented. This growth was accompanied by the shoreline retreat of its original glacial core (Kelletat, 1992), shown in Figure 8. The modern island consists of extensive tidal flats on the lee side while with sandy beaches and dune cliffs up to 25 meters high on the exposed West coast which dissipates the incoming waves from the North Sea (Sistermans & Nieuwenhuis, 2004).

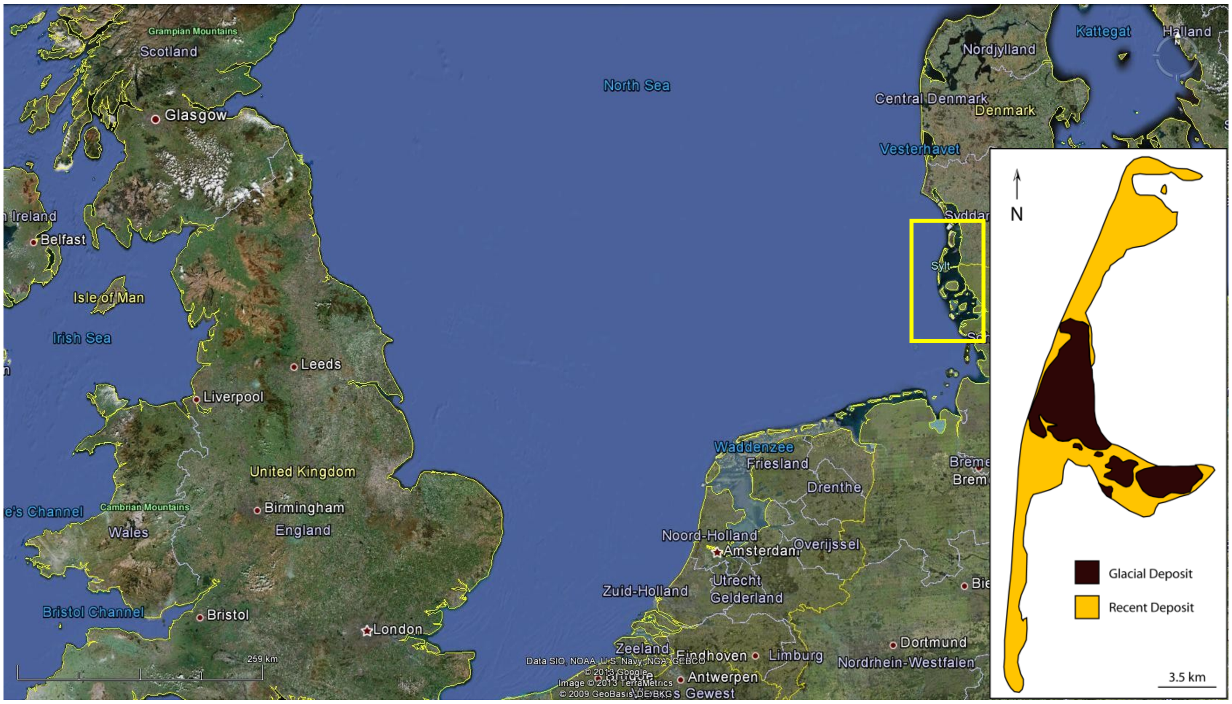


Figure 8: Localization of Sylt Island as part of German Waden Sea within the North Sea. Right panel shows the sketch of Sylt's geomorphology from Kelletat (1992).

The Island has a length of approximately 40 km in its West coast, oriented N-S being exposed to waves from the West, Northwest and Southwest (Figure 9) with tides of 2 m range. However storm surges can reach up to 3.5 meters from the spring high tide (Hamm *et al.*, 2002; Dette, 2003). The coast has an alongshore bar located in the nearshore at approximated 300 m seaward inducing high plunging wave breaking. However this wave energy dissipation effect is lost in the presence of storm surges above 2 meters height when waves can pass freely breaking directly on shore.

Regarding sediment budget, the West coast behaves as an open cell where part of the transported material is: (1) lost on both ends of the island towards the tidal inlets between the adjacent islands, (2) contributes on the spits growth and also (3) deposited on the tidal flats (Kelletat, 1992; Hamm *et al.*, 2002; Hanson *et al.*, 2002; Dette, 2003; EUROSION, 2004; Kroon *et al.*, 2008). This scenario characterizes a structural erosion case; hence the West coast of Sylt is classified as a sediment starved coast where the natural evolution represents the erosion of the center (*i.e.* glacial deposit) followed by the growth and loss of sediments towards the South and North ends.

This alongshore transport is mainly wave induced, being southward at the south and northward in the North. This pattern is due to the combination of wave climate and shoreline orientation where the divergence point is located approximately in the middle point. Shoreline retreat has been estimated in 13 km over the last 7,000 years and more recent studies evaluated this rate ranging from 0.4 to 2.2 m/year between 1870 and 1985 (Hamm *et al.*, 2002; Hanson *et al.*, 2002; Dette, 2003; EUROSION, 2004; Kroon *et al.*, 2008). In this last scenario there is a loss of 1.5 million m³/year of sand.

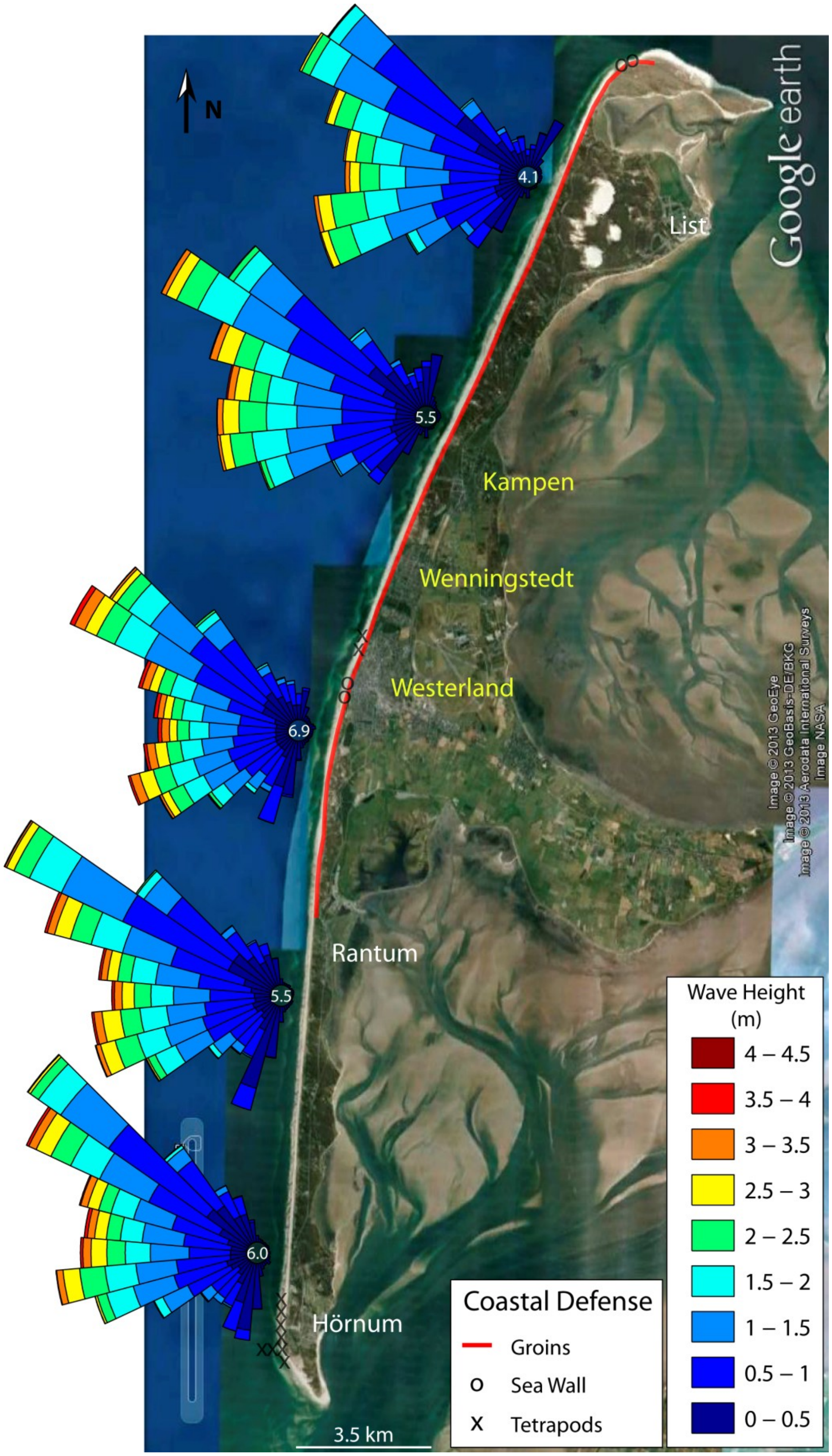


Figure 9: Top view of the Sylt Island with shallow water wave roses (depth in white for each wave rose) and some hard coastal protection works done in Sylt, not in scale.

On average 1.2 million m³ of sediment is lost per year: 800,000 m³ to the North and 400,000 m³ to the South as shown in Figure 14 (Hamm *et al.*, 2002; Hanson *et al.*, 2002; EUROSION, 2004). The hard methods applied to mitigate shoreline retreat (*e.g.* seawalls, groins and tetrapods in Figure 9) did not solve the problem properly. Those works actually aggravated the issue on the downdrift sides (Kelletat, 1992; Hamm *et al.*, 2002; Hanson *et al.*, 2002; EUROSION, 2004).

A historical example of such structures was executed a century ago in front of Westerland, in order to protect the Miramar Hotel. The Miramar Sea wall through the years had to be reinforced (Figure 10) as well as protected by several nourishments (Figure 13) as remarked by (Dette, 2003). The protection of this seawall triggered the application of sand nourishments at Sylt on 1972.

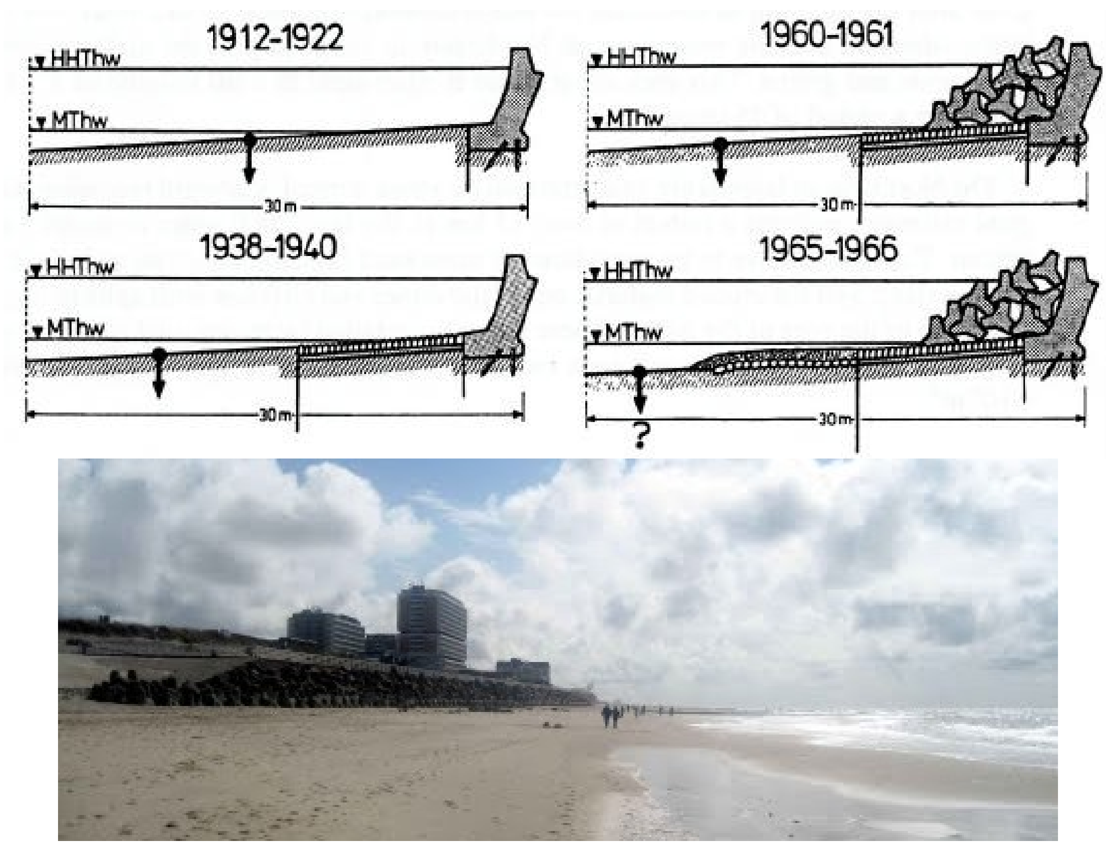


Figure 10: Evolution of Miramar seawall through time (Dette, 2003).

Besides having its stability harmed by erosion, the construction of such structures can enhance the downdrift erosion due to dominant littoral drift, as demonstrated in Figure 11.

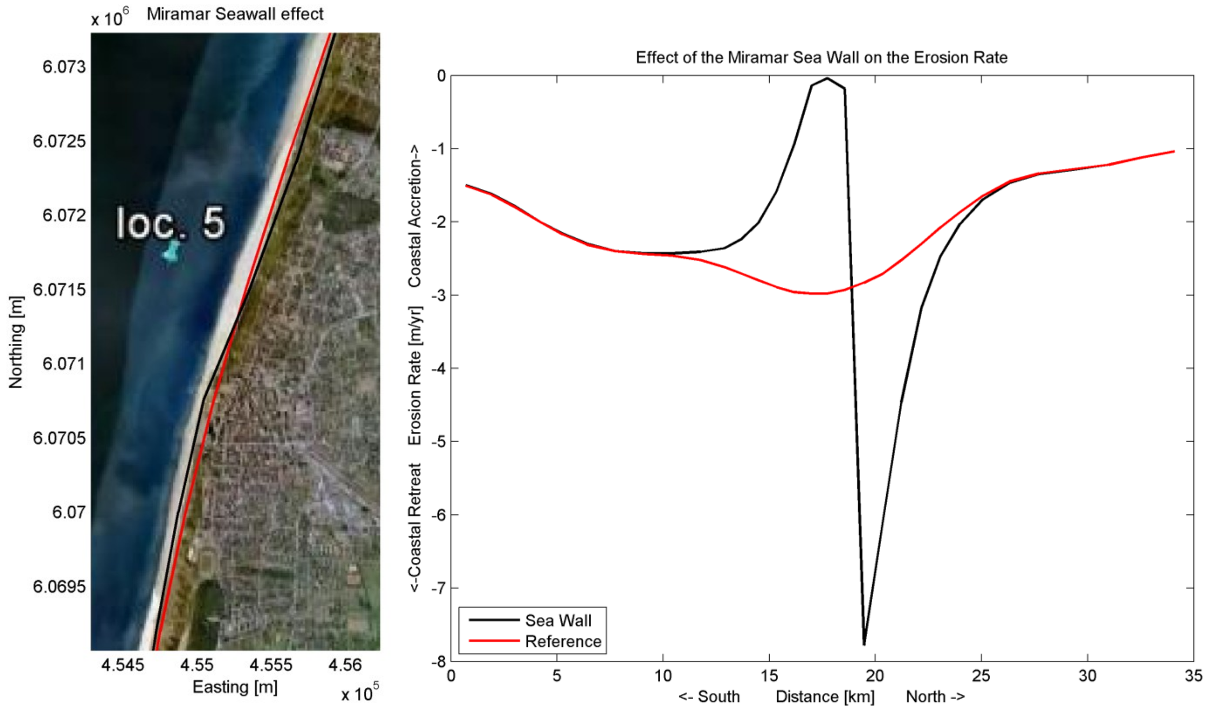


Figure 11: Effect of Miramar Seawall on the longshore sediment transport and shoreline displacement.

The blockage of littoral drift has lead to extreme shoreline re-orientation on the southernmost point of Sylt, as it can be visualized in Figure 12.

Figure 12: Influence of structures on the littoral drift at Hörnum, South of Sylt.

Since 1985 the coastal authorities have implemented a protection plan until 2020[5] which decided to counteract erosion by means of shoreface and beach nourishments. The goal is to keep the coastline at its 1992 position (*i.e.* trigger of action). Therefore the government adopted the "*hold the line*" strategy; consequently this volume loss has to be compensated somehow.

[5] Lately updated in 1997

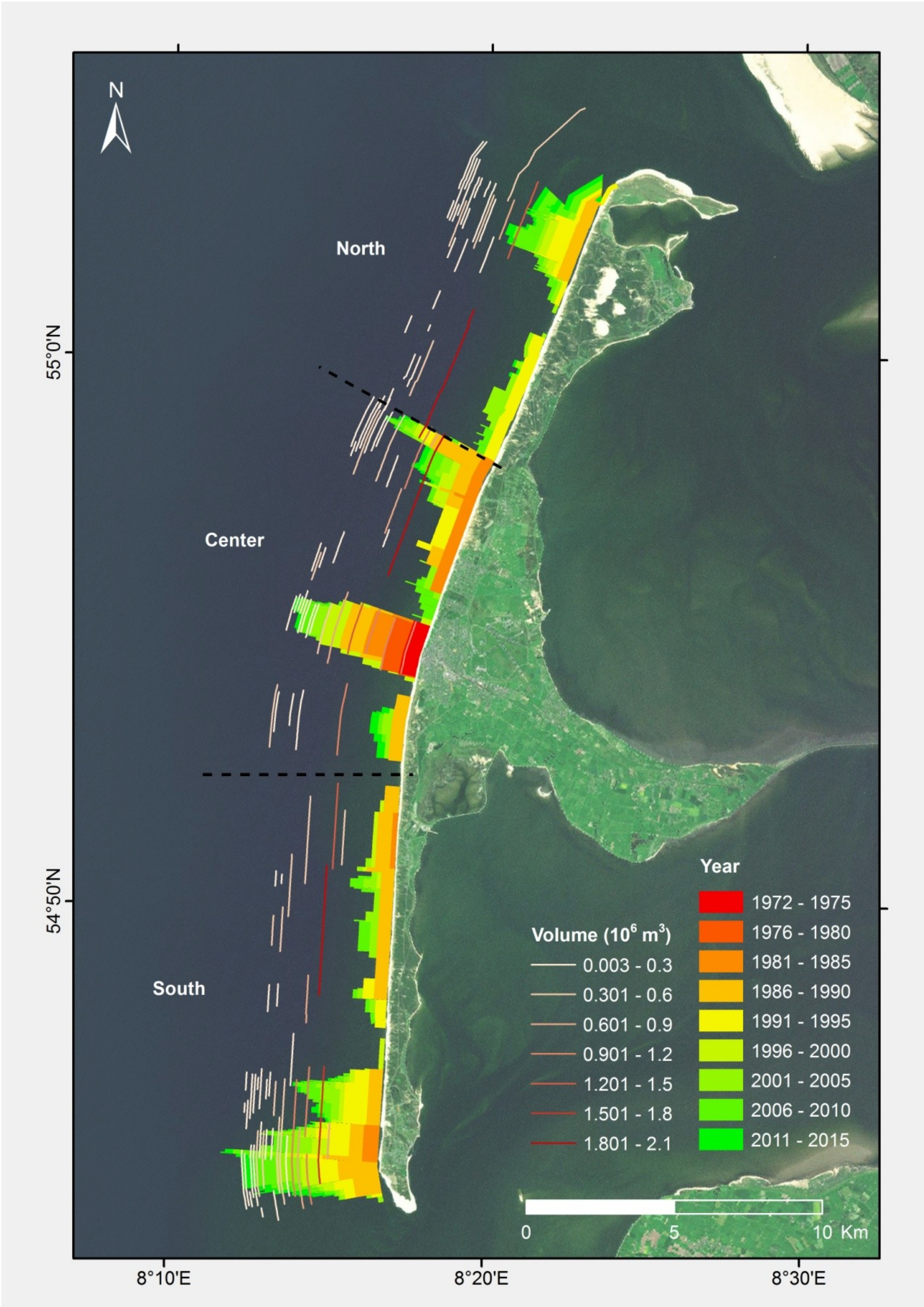


Figure 13: Distribution of nourishment works in time and place along Sylt with correspondent added volumes. Data courtesy from Landesbetriebes für Küstenschutz, Nationalpark und Meeresschutz - Schleswig-Holstein (LKN-SH).

To better assess and compare volumes, the Island is divided into 3 sectors: North, Central and South (Figure 14). An extensive review of nourishment works in Sylt can be seen in Appendix 9.3 summarized for each sector in Table IV.

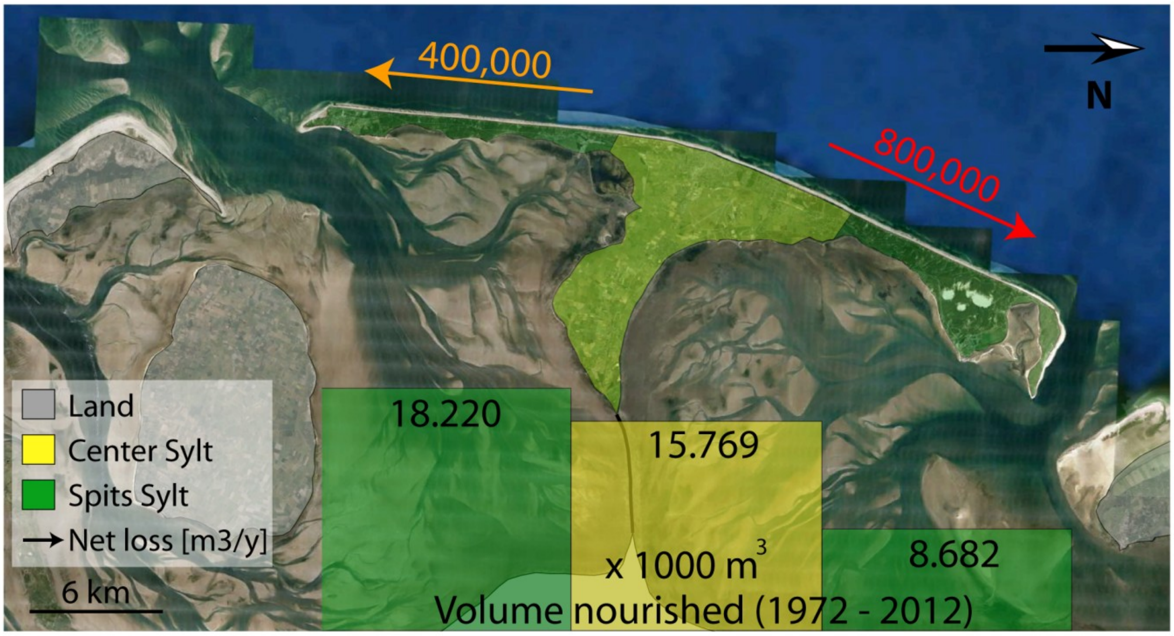


Figure 14 - Top view of Sylt showing the net sediment loss towards South and North with nourished volumes on the West coast for each of three areas (*i.e.* South, Center and North) from 1972 to 2012 (Hanson *et al.*, 2002).

Most of nourishments in frequency and volume have been executed at the South followed closer by the Center. Those works have been performed mainly to increase the berm in order to protect the already existent structures or for general protection. On Westerland several types of designs were tested, including the most common linear shape, but also spit and girland[6] type. In average, volumes of around 1.3 million cubic meters have been added per year.

Table IV: Nourishments performed at Sylt in each region discriminated by volume, time and number of projects[7].

	South	Center	North
Total Volume [10^3 m^3]	18.220	15.769	8.682
Time Spam	1983 – 2012	1972 - 2012	1988 - 2012
Number of Projects	47	38	29
Volume [m^3/year]	628.000	395.000	362.000

It important to note that despite the high volume added per region, its distribution is rather concentrated (Figure 13). At the South most of works have been executed nearby the end spit around the tetrapod groin of Hörnum. At the Center most of effort is to protect the Miramar seawall. Similarly

[6] Combination of linear and spit schemes (Appendix 9.2).
[7] Data courtesy from Landesbetriebes für Küstenschutz, Nationalpark und Meeresschutz - Schleswig-Holstein (LKN-SH).

happens on the North in the surrounds of the List seawall. This pattern illustrates that most of nourishments are performed to keep the stability of unsuccessfully installed coastal structures.

From the report of Sistermans and Nieuwenhuis (2004), part of EUROSION project, a total amount of approximately 115 million Euros were applied in 30 million m³ of sand between 1972 and 2000, making an average of 3.9 Euros/m³ and 4 million € per year. In eleven year from 1985 to 1996 a total of 23 interventions were performed summing approximately 20Mm³ of sand replenished.

In Germany the federal government is responsible for funding coastal protection works and 95% of the nourishments there have been granted from that (Hanson *et al.*, 2002). In case of small fills for recreational purposes local authorities are usually the main sponsors. After more than 50 years experience, repeated nourishments is considered a standard tool for coastal protection of sandy coasts in Germany (Dette, 2003).

Concomitantly, the island was included as part of the Schleswig-Holstein Wadden Sea National Park in 1985 due to its important ecological role for being member of the Frisian Islands in the North Sea. This area provides habitat for birds, benthic fauna and large rich intertidal environments. This characteristic limits the extension and magnitude of human impacts, including nourishment projects.

4.2 Problem, Motivation and Proposal

The question to be brought up in debate here is towards a more sustainable sand nourishment strategy for the Sylt Island which fulfills three main points of their policy: (1) the protection of hinterland, (2) beach and associated leisure that represents a public wealth and also an economic activity in the whole island and (3) environmental constrains since the island is a recognized vital ecosystem and part of a natural reservation.

Therefore the motivation here is to propose a sustainable long term nourishment strategy which fits this scenario. The current nourishment strategy has been fulfilling most of three goals, although this scenario can be improved and optimized, enhancing the results while lowering the negative impacts.

In this context the recent discussion in Sylt is to instead of the current "*hold the line*" protection approach, the trend nowadays is going towards protecting selected areas as a function of risk[8]. In risk assessment for Sylt the main towns in the central part of the Island (Westerland, Wenningstadt and Kanpen) are pointed as the main protection focuses considering the economical and populational values. Meanwhile, the spit ends are important for their ecological, leisure and touristic functions with lower risk. Therefore an optimized protection scheme needs to perform protection function on the center while simultaneously not allowing the parts with ecological and touristic relevance to disappear under erosion whilst not impacting them extensively with nourishment works.

Based on this review, two protection schemes will be evaluated considering protecting the whole island (*hold the line*) or only the high risk area, directly (*optimized protection*). Therefore the study first

[8] Defined as probability times the consequences

provides a strong coastline numerical model in UNIBEST based on hindcast and sensitivity analysis which follows the simulation of alternative nourishment strategies.

4.3 Methodology

In this section the UNIBEST model set up is shown for Sylt. The basic model description is presented at Appendix 9.1 and also in Deltares (2011).

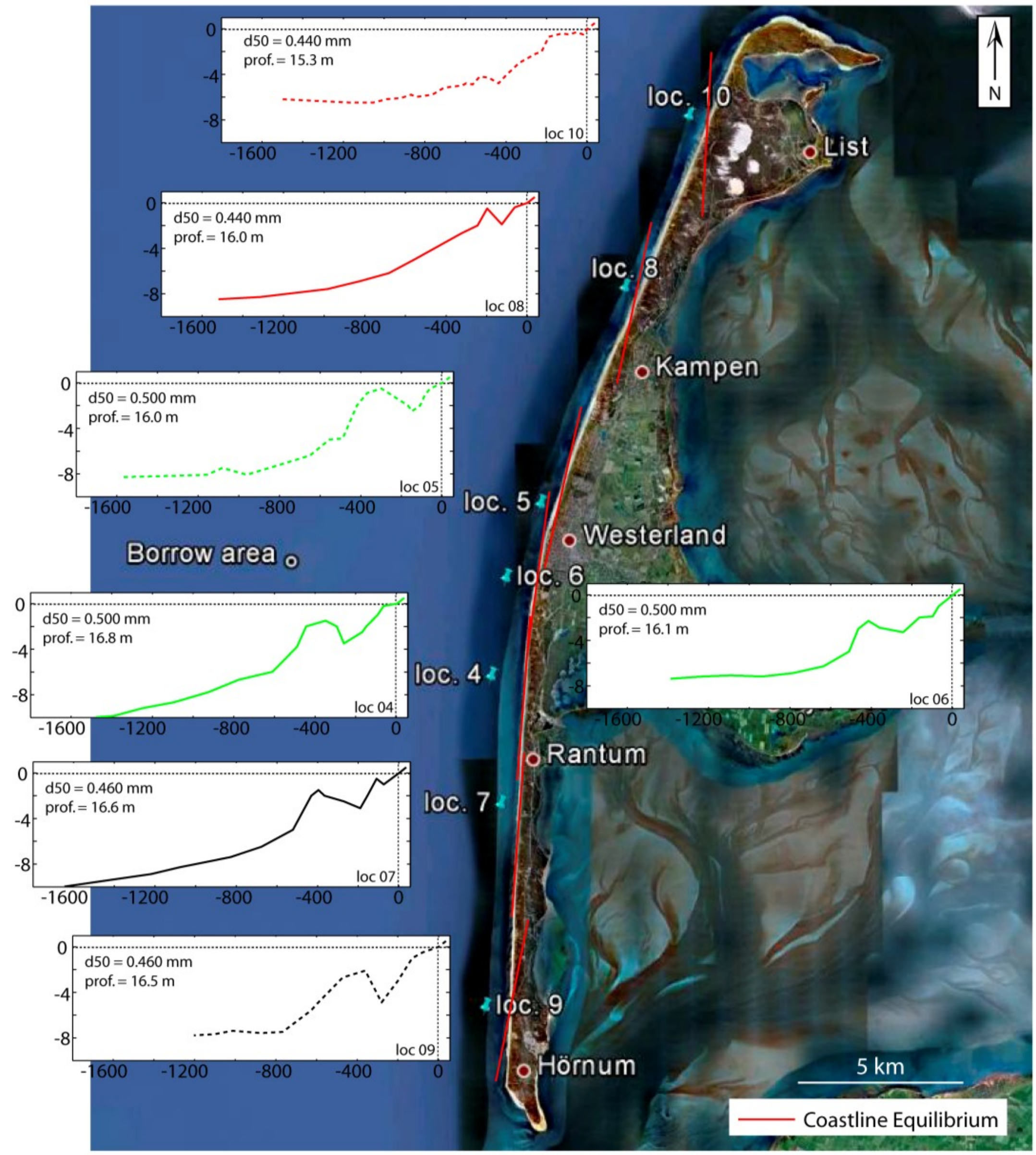


Figure 15: Wave input location with beach profile, sediment size and profile height for UNIBEST-LT along Sylt Island. The red lines represent the equilibrium coastline orientation calculated from S-ϕ curves.

To model with UNIBEST-CL a series of results and input data comes from UNIBEST-LT which derives the alongshore transport from calculated S-ϕ curves[9]. In case of Sylt, seven locations are chosen to represent the alongshore variation throughout the West coast (Figure 15).

For each location a series of inputs are necessary to derive the S-ϕ curves from the LT module among:

- Probabilistic wave data;
- Probabilistic tides;
- Beach profiles;
- Coastline orientation;
- Sediment size and transport formula;
- Active profile height;
- Numerical Inputs and other parameters

that will be explained on the following.

4.3.1 Probabilistic wave data

The wave climate has been derived by performing simulations, translating ten years of data from offshore to nearshore. The WorldWaves offshore wave data at 54.5°N 7.0°E based on ECMWF (European Centre for Medium Range Weather Forecast) simulations are used as boundary condition. The 10 years time-series of wave data are verified against buoy and radar measurements by Fugro Oceanor[10]. The WorldWaves package as a shell runs the SWAN model (Booij *et al.*, 1999) to translate offshore waves to the nearshore condition. The SWAN model is an open source, third generation, phase-averaged wave model, that includes the effects of wind generation, shoaling, refraction, dissipation (wave breaking, bottom friction, and white-capping), diffraction, and wave-wave interaction (quadruplet and triad). The data comprises time-series of wave height with 6-hour interval from 1-1-1997 to 31-12-2006 for 7 locations (Figure 9). This data is filtered in order to optimize the computational time and to compile the necessary probabilistic wave input file which consists of four variables: wave height, wave direction, wave period and duration to be introduced in UNIBEST.

To do so, the waves have been classified according to their height in classes of 0.5 meters, every 10 degrees. For each quadrant the average height, direction, correspondent wave period and duration are selected as shown in Figure 16 as an example[11]. Important to note that waves below 0.25 meters are discarded due to their lower or null sediment transport capacity.

[9] Curve which calculates the sediment transport magnitude as a function of the relative angle between the incident waves and coastline orientation.
[10] see http://www.oceanor.com/Services/worldwaves/
[11] All wave data used are shown in Appendix section 9.4

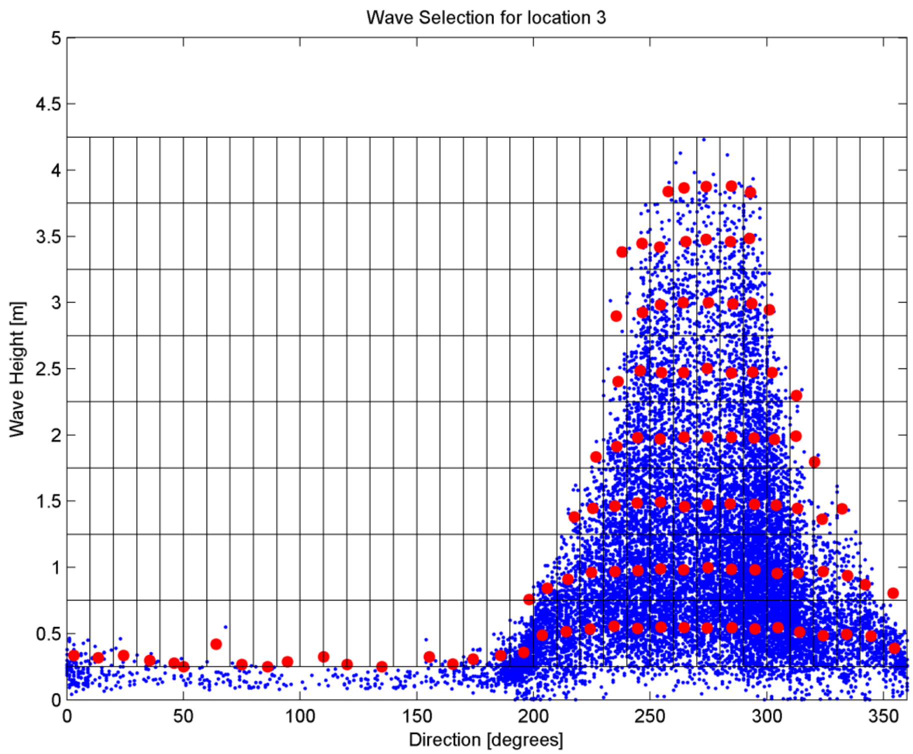


Figure 16: Selected wave cases in red dots as a function wave height and direction, with 0° referring to North, from the original data set marked with blue dots.

Applying this method for selecting wave cases, different wave climates are accounted in the simulation since sea and swell waves can come from different directions and associated period. In this case, especially the effect of wave period is included, as shown in Figure 17. From this figure it is possible to realize the dispersion of wave period for the same wave height, demonstrating the efficiency of such technique.

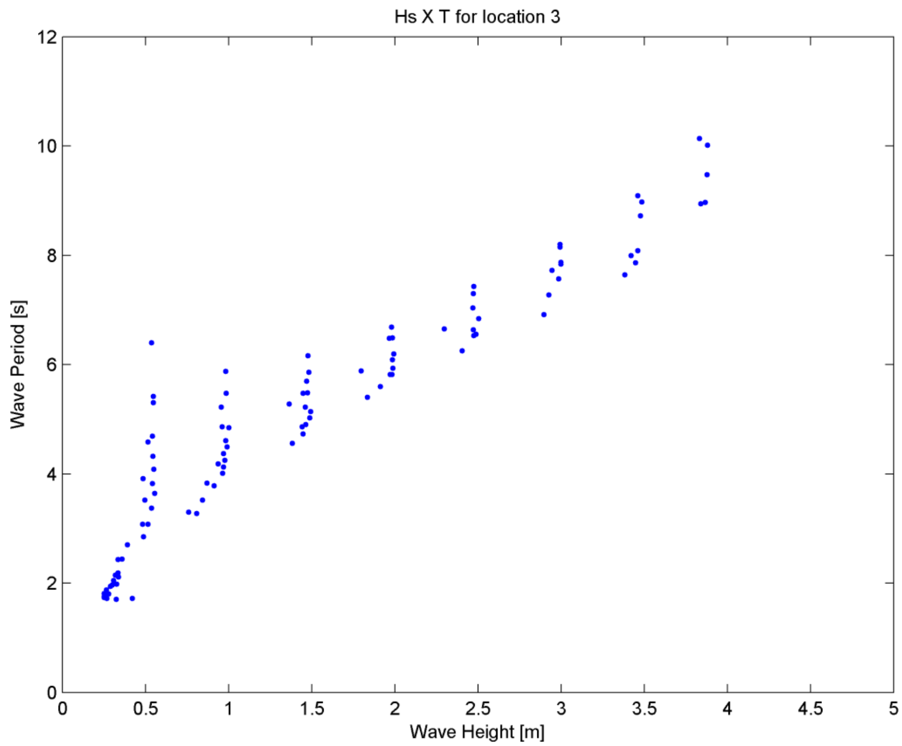


Figure 17: Selected wave cases as a function of wave height and wave period.

By the end the duration is calculated as the sum of all waves for each quadrant. Therefore every red dot in Figure 16 contains full information of every quadrant.

4.3.2 Probabilistic tides

Another input is the tidal regime as probabilistic duration. In this case the values are acquired from local nautical charter[12]. As mentioned before the tides in Sylt are semi-diurnal with an average range around 2 meters. For the model the values used are in Table V, ranging from 0.5 to 2.5 meters during spring tide and 0.7 to 2.2 meters during neap tide.

Table V: Tidal regime for Sylt obtained from Nautical Charter (3767).

Tide	Tidal Elevation (MLSWL) [m]	Duration (%)
Spring Tide	0.5	12.5
Spring Tide	1.5	25
Spring Tide	2.5	12.5
Neap Tide	0.7	12.5
Neap Tide	1.45	25
Neap Tide	2.2	12.5

[12] Catalogue number: 3767

The option for inserting horizontal tides is disregarded since the already mentioned alongshore sediment transport is attributed mainly to waves. Nonetheless the possible effect of tidal currents will be included within the sensitivity analysis in section 4.4.2.

4.3.3 Beach profiles

Beach profiles are obtained from nearshore bathymetry data from Boskalis. All profiles are extracted in perpendicular direction from the coast and are shown individually in Figure 15. No data is available for the dry beach although compiling information from literature and orthophotos a value of 35 meter wide beach is used until the dune foot (Figure 18).

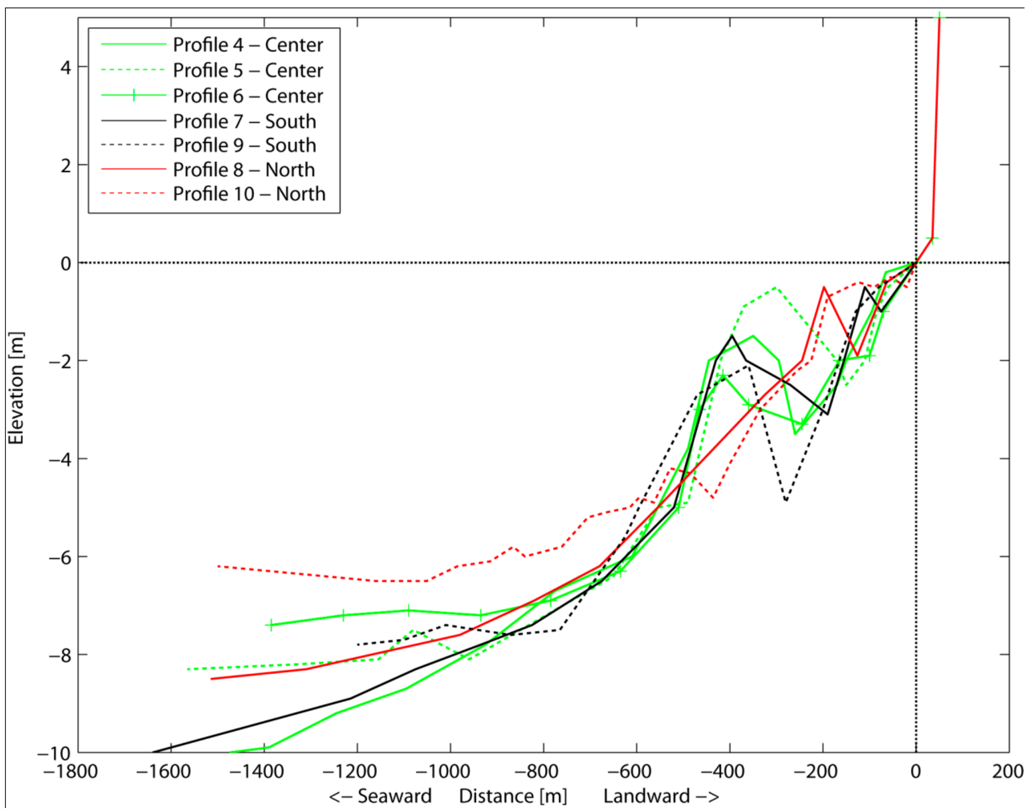


Figure 18: Beach profiles used in UNIBEST representing 7 locations.

4.3.4 Coastline orientation

The coastline orientation, important for the UNIBEST-CL module, is drawn from georeferenced orthophotos directly in UNIBEST environment. The limits are chosen until the influence of two coastal defense structures: (1) Southern tetrapods groin (at Hörnum) which blocks the sediment transport and is the cause of the abrupt coastline direction change on the south end of the island and (2) the revetment and seawall on the northernmost end (at List) which causes similar effect, although in a spit shape. The choice of not including those areas is based on the fact that both influences are on the end of the study area and could deal to unnecessary disturbances on the model since the main interesting of the present study is along the entire west coast, and not only the ends or in their evolution.

Nonetheless, in order to make the simulation realistic the sediment loss in both ends is calibrated to reproduce the real volume loss of about 1 to 1.5 million cubic meters of sand per year.

4.3.5 Sediment size and transport formula

The sediment grain sizes are from literature and documents reporting nourishment works along the Island (Hanson *et al.*, 2002; Menn, 2002; Dette, 2003). Due to possible different sampling places and techniques there is a variety, ranging from 290µm to 550µm, from medium to coarse sand. In this case the sediment grain size uncertainty is also included in the sensitivity analysis in order to account for this possible source of error in the quantitative assessment.

Coupled with the sediment characteristics, the sediment transport formula of Van Rijn (2004), described in Deltares (2011), is used based on personal conversation with Van Thiel de Vries (2013) due to its reliable application as default sediment transport formula in other numerical models such as Delft3D. The case-by-case inspection of velocities and sediment transport shows coherent results and consequently this formula is selected.

4.3.6 Active profile height

As the last physical input for UNIBEST, the active profile height represents the vertical extension of the profile which migrates in function of the mass balance. This value constitutes a key variable translating the sediment balance into shoreline retreat or accretion. For more details check Appendix 9.1 for model equations.

To find the active profile height first the closure depth is calculated from Hallermeier (1981) and then summed with the dune height. As from personal conversation with Huisman (2013) the choice for the upper profile extension corresponding to the dune foot is valid only in case of shoreline accretion. Cases where erosion is expected the choice for the dune crest represents a more realistic evaluation the whole dune acts as a sediment source to be eroded while in the former case sand can only be withdraw until the dune foot[13].

Finally the dune height to be summed is estimated in around 8 meters, since there is no direct measure data available but only description in literature. In this case, uncertainties regarding this parameter are also included in the sensitivity analysis.

4.3.7 Numerical Inputs and other parameters

The model simulations are performed with 100 time steps per year (*i.e.* approximately 3.5 days each step) for 50 years, with open boundary conditions[14], as in the natural system, in order to assess the model calibration regarding the transport, erosion and sediment losses towards the South and North ends of the study area.

[13] Assumption made considering no significant aeolian transport as well as no long term sand migration towards the dunes.

[14] Allows free sediment transport in and out the domain

Other parameters are set as default *e.g.* wave breaking coefficient, sediment porosity, bottom roughness, among others.

4.4 Model Results and Site Characterization

To create robust simulations with consistent results the shoreline model is calibrated with previously known sediment transport values, shoreline retreat rates and volume losses documented in literature: Sediment grain size from Hanson *et al.* (2002), Menn (2002) and Dette (2003); Erosion rate from Sistermans and Nieuwenhuis (2004) and Kroon *et al.* (2008); Volume losses and sediment transport from Hamm *et al.* (2002); Hanson *et al.* (2002); Sistermans and Nieuwenhuis (2004). This section shows first the hindcast modelling followed by a sensitivity analysis. The combination of both results makes this assessment valid for qualitative and quantitative behavior of Sylt.

4.4.1 Model Hindcast

The values available for calibration are shown in Table VI representing the range of numbers found on the literature versus the ones used in the model.

One of the main calibration variables is the sediment grain size. It is important to note the alongshore difference in grain sizes simulated (Figure 15) where the Center is composed by coarser sand (*i.e.* D_{50} = 500µm) which gradually gets smaller towards North (*i.e.* D_{50} = 440µm) and South (*i.e.* D_{50} = 460µm). All values lay within the expected range from 290 to 550µm. This gradation pattern is further supported by the sediment selection derived from decreasing in transport capacity[15] from the Center towards the spit-ends[16] spreading the poorly sorted morainic deposit described by Kelletat (1992) in Figure 8.

Table VI: Comparison between the expected values for model calibration and the hindcast.

	Sediment Size D_{50}	Shoreline migration	Total volume loss	Local volume loss
Expected values range	290µm to 550µm	0.4 to 2.2 m/y	1.0 to 1.5 million m^3/y	400.000m^3 to South 600.000 to 800.000m^3 to North
Model Hindcast	440µm to 500µm	1.5 to 3 m/y	1.1 million m^3/y	400.000m^3 to South 700.000m^3 to North

Starting with the sediment transport graphic, Figure 19 shows the directional sediment transport reverse and also the local volume losses of sediments on the North and South ends of the Island, agreeing with Hamm *et al.* (2002); Hanson *et al.* (2002); Sistermans and Nieuwenhuis (2004), in Table VI. From the model, 700.000 m^3 of sand are flowing toward the Northern inlet and 400.000 m^3 towards the Southern.

[15] Directly proportional to wave energy and consequently wave height.

[16] See the alongshore distribution of significant wave height in Appendix 9.4 showing a decrease in transport capacity towards the island ends.

Another important hindcast parameter is the transport gradient which shows the actual loss or accumulation of material that causes shoreline migration. Figure 20 presents the initial simulated period (*i.e.* year 0 in Figure 20) with a disturbed behavior pattern demonstrating the high human intervention on the area, especially by means of nourishments which through time gets smother in the absence of interference *i.e.* year 25 in Figure 20. Nonetheless the annual average gradient value is rather uniform in time, being 34 m^3/m. This gradient in 34 km of coast[17] computes a total annual eroded volume of 1,150,000 m^3. This overall sediment loss is reported by Hamm *et al.* (2002); Hanson *et al.* (2002); Sistermans and Nieuwenhuis (2004) as in Table VI.

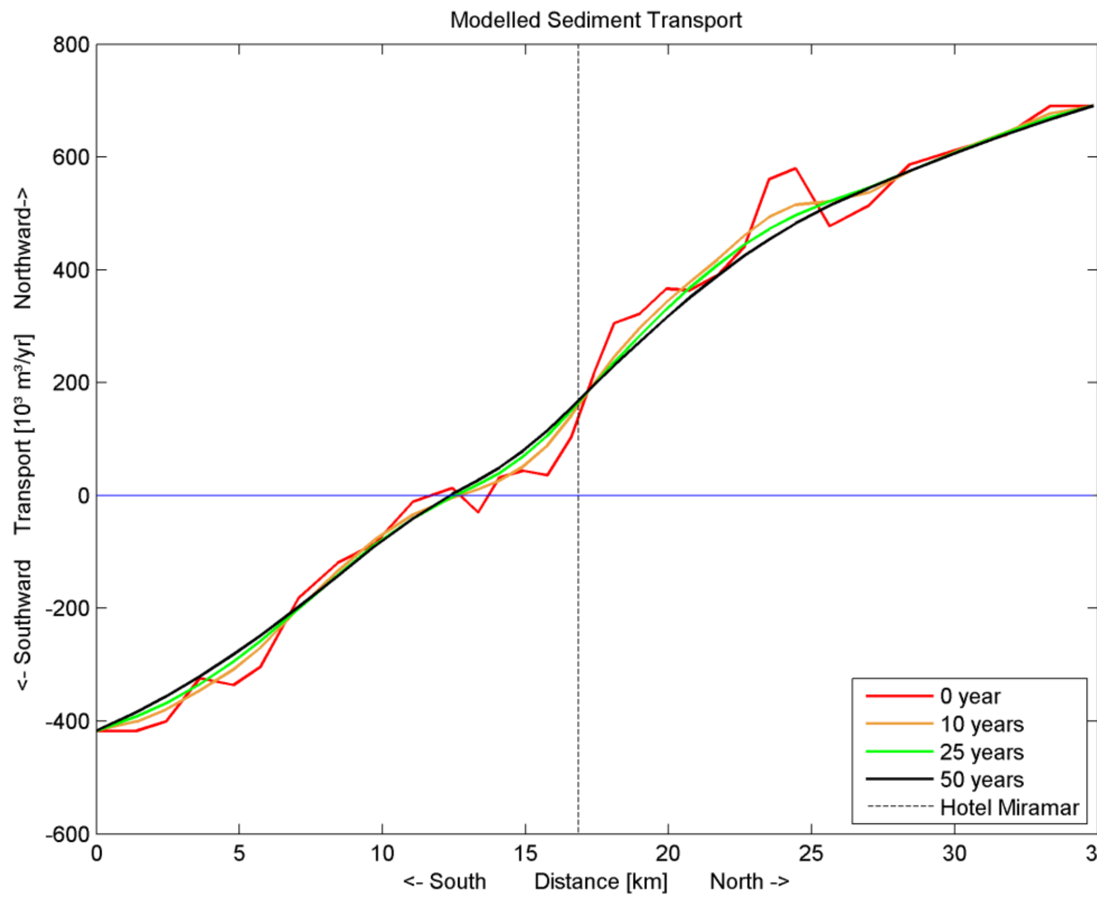


Figure 19 – Modelled sediment transport graphic for Sylt showing the direction and magnitude of sediment transport along the Sylt coast through time.

[17] Alongshore size of the modelled grid

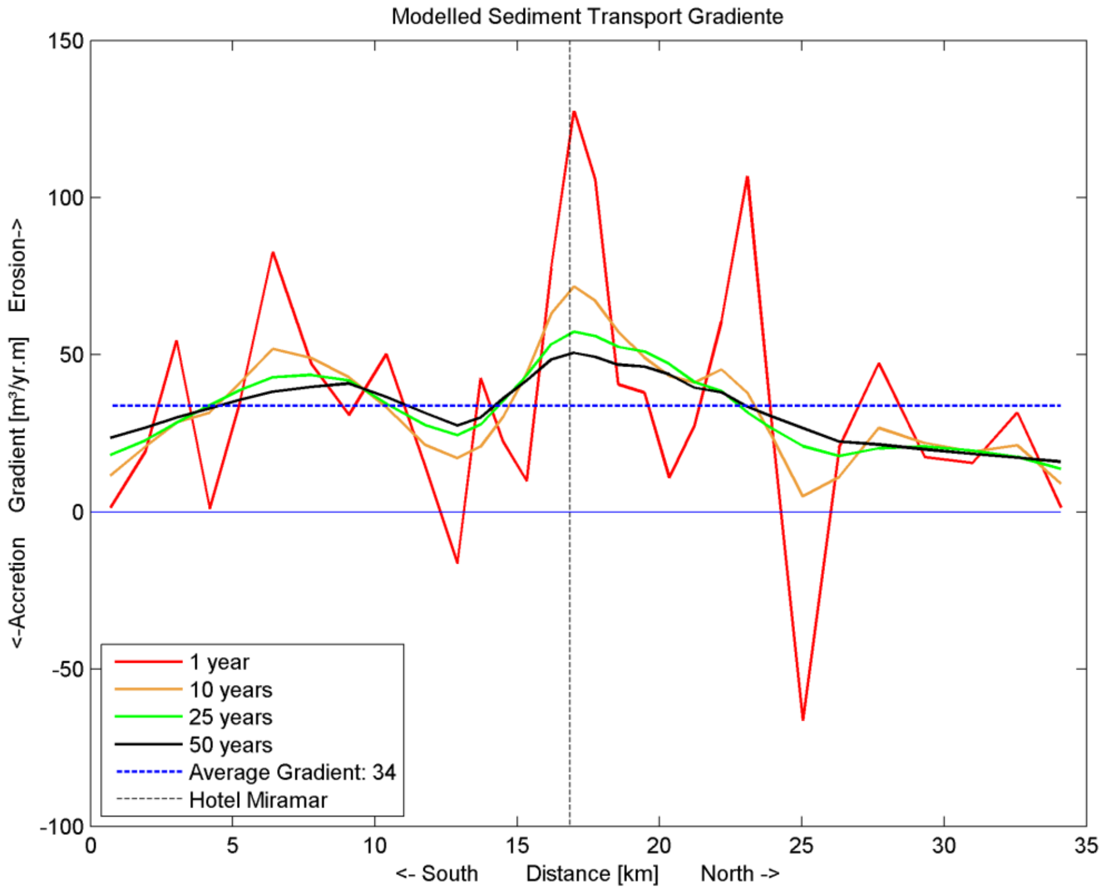


Figure 20 – Modelled sediment transport gradient graphic for Sylt showing the alongshore erosion and accretion distribution through time.

From the gradient and mass balance, the average coastal retreat is computed in 2.2 meters per year. These rates are higher at the center (3 m/y) and diminish towards the ends being 1 meter per year in the North and 1.5 meter per year in the South. The upper boundary value of 3 meters per year is slightly higher than documented, as shown in Table VI although the general picture is rather acceptable since the simulation considers smaller cells than the literature, which can capture local erosion hot spots, smoothed in large scale evaluations.

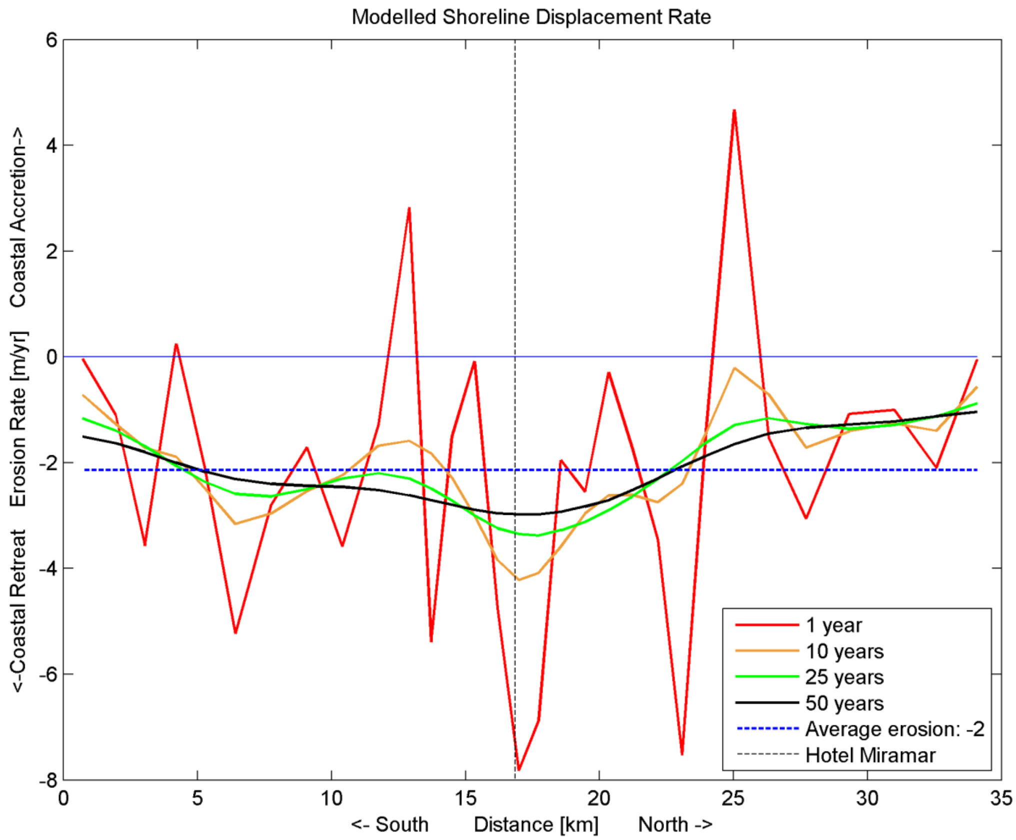


Figure 21 – Modelled shoreline displacement rate along Sylt through time.

The modelled shoreline migration can be seen in plan view on the shoreline evolution maps after 50 years of simulation for three sectors: North in Figure 22, Center in Figure 23 and South in Figure 24.

The larger erosion rates are observed in the center of the island (Figure 23) where the sediment transport diverges Northward on the North and Southward on the South (Figure 19), in agreement with (Kelletat, 1992; Kroon *et al.*, 2008). This diversion takes places right south of Hotel Miramar where the erosion rate is higher, as shown in Figure 25. In that spot if nothing is done the shoreline retreat reaches the Miramar Sea wall in more or less 25 years[18].

[18] Not considering storm erosion, storm surge and wave run-up but only shoreline migration.

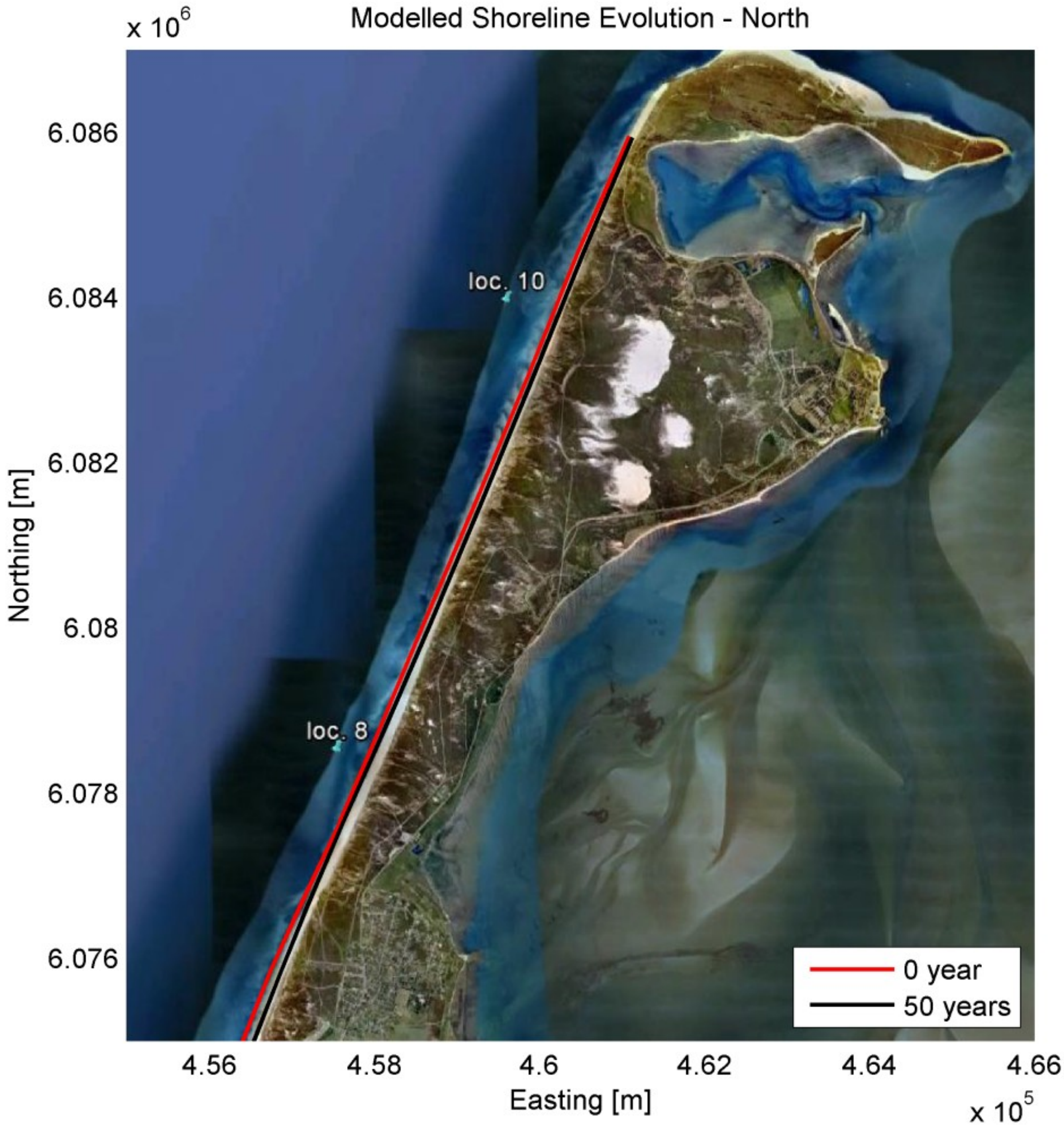


Figure 22: Shoreline evolution map for 50 years modeled coastline on the North section.

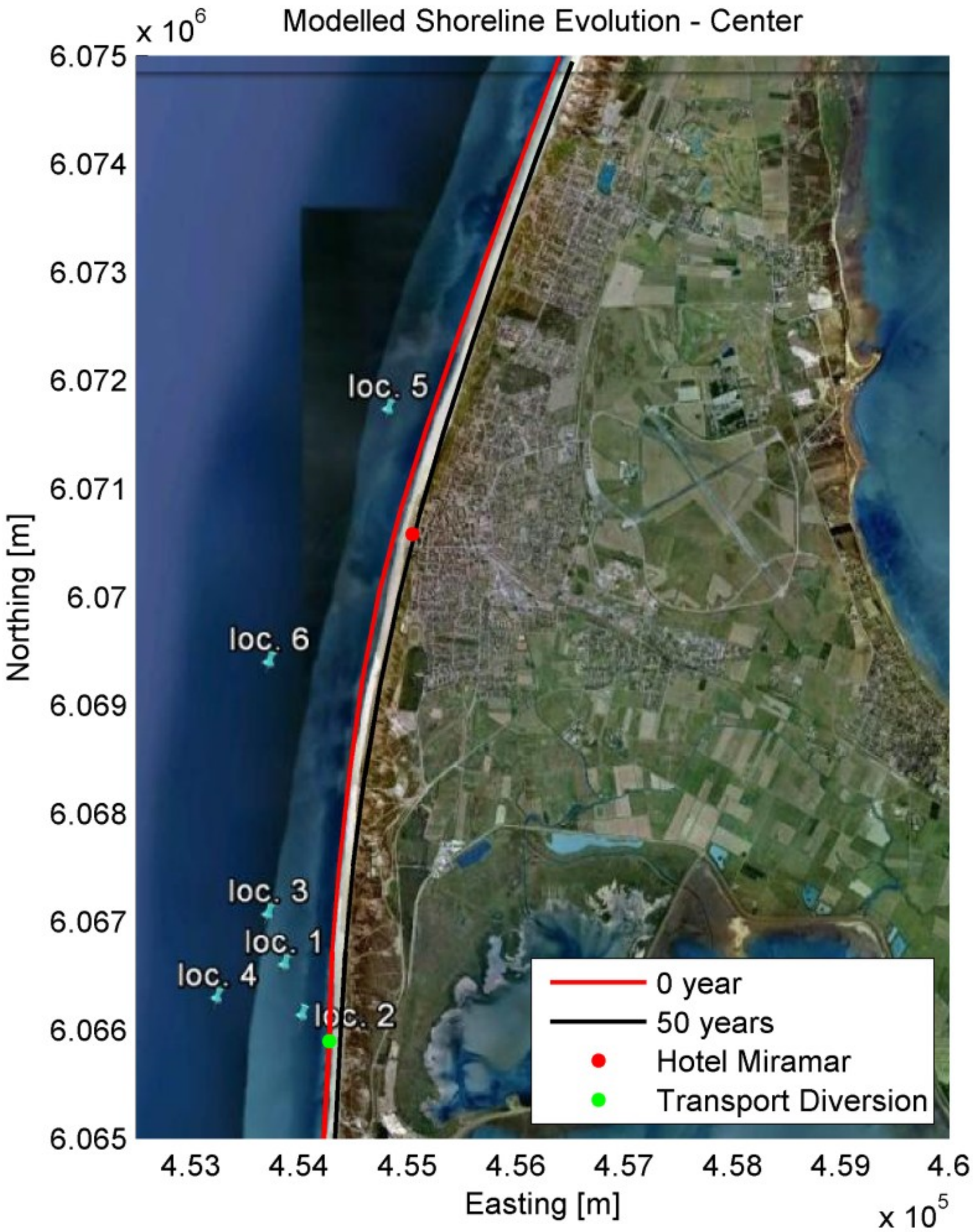


Figure 23: Shoreline evolution map for 50 years modeled coastline on the Center section. The red dot shows the Hotel Miramar reference while the green dot points the sediment transport diversion location.

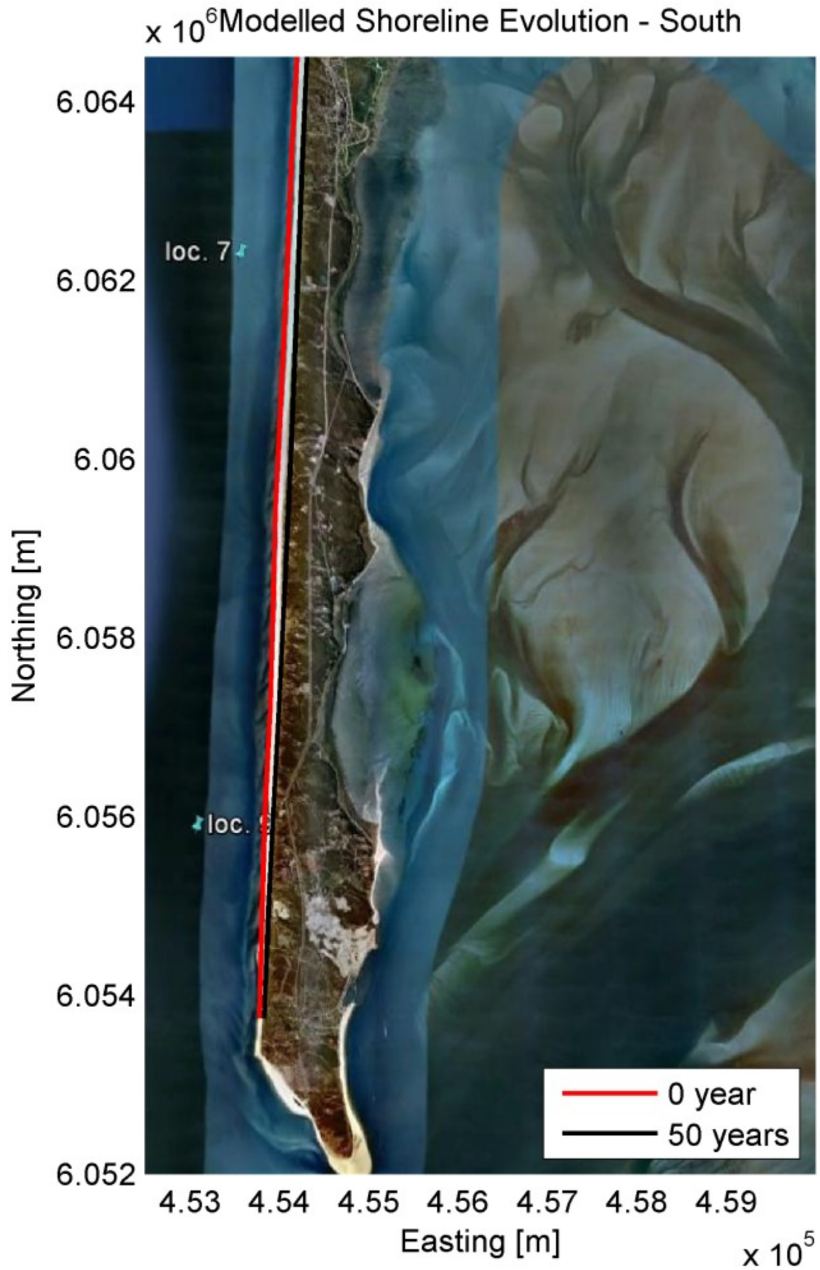


Figure 24: Shoreline evolution map for 50 years modeled coastline on the South section.

Analyzing together the sediment transport and the transport gradient it is clear that even though the North section has larger sediment loss (*i.e.* 700.000m³/y versus 400.000m³/y at the South) the actual retreat is not higher than in the South due to the distribution of the transport gradient. The South experience more erosion due to this latter factor, since it is a function of mass balance and not purely from the sediment transport. In this sense, the Center of the Island, where the transport is close to zero, shows the largest shoreline retreat due to high sediment transport gradients formed by the sediment transport diversion in that area.

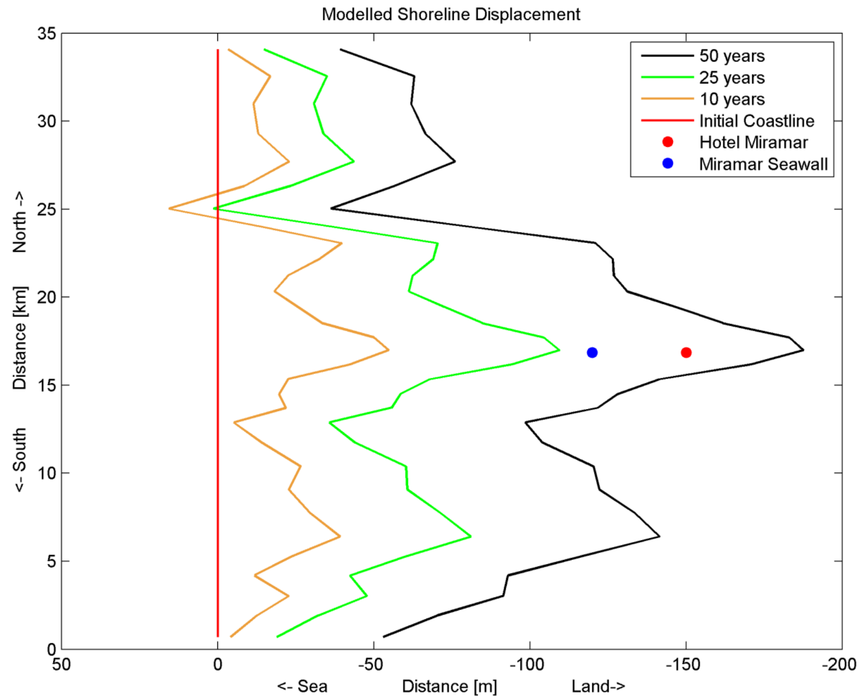


Figure 25 – Erosion chart alongshore Sylt through time showing the shoreline displacement. Figure shows the treat if nothing is done, being the Hotel Miramar reference (Westerland) on the hot spot of the erosion (3 m/y).

As a result the general model hindcast for Sylt is in agreement with both literature and expected coastal processes acting on the island. The whole Western shore has an erosive behavior where the center portion acts as sediment source for both ends, South and North (Kelletat, 1992; Kroon *et al.*, 2008). Due this erosional behavior in addition to human occupation and the intrinsic value of its shore, protection measures needs to be applied.

Therefore, next section will focus on evaluating the model sensitiveness and then some alternatives to keep the coast functionality. From the hindcast evaluation, if nothing is done the Center of Sylt corresponding to the cities of Westerland, Wenningstedt and Kampen will be affected by erosion, especially around the Miramar Hotel and Seawall (Figure 25). From the literature review and results obtained along the hindcast assessment hard measures seemed not effective controlling shoreline retreat since the cause of erosion in Sylt is due to the combination of sediment starvation and sediment littoral drift rather than to storm events when such hard solutions are more suitable.

4.4.2 Sensitivity Analysis

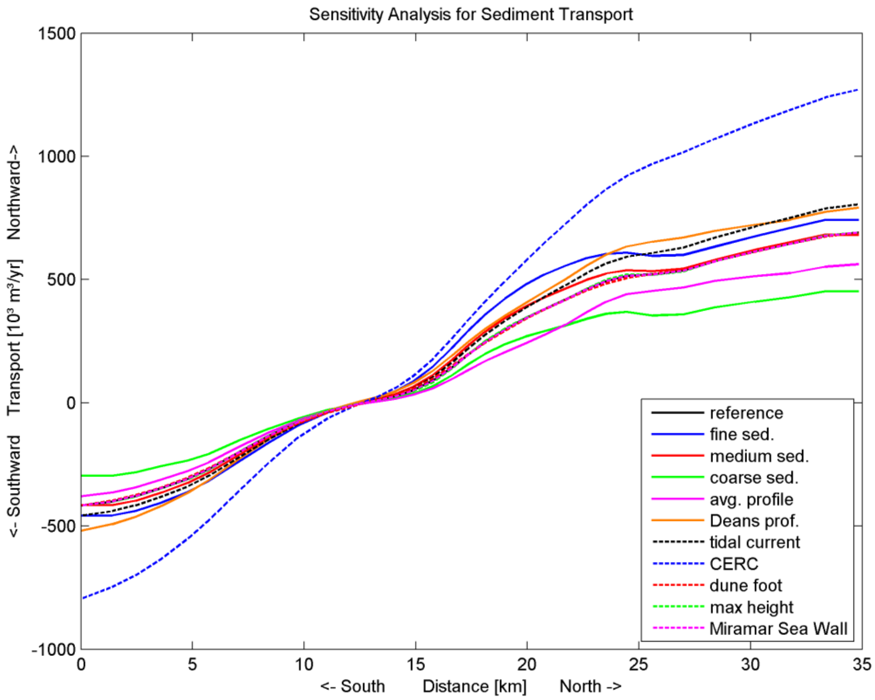
In order to assess the reliability of model results, some key parameters pointed in section 4.3 among other important variants are changed throughout 9 model runs (Table VII) enclosing geomorphologic background variation (*e.g.* profile shape and sediment size), physical forcing (*e.g.* tidal flow), theory in sediment transport (*e.g.* transport formula), assumptions (*e.g.* active profile height).

Table VII: Sensitivity analysis runs description made for Sylt.

#	Label	Description
0	Hindcast	calibrated and reference model;
1	Smaller sand	lower sand size diameter (290µm);
2	Medium sand	medium sand size diameter (420µm);
3	Coarser sand	coarser sand size diameter (550µm);
4	Average profile	average profile height per cross-shore distance of all seven profiles;
5	Dean's profile	Dean's equilibrium profile based on the 420µm sand size;
6	With tidal current	inclusion of tidal currents of 1 m/s (spring) and 0.7 m/s (neap)
7	CERC	application of CERC formula for sediment transport
8	Dune Foot (+3msl)	input of profile height until +3 meter MSL - dune foot
9	Max profile height	input of the maximum allowed profile height – 20 meters

The majority of the runs fulfill the expected range of sediment losses and shoreline migration from Table VI. Sediment transport formula is the most sensitive parameter. From Figure 26, *CERC* formula overestimates the sediment transport and erosion while on the other hand, the *coarser sediment* and *average profile* simulations underestimate them.

Other parameters also present results outside the expected range. For the sediment volume losses the *coarse sediment* and *average profile* runs underestimate the erosion while only the already mentioned *CERC* overestimates it. Regarding shoreline displacement, *smaller sediment*, *Dean's profile*, *with tidal flow*, *CERC*, and *dune foot* runs overestimate documented volumes. All results from sensitivity analysis are shown in Table VIII.



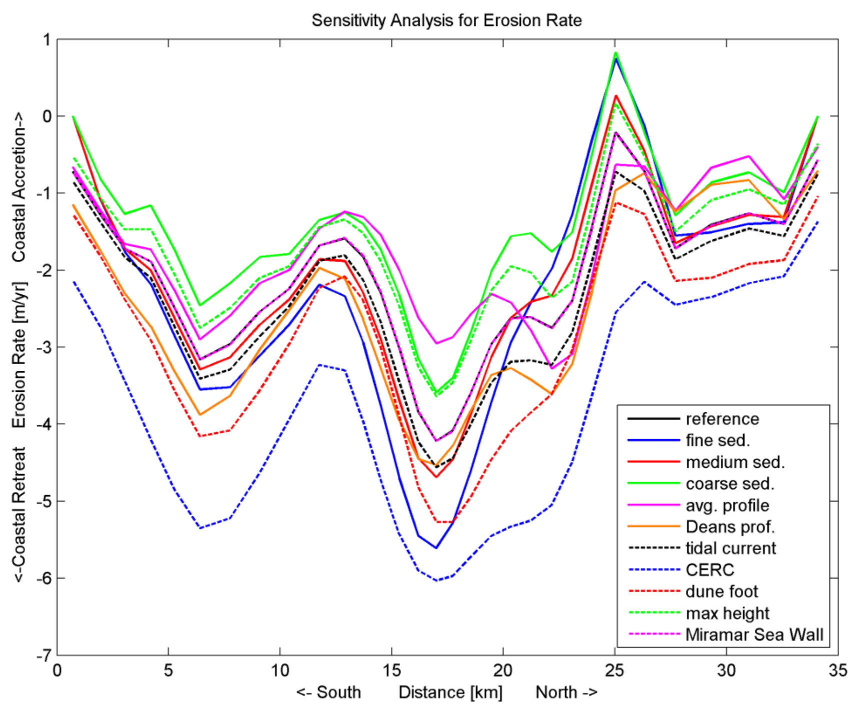


Figure 26: Graphics for sensitivity analysis. (Upper) Sediment transport curves showing the values alongshore for each run. (Lower) Alongshore erosion rates.

In order to include model and background uncertainties in the final results, the analysis carried out in this assessment is statistically compiled to obtain average and standard deviation values. Although after careful evaluation some cases are not considered in the following statistic. The exclusion of Dean's profile is made since real profiles are available, providing more reliable results; similarly, the CERC formula is discarded due to its well-know simplification which is appreciated in the absence of data, *e.g.* lack of sediment grain size data since the formula does not take it into account.

Table VIII: Results from the sensitivity analysis for Sylt Island. (+) indicates overestimation while (-) the underestimate of values. (*) indicates the cases used to calculate the average and standard deviation. No comparison information was available for transport gradient although the volume loss is direct proportional to its measure.

Run	Case Label	Sediment Transport Gradient [m³/m.y]	Shoreline Displacement [m/y]	Volume Loss [10^6 m³/y]
23	Hindcast*	34	-2.2	1.15
111	smaller sed. *	36	-2.4(+)	1.23
112	medium sed. *	33	-2.1	1.11
113	coarser sed. *	23	-1.5	0.77(-)
121	average profile*	29	-1.8	0.98(-)
122	Dean's profile	40	-2.6(+)	1.37
131	with tidal flow*	39	-2.5(+)	1.31
141	CERC	63	-4.0(+)	2.12(+)
151	dune foot (+3 msl) *	34	-3.0(+)	1.15
152	20m profile height*	34	-1.8	1.15

By the end, the statistic encloses 8 cases[19] calculating central and scatter values for transport gradient, erosion rate and total sediment loss (Table IX).

Table IX: Results from the hindcast model of Sylt.

	Sediment Transport Gradient [m³/m.y]	Shoreline Migration [m/y]	Volume Loss [10^6 m³/y]
average modelled	**32**	**-2.2**	**1.10**
lower limit	27	-1.7	0.94
upper limit	37	-2.7	1.26
standard deviation	5	0.5	0.16
observed values	**---**	**0.4 to 2.2**	**1.0 to 1.5**

After this comprehensive analysis, the quantitative assessment for the West coast of Sylt presents an average sediment volume loss of 1.1 million cubic meters per year, ranging from 0.94 to 1.26 considering the standard deviation. Applying this volume loss into shoreline displacement, the coast

[19] marked cases in Table VIII with *****

exhibits an average retreat of 2.2 meter per years varying from 1.7 to 2.7 accounting the standard deviation.

Next section evaluates nourishment scenarios finding more sustainable solutions in doing coastal protection and development on the Sylt Island based on the results from this section.

4.5 Evaluation of Nourishment Strategies

Within this chapter nourishment alternatives are evaluated based on the background built from the previous chapters in order to propose sustainable solutions for the Island of Sylt. Summarizing the underlying processes, the Island faces structural erosion along its entire West coast computing a total volume loss around 1,150,000 (± 155,000) million cubic meters per year. The land was formed by spreading the moraine deposit which through time under sediment transport and selection resulted in the formation of two spits in each end accompanied by a general shoreline retreat. By means of consecutive nourishment works starting in the 1972 the German government have been controlling this shoreline retreat by holding the line around the 1992's coastline position. With an optimized version of this policy in discussion, a new strategy focus on the more strict protection of the center portion corresponding of the main cities while the rest of the island would have a less strict policy regarding protection whilst keeping the tourism and the shore natural function as ecosystem (Sistermans & Nieuwenhuis, 2004).

Innovative solutions can improve results towards this new trend of coastal development by means of concentrating the protection effort in the center of the island, reestablishing the sediment source, as the morainic deposit in the past. Doing so, this strategy enhances protection and safety in the center simultaneously to ecology and tourism on the far sides.

To propose alternative strategies for the already implemented linear, spit and girland replenishment schemes made to last more or less six years, other innovative solutions are evaluated aiming the long-term and sustainable development of the whole area in a scale of 25 years.

A starting point reproduces the supply of material on the center of Sylt. This can be performed for instance by means of constant punctual sediment feeding around the transport diversion point to compensate the sediment loss to both North and South. In practice it can be executed by regularly feeding the Center every year or six months with smaller amounts of sand with fixed pipeline connections pumping straight from the sand reservoir, analogous to a sand bypass system. This strategy excludes the need of vessels and large operations, reducing costs and the spatial extension of environmental impacts since it would benefit from the natural sediment transport diffusing the deposit.

A variation of this scheme towards the *hold the line* policy distributes those sources along the entire coast. Although, this alternative would increase the costs and impacts since it needs longer pipeline installations and discharge points.

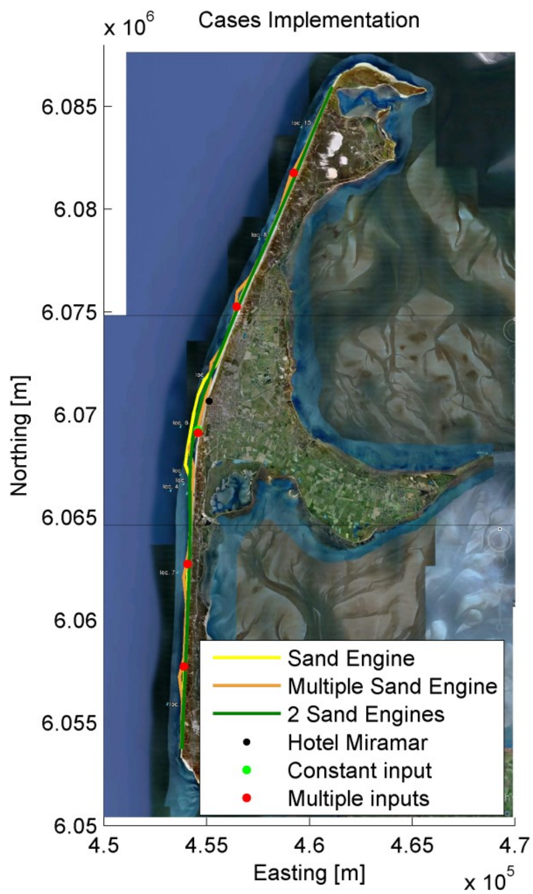
Other solution is based on the Sand Engine performed in The Netherlands (Mulder & Tonnon, 2010; Zandmotor, 2012). It fulfills the requirements for the *optimized protection* despite of reducing costs since vessel and crew mobilization happens only once for the entire lifetime period. For the first insight Sylt has enough sand available, not so far from the coast (*i.e.* around 8 km showed in Figure 15) and therefore the project has initial positive points to be successful. The impacts on environment and leisure are also reduced by concentrating the effort in time and space on the urbanized central area.

The distribution of smaller *Sand Engines* along the coast in time and space represents other two solutions. By splitting the volume in space the scheme benefits the entire coast nonetheless it increases costs and impacts on leisure and environment. While by doing this in time it decreases the impact on leisure activities due to extreme beach width although it increases environmental impacts since the time available for recovery is shorter.

Finally, results are assessed considering both the actual coastal protection policy of *holding the line* and the *optimized protecting* scheme at the center.

In summary six scenarios are assessed in UNIBEST (Figure 27):

1. Do nothing scenario (*reference case*);
   Reference case in which no protection measure is done.
2. Constant sand feed in the center (*constant input*);
   Input of a punctual source of sediment around the transport diverging point (*i.e.* Center of Sylt) twice a year making a total of 1.2 Mm^3 of sand per year.
3. Multiple places with constant sand feeding (*multiple inputs*);
   Input of sand in the same regime of case 2 although distributed in five spots. Two at North (200.000m^3 each), two at the South (200.000m^3 each) and one in the middle (400.000m^3).
4. *Sand Engine*;
   One single input of sand, once, of 30Mm^3 at the central portion of Sylt right South of Westerland.
5. *Multiple Sand Engines*;
   Six sand deposits distributed in space, once, each with 5Mm^3 of sand. Two on the North, two on the Center and two on the South.
6. Sand Engine every 12.5 years (*Double Sand Engine*).
   Same as case 4 although with half of its volume, in this case 15Mm^3 but with a re-nourishment in 12.5 years.



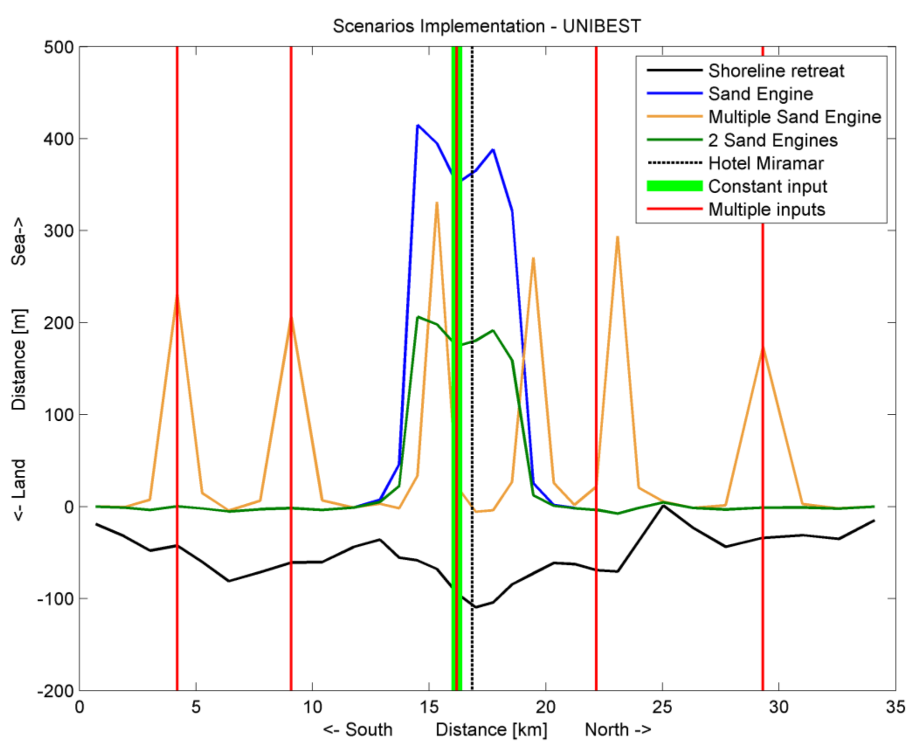


Figure 27: Implementation of nourishment scenarios for the Sylt Island.

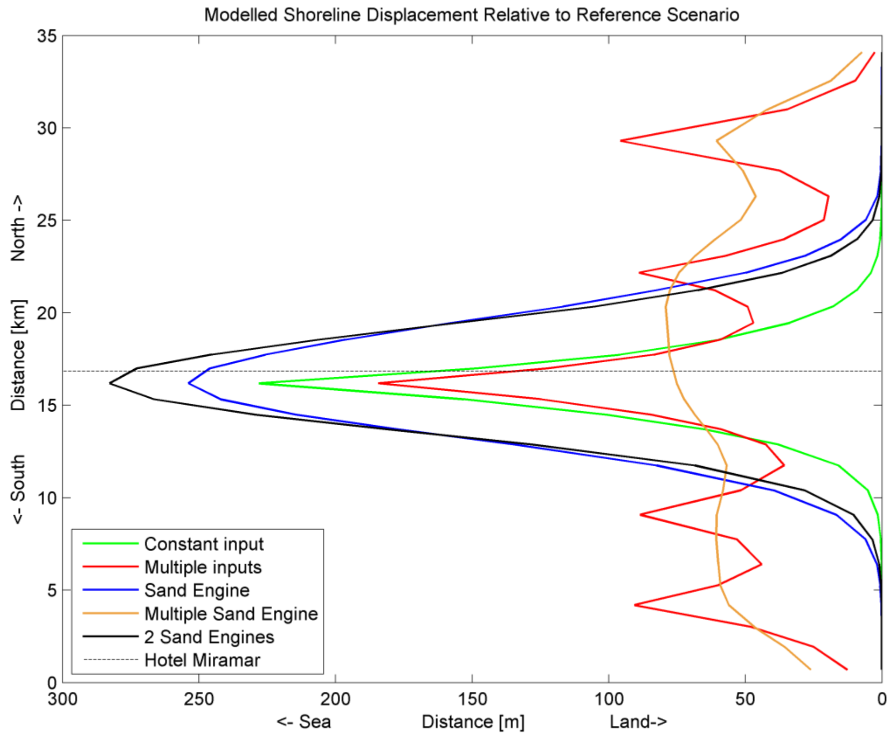
The cases are implemented in the coastline model by means of sediment sources (see Deltares (2011) for model details) along the coast. Based on the annual volume loss of sediment estimated in 1.15 million cubic meters, for all cases 1.2 million cubic meters per year of sand, in average, is added into the system. This volume makes 30 million throughout the entire assessment. Therefore all cases can be directly compared in addition of presenting a realistic volumetric assessment.

All five cases show a positive response regarding coastline evolution when compared to *reference case* (Figure 28 - Upper). Nonetheless, the studied scenarios present different alongshore protection coverage, as expected. The schemes of *multiple constant inputs* (3) and *multiple sand engines* (5) are covering the whole island. Both *sand engines* (4 and 6) have effect over more than half of the island (*i.e.* along more than 20 kilometers), covering the high risk zone (Figure 28 - Lower). The *constant input* (2) presents the least alongshore coverage while provoking the largest shoreline accretion (*i.e.* around 200 meter from the actual coastline).

If the policy of *holding the line* is chosen, *multiple sand engines* and the *multiple inputs* solutions are initially the most suitable to be considered (cases 3 and 5). While if the *optimized protection* policy is adopted the *sand engine* schemes are the most suitable choices (cases 4 and 6). All results are evident in Figure 28 where one can visualize the alongshore extension of each nourishment relative to *do nothing scenario* on the upper figure or with respect to the initial coastline on the bottom panel.

After 25 years the *sand engine* solutions cause coastal progradation and consequently protection over 10 km besides having a positive effect throughout 23 km when compared with no intervention. Hence it offers direct protection on 30% of the coast while indirectly contributing along 65%. Splitting the total operation in two (*i.e.* every 12.5 years) results in a not too wide coast in the feed area while the longshore effect is practically the same as doing only one work (Figure 27).

Solutions such as the *sand engine*, the *constant input* and *double sand engine* represent the lowest impacts on the environment since they cause only local or short direct impact in time and space on the already human modified area. On the other hand, the other schemes have direct impact on almost the whole island, including the natural environments. Nonetheless, the *multiple inputs*, between them, would affect the entire island during the whole time (*i.e.* 25 years) not allowing proper recovery while the *multiple sand engines* presents negative effects relatively shorter in time when considering the entire time spam, where the untouched areas works enhancing the recovery of the adjacent impacted zones.



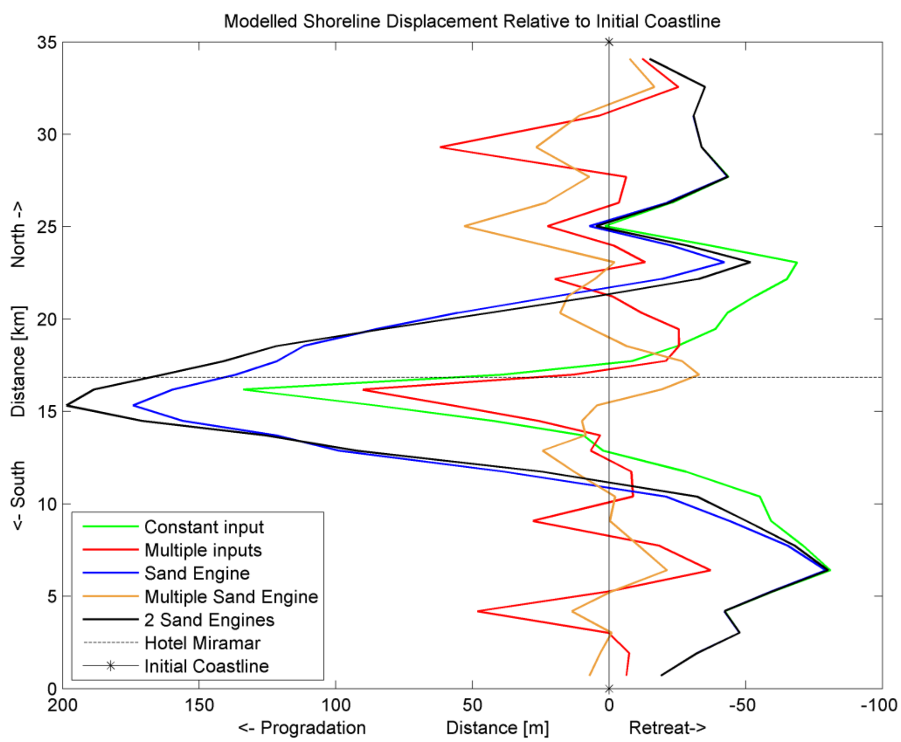


Figure 28: Modelled shoreline evolution of Sylt after 25 years for each solution. (Upper) relative to reference case ("do nothing scenario"). (Lower) relative to initial shoreline position.

Regarding costs, the *multiple inputs* and *multiple sand engine* solutions involves construction spread all over the island which increase the costs; while the *sand engine* and *double sand engine* have relatively lower costs since the efforts is concentrated nearby the borrow area. The *constant input*, if executed by means of pumps does not include dredging vessels which reduce the costs, although it requires maintenance of pipelines and pumps.

Concerning leisure activities and tourism, *double sand engine* similarly to the *sand engine* and *multiple sand engines* show better benefits. This evaluation is the consequence of excessive beach width achieved by the *sand engine* which makes the water front too far (*i.e.* around 500 meter); and also due to beach closure in case of *multiple sand engines*. In this way the *double sand engine* would benefit by not widening the beach too much (*i.e.* around 300 meters) in addition of limiting the extension of beach closure during implementation.

Summarizing results in plusses and minus for each strategy (*i.e.* hold the line and optimized protection), Table X and Table XI presents all scenarios as a function of protection, costs, environment and leisure aspects.

Table X: Table evaluating the solutions regarding coastal protection for Sylt.

	Protection function	
	Hold the line	**Optimized Protection**
constant input	--	0
multiple inputs	+	--
sand engine	--	++
multiple sand engines	++	--
double sand engine	--	++

Table XI: Table evaluating costs, environmental and leisure impacts of each nourishment scheme for Sylt.

	General Aspects		
	Cost	**Environment**	**Leisure**
constant input	+	++	-
multiple inputs	-	--	--
sand engine	++	++	+
multiple sand engines	--	-	0
double sand engine	++	+	++

After this extensive evaluation, *holding the line* strategy shows larger impacts on environment, implementation costs and negative effect on leisure when compared to *optimized solution*. The latter demonstrates that concentrating the protection effort on the center increases the protection, environment, leisure and cost benefits all over Sylt. In this case the high risk area is protected while the further sites benefits from the natural spreading of sand enhancing the natural ecosystem development together with leisure benefits.

4.6 Conclusions and Recommendations for Sylt

Sylt represents a coastline with erosion along its entire extension. This structural erosion is related to the island formation from a glacial deposit on its center which has been eroded and spread out by Northward and Southward transport which shapes the land into two spits. Shoreline modelling and literature description points a volume loss around 800.000 m^3/years of sand to the North and 400.000 m^3/years to the South, making a total of 1.2 million m^3 per year. With a well defined and long applied coastal protection strategy the Island has been managing erosion mainly with sand nourishments after its first application on 1972. From 1985 until nowadays the protection policy is to *hold the line* along the entire 40 km coastline. With the recent desire in optimizing this protection as a function of risk analysis, benefiting protection on important areas but also leisure and environment, new strategies are assessed in this study, for both policies.

The results show that it is possible to develop a long-term nourishment strategy to benefit Sylt Island for the next 25 years. The solutions are based on restoring the sediment supply by large sand deposits either spread out along the entire coast (*i.e. hold the line*) or only at the center (*i.e. optimized protection*). The strategies differ from costs, environment and social impacts besides their protection characteristic.

Analyzing pros and cons of each solution, towards the desired goals shows that if adopting protection of the whole coast the most suitable solution is the execution of several sand engines along the shore (*i.e. multiple sand engine* solution*)*. This strategy protects the entire Island, with relatively lower impacts. On the other hand, to protect only the high risk areas, the *sand engine* and *double sand engine* performed almost similarly showing to be the most suitable alternatives when considering protection, cost, environmental impacts and leisure-aesthetic aspects. They both benefit the high risk area while naturally spreading sand towards the Island ends.

When comparing the two policies, the *optimized protection* strategy shows better benefits. This selective protection effort reduces the need of large interventions all over the island, minimizing impacts and costs while enhancing the desired effects per area. The center benefits with protection while the far sides with environmental and tourism development.

In sum, the single sand engine with lifetime of 25 years or the double sand engine (*i.e.* 12.5 years lifetime) offer the best advantages by protecting the high risk area of Sylt, while also benefiting the North and South ends by means of the natural spreading of sand. This approach reduces erosion on the far sites without direct impacts of nourishments while enhancing the tourism based on natural activities as part of the Schleswig-Holstein Wadden Sea National Park.

In cases where places outside the risk area (*e.g.* the South around Hörnum) demands replenishment due to unacceptable shoreline retreat, foreshore nourishments can be applied. As mentioned before, such method provides protection and represents lower environmental impacts as well as being cheaper. By rainbowing sand could be delivered between the shore and the outer submerged bar. This volume, in some extension, arrives naturally on the beach increasing the protection while not heavily interfering on the natural system.

Further investigation is recommended to assess an optimal design considering the fill shape, time and length of spreading as well as the most favorable nourishment location. Furthermore, the coast of Sylt has highly three dimensional characteristics which would influence on the sediment spreading. In this case, the separate assessment of cross-shore and alongshore transport can lead to misinterpretation of results. The inclusion of processes *e.g.* rip currents, storms, sand bar migration and features as groines on more detailed and different models is therefore advised.

5 S'Abanell Beach

As the second case study, the Spanish coast is marked by famous touristic areas such as the Costa Brava. The volume of tourism promoted the growth demand on Marinas, restaurants and shore related infrastructures around the 70's. However, most of sea front was designed without considering wave impacts and erosion by that time being. This fact coupled with several human interventions that enhanced shoreline retreat has been provoking damage on important touristic areas. In order to protect the hinterland numerous structures have been used along the Spanish coast, *e.g.* groins, breakwaters, detached breakwaters among other (Figure 29). Those methods are largely applied due to the lack of sand reservoirs, although not always successfully. As a consequence, the present chapter evaluates a case study at Blanes, more specifically the S'Abanell Beach which is located in Catalonia along the Mediterranean Sea. This area has been experiencing constant shoreline retreat where hard structures and also nourishments have not controlled erosion yet.

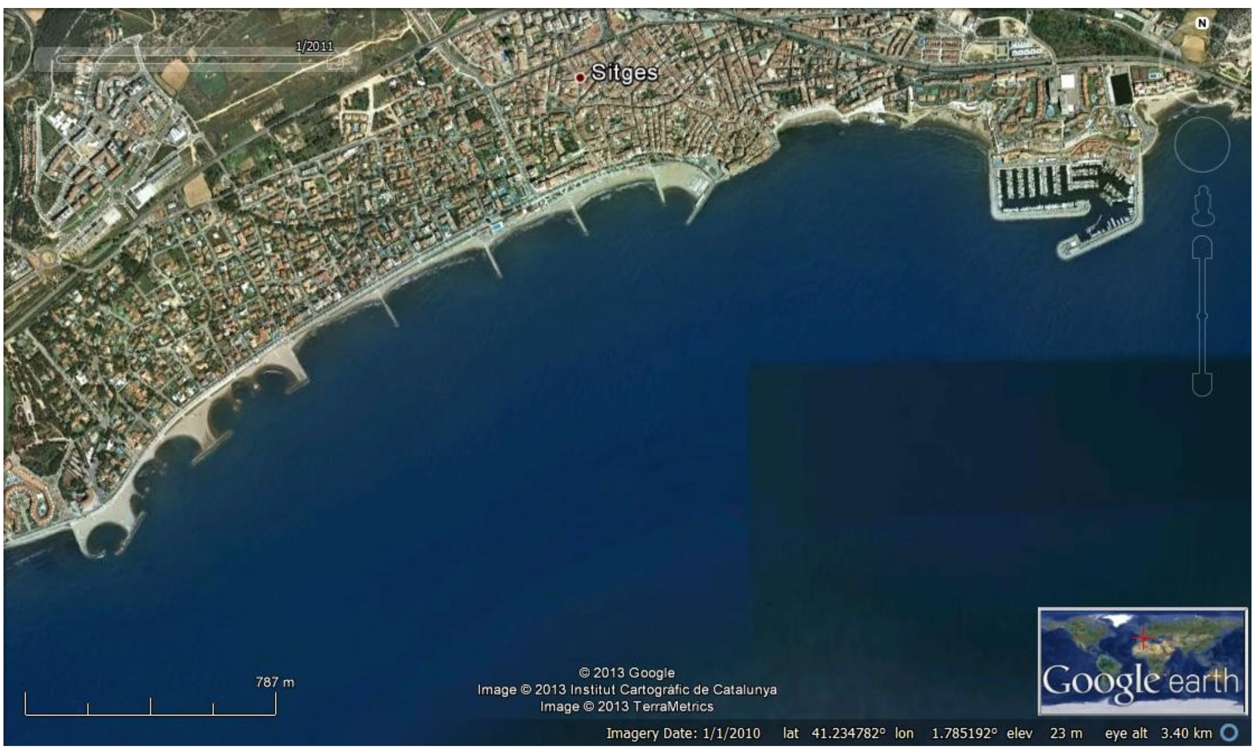


Figure 29: Coast of Sitges at Catalonia illustrating several interventions on the coast line among groins, breakwaters and a marina.

This chapter encloses a description of the coastal morphology and underlying processes followed by the problem identification in addition to motivation and a proposal for studying erosion at S'Abanell. Given sequence, modeling with UNIBEST evaluates the shoreline behavior. Afterwards the erosion mechanism is further investigated. From that some sand nourishment strategies are discussed by the end.

5.1 Coastal Morphology and Underlying Processes

The Catalan coast is part of the Northwestern Spanish Mediterranean shore (Figure 30) along 500 km with large range of environments like the Pyrenees reaching the coast, cliffs, pocket beaches, straight beaches, artificial beaches, river deltas and islands.

It is a semi-enclosed region exposed mainly to winds from NW and N, highly modified by the presence of the Pyrenees (Bolaños *et al.*, 2009). It is characterized by a micro-tidal environment with 30 cm range although meteorological tides can reach up to one meter height. Prevailing waves comes from Northeast and Southwest, as shown in Figure 30 nonetheless they do not highly affect the coast due to the very oblique shoreline orientation along NE-SW direction. The wave climate shows a sharp seasonality when summer and autumn are characterized by calm sea conditions while spring and winter are associated with storm events. Catalonia is noticeable by a high urban concentration on the coast where beach tourism is one of the main economic activities, comprising large important cities such as Barcelona.

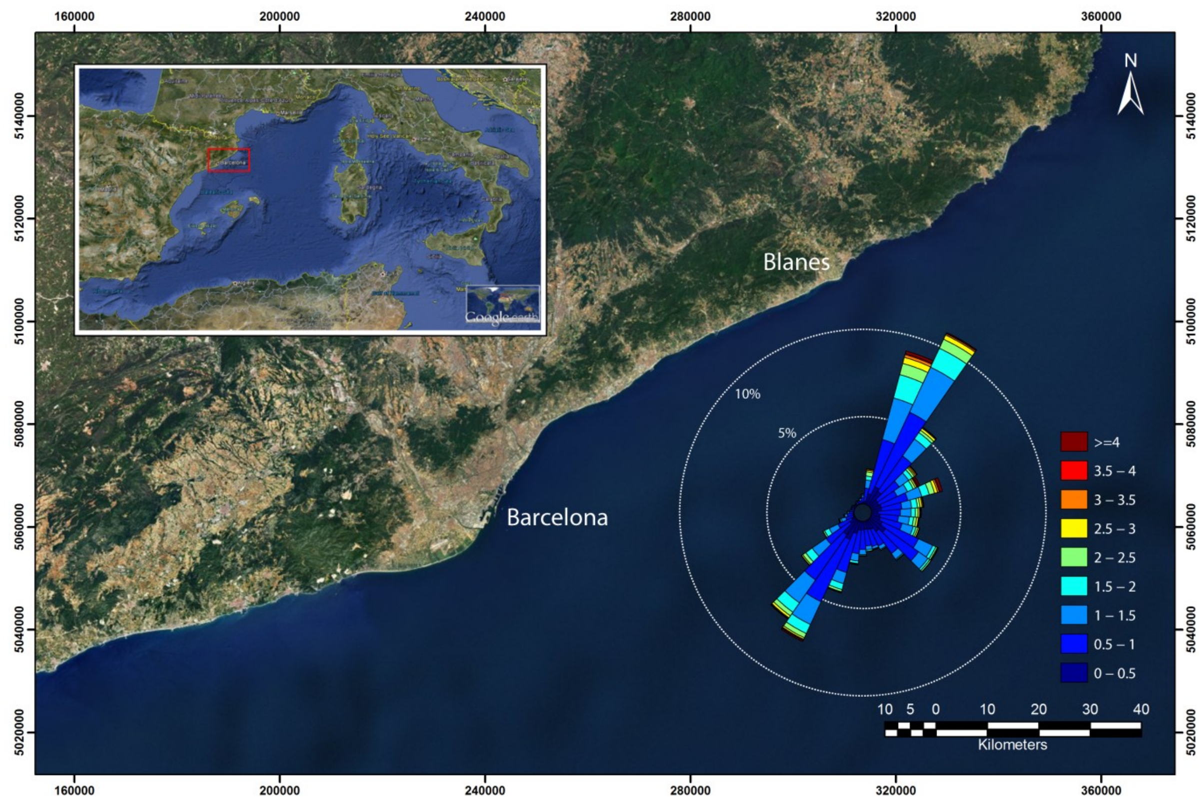


Figure 30: View of the NE coast of Catalonia, Spain with wave offshore data from WWIII (source: Boskalis).

Since beach leisure is one of the main touristic attractions, the available beach area for recreation is a key parameter. Beaches are considered a product and service to be offered to users and visitor according to Shore Act 22/1988 - i.e. *Ley 22/1988, de Costa* (Valdemoro & Jiménez, 2006; Ariza *et al.*, 2008; Jiménez *et al.*, 2011). In contrast several places in Catalonia are under erosion mainly due to the blockage on the sediment transport by natural (*e.g.* headlands and outcrops); or human features, *e.g.*

harbors, groins and also due to the interruption or reduction of fluvial supply, *e.g.* river dams and sand mining. Besides recreation, hinterland safety is another design concern for urban beaches since the coast is impacted by severe storms (Figure 31) that causes damages and losses. Its consequences are further documented in appendix 9.5.1 within emergency interventions in Catalonia: "*Obras de emergencia paseo marítimo de S'Abanell*".

Figure 31: Photos of storms at s'Abanell beach showing from minor overtopping problems on the top until severe damage on the bottom (Jiménez *et al.*, 2011).

Those justifications (*i.e.* coastal protection and recreation) are included in the Spanish normative regarding coastal areas, called: "*Directrices Sobre Actuaciones En Playas*" made by the Environmental Ministry (Ministerio-de-Medio-Ambiente, 2008). However, there is a legal management conflict between institutions. In general the obligations and functions are rather simple and well defined within the *Shore Act*, but it does not prevent delays for actions. From the political and legal aspects the Municipalities receives erosion-induced problems although the actions are dealt in different administrative level (*i.e.* State). According to Ariza *et al.* (2008) this *"reflects the complex administrative scheme governing the coastal area in Spain, where three different administrations have different jurisdictional powers over a narrow piece of land"*, problem also mentioned by Jiménez *et al.* (2011). In general the coast is regulated by The Shore Acts 22/88 which controls the activities on the Maritime Terrestrial Public Domain[20] (DPMT) among beach nourishments and human safety in bathing areas, but also the central government's responsibility of management and guardianship of the DPMT.

Ariza *et al.* (2008) throughout very comprehensive interviews along the Catalan Coast found out that the main concern of local authorities is the lack of sand and consequently beach erosion. In those cases the beach failure is recognized by the failure of protection and recreation functions. The authors also remarked that the persistence of those problems shows the inefficiency of the actual strategies (*i.e.* emergencies/remedial), especially regarding the gap between local authorities and State.

Within this context s'Abanell beach, located in the Municipality of Blanes, Catalonia (Figure 32) has been under erosion caused in part by the long-term negative sediment budget enhanced by storm events. The driving force of erosion still uncertain although Rovira *et al.* (2005) and Jiménez *et al.* (2011) identified the mining activities on the Tordera River around the 70's as the main cause. As a consequence the river nowadays does not supply enough sand to the coast as demonstrated in Figure 33. Currently the lower Tordera presents a complex pattern of sedimentation and erosion of its cross-section in a natural attempt to restore the stable hydraulic condition. This fluvial sediment export was attributed to high discharge events of the lower Tordera River, when the sand used to reach the coast. This lack of supply can be responsible for large erosion rates observed at the beach around the river mouth (Figure 31 – lower pictures and Figure 37).

[20] zona de **D**ominio **P**úblico **M**aritimo-**T**errestre, DPMT

Figure 32: Top view of Blanes and s'Abanell beach on the Catalan coast with pictures emphasizing the erosion problem, including one of the nourishments executed nearby the Tordera river mouth.

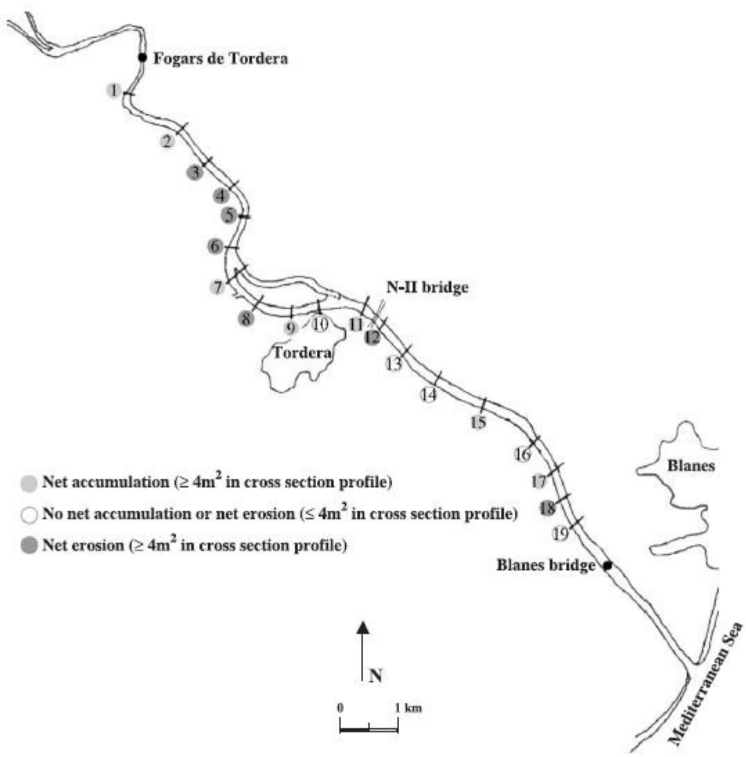


Figure 33: Sedimentation and erosion pattern on the lower Tordera river stretch calculated by Rovira et al (2005) for the period of 1997 - 1999.

Blanes, the Northern beach after sa Palomera and the s'Abanell beaches encloses 3 km of coast aligned NE-SW right North of Tordera River delta which was created by the fluvial sediment supply, as suggested in Figure 34. The light gray area is formed by recent riverine quaternary deposits from the Tordera River watershed (see appendix 9.5.2 and 9.5.3 for complement). According to S-ϕ curves calculated in UNIBEST, this stretch is close to its stable orientation, with small Northward sediment transport as shown in Figure 35; while the Southern area at Conca beach differs more from the equilibrium, suggesting larger littoral drift towards South. The largest shoreline retreat takes place on the river mouth corresponding to the sediment transport diversion point. But large erosion rate is also on s'Abanell beach while the downdrift section is rather stable around the delta vicinities.

Jiménez *et al.* (2011) have pointed out several attempts for mitigating erosion at the s'Abanell which did not work properly (Table XII). First, seawalls and rip rap structures were placed to safeguard the promenade and important infrastructures. Not solving the problem, nourishments were executed for example in 2008 on Figure 37. They average 190.000m^3 per year of loss, since they disappeared after one year. However based on previous shoreline retreat calculations, the same authors suggested an eroded volume of only 30.000m^3 per year.

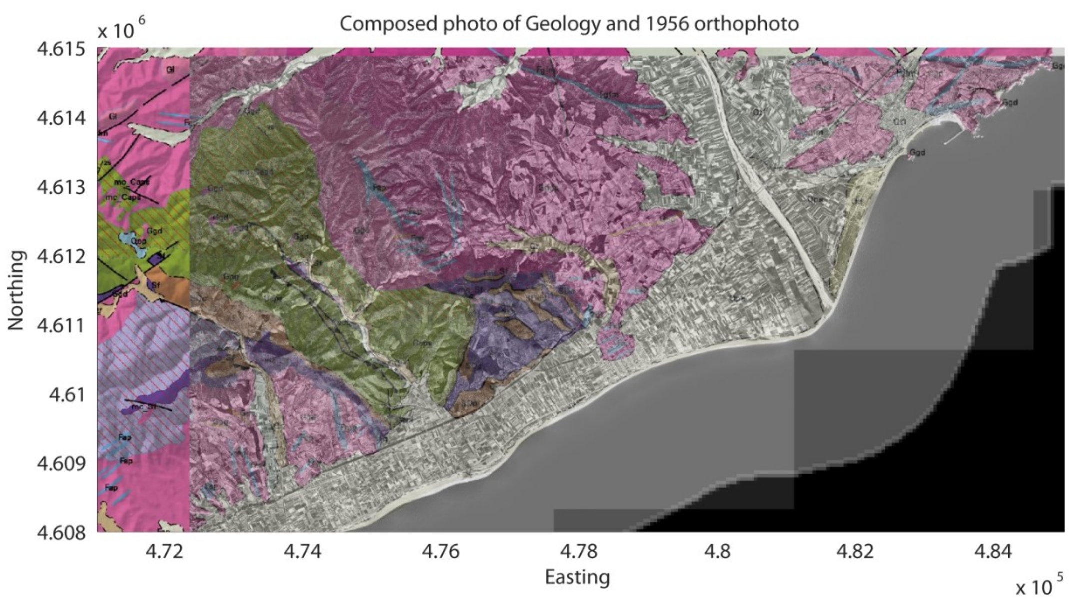


Figure 34: Overlap of 1956 orthophoto on the geological map of Blanes. The light gray coastal deposit corresponds to a recent sand deposit originated from the Tordera River, in deltaic shape.

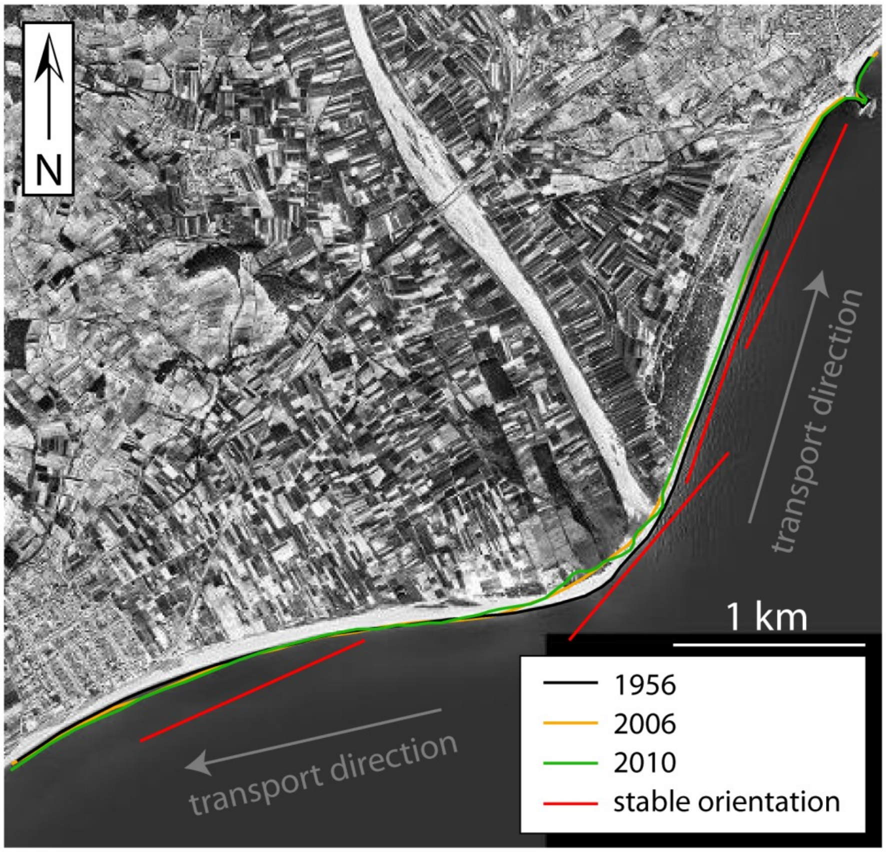


Figure 35: Shoreline evolution based on aerial pictures from 1956 to 2010 with calculated stable shoreline orientation derived from S-ϕ curves and the correspondent sediment transport directions.

An important erosion spot is located right North from Tordera River delta, corresponding to a desalinization station (in Figure 31 and Figure 32), backed by a camping site. From historical pictures it is possible to observe the shoreline retreat in this area with remarks to progressive shortage of the camping area (Figure 37). It is possible to see the retreat of the camping site from 2007 picture before the replenishment and again in 2010 right after a series of 3 nourishments followed by a new fence position at 2011 as a set-back measure. This series shows the completely loss of 575.000m^3 of sand in only three years.

Table XII: s'Abanell nourishment works from Jimenez et al (2011)

Year	Volume [10³ m³]	Type	Volume Remaining	Purpose
2007	180	Berm	0% in 1 yr	Infrastructure protection
2008	144	Berm	0% in 1 yr	Infrastructure protection
2009	250	Berm	n.a	Infrastructure protection
AVG	*190*		*less than one year lifetime*	

This mismatch of volumes between 30.000m³/y calculated by Jiménez *et al.* (2011) and 190.000m³/y added by dredging to compensate erosion suggest an unknown mechanism causing loss of sediments, regardless its added amount. Therefore, besides the shortage of river supply there is another sink of material within this coastal cell.

The study area is characterized by steep and coarse sanded beaches in the vicinity of an underwater canyon (i.e. Blanes Canyon - Figure 36). Nearshore bathymetry shows the lack of continental shelf where the profile goes towards deeper water in few kilometers. Those characteristics can represent a sink of material deposited on the beach.

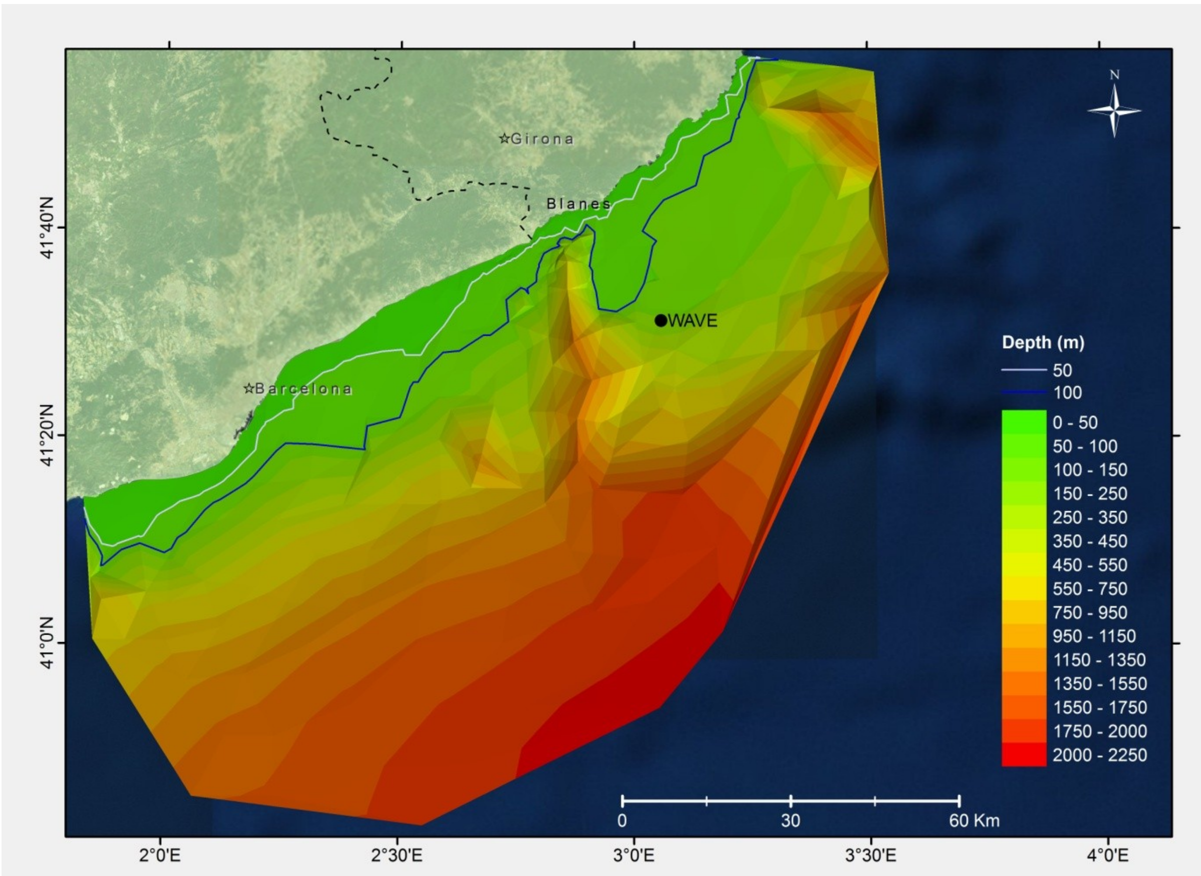


Figure 36: Top view of Blanes area showing the location of off-shore wave data and the presence of Blanes Canyon.

Nevertheless, facing retreat the local authorities are trying to protect the desalinization plant by means of rip rap structures and nourishments which both need to be constantly maintained since storms can easily reach and damage the protection as showed in Figure 31.

Figure 37: Historical satellite pictures of s'Abanell beach at Tordera River from 2005 to 2011.

Tourism wise, s'Abanell needs to offer enough beach area to users. MOP (1970); Valdemoro and Jiménez (2006) suggest a target width of 35 to 40 meters in order to accommodate restaurants, facilities and people. This optimum size is recommended considering the minimum density comfort (*i.e.* people per square meter) on the beach but also the walking distance to the water. Therefore neither too narrow nor too wide beaches are acceptable.

5.2 Problem, Motivation and Proposal

S'Abanell beach is a touristic destination on the Catalan coast which is under shoreline retreat and needs to keep its function as a touristic place and also as a coastal defense for the city and other infrastructures. Currently only remedial interventions with structures and nourishments have been executed, which are not controlling erosion. There is a lack of long term planning to solve this problem besides political conflicts within institutions. In addition the large mismatch between calculated erosion volumes and the eroded nourishments suggests a still unknown sink mechanism of sediments besides the lack of river supply.

In this context the present study looks toward a long term solution to mitigate the erosion problems fulfilling two main goals:

(1) maintaining the recreational and beach leisure function;
(2) protecting S'Abanell's infrastructures and hinterland.

The lack of sand reservoirs in the Mediterranean area limits the application of large nourishments, although from Table I large volumes have been applied around Spain and also at Blanes area (*i.e.*

575.000 m^3 in 3 years). At s'Abanell the natural sediment source used to be the Tordera River, as indicated by Rovira *et al.* (2005), Jiménez *et al.* (2011) and the geologic map in Figure 34. Therefore one solution is the re-establishment of river supply to the beach like previously to the sand mining activities.

In this way, the present study assesses:

(1) how much the fluvial sediment discharge contributes with the beach to keep the coastline stable within UNIBEST model.

(2) the magnitude and cause of sediment losses at s'Abanell. This will be performed by means of assessing UNIBEST results, aerial photos and storm simulations.

(3) a strategy which fulfills the goals and requirements of safety and leisure for this area.

Finally, nourishments strategies are proposed based on the simulations and also the possible erosion mechanism in order to reduce losses and optimize the actual strategy.

5.3 Methodology

This section shows UNIBEST inputs for s'Abanell. To characterize this dynamic area, four locations are chosen to account the variability, being two located at s'Abanell beach, one on the Tordera River delta and another Southward at Conca's beach (Figure 38).

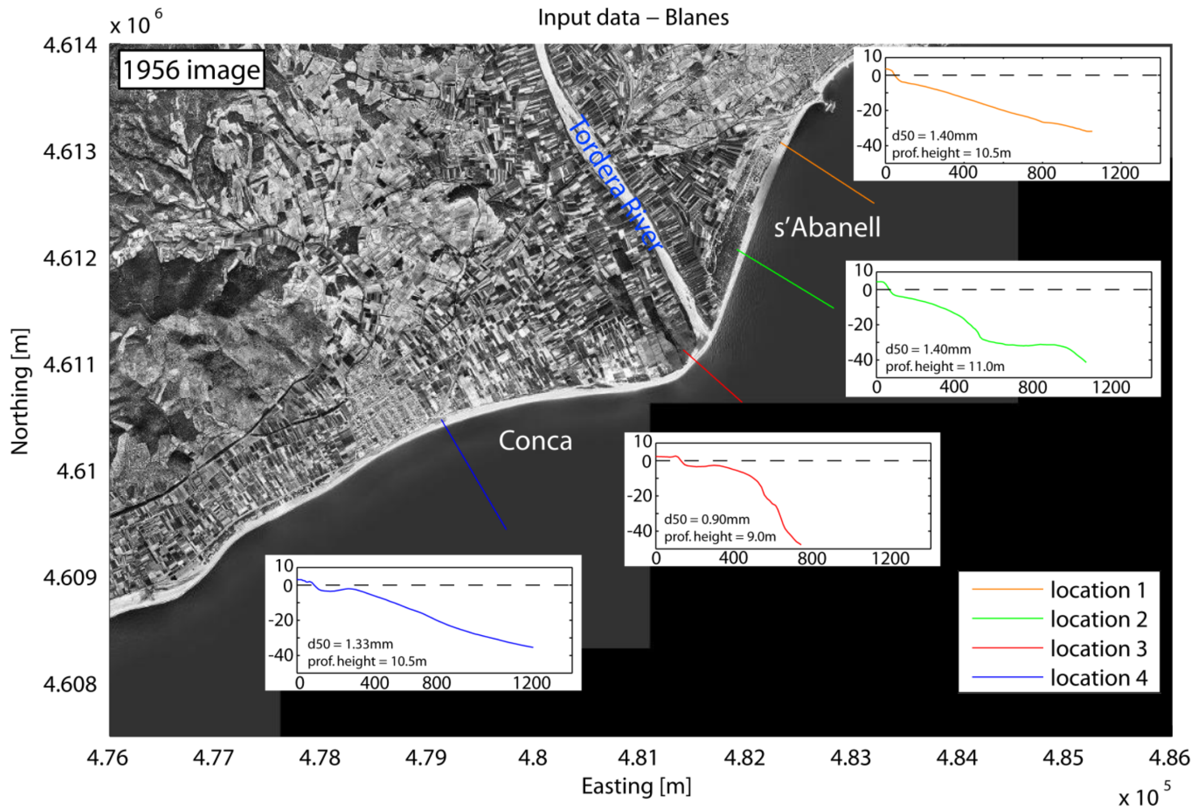


Figure 38: Map with original coastline from 1956 orthophoto, beach profiles, sediment size[21] and calculated active profile height on 4 input points within UNIBEST. Image from Institut Cartogràfic de Catalunya[22].

As described previously, the model requires a series of inputs among: waves, tides, beach profile, sediment grain size, active profile height, coastline orientation and also numerical inputs, among other parameters.

5.3.1 Probabilistic wave data

The wave climate is extracted from the WorldWaves offshore database at 41°30'N 3°E (Figure 36). The WorldWaves offshore wave data derives from WaveWatchIII simulations run at ECMWF (European Center for Medium Range Weather Forecast) enclosing 10-year in 6-hourly time-series of wave conditions verified against buoy and radar measurements by Fugro Oceanor[23].

[21] Beach profiles and sediment grain size were a courtesy from UPC Barcelona.
[22] ICC website: <www.icc.cat>
[23] see http://www.oceanor.com/Services/worldwaves/

This off-shore wave data, presented in Figure 30 has been selected as a function of direction in every 10 degrees and 0.5 meters height (Figure 39) with associated period (Figure 40) and then propagated until the reach of beach profiles (*i.e.* 15 meters depth) using Delft3D-WAVE module as a shell for SWAN model (Booij *et al.*, 1999). Therefore, every wave case has height, period, direction and duration which represent its quadrant. Those results have been coupled with UNIBEST to calculate the longshore transport within the **L**ongshore **T**ransport module.

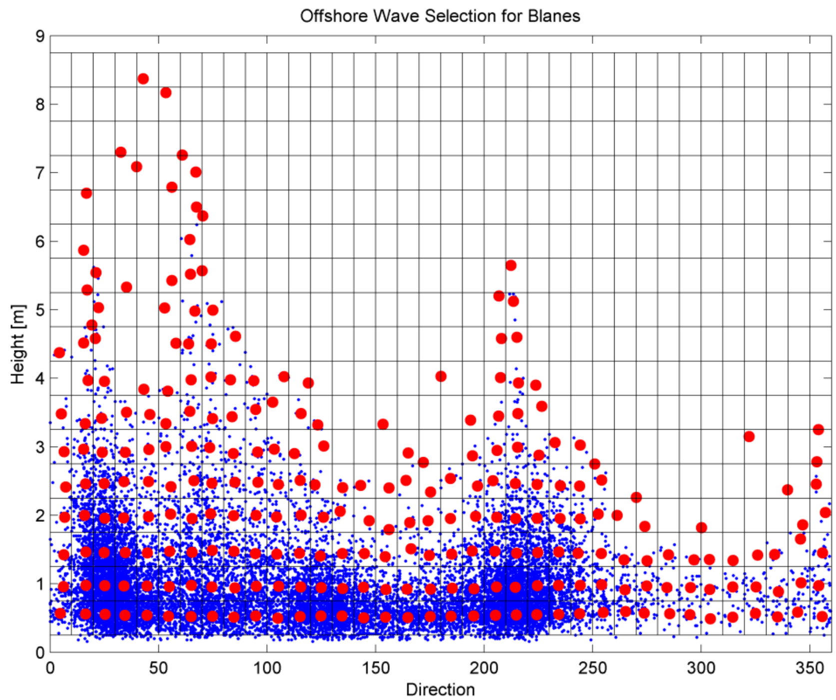


Figure 39: Off-shore Wave selection for Blanes as a function of wave direction and period. The red dots represent the chosen wave cases while the blue dots are the original data.

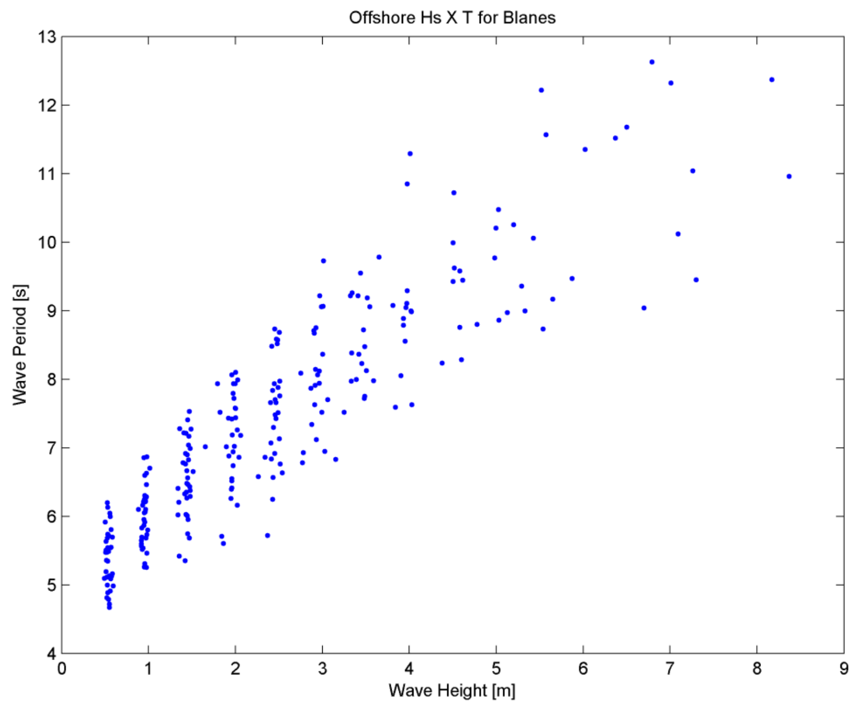


Figure 40: Off-shore selected wave period versus wave height for Blanes.

5.3.2 Probabilistic tides

Tides on the Mediterranean Sea are rather small, being neglected on nautical charters for Blanes area. Therefore it has been ignored during UNIBEST simulations.

5.3.3 Beach Profiles

Four beach profiles have been obtained from UPC Barcelona to represent the study area (Figure 38). In general the profiles are steep[24] without an extensive continental shelf but actually bounded by very deep waters nearby ending in a submerged canyon (*i.e.* Blanes Canyon) reaching 100 meters depth in 3 km from the coast. The overall picture of profiles can be seen in Figure 41.

[24] Slope of 1:18 (maximum of 1:6) on the swash zone and 1:40 beyond the closure depth.

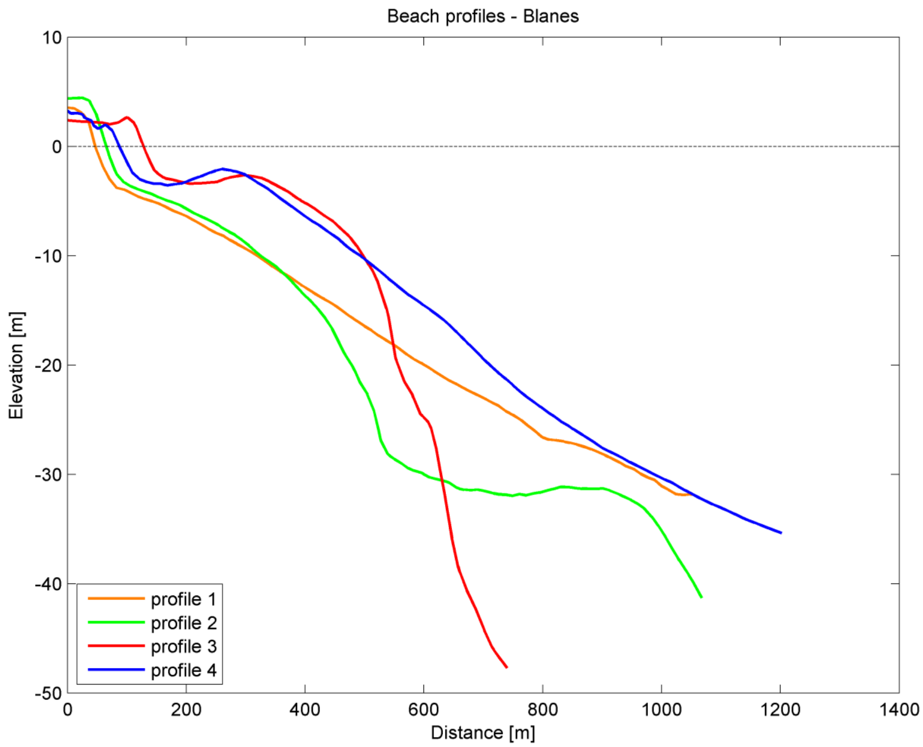


Figure 41: Beach profiles for the 5 locations at Blanes.

5.3.4 Coastline orientation

The initial coastline orientation is drawn from 1956 orthophoto in Figure 38 which represents a stable shape previously from interventions on the river. The grid starts on the s'Abanell beach right South from sa Palomera outcrop where the coast presents already a more straight section beyond the influence of diffraction that shapes the beach parabolic format encountered there. The grid ends at Conca's beach where the coastline is rather stable and therefore would represent the downdrift coast behavior, including the expected littoral drift.

5.3.5 Sediment grain size and transport formula

The sediment grain sizes are provided by UPC Barcelona for four locations, comprising the s'Abanell beach (very coarse), Tordera River mouth (coarse) and Conca beach (very coarse). The original values can be seen in Figure 38 although due to the chosen transport formula and model restrictions, the larger grain sizes at s'Abanell and Conca have been entered as 1 mm at UNIBEST, as shown in Table XIII.

The sediment transport formula of Van Rijn (2004) is chosen, described in Deltares (2011), based on personal conversation with Van Thiel de Vries (2013) due to its reliable application as default sediment transport formula in other models such as Delft3D. The case-by-case inspection of velocities and sediment transport shows coherent results and consequently this formula is selected. The possible effect of using a different grain size than the original surveyed is evaluated in the sensitivity analysis although the initial expected effects are obviouly less sediment transport.

Table XIII: UNIBEST model inputs for Blanes containing active profile height, sediment size and number of select wave cases (see appendix).

	Profile height (m)	D_{50} Sampled (mm)	D_{50} modelled (mm)
Ray 1	10.5	1.40	1000
Ray 2	11.0	1.40	1000
Ray 3	9.0	0.90	900
Ray 4	10.5	1.33	1000

5.3.6 Active profile height

As the last physical input for UNIBEST, the active profile height represents the vertical extension of the profile which migrates in function of the mass balance. This value constitutes a key variable translating the mass balance into shoreline retreat or accretion. For more details check Appendix 9.1 on how the model equations work.

To find this profile height first the closure depths has been calculated from Hallermeier (1981) and those values are summed with the dune heights. As from personal conversation with Huisman (2013) the choice of profile upper limit as the dune foot is valid only in case of shoreline accretion while where erosion is expected the choice for the dune height represents a more realistic evaluation since in this case the whole dune acts as a sediment source to be eroded while in the former the sand can only be deposit until the dune foot[25].

For the present area, the dune height is the upper sand reach on the beach since its coast has promenades, sea walls and other infrastructures limiting the formation of extensive dunes. The final active profile heights are shown in Table XIII ranging from 9 to 11 meters.

5.3.7 Numerical inputs and other parameters

Model simulations have been performed with 500 time steps per year (*i.e.* approximately 0.7 day each step) for 10 years, with closed boundary condition[26] on the North and open at the South[27]. This set up represents the natural system in order to assess the model calibration regarding the transport, erosion and sediment losses towards the South and North ends of the study area.

The other parameters have been set as default *e.g.* wave breaking coefficient, sediment porosity, bottom roughness, among others.

[25] Assumption made considering no significant aeolian transport as well as no long term sand migration towards the dunes.
[26] Allows no sediment transport from and to the boarders in order to simulate the sediment transport blockage by the sa Palomera outcrop.
[27] Allows free sediment transport in and out the domain.

5.4 Model Results and Site Characterization

In order to reproduce qualitatively and quantitatively the behavior of S'Abanell beach this chapter presents the hindcast model followed by the sensitivity analysis. The values used for calibration derived from literature, aerial photos and available data.

5.4.1 Model Hindcast

For the initial evaluation and hindcast of Blanes, no input of sand is utilized to simulate the current lack of fluvial supply situation.

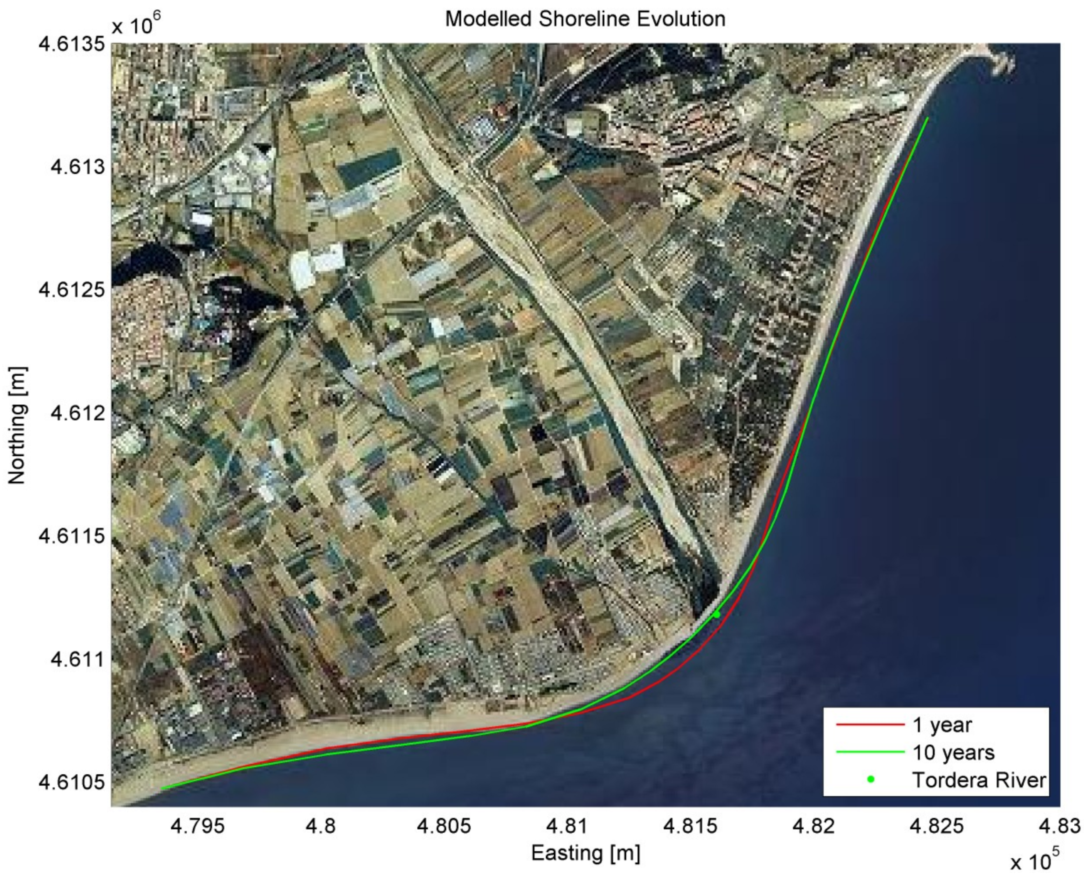


Figure 42: Map of modelled shoreline evolution of Blanes simulating the coastline response without sediment input from Tordera River. Background picture from 2006.

The model reproduces well the erosion pattern matching with the present coastline at the river mouth from the initial shoreline position (Figure 42). The most severe erosion spot corresponds to the river mouth surroundings, as pointed by Jiménez *et al.* (2011) and also observed from the shoreline evolution in Figure 35. This behavior is further assessed from the modelled sediment transport gradient which points alongshore erosional and accretional areas (Figure 43).

However, despite this erosion trend at Tordera, the model shows shoreline stability and progradation on the river mouth vicinities. This is not observed in reality at s'Abanell beach (see Figure 35).

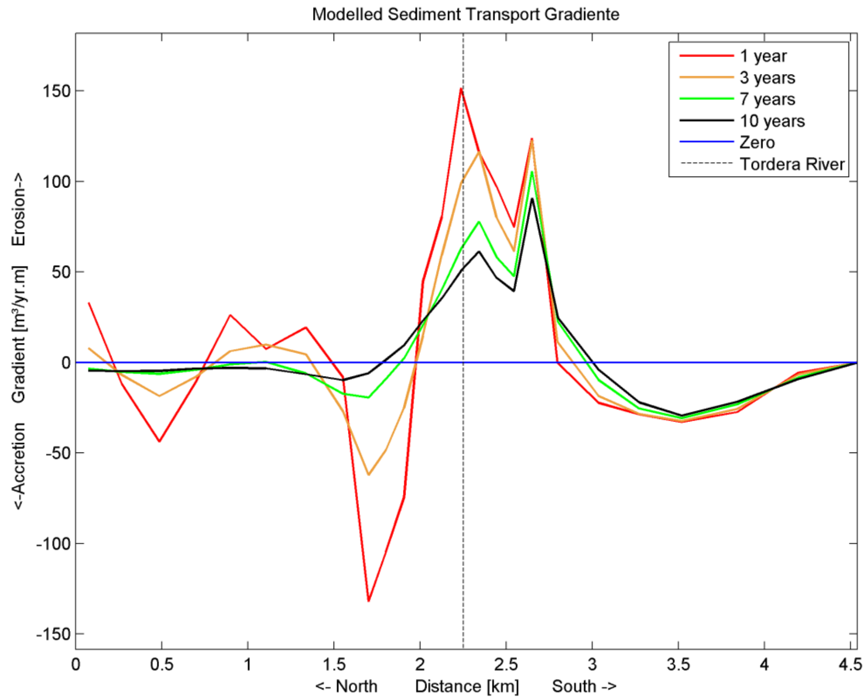


Figure 43: Sediment transport gradient for Blanes in the absence of river supply.

From Tordera to s'Abanell, sediment transport is northward directed, while on the South portion it is southward (Figure 44). Hence being the Northern flux of sediment blocked by sa Palomera outcrop, without a sediment sink, s'Abanell coastline presents a theoretical depositional and transgressive behavior.

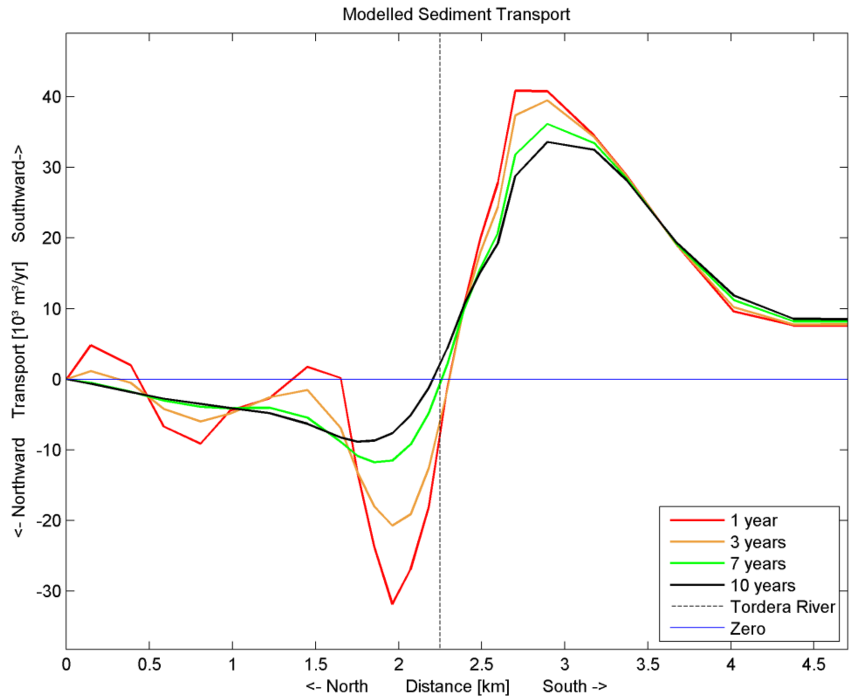


Figure 44: Modelled alongshore sediment transport for Blanes within 10 years.

To evaluate the importance of river supply and other possible sink volumes, a hindcast model based on historical orthophotos assesses the sediment budget necessary to keep the river delta and S'Abanell beach position stable based on the coastline of 1956. This has been performed by introducing and removing sediment as sources and sinks along the coast in UNIBEST-CL model. A supply of 70.000 m³/y of sand is necessary to keep the coastline in its original position around the river delta, while the model also suggests an average erosion volume of 10.000 m³/y at s'Abanell and 50.000 m³/y at Conca's beach after 10 years of simulation (Figure 45). In addition, a volume of 10.000 m³/y for the Southward directed littoral drift is estimated to close the mass balance within the cell (Figure 44).

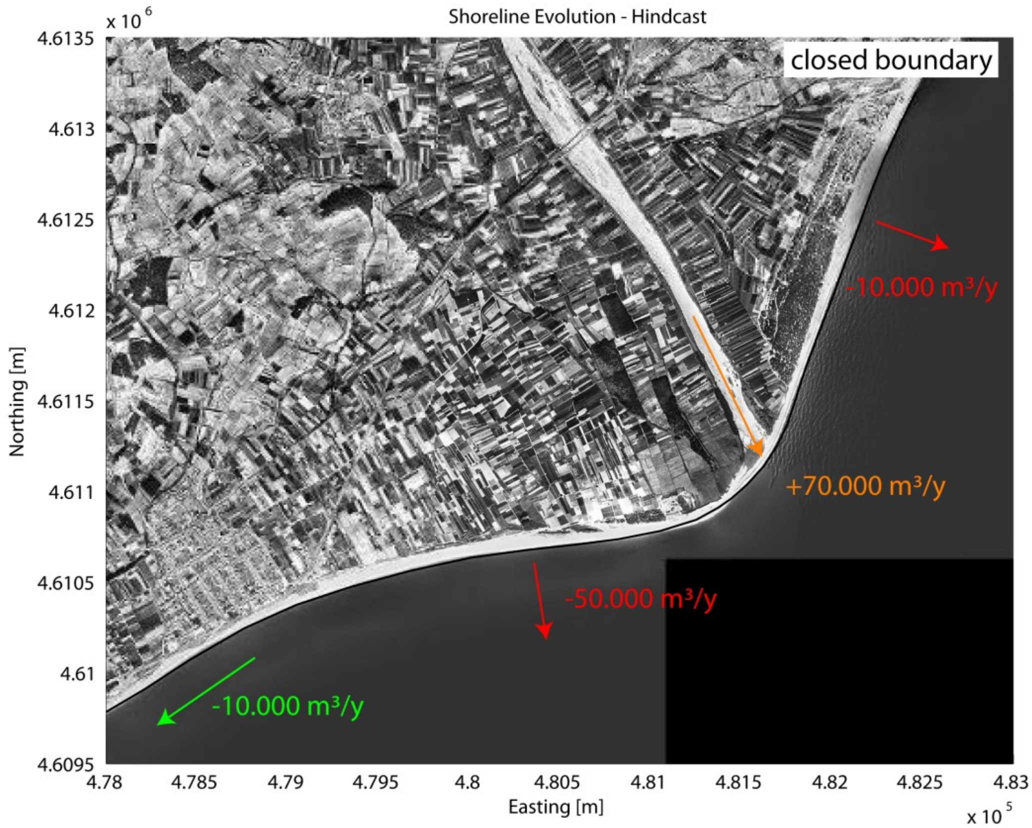


Figure 45: Map for modelled shoreline evolution of Blanes with sediment source in orange, sinks in red and littoral drift in green to simulate the sediment balance necessary to keep the shoreline position stable with reference to 1956's.

5.4.2 Sensitivity Analysis

To further check the model behavior accounting for uncertainties and variabilities, alternative runs have been performed and compared to provide more information and reliability regarding model results. In total, six runs include sediment uncertainty, the seasonal variability of wave climate and the introduction of sinks and sources changing the shoreline orientation.

Table XIV: Description of runs for sensitivity analysis of Spain.

#	Label	Description
1	full waves, no SOS	annual wave climate, no sediment sink and source
2	full waves, with SOS	annual wave climate, with sediment sink and source
3	season waves, no SOS	seasonal wave climate, no sediment sink and source
4	season waves, with SOS	seasonal wave climate, with sediment sink and source
5	full waves, no SOS, sed. grad.	annual wave climate, no sediment sink and source, grain sizes changed to simulate sediment gradient
6	season waves, no SOS, sed. grad.	seasonal wave climate, no sediment sink and source, grain sizes changed to simulate sediment gradient

From Table XIV, the first two runs were already computed and extensively described along the hindcast chapter (5.4.1). For the simulations with seasonal wave climate, first the wave climate is sorted into four sets to assess the variability throughout the year due to the presence of very oblique and seasonal waves from NE and SW[28] (see wave roses in Appendix 9.5.5). This set up also simulates 10 years of coastal evolution, with and without sources and sinks. By separating the wave cases into winter, spring, summer and autumn the net transport can compute possible transport reversals. From Figure 46 there is a clear difference in magnitude between seasons being summer and autumn characterized by mild transport, while winter and spring encompass stronger capacity. The littoral drift varies between 35.000 m³ during spring to less than 10.000 m³ on autumn however no significant reversal is observed.

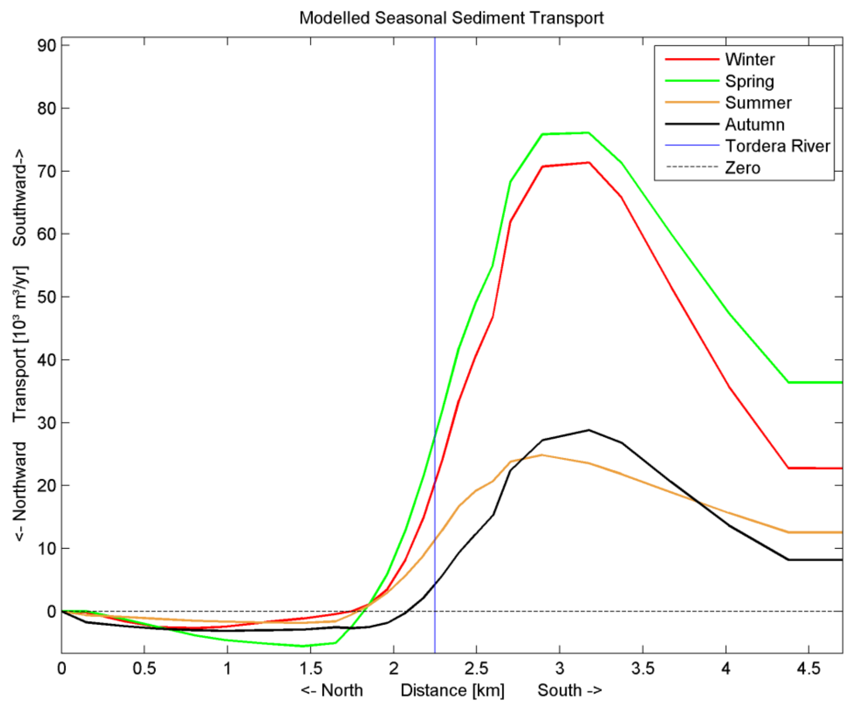


Figure 46: Seasonal alongshore sediment transport for Blanes.

From that, the average transport can be seen in Figure 47 with very low capacity at s'Abanell (*i.e.* less than 10.000m³/year) while increasing towards the river delta. From this picture, southward littoral drift is around 20.000m³/y.

Regarding shoreline displacement, separating the wave climate into seasons also shows stability and even marine regression for s'Abanell. From the model's assumptions, without a sink of sediment the beach for that stretch is accreting or stable even without any sediment from the river but only from its delta erosion (Figure 48).

Hence, the model still does not match with observations and only by means forcing inputs and outputs of sediment the reality can be reproduced. In this seasonal simulation, similar values from the hindcast

[28] See Appendix 9.5.5 for seasonal wave climate

evaluation are found with 70.000 m³ input from Tordera, loss of 15.000 m³ at s'Abanell, 40.000 m³ at Conca and 15.000 m³ for littoral drift.

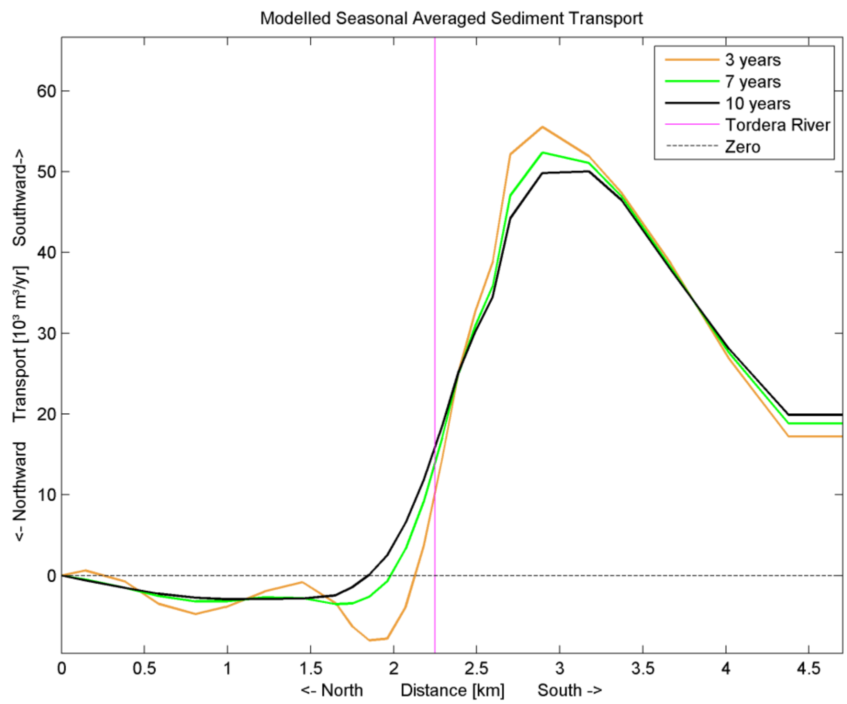


Figure 47: Seasonally averaged alongshore transport for Blanes through time.

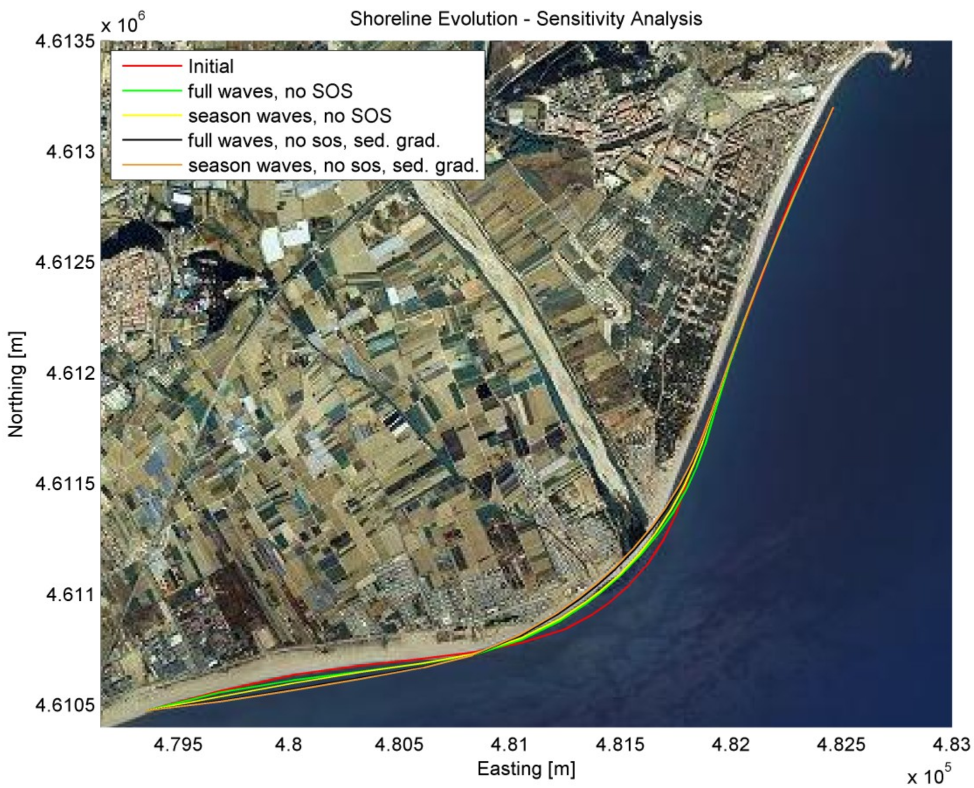


Figure 48: Modelled shoreline evolution for Blanes applying seasonal wave climate, without river supply.

In addition of evaluating the behavior and effect of sorting the wave climate, the introduction of alongshore sediment grain size gradients have been performed into two simulations: (1) within the full wave climate computation and (2) with seasonal wave climate. The goal of those assessments is to investigate possible sediment induced transport gradients caused by this variability of sediment which was not fully accounted in the initial model due to input constriction. For that, instead of just diminishing the sediments at s'Abanell and Conca beach up to 1 mm, all the grain sizes have been scaled down by 0.4 mm, being simulated as: Conca with 0.9 mm, Tordera with 0.5 mm and s'Abanell with 1.0 mm. By introducing this gradient and reducing the grain size on the erosion spot (*i.e.* at Tordera) the shoreline retreat is enlarged, however s'Abanell is still stable or under deposition while Conca's beach presents larger shoreline accretion. Nonetheless, results still similar compared to the other scenarios.

Figure 49 shows that among all runs the sediment transport behavior and magnitude are similar, varying from 35 to 85 thousand cubic meters per year right South from Tordera with yearly average littoral drift from 10 to 35 m³/year southward.

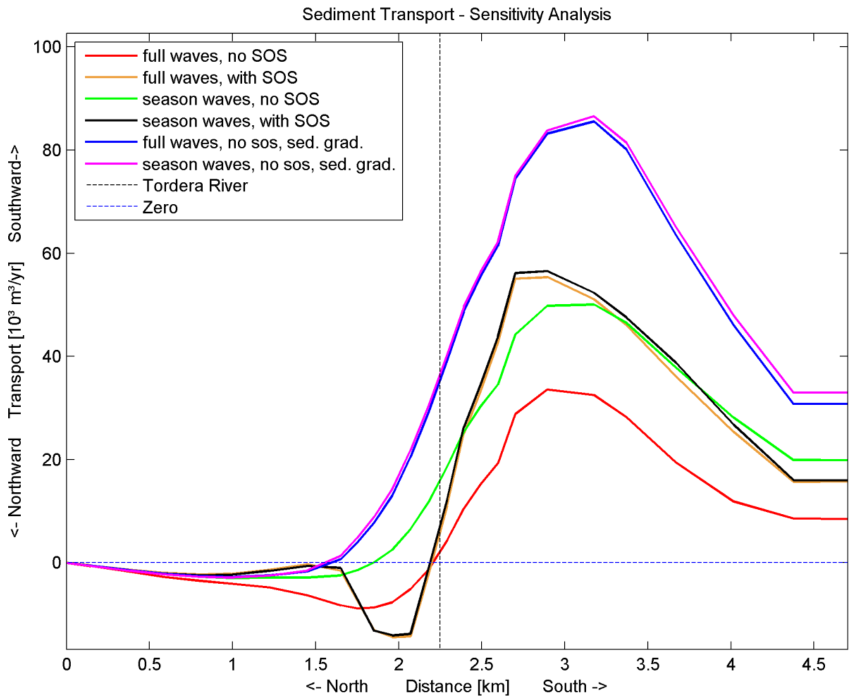


Figure 49: Sensitivity analysis for modelled sediment transport at Blanes.

The summary of important figures is shown in Table XV. From the model S'Abanell is a potential stable beach in the absence of sediment sink, while accretion happens when Tordera inputs sand into the system. The southward littoral drift ranges in between 10 and 35 thousand cubic meters per year, being large during winter and spring. From this assessment Tordera River needs to discharge around 70.000 m^3/y of sand to keep the shoreline stable while s'Abanell needs a sink between 10.000 to 15.000 m^3/y to not show progradation in time, which in reality is a rough minimum estimation of erosion since the beach does not accrete.

Table XV: Sum of figures derived from sensitivity analysis for Blanes.

#	S'Abanell behavior	Littoral drift [10^3 m^3/y]	Tordera input [10^3 m^3/y]	sink at S'Abanell [10^3 m^3/y]
1	Stable	10	---	---
2	Accretion	15	70	10
3	Stable	20	---	---
4	Accretion	15	70	15
5	Stable	30	---	---
6	Stable	35	---	---

Therefore, the hindcast and sensitivity model agreed for the sediment transport capacity behavior and magnitude. But, when comparing the model results with the erosive reality of s'Abanell there is still a volume mismatch to be investigated in the magnitude of thousands cubic meters per year. Next section focus in finding possible processes that could introduce sinks of sediments in this coastal compartment.

5.5 Erosion Causes Evaluation

From the shoreline modelling S'Abanell has a potential northward alongshore sediment transport, together with reported severe storm events. Considering that, sink volumes can be caused by mainly two processes: (1) sediment bypass through sa Palomera outcrop towards Blanes; (2) cross-shore loss due to storms towards the promenade through overwash (2.1) and offshore directed (2.2). Those losses can only be estimated roughly in UNIBEST by volume balance but not as physical processes. Therefore this section focus in assessing the mechanism of sediment loss based on coastal dynamic processes.

Hypothesis 1 – sand bypass

The majority of Catalonia coast presents southward sediment transport, although s'Abanell was formed by an exception of this due to Tordera River that introduced sediment on the shore forming a delta which creates a reversal on the sediment transport due to shoreline orientation. Therefore, one possible loss of sand is the sediment bypass through sa Palomera outcrop on the northernmost point of s'Abanell towards Blanes beach.

In order to evaluate this possibility first the depth of closure have been calculated based on Hallermeier (1981) being 6.2 meters nearby the sa Palomera, while the outcrop extends itself until approximately 8-10 meters deep. In the absence of tidal currents, the sediment transport should not extend further than this wave based assessment, not causing the bypass. Coupled with this simple investigation, orthophotos have been analyzed from 1956 until 2010 in order to verify the possible accretion behavior of Blanes beach as a consequence of this presumed bypass. Blanes beach is enclosed by a long outcrop called Sa Forcanera and nowadays by a harbor which blocks entirely the northward alongshore sediment transport.

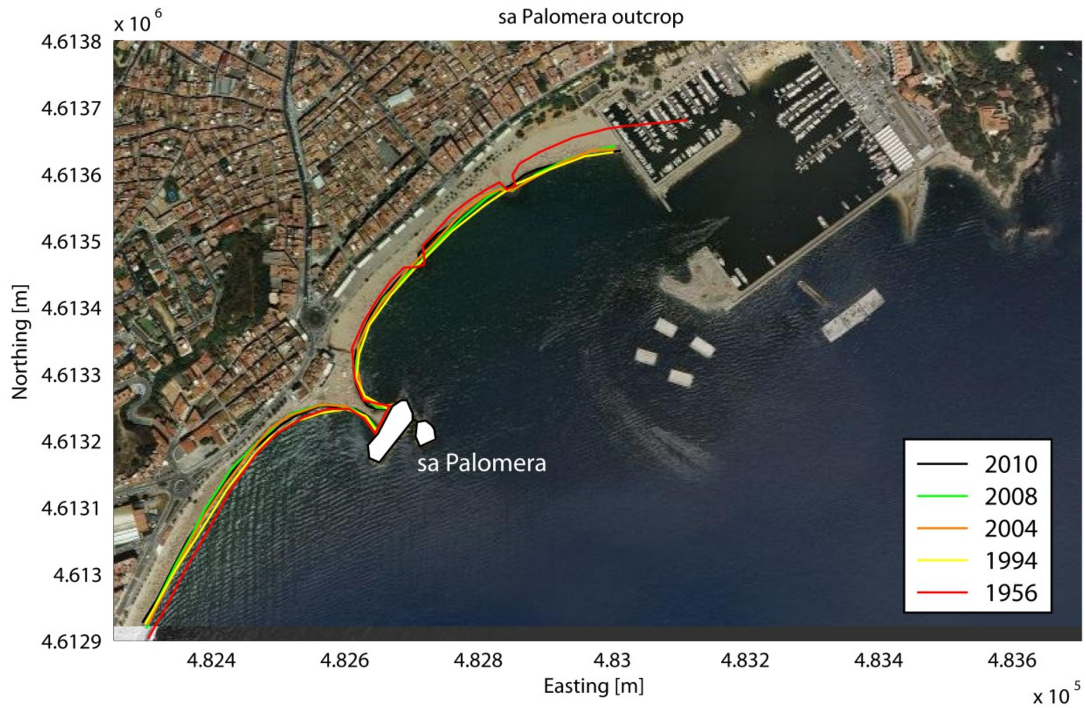


Figure 50: Shoreline evolution around sa Palomera outcrop based on historical orthophotos.

Figure 50 shows a very stable coastline at Blanes beach through time while s'Abanell, although relatively stable shows more variability, as expected for being more exposed. Therefore the bypass hypothesis is either non-existent or very small and ephemeral, not contributing significantly with the erosion pattern on the updrift beach. In case of significant bypass, Blanes beach should be accreting much more than S'Abanell is eroding due to its short relative extension (More or less 1/2 of S'Abanell length).

Hypothesis 2 – Cross-shore loss

Considering storm events, two sinks can be identified. The first (2.1) consists of an onshore loss due to overwash towards the promenade and streets. While a second (2.2) encompass off-shore loss mainly due to undertow and long wave transports.

Considering overwash (2.1), a volume of approximately 150-190 m³ per meter of beach would create an enormous pile of sand on the sidewalk, which is not observed. It is equivalent of 15-19 standard trucks of sand per meter of beach. Nonetheless in some extension, washover deposit happens, as showed in Figure 31. But the magnitude of such events is of different scale and will be considered as minor contribution to s'Abanell erosion.

Regarding the off-shore directed sediment transport (2.2), calculation in storm erosion models *e.g.* DUROS+, SBeach or XBeach can assess the magnitude of such events removing sand from the beach. In this specific case, the process based model XBeach[29] created to simulate extreme events on beach and dune is applied at s'Abanell.

The simulation performs considering the largest wave case from the 10 years record, the measured beach profile near Tordera, natural sand of 1.4 mm and storm duration of 24 hours. The storm growth has been made coupling the 30 centimeters tidal range with storm surge of one meter height. Also the wave case selected of 3.7 meter height and 10.7 seconds period is assumed to grow during the simulation (Figure 51). This simulation consists of a 'worst case scenario', from which 120 m³ of sand are withdrawn from the upper beach, generating a total coastal recession up to 30 meters (Figure 52). This volume is deposit until approximately 5 meters depth, which in theory does not consist of a permanent loss, since the sand still within the active profile, *i.e.* up to 6 meters. Although, considering the wave climate, the coarse nature of the sediments and the beach steepness this volume could not be transported back to the beach. In this case it can actually be slowly transported to deeper areas or even alongshore, but not contributing to the dry beach.

Cross-shore hydrodynamics are very complex and analytical tools, as well as numerical models, do not predict net sediment transport accurately (Bosboom & Stive, 2012). In the upper shoreface there is a mix of bed and suspended load which are transported by undertow, bound and free long waves, short wave skewness in combination with breaking turbulence. During extreme conditions, offshore sediment transport is dominant due to undertow and long waves while under mild wave climate wave skewness drives the onshore transport responsible for building back the beach. However the gross sediment transport is much higher than the net, making net cross-shore transport evaluations very uncertain and dubious. The wave asymmetry, main responsible for the onshore transport together with long free wave, becomes important during shoaling when the symmetrical oscillatory movement is disturbed by the interaction with the sea bottom. In a direct evaluation the skewness is directly proportional to the wave period, as a consequence, higher the period and skewness, higher will be the onshore transport. In this case, swell dominated areas present faster recovery from winter to summer profile when compared to sea dominated coasts. In addition, the vertical sediment transport reach is observed at deeper areas in the former example as well. Therefore, S'Abanell being a sea waves dominated coast, with reflective beaches (*i.e.* coarse grained, steep shoreface with absence of surf zone) do not present conditions for large wave skewness and consequently lower recovery capacity after storms.

By extrapolating this erosion volume along the 2 km area, a total quantity of 240.000 m³ could be removed from the upper beach, similar volume added in 2009 by nourishment.

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[29] XBeach is a public-domain coastal morphology model developed by IHE and Deltares, which simulates flow, waves, sediment transport and morphology, and is capable of handling the interactions between these processes (www.xbeach.org), both under regular and extreme conditions accounting wave propagation, long waves and mean flow, sediment transport and morphological changes of the nearshore area, beaches, dunes and backbarrier during storms.

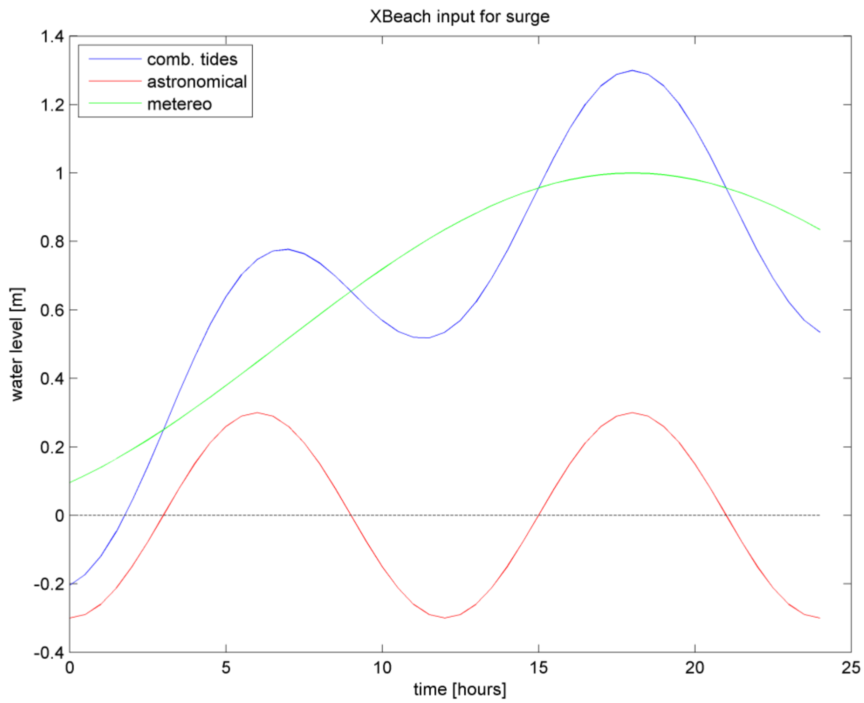

Figure 51: Input storm in XBeach for simulating erosion at s'Abanell.

Further supporting this cross-shore loss, Dean (2002) pointed out the initial deposit slope as an important variable controlling the sediment losses of a nourishment. According to the author, steep foreshore slopes increases the initial cross-shore spreading, and consequently loss of dry beach when the slope tends to find its equilibrium in more gentle inclinations as described by Bruun (1954). Simulating a nourishment of 80 meters width with a foreshore slope up to 1:4 the erosion can reach 170 m^3/m. This result proves the increase of sediment loss due to initial steep slopes.

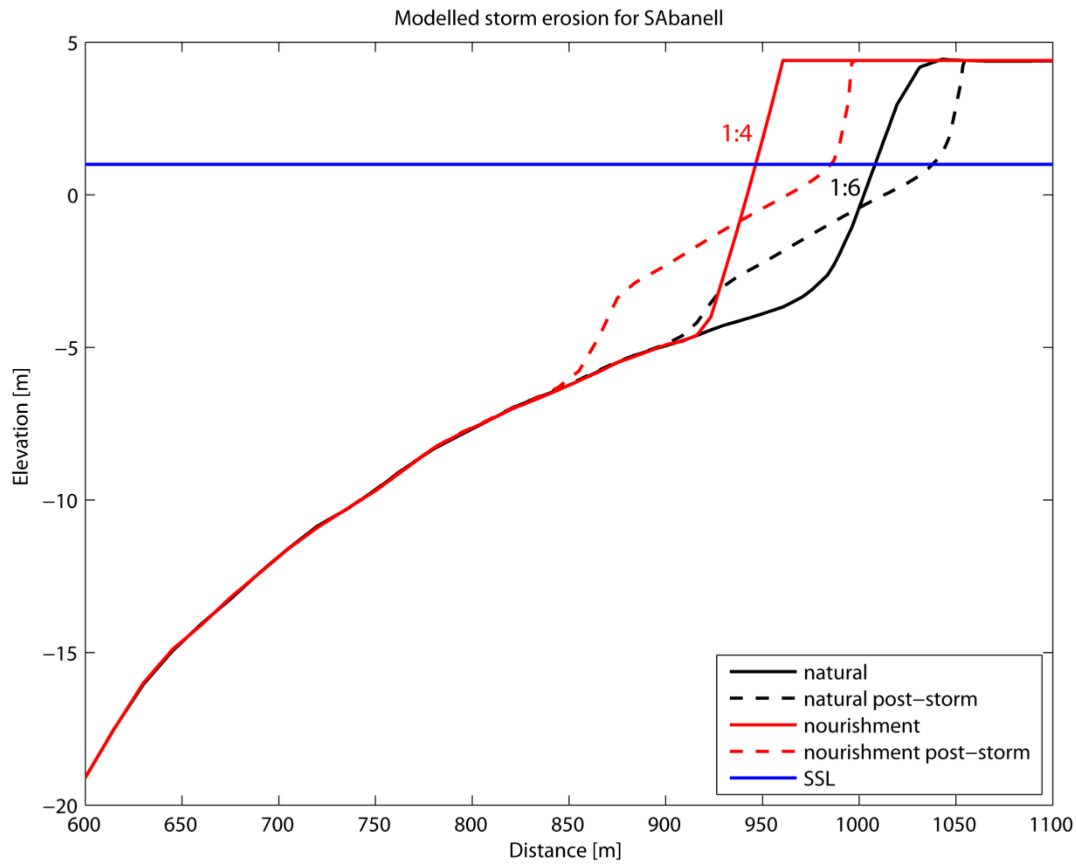

Figure 52: Storm erosion modelled in XBeach for Blanes.

Hence, even though not directly observed but reported as severe damages to infrastructures (Appendix 9.5.1), storm events are the possible sink of sediments on the s'Abanell which can potentially withdraw hundred thousands of sediment from the beach towards underwater profile. Directly, this phenomenon does not provoke the immediate offshore loss of sediment from the original profile, although it can not entirely come back to the beach as in the classic summer and winter profile evolution due to the local dynamics (Short, 1999; Bosboom & Stive, 2012). This hypothesis would explain the reason why all nourishments, regardless volume, disappear within one year from the dry beach.

5.6 Evaluation of Nourishment Strategies

From the discussion developed, s'Abanell constitute of a special case where apparently the lack of integrated management in combination with extensive and large remedial nourishments have not being able to solve erosion problems in the long term. Therefore, the shortage of fluvial supply together with large losses of material in storm events combined with the lack of sand in the Mediterranean area makes the possible solutions be:

(1) restoring the sediment supply from Tordera River. In this case the natural system behavior inputs constant and relatively small amounts of sand into the coastal system from where s'Abanell benefits

from the northward sediment transport. Meanwhile the river mouth is able to keep its stability in addition to restoring the southward littoral drift;

(2) frequent and small nourishments, with gentle foreshore slopes, in order to reduce possible large losses of sediment.

(3) working with a set-back measure on the southern portion of S'Abanell retreating the desalinization plant and the camping site. This retreat decreases the protection necessity on the erosion hot-spot in addition of being a source of sediments that can be used to restore the river.

(4) reducing sediment requirements and losses with perched beaches. It can increase the project successfulness by reducing the necessary amount of sand and by minimizing off-shore losses.

In order to restore the river supply on a decadal base, 700.000 m³ can be placed on the river bed nearby its mouth. By adding sand into the lower Tordera River the natural discharges, especially related with high pluviosity events shall supply material to the coast as it happened before the sand mining activities. In this way, constant and small amounts of sand can enter the coastal system to be further spread out by waves and currents. This option reduces the environment impacts on the beach, as well as beach closure. Sediment grain size selection and fine sediment washing (turbidity) would naturally occur. Regarding costs, doing one large operation on land reduces the total price. The downside of such operation is the accurate sediment input estimation onto the beach. Monitoring with ARGUS cameras[30] can provide great insight on the sediment path from the river towards the coast. Since beach width is important, dredging operations should also be planned as remedial actions.

For the second option involving dredging and discharge on the beach, long contracts with yearly based interventions during the transition from spring to summer represents a suitable strategy. It coincides with the begging of tourism season when the beach width is an important parameter, but also when the wave energy decreases, reducing the sediment spreading. After the season, the shore would also be ready to protect the coast against the severe winter and spring storms, being replenished afterwards, again, for the summer. By planning in this base, the financial, political and logistical constrains are better arranged, enhancing the long term character of this strategy. Those small sized nourishments strategy also agrees with Valdemoro and Jiménez (2006) evaluation for the optimum beach width around 35 to 40 meters wide. From the operational point of view, those small and frequent nourishments can be executed in two ways: (a) by already installed and permanently fixed pipelines where vessels discharge sand on the beach without the need of deploying the whole discharging system every time; (b) or due to the steep bathymetry and absence of nearshore bars, rainbowing is also an suitable possibility.

Applying the set-back measure right North from Tordera, on the South of S'Abanell where lays the camping site and the desalinization plant can benefit in several aspects. This solution first decreases the necessity of protection in that area, since without those infrastructures the beach retreat is rather acceptable. Other positive aspect is when considering the increasing distance from the steep slopes

[30] ARGUS Beach Monitoring Station (ABMS) - Video Metric Systems™ from NorthWest Research Associates, INC. Available at <www.planetargus.com>

which potentially reduces the off-shore losses of material. In addition, to make this solution more sustainable, sand can be withdrawn from this area (approximately 800 x 150 meters) in order to fulfill sand pits on the Tordera River. This latter action makes possible to return approximately 300.000 m³ to the river, helping its recovery from the mining activities. The downside of such intervention is the negative impact and costs related to expropriation and compensation costs to land owners. However the remaining area can be turned into an urban park for recreation.

As the last intervention, perching the beach is not directly based on sand nourishments, as it consist of introducing hard structures. However with large off-shore losses and steep slopes such solution acts together with supplying sand. It can reduce the volume needed to achieve the same beach width and also prevents direct off-shore losses. The structure does not interfere on the wave climate, neither on swimming safety as it happens with detached breakwaters.

5.7 Conclusions and Recommendations for S'Abanell

S'Abanell presents complex coastal dynamics where erosion is caused by two mechanisms working together. The first consist in the lack of fluvial supply from Tordera River after sand mining activities on the past. This input reduction is responsible for large coastal retreat on the river delta, occupied by a camping site and a desalination plant which are both threatened by the sea. The second consists in the off-shore loss due to storms and the steep and deep nearshore slope. As a consequence both tourism and hinterland protection are harmed in this area where management conflicts within governmental institutions have not been able to solve erosion issues in the long term.

After evaluating the underlying processes and alternative strategies this study case also shows that despite the complicate coastal behavior at S'Abanell it still possible to develop a long term sand nourishment strategy to counteract erosion. In this special case, large works on the coast are not suitable due to potentially large losses and undesired wide beaches.

Hence the combination of several measures into a new and innovative strategy comprising: (1) make a set-back (*i.e.* retreat) on the Southern part of S'Abanell beach corresponding to the camping site and desalinization plant. This measure follows the utilization of this lower-urbanized area to first fulfill the sand pits created on Tordera River; and create a recreational park in the remaining area. As positive side effects this action makes the foreshore slope gentler and lowers the protection requirements on the most severe erosion spot; (2) perch S'Abanell beach to reduce the necessary amount of sand to keep the optimum beach width in addition of minimizing off-shore losses during storm events; (3) place sand (*e.g.* 700.000 m³ for 10 years) on the lower Tordera river by means of dredging to allow high discharge events naturally input sand onto the beach and finally (4) monitor the beach by means of ARGUS cameras which can trigger additional beach nourishments in order to achieve the optimum beach width before summer and protect the hinterland during the severe winter season. Those nourishments shall be performed after spring when the littoral drift and sediment transport are lower, therefore reducing losses, in addition of composing the desired beach for users and summer infrastructure.

This combined solution plan reduces the need of dredging by means of restoring the river supply and also optimizes the usage of material minimizing off-shore losses. From the management aspect, diminishing the need of emergency interventions makes this solution better applicable. Restoring the river input and diminishing beach operation this strategy also benefits tourism and the also the environment, although this latter is not of high importance due to high urbanization.

Further assessment is advised enclosing the Tordera River hydraulics. It is important to understand the cross-section river stability and also the potential sand export volume per year. The cross-section stability was first evaluated by Rovira *et al.* (2005) pointing areas of sedimentation and erosion after the sand mining activities. Further investigation shall be performed considering the river discharge variability and its capacity of exporting material in such especial regimes. Also, the optimization of both beach nourishment scheme and river restoration should be conducted. For the beach nourishment the study needs to consider the fill shape, place and slope. While for the river restoration the main concern is the volume and location to place the fill. The assessment should also consider possible blockages of water flux which can lead to floods, a current issue along the Spanish coast. Finally the assessment of results when applying perched beaches holding sand during nourishments and along storms events are highly advised.

In addition it is essential to monitor the beach during the year and when applying nourishments. ARGUS cameras are suitable solution for acquiring continuously beach width, shoreline evolution and nourishment spreading all over the year. This method coupled with fewer nearshore surveys can better track down the sediment path. In this way a more accurate insight of volume losses and sink mechanisms can be identified.

6 Ghanaian Coast

Consisting as the last study case, Ghana is a growing West African economy which has the least tradition in coastal management within the three examples. There is general lack of policies, regulations and data available for designing and implementing coastal protection. Nonetheless the country experiences large coastal erosion along most of the shore. So far only local attempts installing structures has not solved the problem in a global context. Concomitantly, several communities depend on the coast for fishery activities as subsistence and economical activity.

Coastal erosion in this case represents a harm for this growing country as well as a problem for local communities. Other observed effects are the closure and damage of roads and houses in addition to salinization of water bodies and loss of important environments.

This chapter presents basic coastal morphology and underlying processes governing erosion, followed by the problem analysis. From that a plan of approach is suggested on how to organize a sand nourishment based strategy for Ghana.

6.1 Coastal Morphology and Underlying Processes

The West coast of Africa enclosing Ghana is oriented West to East and faces the Atlantic Ocean from South. It is under the influence of semi-diurnal micro tides of about 1 meter. The wave climate is constant with mainly swell waves coming from South, slightly oblique with the shore. The sediment transport is essentially from West to East. The Ghanaian coast is divided into three portions: Western, Central and Eastern (Ly, 1980; Ly, 1981). The western coast is characterized as depositional, being composed by low-energy beaches. Sediment transport can have local reversions into East to West according to Boateng *et al.* (2012) as in Figure 53. Cape Three Points is the division towards the Central Coast and represents a significant reduction in the littoral drift. The Central coast is composed by eroding beaches separated by headlands in a medium-energy environment. This area is marked by presence of several rivers although Pra is the only perennial. Herein are located important regions, enclosing Cape Coast and the capital Accra. The Eastern coast is continuously composed by sandy shores with erosional deltas marked by medium to high-energy environments. The main sediment source comes from the River Volta which in the past built a large delta however nowadays with reduced fluvial supply it shows large shoreline retreat rates.

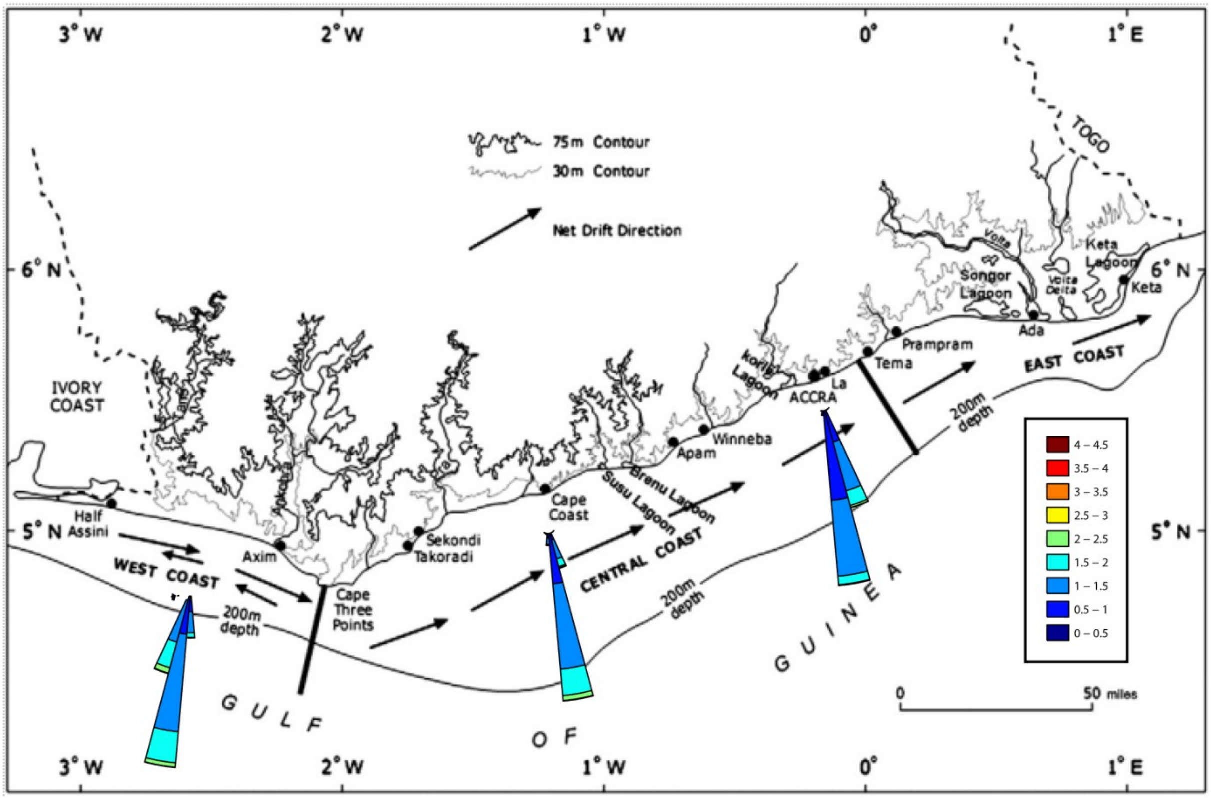

Figure 53: Coastal map of Ghana with general divisions, wave climate and littoral drift. Modified from (Boateng *et al.*, 2012)

From geological analysis Ly (1981) pointed the river sediments as the main source of material into the Ghanaian coast. However after construction of dams boomed by the middle of 20th century this source has been reduced significantly. Nowadays the main supply comes from unconsolidated Quaternary sediments characterizing an erosive regime. Boateng *et al.* (2012) have estimated the fluvial sediment supply reduction of Volta River from 71 x 10^6 m³/year prior to the Akosombo dam[31] to 7 x 10^6 m³/year afterwards. Other similar projects (*e.g.* Densu, Kpone and Owabi) were executed in order to supply water and electricity which further aggravated the sediment budget. Shoreline retreat in the eastern cost of the Volta River delta reaches 8 m/year (Ly, 1980). Nowadays part of this coast is protected by a series of groins around Keta (Figure 54 - upper).

Besides this lack of river supply, other erosion sources are: (1) onshore losses due to overwash events during storms (Figure 54 - bottom); (2) sand mining for civil construction; and also (3) due to alongshore transport gradients induced by the coastline configuration in combination with human intervention *e.g.* hard protection structures blocking the littoral drift.

[31] Constructed at Volta River on 1961. It was the largest artificial lake in the world by that time.

Figure 54: Images showing human intervention blocking the sediment transport at Keta (upper) and natural sediment loss in the washover deposit at Lake Songaw Lagoon (lower).

By computing the transport capacity nearby Accra, the potential littoral drift is around hundred thousand cubic meters per year. Therefore its obstruction by means of structures is not a sound solution (Figure 55).

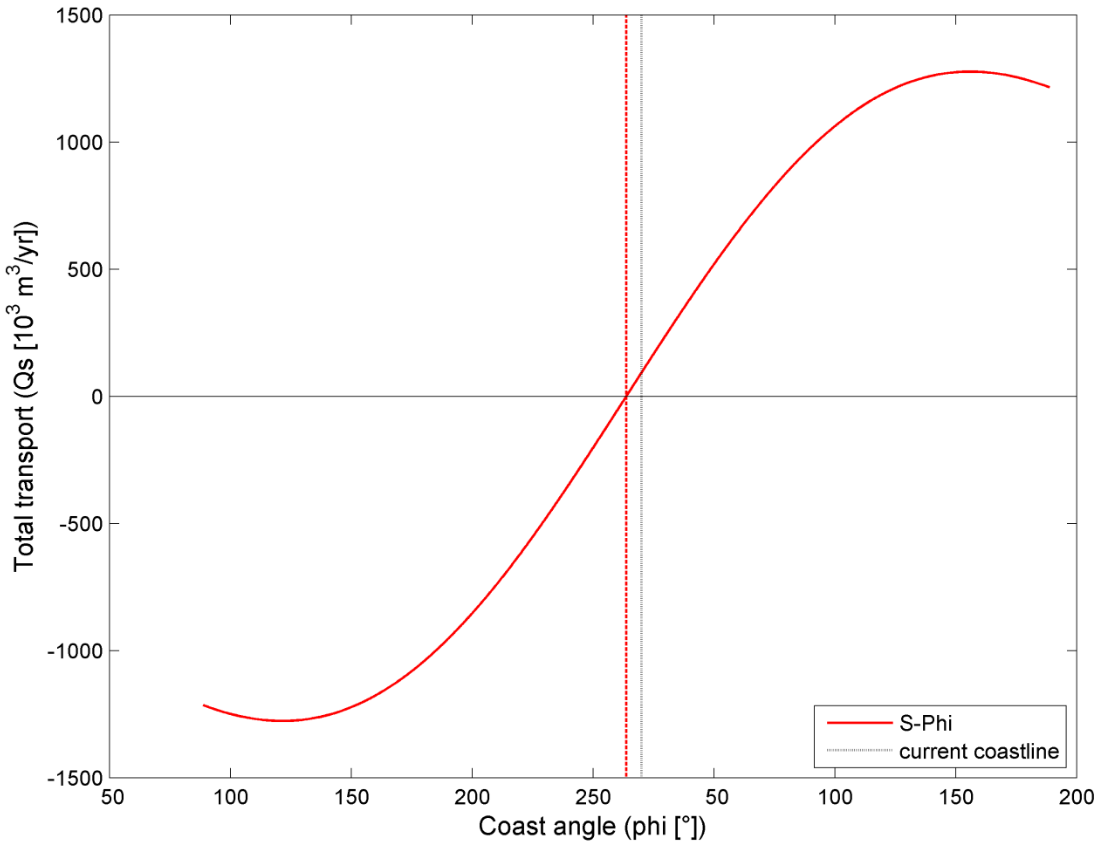

Figure 55: Calculated S-Phi curve for Accra.

In general, coastal retreat is estimated in 1 to 2 meters per years although rates of hundreds meter can be observed locally. Until now, due to the lack of integrated policy mainly hard structures have been deployed to mitigate such effects. The reason relies on the non-maintenance costs of such methods and also the current practice of local companies that only need to manage financial arrangements in order to have its project approved by authorities. Such measures sometimes solved the problem locally, although increased the erosion in the adjacent areas due to littoral drift. So far, the application of soft methods are rather limited and not well known as a possible attractive solution.

The impacts of shoreline retreat in Ghana mainly concerns damage of houses, infrastructures, roads, lack of beach for leisure. Besides the economic impacts, fishery is a survival activity and source of food for several families (between 55 and 67%) which needs beach for discharging the catches (Figure 56) and roads for transporting products (Lawson *et al.*, 2012).

Figure 56: Coastal erosion at Ada (left) and Accra (right) affecting road infrastructures and fishery activities.

From the Ministry of Water Resources, Works and Housing main areas need to be evaluated for coastal protection, enclosing: Komenda (Central Region), Cape Coast (Central Region), Takoradi (Western Region), Amanful Kumah (Western Region), Axim (Western Region), Dixcove (Western Region), Nkontompo / Elmina (Western Region), Eastern delta region (Eastern Region). But no detailed assessment or effective solution has been carried out yet.

Planning long term strategies for Ghana include besides the physical and technical constrains, also social, cultural and political aspects. The lack of available data, policy and management brings the case study analysis to its beginning from where the assessment of global dynamics, protection necessity and main goals for doing coastal development needs to be evaluated and discussed within key stakeholders.

Figure 57: Local fishery activity involving beaching canoes for discharging catches at Accra.

Nowadays besides the traditional fishery as economic and subsistence activity, there is an increasing touristic interest along the Ghanaian coast. The New York Times selected Ghana as the 4th place for tourism in 2013, mainly prompted by its quality in business tourism and the natural and cultural beauty: "*A buzzing metropolis ready for business, and pleasure*" quoted the NYT[32] mentioning Accra, the capital. In this context coastal areas play an important role supporting this activity; therefore this general trend of shoreline retreat can represent harm for this booming country.

6.2 Problem Analysis

Ghana is experiencing economical booming followed by growing touristic interests which can be deprived by coastal erosion. Besides this new demand, the shore supports local communities with fishery as the main income and also source of food.

Although erosion is an issue along the whole Ghanaian shore, funding and policy regarding coastal protection is weak and almost absent. So far the adopted measures only comprise local interventions especially with structures that have not solved erosion in the country level. Whilst nourishment works are practically absent despite they successful potential for sediment starved and littoral drift controlled coasts.

Due to the lack of management, together with few data available Ghana needs to start with a plan of approach. This plan needs to enclose an extensive evaluation of problem, causes, background and goals to be achieved. Therefore next section focuses on listing procedures to do so.

6.3 Plan of Approach

This study case has a lack of knowledge regarding erosion causes, shore dynamics and goals. Facing this reality, planning needs to commence from:

- data acquisition, *e.g.* sediment samples, nearshore bathymetry; inventory of interventions, their response, location and costs;
- local interviews with stakeholders, authorities, local community and coastal researchers in order to promote exchange of knowledge and education towards soft solutions;
- Evaluate the feasibility of implementing sand nourishments on their policy and management.

In order to organize a plan of approach towards understating the problems, goals and proposing a successful long term strategy for Ghana the following information and data should be acquired though local contacts and own effort.

6.3.1 Information Acquisition

Due to the lack of information available some key interviews with local inhabitants, institutions and authorities can provide valuable insight about Ghana. The following contacts should be organized:

- **Local community and population**
  Information about coastal evolution, activities, desires, large storms and their effects;
- **Ministry of Water Resources**

[32] Available in <www.nytimes.com>

Insight regarding polices and possible laws towards erosion and how to get approval; Also important to identify key stakeholders.

- **Hydrological Service Department**
  Possible acquisition of data and information regarding coastal processes, and make contact for possible cooperation;
- **University of Ghana**
  Be in touch with researchers to assess studies and get to know about coastal processes, ecology, important stakeholders, coastal protection trends and fasten possible cooperation, especially regarding data and knowledge exchange.

6.3.2 Building Knowledge

Understand mainly four aspects in order to achieve sustainable and long term solution:

- **Physical Processes**
  Identification of erosion locations, causes, magnitude and also, if applicable, previous interventions and their response and consequences;
- **Ecological system**
  Get insight on important ecological values of the natural environments and possible key species and biomes.
- **Social aspects**
  Define what goals, desires and usage the local population, government and entrepreneurs want for the Ghanaian coast.
- **Political Aspects**
  How the government works. How are the key stakeholders involved? Search for policies and laws benefiting or affecting possible interventions. Is it possible to propose long term contracts, including maintenance or only one intervention?

6.3.3 Data Acquisition

In order to simulate the dynamics of both global and local behavior along the coast the following data shall be acquired, if possible.

Initially, mainly nearshore bathymetry and sediment characteristics are of concern. When detailed bathymetric survey is difficult to be obtained, at least beach profiles should be available for a better evaluation. For further modelling and prediction of local responses or phenomenon, other data proves to be valuable, among: river discharges, storm events, overwash deposits volumes and sand mining activities. Those are important parameters when evaluating the sediment budget and also to hindcast and forecast using numerical models.

The last, but not least variable concerns the availability of sand for nourishment purposes. This controls the costs and suitability of determined projects, as well as operational constrains including type of equipment to be deployed.

6.3.4 Education towards Sand Nourishments

After all steps it is important to exchange knowledge by presenting to authorities, stakeholders and population the benefits of sand nourishments. This feedback is essential since Ghana does not have experience in applying soft methods.

6.4 Conclusions and Recommendations for Ghana

Ghana is an emerging country of West Africa that although not totally rooted with policies and management towards coastal protection shows a high potential due to negative impacts that are currently affecting its growth and local activities. As a consequence of this lack of strategy, planning could start from the beginning. A global approach can be defined and applied in order to use sand nourishment as a successful strategy.

However, for being a new concept, focus should be given in education regarding soft measures especially on how it works and its intrinsic benefits. Together, the well implementation of pilot projects controls the acceptance from local inhabitants, government and stakeholders. In this matter, a straight cooperation with authorities and education centers are of great value.

Due to frequent dredging activities on the West African, long flexible contracts can reduce the total costs since companies can send vessels that are in downtime or passing by Ghana to nourish areas in need, without a tight schedule. Nonetheless, steps as finding and managing sediment reservoirs in addition of monitoring the shoreline evolution constitutes essential aspects in planning the long term interventions. In this flexible way, the initial lack of knowledge can be fulfilled by short term based decisions since there would not be strict conditions for nourishment one place instead of other while throughout time and after studies and monitoring this strategy would be improved towards better planning.

7 Final Conclusions and Recommendations

Planning sand nourishment works involves a complex interaction of factors enclosing technical but also economical, social, environmental and political aspects. This synergy makes rather difficult to create a standard procedure for designing such interventions. Nonetheless the need of longer and more sustainable solutions raised the investigation of good practices and successful strategies.

By grouping study cases as a function of coastal typologies and functions to be achieved, more insight can be drawn enhancing the project successfulness. By only assessing technical aspects the strategy may not achieve the desired effects on public usage and environment, in addition of being unfeasible politically.

Innovative solutions are more likely to fulfill requirements however it can only be implemented with strong management and policies. In addition, knowing the erosion causes and underlying coastal processes are essential for designing winning interventions.

Sylt presents a well structured and defined problem where extensive knowledge derived from long term monitoring provides a solid base for evaluating new approaches. In this case large interventions on high risk area have proven to optimize the current policy lowering the impacts and costs while enhancing the results regarding protection, environment and tourism. The most suitable solution for Sylt is the implementation of a *Sand Engine* (*i.e.* mega nourishment) on the Center of the Island, reproducing its natural formation process. This alternative benefits the whole western shore within decades by the natural sediment spreading.

For S'Abanell a completely different strategy proved to be successful. There, large nourishments prove not being efficient. Due to unknown losses of sediment several large nourishments were completely lost within one year. In this case a combination of a set-back (*i.e.* retreat) lowering the risk and supplying sand to restore the River hydraulics, perching the beach, restoring the Tordera River with large initial nourishment on the lower Tordera River bed coupled with small and constant beach nourishments, when necessary, proved to enhance results. The main concern there is to keep a minimum beach width for the summer season and also for protection during winter. Therefore a constant monitoring with ARGUS cameras is the base for planning those sporadic interventions.

On the last example, being the least known case, Ghana is a booming country where potential successful coastal protection and development can be built from its start. The concerns there are slightly different from the previous two, where also subsistence fishery takes place in addition of coastal protection issues. A strong plan of approach can be developed based on the concepts assessed in this project.

In any case the comprehensive erosion case evaluation, numerical and analytical tools coupled with public education, environmental studies, underlying political and economical constrains can lead to long term coastal protection and developed in a more sustainable way.

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9 Appendix

9.1 UNIBEST Coastline Model (CL and LT)

UNIBEST comes from "**UNI**form **BE**ach **S**ediment **T**ransport" and it is a one line coastal model developed by Deltares. It consists of an engineering tool to simulate nearshore zones under effect of waves and tidal currents that drives alongshore sediment transport and consequently shoreline change. The model can simulate small to large spatial and time scales due to its simplicity. It is an ideal tool to evaluate the natural processes or the impact of human interventions on shoreline evolution resulting in transport gradients and erosion or deposition of sediments.

The UNIBEST pack used for the present project consists of:

- UNIBEST-LT;
- UNIBEST-CL

The LT is the **L**ongshore **T**ransport module that first computes the wave transformation from off-shore towards the coast starting at the seaward point of the cross-shore profile (*i.e.* model input) accounting for the main processes of wave energy change due to refraction, shoaling, wave breaking and bottom friction. From that the alongshore current distribution is obtained from the momentum equation based on the radiation stress and then the sediment transport is calculated by means of one of the eight available formulas which the user can choose among: Bijker (1967,1971), Van Rijn (1992), Van Rijn (1993), Van Rijn (2004), Soulsby/Van Rijn, Kamphuis (2000), CERC or Van der Meer-Pilarczyk – (see Deltares (2011)) working with sand and also gravel and shingle. The product from this step is the S-ϕ curve that computes the change of the longshore transport with the coastline orientation adjustment in relation to the incident waves (Figure 58).

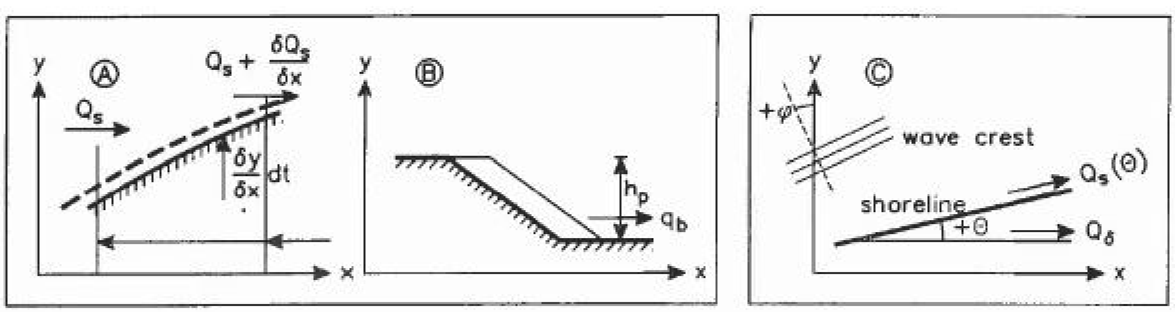


Figure 58: Single line model scheme (Deltares, 2011).

The single line models started with Pelnard-Considère from the diffusion equation, described in Dean (2002), and accounts basically the alongshore sediment transport to shape the coastline. This assumption provides reliable results for long term assessments that can filter the short term cross-shore processes (Dean, 2002; Dean & Dalrymple, 2004). In this assumption there is no change on the profile shape and slope, but only the lateral migration of the active profile (Figure 58 – B). In this matter, this consist the main simplification of this method and in order to translate the sediment transport to shoreline migration the profile height (*i.e.* active profile) translates volume into shoreline displacement by continuity Equation (1).

$$h_p \frac{\partial y}{\partial t} + \frac{\partial Q_s}{\partial x} + q_s = 0 \quad \textbf{(1)}$$

Where:

Q_s – total longshore transport;
Y – coastline position;
h_p – active profile height;
q_b – sediment source/sink.

Where the transport Q varies with the wave approaching angle, then both the change in coastline orientation and different wave trains can shift the alongshore transport magnitude and direction as in Equation (2) and Figure 58 - C, known as the Pelnard-Considère equation.

$$Q_s\,(\theta) = Q_{so} - \frac{dQ_s}{d\theta}\frac{dy}{dx} \quad \textbf{(2)}$$

Where:

Q_s (θ) – longshore transport as a function of coastline direction;
θ – coastline orientation with respect to x-direction
Q_{so} – longshore transport in a straight coastline parallel to x-direction;

Those equations lead to the diffusion Equation (3) from where solutions can be found.

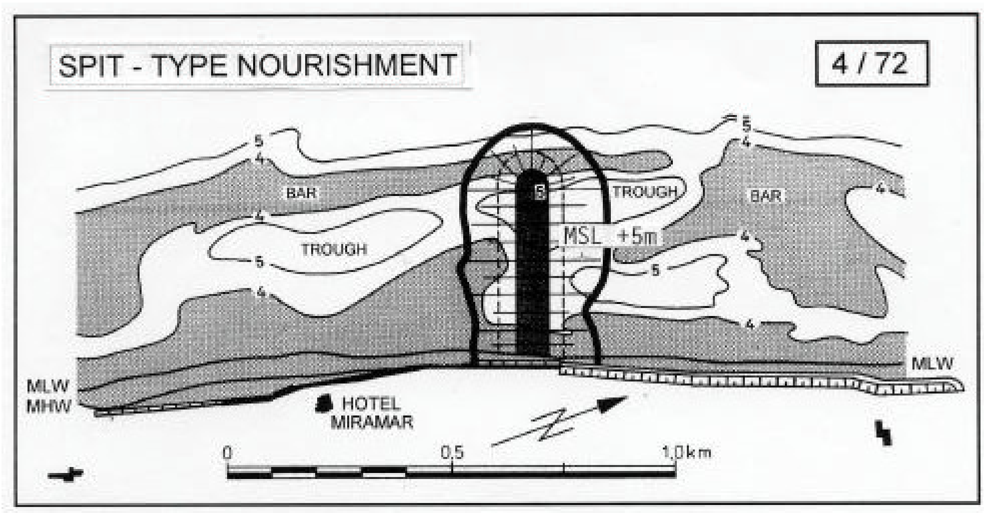
$$\frac{\partial y}{\partial t} = \frac{dQ_s}{d\theta}\frac{dy}{dx}\,h_p\frac{\partial^2 y}{\partial^2 x} \quad \textbf{(3)}$$

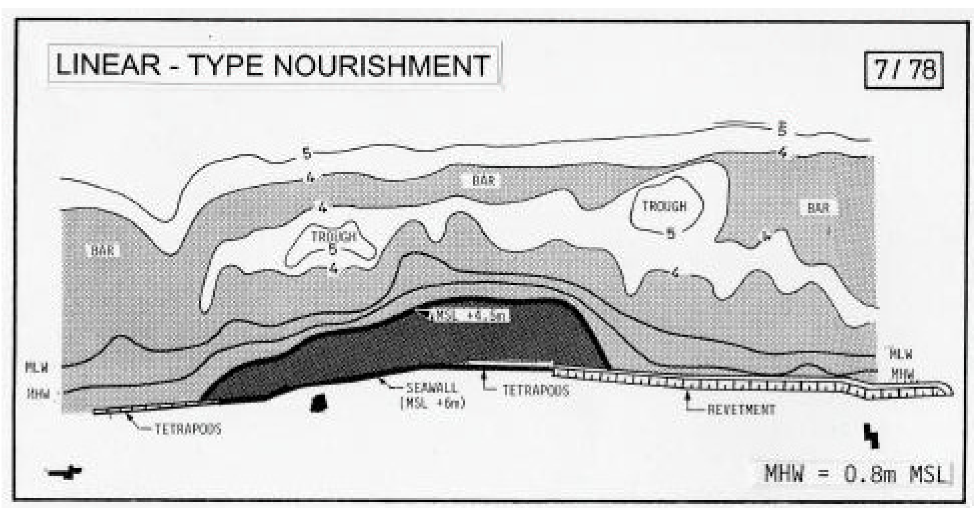
Those transport results are the input for the CL (**C**oast**L**ine) module to calculate the shoreline migration based on a single line representing the parallel migration of the profile seaward (accretion), landward (erosion) or stability. This theory is based on the mass balance of sediment within each grid cell. The model inputs allows several simulations combining different boundary conditions, sinks and sources of sediment, groynes, breakwaters and other common features on coastal engineering.

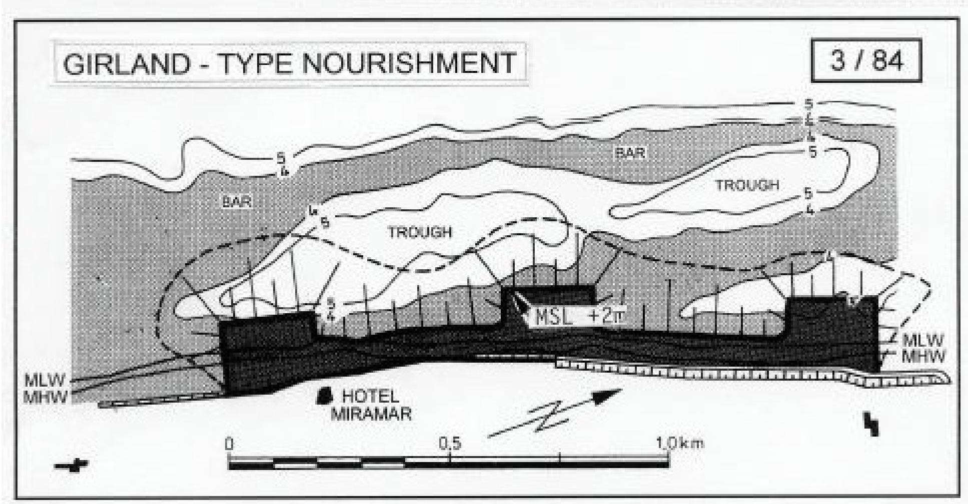
On the following chapter the UNIBEST modules will be applied to evaluate the present scenario as hindcast analysis, model calibration, model sensitiveness and finally to forecast solution behavior in Sylt – Germany and Blanes – Spain.

9.2 Types of beach nourishments in Westerland

Nourishments applied in Sylt for protection of Miramar Seawall (Dette, 2003)







9.3 Nourishment data at Sylt

Data from Landesbetriebes für Küstenschutz, Nationalpark und Meeresschutz - Schleswig-Holstein (LKN-SH).

North:

Place	Year	Length (m)	Volume (10^6 m^3)	Fill density (m^3/m)
List	1988	2.803	1.210	432
Klappholttal	1992	5.002	2.082	416
List	1993	1.410	0.836	593
List (Sued)	1995	1.354	0.236	174
List (Nord)	1995	1.826	0.300	164
List	1999	1.509	0.159	105
List	2000	1.909	0.351	184
Klappholttal	2001	2.012	0.401	199
List	2001	2.107	0.283	134
Klappholttal	2003	1.099	0.195	178
List (Sued)	2003	1.252	0.182	145
List (Nord)	2003	0.548	0.054	99
Klappholttal	2004	0.200	0.043	216
Kampen (Nord)	2005	0.899	0.211	235
Klappholttal	2005	0.643	0.092	143
List (Nord)	2006	0.698	0.042	60
List (Sued)	2006	0.706	0.132	187
List (Nord)	2007	1.710	0.208	122
List (Sued)	2007	0.807	0.108	134
Kampen (Nord - Stechkopf)	2007	0.341	0.074	218
Kampen (Nord - Schleppkopf)	2007	0.300	0.090	299
List	2008	1.684	0.323	192
List	2009	1.360	0.208	153
List (Nord)	2009	0.665	0.119	178
List (Nord)	2010	1.113	0.119	107
List (Mitte/Sued)	2010	0.606	0.122	202
List (Mitte/Nord)	2011	2.375	0.232	98
Klappholttal (Mitte)	2011	0.601	0.055	91
List-Nord	2012	1.213	0.110	91
List-Sued	2012	0.606	0.105	173

Center:

Place	Year	Length (m)	Volume (10^6 m^3)	Fill density (m^3/m)
Westerland	1972	1.740	1.010	580
Westerland	1978	1.690	0.998	591
Westerland	1984	1.390	1.031	742
Kampen	1984	0.100	0.037	365
Wenningstedt-Kampen	1985	4.803	1.973	411
Kampen-Kliffende	1987	0.521	0.651	1250
Dikjendeel	1988	2.166	1.000	462
Westerland	1990	1.490	1.200	805
Kampen	1990	1.909	0.986	516
Wenningstedt	1990	0.611	0.264	432
Wenningstedt-Kampen	1991	1.642	0.858	522
Westerland	1996	2.140	0.744	348
Kampen (Riff)	1996	1.152	0.239	208
Kampen	2000	1.904	0.460	242
Westerland	2000	1.340	0.448	334
Dikjendeel	2002	1.583	0.231	146
Kampen-Kliffende	2004	0.702	0.093	133
Westerland	2004	0.595	0.121	204
Wenningstedt (Vorstrand)	2004	0.991	0.233	235
Kampen	2005	0.703	0.166	236
Westerland (Sued)	2005	0.598	0.100	167
Westerland	2005	0.695	0.110	158
Westerland	2007	0.645	0.091	140
Kampen-Kliffende	2007	1.608	0.252	157
Kampen	2008	1.706	0.301	176
Westerland (Nord)	2008	0.705	0.081	114
Westerland	2008	0.645	0.179	278
Westerland (Ufermauer)	2009	0.795	0.087	109
Kampen	2009	1.649	0.184	111
Westerland-Wenningstedt (Verklappung)	2009	0.987	0.363	367
Kampen	2010	1.308	0.132	101
Westerland (Nord)	2010	1.002	0.165	165
Westerland (Mitte)	2010	0.495	0.068	138
Dikjendeel	2010	0.806	0.109	135
Kampen (Sturmhaube)	2011	0.501	0.055	110
Westerland (Mitte)	2011	0.645	0.056	87
Dikjen Deel (Vorstrand)	2011	1.583	0.423	267
Kampen	2012	1.153	0.212	184
Westerland-Mitte	2012	0.645	0.058	89

South:

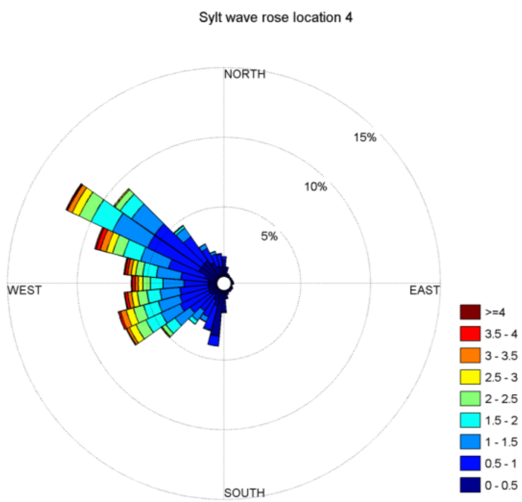
Place	Year	Length (m)	Volume (10^6 m^3)	Fill density (m^3/m)
Hoernum	1983	1.200	0.637	531
Rantum	1984	1.839	0.319	174
Hoernum	1986	3.500	1.601	458
Rantum	1987	2.882	1.441	500
Puan Klent - Rantum	1989	4.401	1.967	447
Hoernum	1990	1.150	1.023	889
Hoernum	1991	2.350	1.159	493
Puan Klent	1993	1.600	0.606	379
Hoernum	1993	2.150	0.763	355
Hoernum	1995	3.300	1.003	304
Rantum	1996	2.938	0.400	136
Puanklent	1997	1.751	0.297	169
Hoernum	1997	1.350	0.281	208
Hoernum	1999	3.500	0.547	156
Hoernum	2000	1.800	0.415	231
Rantum	2001	2.100	0.402	192
Hoernum (Nord)	2002	1.150	0.305	265
Hoernum (Hauptstrand)	2002	1.050	0.279	265
Hoernum-Odde	2002	1.001	0.163	163
Rantum	2003	1.502	0.376	251
Puanklent	2003	0.750	0.140	187
Hoernum (Hauptstrand)	2004	1.000	0.270	270
Hoernum (Jugendstrand)	2004	0.800	0.147	184
Rantum	2004	0.300	0.077	257
Hörnum (Nord)	2005	0.650	0.136	209
Hörnum	2005	1.050	0.341	325
Rantum (Vorstrand)	2006	0.500	0.225	451
Puan Klent (Vorstrand)	2006	1.002	0.391	391
Sansibar (Vorstrand)	2006	0.900	0.135	150
Hörnum	2006	1.200	0.244	203
Hörnum (Nord)	2007	1.350	0.287	213
Hörnum (Hauptstrand)	2007	1.300	0.318	245
Duenenverwallung Hoernum-Odde (Nord)	2007	0.150	0.008	52
Duenenverwallung Hoernum-Odde (Sued)	2007	0.150	0.003	19
Hoernum (Nord)	2008	0.400	0.099	246
Hoernum (Hauptstrand)	2008	0.600	0.178	296
Hoernum-Odde	2008	0.500	0.076	152
Hoernum (Nord)	2009	1.300	0.143	110
Hoernum (Hauptstrand)	2009	0.650	0.107	164
Hoernum-Odde	2009	0.150	0.015	101
Hörnum (Nord)	2010	1.500	0.161	108
Hörnum-Odde	2010	0.500	0.099	199
Hoernum (Nord)	2011	0.950	0.084	88
Hoernum (Sued) / Hoernum-Odde	2011	0.750	0.114	152
Hoernum-Odde	2012	0.450	0.191	424
Hoernum-Sued	2012	0.500	0.138	275
Hoernum-Nord	2012	0.600	0.065	108
Hoernum-Gurtdeel	2012	0.300	0.044	146

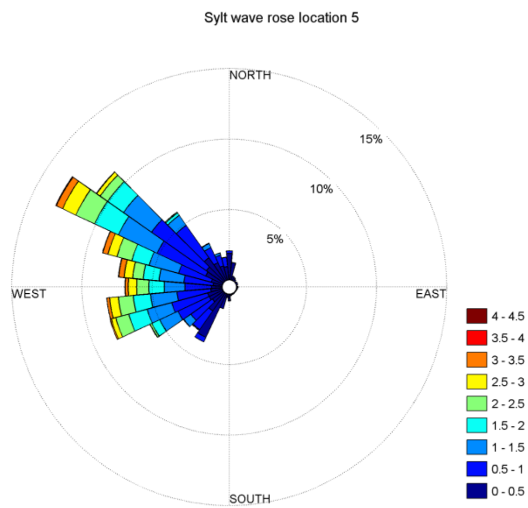
9.4 Hydrodynamic and Morphological data for Sylt

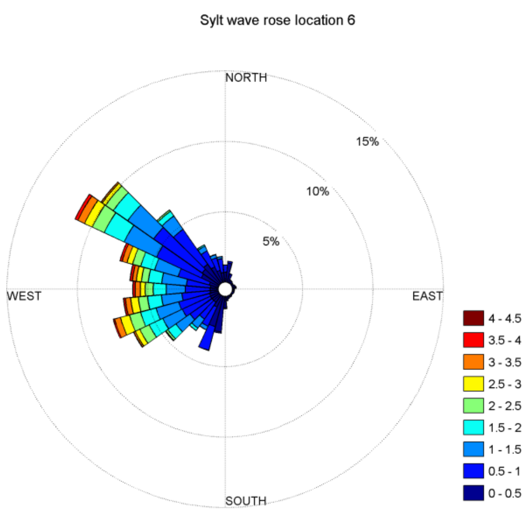
This section contains the input and background hydrodynamic and morphological data applied in Sylt including wave roses, tidal regime, significant wave height, depth of closure, among others.

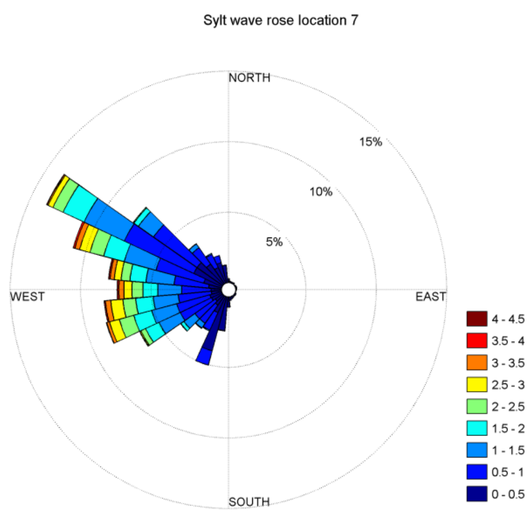
9.4.1 Wave roses for Sylt

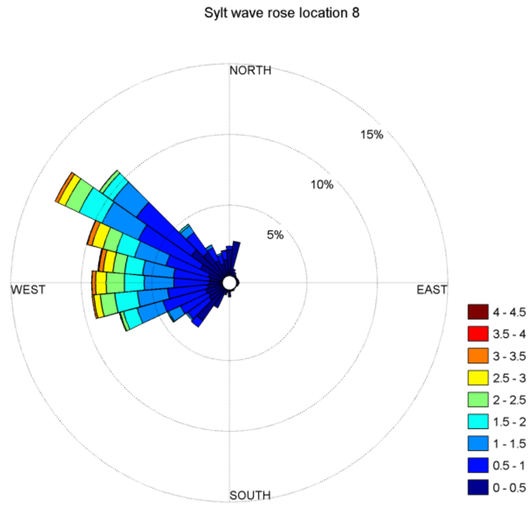
Wave Roses, significant wave height (Hs) and closure depth for Sylt in each of the 7 locations.

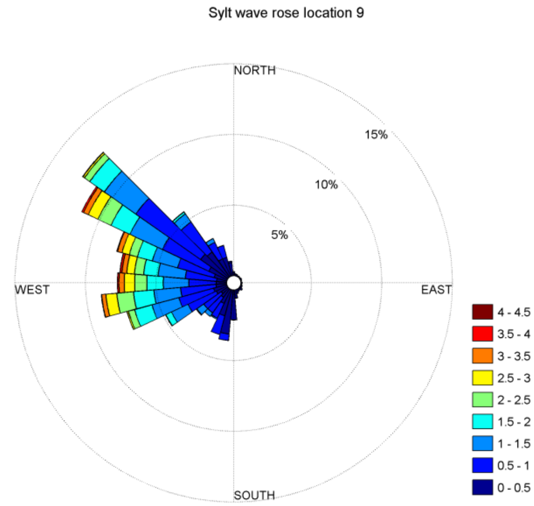


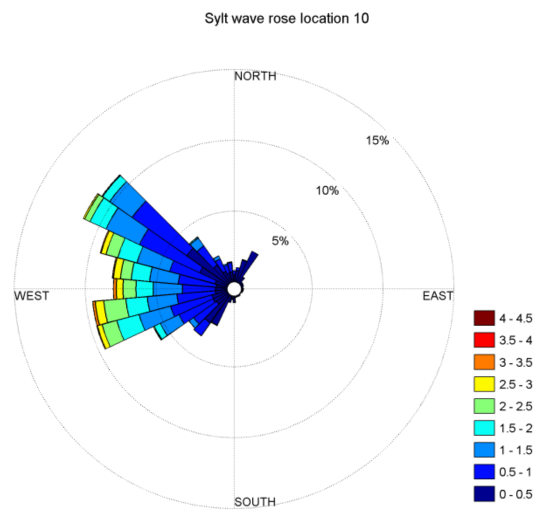










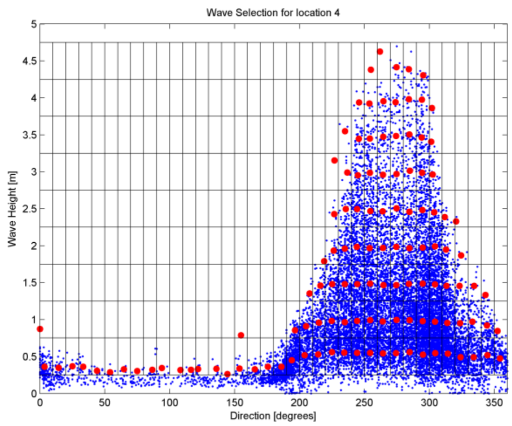


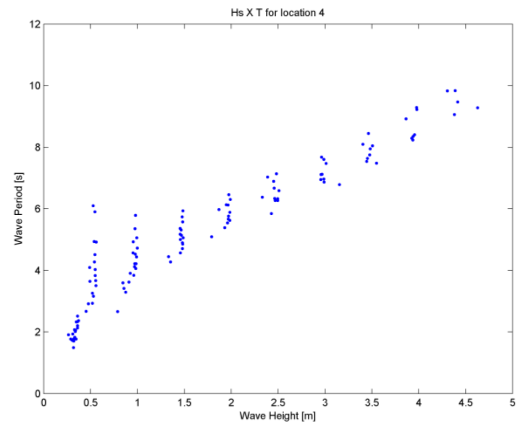
Calculated significant wave height from the raw time series and closure depth according to Hallermeier (1981) which were used to estimate the profile height input for UNIBEST.

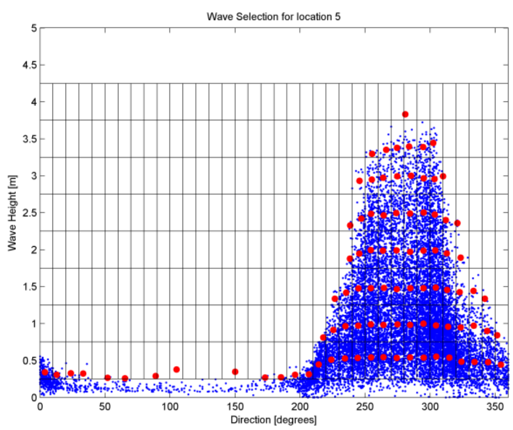
	Significant Wave Height [m]	Closure Depth [m]
Location 10	1.70	7.30
Location 8	1.80	8.05
Location 5	1.93	8.10
Location 6	1.98	8.90
Location 3	1.95	8.85
Location 7	1.88	8.55
Location 9	1.85	8.50

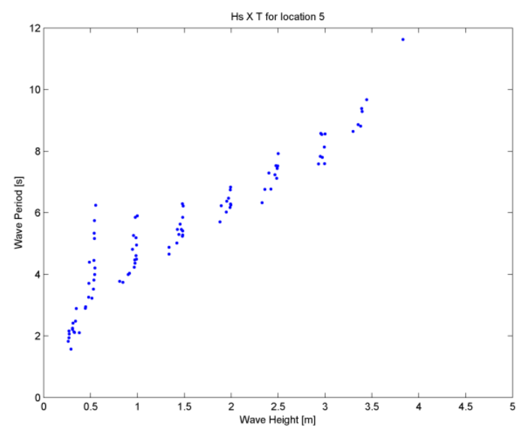
9.4.2 Selected wave cases

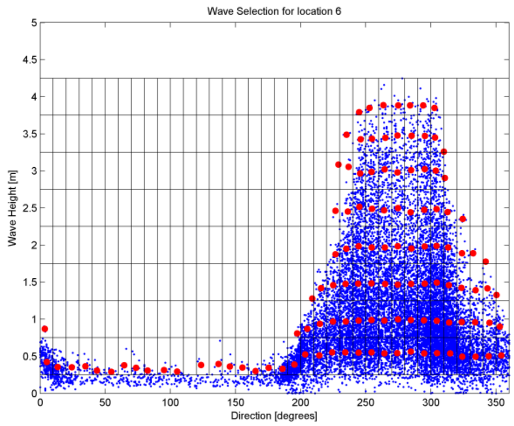
This section shows all the wave data as the blue dots and the selected wave data input to be used in UNIBEST based on the mean wave height and mean wave period for each designated quadrant defined every 10 degrees of direction and 0.5 meter of wave height. In this way it is possible to account for different wave climates, including swell and sea waves from all direction and their associated wave height and period. The total duration from each case was associated with the sum of all original wave data within each quadrant therefore no information was lost during this wave selection.

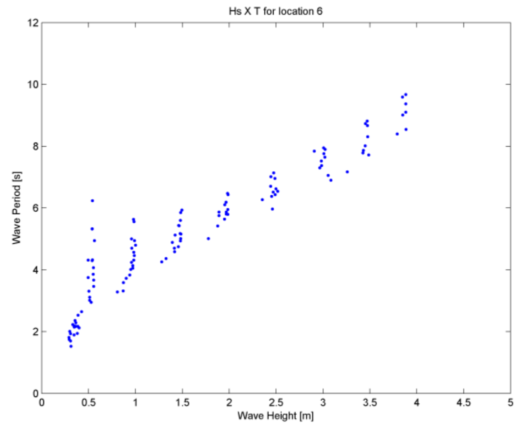


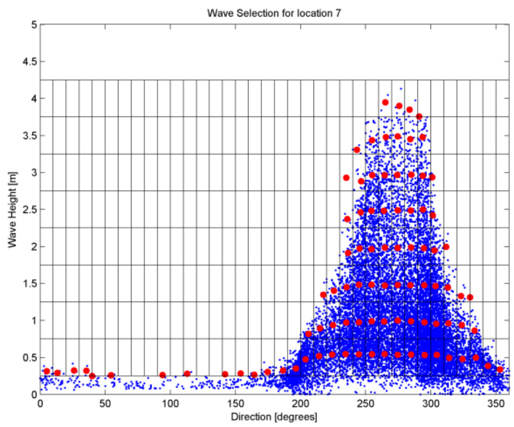


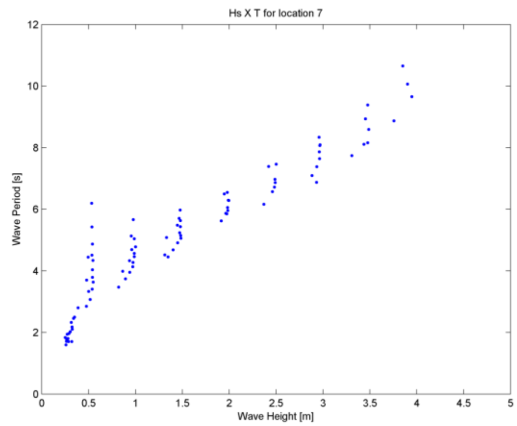


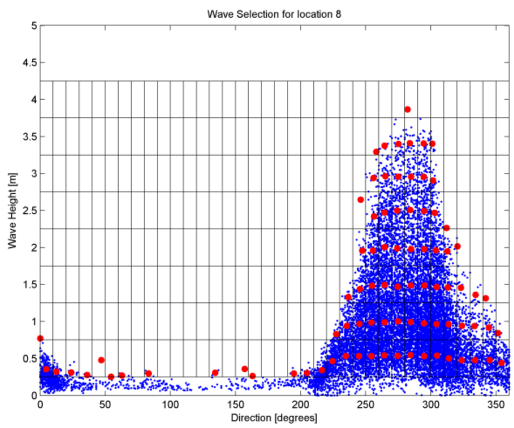


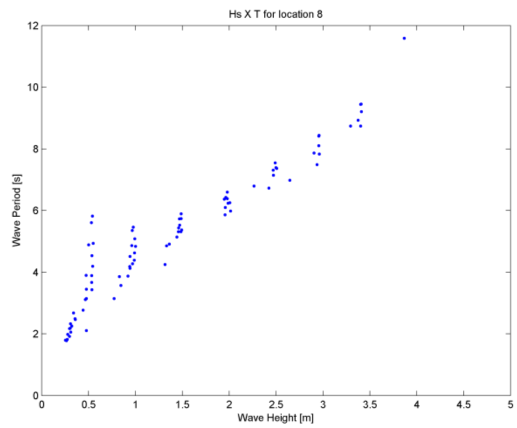

Wave Selection for location 6
Wave Height [m]
Direction [degrees]

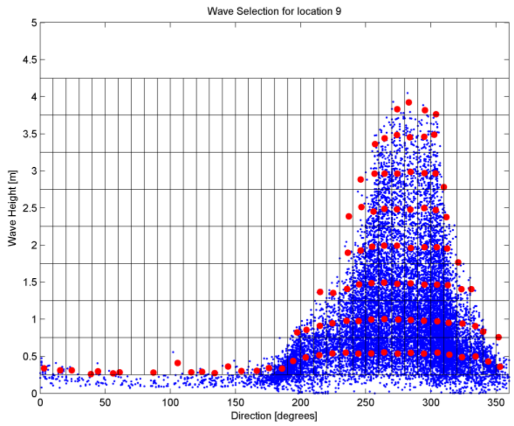

Hs X T for location 6
Wave Period [s]
Wave Height [m]

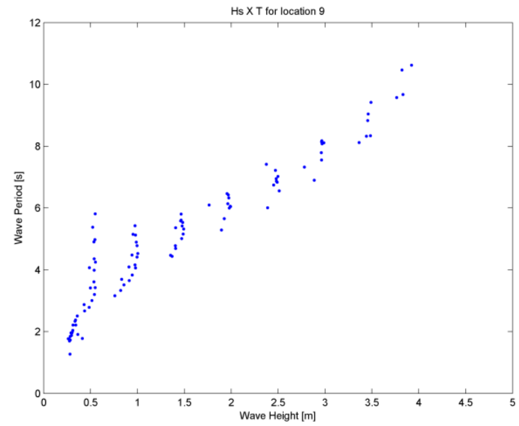

Wave Selection for location 7
Wave Height [m]
Direction [degrees]

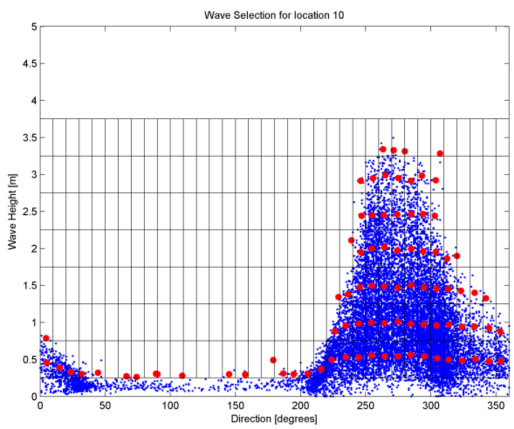

Hs X T for location 7
Wave Period [s]
Wave Height [m]

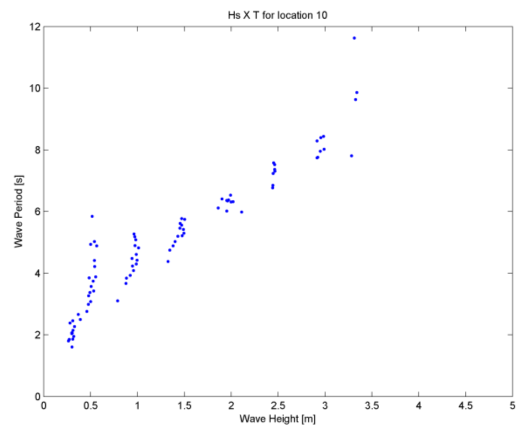

Wave Selection for location 8
Wave Height [m]
Direction [degrees]


Hs X T for location 8
Wave Period [s]
Wave Height [m]


Wave Selection for location 9
Wave Height [m]
Direction [degrees]


Hs X T for location 9
Wave Period [s]
Wave Height [m]


Wave Selection for location 10
Wave Height [m]
Direction [degrees]


Hs X T for location 10
Wave Period [s]
Wave Height [m]

9.5 Blanes - Spain

9.5.1 Documented Erosion Damage at S'Abanell

<u>ACTUACIONES TERMINADAS</u>

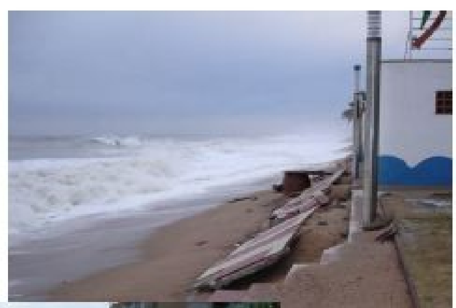
Ref.: 17-0261
Actuación: OBRAS DE EMERGENCIA PASEO MARÍTIMO DE S'ABANELL

Término Municipal: Blanes

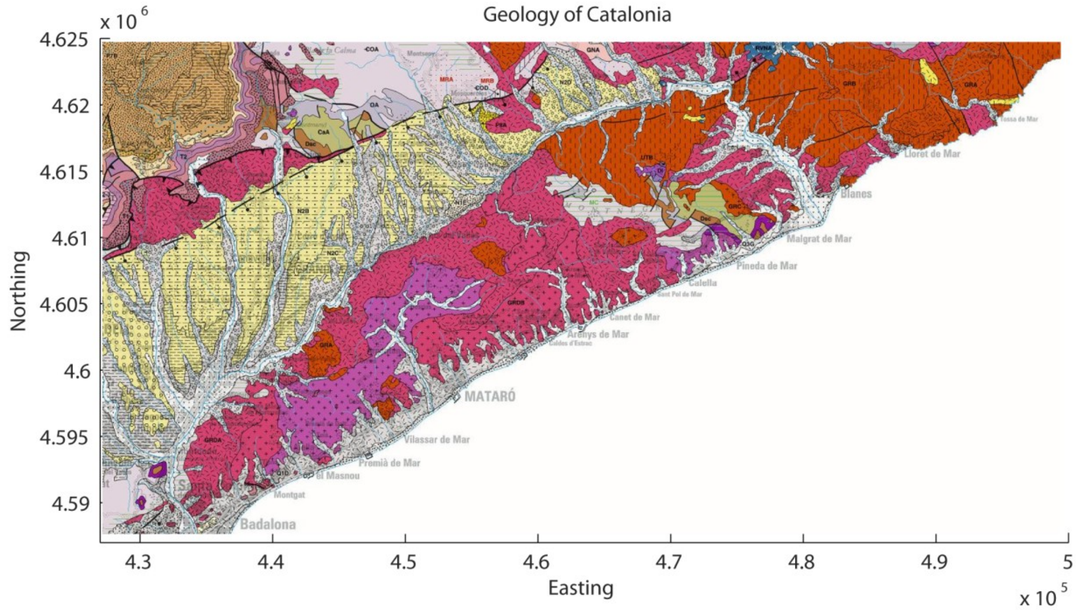
Importe: 2.356 Miles de €

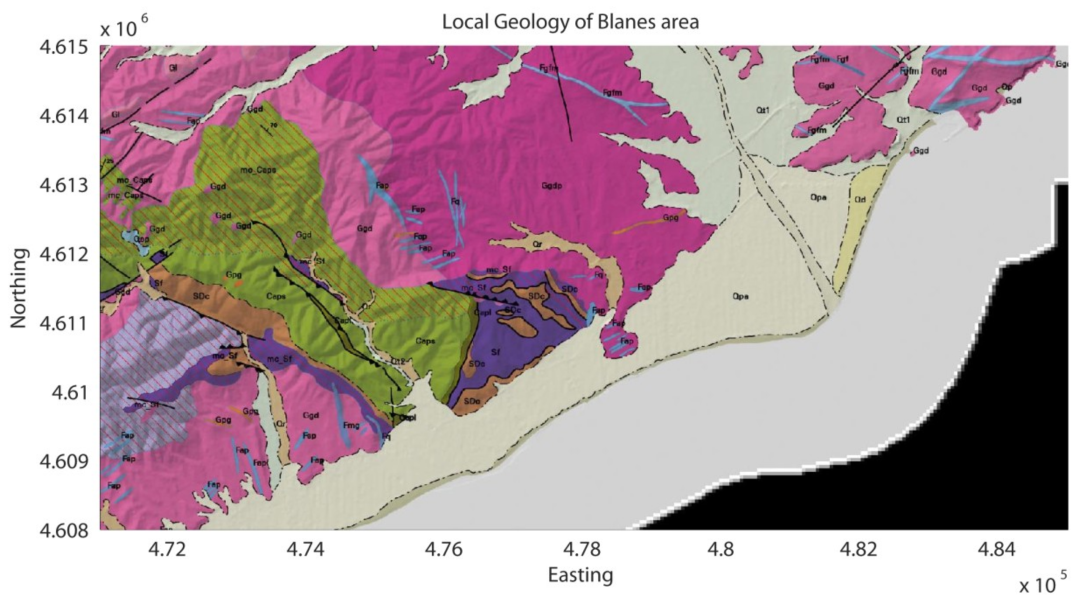
Descripción:

Las obras consistieron en reparar una gran parte del paseo marítimo que había quedado seriamente dañado por los temporales acaecidos durante los días 26 y 27 de diciembre de 2008.
Se reconstruyó la sección de paseo dañada, mediante una sección de escollera de 3 tn con talud y berma de pie. Asimismo, se retranqueó la alineación del paseo con el objetivo de aumentar el resguardo de la playa frente a futuros temporales y adoptar una traza de paseo compatible con futuras actuaciones en el mismo.
Debido a la gran pérdida de material de la playa se puso de manifiesto la necesidad de recuperar volumen de arena mediante la realización de un dragado de procedencia marina.
La parte del proyecto de obras de emergencia correspondiente al dragado de los sedimentos fue reglamentariamente sometido a consultas previas ambientales para evaluar la posible afección a los hábitats y al medio socioeconómico. Las obras del paseo se iniciaron en febrero de 2009 y el proyecto fue presentado a los diferentes organismos relacionados con la gestión del medioambiente y el territorio para realizar las alegaciones oportunas al dragado de arena.
El dragado se realizó entre el 30 de julio y el 20 de septiembre de 2009, con un aporte total de 150.00 m3 de arena en la playa de S'Abanell.

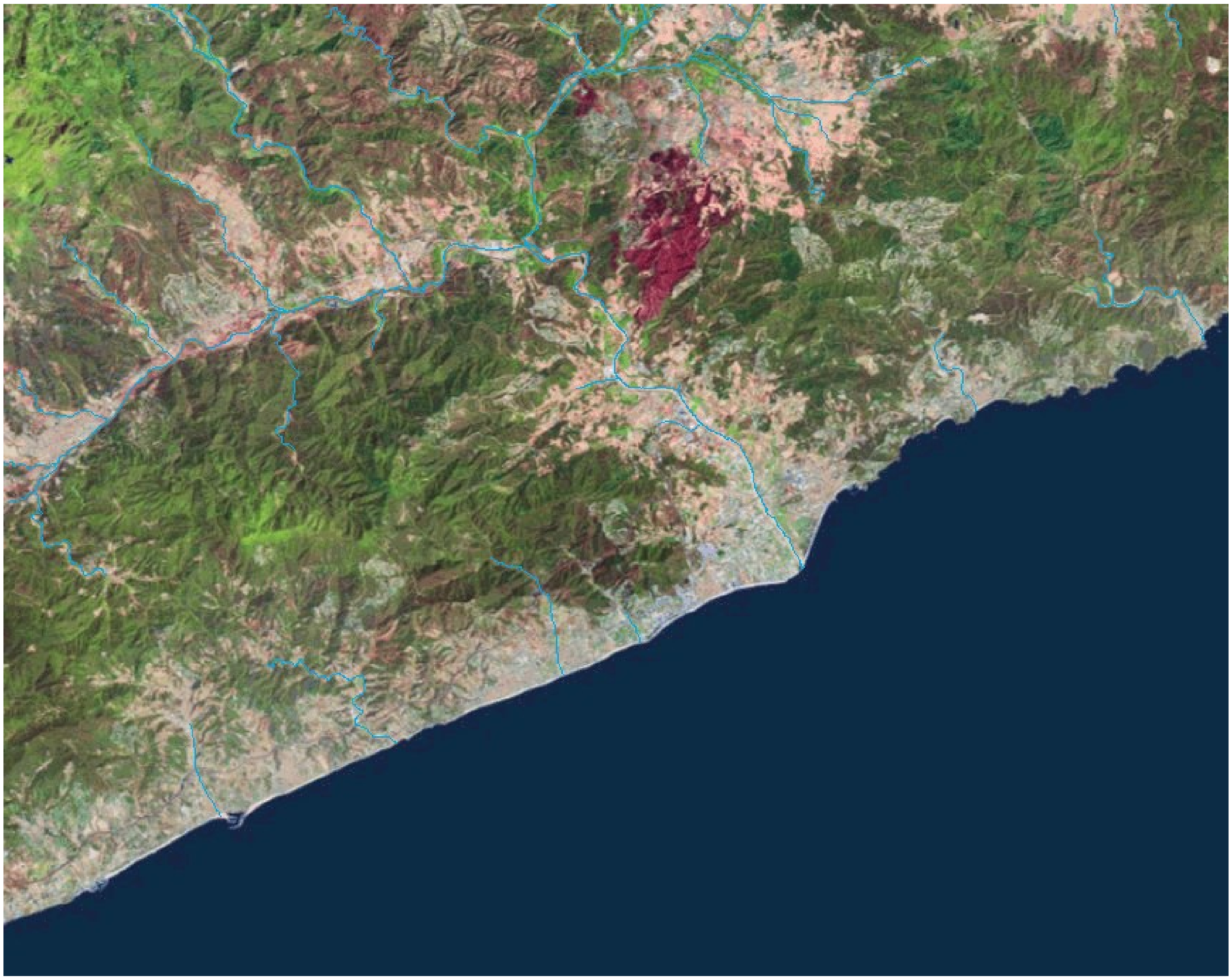


9.5.2 Geologic maps of Catalonia



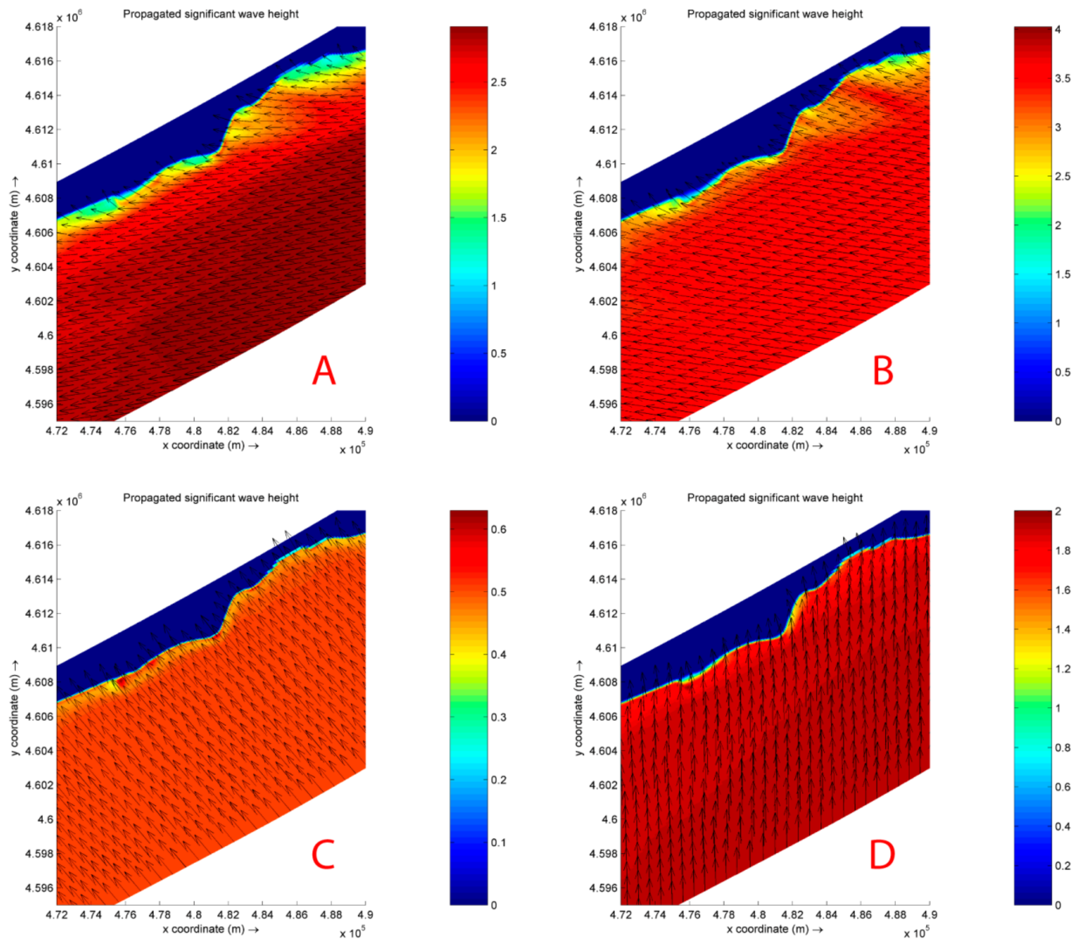


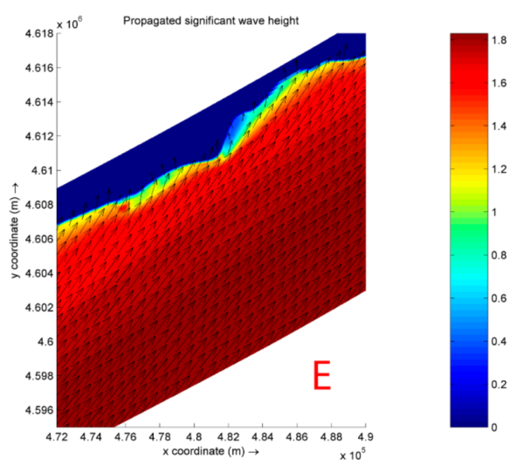
9.5.3 Draining base/watershed of Tordera River



9.5.4 Propagated waves in Swan

Five examples out of 111 in total.

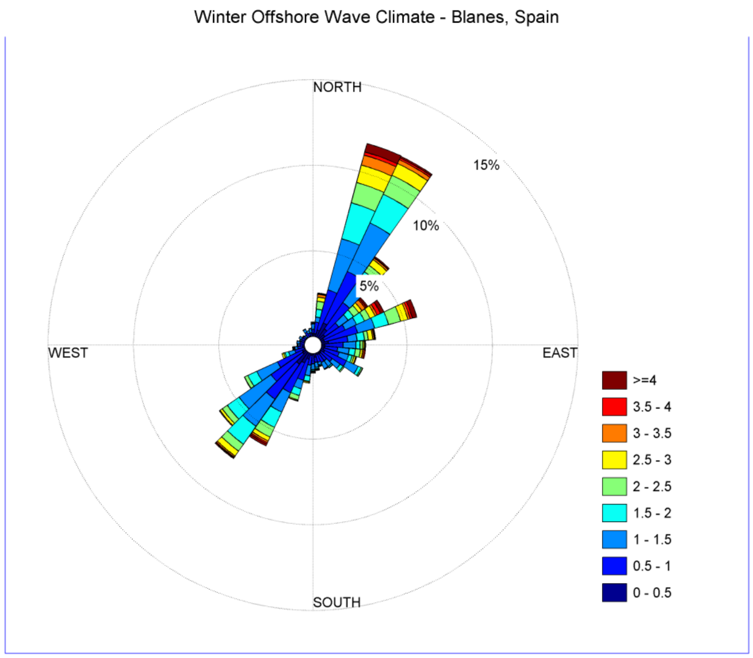


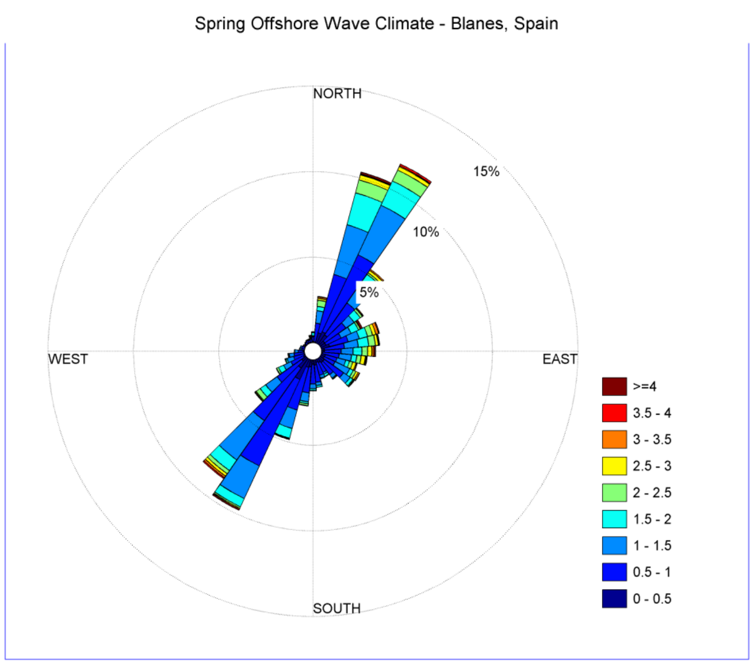


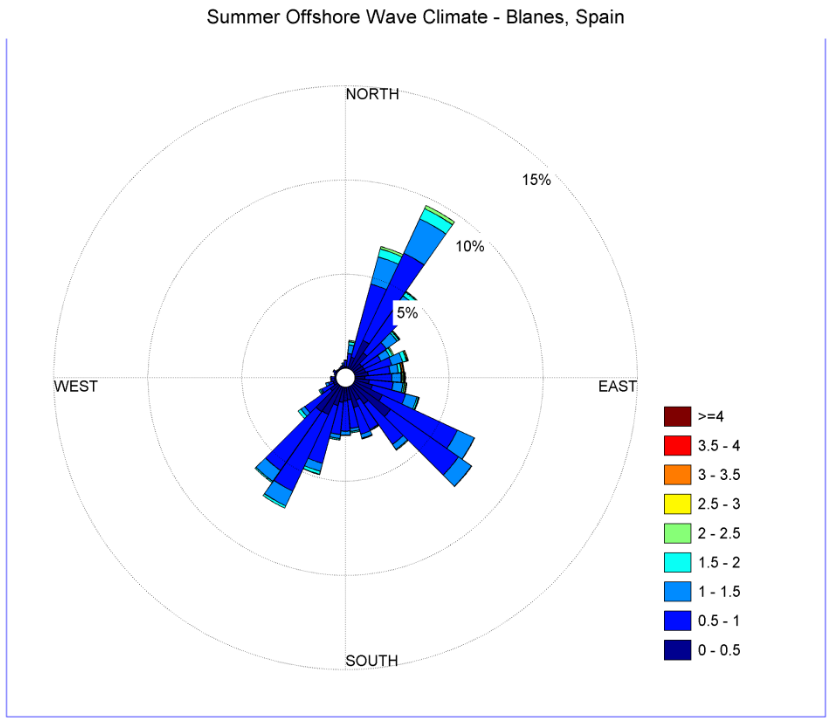
Swan output for waves

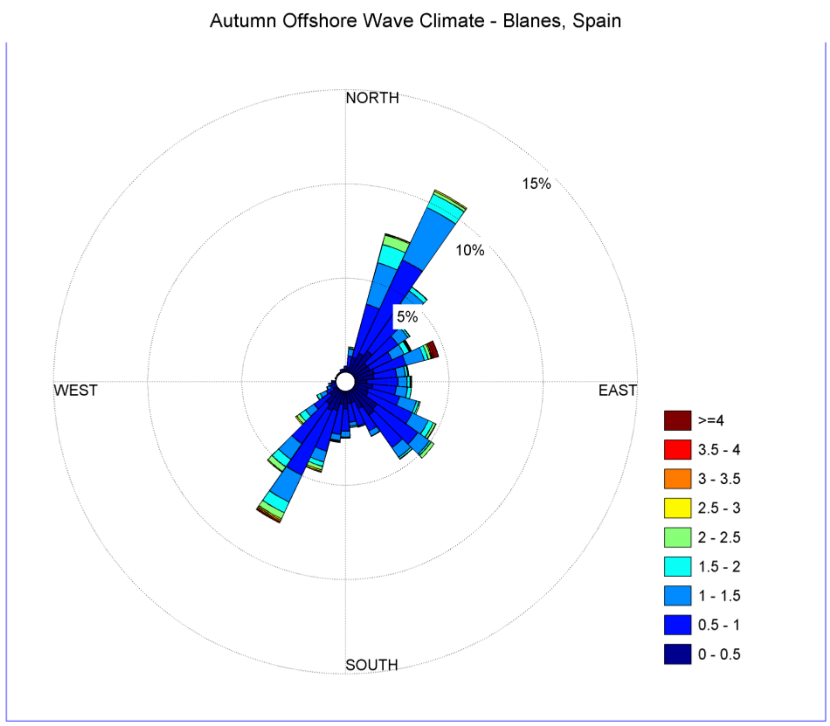
	Hs [m]	Tp [s]	Dir [º]
A	2.5	8	80
B	3.0	9	100
C	3.25	9.5	125
D	1.4	6.3	180
E	1.45	6	220

9.5.5 Seasonal Wave Climate






Summer Offshore Wave Climate - Blanes, Spain
NORTH
SOUTH
WEST
EAST
5%
10%
15%
>=4
3.5 - 4
3 - 3.5
2.5 - 3
2 - 2.5
1.5 - 2
1 - 1.5
0.5 - 1
0 - 0.5


Autumn Offshore Wave Climate - Blanes, Spain
NORTH
SOUTH
WEST
EAST
5%
10%
15%
>=4
3.5 - 4
3 - 3.5
2.5 - 3
2 - 2.5
1.5 - 2
1 - 1.5
0.5 - 1
0 - 0.5