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The applicability of the mega nourishment concept for the purpose of combating erosion in Cua Dai beach

TU Delft

The applicability of the mega nourishment concept for the purpose of combating erosion in Cua Dai beach

by

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Front cover: Photo of Cua Dai beach, including the presence of sandbags along the coast.

Preface

This thesis completes the Master of Science in Hydraulic Engineering at the faculty of Civil Engineering and Geosciences of Delft University of Technology.

I would sincerely like to express my gratitude to all members of my thesis committee. I would like to thank Sierd de Vries, for his continuous support, enthusiasm on this topic and guidance that motivated me to improve my work. I would like to express my appreciation to Professor Marcel Stive, for his interest in this study and for his valuable advices. In addition, I would like to thank Jeremy Bricker for his useful suggestions and contribution to this thesis. I would also like to thank Matthieu de Schipper for his involvement and feedback, offering interesting remarks. Last but not least, I would like to thank Anh Do, for being my daily supervisor. She was always available for me, providing guidance that allowed me to overcome difficult phases in my research.

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Abstract

Nourishments are considered to be a popular soft measure against coastal erosion. In the Netherlands, the concept of a localized mega nourishment has been introduced as an innovative approach, aiming to counteract the anticipated enhanced coastal erosion. The positive results of the Sand Engine implementation lead the way for applying the mega nourishment concept as an innovative solution in many retreating coastlines around the world. In central Vietnam, Cua Dai beach experiences ongoing erosion that propagates to the north over the years which significantly undermines the existence of the coast. The complexity of the prevailing climate as well as the various human interventions that have taken place, complicate the understanding of the system and the determination of a long term solution to the problem of erosion.

The present research investigates the concept of mega nourishment as a measure against the problem of erosion in the Cua Dai beach. A consistent approach has been followed for this purpose, addressed through several research steps. Initially, an overview of the recorded morphological evolution and of the relevant processes has been created as well as an assessment of the stakeholder relations in the area, through available literature. Then, the prevailing dynamics of the overall region that includes Cua Dai beach have been analyzed with the use of representative conditions of the influencing forcing mechanisms, based on characteristic past morphological periods. Extreme flood and storm events have been also investigated. For this purpose numerical modeling simulations with Delft3D have been performed. A design approach has been selected and the primary and secondary design parameters have been determined, formulating the final design solutions. Assessment of the design solutions has been realized, in terms of a qualitative analysis but also an assessment of their seasonal behaviour. For the latter part, numerical modelling simulations have been also made.

An erosive trend has been identified in the north coastline where Cua Dai beach is located that has been present before any interventions in the coast took place. In addition, the trend of formation of an ebb tidal bar has been highlighted as well as its interaction with the north coast. The presence of resorts along Cua Dai beach was found to enhance the erosive pattern. The placement of sandbags across the public Cua Dai beach strengthened further the erosion. The extreme flood and storm events do not alter the erosive trend of the north coast that is present under regular seasonal conditions, but can explain the enhancement of the inspected morphological trends.

The selected design approach that concerns the inclusion of the influencing stakeholders in the financing of the nourishment design solutions, led to the formation of three design alternatives that follow the mega nourishment concept. The required volume, the design lifetime, the location and the shape of the designs formed the main design parameters. The seasonal assessment of the behaviour of the designs has been performed separately for each design alternative, based on the level of diffusion and the trends formed in the alongshore sediment transport gradients. All design solutions have shown a degree of spreading around them, which is directed to the expected locations. Thesis findings suggest that sand nourishment applications that follow the mega nourishment concept can be an option for the problem of erosion in Cua Dai beach.

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1. Introduction

1.1. Background information

Nourishments have been used extensively over the years, being acknowledged as a very common and popular soft measure against structural erosion. The sea level rise effect together with the increasing vulnerability of several coastlines, have triggered the research for an improved nourishment design concept. The potential negative effects of frequent re-nourishments and the upscaling to a more regional approach have given the incentive to look for better methods (de Schipper et al., 2016). In the Netherlands, the concept of a localized mega nourishment design has been developed that intends to provide sediment to a large part of coast by its long term diffusion. The main advantages of the mega nourishment are described by Stive et al. (2013), with the first important to be the expansion of the nourishment cycle, as the coast will require nourishment every 10-20 years, instead of the existing cycle of 2-5 years in the Dutch coast. Furthermore, the diffusion of the nourishment will be slow, advancing the coastline in a more natural way. In addition, the initial local perturbation can provide an environmentally friendly recreational space, while the ecological stress is limited to a small area.

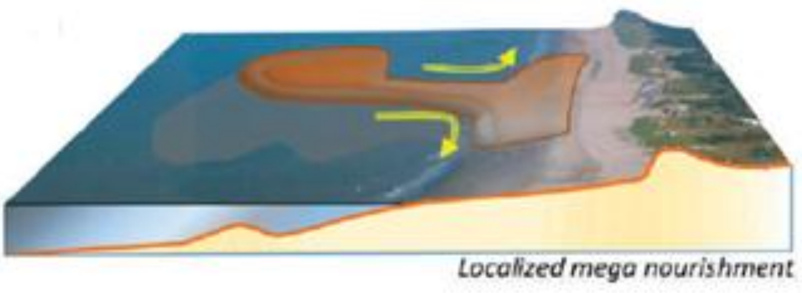


Figure 1.1: The mega nourishment concept (Source: Stive et al., 2013)

The first mega nourishment, named as Sand Engine, has been implemented within the 17 km Delfland coastline stretch. It is designed in a way that the initial amount of sand could diffuse gradually with the aid of the prevailing natural conditions, without disrupting the seabed. More specifically, the effects of the local wind and wave climate, as well as of the tidal influence, will supply the necessary sediment in order to feed the coast over a 20 year period. Additionally, the Sand Engine is able to provide space for recreational purposes, forming a friendly measure to the citizens of the region, as it is easily integrated into the local landscape.

The morphological evolution and the resulting effects that have been monitored after the implementation, indicate that the nourishment is expected to achieve the anticipated goal, creating a long term sustainable solution. The positive results of this approach lead the way for applying the concept of mega nourishment in many more retreating coastlines, in several locations around the world with different climate characteristics. It can provide an innovative measure that can be implemented in the future in other vulnerable areas that are under stress globally and evolve to be established as a dominant coastal erosion management strategy.

1.2. Problem description

Vietnam, with 3260 km coastline and two vast low-lying deltas, could be considered as one of the most vulnerable countries against coastal disasters and climate change (Takagi et al., 2015). The country is constantly confronted with the problem of coastal erosion along its coastline, which significantly affects the ecosystem and creates a negative impact in the life and economic activities related to the coast. The factors that influence coastal erosion can vary and their interaction as well as the magnitude of their effect can be characterized as complex, becoming also critical in several locations. According to Cong et al. (2014) recent weather events have been stronger than usual, which has led, together with the human exploitation of natural resources in the river basins, to alarming rates of coastal erosion in many estuarine and coastal regions in Vietnam, to the destruction of coastal economic welfare project and to the degradation of coastal ecosystems.

The Quang Nam Province, located in central Vietnam, is one of the regions where coastal erosion significantly undermines the existence of the coastal territory. The coastline formation of the area is smooth and flat, with a high concentration of sand and low amounts of mud and clay, characterized also by river mouths (Cong et al., 2014). In this region, Hoi An city is located near the Cua Dai inlet mouth and has heavily influenced the economic development of the area by being a touristic attraction site, since its historic district has been denoted in 1999 as a UNESCO World Heritage Site. Thu Bon River flows into the Cua Dai estuary with an average annual discharge of 327 m^3/s, a catchment area of 4100 km^2 and a total length of 152 km. There is a water exchange between Thu Bon and Vu Gia rivers through two connecting tributaries, Quang Hue and Vihn Dien. This makes them considered as one river basin system named as the Vu Gia-Thu Bon river system with a total catchment area of approximately 10,350 km^2.

The Cua Dai system is located in an area with subtropical climate conditions, influenced by tropical monsoons. Due to this, two main seasons can be distinguished. There is the winter season which is determined by the NE monsoon and takes place from September to March, as well as the summer season that is influenced by the SW monsoon and involves the period between April to August. The seasonal effect dominates the behaviour of the system affecting both the wave climate and the river discharge. In addition, extreme events like tropical storms and typhoons induce abrupt changes. In terms of natural disasters, typhoons appear to pose the biggest threat to coastal communities in Vietnam (Takagi et al., 2015; Cong et al., 2014). In the surrounding area, the presence of the group of Cu Lao Cham islands creates another factor of influence for the incoming waves in the area that contributes to the local morphological development.

In the north side of the inlet the Cua Dai beach extends approximately over a 5 km coastline stretch, accommodating several resorts and being a centerpiece of the touristic activities of the area. The coastline there, experiences severe erosion over the last years that is extending northward. This erosive behaviour causes a big threat to the existence of the coast, creating also a huge impact to the economy of the area. Furthermore, the resorts that have been built together with their defence structures are suspected to cause a further deterioration, influencing the spreading of erosion to the north. Apart from the Cua Dai beach, several human interventions that have taken place over the years in the system, including the construction of hydropower dams and sand mining activities, might have contributed indirectly to the present situation.

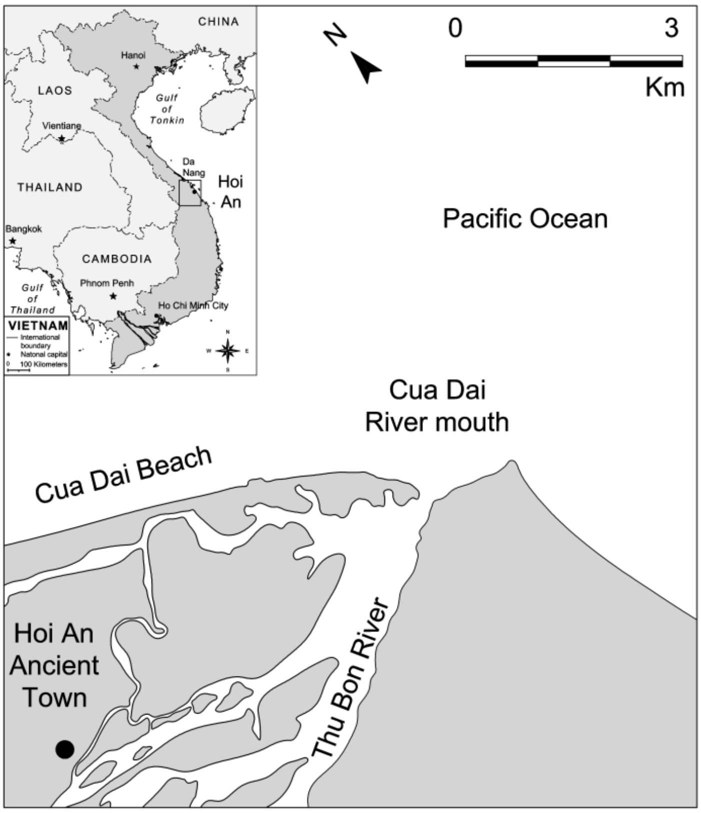


Figure 1.2: Cua Dai map area (Source: Tanaka et al., 2016)

Action is necessary in order to manage and confine the erosional pattern, providing a stable long term solution to the region. Several processes become involved in the area, forming a complex system that has to be understood well in order to deal effectively with erosion. The various interventions due to human activities through the years have also increased the level of complexity. Moreover, the existing approaches that have already been attempted and consist of hard structures, could not provide the desired effect as they lack of a widespread character and were only able to influence the coastline locally. The establishment of a rigid strategy to confront the coastal erosion is necessary. Vietnam should invest in research for the application of modern erosion prevention measures (Cong et al. 2014).

A turn into a soft measure approach seems vital in order to achieve a satisfying outcome in this complex system of the Cua Dai area. Nourishments have already been applied regularly in a large number of cases around the world, with increasing implementation due to the benefits that provide. Because of their presence, there is maintenance and protection of the coastline while also value is added to the land related to the restoration of the coast. The recent development of the mega nourishment approach in the Netherlands comes to optimize these positive effects. The concomitant reduction in the frequency of beach nourishment, from 3-5 years to over a 20 year cycle and the limitation of human intervention to a restricted area of shoreline, reduces the disturbance to the local ecosystem while providing benefits in addition to reduced flood and erosion risk, such as habitat creation and increased amenity for shoreline recreation (Brown et al., 2016). An integrated strategy including a mega nourishment implementation will be investigated in the present research, in order to create a long term but also stable solution to the problem of erosion of Cua Dai beach. The acceptance of the local community is crucial for the development of a nourishment design and attention should be given to the reaction of the people that live in the vicinity of the project. Especially in countries that are not familiar with nourishment strategies, such as Vietnam, time and care should be invested for people to understand the benefits and the growth that can come through such an approach.

1.3. Research objective & research questions

The goal of the present research study is to explore the use of the mega nourishment (or Sand Engine) concept as a measure for dealing with the long term erosion in the Cua Dai beach. The investigation of this approach can provide useful remarks, contributing to the existing research for the Cua Dai area. This can lead to an approach that can be established, setting a nourishment policy for the area.

According to the problem that has been formulated and described above combined with the desired result to be achieved, the following research question has been formulated:

What is an effective mega nourishment design in order to mitigate the erosion of Cua Dai beach?

This question shapes the objective of the research and will be addressed through the following sub-questions:

1. Which are the processes, phenomena and recorded level of erosion in Cua Dai and which are the human interventions that have occurred?
2. What are the seasonal prevailing dynamics in Cua Dai beach?
3. Who are the most influential stakeholders in Cua Dai beach?
4. Which is the mega nourishment design approach?
5. Which are the main design parameters and which are the final designs?
6. What is the seasonal behaviour of the designs?

1.4. Research methodology

In this section the research steps are presented, through which the sub-questions and consequently the main research question will be treated. All the phases considered here are relevant in order to provide a consistent approach for a mega nourishment design that will effectively cope with the erosion in the Cua Dai beach. The approach that is followed consists of a theoretical investigation, a research of the prevailing dynamics of the area, the formulation of the design approach for the mega nourishment together with the design characteristics that will lead to the final design solutions, and the assessment of the designs. The research of the prevailing dynamics through numerical modelling simulations with Delft3D can provide a useful insight and understanding of the overall behaviour of the system in Cua Dai that will have an influence in a nourishment design. Based on this, the mega nourishment design aspects can be defined. Then, numerical model schematizations of Delft3D are created to include the selected designs, so that after an assessment can follow. The phases of the present research study are illustrated in the following flow chart and are briefly analyzed in the following sections.

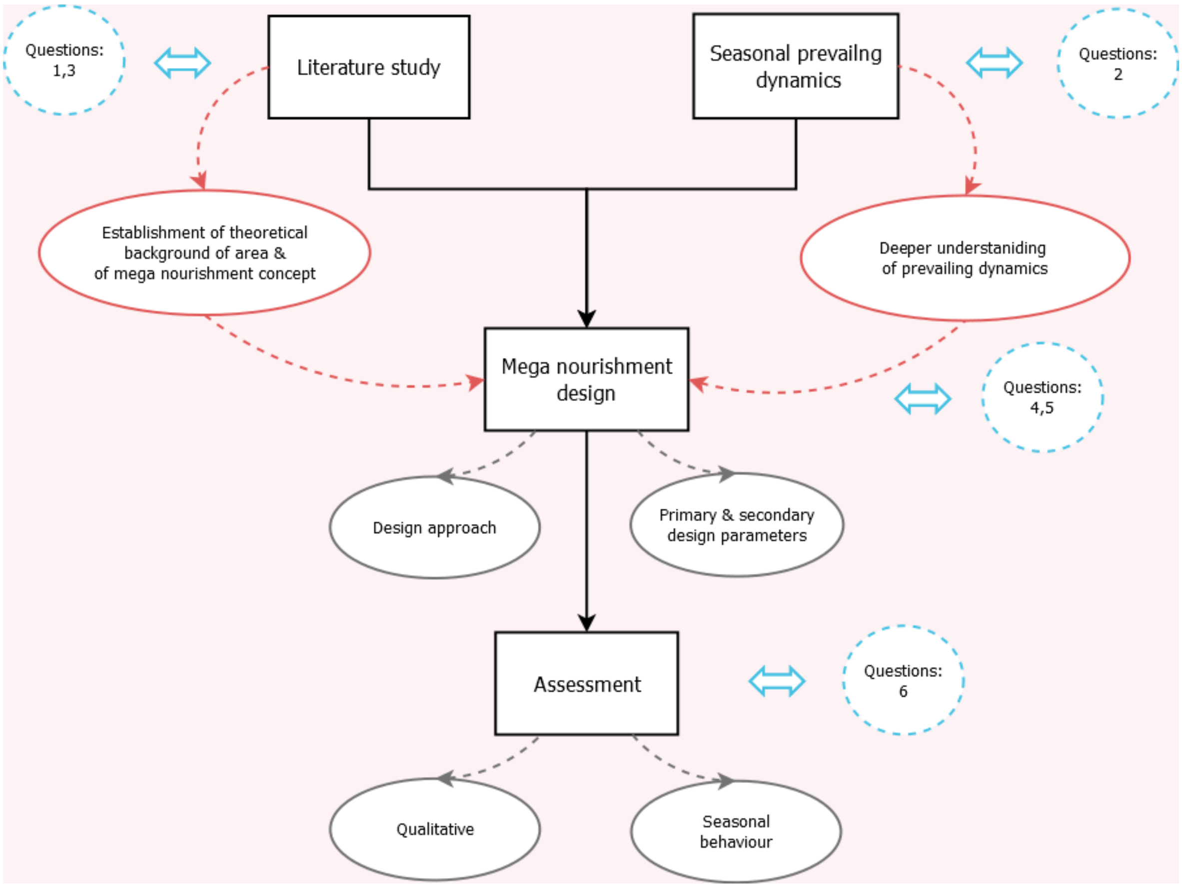


Figure 1.3: Flow chart of research approach

➢ <u>Literature study</u>

The literature study is necessary in order to provide insight in the area of interest, by examining the morphological evolutions that took place, and also to identify the relevant processes. In the same sense, establishing an understanding of the stakeholder relations is essential as it can be an important parameter of the design approach. Furthermore, familiarizing with the existing research that has been undertaken to explain the erosional behaviour of the area is useful because possible gaps can be identified.

Since the aim of the present study is to provide an effective mega nourishment design (Sand Engine), the existing knowledge on the notion of mega nourishment needs also to be explored. Its characteristics and implementation are important to be identified in order to get a view on the relevant aspects to consider in the present research. The pilot mega nourishment project in the Netherlands is presented as a baseline. The aspects that were taken in this design as well as its morphological evolution and overall results are important to be considered in a design for Cua Dai beach. From this phase, the 1st and 3rd research questions can be addressed in a satisfactory level. By answering these questions, insight of the area is established as well as of the prevailing power relations among stakeholders, so that a more detailed analysis can be elaborated further in the next phase.

- Prevailing dynamics

In this research phase and after the relevant processes have been determined, representative conditions are selected, that will be considered for a mega nourishment design. Based on these conditions, the seasonal prevailing dynamics of the overall domain where Cua Dai beach is located are studied. This is achieved by the simulation and reproduction of recorded morphological trends of an annual cycle from three characteristic past periods. Additional simulations are performed for the investigation of the impact of typical representative extreme flood and storm events. Due to this, the use of a numerical model is essential. From an existing Delft3D model of the region, new model schematizations are created in which the representative conditions are used.

Through this approach the behaviour of the system is analyzed and useful informations are obtained for the mega nourishment design characteristics. Also validity of the representative conditions, as well as of the model performance is gained. From this phase, the second research question is treated.

- Mega nourishment design

At first, the design approach is presented that takes into consideration the goals of the influencing stakeholders of Cua Dai beach, forming the final selected design alternatives. Then the primary design parameters of a mega nourishment design are defined. In this part the findings of the previous research phase are considered, in terms of the prevailing alongshore sediment transport trend and magnitude along the coast. Additionally, the remaining design parameters that are necessary for a design are selected, and in this part knowledge of relevant literature is used in order to assist the design choices taken. The final design solutions are then presented. In the end, a new Delft3D model is formed for each design by means of schematized bathymetries. This part of the research provides answers to the 4th and 5th research questions.

- Design assessment

The final part of the present research contains the assessment of the selected design solutions. The assessment is performed initially by means of a qualitative analysis based on common aspects related to the design approach. Then, the seasonal behaviour of each design is investigated. For this purpose, numerical simulations are performed for every design alternative where the representative seasonal forcing conditions are included. The alongshore sediment transport trends that form by the nourishments as well as the level of diffusion comprise the assessment parameters. This phase addresses the final research question.

1.5. Reader

In Chapter 2 the literature study is presented. In Chapter 3, the representative conditions of the relevant processes are selected and the seasonal prevailing dynamics of the area are investigated. Then, in Chapter 4 the mega nourishment design approach is determined and the design parameters of the selected design solutions are defined. In Chapter 5, a qualitative assessment of the design solutions is performed and the seasonal behaviour of the designs is investigated. In Chapter 6, a discussion is made with respect to aspects that have not been explored in the present research, but also a general reflection is made. Finally, in Chapter 7, the overall conclusions of the research study are presented and in Chapter 8 recommendations are given regarding aspects that can be further investigated with future research.

In Appendix A, a detailed description is provided regarding the selection of the representative forcing conditions. Appendix B contains an extensive amount of graphs that display results from the numerical modelling simulation stage of the investigation of the seasonal prevailing dynamics. In Appendix C, modelling results of the seasonal assessment of the nourishment designs are available.

2. Literature study

2.1. Introduction

In this chapter, the ongoing problem of erosion in the Cua Dai beach is explored based on the knowledge provided through the available research. The first step towards addressing the erosional behaviour of the coast is to gain understanding of the complex dynamics of the area, by identifying the morphological changes that took place and the processes related to them. Through this, a better insight in the system can be achieved. In addition, the stakeholder power relations in the area are introduced. Furthermore, the existing research on the area regarding erosion causes and the accompanied results are an interesting and contributing aspect to account for in the current investigation. In terms of nourishment design, the various nourishment approaches that have been developed are briefly described. Finally, the pilot implementation of a mega feeder nourishment, the Sand Engine in the Netherlands, is presented. An insight into the characteristics of the project, the approach followed and the positive results till now can provide an essential paradigm for the implementation of an analogous nourishment design approach into the Cua Dai area.

2.2. The Cua Dai system and overview of morphological changes

The Cua Dai system consists of several elements and includes the estuary where the Thu Bon River flows, the adjacent coastlines north and south, the ebb tidal delta and the Cu Lao Cham island complex. The formation and growth of the Cua Dai inlet was made through sediment deposits from the Thu Bon River and is a process that has occurred continuously over several centuries. The length of advancement over the past several centuries is roughly estimated as 2,900 m (Hoang et al., 2015). Throughout the years, the inlet mouth has shown a continuous southward shift while erosion and accretion have taken place in the adjacent coasts. More specifically, the north coastline where Cua Dai beach is located shows an erosive behaviour that propagates northward over the time, extending the degree of erosion. On the contrary, the south coastline has a steadily accretive character over the years. The morphological changes have been identified mainly through available satellite images. According to the present literature study, the date of the images that was reviewed covers the period between the years 1973-2016.

The varying character of the prevailing climate plays a significant role in the morphology of the overall area around Cua Dai inlet. Do et al. (2017) identified three seasons after combining hydrology and wave climate, an ENE winter monsoon with a flood period from September to December, an ENE winter monsoon in combination with a dry period, covering the period from January to March, and finally a bidirectional SE/ENE summer monsoon with a dry period from April to August. From there, it was pointed out that the dry season is characterized by a low river discharge and low wave heights, while the higher discharge of the river is accompanied by higher wave conditions, flushing out the sediment that has been deposited before in the inlet. A low tidal range is present in the area. Another important aspect that was taken into consideration was the sheltering effects due to the existence of Cu Lao Cham islands that influence the wave propagation, affecting their magnitude and direction. Finally, the estimation of the net wave induced longshore sediment transport rates indicated that for the summer period, the transport had a northward direction increasing across the north coast, where Cua Dai beach is located, and decreasing along the south coast. The net transport during winter showed a divergence point in the north coast, aggravating the erosion there and a convergence point in the south coast that intensified the accretive behaviour. The net annual transport resulted in the same pattern as in the case of the winter period.

Figure 2.1: Elements of Cua Dai system

The occurrence of extreme non cyclic and autonomous events provokes another factor related to the causes of morphological changes in the Cua Dai. Tropical cyclones are the most common incident, inducing typhoons and tropical storms, while tsunamis are seldom to the area. In recent years, floods occur more frequently and with higher peak discharges, often induced by intense meteorological phenomena (i.e. heavy rain, storm, typhoon or tropical depression) (Do et al., 2017).

The morphology of the Cua Dai inlet mouth is determined by the river sediment supply in balance with the transport due to tides and waves, as the sediment that reaches the mouth is then transported to the adjacent coasts. Reduction in the sediment supply causes the straightening along concave-shaped sections (Hung et al., 2017). According to Tanaka et al. (2016) the Cua Dai inlet mouth has asymmetric morphology between the north and south coastline, while it has been observed that the cuspate form of the south coastline remained approximately in the same form over the years, shifting southwards.

Do et al. (2017) and Tanaka et al. (2016) describe the morphological changes of the Cua Dai inlet area with the use of satellite images through similarly identified time periods. Tanaka et al. (2016) notes that during the period of 1975-1989 an offshore sandbar was formed which could be attributed to a huge sediment supply by an extreme flood event. In addition, the research of Do et al. (2017) ascribes the effect of welding of the sandbar forming a new sand spit, which took place during 1989-1995, to the event of typhoon Cecil that occurred in 1989. It also notes that due to this event Cua Dai beach accreted during this period, but erosion started after. Regarding the period between mid 1990s to early 2000s, from both researches is noted that the welding completed and erosion started to take place in the north coast. In terms of the phenomenon of southward shifting of the inlet mouth different explanations are given. Do et al. (2017) gives the explanation that the shifting was triggered due to typhoon Cecil and that extreme floods recorded in the period 1995-2000 could have caused an extra shift to the tip of the south coast. In the research of Tanaka et al. (2016) it is stated that the unequal distribution of sediment supply from the river resulted into the shifting of the ebb delta, providing sediment to the south.

The research of Duy (2016) involves the asymmetric sediment supply amount towards the adjacent coastlines over the period 1973-2016. This study concluded that the southward shifting of the mouth causes asymmetry on the ebb delta in front and subsequent asymmetric river sediment supply. Based on the results, the proportion of sediment supply to the south coast is dominant over the supply to the north coast and ranges from 70%-80% during the 1970s-end 1980s and mid 1990s-2016. Only during the time interval of 1989-1995 the supply proportion is equal for both coastlines.

Over the past decades, the economical growth in Vietnam has led to a high demand of power. Since 2000, there have been many human activities such as the building of resorts at Cua Dai beach, the construction of hydropower plants in the upstream part of the Vu Gia – Thu Bon river basin system, and land reclamations inside the estuary for urbanization purposes (Do et al., 2017). Moreover, sand mining became an increasing activity that is performed under permission of authorities by providing licenses but also several actions are done illegally, leading to the extraction of uncontrolled amounts of sand from the rivers and estuary. It is assumed that all these reduced the amount of sediment supply to the coast, transforming the ebb delta to a sink for the system. Finally, during the construction of the Cua Dai bridge in 2009, the construction site which protruded 350 m to the Thu Bon River from the bank, could be an influencing reason for the asymmetric distribution of sediment from the river, since it diverts the river flow to the right bank (Duy et al., 2016).

The construction of resorts accompanied by defence structures in front of them, starting in the 1999, upgraded the touristic status of the Cua Dai beach but possibly contributed to the northward expansion of erosion. Coastal erosion at many locations has been accelerated by coastal structures installed in adjacent segments of the coast (Takagi et al., 2015; Takagi et al., 2014a). Viet et al. (2015) describes the case of Sunrise Hoi An Beach resort, where a wide beach existed in front of it at the time of its construction, but then intense erosion occurred which led to the construction of a defence structure. Also, it was highlighted that severe retreat of the coast took place in the locations without protection of any hard structures.

These actions possibly influenced significantly the amount of the sediment supply. According to the research of Hung et al. (2017) the annual suspended sediment supply of the Thu Bon River reaches an amount of 390,000 m^3/year and in the case of the total sediment supply Tanaka et al. (2017); Fila et al. (2016) determined that the amount of sediment is 600,000 m^3/year. The eroded area along the overall coast in Hoi An is estimated to be 82.2 ha (822,000 m^2) according to data provided by Takagi et al. (2015); Cong et al. (2014).

2.3. Stakeholders in Cua Dai beach

Cua Dai beach influences significantly the economical activities of Hoi An, as several stakeholder groups become related. The ongoing coastal erosion creates an impact as well as conflicts among their interests. A stakeholder analysis was performed by Fila et al. (2016) that assessed the problems, dilemmas and goals of each stakeholder regarding the erosion of the coast, presenting the level of involvement of all groups. The resulting power versus interest diagram that ranks the influence and interest of the stakeholders is illustrated below. From there, the most influential stakeholders were determined to be the public authorities, as well as the resort owners, whose needs could affect mostly the implementation of a solution in Cua Dai beach. In this section, an overview of the stakeholder analysis that has been made is presented.

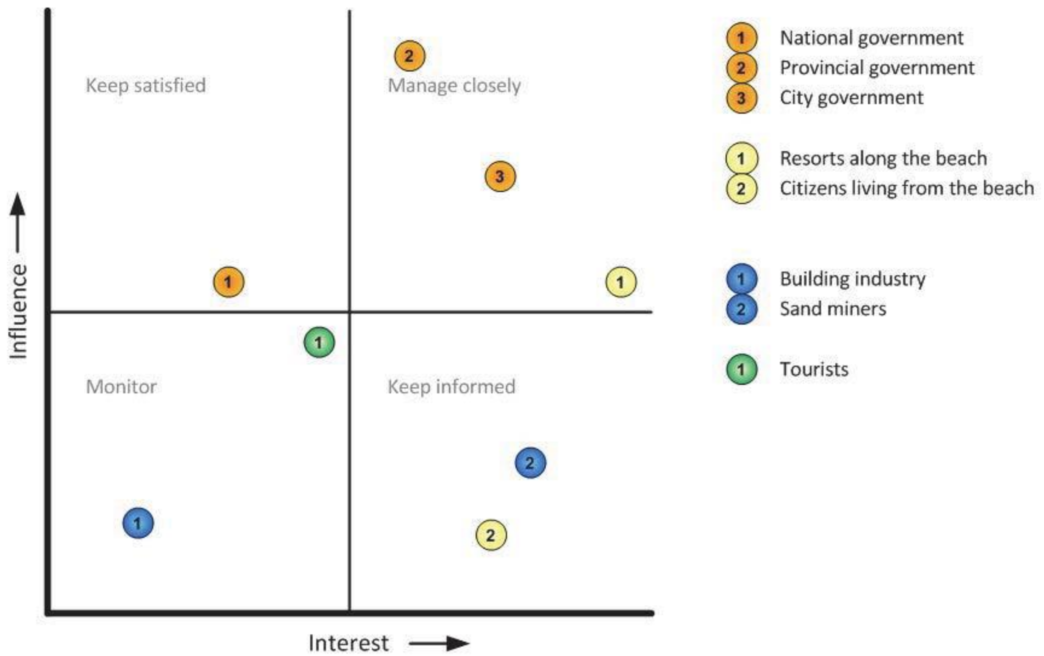


Figure 2.2: Power versus interest diagram (Source: Fila et al., 2016)

The highest administrative body of Vietnam is the National Assembly that controls the activities of the provinces and aims to distribute equally the resources to all local governments and cover their needs. The local government of the Quang Nam province is benefited financially by the touristic activity of Hoi An city, so the mitigation of the erosion in Cua Dai beach is advantageous. However, human activities in the province such as the sand mining and the hydropower dams that are also important to it, may have an effect on the erosion, creating a conflict of interest. The local government of Hoi An is in favor of combating the Cua Dai erosion, since this creates a profit to the area, yet the financing of a project largely depends on the resources that can be provided. The citizens also of Hoi An support any action taken against the Cua Dai erosion, as the income of many professions is largely dependent on the touristic activity of the area, but their influence on any action decided is limited.

A characteristic sign of economic activity is the resorts that are built and are heavily influenced by the touristic services that they can provide. Even though erosion does not affect currently all resorts in the same level, it is a common need for all of them to address the issue. However, it is noted that effective cooperation is not present at the moment. A point that was made in the analysis was to include the resort owners as financial contributors to the solution of erosion, as it increases the value of their properties, but it was noted that this can be most profitable for them only in the case that everyone will decide to invest. The building industry is presented as an another source of influence, creating a pressure in the Cua Dai as it uses sand, possibly affecting the sediment supply to the coast. This action is closely related to the activity of the sand miners that try to cover the sand demand and could be altered if the cost of other available materials could be more competitive and if a stricter state against illegal mining activities would exist. The final stakeholder group that was considered was the tourists, which aim for a wider coast for the overall public Cua Dai beach and not only for the resort owned parts, noting however the difficulty of the government to make this investment.

The goals of the stakeholders shape their expectancies regarding a solution for the ongoing erosion in Cua Dai. These can assess the success of any implemented project in terms of acceptance by the local community. The most important expectation is the recreation of an attractive coastline, in order to maintain the touristic activity. Furthermore, the protection of the buildings is significant as well as the long term result that can be achieved by the solution. Moreover, since the current state of erosion is severe, an action from which immediate results are provided is mostly anticipated. In addition, the solution should not shift the problems to other areas and should be able to provide safe conditions in the beach. Finally, possible conflicts with the remaining activities of the area must be avoided as possible, as they also contribute to the local economy. It was concluded that a nourishment approach can satisfy the aforementioned requirements.

2.4. Research approaches to investigate erosion in Cua Dai

Understanding the mechanisms that influence the erosion of the north coast where Cua Dai is located became an intriguing research topic. For this purpose, different approaches have been followed. The complexity that is introduced in the area, as many phenomena are being involved and interact, complicates the research there which has been focused on the morphological behaviour around the Cua Dai inlet, including the coastlines north and south. Attention has been given to the influence of waves but also to the sediment supply by the river. The difference in the level of complexity that is considered in each approach but also in explanations provided regarding the cause of erosion in Cua Dai beach, highlights the need for continuation of the research in the area. The research methodology that was followed consists mainly of the use of satellite images and modeling results for longshore sediment transport rates.

In the papers of Duy et al. (2016), Tanaka et al. (2016), Viet et al. (2015) the changes in morphology of the Cua Dai area were investigated through analysis of satellite images, that cover a specific time period. Viet et al. (2015) focused on the 6 km lengthwise stretch of the coastline in Cua Dai area. The images, collected from Google Earth, cover the period from 2004-2014 and shoreline positions were extracted and compared. Findings indicated the southward shift of the south part and the erosive behaviour of the north coast highlighting that the total amount of retreat reached 200 m in the area near the mouth for the period of observations and less more northward, attributing this to the reduced sediment supply from the river. However it is pointed out that the results were only based on general information and stresses, so there is need for more extensive research.

Duy et al. (2016) extended the area of research. With the use of satellite images covering the period of 2001-2015, shoreline positions were extracted. A similar erosive trend was observed in the north coastline as before, with a retreat in the order of 180 m near the mouth, while in the south part accretion existed and since the area of research is wider, further downstream erosion was noticed. Finally, the predominant influence of longshore sediment transport was identified as well as the northward direction of transport. The use of Landsat satellite images, covering a long term period from 1975-2015 were included in the research of Tanaka et al. (2016), with the aim of studying the morphological evolution of the Cua Dai inlet mouth. The asymmetric formation of the mouth was inspected as well as the southward shifting trend of about 250 m lengthwise, increasing the asymmetry. It was stated that the unequal sediment supply from the river induced the southward shifting of the mouth and ebb delta, influencing the coastline formation near the mouth. It was pointed out that simulation with one line models must include this unequal sand distribution.

The use of analytical solutions from an one line model were applied by Hoang et al. (2015). The model was used to describe and produce the sediment transport from the river mouth to the adjacent coasts, reproducing the erosion of the north coastline with an increasing effect near the mouth. The cause of erosion was attributed to the reduced sediment supply and the scenario of sediment supply recovery was also examined. It is stated that further investigation of the parameters involved in the model will lead to more detailed results. Duy et al. (2016) provided a method for determining the diffusion coefficient related to the longshore sediment transport coefficient, of the analytical solution from an one line model based on Landsat images. Furthermore, there was focus on proposing a method for calculating the river sediment supply based on the shoreline gradients adjacent to the mouth that were also obtained through Landsat images. The resulted values highlighted the asymmetric river supply in the adjacent coastlines and the phenomenon was ascribed to the southward shifting of the river mouth.

Hung et al. (2017) attributed the erosion of Cua Dai to the reduced sediment supply due to human interventions. It was stated that the imbalance between the wave and flow action induced breaching on the spit, causing wave intrusion in the inlet mouth and sediment loss there, intensifying erosion. In the paper, the erosion rate of sediment volume was estimated with the use of satellite images. The calculated coastal retreat near the river mouth, where shoreline changes are most prominent, ranges between 37-43 m/y for the period 2003-2015. The shoreline retreat was reproduced with the use of a shoreline change model that used a static shoreline equation of parabolic shape and a hard measure solution was proposed as a mitigation measure for the erosion.

Do et al. (2017) made a more extensive research regarding the causes of erosion in the Cua Dai area. With the use of long term satellite images, the shoreline positions were extracted and after that, the shoreline change rates were calculated together with the volume changes for different time periods. The retreat of the Cua Dai beach was estimated to range between 6-31 m/year in the period 1988-2015. More specifically, during 1995-2000 the average retreat was 18 m/year, observed close to the inlet. On average 12 m/year were lost during 2000-2010 with erosion to extend north and in the spit area at the north inlet mouth side the retreat was on average 19 m/year. An average retreat in the order of 6 m/year affecting the coast further north was observed in the period 2010-2015, while in the spit area the retreat reached a value of 31 m/y. For the estimated closure depth of 5.5 m the volume losses over these years have been also quantified. An overall sediment loss of 60,000 m^3/year has taken place in Cua Dai beach in period 1995-2000. In the period 2000-2010 the eroded volume was estimated to be 183,000 m^3/year, reaching a maximum value of 323,000 m^3/year with inclusion of the eroded sediment in the spit area at the north inlet mouth side. During the period 2010-2015, a loss of 103,000 m^3/year has been estimated, that reaches an amount of 247,000 m^3/year when considering also the erosion in the spit area. The rate of accretion of the south coast was determined to vary between 0.7-11 m/year, taking into account only average values, while the sediment gains there until the depth of closure of 5.5 m range between 25,000-139,000 m^3/year. The CERC formula was used in order to estimate the wave induced longshore sediment transport rates including the seasonal wave climate effect in the problem. The main conclusion was that a reduction of sediment supply from the river due to human interventions might have played a significant role to the erosion, but has also influenced the existing morphology of the area, as the seasonal climate and the non cyclic extreme events already induced an erosional pattern in the Cua Dai beach.

The majority of the research approaches that have been presented here assessed the level of erosion in the Cua Dai area in terms of the rate of retreat and advancement of the coastline. Limited research in terms of sediment budgets was observed, in order to quantify the total volume of sediment that induces the coastline changes over the considered time periods. By extending the research to include records of sediment volume changes, a deeper understanding to the problem could be reached, leading to a more effective treatment, approached with more targeted suggestions. An overview of the coastline evolution of Cua Dai by means of the rates of retreat, taken from the research study of Do et al. (2017) is

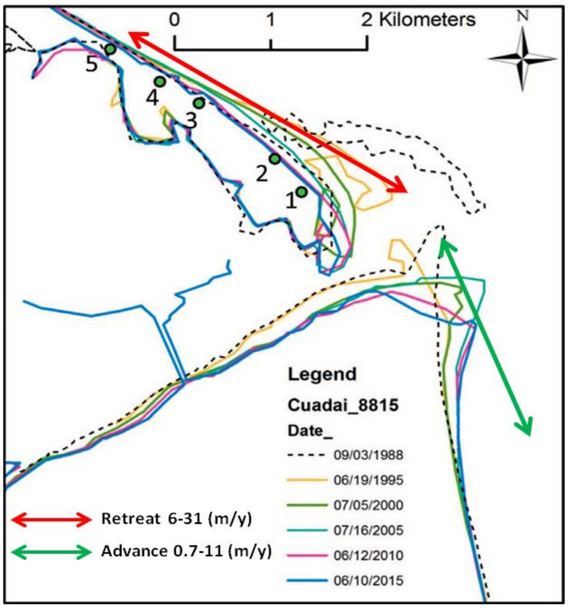


Figure 2.3: Coastline positions over period 1988-2015, taken from Do et al. (2017) and overall coastline retreat and advance

illustrated in Figure 2.3. The ranges of values obtained by Do et al. (2017) cover the period 1988-2015 and correspond to the average coastline changes of Cua Dai extracted by the satellite images.

2.5. Nourishment design

2.5.1. The development towards the mega nourishment concept

The nourishment design is based on the concept of working with nature, aiming at the exploitation of the natural dynamics of an area that will distribute the imported sediment appropriately to the natural environment. In a European level, the recognition in the early 1990s of the necessity for sustainable development of the coastal environment, has led coastal engineers to the present interest in developing a “soft engineering” approach (Hamm et al., 2002). In the Netherlands, over the last decades sand nourishment volumes have increased greatly, and the demand for nourishments is anticipated to increase further in coming decades due to sea level rise (Luijendijk et al., 2017). Ongoing research on this field aims to optimize their positive effects, as well as to provide improved and sustainable nourishment designs that can establish the main future approach in coastal management applications against the increasing coastal pressures.

In developed countries, this type of adaptation measure is one of the oldest “soft” structures utilized to cope with beach erosion (Linares, 2012), with the first approach of beach replenishment to be documented in the U.S. in 1922 (Davidson et al., 1992). The history of nourishment in Europe is relatively recent, starting in 1950s according to Hamm et al. (2002). In the Netherlands, the sand nourishment approach became a governmental policy to maintain the Dutch coastline at its 1990 position at all costs, as primary mitigation intervention (Stive et al., 2013).

Throughout the years and as research on the topic evolved, various nourishment strategies were distinguished that consist of dune, beach and shoreface nourishments. Beach and dune nourishments comprise the older nourishment implementations. In these cases, sand is positioned directly on the beach and dune area respectively, providing the necessary protection and restoration for short-term emergencies (i.e. storm-induced erosion) as well as for long term-issues (structural erosion and sea level rise) (Hamm et al., 2002). Ongoing maintenance in both approaches is required in order to provide a long-term solution. The usual maintenance interval in the Netherlands is 3-5 years. The source of sand can be land-based or from offshore, transported by pipes. Since a nourishment cannot stop erosion but only maintain the coast, its lifetime depends on the grain size of the borrow sand. If the grain size of the borrow sand is the same or larger compared to the sand grain of the coast, the longshore sediment transport rate can decrease, leading to an increased nourishment life (Bosboom & Stive, 2015).

The implementation of shoreface nourishments gained wide recognition through the years due to the fact that they provided a positive effect against erosion that was more economically efficient. In this case, a larger amount of sand is positioned in the outer side of the coastal profile, usually on the seaward part of the sandbars. Wave attenuation is formed, as waves break on the nourishment during storm conditions, reducing the wave energy and longshore wave driven currents in the higher profile, but also a feeder effect is caused and a gradual landward movement of sand is stimulated (de Schipper et al., 2016). The origin of sand in this case comes from a near borrow area and repetition is required in the order of 5 years. According to Stive et al., (2013) the majority of nourishments at present in the Netherlands are implemented as shoreface nourishments rather than beach nourishments.

The current development of mega nourishment provides a new option that strengthens the benefits of the nourishment approach. It shapes a promising way of action against the increasing coastal needs in terms of sediment supply, as described earlier. By exploring the characteristics and evolution of the Sand Engine implementation, useful remarks can be drawn that can be taken into account in the present mega nourishment design approach for Cua Dai.

2.5.2. The Sand Engine

The Sand Engine was constructed in the Dutch coast, between the Hook of Holland and Scheveningen in 2011, comprising a 21.5 Mm^3 sand mega nourishment. The initial form was a hook-shaped peninsula with a curved tip, containing also a small lake and was attached to the shore over a 1 km coastline stretch. The initial dimensions were a 2.4 km longwise base and a 1 km offshore extension, while an offshore location was used as a sand source. Its highest point is +7.3 m above sea level which is well above the average annual storm surge level (de Schipper et al., 2014). The shape was largely inspired by the potential to provide areas for nature and recreation (Stive et al., 2013). The initial predictions for the evolution of the Sand Engine concerned approximately a 1 Mm^3/year sediment loss that would be inserted in the coastline, setting the nourishment lifetime to 20 years.

The mega nourishment concept emerged from the coastal policy of Netherlands that required an increase in the nourishment amount used for protection against floods and coastline maintenance at its 1990 position, due to the increasing sea level rise effect. The Sand Engine aim was to nourish the coastline through a large sand quantity from a restricted area that would be redistributed over its lifetime with the aid of the natural prevailing processes, providing safety conditions, in combination with extra space for recreational purposes. During its development phase, the morphodynamic model Delft3D was implemented in order to predict the diffusion of the nourishment and the feeding of the coast, over the expected lifetime. Several locations and designs ranging from shoreface nourishments, detached islands, peninsula’s, bell and hook-shaped designs were modeled, but based on costs, safety, ecological and recreational aspects the hook-shaped peninsula design was selected by the Environmental Impact Assessment (Mulder & Tonnon, 2010). The curved tip of the peninsula is a shelter for the wave action, while the artificial lagoon created can offer habitat for organisms (Stive et al., 2013).

The evolution of the Sand Engine became an interesting research topic that included regular monitoring by topographic surveys in site and numerical modelling simulations before and after its implementation. Based on the results of the initial topography surveys and aerial photographs from de Schipper et al. (2014), significant changes took place during the first period of 18 months. A spit feature was created in the north part of the nourishment, forming a lagoon. This evolved further into a small channel as its entrance became restricted due to the curving shape of the spit, while several short-cuts of this channel formed later. It was also observed that the overall width of the nourishment reduced and its length increased whereas the original shape transformed in to a more symmetric bell-shape because of the erosion of the more seaward parts of the nourishment and the accretive behaviour of the coast. From the sediment losses of the nourishment, 70% was observed to be transported to the adjacent coasts and the rest to be lost, while these changes did not have a constant pattern but were related to the periods of stronger wave forcing. Stive et al. (2013) presented the predictions of the morphological evolution of the Sand Engine, which proved to be close to the observed changes and noted that the estimated amount of sediment loss coincides with the preliminary predictions. One can conclude that the morphological evolution in the coming years will continue to comply with the predictions, stressing the power and effectiveness of the Sand Engine project as well as the strong predictability of Delft3D.

A study conducted by Luijendijk et al. (2017) aimed to hindcast the initial response of the Sand Engine during the first year, with the use of Deft3D in order to analyze the results and investigate the contribution of each environmental process into the erosional mechanism of the mega nourishment. Valuable data regarding the forcing conditions and the behaviour of the nourishment were provided by the monitoring campaign through monthly resolutions and the use of the numerical model was selected in order to provide a more detailed insight into the processes that controlled the initial development of the Sand Engine. The initial forcing mechanisms in the nourishment location comprise the tidal variation, the spatial and seasonally varying wave climate, the reduced fluvial sediment supply and the prevailing northward sediment transport trend. The successful reproduction of the initial nourishment evolution allowed the detailed investigation of the processes. The results gave prominence to the dominant influence on the erosion of Sand Engine, being the high energy wave action that transported the sediment into the adjacent coasts, with the second most dominant process to be the vertical tide. The wave direction, the horizontal tide but also the wind and surge phenomena seemed to be less relevant to the erosion. By this study the predictive skills of Delft3D were highlighted, stressing its important contribution to the mega nourishment design and assessment. Implementing a similar strategy for coastlines where the intrinsic dynamics and geomorphology are more complex (e.g. interacting systems of rock coastline, estuaries, sand dune systems, etc.) will require different designs and aggregate sizes (or combinations of aggregates) according to the environmental challenge being addressed (Brown et al., 2016; Bishop et al., 2006).

2.6. Conclusion

From the existing research on the topic, the complexity of the problem of erosion in Cua Dai beach is highlighted and the existent results can help towards identifying and investigating with more detail all the parameters that play a role as well as their interaction. The application of mainly one line models can provide a solution based on a computationally cheaper approach, which ignores on the contrary the complexity of processes. The use of process based modelling should be introduced more. Thus, it is noted that for any future research and measures against erosion in the Cua Dai, all the relevant processes and their interactions should be taken into account to the highest level possible, in order to achieve a sustainable long term solution. The morphology of the area that causes sheltering effects, the seasonal wave climate and the seasonal variation in the river discharge are fundamental aspects to be considered. Furthermore, the effect of tide should be also included, as well as the ongoing impact of the various human interventions. Finally, the impact of extreme events is important to be investigated as it creates a major influence into the system.

The promising results of the Sand Engine have proven that the concept of mega nourishment is an effective solution that can be implemented efficiently also in other vulnerable locations around the world, adapted to the characteristics and the needs of each area. The high level performance of the numerical process based model Delft3D was acknowledged, justifying the choice for further use as a design tool in the future mega nourishment projects. A mega nourishment design can be a sustainable solution to the problem of erosion in the Cua Dai area and research on this topic is expected to provide beneficial results, contributing to an effective strategic approach.

The focus of the present research study is to investigate the mega nourishment concept in order to combat the erosion at the Cua Dai beach. The approach followed aims to evolve the existing research that has taken place in the area, providing a better understanding of the prevailing dynamics as well as a long term and steady solution.

3. Prevailing dynamics in Cua Dai

3.1. Introduction

The aim of the present chapter is to explore the prevailing dynamics in Cua Dai in order to derive useful conclusions for the design characteristics of a mega nourishment, which will be implemented for the purpose of combating erosion. The assessment is based on representative conditions of all influencing processes. In order for this to be achieved, at first presentation of all the available data is necessary, including datasets as well as nominal values when real data are not available. From these, representative values are extracted forming the basis on which the mega nourishment design parameters are derived. The validity of these representative values and of the existing Delft3D model of the domain is tested by reproducing characteristic morphological periods of the area of interest that have been recorded in the past, through numerical modelling simulations. In addition typical extreme events are examined. In this way also the dynamics of the area are investigated. After the representative values are verified and the behaviour of the area is analyzed, the resulting mega nourishment design characteristics can be determined based on the observed sediment transport magnitudes and patterns. This chapter forms the basis for the following research in which the mega nourishment design parameters are selected and after the design approach is defined, the final design solutions are incorporated in the numerical model (Chapter 4). Then, assessment is performed again by means of numerical modelling simulations (Chapter 5).

3.2. Available data

3.2.1. Waves

The prevailing wave conditions in Cua Dai are influenced by the seasonal character that dominates in the area, as a result of the monsoon climate. As previously mentioned in Chapter 1, the two main seasons that can be distinguished comprise the winter season, where NE monsoon takes place and the summer season with the SW monsoon to prevail. The wave data that are being used in the present study have been obtained from the research of Do et al. (2017). Their acquisition is briefly described here and the reader is referred to the corresponding paper for detailed information. Because of the limited continuous wave time series available for the domain of consideration, the selected hindcast measurements have been acquired from the NOAA Wave Watch III archives, from a grid point that is located approximately 65 km offshore of Cua Dai beach (16.0^o N,

Figure 3.1: Location of offshore wave data collection point

109.0° E), covering the period 2005-2013. From these offshore wave data, the nearshore wave climate can be derived with the wave generation and propagation model SWAN, using seasonal representative wave conditions. In order for this to happen, the offshore wave climate has been already classified and subsequently the most influencing seasonal wave directions have been extracted.

The dominant wave direction during the winter season (September-March) is the ENE, with a frequency of occurrence of 79.5%. Waves come also from NE with a frequency of 7.1%. In the summer (April-August), a bidirectional regime prevails with waves coming from the SE and ENE directions that occur 44.7% and 34.9% respectively. The wave height varies in the two wave seasons, ranging normally between 0-2 m during the summer with a period of 6-8 sec, while the highest wave height measurements can reach up to 3.5 m. Stronger wave conditions are observed normally during the winter, ranging from 0-3.5 m with a period of 7-9 sec and can extend up to extreme wave height values of 4-9 m, indicating the occurrence of storm events.

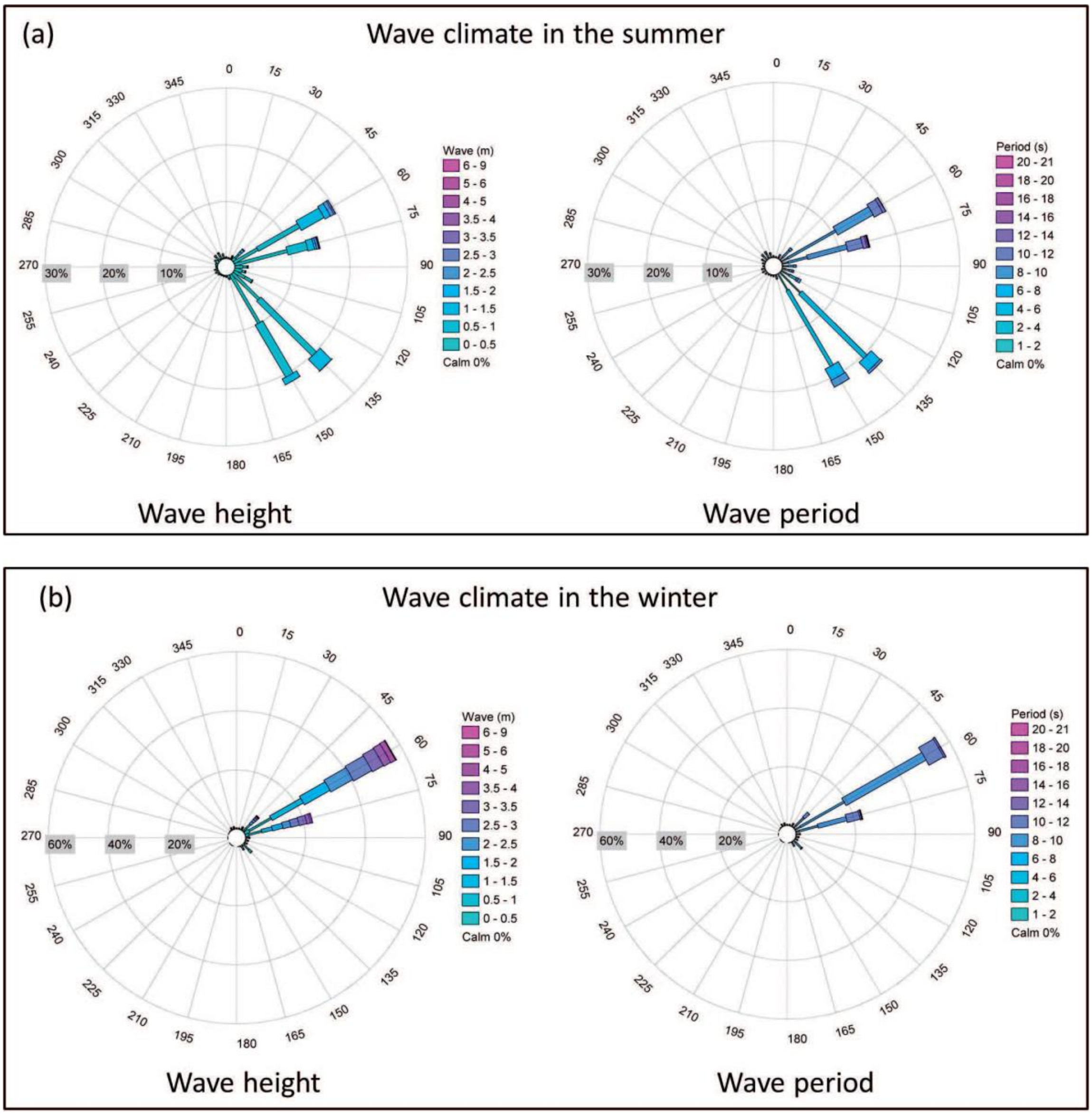


Figure 3.2: Summer and winter wave roses of the available offshore wave data (Source: Do et al., 2017)

3.2.2. River discharge

The seasonal effect of monsoons influences also the river flow, altering the quantities that are discharged into the ocean. A flood season is present from September to December, while dry conditions exist from January to August. Since the river is included in the model area the effect of the river discharge is relevant to be considered and so, corresponding representative input parameters are necessary. The presence of higher or peak discharges indicates intense meteorological phenomena with small duration that impose severe consequences in the surrounding area. The river discharge data have been provided by Do et al. (2017). They have been acquired from the Nong Son hydrology station that is located in the upstream area of Thu Bon river. These data cover the period 1977-2011 and although more recent information is not available, the long term record is considered to be a trustworthy source from which reliable representative seasonal values can be extracted.

Analysis of the available data set indicates that the frequency of occurrence of flood events is increasing over the years in the Vu Gia-Thu Bon river basin (Do et al, 2017). The seasonal variation of the monthly averaged river discharge is presented in the following figure, showing also the corresponding prevailing wave conditions. From there it can be observed that during the summer period from April to August, the river discharge varies approximately between 71.2-107.6 m^3/sec. During the winter months, when a dry river season exists from January to March, the average discharge levels range between 95.5-247.2 m^3/sec. The monthly averaged river discharge levels during the winter months where a flood season takes place, from September to December, have a significantly higher value in the range of 192.4-1037 m^3/sec.

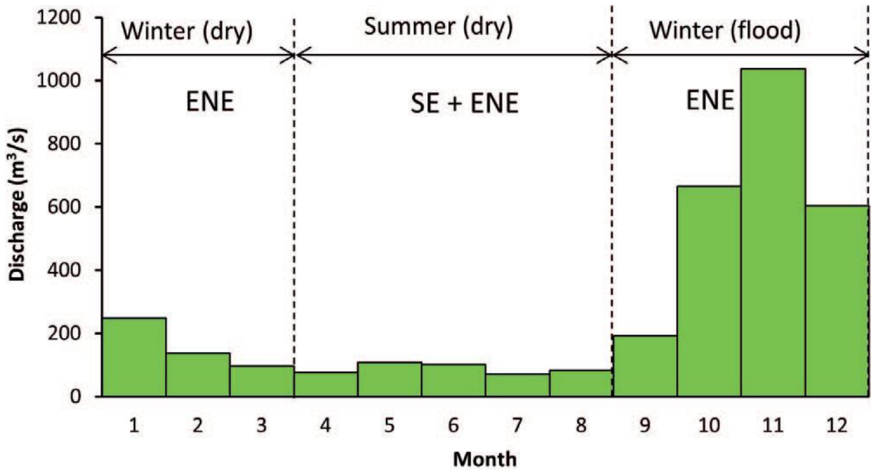


Figure 3.3: Monthly averaged river discharge levels in Nong Son Station (Source: Do et al., 2017)

3.2.3. Tide

The mean tidal range in the region is identified to be 0.7 m (Lam, 2009). For the present study tidal time series are available, with duration of two spring neap tidal cycles. They have been acquired by Do A.T.K. (2018). These data can represent the flow boundaries of the numerical model of the present study. For their acquisition, a regional ocean tide model has been created, which encloses the domain of interest with the purpose of generating the resulted tidal time series. The boundary conditions of this model have been obtained by the global tide model TX08.0. There, a total of 13 tidal constituents have been used. Validation of the tidal data has been performed from the nearby tidal station of Da Nang.

3.2.4. Extreme storm and flood events

The presence of non cyclic extreme events is frequent, inducing abrupt morphological changes in the region. The impact of storm and flood events poses a big threat, since the human activity on the coast becomes significantly affected. It is essential to investigate the additional morphological effect that these extreme events induce in the wider domain of interest, where Cua Dai beach is located. This assessment can possibly explain the presence of features that cannot be linked to the regular prevailing seasonal forcing conditions.

From the available offshore wave data and river discharge record, the identification of extreme events is possible. After observation of the summer and winter wave roses, it can be deduced that the presence of high wave conditions is restricted to the winter period. According to measurements recorded in nearby region, Da Nang, Hoi An experiences almost 25% of storms in Vietnam, while the most severe storms usually occur in the years that abnormally high rainfall (over 2,400 mm per year) is observed (UN-Habitat, 2014). In the wave record, the occurrence of very high waves covers the directional domain of 345^o-60^o, in accordance to the regular winter prevailing wave direction. The occurrence of extreme events in the winter and flood season is also verified by the long term record of extreme storm events. In the summer season the possibility of occurrence of an extreme storm event is low, even though exceptions existed, as it is the case of typhoon Cecil in May 1989.

Flood events can be determined from the maximum monthly discharge values that have been recorded in the period 1977-2008 obtained from the available river discharge data of Nong Son station. The presence of floods is restricted mainly in the period between September and December, yet single extreme flood events have been also recorded in May. The available monthly averaged maximum river discharge values are presented in the following figure.

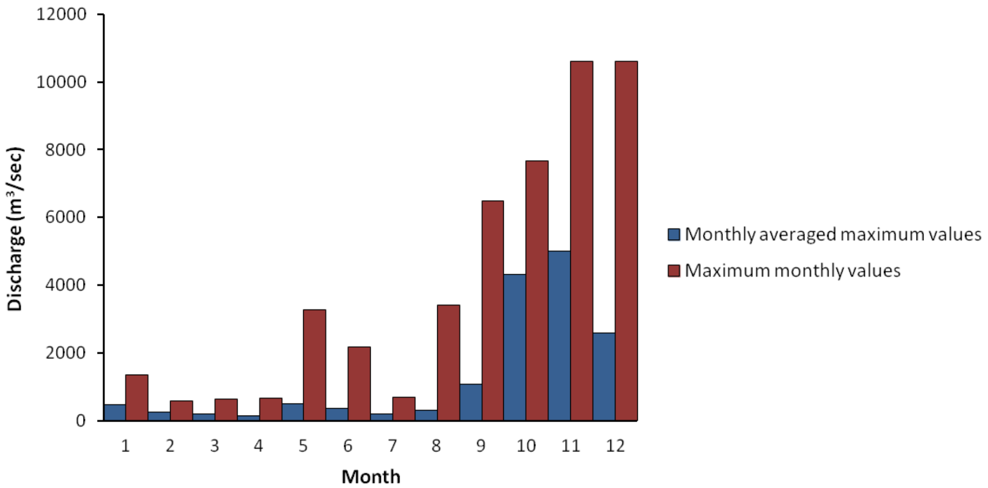


Figure 3.4: Maximum river discharge data per month for the period 1977-2008 (Nong Son station)

3.3. Methodology

From the available data, appropriate selection of representative conditions based on which a mega nourishment design will be made is essential. These conditions have to be verified but also the model performance must be validated. For this to be accomplished, simulation scenarios are created. Three characteristic morphological periods of the broader area where Cua Dai beach is located, are aimed to be reproduced through modeling simulations from a numerical model. By achieving a reproduction of a typical annual cycle of these morphological periods, the effectiveness of the selected representative conditions is proven, but also the model validity. Furthermore, a better insight and understanding in the dynamics of the area is obtained and important conclusions can be drawn. The assessment of the morphological behaviour of the area with additional simulations of typical extreme storm and flood events assists the investigation.

For this purpose, an existing Delft3D numerical model is used from which model schematizations are created, while for every morphological period four simulations are performed corresponding to each of the characteristic seasonal conditions that prevail in Cua Dai through the year. In all simulations single representative wave conditions and river discharge values are used in the model. The seasons in all morphological scenarios are examined under a common simulation period, in order to allow for comparisons among them. This period has been selected to be one month since this time span is considered long enough in order to observe morphological changes in the domain. Additionally, the simulations are also performed for an extended duration of one year in order to allow comparisons among the different scenarios, because then the morphological features are better formed. It must be mentioned that through these simulations where single representative conditions are used, only a trend of the actual morphology that existed in each period is going to be reproduced, as in reality the observed variations have been also influenced by other events, such as the presence of extreme conditions. The recorded morphological trend of each period has been identified through shoreline changes that have been extracted from satellite images in the research of Do et al. (2017) and covers the coastlines north and south of the Cua Dai inlet. The impact of two typical extreme storm and flood events is simulated with appropriately selected representative conditions for a simulation duration of four days.

In the remaining chapter the representative parameters that will be used are selected. Then, an overview of the morphological scenarios is provided, indicating the recorded morphological trends that are expected to be reproduced. After that, the simulation approach of each scenario is described and the results are presented. Also in each scenario, analysis and discussion of the obtained results is performed. In the end, the simulation results and analysis of the extreme storm and flood events is discussed.

3.4. Selection of representative parameters

The representative wave conditions that will be used in the simulation of the morphological scenarios are selected from the available classified wave record which contains the most influencing wave directions. These directions have been determined based on their annual occurrence percentage. Because of the seasonal character of the area, every morphological scenario is simulated for all the seasons that are dominant annually after combining the wave climate with hydrology. It must be noted that the bidirectional character of the summer season, leads to the selection of two representative wave conditions in order to cover efficiently the main wave trend of the summer period. From now on these resulted four seasonal conditions are going to form a typical annual cycle in Cua Dai.

Cua Dai seasons	Duration
Winter & Flood season	September – December
Winter & Dry season	January – March
Bidirectional Summer & Dry season	April – August

Table 3.1: Seasons in Cua Dai after combining the wave and river discharge variation

The selection of the seasonal representative wave conditions is performed based on three criteria that have to be satisfied by all the selected wave height values. All criteria are related with the alongshore sediment transport pattern that is induced by every wave condition. These criteria comprise the magnitude of the sediment transport along the coast, the sediment transport pattern in comparison to the corresponding net seasonal transport pattern of a certain wave direction and finally the annual percentage of occurrence of each of the wave conditions. For this purpose, existing sediment transport patterns that have been derived with the CERC formula from hydrodynamic simulations for the coastlines south and north of the Cua Dai inlet by Do et al. (2017) are used.

The first criterion is important, as it is of high relevance to choose a wave condition that induces a large sediment transport. This is essential in the present approach where single representative conditions are used, because the net transport magnitude of each season can be better represented. The second criterion is also significant and can be considered as a relevance index. This is the case due to the fact that the net sediment transport pattern of a specific wave direction is clearly influenced more by certain wave conditions, and these are the ones that produce the most similar transport pattern. Finally, the occurrence frequency is also very relevant, as each of the selected representative condition has to occur regularly. A condition that matches only the first two criteria cannot be representative, because a certain wave that rarely occurs cannot form a proper representative choice.

The criteria are applied to all characteristic wave class values of the available wave record. From this procedure the most influencing seasonal wave conditions are being determined. It must be noted that all three criteria have to apply in order for a wave condition to be selected. The characteristic wave conditions of the reduced wave record as well as the process of selection of the final representative values are presented in detail in Appendix A.

Representative river discharge values are also selected in order to accompany the wave conditions and finalize the hydrodynamic inputs of every morphological scenario. In total four representative river discharge conditions must be selected in accordance to the seasons that are considered. For this purpose, the available record of the monthly averaged river discharge data is used. The method of selection of these characteristic river discharge values is described in Appendix A.

The final selected representative seasonal parameters for the waves and the river discharge are summarized in the following table.

Season	Wave Direction (^{0})	Wave Height (m)	Period (sec)	Occurrence (%)	River Discharge (m^3/sec)
Winter & Flood	ENE (60^0)	H_s =1.75	T_p = 7.57	11.3	Q_{peak} = 1037
Winter & Dry	ENE (60^0)	H_s =1.25	T_p = 7.9	13.8	Q_{avg} = 168
Summer & Dry	ENE (60^0)	H_s =0.75	T_p = 6.42	10.4	Q_{avg} = 88
Summer & Dry	SE (135^0)	H_s =0.75	T_p = 6.4	17.18	Q_{avg} = 88

Table 3.2: Seasonal representative wave and river discharge parameters

For the tide, no representative values are selected. The available tidal time series of the numerical domain, with duration of two spring neap tidal cycles in the boundaries of the model region are being used in all simulations. The reason is that the influence of the tide is not expected to be large on the sediment transport. The area of interest is characterized by a wave dominated, microtidal regime with low tidal range, as the mean spring tidal range is less than 2 m (Bosboom & Stive, 2015). After all seasonal representative values have been determined the model simulations can be formed in order to reproduce an annual cycle of the three morphological periods of the Cua Dai beach, as well as of the wider domain around Cua Dai inlet.

The assessment of the effect of extreme events in the region is performed with additional simulations. For this purpose, extra representative values are necessary in order to reproduce the short term impact of individual incidents in the coast. Two characteristic cases of flood and storm events are modeled. These events are studied separately in order to identify and link the evolution of morphological features to the corresponding extreme forcing condition. The available record of extreme floods is used, as well as the recorded storm wave height data. It must be highlighted that in all extreme event simulations, the regular seasonal representative values are used for the remaining forcing parameters of the model. The final selected representative flood and storm conditions are presented in the following tables. More information is provided in Appendix A.

Flood events	River Discharge (m^3/sec)
Extreme flood event 1	Q_1 = 5018
Extreme flood event 2	Q_2 = 7660

Table 3.3: Representative extreme flood conditions

Storm events	H (m)	T (sec)	Direction (^{o})
Extreme storm event 1	H= 6.5	T = 7.34	60^o (ENE)
Extreme storm event 2	H= 8	T= 8.21	0^o (N)

Table 3.4: Representative extreme storm wave height conditions

3.5. Simulation of characteristic morphological scenarios and extreme events

3.5.1. Overview of morphological scenarios

The first morphological period that is simulated, refers to an era in which no human interventions were present in the coastline or the river, serving as a baseline condition for the upcoming cases. A typical year that belongs to the morphological period of 1995-2000 is aimed to be reproduced. At that time no resorts were built along the Cua Dai coast and also no hydropower dams were constructed in the upstream part of Thu Bon River. According to the detected shoreline changes of that period, erosion has been inspected along 1.1 km area close to the inlet in the north coast, while further upstream sedimentation was present for a 2.5 km region. The erosive feature near the inlet is dominant compared to the sedimentation that exists in the south coastline. There, an accretive trend has been identified near the inlet for a distance of 1.4 km that transforms after into an erosive segment. The observed erosive conditions in the north coast follow a morphological period where significant sediment accumulation was present there, linked to the welding of an ebb tidal bar to the north coast over the period 1989-1995. This difference in morphology over these years implies that an erosive trend is present in the north coast that is expanding from the inlet to the north. So, these morphological trends are expected to be observed by the first simulation scenario.

The second morphological period that is going to be reproduced represents the evolution of the coast when human interventions took place. It refers to the period of 2010-2015 that includes the presence of all the resorts in Cua Dai. They are illustrated in Figure 3.5. Initially a beach existed in front of each of the resorts, but the prevailing erosive trend took away the coastline in front of them. After that, the resorts are expected to behave as groynes, initially blocking the expansion of erosion together with the presence of the defence structures that were built for this purpose in front of them. However, in the long term the erosion has been extended further to the north. The south coastline continued to show an accretive behaviour even though the magnitude varies over the years. These are the anticipated trends that can characterize the morphology of this period during the second simulation scenario.

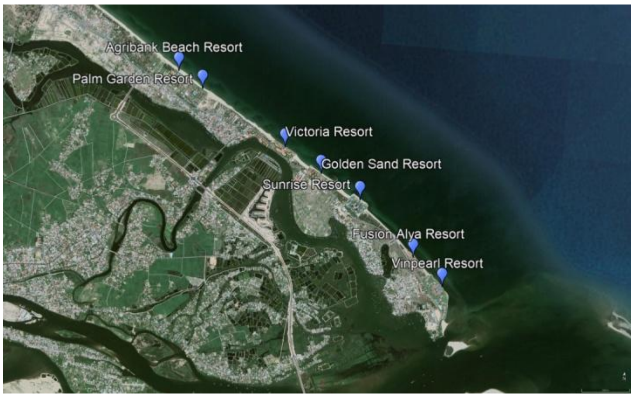


Figure 3.5: Location of resorts along Cua Dai beach

Finally, the last morphological period that is simulated, recreates the trend in the coast during 2016-2017, when sandbags were placed along the public Cua Dai beach between Victoria and Palm Garden resorts as a measure to prevent further expansion of the erosion that reached the location on 2016. The effectiveness of this solution was not permanent and after, it was observed that the erosion shifted further to the north (Stive M.J.F, personal observation 2018). Since the bags are not resilient against the energetic wave conditions that are predominant in the region, they became useless after a certain period of time and it is hypothesized that erosion was further enhanced due to their presence. Therefore, the expected morphology that is aimed to be reproduced by the third morphological scenario includes the enhancement of erosion in the north coast after the presence of sandbags and the lasting accretion in the south coastline.

3.5.2. Model description

After presenting the morphological scenarios that are being simulated, it is essential to describe briefly the basic characteristics of the numerical model that is used in this approach. An existing Delft3D model of the overall domain of interest is going to be used, that has been created by Do et al. (2017) for the purpose of research in the area around of the Cua Dai inlet. Based on this, new model schematizations are created in order to simulate appropriately the seasonality in the various morphological scenarios.

The numerical model was selected for performing complex hydrodynamic computations, through an online coupling between the Delft3D WAVE and FLOW modules. In this way, the influence of waves into the hydrodynamic flow pattern is taken into account. Delft3D FLOW module performs 2D or 3D hydrodynamic computations by solving the unsteady shallow water equations (Deltares, 2014a). The horizontal momentum equations, the continuity equation and the transport equation comprise the system of governing equations. The model is appropriate to be used in coastal areas, since vertical accelerations are ignored with respect to the gravitational acceleration, reducing the vertical momentum equation into the hydrostatic pressure equation. Initial and boundary conditions are necessary in order to reach a solution (Lesser et al., 2004). The nearshore wave field can be obtained through the Delft3D WAVE module, in which SWAN model is incorporated in order to perform the necessary wave computations. Processes such as wind induced wave generation, depth induced wave breaking, non-linear wave interactions are included. The basis of SWAN model is the discrete spectral action balance equation and is fully spectral in all frequencies and directions (Deltares, 2014b). For further information regarding Delft3D FLOW and WAVE modules, the reader is referred to the corresponding manuals.

A brief description of the basic characteristics of the existing Delft3D model is also made. The Delft3D model domain is presented in Figure 3.6. It has been created from the combination of the FLOW and WAVE numerical domains. A curvilinear grid is selected for both modules, to allow for a complete coupling between them. Their grid dimensions differ, with the WAVE domain to be expanded around the FLOW domain. Due to the fact that unreliable results may arise in the lateral boundaries of the wave domain, an expanded wave grid allows the damping of these, before reaching the flow grid (Roelvink & Reniers 2011). The WAVE grid is extended around the FLOW grid approximately 17 km in the north and south, as well as 36 km in the offshore direction.

The grid resolution varies within the domain. A higher resolution is achieved for the areas of interest, while a lower resolution is selected for the remaining region in order to gain computational efficiency. More specifically, near the outer edges of the domain, offshore of Cu Lao Cham island group where only the WAVE grid is present, the average grid size has a value of 2070.7 m. A finer resolution is obtained nearshore at the north and south coastline, located in the edges of the wave domain, but also within the river. The average grid size there has a value of 665 m. The resolution becomes higher around the inlet area, from the river mouth towards the Cu Lao Cham island group and a very fine grid is obtained in the region that includes the ebb tidal delta for the purpose of studying detailed flow conditions, with a grid value in the level of 52.5 m. Inside the river, the resolution is on average 282.8 m.

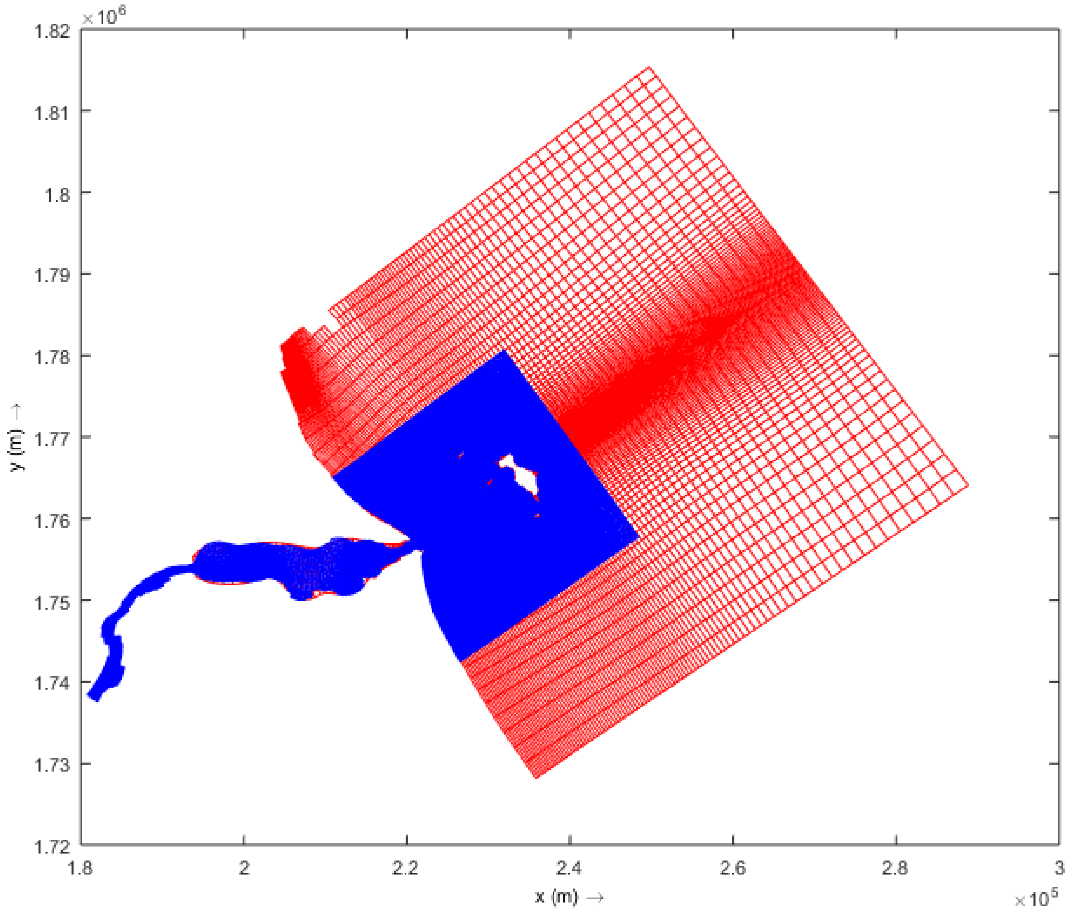


Figure 3.6: Delft3D WAVE (in red) and FLOW (in blue) model grid domains

Available bathymetric data of the area of interest have been used from the year 2014. The boundary conditions of the domain comprise valuable forcing input parameters inserted in the FLOW module. The open sea boundary consists of three sections, water level controlled, with time series of one month duration. The values are appointed to both ends of each boundary section. Furthermore, uniform discharge quantities represent the effect of the river in the numerical domain. With respect to the initial conditions a restart file is used, containing realistic water level values of the overall domain that have been calculated from a past hydrodynamic simulation in the area. A hydrodynamic simulation period of one month is considered and the time step is selected to be 0.2 minutes. The input parameters in the boundaries of the WAVE model pertain to characteristic single wave conditions uniformly forced, that have been obtained from the available offshore wave location.

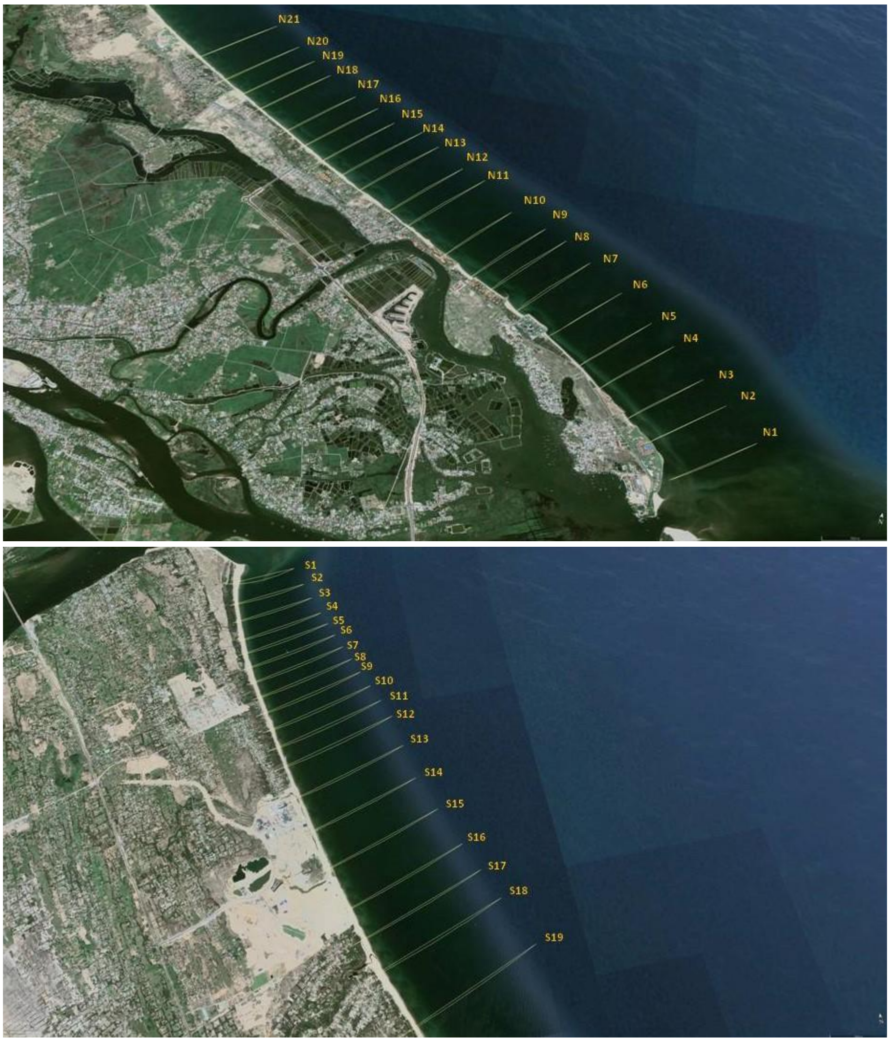


Figure 3.7: Map of transects along the north (upper image) and south (down image) coastlines

Non cohesive sediment (sand) is selected with a specific density of 2650 kg/m^3, dry bed density of 1600 kg/m^3, and a median grain size of 200 μm. The formula that describes the sediment transport is the default formula of van Rijn 2000. Several observation points have been created along the offshore boundary of the numerical model, but also in the upper river boundary and the Cua Dai inlet, in order to monitor the behaviour of the water levels and fluxes in time. Furthermore, the coastlines adjacent to Cua Dai inlet, have been divided into cross sectional transects creating a total of 40 monitoring points as illustrated in Figure 3.7.

In the present part of the research, the basic characteristics of the existing Delft3D model are preserved. However, a different parameterization is performed in which the selected representative wave and river discharge conditions are used in the model boundaries, aiming to simulate the seasonal variation that is predominant in the model domain. In addition, in several cases alterations in the schematization of the model bathymetry are performed. Furthermore, the model now is extended in order to simulate the effect of the complex hydrodynamic conditions on the morphology. This is expected to result in a more realistic and complex sediment transport pattern as an outcome, and to allow for a better observation in the behaviour of the coast. For the morphological simulations with duration larger than one month, a morphological acceleration factor (MorFac) is applied for the bathymetry update.

3.5.3. Introduction of morphological scenarios

It is essential to present the bathymetric map of the wider domain of interest in order to obtain information regarding the prevailing depth variability. This allows for a better insight into the morphological changes that are created over the simulations. It is inspected that the depth variation is significant nearshore. Along the coastlines the depth is limited, increasing gradually further offshore. The region with the largest depth levels is located offshore of the Cu Lao Cham island group and is in the order of 60 m. In the river the local depth is restricted to values less than 10 m, but near the river mouth there are locations where the depth increases more. Figure 3.8 illustrates these observations. The simulation of all scenarios results in bathymetric changes which are mainly restricted in the nearshore area due to the local dynamic prevailing conditions, affecting the north and south coastlines, as well as the river and the ebb tidal delta. Consequently, the observation and assessment of scenarios is restricted to these regions.

In the following sections, the simulations of scenarios that represent three characteristic morphological periods but also of typical extreme events are assessed and interesting conclusions are drawn. These allow a deeper understanding of the dynamics of the system in the region where Cua Dai beach is located.

The importance of seasonality is highlighted in all morphological scenarios. The morphology varies over the seasons in terms of magnitude and behaviour, with the most significant morphological changes to take place during the winter flood season, since the highest wave height and river discharge are present then. In the winter dry season the inspected morphological changes are still significant even though the magnitude is smaller. During the summer, changes are milder, as the prevailing conditions have a lower intensity that leads to the development of subtle morphological features. The predominant bidirectional character of the wave forcing determines the morphological behaviour. Similar features are formed under the effect of ENE wave conditions with a magnitude that varies with the wave and river forcing, while changes are present when SE waves prevail.

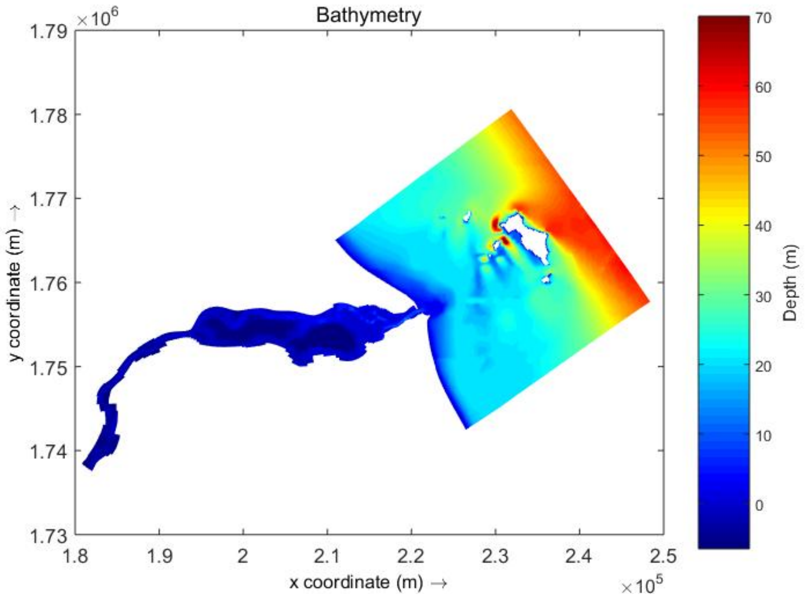


Figure 3.8: Model bathymetry

Due to this, in all morphological scenarios the results of a characteristic ENE and SE forcing condition will be presented in order to highlight the main differences in the behaviour of the domain. The impact during the winter flood season, where the intensity of changes is the strongest, is the most representative example that allows the inspection of all morphological features which are formed under ENE waves. Together with the effect of the SE summer waves, the overall behaviour of the domain can be sufficiently assessed. The results of the remaining seasons in every scenario are presented in Appendix B.

3.5.4. Scenario 1: Absence of human interventions (1995 -2000)

The resulted intensity of the morphological changes is in accordance with the monthly duration of the simulation period. The level of sedimentation and erosion in the areas of interest is displayed in Figure 3.9. It must be noted that along the land boundary of the north coastline a thin line is present that indicates sedimentation. However this area represents the presence of land and does not imply sediment accumulation under the forcing conditions. Thus, this thin area can be ignored in the analysis of the simulation results here, as well as in the remaining morphological scenarios and only additional sedimentation zones are going to be taken into account.

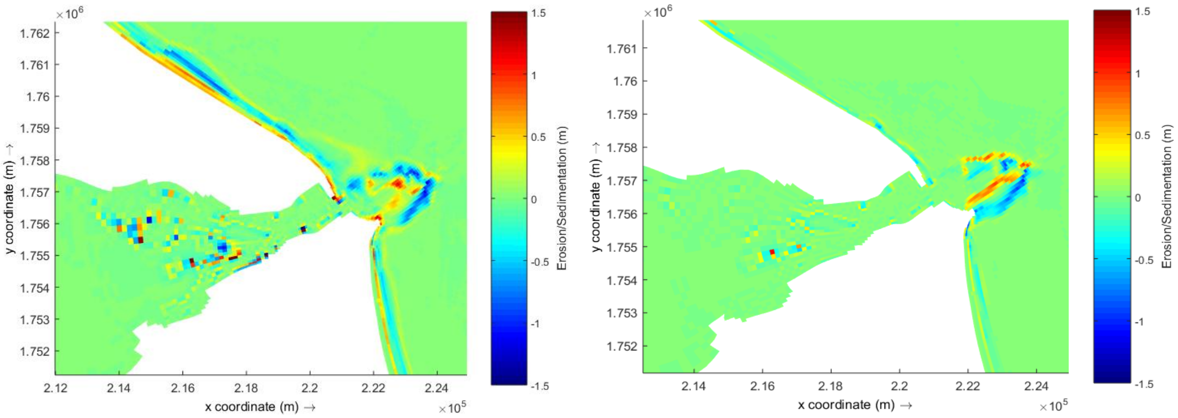


Figure 3.9: Morphological changes during (a) winter flood and (b) summer (SE) seasons in the first morphological period

The ENE wave conditions create a stronger impact in the north coastline compared to the south. The sediment transport magnitude there is large and varies, indicating morphology changes. In general, erosion is dominant along the north coast. In the location between the sixth and eighth transect, approximately 3 km from the inlet, significant local erosion exists, indicated by the darker blue color. There, a divergence point is formed, downdrift of which sediment is transported towards the inlet, forming a more complex pattern with local divergence and convergence areas over a distance of approximately 2 km. These explain the observed variations of the morphology. Mainly there erosion is present, even though closer to the inlet side sedimentation develops, linked to the convergence point that is located approximately 1 km from the inlet. Because of this transport pattern, sediment is transported to the north inlet mouth side which experiences local sedimentation. The resulted trend can be attributed to the complex interaction among the waves, the tide and the river discharge which takes place in the region. Further to the north, the level of erosion remains strong, highlighted by the steep gradient that can be observed in the corresponding alongshore sediment transport graph. In this region, the transport intensity is largest during the winter flood season, as a result of the strong prevailing conditions. The magnitude of the observed patterns is lower during the winter dry season and becomes significantly milder over the summer ENE season, attributed to the lower forcing conditions.

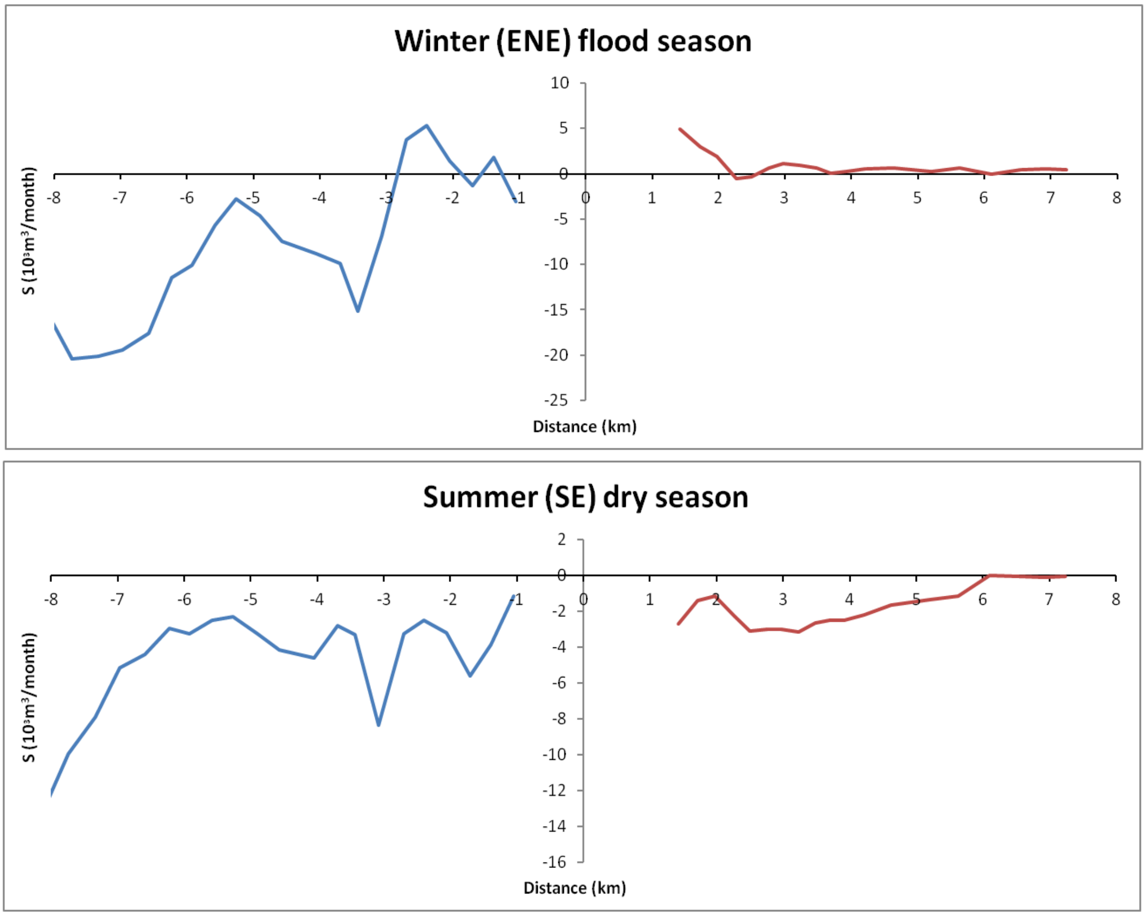


Figure 3.10: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the first morphological period

Along the south coastline during ENE conditions, sedimentation takes place. A more stable trend is observed compared to the north coast and no intense changes are present. A steady southward sediment transport pattern prevails and the transport magnitude is significantly smaller compared to the north coastline. However, near the inlet over a 1 km distance, a strong southward transport gradient exists inducing larger sediment accumulation there with respect to the remaining coast. This southward transport is caused by sediment bypassing from the ebb tidal delta. In the summer, the sediment transport is more uniform with minimum gradients. However, even in this case some small changes can be also inspected in accordance to the winter ENE periods. The prevailing pattern of the south coast with minimum gradients, could be explained by the interaction of the local forcing conditions. In general, the ENE wave direction triggers a northward sediment transport. Sheltering effects due to the presence of the ebb tidal delta as well as the southward directed sediment bypassing from it, alter this trend influencing the resulted net southward transport pattern. The difference in the wave mangitude among the ENE seasons together with the level of bypassing, forms the intensity of the final southward pattern.

Changes inside the river domain are observed in the river mouth as well as along the left river bank, with erosion and sedimentation locations, caused by the sediment transport due to the river flow towards the ebb delta. The amount of sediment that is being flushed out depends on the seasonal river discharge conditions. The transport is significant during the winter flood season. In the winter dry period, the moderate river discharge levels still create enough capacity to flush out a certain amount of sediment and in the summer a lower level of changes is inspected. The most pronounced morphological changes are located at the inlet mouth. This is anticipated since the area is constantly affected over the annual cycle, even during the summer season where a lower amount of river discharge flows out of the river.

From the river mouth sediment is transported towards the ebb tidal delta. Even though the transport magnitude is not large, it is expeceted to influence the morphology heavily during events with higher river dishcarge. In the ebb tidal delta, the most energetic conditions are present creating distinct morpological changes. A significant amount of the sediment that comes from the river is transported offshore towards the northwest outer region inducing local sediment accumulation there. The local wave breaking that takes place there due to the incoming ENE waves, enhances this feature. Its intensity varies through the year as it is affected by the magnitude of the river disharge in combination with the wave pattern. The presence of this ebb tidal bar in the region reinforces the local sediment supply to the north coast, in the region downdrift of the divergence point, enhancing also the sediment supply towards the north inlet mouth side. The impact during the winter flood season is the largest, while a minimum effect is present in the summer. Along the remaining outer region of the ebb delta local wave breaking takes place, relocating the sediment offshore but also towards the ebb delta center. At the south outer area of the ebb delta, a part of sediment is also transported to the south coastline as a result of bypassing from the ebb tidal delta.The intensity of this trend is linked to the magnitude of the imposed wave and river discharge conditions, that increase in the two winter seasons and are moderate in the summer.

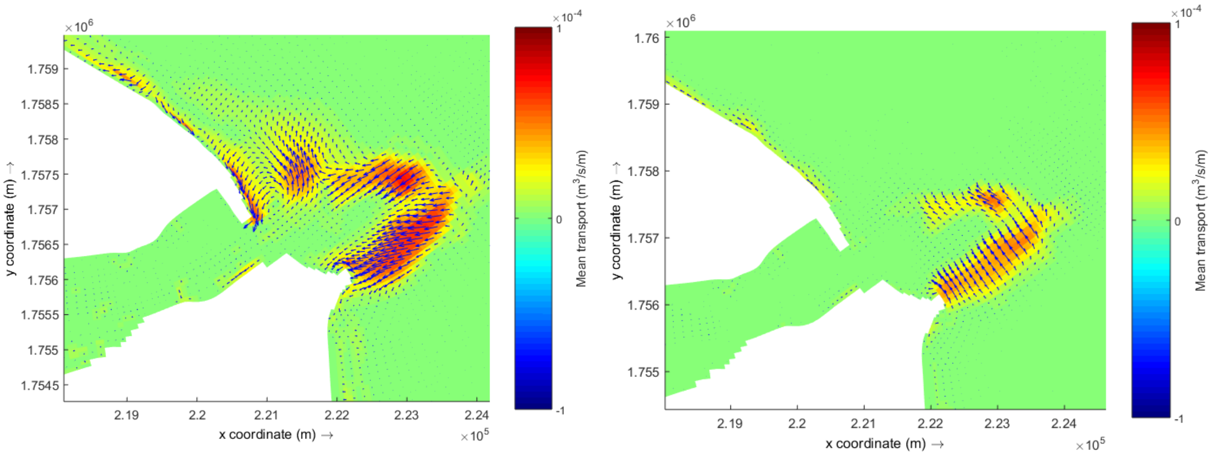


Figure 3.11: Mean transport pattern around ebb delta during (a) winter flood and (b) summer (SE) seasons in the first morphological period

When SE incoming waves prevail during the summer, a different trend is present. In general the intensity of the morphological changes is moderate, as low wave heights and a low river discharge are present. The morphological changes affect the south coast and have a low intensity in the north coastline. This is attributed to the SE wave direction that makes a stronger effect in the south coast, while for the north coastline the ebb tidal delta creates sheltering conditions that block the SE waves. Because of this reason also the ebb tidal delta experiences the strongest changes with respect to the rest of the areas.

A net northward transport direction is present in both north and south coastlines. The north coast experiences erosion that is stronger mainly in the area near the inlet as well as along the last transects, while in restricted locations sedimentation is present. The transport pattern near the inlet is more variable and large gradients are present, over a distance of approximately 2.7 km. After this region a steady erosive trend takes place, as sediment transport propagates towards the north with a constant increasing magnitude. The convergence and divergence locations have now eclipsed. In the inlet mouth side the transport direction alters locally, and is directed towards the river.

The south coast experiences also erosion. A steady transport gradient is present that increases in the transport direction, while along the last transects the morphology becomes steady. The gentle gradient indicates that the level of erosion is not so strong. Now the abcense of sediment bypassing from the ebb tidal delta to the south coast, allows the reinforcement of the northward wave induced transport pattern.Within the river no significant transport takes place, although a constant amount of sediment is transported from the mouth to the ebb delta. The sediment transport towards the northwest outer side of the ebb delta is now is now very weak. In addition, the shadow zone that the ebb delta creates for the SE waves, reduces further the transport to this location. Since the sediment transport from the river to the north outer edge is weak and is not reinforced by the SE wave pattern, it can be seen that the transport that was provided to the north coast by these two local forcing mechanisms is not present now. In the adjacent outer region of the ebb delta sediment is redistributed offshore due to local wave breaking that takes place. Finally, waves mainly break in the south outer side of the ebb delta, inducing local transport of sediment there towards the ebb delta center.

Figure 3.12: Main sediment transport patterns for ENE and SE wave conditions in the first morphological period

To conclude, the regular effect of the seasonal wave climate and river discharge in the morphology is an important factor to account for, since different morphological features are formed over the year. During the period where no human interventions took place in Cua Dai, the morphological trend that was present along the north and south coastlines was investigated, and can serve as a baseline to the upcoming scenarios that include human interventions. From the simulations, the erosive behaviour of the north coast is being reproduced successfully, indicating the presence of an ongoing erosive trend that takes place annually and is propagating in time further to the north. In addition, the existence of a local divergence point under ENE waves, creates variability in the sediment transport pattern redirecting the transport along the first transects towards the inlet. The formation of an ebb tidal bar during ENE conditions increases the local complexity in the region. Finally, the accretive tendency of the south coast was verified through the various graphs presented that describe the annual variability. Thus, it can be concluded that the present morphological scenario can reproduce successfully the prevailing trend of the morphological period 1995-2000, where no human interventions affected the north and south coastlines.

3.5.5. Scenario 2: Interventions along Cua Dai beach (2010-2015)

The presence of resorts in the Cua Dai beach could have influenced the prevailing seasonal alongshore sediment transport pattern, inducing differences in the morphology. Observations of Landsat images that cover the period during which the construction of resorts takes place, indicate that resorts might create an additional impact in the local morphology. During their construction in period 2000-2011, a beach existed in front of them. However, the prevailing erosive trend in the north coast that has been already described and reproduced by the results of the first scenario, caused retreat there. The effect of extreme non cyclic events is expected to accelerate this trend. Nevertheless, during the period 2004-2011 major erosion can be inspected in the region that starts from the north inlet side and reaches the location of Sunrise resort. There, a different hypothesis is made in the present study, as the magnitude of erosion cannot be only explained by the regular prevailing conditions. The evolution of the coastline trend in this region during 2004-2012 has been obtained from Google Earth and is presented in the Figure 3.13.

The welding of an ebb tidal bar to the north coast that took place in the period 1989-1995 and was triggered by typhoon Cecil, reduced the volume of the ebb tidal delta. Considering the fact that the equilibrium conditions of the system did not alter, it could be assumed that a large amount of sediment was provided during that period from the north coast back to the ebb tidal delta in order to restore the equilibrium state. The ebb delta acts as a buffer for all the elements of the system, sharing sand when there is lack of sediment, but this supply is only a ‘short term loan’ that will be paid back by the adjacent coasts in the long term (Bosboom & Stive, 2015). It was previously highlighted that a regular interaction exists between the ebb tidal bar that forms in the northwest outer ebb delta area and the north coast. Based on this, it can be hypothesized that this area might have provided sediment back to the ebb tidal delta. The smaller level of erosion in the region where Golden Sand resort is located but also a bit further to the north, in front of

Victoria resort, indicates that the trend there could be only a result of the seasonal prevailing conditions including also the impact of extreme events.

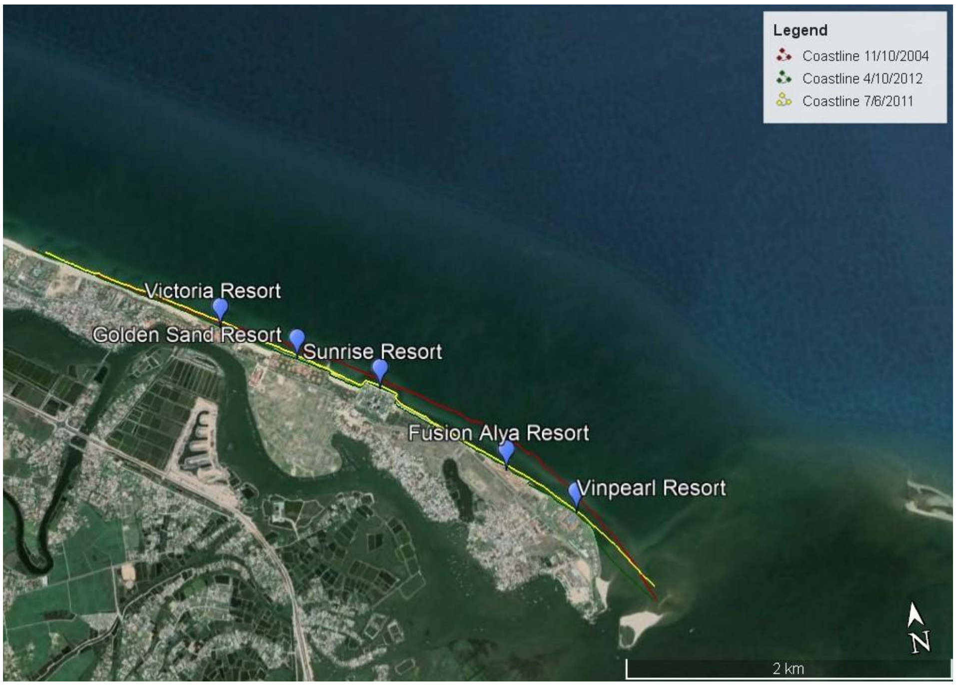


Figure 3.13: Coastline evolution during period 2004-2012, obtained from Google Earth

The ongoing erosion as well as the need to maintain the remaining coastline in front of the resorts, led to the decision for construction of defence structures. Seawalls were constructed in the front sides of Vinpearl and Fusion Alya resorts as an erosion preventive measure. Along the region between Fusion Alya and Sunrise resort an embankment has been created, that was though unable to prevent morphological changes. Groynes were placed in the Sunrise resort in order to maintain the beach in front of it. For the Golden Sand and Victoria resorts, rip rap stone embankments were used as a protective measure. The resorts together with the defence structures are suspected to have an impact in the morphology in Cua Dai beach. In addition to this, a more stable coastline trend in the areas among where resorts are located has been created. There, even though erosion and sedimentation takes place, the close location of all resorts does not allow for an expansion of these morphological features.

The observed morphological pattern suggests that resorts start to behave as groynes when the beach is eroded in front of their location, creating an erosive pattern in the north that ultimately intensifies the erosion in Cua Dai. In the present section, the resorts are included in the model and it is investigated whether the selected representative seasonal wave and river discharge conditions can reproduce the morphological pattern that has been observed over the period 2010-2015. In this period, the five resorts of the Cua Dai beach, begin to have effect in the morphology of the north coast. The Palm Garden and Agribank resorts are located further to the north and do not play a role in the morphology during this period, since the coastline exists in front of them. Due to this reason they are excluded from the simulation in the present scenario. The same simulation duration of one month is used in order to allow for comparisons.

Schematizations in the existing bathymetry are necessary for the inclusion of resorts in the model. In their location, no hydrodynamic pattern must be present, prohibiting the presence of any flow or waves there. This effect is represented by the inclusion of dry points in the FLOW module, which indicates points that must be permanently dry during the simulation. In accordance to this, the WAVE module is modified in the region of resorts with the addition of obstacles that interrupt the wave propagation from reaching these locations. Moreover, the depth is altered accordingly in both the wave and flow domain in order to indicate land and thus, no overtopping or overflow to be possible.

In addition, extra simulations are performed considering the effect of increased seasonal variation in the river discharge, derived by the available data record, that could be related to anthropogenic influences and climate change effects. A higher representative river discharge is used in the winter flood season, being the maximum of the montlhy averaged river discharge values that take place in the corresponding season. In accordance, in the summer season a lower representative river discharge is considered, being the minimum monthly averaged river discharge value that is present then. The previously selected representative river discharge for the winter dry season is kept the same. The representative river dicharges are presented in the following table.

Seasons	River discharge (m^3/sec) with increased seasonal variation
Winter & Flood	Q_{peak} = 2230
Winter & Dry	Q_{avg} = 168
Summer & Dry	Q_{avg} = 28

Table 3.5: Representative river discharge values including the effect of increased variation over the seasons

After assessing the general morphological trend that develops with the inclusion of resorts in the model domain, their direct impact in the morphology will be highlighted in each case. For this purpose, a comparison of the alongshore sediment transport trends is performed. Attention to the corresponding changes in morphology is also given. Due to this, the additional simulations with duration of one year that have been created with the same input parameters are used, in order to allow the development of more distinct morphological features and illustrate differences with greater accuracy. In the same sense, the effect of the increased seasonal variation in the river discharge levels is also assessed.

3.5.5.1. Resorts

Significant morphological changes are inspected along the north coastline with respect to the south, especially during the winter flood period, which are in accordance with the energetic wave conditions as well as with the strong river discharge flow. Now a different trend is formed there compared to the previous morphological period. The transport magnitude varies, introducing locations with higher sediment transport near the inlet as well as along the last transects, with steep gradients to form. The resorts appear to create an impact in the coastline, inducing sedimentation in the region immediately downdrift of Vinpearl resort and erosion closer to the inlet. In the area north of the resorts erosion is observed, causing a significant effect in the morphology there. Thus, it is obvious that the groyne effect in the morphology of the north coastline has been reproduced in a satisfying level. The morphology in the region among the resorts is steadier and the transport magnitude is less, but local effects also appear.

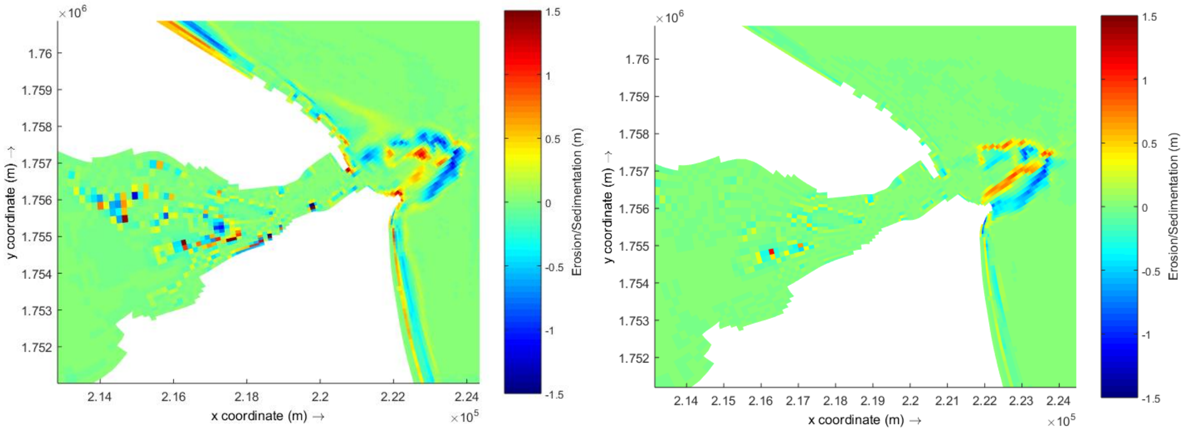
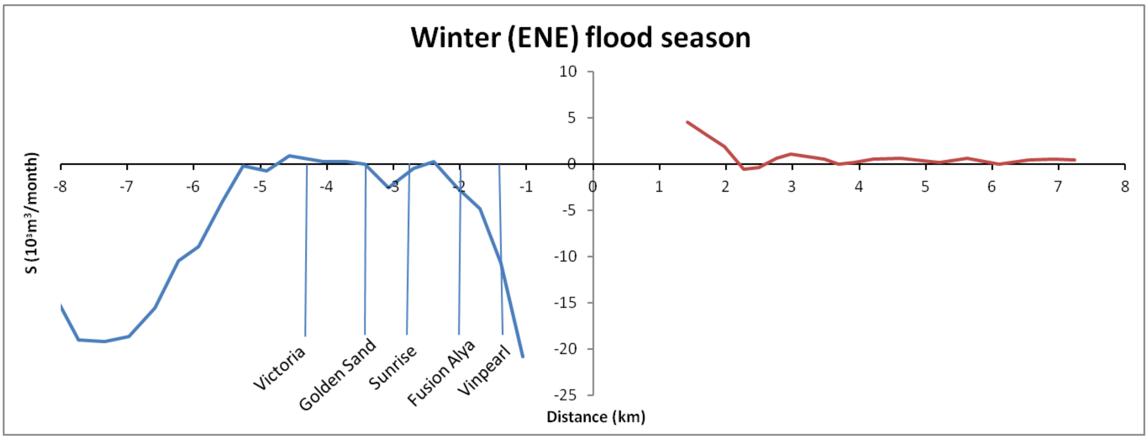


Figure 3.14: Morphological changes during (a) winter flood and (b) summer (SE) seasons in the second morphological period due to resorts

Under ENE waves, sediment accumulation is present near the inlet over a distance of approximately 1 km. This region includes the Vinpearl and Fusion Alya resorts. In the regions between Fusion Alya and Golden Sand resorts a more complex pattern takes place with erosion and sedimentation locations. Assessment of the mean transport trend in the region shows that the divergence point has now shifted a bit to the south between Sunrise and Fusion Alya resorts, due to the construction of Sunrise in the location that was formerly observed during the assessment of scenario 1. In this area enough undistrurbed coastline exists for the hydrodynamic pattern to form a new divergence point. There, erosion is formed downdrift of Sunrise resort and sedimentation updrift of Fusion Alya in accordance with the local alongshore sediment transport trend. This is also verified after observation of the present morphology of the location.The coastline there becomes concave, showing local sediment accumulation as sediment moving towards Fusion Alya and erosion in the south side of Sunrise resort. The divergence of sediment transport is stronger in the winter dry period. In this season wave conditions are still significant, while the river flow is reduced. The interaction in the region between the river and waves that has been highlighted in scenario 1, affects the intensity of the sediment transport divergence. Consequently, the high river discharge dampens this local wave feature, which is the case in the winter flood period. During summer the divergence of sediment transport is still present even though the waves are mild, since the effect of the river flow then is limited.



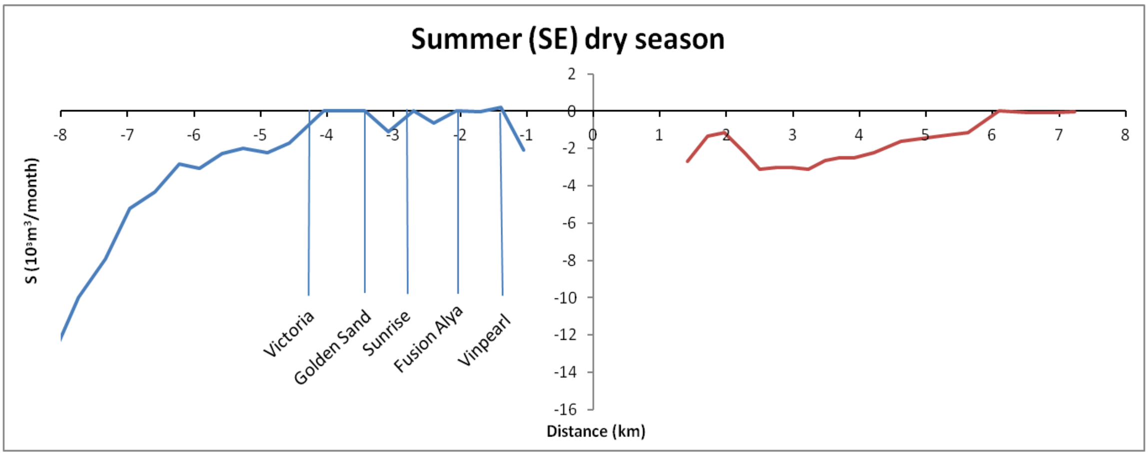


Figure 3.15: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the second morphological period due to resorts

Between the Sunrise and Golden Sand resorts that are at a distance of approximately 600 m, erosion and sedimentation is also observed while the transport direction is towards the north. The groyne function of the resorts is visible there, having enough space to form, since north of the Sunrise resort erosion exists while then sedimentation is present before Golden Sand resort. The morphology between Golden Sand and Victoria is steady, experiencing only sublte changes. A small local divergence of flow is also observed in the updrift side of Victoria resort, where a small amount of transport goes towards the resort, while the rest follows the strong northward transport trend that starts there, inducing significant erosion. The level of erosion is in accordance to the seasonal ENE wave energy conditions.

The morphological changes in the south coastline, when ENE waves prevail are milder. Along the coast a sedimentation trend is visible with gentle gradients along the transects and the net transport direction is to the south. However, near the inlet, a stronger southward directed gradient forms and sedimentation takes place along a distance of approximately 1 km. In this region the complexity is high, attributed to the interaction of the coast with the ebb tidal delta due to sediment bypassing. The effect is less visible during the summer where milder conditions are present.

Inside the river, the left river bank together with the mouth area become affected by the river outflow, forming local morphological variations with erosion and sedimentation locations. Their intensity is in accordance with the significance of the river discharge. From there, sediment is directed to the ebb delta center although the mangitude is small. The transport increases towards the northwest outer ebb delta region where sediment is flashed out, forming an ebb tidal bar that is enhanced by the ENE waves and has been observed in the previous morphological period. Thus, it remains unaffected by the presence of resorts. The level of sedimentation depends on the magnitude of river discharge and the severity of the wave conditions. During the energetic conditions of the winter flood season a larger impact is created compared to the remaining seasonal ENE conditions. This feature inteacts with the north coast, providing sediment mainly until Fusion Alya resort, yet its effect is present until the divergence point.

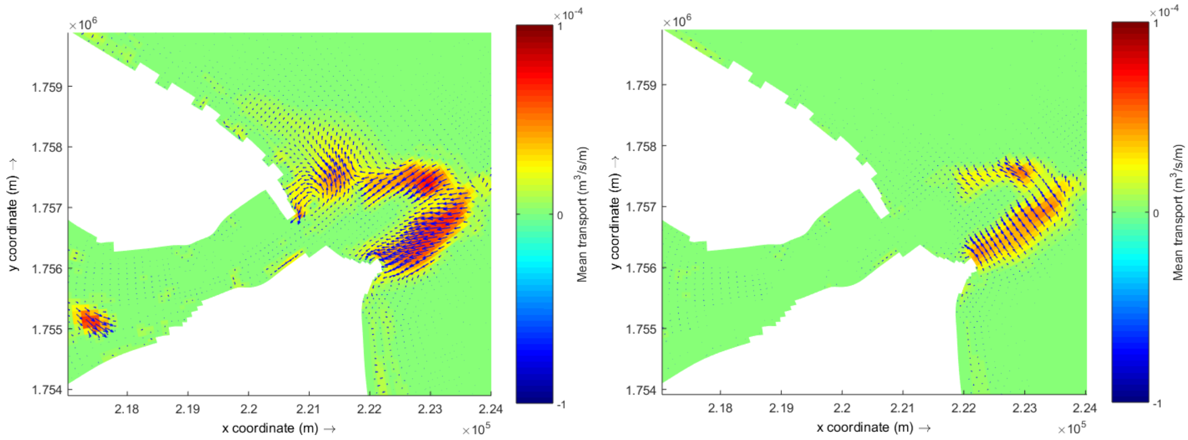


Figure 3.16: Mean transport pattern around ebb delta during (a) winter flood and (b) summer (SE) seasons in the second morphological period due to resorts

This interaction with the north coast reinforces the local southward directed sediment transport near the inlet towards the north inlet mouth side, which has been already strengthened due to the presense of Vinpearl resort. There, the reciprocal influence between the southward directed transport and the outward river flow forms a local sedimentation area that is strong during the flood season and milder in the summer. Again, the intensity of this feature varies in accordance to the prevailing wave height and river discharge. In the remaining ebb tidal delta, significant erosion is observed along its outer sides, while sedimentation takes place in the inner parts. The erosion is attributed to the energetic conditions that take place locally, due to wave breaking that transports sediment away from delta but also towards its center.

When SE waves prevail in the summer, the morphological impact is mild. In general, the most significant transport takes place in the ebb delta. In the north coast the transport magnitude increases only at restricted locations. This is the case in the region updrift of resorts, where transport is directed to the north. Among the location of resorts, a northward constant pattern is present and no flow divergence takes place. This is also the case downdrift of the Vinpearl resort. In the area between Fusion Alya and Golden sand resorts erosion and sedimentation regions is present. Immediately downdrift of Vinpearl resort sedimentation is observed as sediment is transported towards the resort, but the feature is mild, while now the region between Vinpearl and Fusion Alya does not experience changes in morphology. An erosive pattern is formed north of the resorts, indicated by the presence of an alongshore gradient that increases in transport direction.

In the south coast a steady northward transport is also observed, causing erosion. Near the inlet though the observed pattern has a higher complexity with erosion and sedimentation. However, along the last transects in the south there is absence of gradients and a stable pattern is present. Within the river, the transport affects the left river bank and the river mouth area. A limited amount of sand is transported through the inlet and the transport to the outer northwest ebb delta region is very weak. In addition, the prevailing wave climate does not enhance the transport there since the ebb delta creates a shadow zone at its north side for the SE waves. Thus, the local sediment accumulation that forms during ENE conditions does not take place now. Due to this, the local sedimentation in the north inlet side is also minimum in this season since a little amount of sediment is transported to the inlet side. In addition, there is no enhancement by the river flow. In the neighbouring outer ebb delta region significant sedimentation is present, as sediment is redistributed due to local wave breaking. The same phenomenon causes erosion across the south outer ebb delta area, but the breaking magnitude there is significantly larger. This different pattern is attributed to the SE wave induced sediment transport that affects the ebb delta in a different way.

3.5.5.2. Morphological impact due to the presence of resorts

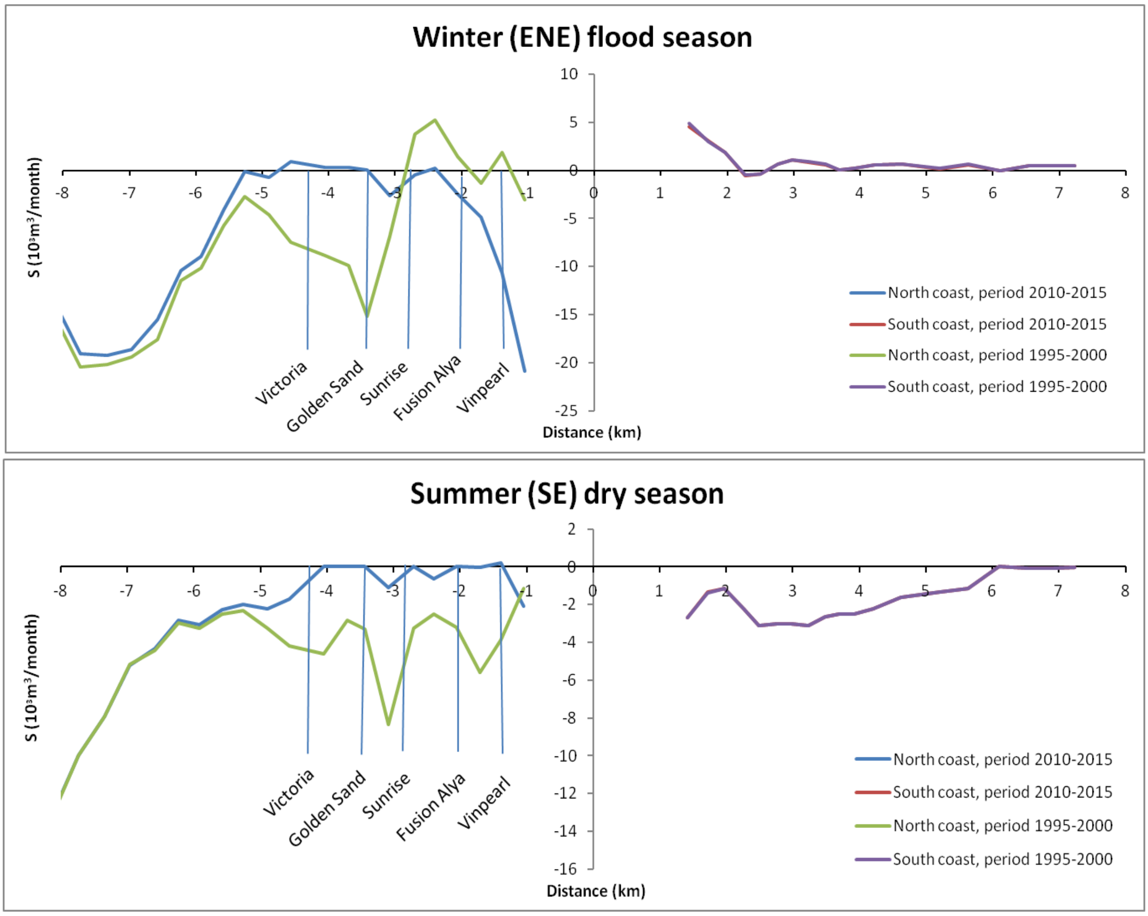


Figure 3.17: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the first and second morphological periods

In Figure 3.17 a comparison of the seasonal alongshore sediment transport patterns between the two morphological scenarios is presented. As expected, the impact of resorts is restricted in the north coast and the south coastline is steady over the two periods. Through all seasons it is observed that the overall sediment transport gradient north of the resorts became steeper, indicating stronger erosion in the area. The region directly after Victoria resort experiences stronger erosion due to the presence of resorts. Moreover, in the close area downdrift of Vinpearl resort the decreasing gradient was found to be steeper when resorts are present in the area, which is linked with stronger local sedimentation. The overall seasonal sediment transport gradients in the area north of resorts for the two scenarios are presented in the following table.

Season	Scenario 1 (m^3/m/month)	Scenario 2 (m^3/m/month)
Winter (ENE) Flood	7.2	7.6
Winter (ENE) Dry	4.4	5.1
Summer (ENE) Dry	2.9	3.6
Summer (SE) Dry	3.4	3.7

Table 3.6: Comparison of alongshore sediment transport gradients updrift of resorts in the north coastline

The seasonal morphological changes due to the construction of resorts are presented in Figure 3.18. The affected regions are the north coastline, the inlet mouth and the ebb delta, while the south coast becomes affected near the inlet only during winter flood season. The focus for the effect of resorts is restricted in the north coastline and the remaining features are considered to be the outcome of the local energetic pattern which creates variations in the magnitude of the observed features, even in the case of simulations with identical input parameters. The order of magnitude of the inspected features is 1m. Through all seasons the stronger erosion in the region north of the resorts, as a result of their construction can be observed.

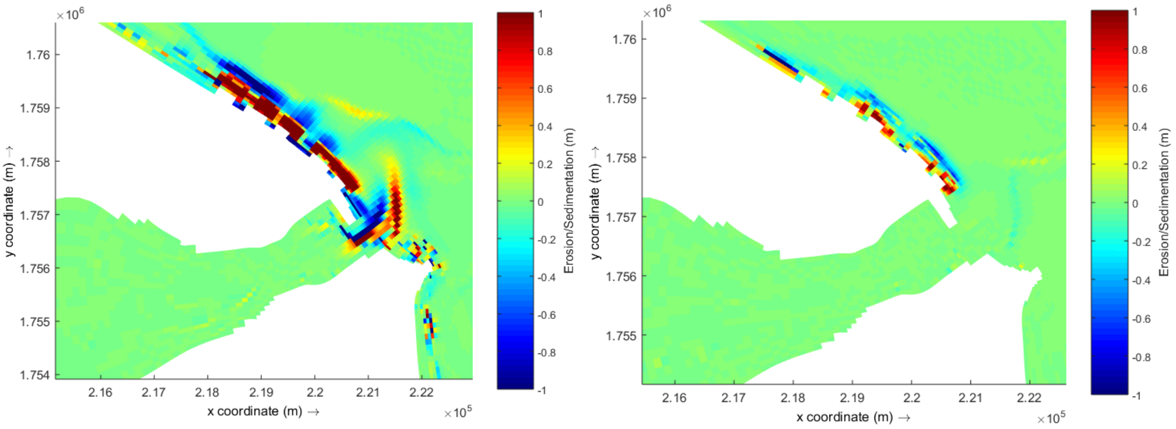


Figure 3.18: Morphological impact due to resorts during (a) winter flood and (b) summer (SE) seasons

The magnitude of erosion varies accordingly to the forcing conditions during ENE waves and a strong erosive effect is also present during SE conditions. The feature is stronger in the region adjacent of resorts, while further to the north erosion is minimized, highlighting the additional northward propagating erosion induced by their construction. In the region immediately downdrift of Vinpearl resort, the stronger sedimentation that forms when the resorts are constructed can be observed. Closer to the inlet, the erosive trend that is present due to resorts is attributed to the stronger southward directed flow towards the inlet triggered by the presence of Vinpearl resort that erodes more sediment and distributes it further to the north inlet side. The observed features in front of the location of resorts represent the local disturbance of the sediment transport pattern due to their presence, with sediment transport towards them and subsequent reflection and transport offshore. These two effects compensate for each other. This can be verified from the trend of the alongshore sediment transport graph, where the cumulative sediment transport values through each transect in front of resorts are in the order of zero.

3.5.5.3. Increased seasonal variation in river discharge levels

The effect of increased seasonal variation in river discharge levels in the morphology of Cua Dai is now investigated for the period that resorts are also present in the north coast. In the winter dry period, the same morphology is created since the river discharge has been kept the same. During winter flood season the combined effect of resorts and of a higher representative river discharge is significant. Changes are visible in the inlet mouth, the ebb delta as well as the north and south coastlines. On the contrary, sublte effects are present in the domain of interest in the summer season, where only the ebb delta seems to be affected more.

The north coastline continues to experience morphology changes under ENE wave conditions with the inclusion of a larger seasonaly varying river discharge. The same transport trend exists as before, where only the impact of resorts was included in the model, in terms of magnitude and direction in accordance to the seasonal intensity. North of the resorts, significant sediment transport takes place that is northward directed inducing erosion there. The feature is less intense in the summer as the forcing conditions are smaller. Within the resorts a steadier morphology is present and the transport magnitude is more uniform. The same morphological features are formed again there. The flow divergence between Fusion Alya and Sunrise resorts still takes place, while in general erosion and sedimentation is present between Fusion Alya and Golden Sand resorts. Downdrift of Vinpearl, a small amount of sediment is directed towards the resorts but the majority is transported towards the north inlet side with a magnitude that is high during the winter flood season and minimum in the summer. There, sediment accumulation is observed that reaches until the region between Vinpearl and Fusion Alya, while closer to the inlet erosion takes place.

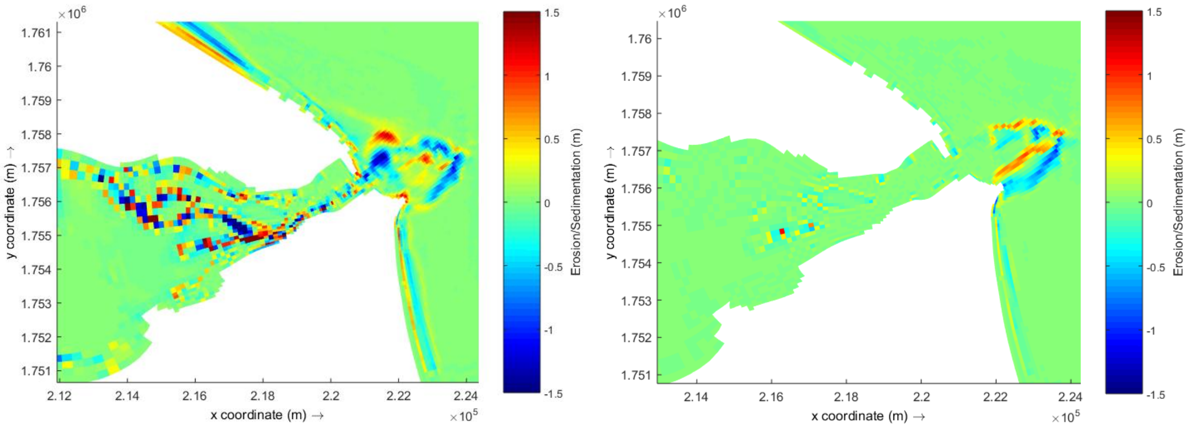


Figure 3.19: Morphological changes during (a) winter flood and (b) summer (SE) seasons in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

The transport divergence is observed to be stronger now during the winter flood season. The higher river discharge that is now included, creates a more concentrated outward directed transport towards the ebb delta resulting in stronger sediment accumulation in its northwest outer region, further reinforced by the local ENE wave pattern. The same interaction is present with the north coast, with sediment to be supplied by the ebb tidal bar but now the effect reaches until Fusion Alya resort. Also, since the feature has a stronger shape, less sediment is transported to the north coast.

In the summer period the magnitude of the bar is significantly less since the river flow reduces a lot and the prevailing wave height is small. Generally, the sediment supply from this feature strengthens furhter the sediment transport towards the north inlet mouth side and the sediment accumulation there. The complex local interaction with the outward transported sediment by the river flow is the cause of this local formation, so a seasonal varying character exists also there. Their interaction is limited in the summer, due to the minimum river flow and the low wave height. From the flood scenario, the interaction of the feature with the sediment that is being flushed out in the ebb delta edge can be observed.

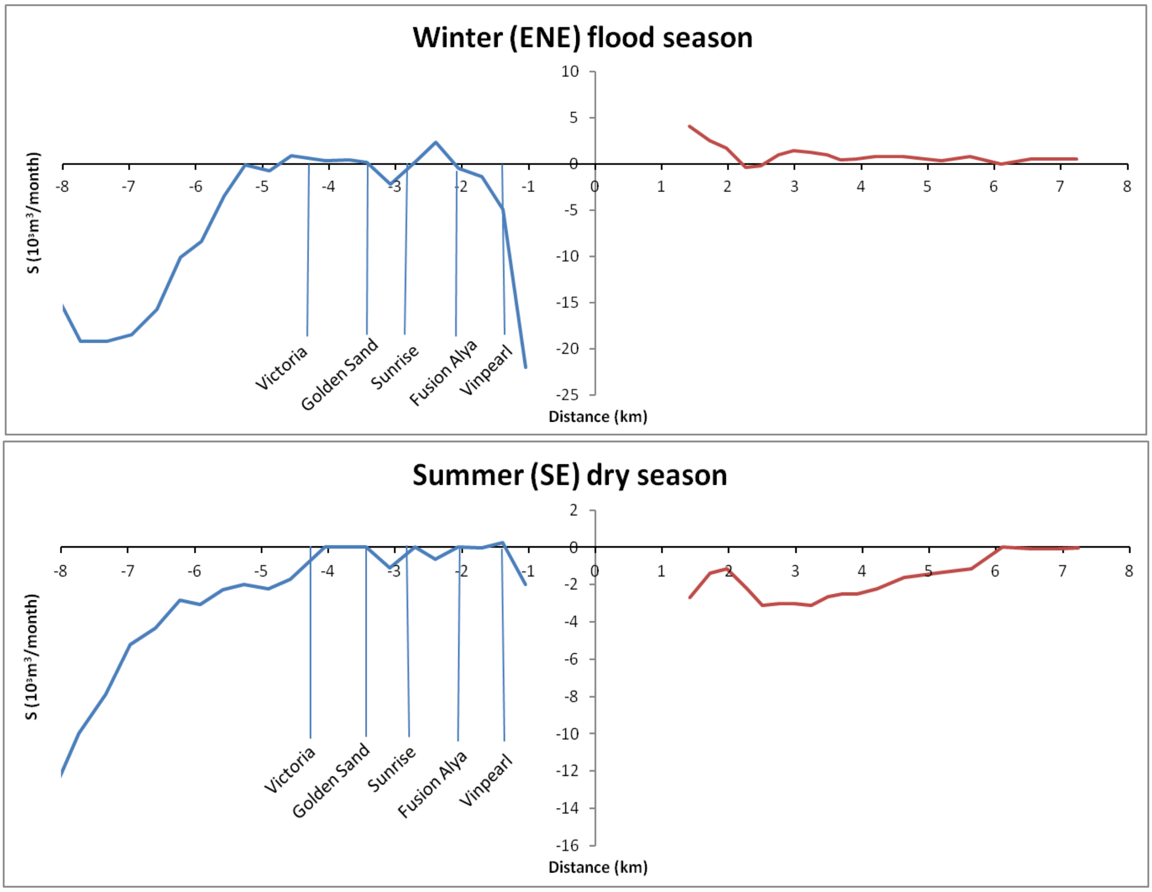


Figure 3.20: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

The effect on the ebb tidal delta is significant in all seasonal conditions. During ENE waves and especially in the flood season, significant erosion takes place along its outer sides and sedimentation is present at the ebb delta center. Local wave breaking is the cause of erosion that redistributes sediment in the center of the delta as well as offshore. Within the river, the effect on the left river bank and the inlet mouth becomes visible over all seasonal conditions. In addition now, the presence of a higher discharge value in the winter flood season creates an impact in the right bank near the inlet. In this case a part of sediment is transported through the inlet towards the ebb delta center while the majority of sand continues to be directed towards the northwest outer ebb delta region. Thus, during the flood season the morphological changes are enhanced significantly while during the summer where the river flow is lower, subtle effects are only present localy. In the south coastline a similar morphological pattern seems to be present again and the morphology is less affected compared to the north coast. Under ENE waves, a constant southward trend takes place and sedimentation is present along the coast with the feature to be stronger during winter flood season. Near the inlet, enhancement of sediment accumulation exists due to the local interaction with the ebb tidal delta.

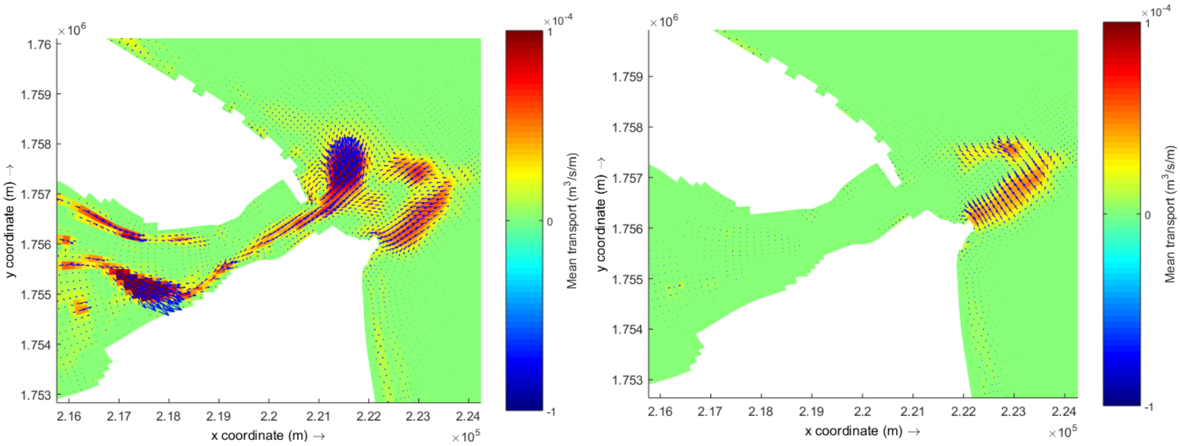


Figure 3.21: Mean transport pattern around ebb delta during (a) winter flood and (b) summer (SE) seasons in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

For the SE conditions in the summer the effect in the domain is limited, since also resticted water is discharged through the river. Mild morphological changes are present in the domain and only in the ebb delta the variation in the morphology is more intense. Along the north coastline a net northward transport takes place in all locations and now the divergence point is not present. Erosion is still dominant northward of the resorts, while within their region steadier conditions exist, with limited erosion and sedimentation that is present as previously between Fusion Alya and Golden Sand. In the north inlet side a smaller amount of sediment is transported there locally and the sediment accumulation is mild, which can be expected since the river flow is limited.

Furthermore, due to the low river discharge and small waves the ebb tidal bar is not formed in the northwest outer side of the ebb delta, so the interaction with the north coast is absent. A different morphology is present in ebb delta, with sedimentation along its north outer side and erosion across the south edge. The pattern is infuenced by the prevailing SE wave direction that creates significant wave breaking in the south ebb delta area, relocating sediment towards the ebb delta center and offshore, while sheltering conditions are present in the north outer side.The prevailing lower summer river discharge has a subtle effect in the morphology of the river domain now, that is limited only in the inlet mouth. Finally, in the south coastline a net northward directed sediment transport is present along the coast inducing mild erosion. Near the inlet the pattern becomes more compex with erosion and sedimentation, while across the last transects a steady morphology is observed.

3.5.5.4. Morphological impact due to increased seasonal variation in river discharge levels

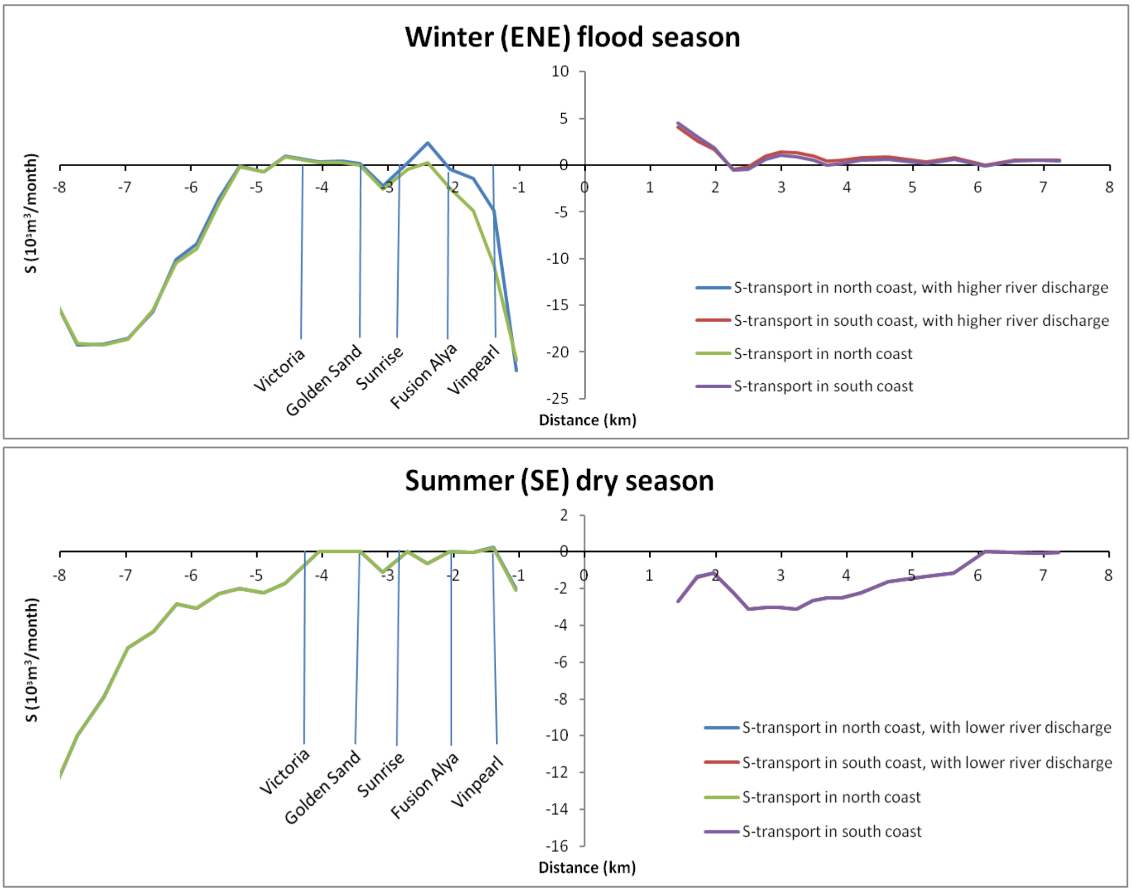


Figure 3.22: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the second morphological period assessing the effect of increased seasonal variation in river discharge levels

The seasonal alongshore sediment transport graphs of Figure 3.22 indicate that the increased seasonal variation in the river discharge imposes a mild effect in the domain that is restricted in the north coast. This effect is present, as expected, in the winter flood season when the river discharge levels increase significantly. From the graph it can be observed that in this season, the region until Sunrise resort experiences directly an escalation of the prevailing wave induced features that dominate locally due to the presence of resorts. More specifically, stronger sediment accumulation is found in the region that starts immediately downdrift of Vinpearl and extends until Fusion Alya resort. The intense offshore river outflow allows the strengthening of the transport divergence between Fusion Alya and Sunrise resorts but also the enhancement of the local erosion and sedimentation there, since the interaction of river flow with the coast is now limited. In the region north of the resorts erosion is still present and only a slight enhancement of this feature is observed in the transects that are located north of Victoria resort. During the summer seasons where the river flow is now significantly reduced, the impact is considered absent and no enhancement of erosion upstream of the resorts is noticeable. The similar transport gradients in the area north of the Victoria resort with the case where the resorts are present without accounting for an increased seasonal variation in the river discharge levels, support the aforementioned remarks and are presented below.

Season	Scenario 2 (m^3/m/month)	Scenario 2 (with increased seasonal variation in river discharge) (m^3/m/month)
Winter (ENE) Flood	7.6	7.7
Winter (ENE) Dry	5.1	5.1
Summer (ENE) Dry	3.6	3.6
Summer (SE) Dry	3.7	3.7

Table 3.7: Comparison of alongshore sediment transport gradients updrift of resorts in the north coastline including also the effect of increased seasonal variation in river discharge levels

The seasonal maps of the domain that present the morphological influence of increased seasonal variation in the river discharge levels, through the induced erosion and sedimentation regions, are illustrated in the following figure. In general, the morphology of the river mouth and the ebb delta is affected, mainly in the winter flood season. The restricted features in the north coastline include a slight enhancement of erosion in the close region north of Victoria resort and less sediment transport and deposition to the north inlet mouth side. The level of morphological variations is in the order of 1 m. The limited influence of the lower river discharge during the summer is also visible. The order of magnitude of the features now varies around 0.1 m. The low amount of sediment transport to the ebb delta results in less erosion in its center. Also the stronger erosion near the inlet then, highlights the enhancement of the local wave transport in this region since the effect of the river is limited.

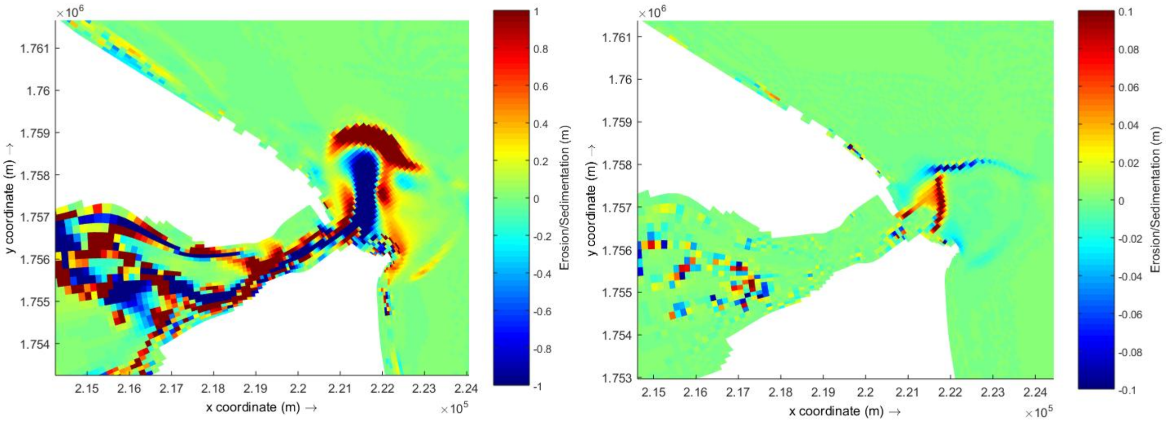


Figure 3.23: Morphological impact due to increased seasonal variation in river discharge levels during (a) winter flood and (b) summer (SE) seasons

3.5.5.5. Final remarks

The assessment of the impact of resorts that represent the second morphological scenario led to important concluding remarks. It has been observed that the construction of resorts created a more stable coastline among them, while sedimentation and erosion became stronger in the neighbouring areas downstream and upstream of their location, verifying their groyne function in the north coastline. Thus, the enhancement of the northward propagation of erosion updrift of resorts was confirmed. The increased seasonal variation in the river discharge levels enhanced slightly this trend during the winter flood season. Additionally, a stronger impact in the region downdrift of the divergence point was also created. In general, the main effect in this case is linked to the changes in the morphology of the river mouth and of the ebb delta that experience additional variation. The impact on the south coast during this morphological period is absent, which continues to experience a steady accretive trend.

Figure 3.24: Main sediment transport patterns for ENE and SE wave conditions in the second morphological period

In addition, the simulations bear resemblance with the recorded morphological features during 2010-2015 in the north coast that have been obtained from available Google Earth images. The continuous erosion near the inlet area is observed, which has been already linked to the simulated strong transport towards the inlet mouth that is influenced by the presence of Vinpearl resort. In the region between Vinpearl and Fusion Alya resorts erosion is present in reality, although the simulations indicate sediment accumulation. The presence of extreme flood and storm events could be a possible explanation for the prevailing erosion, enhancing also further the erosion near the inlet. However, the continuous erosive trend of the region in the period 2010-2015 implies that the erosion there is caused probably by the local complex alongshore transport pattern due to the building of resorts, which the model has not been able to reproduce.

Figure 3.25: Coastline evolution among resorts during period 2010-2015 obtained from Google Earth

The erosion and sedimentation areas in the regions among Fusion Alya and Golden Sand resorts that the model has highlighted, are verified. The northward propagating erosive trend between Golden Sand and Victoria as well as the further propagation of erosion to the north is also confirmed. Based on these, it can be concluded that the present scenario can reproduce in a satisfying level the actual morphological trends that have been observed during the period 2010-2015.

3.5.6. Scenario 3: Intervention in public Cua Dai beach (2016-2017)

The present morphological scenario assesses the influence of sandbags that have been placed along the public Cua Dai beach. In general, sandbags have been placed in several locations across Cua Dai beach over the years aiming to cope with the ongoing erosion of the coast, since it was considered as a measure that could provide stability and reduction of sediment transport. The use of geotextile bags filled with sand, even though it is considered to be an ecological approach, cannot provide a long term solution because the resilience against the prevailing conditions is small. In addition, the cost of such an approach is high, after taking into account its restricted lifetime.

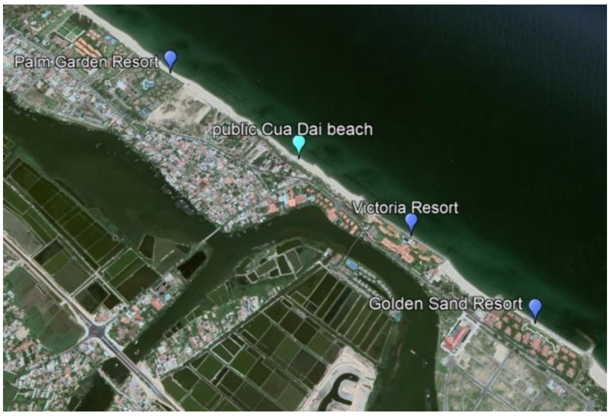


Figure 3.26: Location of public Cua Dai beach

Due to the existing northward propagating erosive trend that has been presented in the previous morphological scenarios, erosion has reached the public Cua Dai beach that is located between Victoria and Palm Garden resorts. Sandbags have been placed as measure against expansion of the erosion and the morphological influence of them is investigated in the present scenario that aims to reproduce the morphology of the period 2016-2017 under the selected representative wave and river discharge conditions. The inspected enhancement of erosion updrift of their location is attempted to be simulated here, since by 2017 erosion reached the coast in front of Palm Garden and Agribank resorts. During this period, the south coastline experienced sediment accumulation as in the previous morphological periods.

The sandbag behaviour is included in the model schematizations with short groynes, due to the fact that sandbags are expected to block the alongshore sediment transport across their location, in the same way as the resorts were represented in the model. The shorter groyne length is chosen because the impact of sandbags in the coast is not persistent, due to their limited resilience. Although their presence is not expected to induce intense changes in the morphology, the significant coastline length that is occupied is anticipated to be the most influential factor for the northward propagation of erosion. For this morphological scenario, Palm Garden and Agribank resorts are still not included in the simulation as the coastline in front of them is not eroded yet. The same simulation period is considered as in the previous scenarios, in order to allow comparisons and investigation of the effect of sandbags in the evolution of the local morphology of the coast. The representative river discharge values used are the ones that indicate an increased seasonal variation in the river discharge levels. In the end of this section the effect of the sandbags is investigated separately, in order to highlight the changes that have been present in the morphology strictly due to their presence.

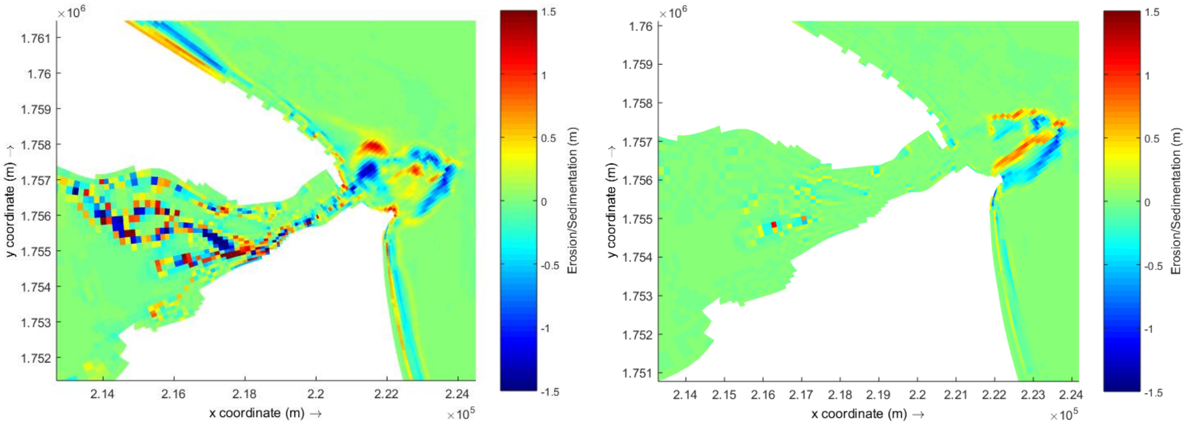


Figure 3.27: Morphological changes during (a) winter flood and (b) summer (SE) seasons in the third morphological period

The north coastline experiences a similar morphological trend under ENE wave conditions with the second morphological period. Among the resorts stable conditions exist with restricted local features in the region between Fusion Alya and Golden Sand resorts. There, erosion and sedimentation can be observed in accordance to the previous morphological scenario, since the interventions and the forcing conditions are not different. The transport divergence is still present between Fusion Alya and Sunrise resorts. The high river discharge in the winter flood season reinforces the concentrated outflow from the river towards the northwest ebb delta region, reducing the existing interaction with the north coast and strengthening the wave induced alongshore trend. The lower river flow during the winter dry season reestablishes the interaction with the region downdrift of the divergence point, weakening the transport divergence and affecting the southward directed transport there. Sediment accumulation is observed between Vinpearl and Fusion Alya resorts, covering a distance of 1km. Near the inlet, adjacent to Vinpearl resort, sedimentation also takes place as sediment is locally diverted towards the structure. The magnitude varies with respect to the seasonal conditions. Closer to the inlet, erosion is present as sediment is transported towards the north inlet side and sediment accumulation takes place there locally due to the local interaction of the sediment transport towards the inlet and the outward sediment transport induced by the river. This pattern is further enhanced by the ebb tidal bar that forms under ENE conditions in the northwest outer ebb delta, causing sediment transport to the region when the wave pattern and river discharge are more dynamic. In the area north of sandbags, a strong northward transport pattern is now present that induces erosion. The feature is more intense during the winter flood period and a milder effect is present in the summer. A small sediment transport divergence is created adjacent to the sandbags, transporting sediment to the south for a distance of approximately 600 m. This effect is stronger when the wave conditions are more energetic and does not seem to be affected by the river discharge, since the presence of resorts and the sanbags interferes and alters the transport pattern north.

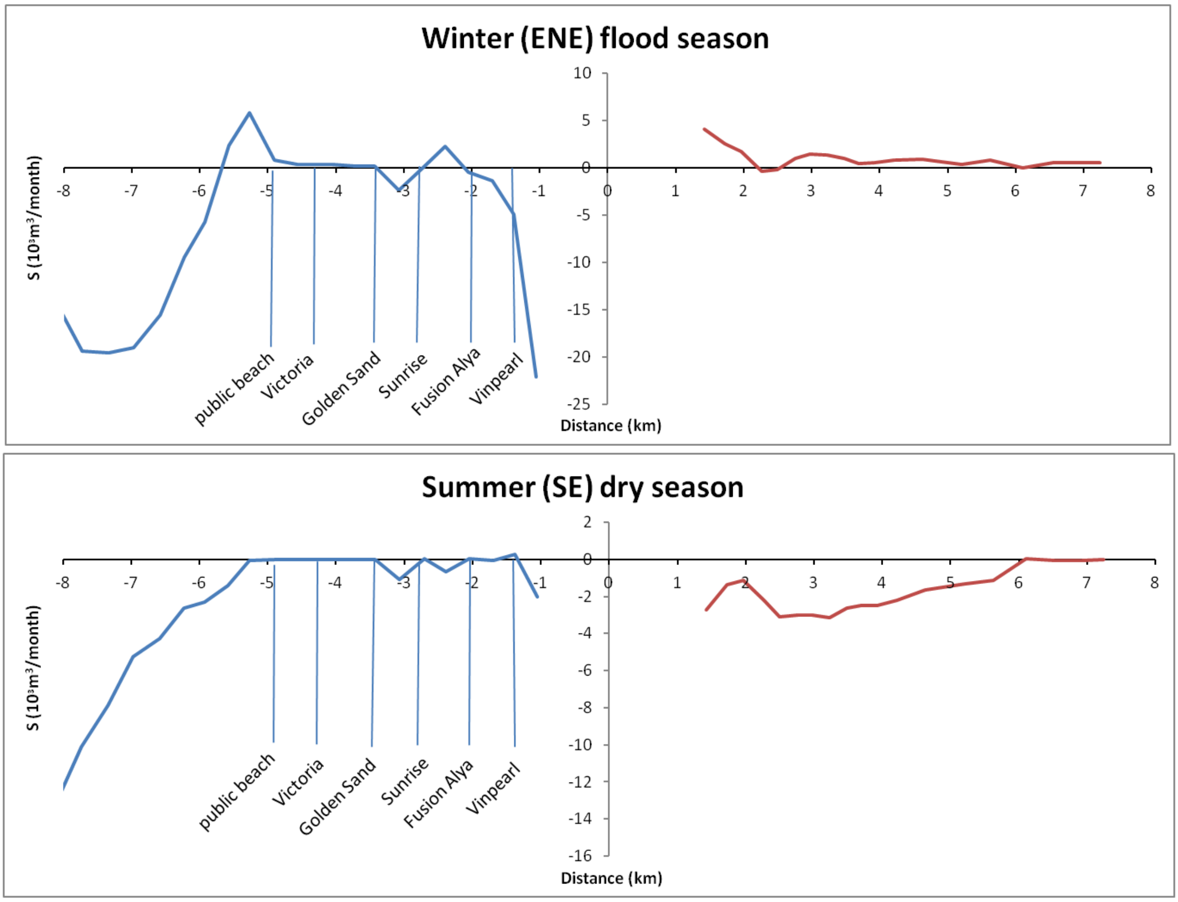


Figure 3.28: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the third morphological period

Inside the river, constant regions are affected and the magnitude is related to the river discharge levels. The left river bank and the area near the inlet experience more intense sediment transport. The increased river discharge during the winter flood season affects also the right river bank near the mouth, causing erosion that is not present in the remaining seasons where the river discharge is less. The sediment is transported through the inlet towards the northwest ebb delta edge, creating the previously observed ebb tidal bar, which now continues to have a strong form in the winter flood season. In the remaining ebb tidal delta, erosion can be observed along the outer regions from where sediment is relocated to its center causing local sedimentation, but also offshore. The prevailing trend of the south coastline is more uniform during ENE waves. A net southward transport is observed and the coast accretes. The transport increase near the inlet is attributed to the local dynamic interaction between the waves and the ebb delta.

When SE conditions prevail in the summer, a different trend can be observed in the overall domain. In general, milder changes are present in accordance to the level of forcing. The north coastline experiences a net northward directed alongshore sediment transport. Erosion is the main feature there, with restricted sediment accumulation in the area immediately downdrift of Vinpearl resort. The transport intensity in the region north of sandbags is stronger and the northward trend is still present. Among the resorts the transport magnitude is limited and local erosion and sedimentation is only observed between Fusion Alya and Golden Sand resorts. Near the inlet the transport has also a northward direction and only in the in the north inlet side there is transport to the river. Now there is no interaction with the ebb delta, since the ebb tidal bar does not form. The outflow from the river is limited and is directed towards the ebb delta center. In addition, the prevailing wave direction has a weakening effect there. The morphological changes in the ebb delta are also different. Sediment accumulation is created along its north outer region and erosion is present in the south outer ebb delta area, influenced by the prevailing SE wave direction. Along the south coast, a constant transport direction to the north is created that causes erosion. Near the inlet erosion and sedimentation is observed due to the local complexity in the region, while across the last transects the morphology does not change.

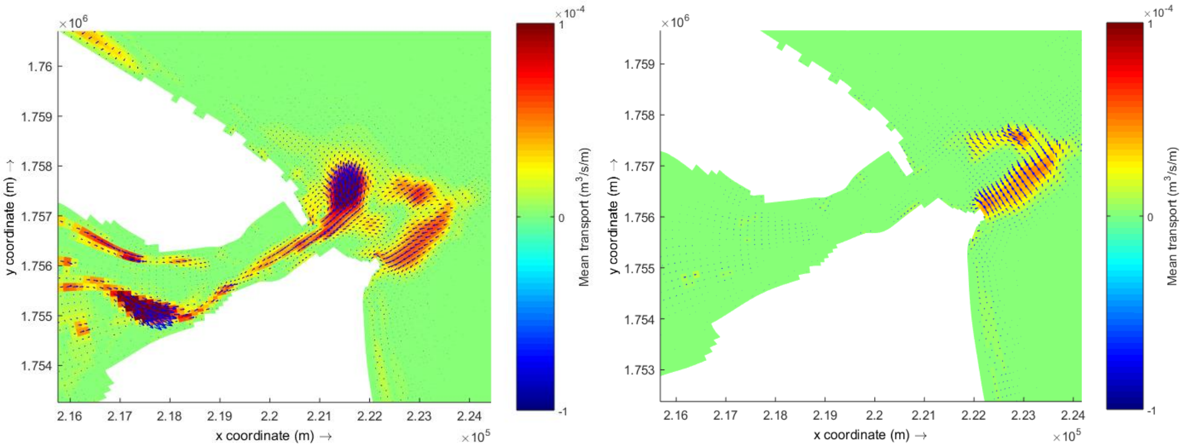


Figure 3.29: Mean transport pattern around ebb delta during (a) winter flood and (b) summer (SE) seasons in the third morphological period

3.5.6.1. Morphological impact due to sandbags

By inspection of the alongshore sediment transport trends, it can be observed that the effect of sandbags is restricted, as expected, into the region north of their location. There, the steeper gradient that increases in transport direction indicates stronger erosion in the scenario that sandbags have been included in the model, compared to the second morphological scenario that includes also the effect of an increased seasonal variation in the river discharge levels. In the remaining north coast the same trend is observed, indicating that the area remains unaffected by the presence of sandbags. The overall transport gradients in the region north of the location of sandbags are presented in the following table.

Season	Scenario 2 (m^3/m/month)	Scenario 3 (m^3/m/month)
Winter (ENE) Flood	7.7	10.2
Winter (ENE) Dry	5.1	7.0
Summer (ENE) Dry	3.7	4.7
Summer (SE) Dry	4.2	4.9

Table 3.8: Comparison of alongshore sediment transport gradients updrift of sandbags in the north coastline. In both cases the increased seasonal variation in the river discharge levels is considered.

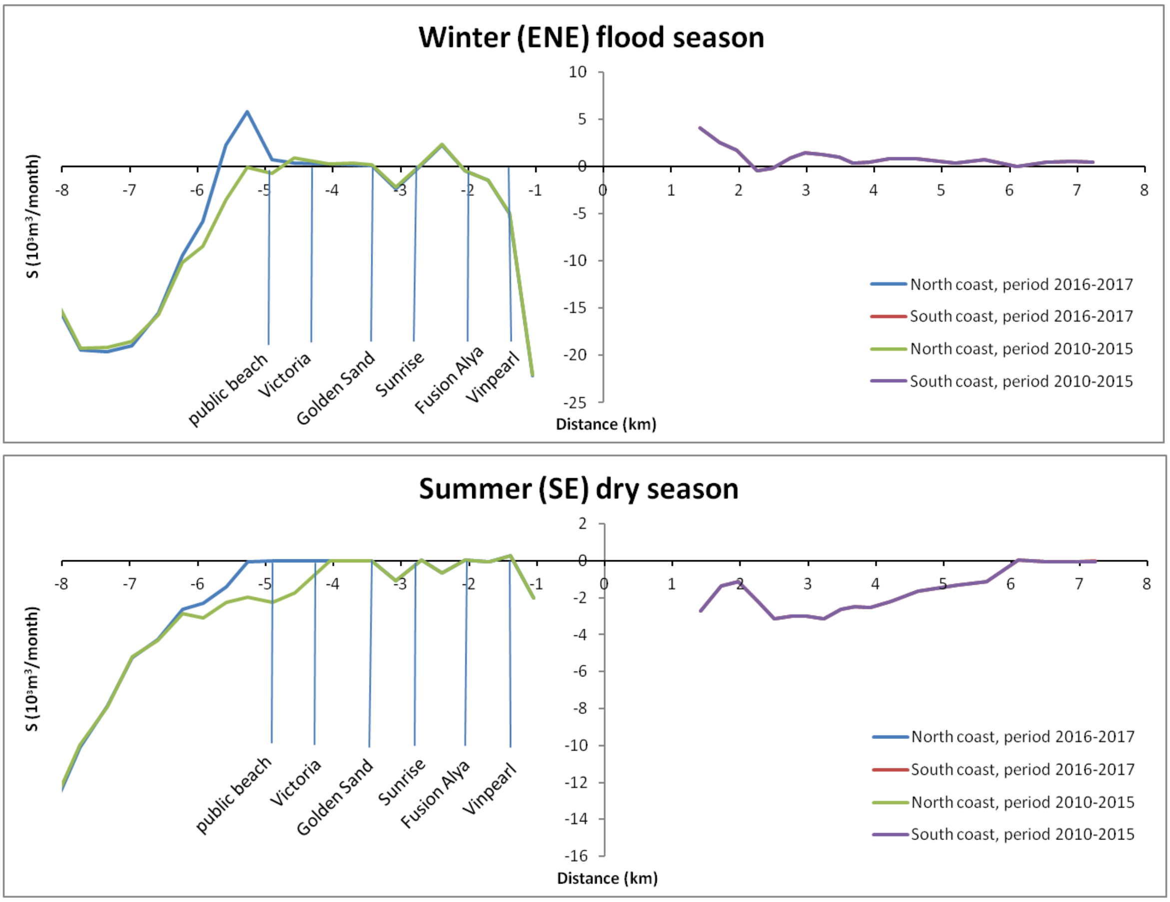


Figure 3.30: Alongshore sediment transport patterns during (a) winter flood and (b) summer (SE) seasons in the second and third morphological periods

The resulted seasonal morphological changes due to the presence of sandbags in the public Cua Dai beach after an annual forcing duration, are presented in the following figure. From here, it can be verified again that the effects on the morphology are restricted to the region north of the public beach. The additional changes that are observed in the inlet mouth and ebb delta are not taken into account. This is the case because the dynamic prevailing conditions there result in a small variability in the intensity of the observed features, even though the same forcing parameters have been used as input in the numerical simulations. So, the local limited differences there do not imply an actual effect.

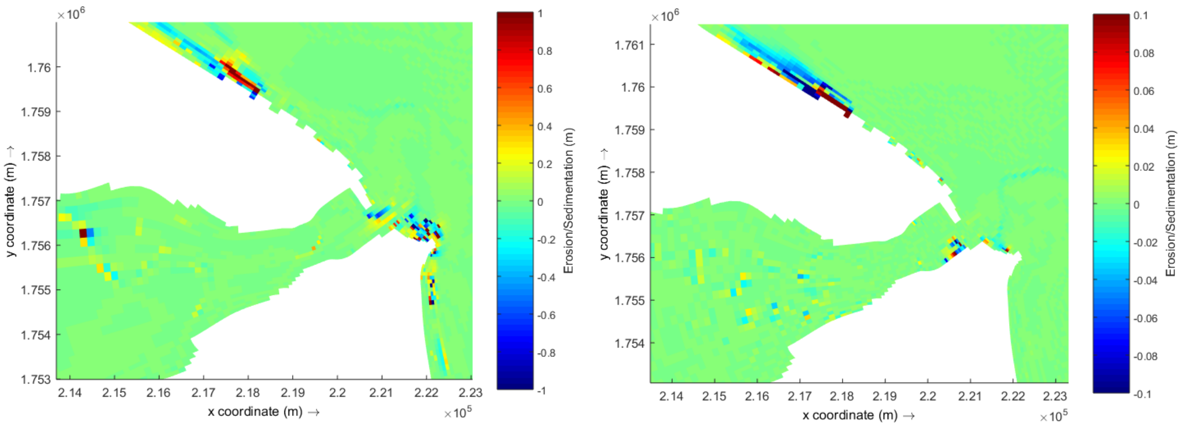


Figure 3.31: Morphological impact due to sandbags during (a) winter flood and (b) summer (SE) seasons

The level morphological changes is not the same through all seasonal conditions. During the summer, the observed features have a lower intensity and a smaller scale is used in order to illustrate them, which is in the order of 0.1 m. On the contrary, the erosion and sedimentation features in the winter seasons have a magnitude in the order of 1 m. This difference is explained by the level of wave and river forcing that takes place in each case. In all periods, the additional erosion upstream of the location of sandbags is presented and verifies the stronger morphological impact that is induced by their presence. As it can be seen, the stronger erosive feature is located close to the region of sandbags, while further away to the north the morphology is not affected yet which shows the enhancement of the propagating character of erosion. Furthermore, the absence of changes in the remaining north coast proves that this human intervention did only impose a local influence in the morphology without affecting the overall trend of the north coast. Offshore of the location of sandbags, the morphological variations are the result of the local disturbance in the sediment transport pattern, with sediment transport towards them and subsequent offshore reflection that compensate for each other.

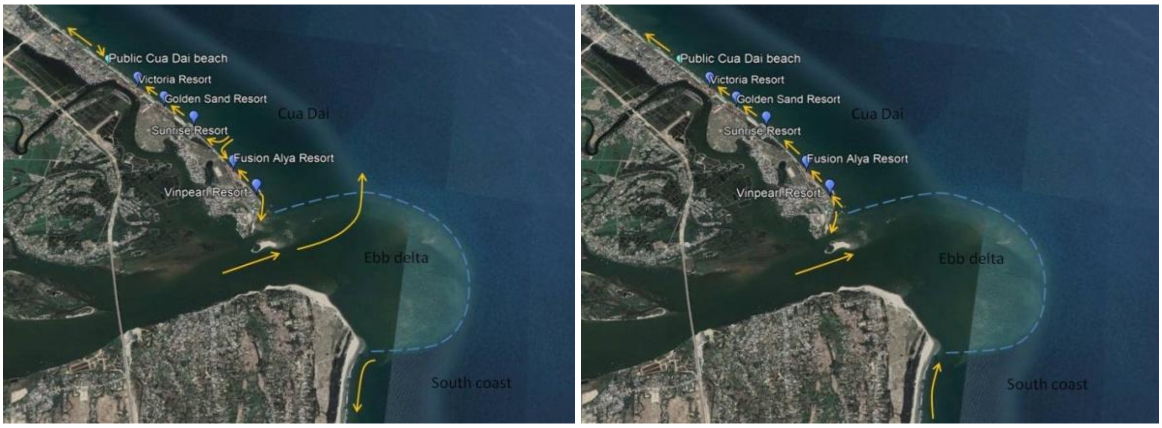


Figure 3.32: Main sediment transport patterns for ENE and SE wave conditions in the third morphological period

After examining the presence of sandbags in the morphology of the overall domain where Cua Dai is located during the period of 2016-2017, several conclusions were extracted. The morphological pattern that has been observed in the previous scenario with inclusion of a larger variation in the river discharge levels is still present. Erosion has been observed in the north coast in the region updrift of the location of the sandbags, while in the south coast a steady accretive behaviour is present. The enhancement of erosion that is shifted further to the north due to the presence of sandbags is also highlighted, indicating the additional impact that has been induced in Cua Dai, accelerating the existing erosive trend. Therefore, the anticipated groyne function of the sandbags on the morphology is reproduced. The present morphological scenario has been able to mimic the real morphological trends that have been observed in the wider domain where Cua Dai beach is located in a satisfying level.

3.5.7. Extreme flood and storm events

The assessment of extreme events is essential, as they influence abrupt changes during their small forcing duration that alter significantly the local morphology. The recovery of the coast after the occurrence of an extreme storm or flood event is slow and a long term period may be necessary in order to restore the original condition there. The impact of extreme events needs to be explored in the case of Cua Dai since the presence of storms and floods affect frequently the overall domain during the flood season. For this purpose, the effect of the two characteristic storm and flood events that take place in the winter flood season and have been presented before are assessed through model simulations. In all cases, a simulation duration of four days has been selected, as it is considered a typical time period to represent an extreme event. For the remaining forcing parameters, the regular representative conditions of the winter flood season are used. All simulations consider the morphological conditions of the period where no human interactions took place in Cua Dai beach, in order to observe their actual impact on the coast, without being influenced by additional features. In the beginning of the section the extreme flood event scenarios are presented, followed by the assessment of the extreme storm cases. The figures that contain the morphological changes and transport patterns are selected to illustrate the prevailing phenomena, while in Appendix B the alongshore sediment transport trends in the north and south coastlines can be observed.

3.5.7.1. Extreme flood events

For the first flood event with a discharge of Q_1=5018 m^3/sec, a clear morphological impact along the river and the ebb delta is observed. The strong river discharge flushes out sediment, causing local morphological changes that are concentrated along the left river bank and the mouth area. Also, the right river bank becomes affected by the high outflow. The ebb tidal delta morphology alters by the energetic conditions, with erosion in its centre and sedimentation along its outer regions, which is explained by the strong sediment transport through the mouth that erodes the sediment in the ebb delta centre and causes deposition further away. The magnitude of the ebb tidal bar that has been observed under regular seasonal conditions has now significantly increased. Its interaction with the north coast is now limited as the strong outflow shapes a distinct feature, which does not diffuse in the region.

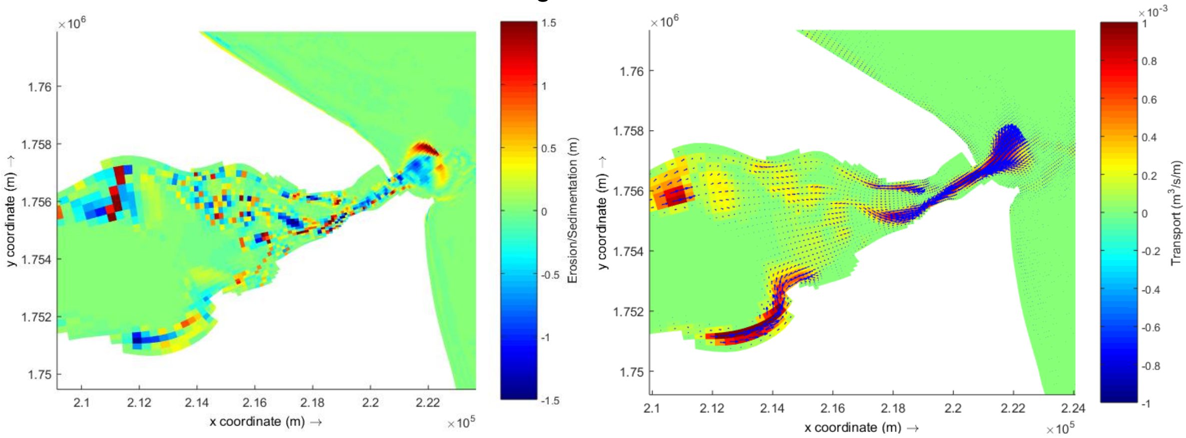


Figure 3.33: Morphological changes and transport pattern for flood event 1 (Q= 5018 m^3/sec)

The morphological changes in the coastlines adjacent to Cua Dai inlet are milder and subtle features are created compared to the flood affected regions. The alongshore sediment transport graph reveals that the transport magnitude during the flood event is low. In the north coastline erosion dominates, yet local accretive locations are present. Furthermore, the transport divergence point is observed, located at a distance of approximately 3 km from the inlet. After comparison with the corresponding alongshore sediment transport trend during flood season of the first morphological period, it is indicated that a similar pattern is formulated. It can be concluded that the less complex transport pattern that is present now downdrift of the divergence point results from the reduced effect of the river discharge in the region. The south coastline seems unaffected as very gentle gradients exist, while also the sediment transport magnitude is close to zero, apart from the region near the inlet. There, the local bypassing from the ebb delta induces more energetic transport conditions.

The same regions become affected in the second representative flood event, which is simulated for an extreme river discharge of Q_2= 7660 m^3/sec, being the river area and the ebb delta. A stronger magnitude of the observed features is now present. Due to the larger prevailing river discharge, the stronger outflow of sediment induces major erosion in the ebb delta centre. The transported sediment is mainly directed towards the outer northwest ebb delta region, creating a more distinct ebb tidal bar which now occupies also a larger area. Furthermore, now a significant amount of sediment is transported to the ebb delta centre. Along the north coast a similar transport magnitude is present that creates the same morphological features as in the previous flood scenario, which is anticipated since the wave forcing conditions are the same. Again, no interaction with the ebb tidal bar is observed. The south coastline continues to experience stable conditions. Moreover now, the small bypassing from the ebb delta that has been noticed in the previous scenario is absent, since the strong river outflow transports sediment to the south, but this pattern takes place now further offshore.

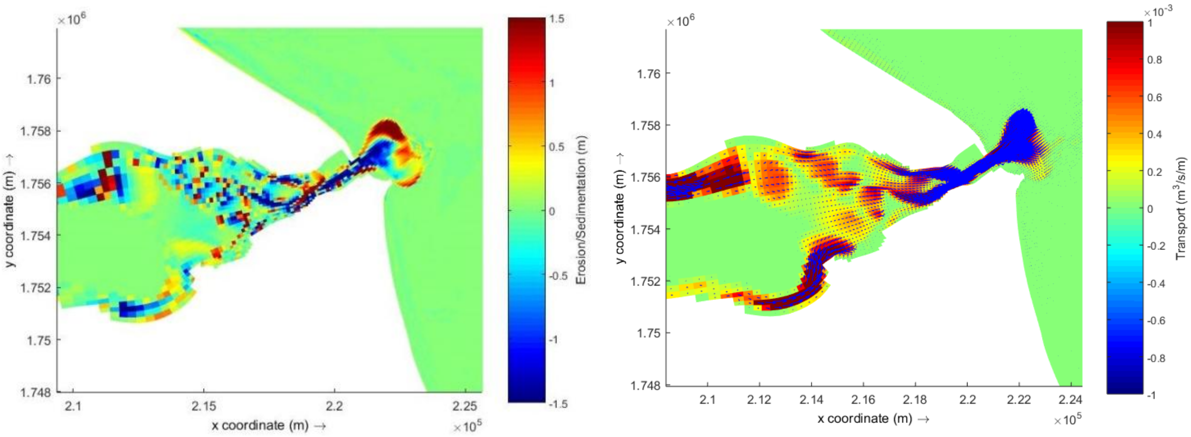


Figure 3.34: Morphological changes and transport pattern for flood event 2 (Q=7660 m^3/sec)

To conclude, a similar morphological behaviour is identified for the two extreme flood scenarios, with a different intensity. The main affected areas are the river and the ebb delta. In the river mouth a strong erosive effect along the right river bank has been observed, which is not present during the simulation of the regular representative seasonal conditions. The presence of this feature starts to be visible only with the inclusion of a larger seasonal variation in the river discharge, as the river discharge in the flood season increases. This behaviour could be linked to the recorded erosion of the river mouth that induced channel shifting in 1989 and subsequent welding of an existent ebb tidal bar to the north coast in the following years. Thus, the presence of extreme floods can explain the rapid morphological change of the inlet morphology. Furthermore, the formation of the ebb tidal bar in the northwest outer ebb delta that has been already observed during the investigation of the morphological scenarios is now stronger. It can be concluded that the observed behaviour of the river sediment transport pattern under extreme flood events has influenced the creation of the ebb tidal bar that was present in the region in 1988 and could be the result of a strong flood event or of recurrent flood events. Finally, it is highlighted that the presence of extreme flood events weakens the interaction between the river flow and the waves along the north coast, since in this case the river outflow is more offshore directed.

3.5.7.2. Extreme storm events

During the representative ENE storm the morphology changes along the north and south coastlines, as well as in the ebb tidal delta. The river area is not affected, since the regular winter flood discharge creates a milder effect in the local morphology compared to the storm induced wave pattern. The level of morphological changes is in the order of 1.5 m, which is considered to be large after taking into account the limited duration of the event. Erosion and sedimentation take place across the north coast. Now the divergence of transport is small and is located more south, approximately 1.5 km from the inlet. In the updrift area, the sediment transport is directed to the north while downdrift the transport is towards the inlet. In general, the alongshore pattern is heavily influenced by the sediment that is coming from offshore that also induces transport at the north outer ebb delta area. Due to the prevailing wave pattern the previously observed ebb tidal bar has now a more diffused shape in that region. Across the south outer region of the ebb delta sediment transport takes place towards its centre. Strong sedimentation is mainly observed in the south coastline. The southward directed transport amount near the inlet is significant. There, approximately 3 km from the inlet sediment transport convergence takes place, creating a local sedimentation region. Further away along the last transects, erosion can be also found but the intensity is not large, since a gentle northward transport gradient exists. The transport trend results from the interaction between the prevailing wave pattern and the sediment bypassing near the inlet from the ebb delta, which influences the transport behaviour there.

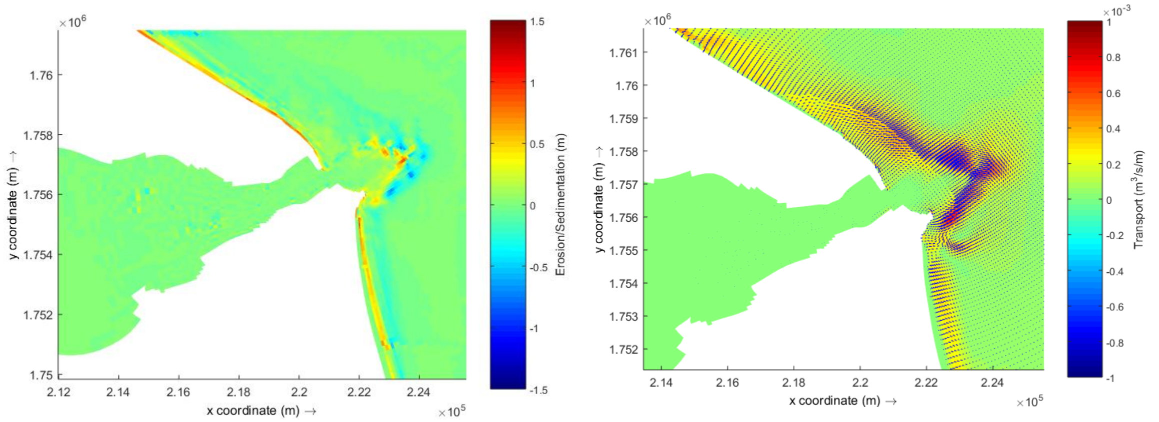


Figure 3.35: Morphological changes and transport pattern for ENE extreme storm event

A different morphological behaviour is created for a storm induced by north incoming storm waves. Again, the impact is mainly located in the north and south coastlines as well as the ebb delta, while the river area remains unaffected and the morphological changes there are limited compared to the remaining region. The intensity of the observed morphological features is stronger than before, influenced by the strong wave forcing despite its short duration. The extreme gradients that take place along the north coast in comparison to the milder gradients that prevail in the south coastline, point out the sheltering effect of the ebb delta there. This is also supported by the significantly larger transport magnitude at the north coast. A net southward sediment transport is observed along the north coastline as expected due to the forcing direction. Erosion is present along the last transects that transforms into sediment accumulation in the area adjacent to the inlet, over a distance of 4 km. No divergence of transport exists now, since the wave direction is more parallel to the coast creating a constant trend.

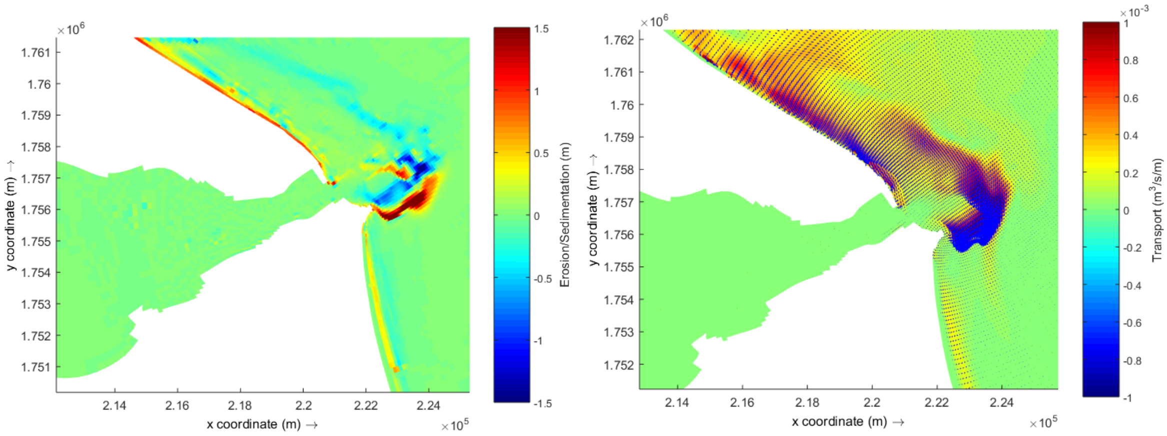


Figure 3.36: Morphological changes and transport pattern for N extreme storm event

Along the north outer area of the ebb delta, the sediment is transported towards its centre, inducing sedimentation. Adjacent to this region, the strong incoming wave pattern creates extreme erosion, relocating the sediment towards the south outer area of the ebb delta. A large local sediment accumulation is created in that location and the sediment transport from the ebb delta reinforces this trend. Only a small amount of this southward directed sediment transport reaches the south coastline. There, stable conditions are found even though near the inlet erosion is formed due to the local dynamic pattern.

The assessment of the impact of two characteristic storm wave conditions has been realized for the wider domain that includes Cua Dai. The varying forcing direction influenced the formation of different morphological features. The north and south coastlines, as well as the ebb tidal delta became affected. During ENE storm conditions, similar morphological features to the previously observed regular ENE seasonal simulations are inspected, that now have a stronger intensity. When a north incoming wave forcing direction prevails, a uniform transport direction is observed in both coastlines. The erosive trend in the upper region of the north coast has been observed in all cases. On the contrary the south coastline experiences milder changes. Finally, it must be highlighted that the morphological impact due to an extreme storm event is significant, creating abrupt changes that form during a short term period. The variation of the morphology due to these events accelerates the existing impact of the regular seasonal forcing conditions, enhancing the magnitude of the resulted features. Thus, it can be concluded that the presence of storm events reinforces the prevailing regular morphological trend in the area.

3.6. Conclusion

Representative seasonal conditions have been selected for the influencing forcing parameters that prevail in the wider domain where Cua Dai beach is located. The performance of the existing numerical model under these selected conditions has been verified by reproduction of characteristic morphological trends that have been recorded in the region. For this purpose, simulation scenarios have been created, assessing the seasonal morphological patterns over an annual cycle of three morphological periods. The impact of extreme events is another influencing aspect that has been explored. Additional simulations of characteristic storm and flood events during the winter flood season have been performed in order to assess the morphological features that could be linked strictly to extreme forcing conditions. Based on these, understanding of the system is gained and important remarks are made.

The local wave climate and river discharge conditions through a year are represented with single values for each of the winter seasons while two wave values are selected for the summer period due to the prevailing bidirectional character, creating a total of four representative seasonal conditions. A method is proposed in order to acquire the seasonal representative wave parameters that is based on comparison between available alongshore sediment transport graphs of each of the influencing wave classes with the ones of the corresponding net seasonal direction. For this purpose three criteria have to be satisfied, being the sediment transport magnitude, the transport trend along the north and south coastlines and the occurrence frequency. In the case of river discharge, the seasonal selected parameters are determined based on the available monthly averaged database. For the selection of representative conditions for extreme storm and flood events, the corresponding available extreme records are used.

From the first morphological period that is simulated, where no interventions existed in the coast, the prevailing seasonal morphological pattern of the domain is identified. Common features are observed for ENE waves with a magnitude that varies with the forcing intensity, while a different result is formed for SE conditions. Under ENE wave conditions, divergence of sediment transport is inspected in the north coast. Updrift of this location, an erosive trend is found. In the downdrift region the transport pattern is more complex with erosion and sedimentation areas, and the transport is southward directed. From there, sediment is transported to the north inlet side and a local sedimentation region is formed. Interaction is present with the outward directed river discharge that affects mainly the area along the left river bank and the inlet mouth. From the river, most of the outward directed sediment is transported to the northwest outer region of the ebb delta, forming a local ebb tidal bar. It has a stronger magnitude during the winter flood period and a milder effect is present during the summer. The local prevailing wave pattern reinforces this trend. The feature interacts with the north coast in the region downdrift of the divergence point, as sediment is transported from it, reinforcing the southward directed transport trend near the inlet and increasing the complexity in the region. Along the south outer side of the ebb delta, erosion is present due to sediment redistribution that is induced by the local wave breaking. A steady accretive trend is observed along the south coastline that has a net southward direction. The sediment accumulation is stronger near the inlet as a result of the local interaction between the ebb delta and the south coast due to sediment bypassing.

The presence of SE wave conditions induces a net northward transport pattern in both coastlines. The erosive trend in the upper north coast is still present, while divergence of transport is absent. Now, a restricted amount of sediment is transported to the north inlet side, minimizing the local sediment accumulation that has been previously observed there. No ebb tidal bar is formed now since the prevailing river discharge does not create significant sediment transport towards the northwest outer area of the ebb delta. In addition, the wave pattern now has a weakening effect there. Due to the dominance of SE waves a different trend is present in the ebb delta, as the waves hit mainly the south area, creating local erosion and transport of sediment towards the ebb delta centre. The net northward transport direction that is present along the south coastline, influences erosion even though the feature is mild.

The impact of resorts along Cua Dai beach is assessed in the second morphological scenario. Their presence affected only the morphology of the north coast, creating a more stable coastline among them with limited features. Due to their construction, the sediment transport divergence location shifted more south. It has been concluded that the resorts enhanced the propagation of erosion further to the north. By considering also the effect of an increased seasonal variation in the river discharge levels, additional remarks have been made. The impact is mild and is restricted in the north coast, affecting the area downdrift of the transport divergence location. There, the larger prevailing river discharge during the winter flood season creates a stronger outward transport from the river to the northwest outer ebb delta area, limiting the interaction with the north coast and strengthening the effect of the local wave pattern. In the remaining seasons no effects are present.

The influence of sandbags is assessed in the third morphological scenario. A local impact is observed, restricted into the upper north coast, updrift of their location. It is highlighted that there the propagation of erosion has been enhanced, shifting further to the north. The effect on the morphology is found to be larger during the winter seasons and milder during the summer.

Finally, the simulation of extreme events provides additional insight in the prevailing dynamics. The erosive trend in the north coast remains present under non cyclic abrupt events, while its magnitude is related to the level of forcing. During extreme flood events, the impact along the north and south coastlines is found to be limited compared to the significant morphological changes in the river and ebb delta. A large amount of sediment is flushed out from the river towards the northwest outer ebb delta, strengthening the formation of an ebb tidal bar. When extreme storm events are present, the effect along the north and south coastlines as well as in the ebb tidal delta becomes dominant. The erosive trend in the upper region of the north coast is now more intense. The assessment of extreme events can explain the acceleration of inspected morphological trends. Furthermore, it can provide insight to the formation of morphological features that are not influenced by the regular seasonal conditions.

It can be concluded that the main recorded morphological trends of the domain have been reproduced in a satisfying level. A common observation in all simulation scenarios is the significant impact that the north coast experiences by the prevailing forcing conditions compared to the south coastline, where in general mild changes are present.

During all seasonal conditions, the prevailing erosive behaviour of the upper region in the north coast has been highlighted. The various interventions that took place in Cua Dai as well as extreme events accelerated this pattern.

4. Mega nourishment design

4.1. Introduction

This chapter begins by introducing the design approach. Then, the design characteristics that a mega nourishment design has to have in order to effectively deal with the problem of erosion in Cua Dai beach, are being determined. For this purpose, several design aspects are defined. The required amount of sediment, the lifetime, the location as well as the shape of the nourishment, form the primary design aspects that are investigated. Design choices are taken for the remaining parameters. After all parameters are defined, the incorporation of the designs in the numerical model is presented. Furthermore, the prevailing dynamic environment of Cua Dai highlights factors that need to be considered for the simulation of the designs. The assessment of the final nourishment designs in terms of their seasonal behaviour is thoroughly examined in the next chapter (Chapter 5).

4.2. Design approach

A design solution must be proposed that can cope with the long term problem of erosion in Cua Dai beach in an optimal way. An essential aspect that safeguards the success of any mega nourishment design is the inclusion of the social parameter in the design approach. Various stakeholders are connected to Cua Dai beach through economical activities and interests that are heavily affected by the ongoing coastal erosion. Based on the stakeholder analysis that has been conducted by Fila et al (2016) and has been briefly introduced in Chapter 2, the power and interests connected with the Cua Dai beach can be linked mainly to two influencing stakeholder groups.

The public authorities are responsible for the benefit of all the economic activities of the citizens in Hoi An, related also to Cua Dai beach. Their aim is to provide a solution that will not impede the existing balance by giving privileges or hampering individual stakeholder groups. Yet, they recognize the importance of preserving the existing touristic activity that takes place across the coast from which Hoi An benefits largely. However, the resort owners will have a larger direct benefit on any nourishment attempt on Cua Dai beach if the coast in front of their properties is expanded. The resorts are spread across Cua Dai in a distance of approximately 5 km, occupying the majority of the coast there. Thus, a mega nourishment design that will feed Cua Dai beach will significantly benefit the resort owners which will be strengthened economically on the long term.

Based on the above reasoning, it has been considered crucial to include the resort owners as financial contributors to a mega nourishment design. The recreation of a significant part of the coast in front of their properties is an essential motive for them in order to contribute financially to a nourishment design solution. However, it is possible that the resort owners may deny any financial contribution. In this case, the public authorities must be able to provide a solution that will deal with the ongoing erosion in the coast that has now reached the region of Palm Garden and Agribank resorts and is moving further to the north, including the public Cua Dai beach. A design that will nourish only these specific parts of the coast is going to be implemented, which can continue to contribute to the touristic development of the region there. Then, only the present ongoing erosion will be confronted, prohibiting a further expansion to the remaining coastline together with the public beach in Cua Dai.

Eventually, the design approach that will be followed for Cua Dai is divided in two parts, offering two separate design solutions. The main criterion is the possible financial inclusion of the resort owners in the project. In the scenario that only the public authorities will finance the mega nourishment, a design will be implemented that will nourish only the public Cua Dai beach and the coastline north. The overall distance for this area is approximately 3.5 km. For the remaining thesis study this solution will be referred to as Design 1. In the case that also the resort owners will agree to contribute financially to the mega nourishment approach, a different design will be implemented, which will aim to recreate the whole region of the north coast that is examined in the present study. This solution is denoted as Design 2.

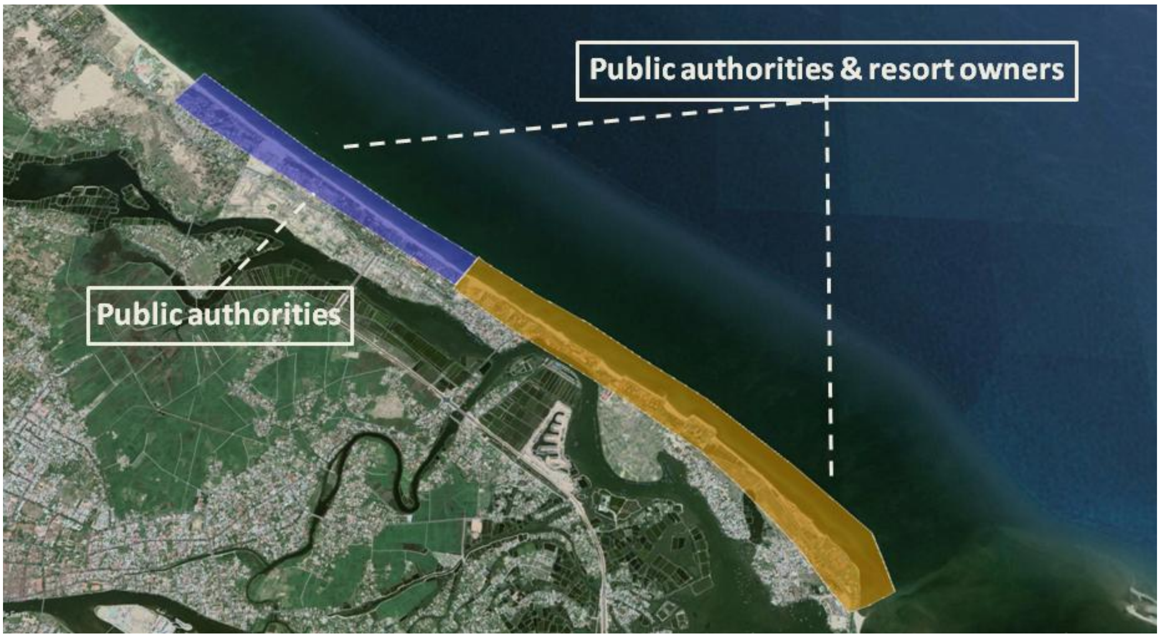


Figure 4.1: Mega nourishment design approach

The primary parameters that will influence the final form of the design in each solution are the required nourishment volume related to the design lifetime, the location of the mega nourishment, but also the shape of the design. Apart from these decisive factors, additional aspects have to be considered as design parameters. The top elevation, the cross shore and side slopes of the design but also the median grain size are important parameters that must be properly determined. The analysis and selection of all these aspects of the mega nourishment designs is explored in the following sections.

4.3. Mega nourishment design parameters

4.3.1. Primary design parameters

4.3.1.1. Lifetime

For each of the design scenarios the required sand amount has to be determined for a desirable design lifetime. Since the aim of the present study is to provide a design solution that can diffuse and nourish gradually a coastline stretch over a long term period, the nourishment design life is selected accordingly. A predefined nourishment lifetime for both design options is considered to be 10 years. During this period the sediment must be able to spread from its original position into the desired locations and expand the coast, following the mega nourishment concept.

4.3.1.2. Volume

The analysis of the prevailing dynamics in Cua Dai highlighted the erosive behaviour of the north coast under examination, including the Cua Dai beach, due to the local seasonal climate. The construction of resorts and the positioning of sandbags has ended up influencing the alongshore sediment transport pattern, enhancing this existing erosive trend to the north. Thus, it is essential to quantify the annual sand losses based on the present gradient of the north coast. From the net annual alongshore sediment transport pattern along the north and south coastlines, the largest erosive gradient can determine the maximum amount of sand that is lost annually in the area of interest.

The nourishment must be able to feed the north coast and alter the existing trend of coastal erosion. Figure 4.2 shows that this area is located updrift of the public Cua Dai beach covering an overall distance of 2.47 km. There, currently 50,882 m^3 of sediment are lost every year. This amount of sand should be provided back in the region in order to limit the erosion there and prevent its further propagation to the north. Taking into account the desired nourishment lifetime, a total amount of approximately 0.5 Mm^3 of sand is necessary in order for the coast to maintain its current position.

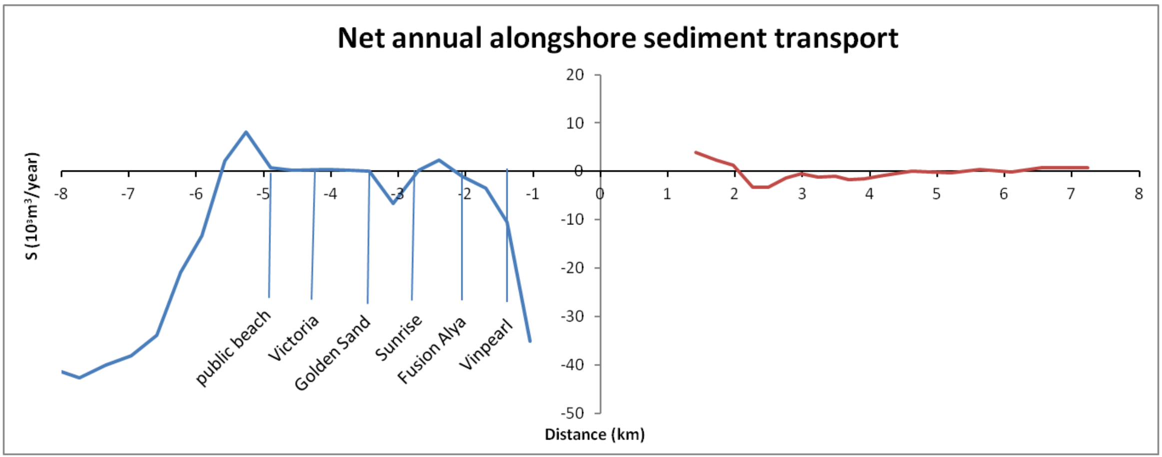


Figure 4.2: Net annual alongshore sediment transport pattern in the coastlines north and south of Cua Dai inlet

Design 1 must contain the sand volume of 0.5 Mm^3 in order to preserve the current coastline position. In addition, an extra quantity must be considered so as to nourish the coast in front of the public Cua Dai beach. However, the zero sediment transport gradient that has been formed there, necessitates a different approach. This volume is calculated based on the recorded annual average shoreline retreat along the desired coastline length, considering the sand volume loss until the active depth. From the resulting annual eroded volume, the required nourishment volume is determined for the nourishment lifespan.

Do et al. (2017) has highlighted that the shoreline retreat of that region reached an average value of 6 m/y during the period 2010-2015. Due to the lack of available data, it is assumed that the level of retreat remained constant in the following years. Consequently, considering the total length of the public beach and the estimated active depth of 5.5 m, an extra amount of 0.4 Mm^3 of sand must be added to restore the public Cua Dai beach. So, in total a volume of 0.9 Mm^3 is required in order to fulfill the goal of Design 1. It is expected that a nourishment of this size, if located appropriately, can successfully provide a design solution that can recreate the public Cua Dai beach and maintain the present coastline further to the north, restricting the existing erosive trend that is currently present there.

The required volume for the solution of Design 2 that will include also the nourishment of the coast in front of the resorts in the Cua Dai beach, is significantly larger. Now, an extra amount of sediment must be present on top of the 0.5 Mm^3 that are required in order to restrict the prevailing coastal erosion in the north coast. The limited gradients across the location of the resorts are not representative in order to determine the volume that is needed to restore the coast there. Again, the recorded annual average erosion rate can be used to indicate the desired level of coastline expansion per year in that region by the nourishment. During the period 2000-2010 in which the resorts have been constructed, the average annual erosion rate according to Do et al. (2017) was estimated to be 12 m/y. For the region of the public Cua Dai beach the erosion rate has been already determined in Design 1. Assuming again these values as constant, the nourishment volume of the second design scenario can be calculated. Considering the total length of the coast along the desired regions and the active depth of 5.5 m, the desired volume for the 10 year duration can be found. Finally, the total required nourishment volume of Design 2 with the purpose to restore the coast in front of the resorts and the public Cua Dai beach as well as to maintain a part of the remaining north coast, is determined to be approximately 3 Mm^3.

The impact of extreme events must be assessed separately in order to investigate whether an extra amount of sediment should be added in the required nourishment volume of both designs. During the span of an extreme event strong alongshore gradients can form, enhancing the morphological changes in the area of interest. Even though the forcing period is limited, the frequency of occurrence over the nourishment life could create an additional impact in the winter flood season. Because of this, the level of the extra erosion that can be present due to an extreme event over the nourishment design life should be examined.

For this purpose, the characteristic recorded extreme flood event with a discharge of 7660 m^3/s that has been modeled in the previous chapter is used. The assessment of its impact can show the influence of floods in the nourishment design volume. This event is considered representative based on the available flood record, due to the fact that a significant number of events with similar magnitude have been recorded in the period 1977-2008. The influence of storms in the nourishment volume is not investigated in the present study.

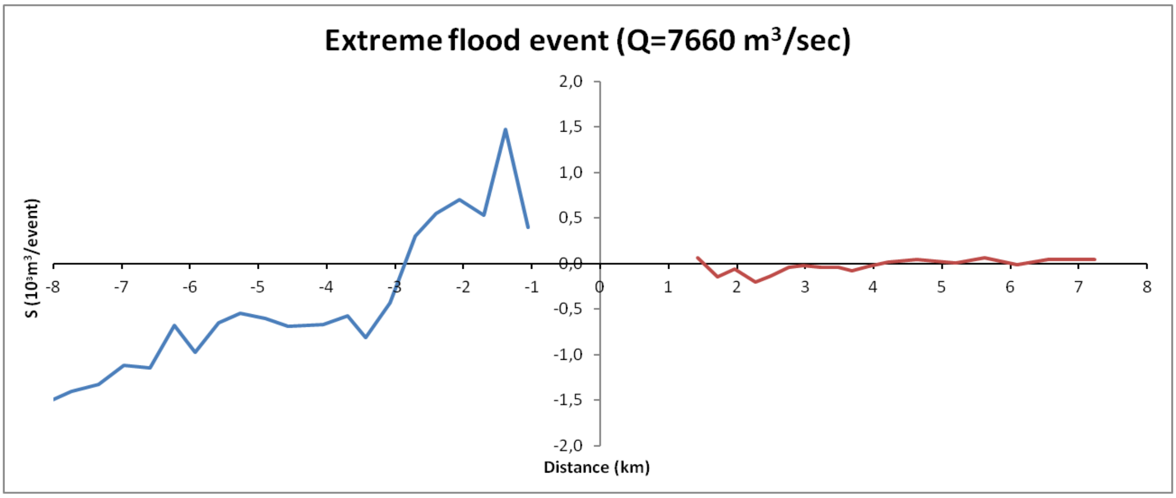


Figure 4.3: Alongshore sediment transport due to an extreme flood event with a river discharge of 7660 m^3/sec

It has already been highlighted that during a flood event, the impact in the coastlines adjacent to the river is limited to the area close to the ebb delta, affecting locally the sediment transport. Based on the alongshore erosive gradient that is formed in the north coast during the impact of this flood event, an overall amount of 0.003 Mm^3/event is found to be lost. However, the frequency of occurrence of this characteristic event during the nourishment lifetime needs to be specified in order to estimate accurately its final impact.

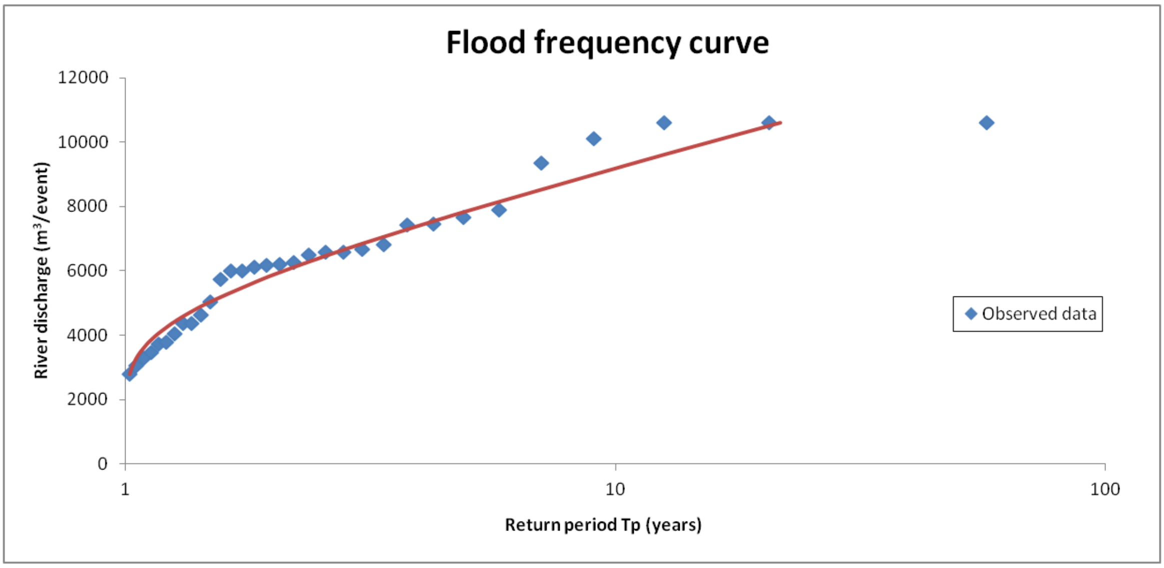


Figure 4.4: Flood frequency curve of the available flood discharge data

A flood frequency curve is constructed from the available maximum annual recorded river discharges, covering a period of 32 years. A curve that follows the Gumbel distribution is selected as the fitting curve to the data. Good agreement can be observed in the desirable band, which makes the selection of this distribution acceptable although deviations are present for the largest flood values. From there, the return period of the recorded 7660 m^3/s flood event is estimated to be 4.5 years. During the 10 years of the nourishment lifetime this translates to a 22.2% possibility of occurrence. Thus, due to the presence of the 7660 m^3/s flood event an extra amount of erosion across the north coast will be present in the order of 0.0066 Mm^3/nourishment life. So, the presence of such an event would only slightly increase the required nourishment amount. It is concluded that the regular seasonal conditions are the primary factor which determines the required nourishment amount, while the extreme flood events do not increase significantly the required sediment volume and are excluded from the volume calculations.

Based on the approach used for calculating the required nourishment volume, different morphological changes are expected along the coast. In the end of the nourishment lifetime the coastline is expected to be maintained in the region north of the public Cua Dai beach since the sediment that will be supplied each year there is enough in order to counteract the prevailing erosive gradient. Along the Cua Dai beach, the design volume is calculated based on past recorded coastline retreat levels. There, the presence of a nourishment is anticipated to widen the current coast and recreate an open space.

4.3.1.3. Location

The appropriate location is linked to the target of each design approach. Design 1 focuses on nourishing the public locations of the north coastline which include the public Cua Dai beach and the area north of it. A nourishment design that contains the necessary amount to cover the annual losses in that region is expected to maintain the coastline there and widen the public Cua Dai beach. The trend of the net annual alongshore transport gradient shows that north of the public beach the local transport divergence point transports the sediment mainly to the north, while a smaller amount is distributed south and is connected to the public beach. In front of the public Cua Dai beach the current gradient is minimum.

Figure 4.5: Locations of nourishments of Design 1

Based on this, the nourishment volume of Design 1 is split in two locations. The volume of 0.5 Mm^3 that is required to nourish the coastline north of the public Cua Dai beach is positioned north of the public Cua Dai beach in the local divergence location. From there sediment can spread mainly to the north, while a smaller amount can be distributed south to the public beach. There, the required volume is placed directly in front of the public beach as the local transport conditions are expected to limit its diffusion south. The final form of Design 1, although it is split into two neighbouring locations follows the mega nourishment concept because it is expected to diffuse from the initial localized position into the desired locations over the anticipated long term time period. The location of Design 1 is illustrated Figure 4.5.

Design 2 aims to recreate the coast in front of the resorts and the public Cua Dai beach, but also to cope with the effect of the strong erosive gradient that is currently present north. The long coastline length that is intended to be nourished and the prevailing alongshore sediment transport trend, have led to the decision of two alternative design locations. The transport divergence point that is present in the region between Fusion Alya and Sunrise resorts is considered as the first location for the second design. There, the local placement of the required nourishment volume is expected to influence the existing local trend of the transport gradients, spreading the sediment of the mega nourishment north and south over the design lifetime.

In the other alternative the required design volume is split in multiple locations, in front of each of the resorts in Cua Dai beach. Their presence will formulate alongshore gradients in the nourishment sides and during the design life span the nourishments are expected to spread and connect to each other widening the coast in Cua Dai. Gradually, the alongshore sediment transport pattern that was present before any intervention along Cua Dai beach will be recreated. In addition, the nourishments of Design 1 will be used for the nourishment of the remaining area in front of public Cua Dai beach and north. Again, this design alternative conforms to the mega nourishment concept since the localized sediment perturbations will reform and spread over the considered long term period, nourishing the desired coastline stretch. The two alternative locations of Design 2 are presented below.

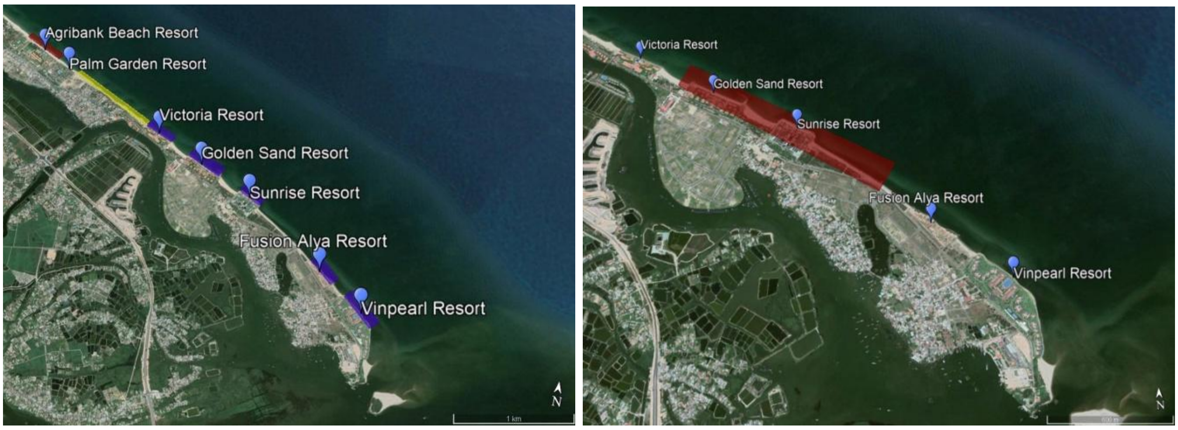


Figure 4.6: Alternative locations of Design 2. In the left figure the locations of multiple nourishment designs is illustrated. In the right figure the location of the localized nourishment design is depicted.

4.3.1.4. Shape

The shape of a mega nourishment design influences the alongshore spreading of the sediment during the predefined life span. Sharp coastline angles can redistribute rapidly the sand by means of alongshore diffusion (de Schipper et al., 2016). The nourishment shapes that are selected here aim to assist the feeding behaviour of the designs. A simple rectangular shape is decided for the nourishments of Design 1, as well as for the alternative of multiple nourishments of Design 2. In this way local bumps are formed in the coastline, inducing large wave angles with respect to the coast and allowing the spreading of the sand towards the desired directions. This shape is also preferred for constructional purposes, as in both design solutions the nourishments are closely located. For the localized mega nourishment solution of Design 2, an abstract shape is selected. Now the sediment volume varies in the cross shore direction, aiming to distribute a different amount north and south, since the nourishing areas are not the same. In all cases, fast adaptation is expected within the initial period after the implementation, with the nourishments to reach then a smoother form, reducing gradually the sediment diffusion over the design life span.

4.3.2. Remaining design parameters

Apart from the primary design parameters that have been determined, choices are necessary for additional design characteristics. The final elevation of the designs, the cross shore and side slopes, the median grain size but also the possible sediment losses need to be defined in order for the designs to be finalized. These parameters remain the same for all design solutions. In this section, the final selected values of these parameters are justified and presented.

In all designs the nourishment elevation must be such, so that the existing beach is extended offshore. The nourishment designs must be able to advance the coast, gradually extending in the longshore direction. Based on the available bathymetric data, a +0 m elevation is incorporated in the numerical model in order to indicate the presence of the land. In the same sense, the nourishment elevation is set to +0 m in order to extend naturally the coastline, without causing bumps in the model domain.

The sediment size characterizes the nourishment and is a fundamental design parameter to consider. It influences the nourishment behaviour and the amount of losses. The profile after the nourishment will eventually be the same as before the nourishment, provided that the same type of sediment has been used (Verhagen, 1992). This is especially true in an environment where the forcing conditions remain unaltered. In the case that grain size of the nourishment is the same with the native material the alongshore sediment transport does not get affected and the same morphological processes continue to prevail (Bosboom & Stive, 2012). In this study, borrow sand with the same median grain size is selected to be an input in the numerical model, having a value of D_{50} =200 μm.

Another influential design parameter is the slopes of the nourishment designs. Research has been performed regarding the effect of the cross shore slope to the nourishment design. It is crucial to select an appropriate slope in order to achieve the anticipated behaviour of the nourishment. Steeper slopes yield to larger longshore sediment transports (de Schipper et al., 2015a; de Schipper et al., 2016; Kamphuis, 1991; Mil-Homens et al., 2013). The steepness of the slope can significantly enhance the feeding behaviour of the mega nourishment. Based on the early monitoring results of the Sand Engine, analyzed by de Schipper et al. (2016), the initial steep cross shore profiles adapted to a more natural shape. Thus, a straight slope that is steeper than the local cross shore profile of the domain will be selected for the nourishment designs.

Along the Cua Dai beach, the limited available information regarding the existing cross shore profile prior to the nourishment implementations are taken into consideration. The available bathymetric data provided by Do et al. (2017) show that the slope of the upper surf zone region in general is mild, in the order of 1:80, acquiring a more gentle form in the remaining surf zone area. In addition, the measured profiles from Asplund & Malmstrom, (2018) which cover the foreshore and nearshore area in the period 2014-2016 reveal an overall mild slope along the north coast. Since all nourishment designs will be located within the upper region of the surf zone, a design cross-shore slope of 1:50 is selected. Regarding the side slopes of the design, a more natural result it is aimed to be achieved, without significantly disrupting the local profile of the existing bathymetry, still though being steeper in order to stimulate the nourishment diffusion there. Based on these prerequisites, a slope of 1:150 is considered an appropriate design choice.

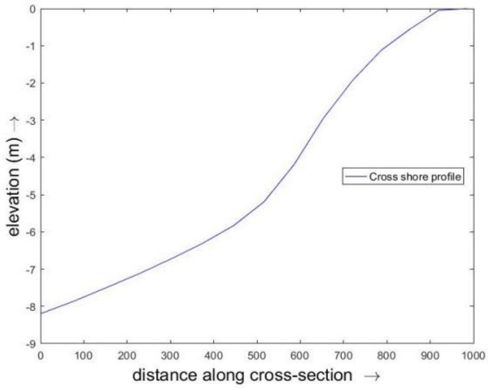


Figure 4.7: A characteristic cross shore profile in Cua Dai beach

Finally, sediment losses are expected in the nourishment implementations. Since the designs follow the mega nourishment concept, a diffusive behaviour is desired that will trigger the anticipated losses and sediment transport to feed the coastline. However, additional causes of initial sediment loss can lower the design volume which is expected to be added to the coast. Washing out of fine particles as well as cross-shore transport to the offshore can trigger the initial erosion rate right after the nourishment installation (de Schipper et al., 2015a; Dean 2002, Verhagen 1992). In terms of the Sand Engine project, measurements of the initial morphological evolution presented in the research of de Schipper et al. (2016) indicate that approximately 0.5 Mm^3 were lost, attributing a part of these losses among others to transport to the offshore as well as to the washing out of fines. The dynamic prevailing environment in Cua Dai implies that sediment losses will occur, yet the lack of implementation of nourishment projects in the area complicates the prediction of these losses. Based on these, a loss factor will not be considered for the nourishment designs.

4.4. Final design solutions

After all necessary design aspects have been determined the alternative design solutions can be finalized and implemented in the numerical model. In each case, the model bathymetry is schematized accordingly in order to accommodate the design volume in the selected locations. There, also the resorts and the sandbags in the Cua Dai beach are included, as the designs are implemented in the present condition of the coast. A common predefined slope extension has been set for all designs. Because of this, an increase of sediment amount in the order of 10% is present in all designs for constructive purposes, forming a steeper slope end until the reattachment point. This extra amount is not accounted in the design volume.

For the first design solution, the final nourishments are presented in the following figure. The first nourishment located north of the public Cua Dai beach is extended in the alongshore direction over a distance of 622 m and the cross shore extend is 403 m. In front of the public Cua Dai beach, the sediment is distributed along the region and extends offshore over a distance of 177 m. Now, in order to meet the design shape and achieve a uniform offshore extension, the final volume that is added there is eventually approximately 0.5 Mm^3. Thus, the final volume of Design 1 implemented in the model becomes 1 Mm^3.

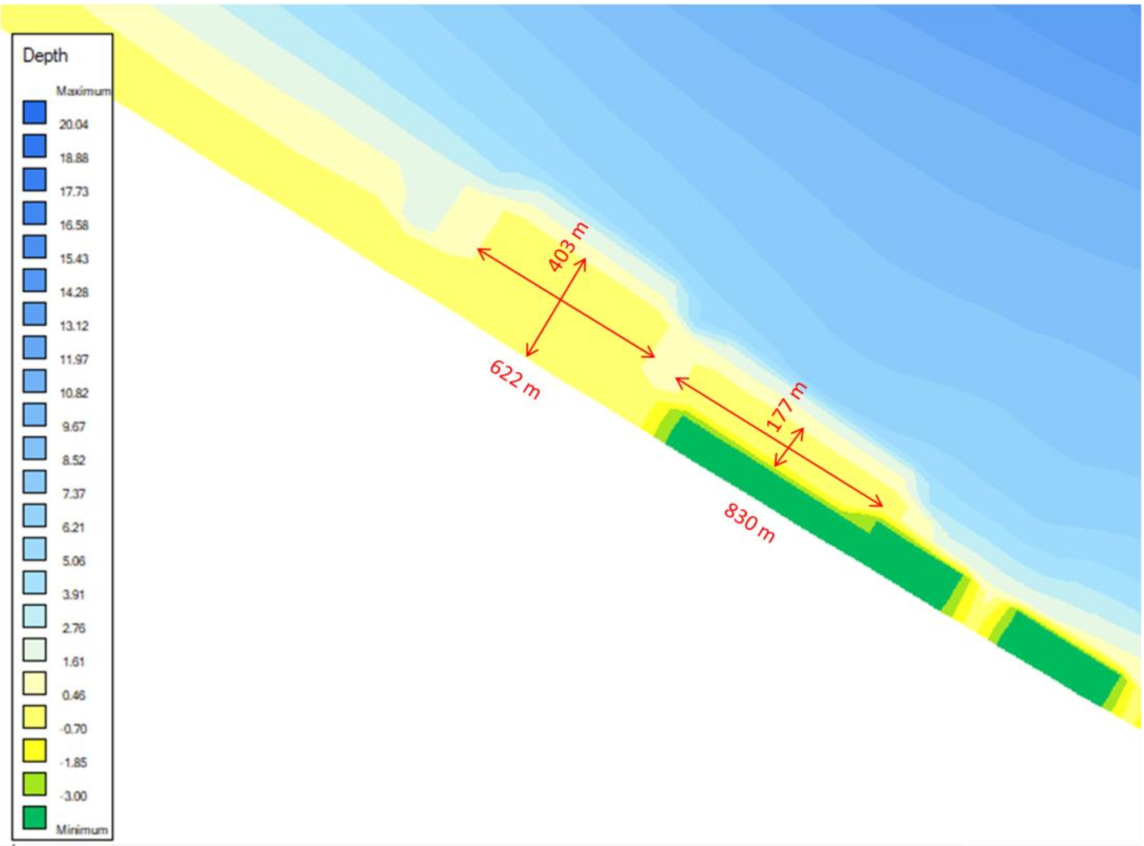


Figure 4.8: Top view and dimensions of Design 1. The green areas in the model, starting from the right to the left, indicate the locations of Golden Sand and Victoria resorts as well as the sandbags in public Cua Dai beach.

The alternative solution of Design 2 with the multiple nourishment designs is displayed in the following figure. The nourishments in front of the public Cua Dai beach and north are identical with Design 1. For the remaining designs, the required volume that has been estimated for the Cua Dai beach is split in front of each of the five resorts of the region. The nourishments are not identical in size and volume, although they have the same shape. In front of the third resort, which is Sunrise resort, the nourishment has a large offshore extension of 250 m in order to increase the sediment volume of that location, as the sediment there is expected to spread more due to the local divergence of transport. The nourishments in front of Vinpearl and Fusion Alya are the smallest designs, because the dynamic environment of the region close to the inlet is expected to affect their feeding behaviour, with possible offshore losses but also sediment gains due to the river outflow.

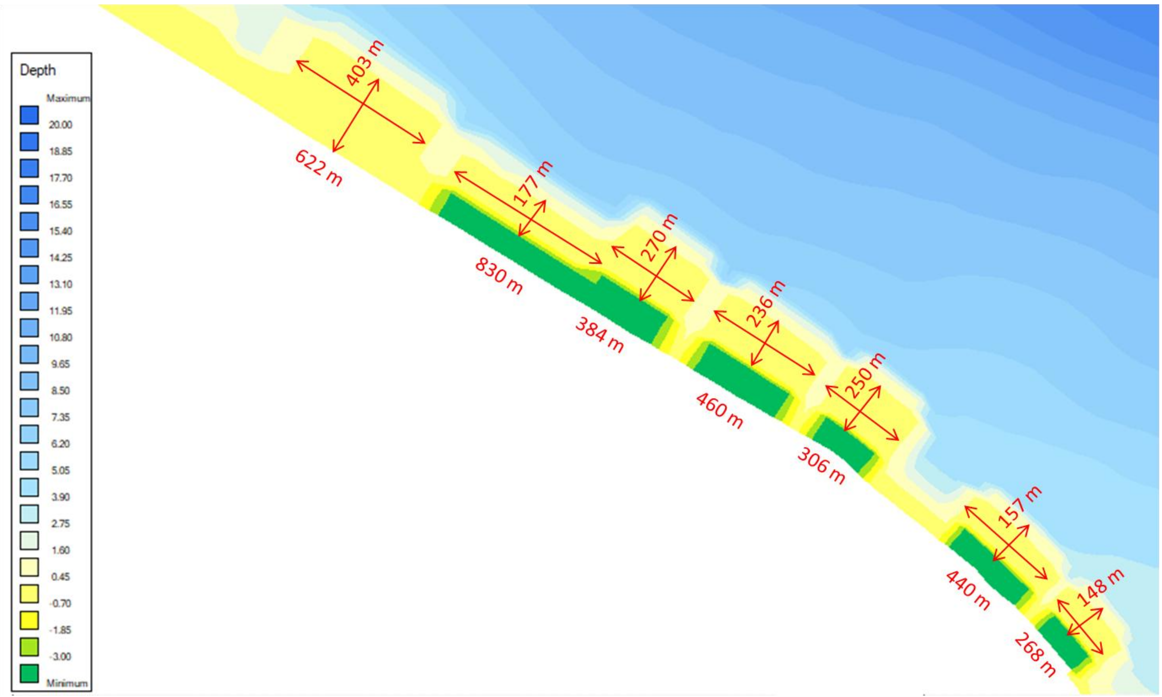


Figure 4.9: Top view and dimensions of multiple nourishments alternative of Design 2. The green areas in the model, starting from right to left, indicate the five resorts of the Cua Dai beach, with the last location to be the public beach of Cua Dai.

The localized nourishment of Design 2 is illustrated in Figure 4.10. It covers an overall alongshore distance of 1476 m, that includes the transport divergence point and the area in front of Sunrise and Golden Sand resorts. The maximum cross shore extension is 557 m in the part that is located updrift of Sunrise resort, while in the downdrift region the offshore extension is 331 m. The two nourishment areas are connected with an oblique designed part that is present in front of the location of Sunrise resort.

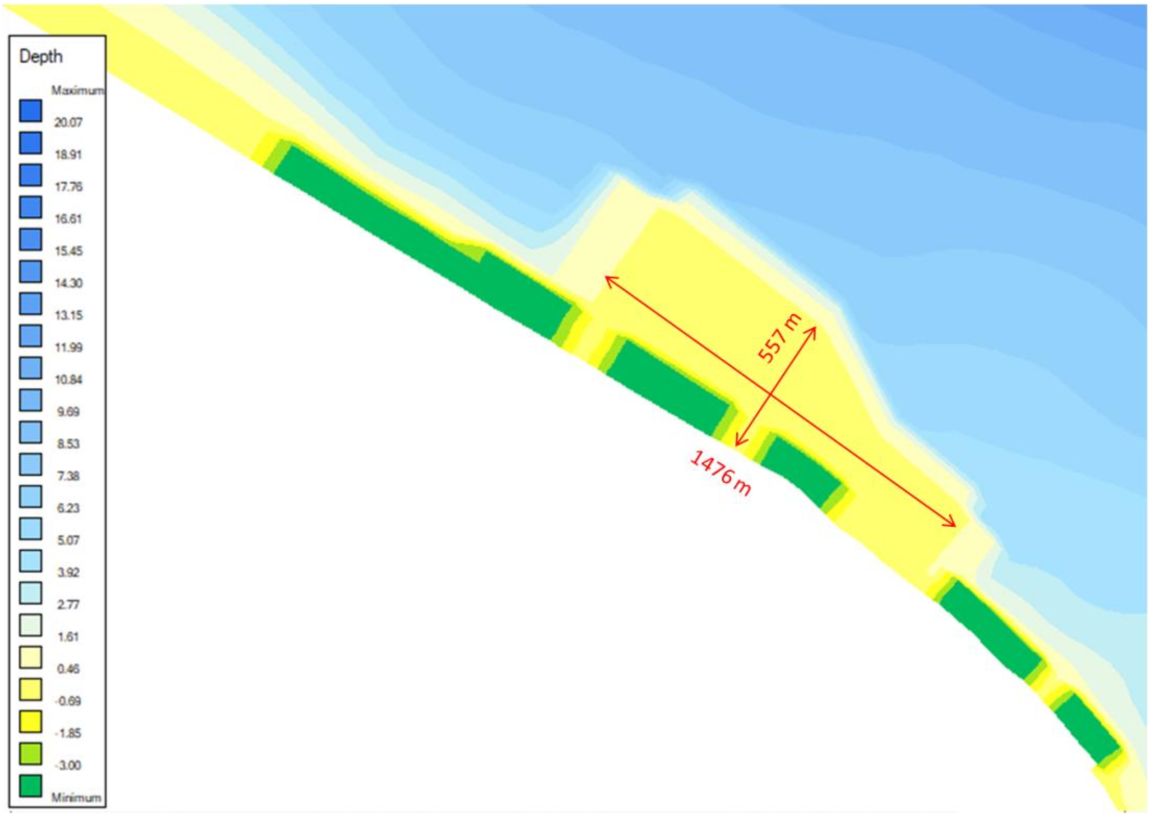


Figure 4.10: Top view and dimensions of localized nourishment alternative of Design 2. The green areas in the model, starting from right to left, indicate the locations of the five resorts of the Cua Dai beach, with the last location to be the public beach of Cua Dai.

An overview of the final design solutions in terms of volume and dimensions implemented in the numerical model is presented in the following table.

Designs		Volume (Mm^3)	Alongshore extension (m)	Cross shore extension (m)
Design 1	public Cua Dai beach	≈ 0.5 Mm^3	830 m	177 m
	north coast	≈ 0.5 Mm^3	622 m	403 m
Design 2 (multiple nourishments)	Vinpearl	≈ 0.15 Mm^3	268 m	148 m
	Fusion Alya	≈ 0.3 Mm^3	440 m	157 m
	Sunrise	≈ 0.45 Mm^3	306 m	250 m
	Golden Sand	≈ 0.5 Mm^3	460 m	236 m
	Victoria	≈ 0.6 Mm^3	384 m	270 m
	public Cua Dai beach	≈ 0.5 Mm^3	830 m	177 m
	north coast	≈ 0.5 Mm^3	622 m	403 m
Design 2 (localized nourishment)	-	≈ 3 Mm^3	1476 m	557 m

Table 4.1: Overview of final design solutions

4.5. Influence of the dynamic environment in the nourishment simulations

A new model schematization of the existing Delft3D model of the domain needs to be created for the simulation of each of the nourishment designs. The most crucial aspect is the selection of the wave and river forcing boundary conditions. The seasonal character that prevails in Cua Dai and has been highlighted in the previous chapter must be properly incorporated in the numerical model. The use of single representative conditions cannot imitate the hydrodynamic forcing variation that exists in reality in terms of prevailing wave directions and river discharge levels. The seasonal variation in the waves and river discharge is an important aspect of the area of interest that needs to be taken into account.

Based on this, it has been concluded that seasonal wave conditions should be imposed through the model boundaries for the simulation of the nourishment designs, varied in accordance to their weighted annual effect. It is expected that this approach can simulate more accurately the local wave environment, leading to a more precise prediction of the alongshore feeding behaviour of the nourishment designs. In accordance to this, the seasonal effect of the river discharge through the year should be considered.

The previously selected representative wave and river discharge conditions that describe a typical annual cycle in Cua Dai after combining the hydrology and the waves, are considered for the assessment of the nourishment designs in the following chapter. The nourishment behaviour is investigated in the current condition of the coast, where the resorts and sandbags are included in the model domain of each design and the representative river discharge does not account for the effect of an increased seasonal variation. The available river discharge record of Nong Son station covers the period 1977-2011 and since more recent data are not available, the typical representative average river discharge values are considered as a more reliable choice.

4.6. Conclusion

The inclusion of the stakeholder aspect in the design approach of the mega nourishment led to the selection of two design solutions, based on the possible presence of resort owners as financial contributors to the nourishment implementation. Finally, three design alternatives have been determined. The primary parameters that influence the final form of each design are the required nourishment volume in relation to the desired lifetime, the location, as well as the shape of designs. The required nourishment volume of each design solution is determined based on the net annual erosion rate together with the recorded annual average shoreline retreat in the regions where the current alongshore gradients are limited.

Design 1 aims to nourish the public Cua Dai beach and cope with the prevailing erosive gradient north, financed by the public authorities. For this purpose a nourishment of 0.5 Mm^3 is located north of public Cua Dai beach and is intended to spread north over the desired lifetime of 10 years. An extra 0.5 Mm^3 of sand are placed directly in front of the public Cua Dai beach to assist the widening of the coast there. For both, a simple rectangular shape is chosen. In Design 2, the coastline north of the Cua Dai inlet including the resorts in the Cua Dai beach is nourished, with the resort owners to support the financing. For this solution, two alternative nourishment designs have been formed. A 3 Mm^3 localized nourishment of abstract shape is positioned in the sediment divergence transport point in the region between Fusion Alya and Sunrise resorts, with the aim to distribute the sediment to the north and south over a 10 year period. In the second alternative, the desired volume of 3 Mm^3 is divided in multiple nourishments in front of the resorts in Cua Dai beach and to the nourishments that are included in Design 1. The closely located perturbations of rectangular shape are expected to spread and connect to each other in accordance with the mega nourishment concept.

Common choices have been made for the remaining design parameters. The top elevation of the nourishments is set to +0 m. A median grain size of 200 μm is selected for the nourishments, matching the native material of the coast. A cross shore slope of 1:50 is selected in order to assist the feeding behaviour of the designs, while a gentle side slope of 1:150 is considered appropriate, to avoid local disruptions in the bathymetry close to the coast.

For each of the selected designs, a numerical model has been formed by means of schematizations of the initial bathymetry in the desired locations together with their final alongshore and cross shore dimensions. In addition, the necessity of inclusion of the seasonal character of the region in the simulation of each design has been highlighted. Finally, the representative wave and river discharge conditions that will be implemented in the numerical simulations for the assessment of the designs have been presented.

5. Assessment of design solutions

5.1. Introduction

In this chapter an assessment of the design solutions is performed. Initially, a qualitative analysis of the designs is presented that gives an overview of all solutions and allows for a comparison among them. In addition, the influence of the seasonal character of the domain in the nourishments is investigated, associating trends in behaviour with the forcing conditions. Results are discussed, providing important remarks.

5.2. Qualitative assessment of design solutions

A qualitative analysis of the proposed design solutions is performed that aims to assess the nourishments designs based on common criteria related to the design approach, highlighting their strengths and weaknesses. The criteria that are used can indicate the influence of the different stakeholder groups involved in each design solution. The different choices made with respect to the location, the shape and the sediment volume do not allow for an assessment based on their seasonal behaviour, as safe conclusions cannot form. For the purpose of qualitative assessment a spider chart is created for each nourishment design. Relative qualitative scores are given in the scale of 1-10, with 1 to be the lowest possible score that a parameter can achieve and 10 to be the maximum. The following evaluation parameters have been selected:

- the required nourishment volume
- the construction aspect
- the cost of the nourishment designs
- the level of stakeholder satisfaction
- the communication of involved stakeholders

The required nourishment volume indicates the amount of sediment and consequently the area that is aimed to be nourished in every design solution. The construction aspect shows how easy it is to construct each design alternative. This criterion is affected by the required shape and the volume of every nourishment design, but also by the selected location in each case. The cost is mainly affected by the required volume of sediment in a nourishment design, yet the desired shape is also an influencing aspect for this criterion. The level of satisfaction of all stakeholders highlights the positive impact that is offered to every group by the nourishment designs. This is also influenced by the immediate results that can be achieved by each design alternative. Finally, the communication of the involved stakeholder groups in every design solution shows possible delays that can occur during the period before a nourishment implementation, due to required arrangements among them, but also due to cost division. The resulted graphs for the nourishment designs are presented in the following figure.

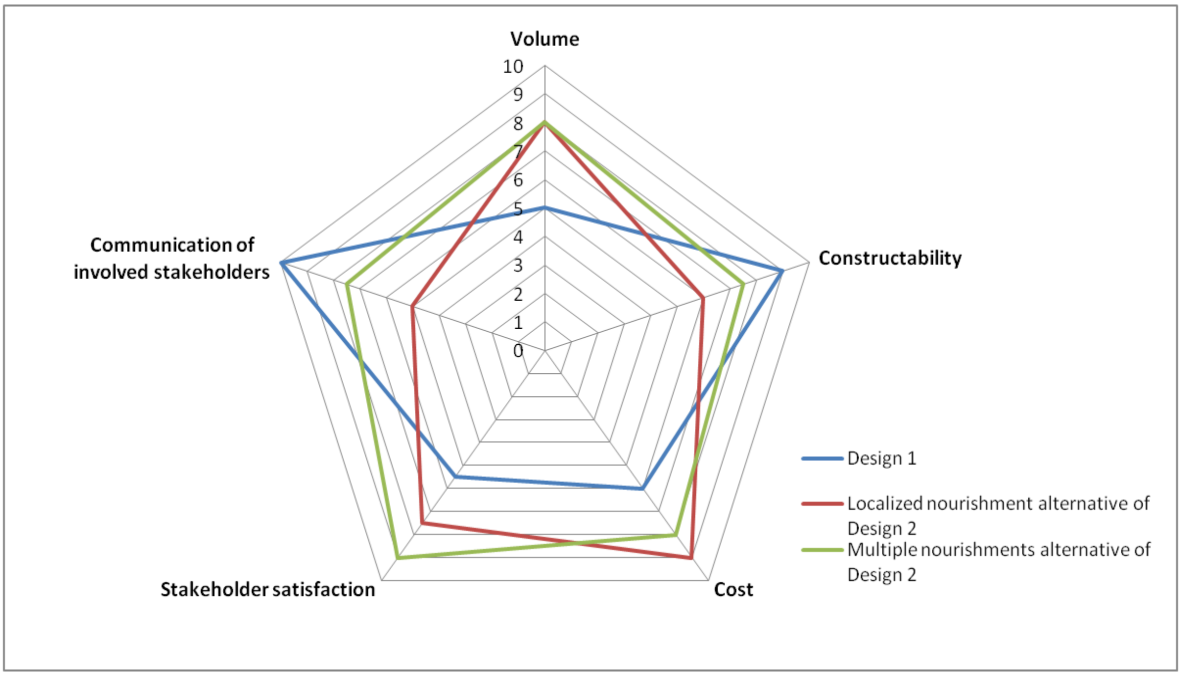


Figure 5.1: Spider chart of nourishment design solutions

A different outcome is created for each design solution that allows for interesting remarks. In terms of the nourishment volume, Design 1 achieves a lower score since the area that is aimed to be nourished in this case is less compared to the remaining solutions. Yet, the lower required volume and simple shape of this design ranks it as the easiest to construct. The two alternative solutions of Design 2 are more difficult to construct for different reasons. The larger required volume and the demanding shape of the localized nourishment are expected to cause difficulties during the construction phase. The construction of multiple nourishments along the coast can also cause problems that are expected to be less though, due to the simpler shape of all designs. In the same sense, a higher cost is required for the localized nourishment and less for the multiple nourishments design alternative. Design 1 is linked to the lowest cost.

Considering the satisfaction of all stakeholders for each design solution, the maximum score is achieved for the multiple nourishments design alternative. In this case, the goals of the primary stakeholder groups are accomplished and the immediate widening of the coast in many of the desired locations provides satisfaction. The localized nourishment satisfies also the goals of the stakeholders, yet the positive impact in many locations is expected to delay in time. The lowest score is reached by Design 1, as in this case the primary stakeholder group of the resort owners is not included. Finally, as expected, in Design 1 no communication issues will be present. On the contrary, the inclusion of resort owners in the financing of Design 2 is possible to cause delays. If the localized nourishment design alternative is selected, meetings among the stakeholders are necessary that can extend the preparatory period before the implementation of the design. In addition, the required arrangements regarding the distribution of cost can increase the communication issues. Due to all these, a lower score is given. In the case of the multiple nourishments design, the required stakeholder meetings can still influence the stakeholder communication, but now the cost division is less demanding.

The overall symmetric form of the spider chart for both alternatives of Design 2, points out the holistic character of this design approach. Even though the aim of the two solutions is common, the qualitative evaluation highlights possible difficulties that can arise in the case of the localized nourishment with respect to the coastal zone management aspect but also during the construction phase. This does not mean that the localized nourishment should not be preferred, but only that a more careful planning could be necessary. The abstract shape of the spider graph for Design 1 highlights the limitations related to this design approach. Yet, in the case that this solution will be selected, the positive aspects related have been recognized.

5.3. Seasonal trends of designs

The importance of the inclusion of the seasonality aspect in the simulation of the design solutions has been already highlighted in Chapter 4. For this purpose it is considered relevant to investigate the seasonal trends in the nourishment behaviour. Based on this, a better understanding of the impact of the seasonal conditions can be achieved and useful remarks are collected that can assist an assessment of the long term simulations. In the present section, four simulations are performed for every design, where the representative wave and river discharge conditions of the four seasonal conditions that form the typical annual cycle in the Cua Dai area are used. A common simulation period of 1 year has been selected in order to observe morphological changes and to allow for comparisons in each case. The effect of seasonality is assessed by the level of diffusion over the simulation period and the trends formed in the alongshore sediment transport gradients after the nourishments are implemented. For the level of diffusion, a control box has been created around the main area of the designs. Within this area the volume change over the simulation period is determined indicating the spreading of sediment. A comparison among the different design solutions cannot be performed since the diversity of volume, shape and location creates a different base of assessment. In the following paragraphs the results for each design solution are presented and discussed. In all cases a characteristic ENE and SE condition is displayed. The remaining results are presented in Appendix C.

5.3.1. Seasonal trends of Design 1

A different behaviour is observed, related with the magnitude and direction of the wave forcing, while variation in terms of the transport magnitude is present along the coast due to the influence of bathymetric variability in the wave forcing. For ENE waves during the winter flood season, a stronger sediment transport is created for the nourishment that is located north of the public Cua Dai beach compared to the nourishment placed in front of the public beach. In both cases sediment from the nourishments has spread around them, connecting the two designs and in the nourishment north of public beach the morphological changes indicate a northward directed diffusion of sand, as expected based on the net annual alongshore transport trend of the region. The sand has also eroded in the cross shore direction, forming a milder slope.

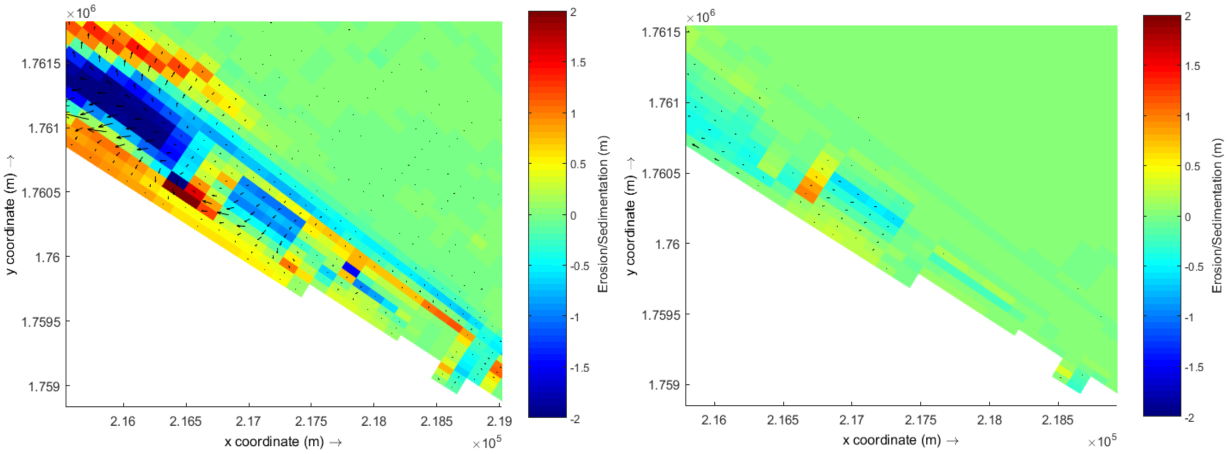


Figure 5.2: Morphological changes and transport patterns in Design 1 for (a) winter flood and (b) summer (SE) seasons

The sediment transport pattern highlights the onshore transport that is created in the top of the nourishments because of wave overtopping, moving sediment towards the coast, but also influencing the spreading in the sides. This behaviour is more evident for the nourishment that is located north of public Cua Dai beach. The same trend is observed for the remaining ENE waves during the winter dry and summer dry seasons, with a magnitude that is in accordance to the prevailing wave height in each case. The alongshore sediment transport trends support these observations. In the graphs of Figure 5.3, the nourishments of Design 1 are located around the areas denoted as north coast and public beach. Larger alongshore transport gradients are created under stronger wave action. The lower erosive gradient during the winter flood season in the upper area of the nourishment of public Cua Dai beach could be attributed to the more complex local pattern between the two designs. In general low gradients have been formed in the upper area of the nourishment of public Cua Dai beach, while the stronger erosive gradient in the location of the nourishment design north shows the more clear northward directed spreading of sediment and further deposition. The resulted transport gradients in these regions are presented in Table 5.1.

Alongshore transport gradients (m^3/m/month)	Winter (ENE) flood season	Winter (ENE) dry season	Summer (ENE) dry season	Summer (SE) dry season
north coast	9.1	7.6	4.4	1.9
public Cua Dai beach	1.6	2.1	2.0	0.3

Table 5.1: Alongshore sediment transport gradients in the nourishment locations of Design 1

For the SE incoming waves during the summer, the changes are milder and the transport has in general a low magnitude in the area, being stronger in the nourishment north of public Cua Dai beach. Now since the waves act more parallel to the coast, the net northward direction influences the spreading to the north. Also because of this, now the onshore transport is limited. Along the slopes sediment is transported more parallel to the coast but also offshore. The corresponding alongshore transport gradient highlights this trend.

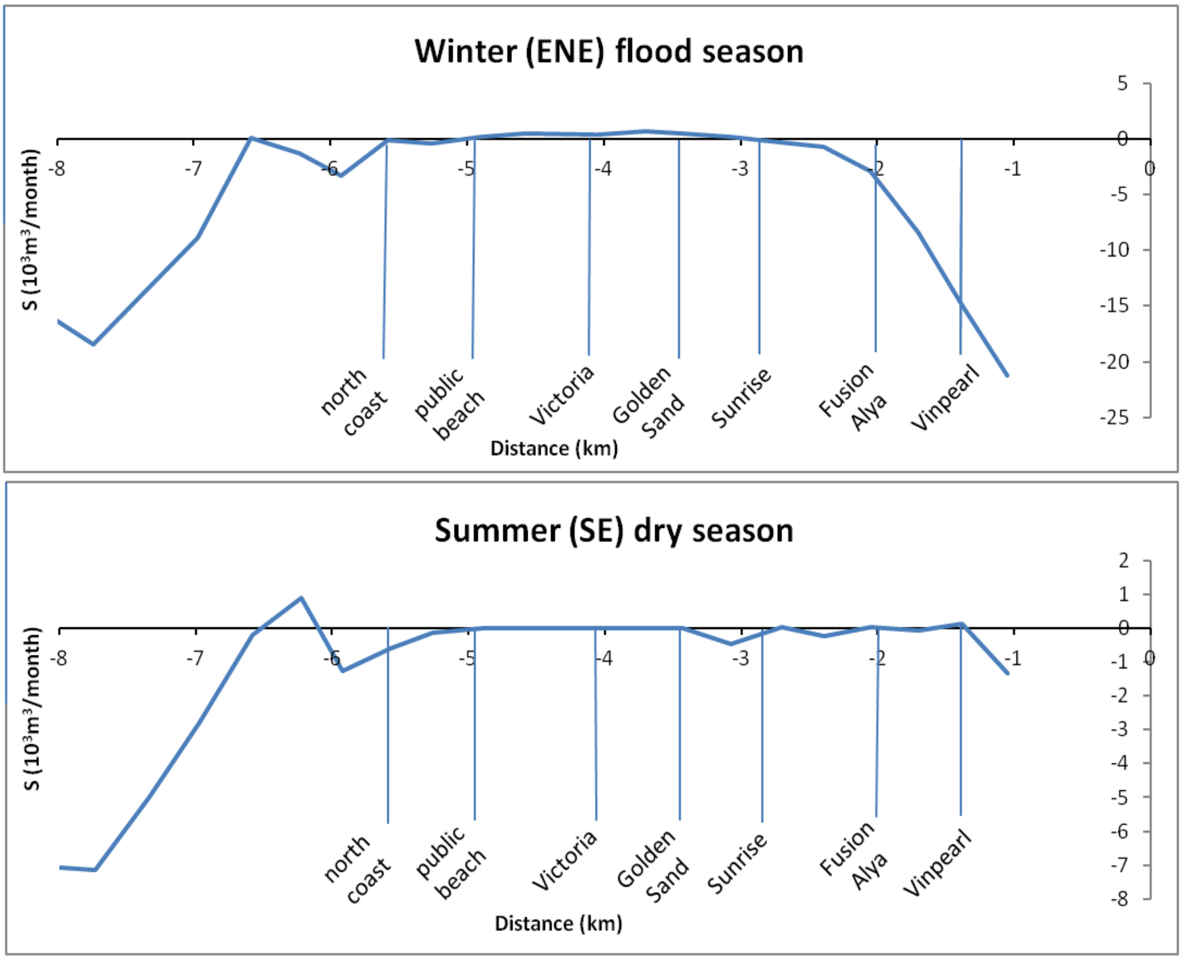


Figure 5.3: Alongshore sediment transport trends in Design 1 for (a) winter flood and (b) summer (SE) seasons. The nourishments of Design 1 are located around the areas named as north coast and public beach

The inspection of the level of diffusion within the control box points out that the largest diffusion for both nourishments takes place for the summer ENE waves. This can be explained by the fact that although the higher ENE waves are able to influence more alongshore spreading, they cause also larger overtopping. This behaviour results in a larger onshore transport and sediment deposition closer to the coast, within the control volume. On the contrary, the lower ENE waves create less onshore transport but also less alongshore spreading. The lower diffusion of the SE waves can be attributed to their different behaviour, as mainly sediment is relocated to the north, altering less the control volume of the nourishments. Finally, another important remark that can be made is that the stronger seasonal trends in terms of diffusion and alongshore sediment transport for the nourishment located north of public Cua Dai beach, indicate that this design can experience stronger changes compared to the nourishment in the public Cua Dai beach.

Design 1 locations	Winter (ENE) flood season	Winter (ENE) dry season	Summer (ENE) dry season	Summer (SE) dry season
north coast	34,8 %	39,7 %	43,4 %	34 %
public Cua Dai beach	23,4 %	23,9 %	26,1 %	22,8 %

Table 5.2: Seasonal diffusion trends in nourishment control volumes of Design 1

5.3.2. Seasonal trends of Design 2

5.3.2.1. Design alternative of multiple nourishments along the coast

The behaviour of the design alternative of multiple nourishments is affected again by the magnitude of the forcing conditions. Also, variability in the sediment transport magnitude is present in the domain related to the impact of the varying bathymetry in the wave forcing. The closely located perturbations along the coast influence differently the alongshore sediment transport pattern. A common trend is observed for the ENE waves, with a magnitude that is linked to the forcing intensity. The sediment transport has a stronger magnitude in the location of Sunrise resort and in the region north of public Cua Dai beach. During the winter flood season the strongest variations in the morphology are present. The most affected nourishment is the one located north of the public beach. The transport pattern that forms there, but also in the nourishment in front of public Cua Dai beach is the same as in Design 1, since the nourishment designs are identical, with onshore sediment transport due to wave overtopping and spreading in the sides.

In general, the same transport trend is formed for the remaining nourishments of Design 2. In front of the resorts, the nourishment in Sunrise experiences, as expected, the strongest changes. The nourishment located front of Vinpearl has also strong morphological variations. There, the river outflow enhances the onshore transport of sediment towards the nourishment, strengthening also its spreading behaviour to the north inlet side. However, immediately downdrift of Vinpearl resort the local interaction of waves and river outflow continues to create sediment accumulation in the resort side that cannot be attributed to the nourishment behaviour.

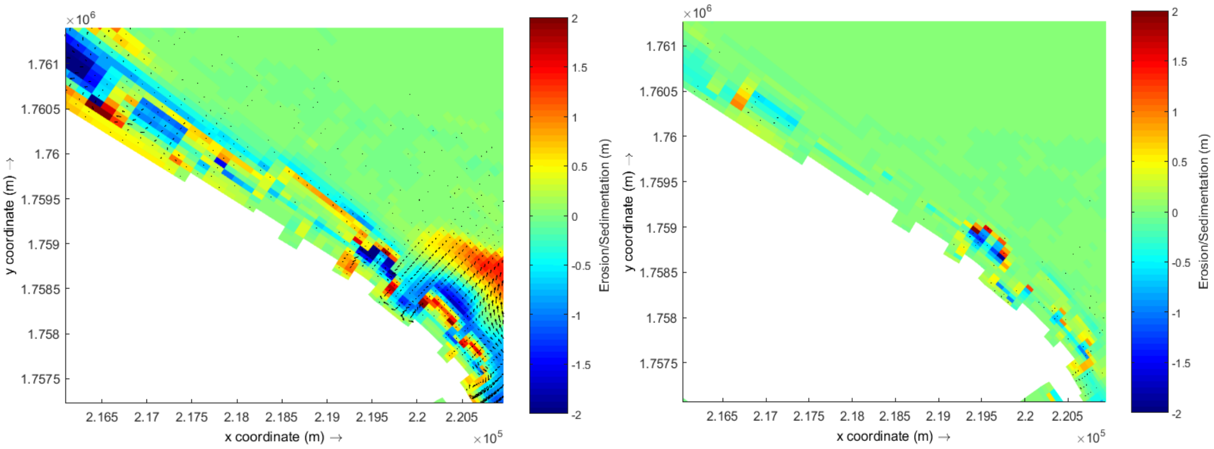


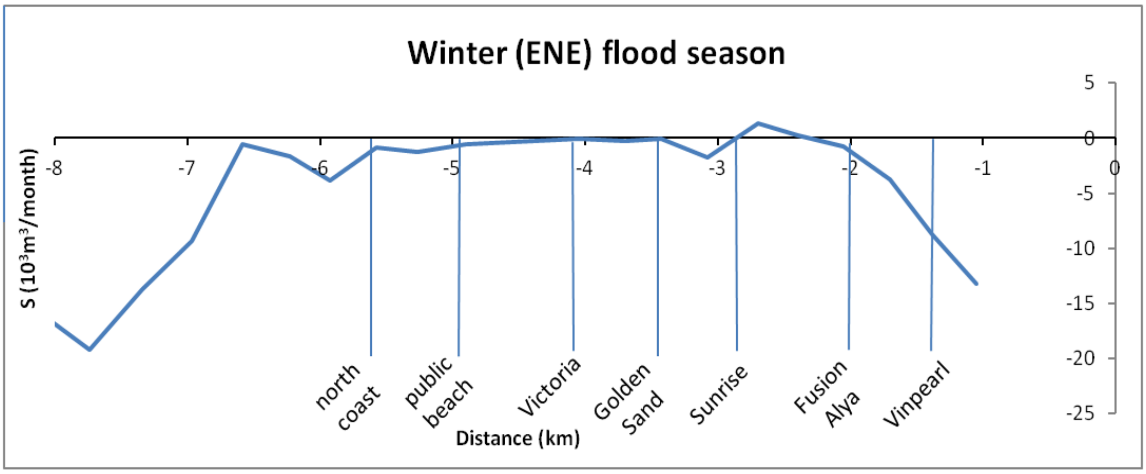
Figure 5.4 Morphological changes and transport patterns in multiple nourishments alternative of Design 2 for (a) winter flood and (b) summer (SE) seasons

In the nourishment in front of Fusion Alya resort, the morphological changes are smaller. However, the morphology in front of the design becomes more complex, as sediment is redistributed towards the nourishment, but also further offshore to the ebb tidal delta. Generally, the presence of the high river flow in the winter flood season influences the transport pattern in the region downdrift of Sunrise resort, causing transport in the region offshore of the coast towards the ebb tidal delta. The nourishments in front of Golden Sand and Victoria resorts, experience the least changes. The locally lower prevailing transport gradients but also the close locations of the designs in the area can explain the small morphological changes. The alongshore sediment transport pattern confirms the observed trends. Stronger gradients are formed in the winter flood season, as a result of the higher waves compared to the milder gradients induced by the lower ENE waves. In the graphs of Figure 5.5, the northward spreading in the nourishment north of the public Cua Dai beach and the bidirectional transport pattern of sediment in the location of Sunrise resort are highlighted. Also, the low gradients that form in the upper area of the nourishment in public beach and the spreading of sediment from Vinpearl towards Fusion Alya resorts can be observed. As in Design 1, the lower erosive gradient during the winter flood season in the upper area of the nourishment of public Cua Dai beach could be attributed to the more complex local pattern between the two designs there. The alongshore transport gradients in these regions are presented in the following table.

Alongshore transport gradients (m^3/m/month)	Winter (ENE) flood season	Winter (ENE) dry season	Summer (ENE) dry season	Summer (SE) dry season
north coast	8.7	7.4	4.3	1.8
public Cua Dai beach	2.1	2.4	2.2	0.3
Sunrise resort	7.9	7.0	4.9	1.6
Vinpearl resort	15.9	8.2	3.3	1.4

Table 5.3: Alongshore sediment transport gradients in the nourishment locations of multiple nourishments alternative of Design 2

A different result is formed under SE conditions. Now the morphological changes are milder, located mainly in the nourishments at the Sunrise and Vinpearl resorts, as well as in the nourishment north of public Cua Dai beach. In general, a northward directed transport trend is observed. Yet, in the nourishment in front of the Sunrise resort the spreading of sediment in the north and south still takes place. The nourishment at the Vinpearl resort, due to its close location near the inlet, still experiences the effect of the river outflow, even though lower, influencing the onshore transport in front of the design and sediment spreading in the sides. Also during this season, the local transport trend downdrift of Vinpearl resort causes local sediment accumulation that is not related to the nourishment. These observations agree with the alongshore transport trend that highlights the prevailing northward directed gradients along the coast.



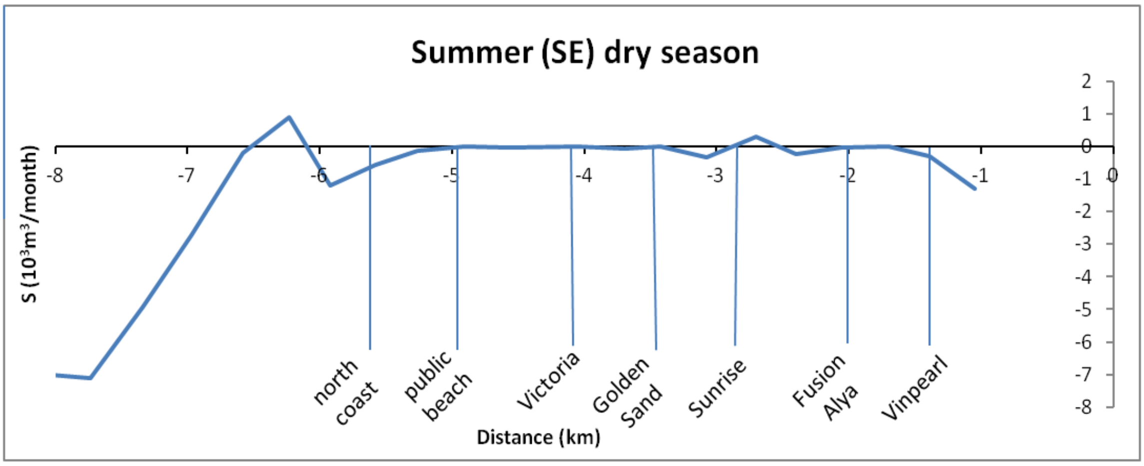


Figure 5.5: Alongshore sediment transport trends in multiple nourishments alternative of Design 2 for (a) winter flood and (b) summer (SE) seasons

The level of diffusion within the control boxes shows that the most affected nourishments are the ones located north of public Cua Dai beach, but also in front of the Sunrise and Vinpearl resorts, in accordance to the observations. Again, for the nourishment designs located in the public Cua Dai beach and in the region north, the stronger diffusion is observed for the lowest ENE wave heights. The larger onshore transport due to overtopping of the higher waves can explain this feature, even though the alongshore spreading is stronger. In the nourishments in front of the resorts of Cua Dai beach, the erosion within the control volume is in the same range for the ENE waves which can be explained by the fact that the nourishments are closely located, so their spreading behaviour cannot differ much. Furthermore, due to the lower prevailing transport magnitude in many locations there, the onshore transport does not cause sedimentation in the coast and sand is mainly distributed in the sides. The largest variation in diffusion is created in the nourishment of Vinpearl resort. There, the river enhances the onshore transport trend within the control volume, causing higher sediment accumulation in front of the resort in the winter months and stronger spreading. For the SE waves, the lower level of diffusion is attributed to the different behaviour due to the northward transport pattern that is present in most locations.

Design 2 locations	Winter (ENE) flood season	Winter (ENE) dry season	Summer dry (ENE) season	Summer dry (SE) season
Vinpearl resort	22,3 %	29,9 %	30,8 %	23, 5 %
Fusion Alya resort	17,6 %	17,9 %	17,4 %	13,8 %
Sunrise resort	32,9 %	32, 1 %	30,1 %	22,9 %
Golden Sand resort	14,3 %	13,8 %	13 %	11,6 %
Victoria resort	18,7 %	18,9 %	18,7 %	17,9 %
public Cua Dai beach	24,8 %	24,9 %	27,7 %	25,1 %
north coast	34,1 %	39,7 %	43,2 %	33,5 %

Table 5.4: Seasonal diffusion trends in nourishment control volumes of multiple nourishments alternative of Design 2

It can be concluded that the nourishments are expected to behave differently. The strong transport gradients in the location of the nourishment north of public Cua Dai beach can justify the stronger changes that are anticipated with respect to the remaining designs. In the region across the resorts, the trend is more complex. The lower prevailing transport magnitude and the smaller transport gradients that form due to the fact that the nourishments are at a close distance, are expected to affect less the nourishments at Fusion Alya, Golden Sand and Victoria resorts. Larger changes can be anticipated for the nourishments in front of Vinpearl and of Sunrise resort, where stronger gradients form due to the local divergence of transport and the open space.

5.3.2.2. Design alternative of localized nourishment

The trends of the localized nourishment give prominence to interesting remarks. Now a large area is occupied by the design, from the region between Sunrise and Fusion Alya resorts until Golden Sand resort. The ENE wave conditions affect the design in a similar way and the magnitude of morphological changes varies with the forcing. In general, the transport magnitude in the location of the nourishment is not large. The prevailing seasonal transport pattern transforms the initial shape of the design, which takes a more symmetrical form, smoothing out the sharper edges.

For ENE waves, in the nourishment area updrift of Sunrise resort onshore transport takes place, eroding sediment from the upper part of the cross shore slope and of the top, which is then further spread to the north but is deposited also closer to Golden Sand resort. In accordance, at the oblique region of the design the onshore directed transport erodes sediment, distributing it further onshore but also to the north and south. At the area downdrift of Sunrise resort, the onshore transport moves sediment towards the coast and spreading is observed to the south towards Fusion Alya resort. The expected transport divergence trend of the ENE waves in the nourishment location is present, assisting its bidirectional spreading behaviour. It must be noted that the sediment accumulation trend that forms in front of Vinpearl resort and reaches until Fusion Alya resort is not induced by the nourishment and is the result of the prevailing river impact and wave pattern. The alongshore sediment transport trend in Figure 5.7 agrees with the observed features, highlighting the erosion of sediment in the sides of the nourishment and the transport to the north and south. Stronger gradients form under the higher ENE wave action in the sides of the design, in comparison to the milder alongshore gradients induced by the lower ENE waves. However, it is observed that in the south side of the design the alongshore gradient is not the strongest in the winter flood season, which can be attributed to the impact of the prevailing high river flow of the season in the region that weakens the wave effect. The alongshore transport gradients in these regions are presented in Table 5.5.

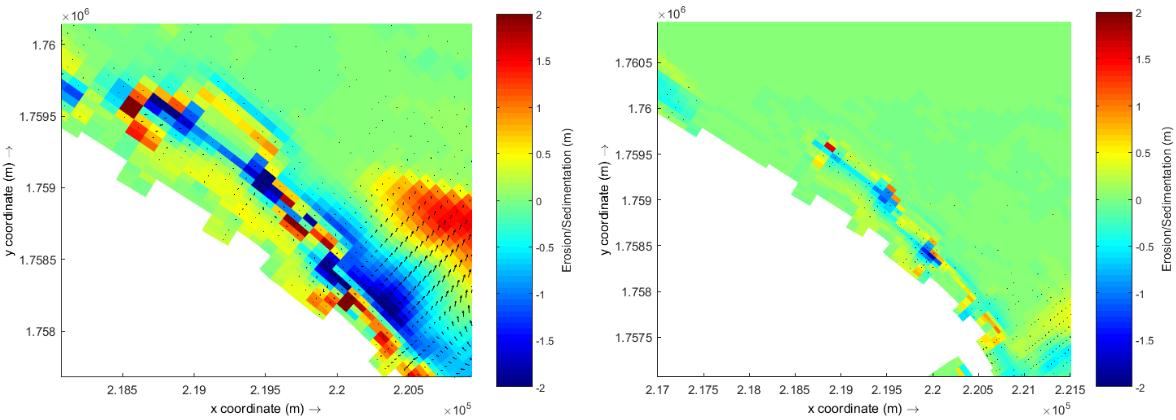


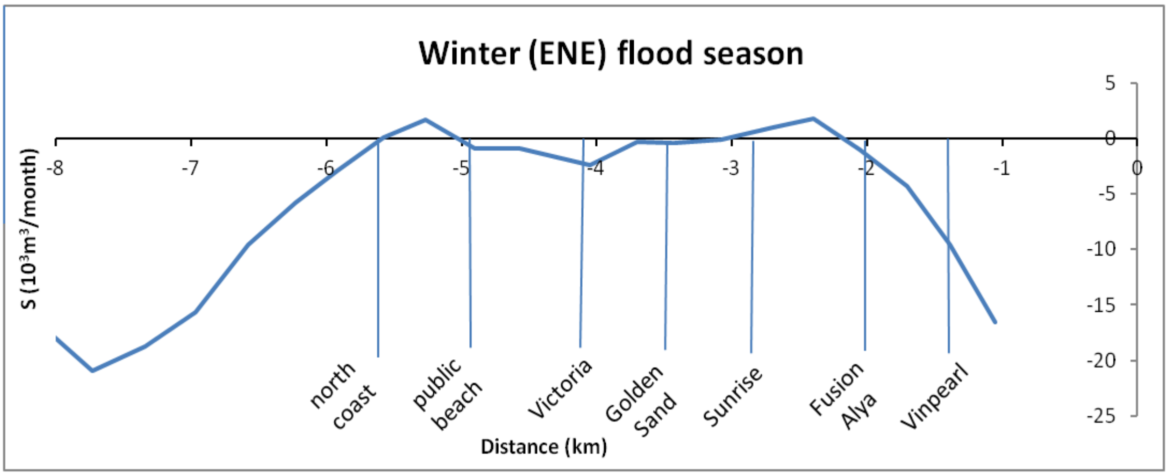
Figure 5.6: Morphological changes and transport patterns in localized nourishment alternative of Design 2 for (a) winter flood and (b) summer (SE) seasons

In the offshore area around the design two local-scale horizontal circulation zones of flow are observed. The first one is located close to the updrift edge of the nourishment, enhancing the onshore transport pattern in the nourishment region in front of Golden Sand resort, and being influenced by the northward directed spreading trend at the upper side slope. The second horizontal circulation zone of flow is present offshore of the oblique region of the nourishment and creates sediment transport onshore but also towards the ebb tidal delta. These flow patterns have a lower magnitude in the winter dry season and are not formed under the lower ENE summer wave conditions, when the wave impact is milder. Their presence could be attributed to the local high bathymetric gradients that exist in the region, due to the presence of the nourishment design, in combination to the impact of the wave forcing. The complex pattern of waves and river flow in the region downdrift of Sunrise resort enhances the interaction with the ebb delta. This causes some transport of sediment that is located away of the design towards the ebb delta. Attention should be paid, as this trend may create in the future possible losses from the nourishment in that region, mainly in the winter flood season when the effect of river flow is stronger.

Alongshore transport gradients (m^3/m/month)	Winter (ENE) flood season	Winter (ENE) dry season	Summer (ENE) dry season	Summer (SE) dry season
south side	2.4	3.7	2.9	-
north side	6.1	4.2	2.0	-
Center	-	-	-	1.7

Table 5.5: Alongshore sediment transport gradients in the locations of localized nourishment alternative of Design 2

When SE wave conditions prevail, a different transport trend is observed. The level of morphological changes is low, which is expected since the forcing is mild. Now the horizontal circulation zones of flow are absent, as the wave height is lower and has a different direction. The behaviour of the nourishment now is different. The transport has a northward direction as the waves move alongside to the coast and divergence in sediment transport is absent. Also, along the cross shore slope the sediment is transported to the north as well as offshore. The alongshore transport pattern highlights the northward directed trend that now erodes sediment in the center area of the nourishment and the magnitude of this gradient there is presented in Table 5.5.



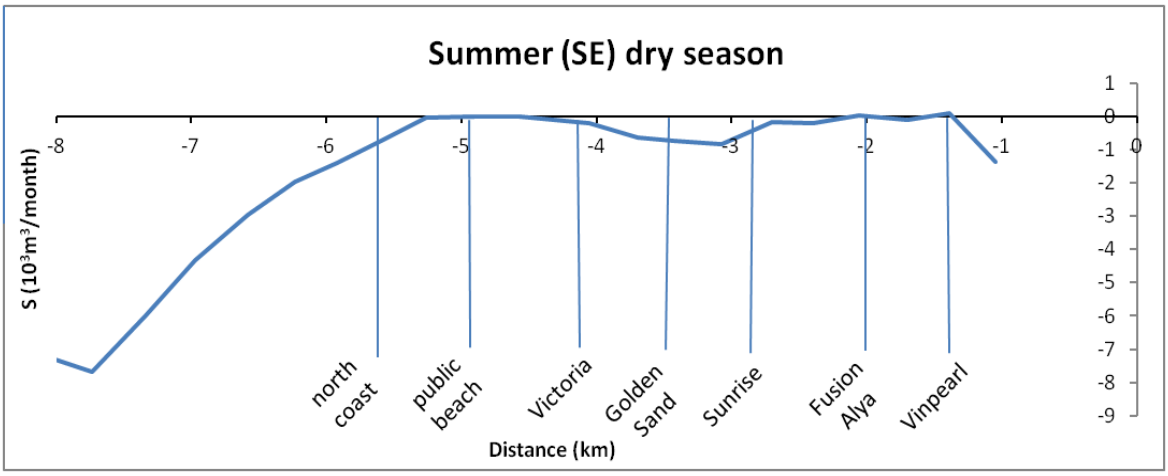


Figure 5.7: Alongshore sediment transport trends in localized nourishment alternative of Design 2 for (a) winter flood and (b) summer (SE) seasons

The diffusion of sediment within the control box is not high, which can be expected since now the volume of this nourishment design is significantly larger with respect to the other design solutions. The largest diffusion is created under the low ENE summer waves. The large onshore transport due to wave overtopping and deposition closer to the coast caused by the higher ENE waves, reduces the amount of sand that leaves the control box, although the alongshore spreading is generally stronger. In accordance, since the onshore transport of the smaller waves is less, a larger level of diffusion can be created, even though the spreading to the sides is lower. The summer SE waves trigger a relatively low diffusion of sand, due to the different behaviour they provoke because of the northward directed transport pattern. Furthermore, now that the design occupies a large space, the diffusion does not range a lot among the seasonal conditions, because the main volume does not alter significantly.

	Winter (ENE) flood season	Winter (ENE) dry season	Summer (ENE) dry season	Summer (SE) dry season
Design 2	4.3 %	5.1 %	6 %	5.1 %

Table 5.6: Seasonal diffusion trends in nourishment control volume of localized nourishment alternative of Design 2

5.4. Conclusion

In this chapter, an assessment of the selected design solutions has been performed. The scope of the present analysis is limited to the investigation of the seasonal behaviour of the nourishment designs. In addition a qualitative assessment has been presented. The aim of the qualitative analysis is to allow for an overview and comparison among the design solutions, since their differences in terms of the selected locations, the required volume and shape restrict a comparison based on their seasonal behaviour. A spider chart has been created for each nourishment design based on evaluation parameters related to the design approach. The overall symmetric chart form in both nourishment alternatives of Design 2 highlights the integrated character of this design approach, even though variations are present between the two proposed design alternatives that require careful choices. The abstract chart form of Design 1 indicates the positive aspects and the limitations that follow from this design solution.

With respect to the investigation of the seasonal trends in the behaviour of the nourishment designs, two common criteria have been considered. The trends in the alongshore sediment transport gradients that form after the nourishments are constructed, but also the level of diffusion which is assessed based on the volume changes within a control box that covers the main area around each nourishment. In all designs the spreading behaviour has been observed, with sediment to be directed towards the desired locations. Common trends in each design are present under ENE waves varying in accordance to the forcing magnitude, which differ for the SE wave forcing.

The assessment of Design 1 indicates the stronger changes that take place in the nourishment north of public Cua Dai beach. For the ENE wave conditions onshore sediment transport has been observed and alongshore spreading of sediment, connecting the two nourishment designs. During higher ENE waves, larger sediment accumulation is created in the top of the nourishments despite the stronger alongshore spreading that results ultimately in less diffusion. The northward directed sediment transport trend that forms when SE waves prevail, limits the onshore transport and the low level of diffusion shows the mild morphological changes of this season.

For the multiple nourishments design alternative, variation in the level of morphological changes is observed among the designs. The most affected nourishments are the ones located north of public Cua Dai beach and in the regions of Sunrise and Vinpearl resorts. The nourishment in front of Sunrise resort experiences a constant bidirectional transport pattern under all seasonal conditions. The river creates an impact for the nourishment design in front of Vinpearl resort, enhancing the onshore transport and spreading towards the inlet. The local sediment accumulation in the region immediately downdrift of Vinpearl resort is not related to the nourishment behaviour and is a result of the prevailing interaction between the waves and the river flow.

The localized nourishment design experiences alterations in shape in all seasonal conditions, taking a smoother form. The anticipated bidirectional spreading under ENE wave conditions is observed. The level of diffusion highlights the higher onshore transport created by the high ENE waves, limiting the amount of sand that leaves the control box, even though the alongshore spreading is stronger. For the winter ENE waves, two local-scale horizontal circulation zones of flow are observed close to the design that can be attributed to the local bathymetric gradients because of the presence of the nourishment in conjunction with the impact of waves. When SE waves prevail, mild changes are present with sediment to be eroded in the center of the nourishment and a northward directed transport trend forms. The sediment accumulation in the region in front of Vinpearl resort, that reaches until Fusion Alya is a result of the local wave and river interaction. In general low diffusion levels are observed, attributed to the initial large volume that makes changes to be less noticeable.

6. Discussion

In this chapter a discussion is made regarding aspects that have not been encountered in the present thesis study and can be part of future research on this topic. In addition, reflection is performed in terms of the research approach that has been followed, but also with respect to the applicability of the mega nourishment concept in Cua Dai beach.

6.1 Long term simulation of nourishment designs

In the present study the assessment of the proposed nourishment design solutions is focused on the observation and analysis of the seasonal trends in their behaviour, based on selected representative seasonal wave and river discharge forcing conditions. Through this, the influence of the seasonal climate has been explored and important observations have been made in terms of the feeding character of the nourishments. The simulation of the nourishment designs over the defined lifetime of 10 years is also a necessary step that can reveal their long term behaviour as well as the response of the coast.

In chapter 4, the inclusion of the seasonal character of the region in the simulations of the designs has been highlighted, in order to achieve a realistic feeding behaviour. The inclusion of the schematized wave climate of the domain that consists of four representative seasonal wave conditions should be imposed through the WAVE model boundaries, varied in time according to their weighted effect over the year, for the purpose of long term simulations. The influence of the seasonal variation over an annual cycle of the river discharge through representative conditions is also relevant to be included. Yet, the complexity that is introduced in the model domain due to the seasonal interaction of processes could be limited in order to avoid possible model instabilities. In this case, the selection of a uniform river discharge, retrieved from the available data record of Nong Son station, which can represent sufficiently a large amount of discharge levels that occur through a year in the river, could be considered suitable.

6.2 Influence of borrow site location

This research does not take into consideration the location of the borrow area from which the required sediment for the nourishment design solutions will be provided. Possible sources of sediment can be mainly locations offshore of the nourishment designs. These can provide the necessary amount of sediment for the nourishments and have a relatively close distance to the coast, limiting the transfer time of the sediment and consequently the associated costs.

The presence of borrow sites directly offshore of the area where the nourishments are located could affect the nearshore wave field and sediment transport patterns. Borrow pits are perturbations and thus, when located in intermediate to shallow waters they can influence nearshore wave processes, such as shoaling refraction and dissipation, altering consequently the sediment transport pattern. This is supported by the research of Benedet & List (2008), Dalyander et al. (2015) and Hartog et al. (2008). Therefore, it is considered relevant to assess their effect and influence in the nourishment designs. The magnitude of this influence could be explored through a sensitivity analysis with numerical modelling simulations. The consideration of various borrow site location scenarios can highlight their impact on the nearshore wave pattern and the alongshore sediment transport trends. From there, the optimal location that can limit their influence in the projected evolution for each of the nourishment design alternatives can be indicated.

6.3 General reflection

The present research aims to cope with the ongoing erosion in Cua Dai beach, through a nourishment strategy that incorporates the mega nourishment concept, following the successful implementation of the Sand Engine in the Netherlands. The approach that has been considered for this purpose formulates design solutions based on the information gained through investigation of the dynamics of the system. Modelling results of the broader area that includes Cua Dai beach were able to provide necessary information and insight in the seasonal dynamics of the region, with inclusion and assessment of the relevant processes involved. Through this, contribution and extension of the previous research in the area has been achieved. Information has been provided with respect to the influence of the seasonal prevailing climate and of extreme events but also regarding the impact of certain human interventions along the coast. The selected method can be considered sufficient for providing a reliable sandy solution to a coast characterized by seasonal complex changes, in which lack of experience in nourishment implementations exists.

In addition, a Sand Engine solution cannot be directly translated into every retreating coastline with different climate conditions. The implementation of the mega nourishment concept into Cua Dai beach highlights the need for adaptation of the Sand Engine design in order to be applicable to a coastline with different climate characteristics, in a system with a high level of complexity due to the prevailing processes that interact. Investigation and understanding of the local system dynamics is considered to be a necessary step. The approach followed indicated the different form of the mega nourishment concept in terms of required nourishment sizes, design shapes and potential locations, as well as the emerging restrictions that influenced the final design solutions. The results of this research imply that sand nourishment applications can be applicable for retreating coastlines that are located adjacent to an inlet and are dominated by seasonally varying climate conditions. Thesis findings suggest that nourishment designs that follow the mega nourishment concept can be an option for the problem of erosion in Cua Dai beach.

7. Conclusions

The objective of the present study was to investigate the applicability of the mega nourishment concept with the purpose of combating erosion in Cua Dai beach. A goal was set: to create a design that can cope with the long term problem of erosion. In order for this to be achieved, a strategy has been decided that aims to investigate the level of effectiveness of a mega nourishment in the region and contribute to the ongoing research in the area with useful remarks. For this purpose, the numerical model Delft3D has been used. The approach that has been followed together with the concluding remarks address the research objective through the research questions that have been set in part 1.3. These are presented in the following sections.

7.1. Physical processes in Cua Dai

In the beginning (Chapter 2), an overview of the morphological changes in Cua Dai beach has been presented, together with previous research approaches to investigate the problem of erosion at the coast. Also, the stakeholder dynamics in the area have been briefly highlighted. In addition, the Sand Engine concept has been introduced.

7.1.1. Which are the processes, phenomena and recorded level of erosion in Cua Dai and which are the human interventions that have occurred?

- The elements of the Cua Dai system are the estuary where Thu Bon river flows, the adjacent coastlines north and south, the ebb tidal delta and the Cu Lao Cham island complex. During the period of 1975-1989, an offshore sandbar has been formed that has later welded into the north coast. Also, a continuous shift of the inlet mouth to the south has been observed. In addition, the north coastline where Cua Dai beach is located has shown a continuous erosive pattern that propagates to the north over the years, while the south coast shows an overall accretive behaviour.
- The seasonal character of the prevailing climate has been presented. Two dominant wave directions have been highlighted, being the ENE and SE. Also, the varying river discharge was introduced, creating a flood and a dry season. Finally, the occurrence of non cyclic extreme flood and storm events was described.
- Based on available literature, the overall retreat in the north coast in the period 1988-2015 was estimated to be in the range of 6-31 m/year. In the Cua Dai beach, during 1995-2000 the average retreat was 18 m/year, observed close to the inlet and the sediment loss was estimated to be 60,000 m^3/year. On average 12 m/year of coastline were lost during 2000-2010, with erosion to extend north and a sediment loss of 183,000 m^3/year has been estimated. An average retreat in the order of 6 m/year was observed in the period 2010-2015 affecting the coast further north, with a total of 103,000 m^3/year of sediment to be lost.

- Resorts have been built along the Cua Dai beach and hydropower dams have been constructed in the upstream part of Thu Bon-Vu Gia river system. Also, land reclamations took place and sand mining has been regularly performed.

Then (Chapter 3), representative conditions have been selected in order to investigate the seasonal prevailing dynamics in the overall region in which Cua Dai beach is located and be used later in the mega nourishment design approach. With these conditions, recorded morphological trends from three characteristic past morphological periods have been simulated and reproduced. In addition, the effect of extreme events has been investigated separately. In this way the dynamics of the area have been examined. Also, the model performance and the representative conditions have been validated. Based on all these information understanding of the system is gained and the nourishment design parameters can be defined.

7.1.2. What are the seasonal prevailing dynamics in Cua Dai beach?

- The annual cycle of three past morphological periods has been simulated and assessed in separate scenarios. During the period 1995-2000 where no interventions were present in the system, an overall erosive trend has been reproduced in the north coast. There, under ENE wave conditions a sediment transport divergence point is present. Furthermore, the trend of formation of an ebb tidal bar has been highlighted, as well as its interaction with the north coast. In the second period 2010-2015, where resorts have been constructed in Cua Dai beach, enhancement of the propagation of erosion further to the north has been simulated. Finally, the presence of sandbags across the public Cua Dai beach in 2015-2016, reinforced further the erosive northward trend of the north coast.
- The extreme flood and storm events do not alter the prevailing erosive trend of the north coast. They can provide insight to formation of features that have not been influenced by the regular seasonal conditions but also to explain the acceleration of inspected morphological trends.

7.2. Mega nourishment design approach

In the second part of this report (Chapters 4 and 5), the selected design approach for a mega nourishment implementation is introduced. Then, the most important design parameters are highlighted and determined. Choices are made for the remaining design aspects. The final design solutions are then presented. An assessment follows, based on qualitative criteria but also on their seasonal behaviour.

7.2.1. Who are the most influential stakeholders in Cua Dai beach?

- Based on available stakeholder analysis the public authorities, as well as the resort owners have been determined to be the most influential stakeholders in Cua Dai beach. Their needs and interests can mostly affect the implementation of a solution that can deal with the problem of erosion in the coast.

7.2.2. Which is the mega nourishment design approach?

- The stakeholder influence shapes the design approach. Because of this aspect, two design solutions have been selected. The first design solution considers only the treatment of the ongoing erosion, by nourishing the public Cua Dai beach and the coast north, aimed to be funded only by the public authorities. In the second design solution, the coast in front of the resorts is also included in the nourishment design. In this case, the resort owners are included in the financing of the design. For the second solution, two alternative designs have been proposed.

7.2.3. Which are the main design parameters and which are the final designs?

- The main design parameters are the nourishment volume, the location of the design, the design lifetime and the shape.
- The nourishment volume is derived based on the net annual erosion rate in combination with the available recorded annual average coastline retreat levels, for the predefined design life. The alongshore sediment transport trend together with the desired locations that aim to be nourished, are the criteria that determine the position of each of the designs. The shape of the designs aims to assist the alongshore diffusion of nourishment by the waves.
- For the first design solution a total volume of 1 Mm^3 of sediment has been determined. A volume of 3 Mm^3 is required for the second design solution. These volumes consider a lifetime of 10 years. In the first design solution the required volume is split in two adjacent locations and the shape of the nourishments is rectangular. An amount of 0.5 Mm^3 is located north of the public Cua Dai beach, aiming to spread and nourish the coast north, while the remaining volume is placed in front of the public beach where a limited gradient exists. In the first alternative of the second design solution where multiple nourishments are considered, a rectangular shape is also selected. The nourishments are constructed in the same locations of the first design, as well as in front of each resort across the Cua Dai beach with the intention to spread and connect, widening the coastline. In the second alternative of Design 2, an abstract shape is created that aims to enhance the nourishment spreading. The design is positioned in the observed divergence point in the north coast, aiming to be spread north and south.
- The nourishment design solutions are illustrated in the following images.

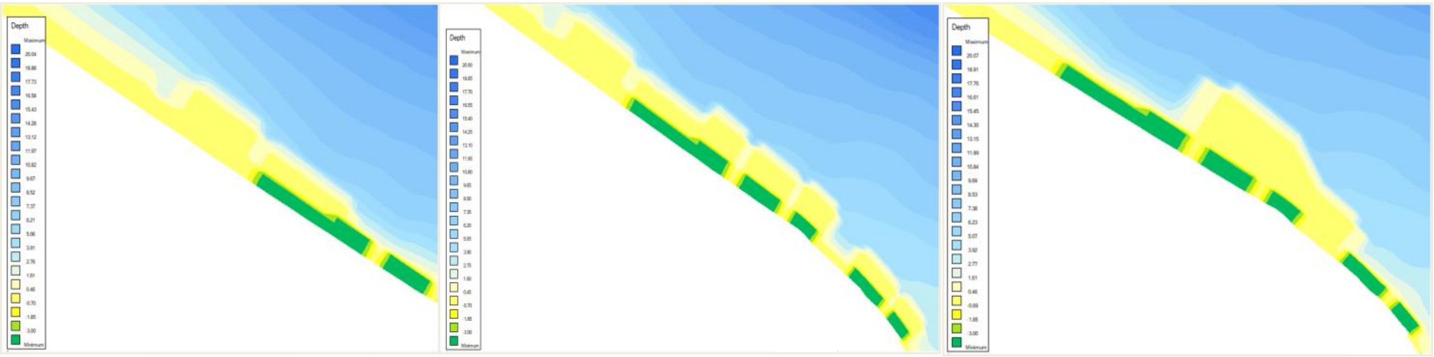


Figure 7.1: Final design solutions. In the left figure, Design 1 is illustrated (Figure 4.8). In the middle figure, the design alternative of multiple nourishments of Design 2 is depicted (Figure 4.9). The right figure shows the localized nourishment of Design 2 (Figure 4.10).

7.2.4. What is the seasonal behaviour of the designs?

- The proposed designs are assessed under the prevailing representative seasonal wave and river forcing conditions in order to inspect trends that can identify their behaviour. For this purpose two criteria have been selected, the level of diffusion and the alongshore sediment transport gradients. A common simulation period of 1 year has been selected.
- The nourishment design solutions due to their differences in location, volume and shape behave differently and cannot be compared. In each case, the behaviour is linked to the magnitude of forcing and to the prevailing wave direction. A common behaviour is observed for ENE incoming waves that differs for SE waves. All design solutions show a degree of spreading around them, directed to the expected locations.
- In Design 1 the higher ENE waves influence a larger onshore transport, creating sediment accumulation towards the coast, but on the same time they induce the strongest alongshore spreading. During SE waves a net northward transport trend is present and the onshore transport is limited. The larger seasonal trends in alongshore gradients and diffusion levels for the nourishment located north of the public Cua Dai beach, indicate that this design can experience stronger changes compared to the nourishment in public Cua Dai beach.
- In the multiple nourishments alternative of Design 2, a different behaviour is observed among the designs. The most affected nourishments are the ones located north of public Cua Dai beach, as well as in front of Sunrise and Vinpearl resorts. The nourishments in front of the resorts show a similar level of diffusion under ENE waves, attributed to their close location that restricts the formation of alongshore gradients. The largest variation there is present for the nourishment in front of Vinpearl resort, where the river flow enhances the onshore transport and the subsequent spreading towards the inlet. For the summer SE waves changes are milder and an overall northward transport trend is present. Under all seasonal conditions, the nourishment in front of Sunrise resort experiences a bidirectional transport trend. The sediment accumulation immediately downdrift of Vinpearl resort is not linked to the nourishment diffusion and results from the local interaction of waves and the river. The strong seasonal transport gradients that form north of public Cua Dai beach are expected to cause stronger changes compared to the lower gradients in the nourishments in front of resorts. There, larger changes are anticipated for the locations of Sunrise and Vinpearl resorts.
- For the localized nourishment alternative of Design 2, the initial abstract shape of the design takes a smoother form. The expected bidirectional spreading trend in sediment transport under ENE waves is observed. The higher ENE waves cause larger onshore transport and subsequent sediment accumulation, but also stronger alongshore transport. Two local-scale horizontal circulation zones of flow form close to the design in the winter seasons. For the SE waves a northward transport trend that causes erosion in the center of the nourishment has been observed. In general, the level of diffusion does not range significantly among the different seasonal conditions, due to the fact that the initial design volume is large and changes are less noticeable. The sedimentation in the

region in front of Vinpearl resort until Fusion Alya resort is not induced by the nourishment and is the result of the prevailing river impact and wave pattern.

8. Recommendations

This chapter provides recommendations for future research on the topic. They are the outcome of the observations and limitations that have been encountered over the research period. Investigation of them is expected to evolve the research study that has been presented here.

The most essential recommendation is the long term simulation of the proposed nourishment design solutions, in order to make an assessment of their feeding behaviour and evolution over the selected design lifetime. The simulation with the inclusion of the varying waves is required for this purpose. In addition, the investigation of the allowable MorFac value is considered relevant in order to verify the accurate morphological evolution of the designs, through a sensitivity analysis before the implementation of the long term simulations.

The investigation of the influence of the location of the borrow area in the nearshore wave field and the sediment transport pattern is also recommended. By performing a sensitivity analysis considering various borrow site locations, their effect in the coast and in the evolution of the nourishment designs can be determined. In addition to this, the optimal configuration of the borrow site can be also explored.

The simulation of the effect of extreme storm conditions in the alongshore spreading of the designs and in the plan form changes is another interesting aspect to investigate. Considering the strong impact of waves during the short term period of an extreme event along the coast of Cua Dai that has been highlighted in this research and the frequent occurrence during the winter, it is relevant to explore the impact of storms in the nourishment designs.

Design choices have been made in order to formulate the nourishment design solutions, with the aim to stimulate the feeding behaviour that follows from the mega nourishment concept. The optimization of design parameters can maximize the design performance. A sensitivity analysis regarding the selected cross shore and side slopes of the nourishments, is recommended for this purpose. Furthermore, the overtopping effect that has been observed in all designs under higher wave action, with the subsequent onshore transport could be reduced with a sensitivity analysis for the top elevation in each of the nourishments. Finally, in the same sense the selected shape of the localized nourishment design alternative could be further improved by assessing the influence of different plan form slopes of the abstract region of the design to the alongshore sediment transport gradients that form, aiming to maximize the bidirectional spreading there.

Another recommendation would be to investigate the effect of the locally formed horizontal circulation zones of flow that have been observed close to the localized nourishment design under certain seasonal conditions and their relation to the wave forcing, in terms of magnitude and direction. Also, the degree of influence of the local bathymetric gradients due to the slopes of the nourishment on this hydrodynamic feature is interesting to be assessed.

A final recommendation would be to examine the relationship between the prevailing alongshore transport gradients in a coastline stretch with the ones that form after a nourishment design is positioned there. During the assessment of the seasonal behaviour of each of the nourishment designs, a positive correlation has been observed between the magnitude of the gradients before and after a nourishment was implemented. The existing knowledge does not allow for an estimation of the role of the prevailing alongshore gradients in the future spreading behaviour of a nourishment. It is believed that research in this topic could lead to interesting remarks.

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A. Appendix: Representative forcing conditions

In this part, the methodologies for the extraction of the seasonal representative wave and river discharge conditions are presented, in order to support the choice of the final selected values that have been used in the main report of the thesis. Additionally, characteristic representative extreme storm and river flood parameters are determined so as to evaluate the impact of extreme events in separate simulation scenarios. The available data records that are being used for this purpose have been presented in section 3.2.

A.1. Representative wave conditions

For the wave conditions, three criteria are considered in order to end up with the final seasonal representative values. The wave induced alongshore sediment transport pattern of each condition forms the common assessment parameter. Existing alongshore transport patterns over the north and south coastlines of the Cua Dai inlet obtained from Do et al. (2017) are used. These have been extracted with the CERC formula, in which the nearshore wave breaking wave height has been used, derived with SWAN computations. In order for a wave condition to be selected, all three criteria have to be satisfied. A wave condition must induce a high amount of sediment transport. In addition, a similar transport pattern in comparison to the one induced by the corresponding net seasonal wave direction must exist. Finally, the wave condition has to occur frequently.

The implementation of the aforementioned criteria is briefly described. To begin with, inspection of the magnitude of the alongshore sediment transport rates is performed. In addition, it is important to compare the sediment transport pattern induced by each wave height condition, to the net sediment transport pattern of the corresponding wave direction. A certain wave direction contains several waves, but individual conditions can be distinguished, which influence the net trend of each direction. Based on these two criteria, certain wave conditions stand out. Furthermore, the annual percentage of occurrence is the third dominant parameter to be evaluated, based on which a selection among conditions with similar sediment transport magnitudes and patterns can be made. The result of this process leads to the selection of a number of wave conditions that represent each of the influencing directions. After obtaining this reduced number of wave conditions, the dominant ones that will represent each season are selected using the same set of criteria. Through this process, the final representative seasonal wave conditions are defined. In the remaining part, the available classified wave data record of the influencing wave directions that is used is summarized in the following table. Then, the process of choosing the resulted representative summer and winter wave conditions is presented.

	H_s (m)	T_p (sec)	Direction (^{0})	Seasonal Occurrence (%)
Summer	0.25	6,51	ENE (60^0)	6.02
	0.75	6,42	ENE (60^0)	10.41
	1.25	6,13	ENE (60^0)	5.72
	1.75	6,76	ENE (60^0)	1.37
	2.25	7,51	ENE (60^0)	0.87
	0.25	6,71	ENE (75^0)	11.89
	0.75	6,35	ENE (75^0)	4.44
	1.25	6,18	ENE (75^0)	1.48
	1.75	6,3	ENE (75^0)	0.48
	2.25	5,82	ENE (75^0)	0.47
	0.25	6,33	SE (135^0)	8.19
	0.75	6,4	SE (135^0)	17.18
	1.25	6,06	SE (135^0)	3.52
	0.25	6,39	SSE (150^0)	12.42
	0.75	6,32	SSE (150^0)	13.35
	1.25	6,27	SSE (150^0)	1.43
Winter	0.25	7,76	ENE (60^0)	2.14
	0.75	7,9	ENE (60^0)	9.73
	1.25	7,9	ENE (60^0)	13.8
	1.75	7,57	ENE (60^0)	11.3
	2.25	7,64	ENE (60^0)	9.78
	2.75	7,75	ENE (60^0)	8.12
	3.25	7,56	ENE (60^0)	4.89
	3.75	7,28	ENE (60^0)	3.04
	4.25	6,86	ENE (60^0)	1.45
	4.75	7,38	ENE (60^0)	0.66
	0.25	8,41	ENE (75^0)	1.34
	0.75	8,23	ENE (75^0)	5.16
	1.25	8,39	ENE (75^0)	4.16
	1.75	8,04	ENE (75^0)	4.15
	2.25	8,09	ENE (75^0)	3.06
	2.75	8,16	ENE (75^0)	3.28
	3.25	8,3	ENE (75^0)	3.04
	3.75	7,84	ENE (75^0)	1.44
	4.25	7,02	ENE (75^0)	0.63
	0.25	8,29	NE (45^0)	0.47
	0.75	8,66	NE (45^0)	1.09
	1.25	8,58	NE (45^0)	2.28
	1.75	8,67	NE (45^0)	1.36
	2.25	8,45	NE (45^0)	1.05
	2.75	8,74	NE (45^0)	0.82
	3.25	8,61	NE (45^0)	0.58

Table A.1: Record of available influencing wave conditions

Starting with the summer season where a bidirectional regime exists, the most influencing wave heights are selected for each of the prevailing wave directions. The criteria that have been presented are now applied in order to obtain the reduced amount of conditions, from which the final parameters will be chosen.

- ENE (60^0): The most influencing wave height conditions based on the sediment transport magnitude they create in the north and south coastline, reduce to H=0.25 m, H=0.75 m and H=1.25 m. In addition, all these three cases induce a similar sediment transport pattern that resembles the net sediment transport pattern of the ENE (60^0) direction. In the end, the wave height that is selected is H=0.75 m, because it produces the largest sediment transport but also occurs more frequently than the rest wave height conditions of this direction. The occurrence reaches a value of 10.41% over the summer period.
- ENE (75^0): The resulting wave heights that produce the most significant sediment transport are H=0.25 m, H=0.75 m and H=1.25 m. In this case again, the corresponding transport patterns of each of these wave heights are similar to the net sediment transport pattern of the ENE (75^0) direction. Based on the largest magnitude and occurrence, the wave condition H=0.25 m is chosen, that occurs 11.9% over the summer season.
- SE (135^0): For this wave direction, the consequent dominant wave height that satisfies all the three criteria is H=0.75 m. It has the most frequent occurrence for the SE (135^0) direction. Its presence during summer period reaches a value of 17.18 %.
- SSE (150^0): The resulting influencing wave height of this direction is H=0.75 m. It emerges as the dominant condition for all criteria considered, with an occurrence percentage of 13.35% over the summer.

The selected representative summer wave conditions are summarized in the table below.

Summer wave condition (^{0})	Wave Height (m)
ENE (60^0)	H= 0.75 m
ENE (75^0)	H=0.25 m
SE (135^0)	H=0.75 m
SSE (150^0)	H=0.75 m

Table A.2: Influencing summer wave height conditions

Since now wave conditions have been derived in order to represent the influencing summer wave directions, the selection of the final summer representative waves that will be used in the three morphological scenarios can be accomplished. The prevailing bidirectional character of the summer period leads to the conclusion that two representative conditions must be selected, one for each of the two dominant wave directions. As already mentioned, the criteria that will be used to select these two final cases are the same again. The sediment transport magnitude forms an essential factor together with the occurrence frequency. Finally, the similarity in the sediment transport pattern between each condition, which now represents an influencing wave direction, with the net resulted seasonal sediment transport pattern is a crucial factor to be satisfied. The sediment transport patterns of the selected influencing wave conditions together with the net summer transport pattern are presented in Figure A.1.

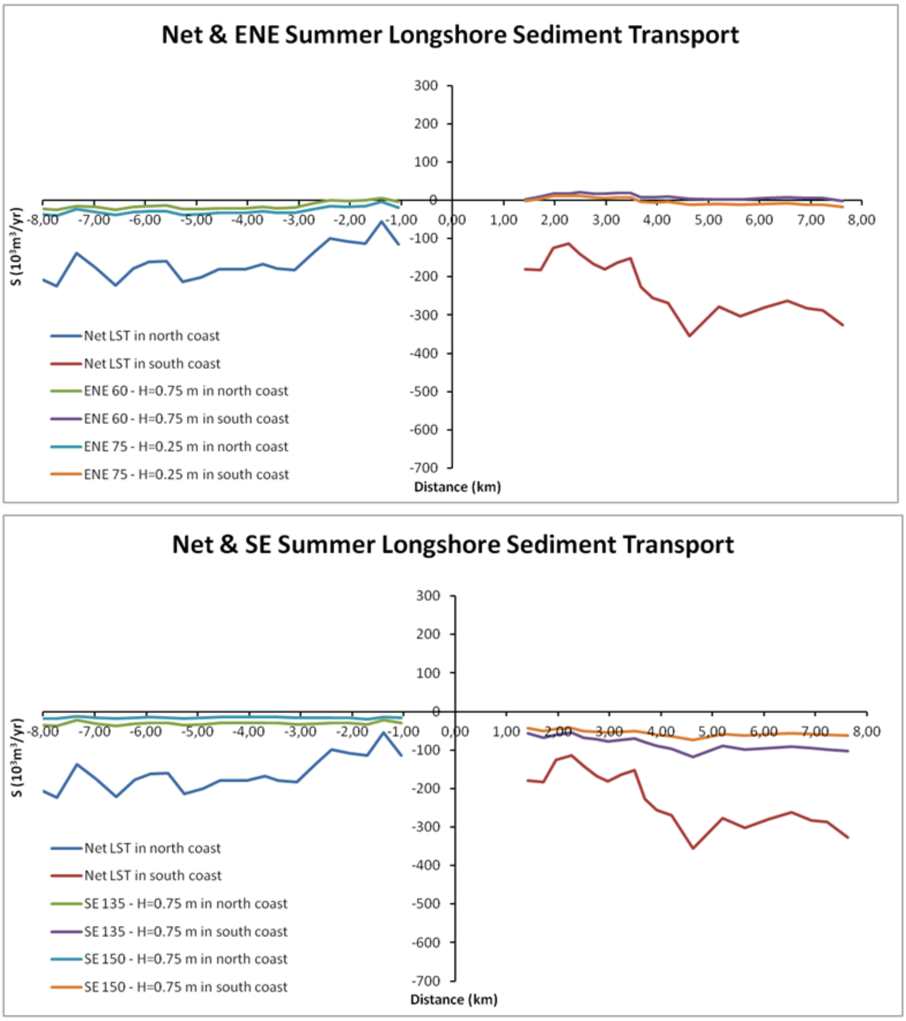


Figure A.1: Dominant sediment transport patterns of summer season (Source: Do et al., 2017)

A net northward directed sediment transport pattern prevails in the summer, indicated by the negative sediment transport values. By observing the sediment transport patterns induced by SE incoming waves, it is concluded that the SE (135^0) direction with a corresponding wave height of H=0.75 m is the one that fits better to the net summer pattern. Furthermore, it creates a larger sediment transport magnitude and has a more frequent occurrence. This is the most obvious choice for the SE representative wave height condition in the summer season. In terms of the ENE wave direction, the condition ENE (60^0), with a wave height of H=0.75 m is selected. The similarity of both ENE conditions is great. The sediment transport magnitude as well as the occurrence frequency in the case of the ENE (75^0) is slightly larger. However, because their differences are very small and due to the fact that the net ENE (60^0) provides a more influential effect in the coast with respect to the ENE (75^0), the aforementioned choice is made in this case.

In the winter period the same procedure is followed in order to end up with the representative wave heights of each wave direction that is predominant in this period. Because of the fact that two seasons can be distinguished within the winter months, taking into account the influence of the river discharge, the final selected representative wave conditions will be two, corresponding to the flood and dry winter seasons. To account for this, two characteristic wave conditions are being distinguished initially for every wave direction.

- NE (45^0): By taking into consideration the sediment transport magnitudes in the north and south coast, certain wave heights can be eliminated, leading to the following choices of H=0.75 m, H=1.25 m, H=1.75 m, H=2.25 m and H=2.75 m. Two wave heights can be distinguished based on the sediment transport magnitudes and patterns as well as their seasonal occurrence, being H=1.25 m and H=2.25 m. The first wave condition creates the largest sediment transport in the south coast will the latter is the dominant condition for the sediment transport in the north coast. The transport pattern is similar in both cases with respect to the net pattern of the NE (45^0) wave direction, while also their occurrence is more frequent compared to the remaining conditions.
- ENE (60^0): The prevailing wave heights for the current wave direction comprise H=1.25 m, H=1.75 m, H=2.25 m, H=2.75 m. The most influencing sediment transport case is the one created by the wave height H=1.25 m with an occurrence of 13.8% over the winter months. It creates the largest magnitude of sediment transport while its pattern fits well enough to the net ENE (60^0) sediment transport trend. A second condition could be also considered, since it provides very similar results. This is the wave height of H=1.75 m that is present 11.3% over the winter. The corresponding occurrence frequencies in both cases are the most dominant for the present direction, which supports the decision made.
- ENE (75^0): An initial reduction of the wave conditions based on the criterion of the sediment transport magnitude leads to the following resulting choices, being H=0.75 m, H=1.25 m, H=1.75 m, H=2.25 m, H=2.75 m and H=3.25 m. For all these cases, the sediment transport pattern is similar and the occurrence frequency ranges in the same level. After a more detailed observation in the sediment transport magnitude, two wave heights stand out, as each of them influences heavily a certain part of the coastline. The wave height condition H=0.75 m is predominant in the north coastline, occurring 5.16% through the winter season. Additionally, the wave height condition H=3.25 m creates a significant alongshore sediment transport over the south coast, that occurs 3% during the winter months.

The selected characteristic winter wave conditions are summarized below in Table A.3. In the same sense as in the case of the summer season, the final selection of the two representative winter wave conditions will take place. The same criteria as before are used. The sediment transport patterns of the reduced amount of conditions together with the net winter transport pattern are presented in Figure A.2.

Winter wave condition (^{0})	Wave Height (m)
NE (45^0)	H= 1.25 m
NE (45^0)	H= 2.25 m
ENE (60^0)	H= 1.25 m
ENE (60^0)	H= 1.75 m
ENE (75^0)	H= 0.75 m
ENE (75^0)	H= 3.25 m

Table A.3: Influencing winter wave height conditions

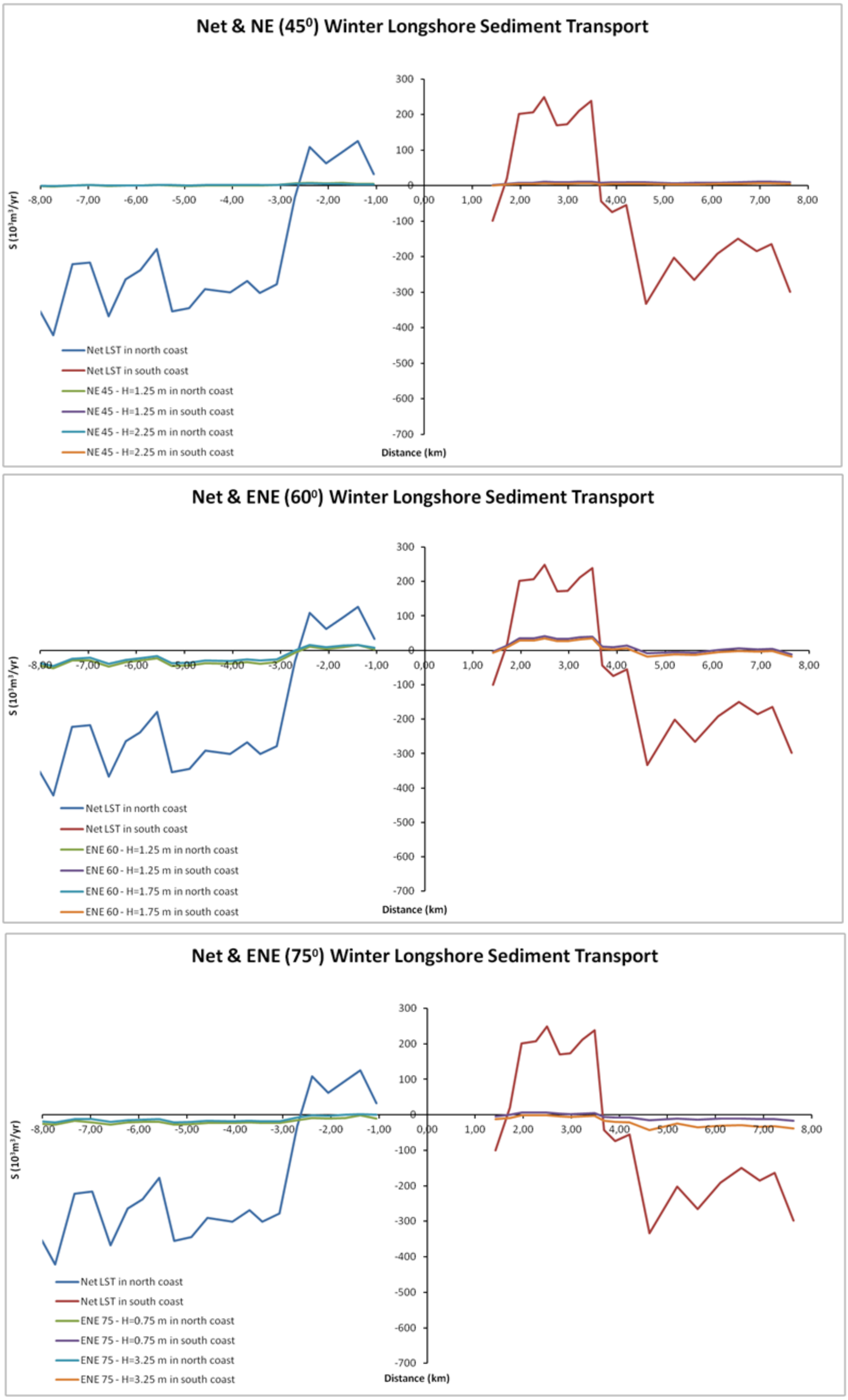


Figure A.2: Dominant sediment transport patterns of winter season (Source: Do et al., 2017)

Based on the net sediment transport pattern that prevails over the winter months, two distinct features can be observed. A divergence point is visible in the north coastline. In the south coastline two locations of interest exist, a divergence point approximately 1.8 km away from the inlet and further away, a convergence point is present at a 3.6 km distance from the inlet. From the image, it can be easily observed that the ENE (60^0) direction influences heavily the final net transport pattern while the other directions are not equally representative, as in none of the cases the convergence and divergence points form. Based on this observation, the two representative wave conditions will be selected only from the ENE (60^0) direction, as the others do not impose a dominant effect in the winter sediment transport along the coastlines. Thus, the selected wave conditions are H=1.25 m and H=1.75 m. They will be used in the calculation of the alongshore sediment transport for all the considered morphological scenarios in the dry and flood winter seasons respectively. The seasonal representative wave conditions are summarized in the following table.

Seasons	Wave Height (m)	Wave Period (sec)
Winter & Flood	H=1.75	T=7.57
Winter & Dry	H=1.25	T=7.9
Summer (ENE) & Dry	H=0.75	T=6.42
Summer (SE) & Dry	H=0.75	T=6.4

Table A.4 Seasonal representative wave height conditions

A.2. Representative river discharge values

The representative river discharge forms the second hydrodynamic forcing parameter that must be selected. Careful choice is essential also in this case, as it constitutes an important condition, influencing heavily the sediment amount that is supplied by the river and consequently transported by the waves. The appropriate combination of the representative discharge and wave condition for every season aims to reproduce efficiently the seasonal state of the morphological scenarios. The river discharge quantities and their variation over the year shape the boundaries of the allowable representative values. Because for every morphological scenario four seasonal cases are studied, a corresponding number of representative discharge values will be derived based on the time span that each seasonal case takes place.

For this selection, the monthly averaged river discharge data will be considered. According to the provided data, the average river discharge value of every season is selected as representative in order to relate to the mean prevailing trend of the period. However, only in the case of the winter flood season the highest average occurring river discharge is chosen as a representative parameter. The value can represent better the stronger intensity of the prevailing phenomena. Based on this remark, the representative river discharge values for every season are presented in the following table.

Seasons	River Discharge (m^3/sec)
Winter & Flood	Q_{peak} = 1037
Winter & Dry	Q_{avg} = 168
Summer & Dry	Q_{avg} = 88

Table A.5 Seasonal representative river discharge conditions

A.3. Representative storm and flood conditions

Additional simulations assess the effect of extreme storm and flood events that can occur during the winter flood season. Two representative wave heights and river discharges are selected in order to mimic characteristic extreme conditions in the wider domain that includes Cua Dai and explore the behaviour of the local morphology under short term abrupt conditions. It is important to evaluate each forcing condition separately, in order to identify the direct influence of the coast and possibly explain the formation of morphological features.

The two extreme flood scenarios that are being simulated are based on the presented maximum monthly river discharge data, which are available from Nong Son station and cover the period of 1977-2008. For the first flood scenario the maximum of the monthly averaged maximum conditions during flood season has been selected as a representative parameter. It has a value of Q_1= 5018 m^3/sec. In addition, for the second extreme scenario a characteristic recorded maximum river discharge value of Q_2= 7660 m^3/sec has been chosen. This value is not the highest observed, yet it represents an extreme condition during the flood season that is expected to occur more often, as it has been noted that an important number of recorded maximum discharges are in the same range. The selected representative river discharge parameters are displayed in the following table.

Flood events	River Discharge (m^3/sec)
Extreme flood event 1	$Q_1 = 5018$
Extreme flood event 2	$Q_2 = 7660$

Table A.6: Representative river discharge values for extreme flood events

The following extreme wave height conditions that occur in the winter flood season are selected to represent the effect of storms in the area of interest. The directional domain for which storm wave heights occur during the winter period, includes the 345^o-60^o directions and from this limited region, the two characteristic representative storm waves are selected. Again the frequency of occurrence of each wave condition forms an essential criterion. Based on this, the first representative storm wave results from the ENE (60^0) direction with a wave height value of H= 6.5 m, since it has the largest frequency of occurrence. Due to the fact that the remaining storm conditions have a similar frequency, the impact of a stronger wave height from a different direction is examined for the second representative storm wave parameter. Based on this, the second representative storm wave condition comes from the north and has a wave height value of H= 8 m. This forcing is expected to create a difference in the morphology that could provide a better insight of the behaviour of the domain. The characteristics of the selected input parameters are presented in the following table.

Storm events	H (m)	T (sec)	Direction (^{o})
Extreme storm event 1	H= 6.5	T = 7.34	60^o (ENE)
Extreme storm event 2	H= 8	T= 8.21	0^o (N)

Table A.7: Representative wave parameters for extreme storm events

B. Appendix: Simulation results of morphological scenarios

Scenario 1 (Period 1995-2000)

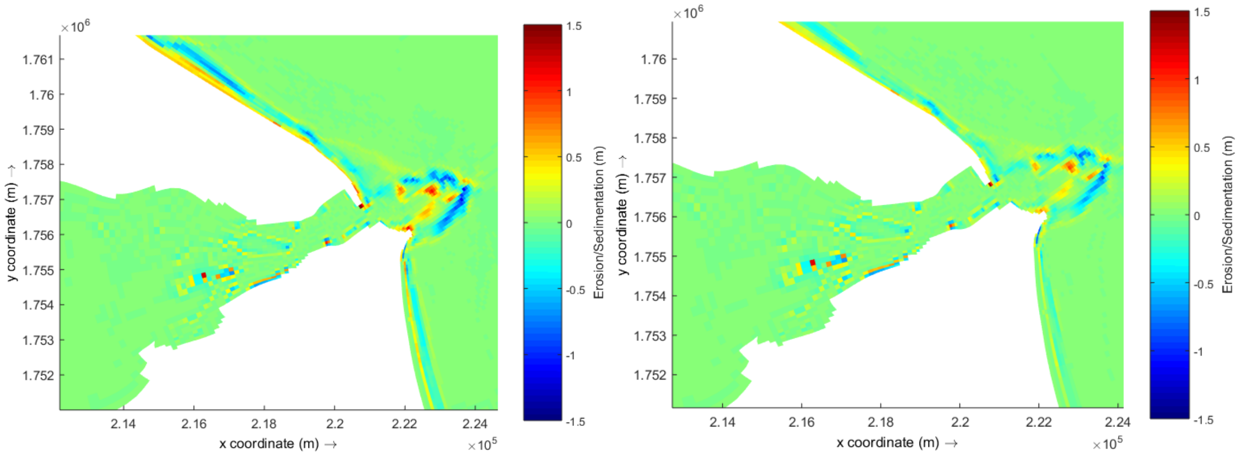


Figure B.1: Morphological changes during (a) winter dry and (b) summer (ENE) seasons in the first morphological period

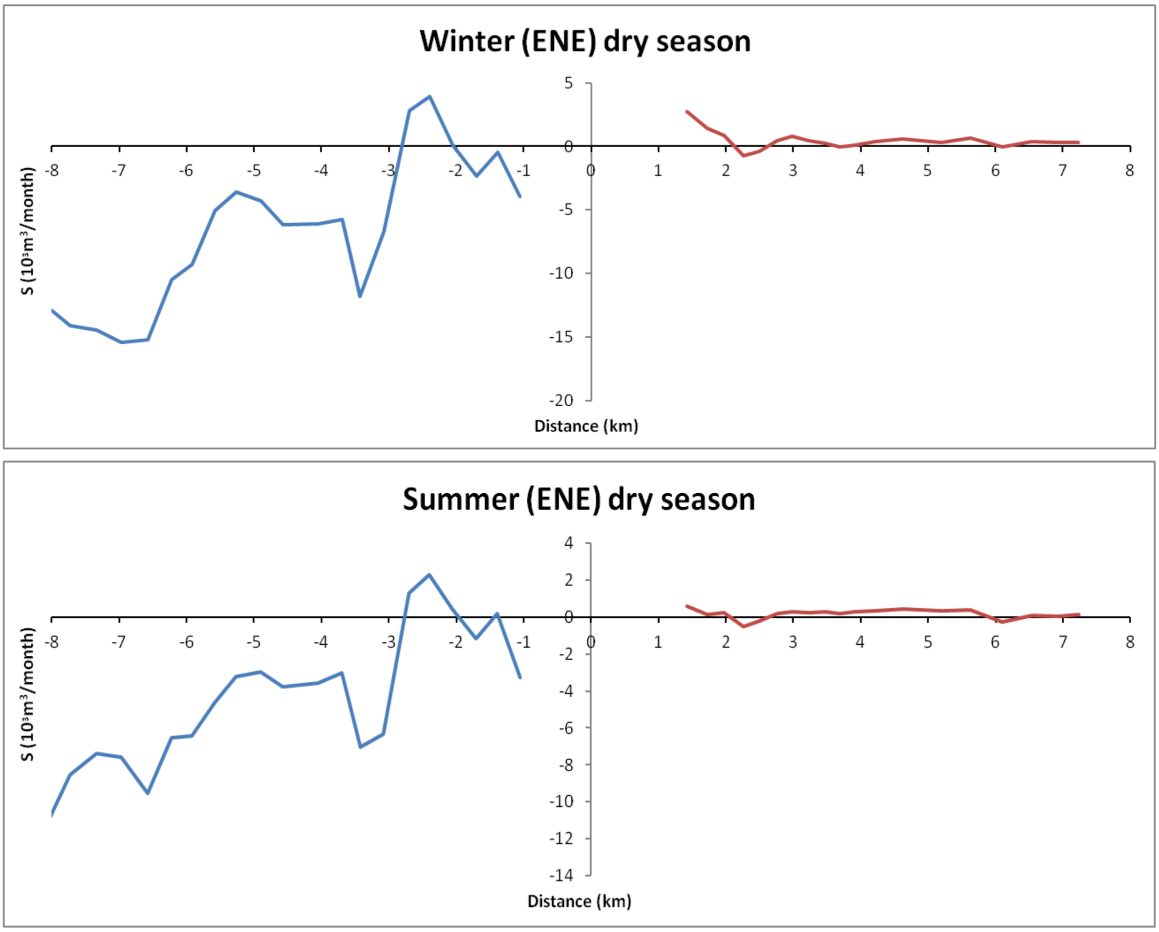


Figure B.2: Alongshore sediment transport patterns during (a) winter dry and (b) summer (ENE) seasons in the first morphological period

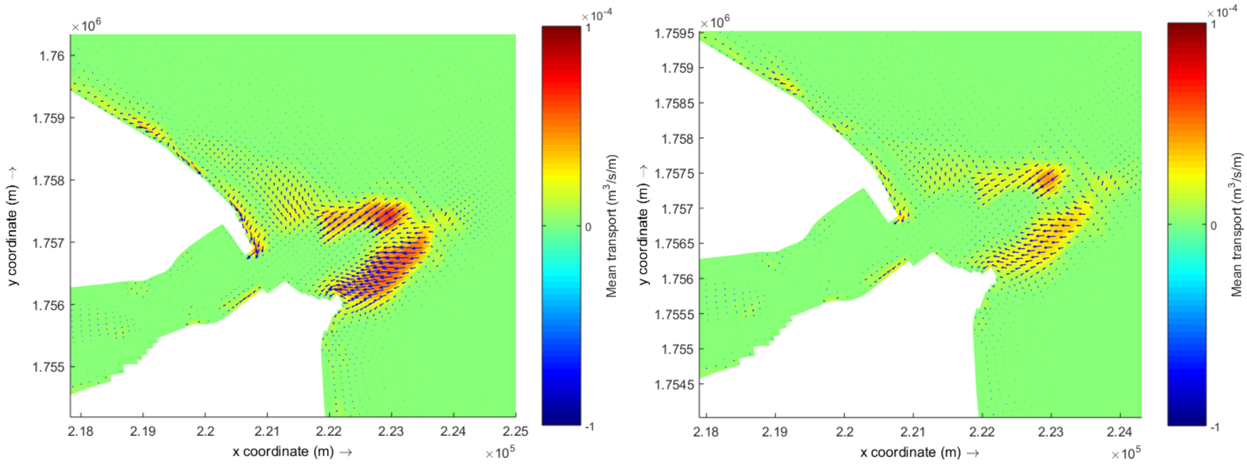


Figure B.3: Mean transport pattern around ebb delta during (a) winter dry and (b) summer (ENE) seasons in the first morphological period

Scenario 2 (Period 2010-2015)

Resorts

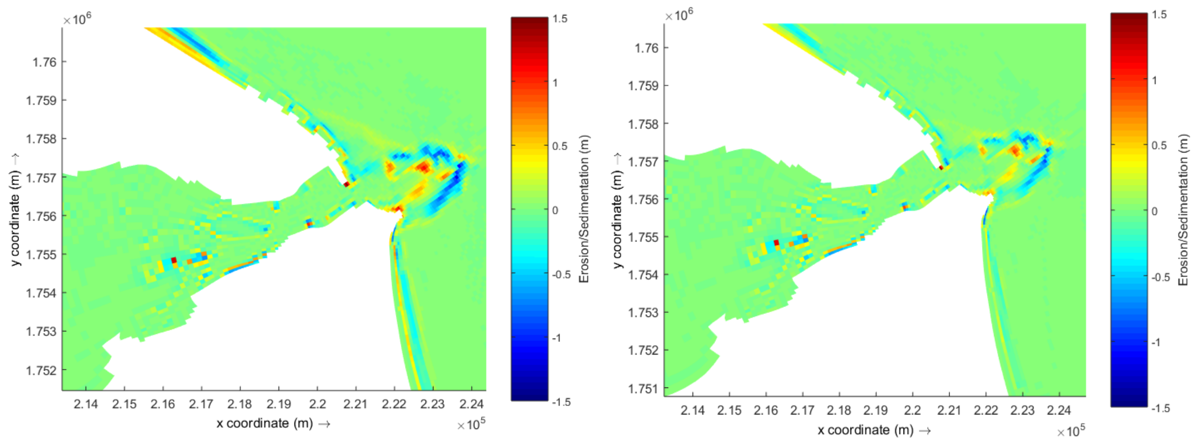
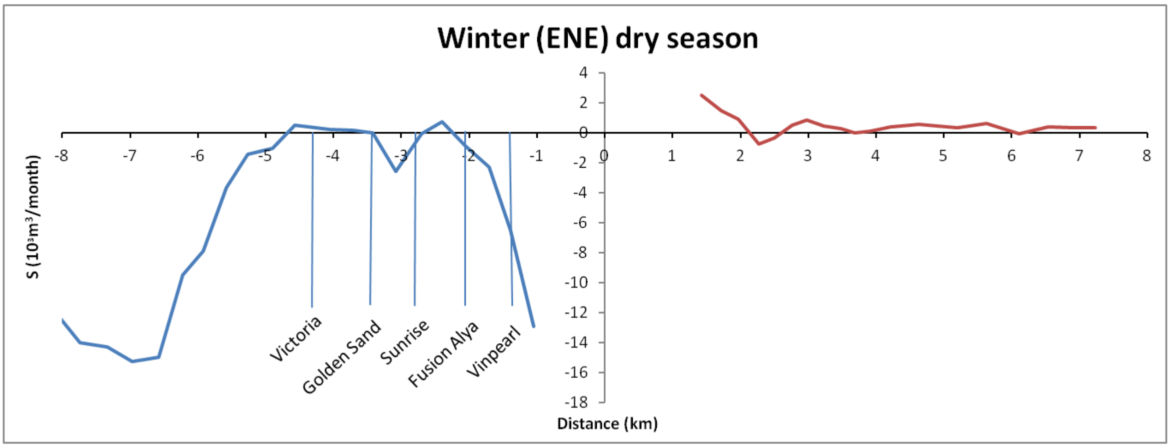


Figure B.4: Morphological changes during (a) winter dry and (b) summer (ENE) seasons in the second morphological period due to resorts



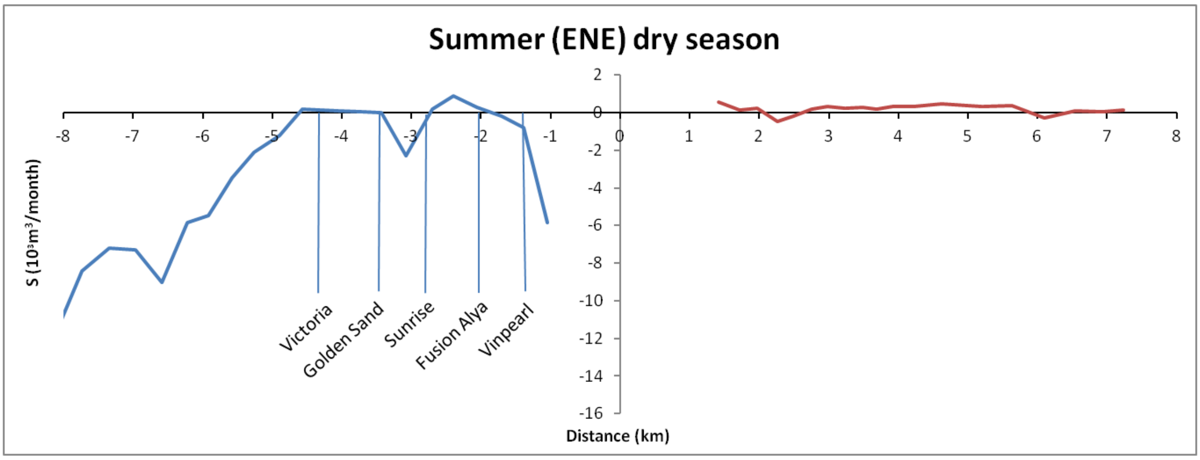


Figure B.5: Alongshore sediment transport patterns during (a) winter dry and (b) summer (ENE) seasons in the second morphological period due to resorts

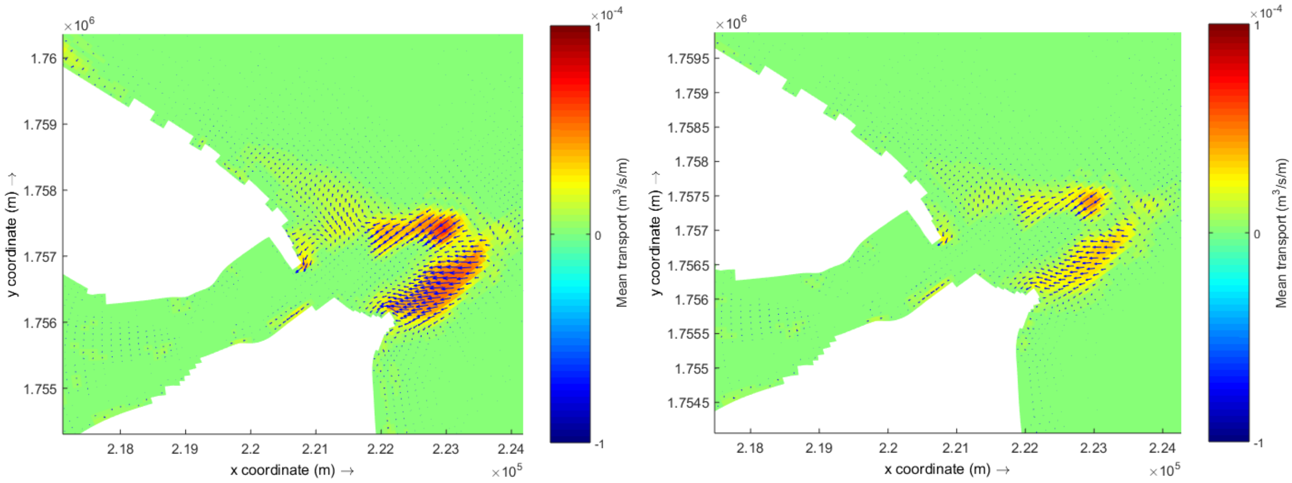
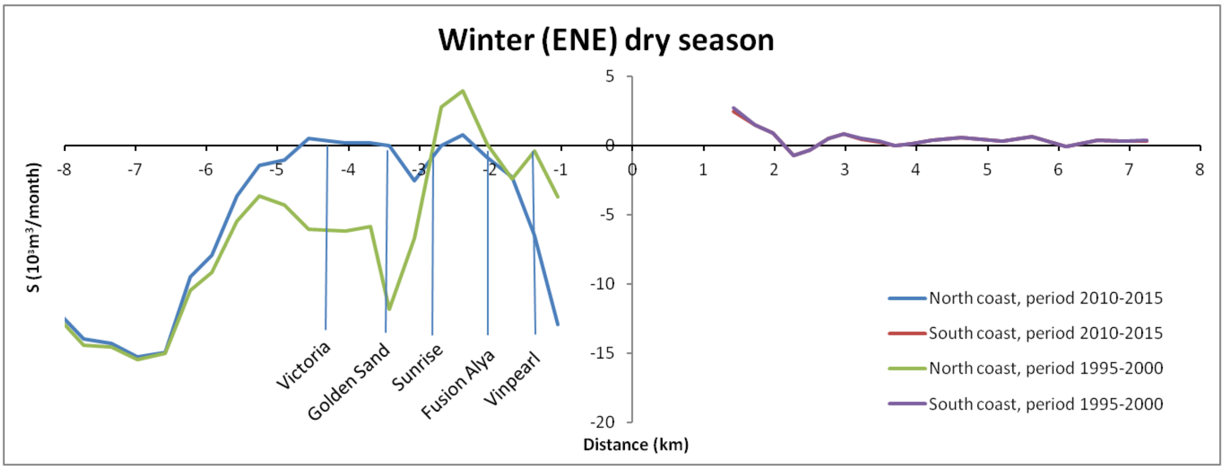


Figure B.6: Mean transport pattern around ebb delta during (a) winter dry and (b) summer (ENE) seasons in the second morphological period due to resorts



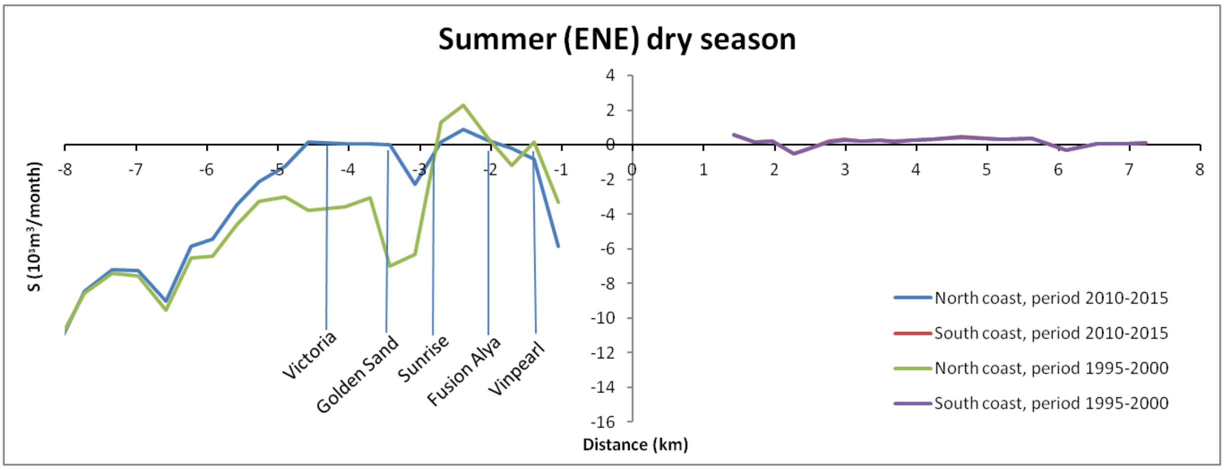


Figure B.7: Alongshore sediment transport patterns during (a) winter dry and (b) summer (ENE) seasons in the first and second morphological periods

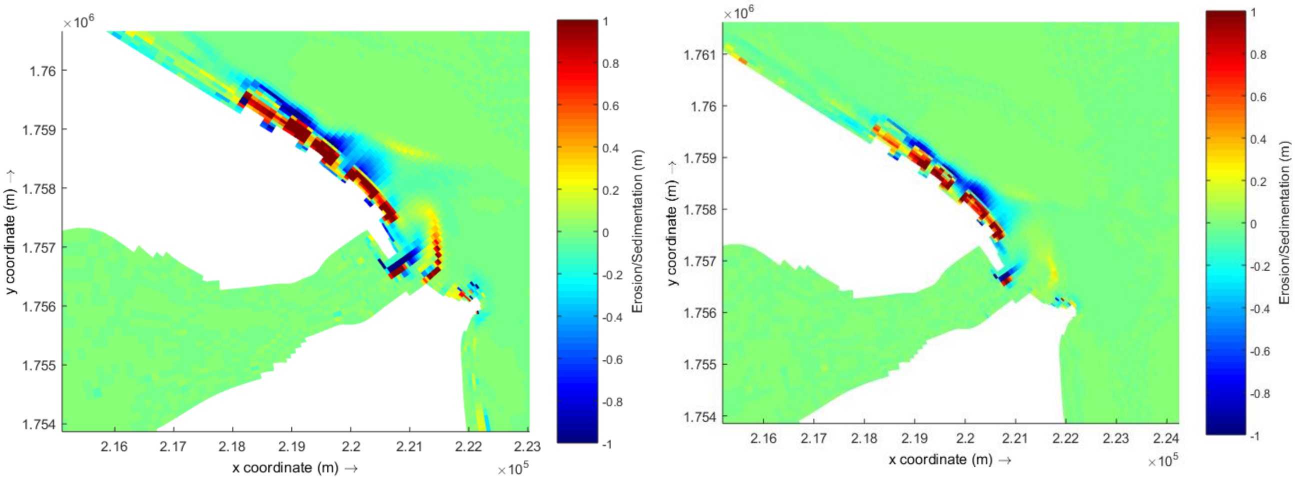


Figure B.8: Morphological impact due to resorts during (a) winter dry and (b) summer (ENE) seasons

Resorts including increased seasonal variation in river discharge levels

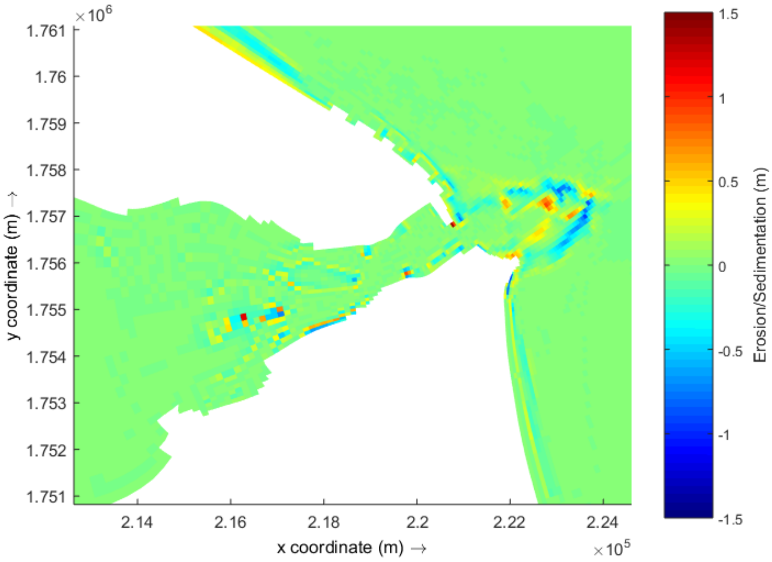


Figure B.9: Morphological changes during summer (ENE) season in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

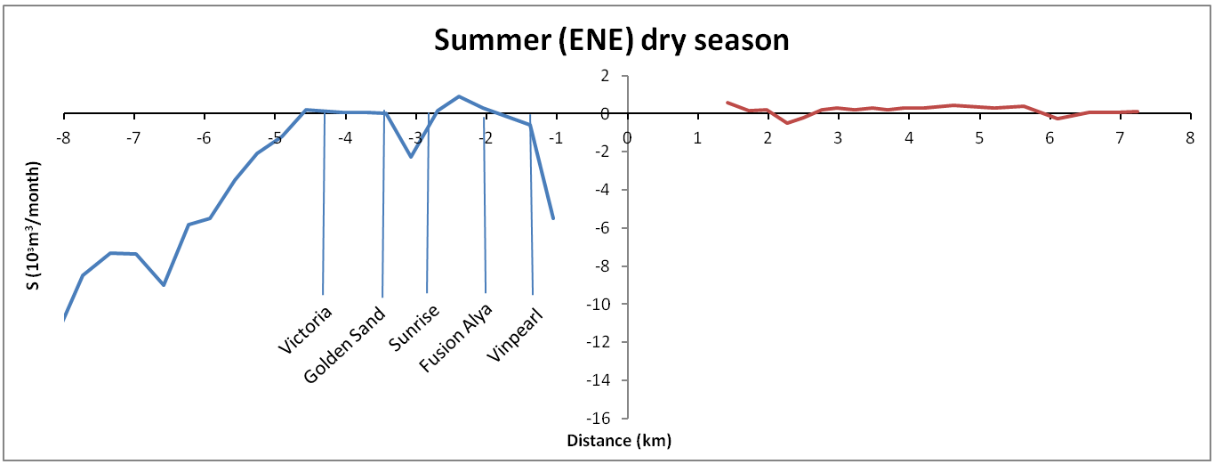


Figure B.10: Alongshore sediment transport pattern during summer (ENE) season in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

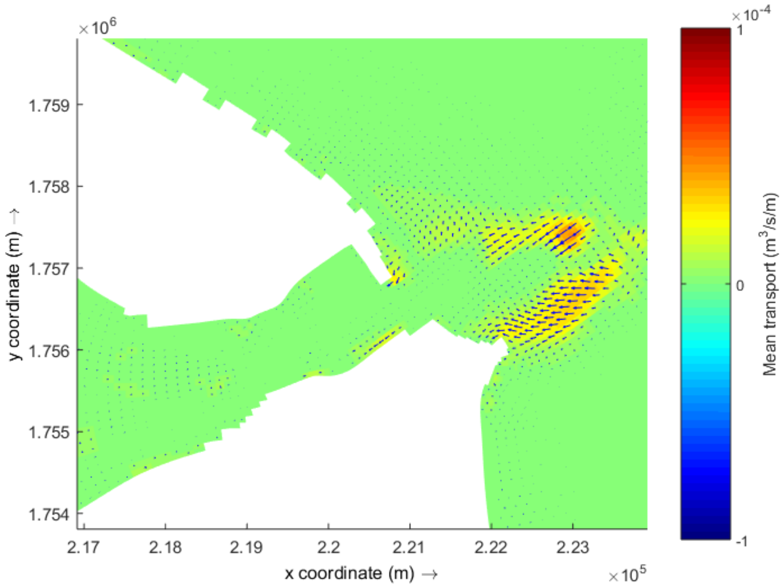


Figure B.11: Mean transport pattern around ebb delta during summer (ENE) season in the second morphological period with inclusion of a larger seasonal variation in river discharge levels

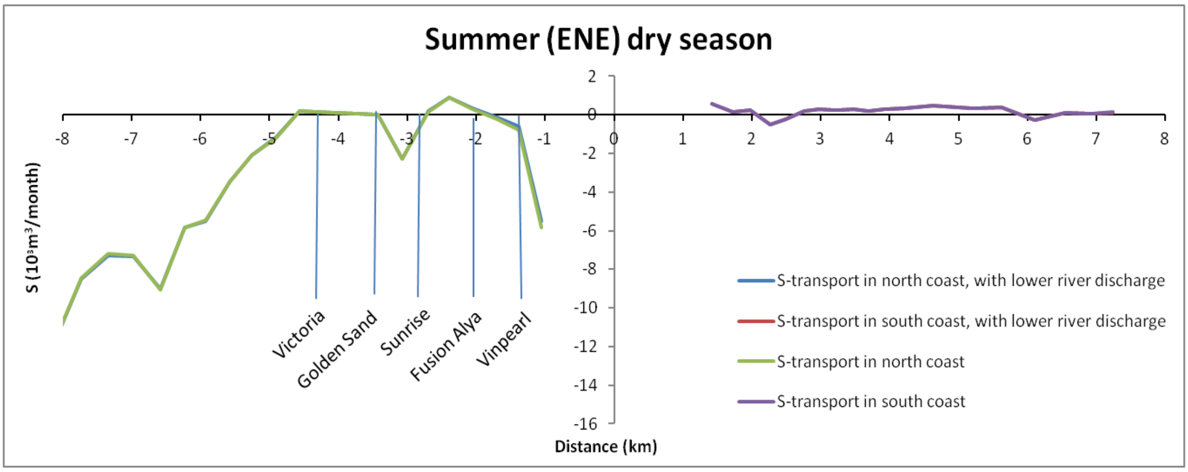


Figure B.12: Alongshore sediment transport pattern during summer (ENE) season in the second morphological period assessing the effect of increased seasonal variation in river discharge levels

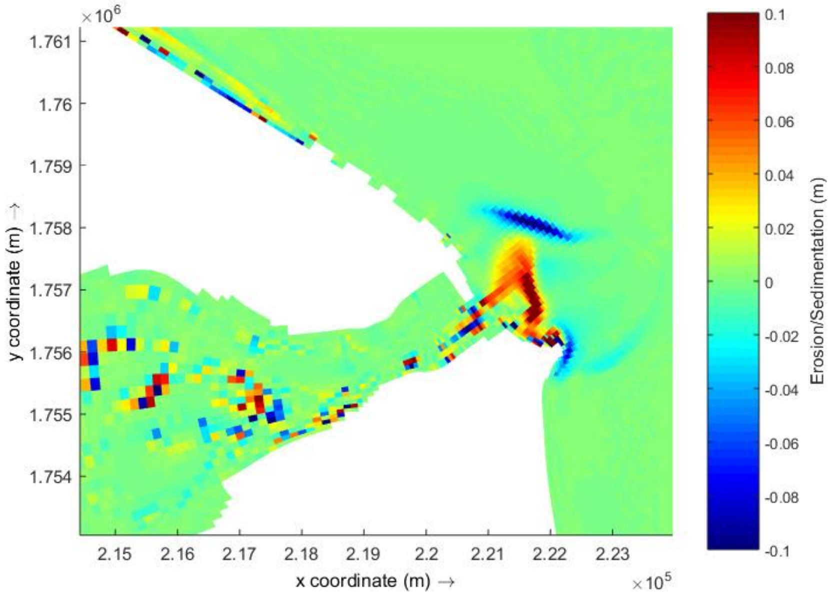


Figure B.13: Morphological impact due to increased seasonal variation in river discharge levels during summer (ENE) season

Scenario 3 (Period 2016-2017)

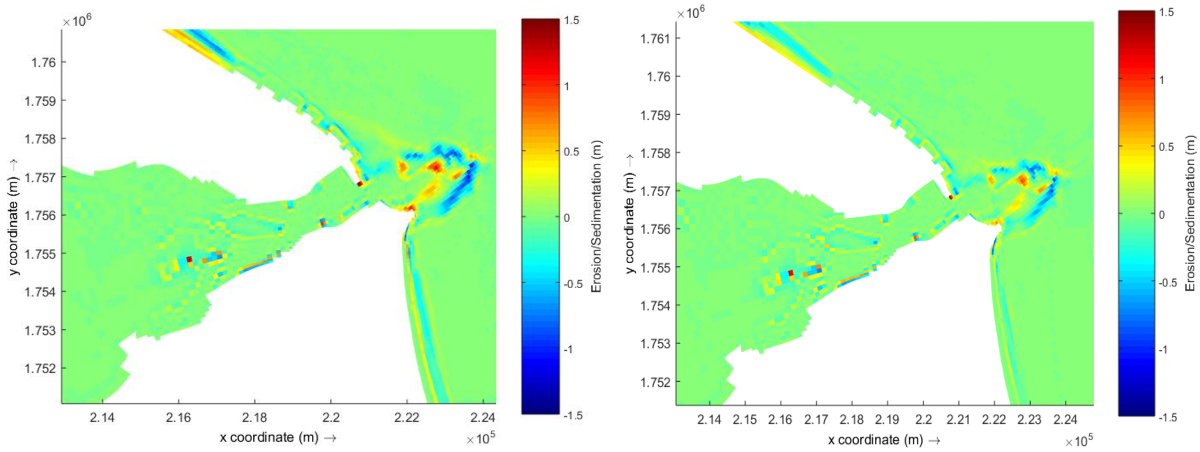
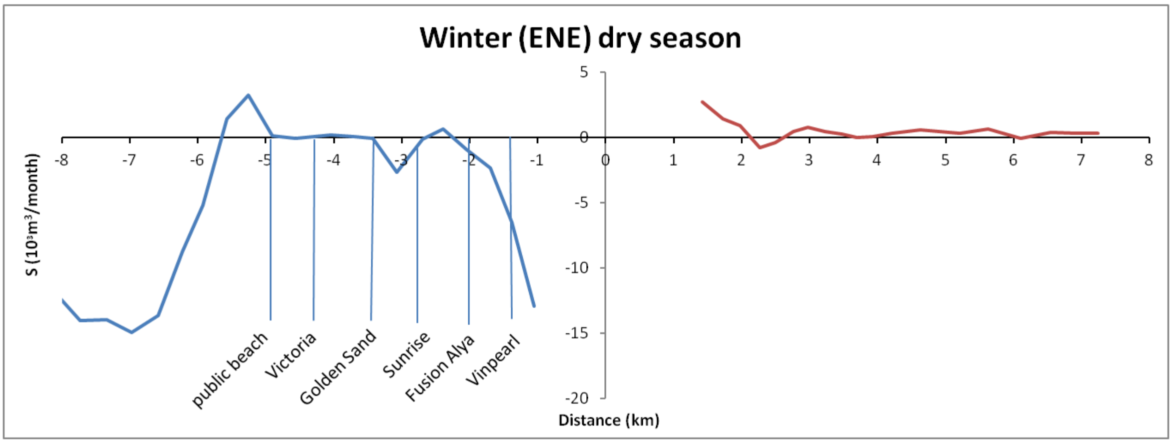


Figure B.14: Morphological changes during (a) winter dry and (b) summer (ENE) seasons in the third morphological period



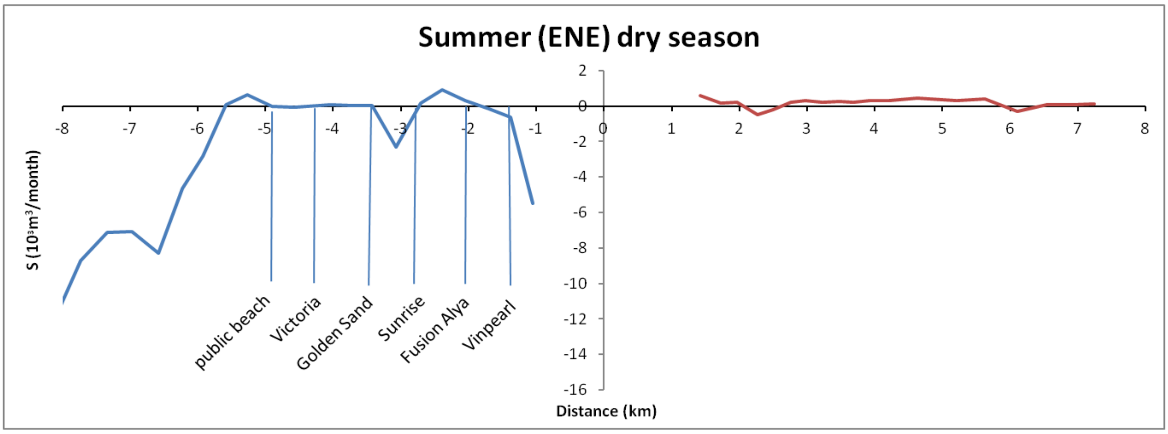


Figure B.15: Alongshore sediment transport patterns during (a) winter dry and (b) summer (ENE) seasons in the third morphological period

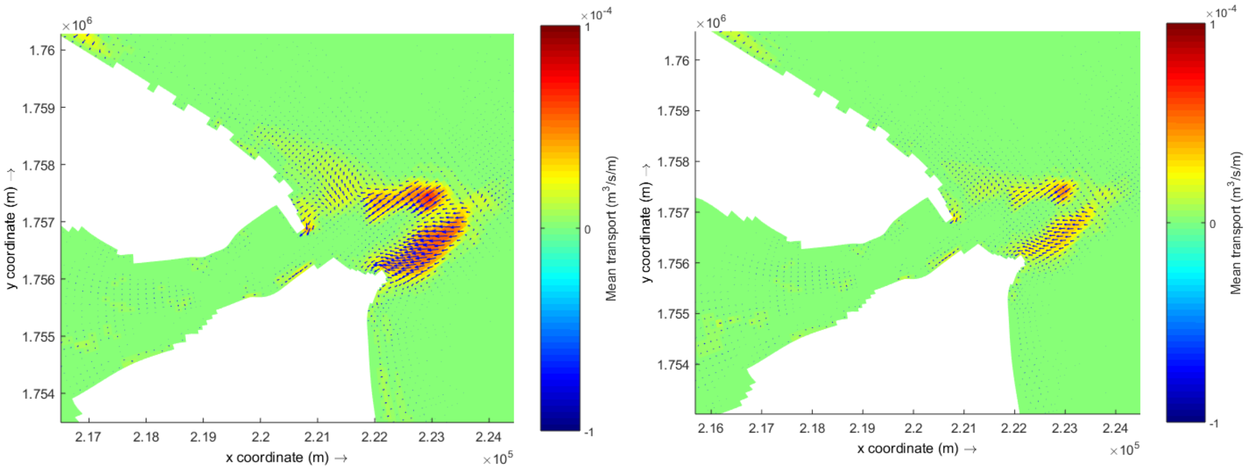
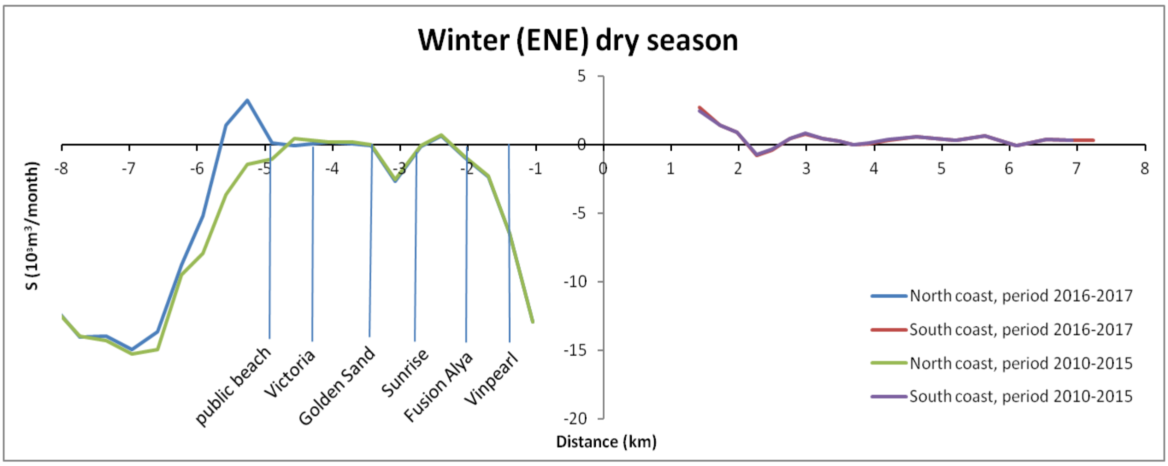


Figure B.16: Mean transport pattern around ebb delta during (a) winter dry and (b) summer (ENE) seasons in the third morphological period



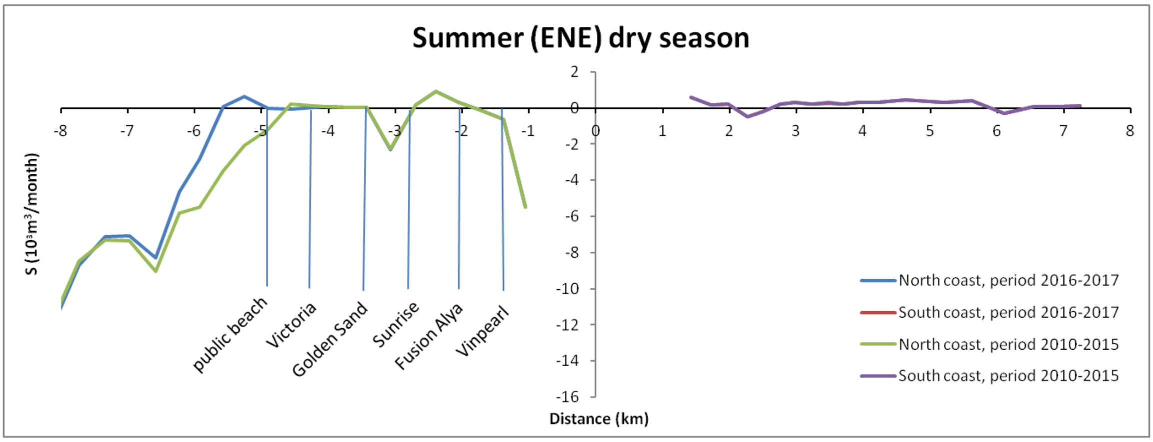


Figure B.17: Alongshore sediment transport patterns during (a) winter dry and (b) summer (ENE) seasons in the second and third morphological periods

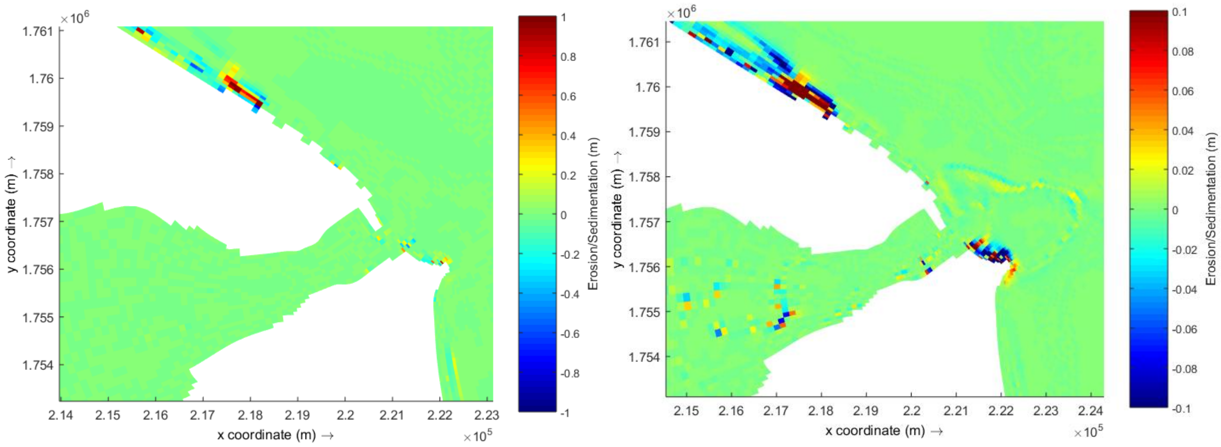


Figure B.18: Morphological impact due to sandbags during (a) winter dry and (b) summer (ENE) seasons

Extreme flood and storm events

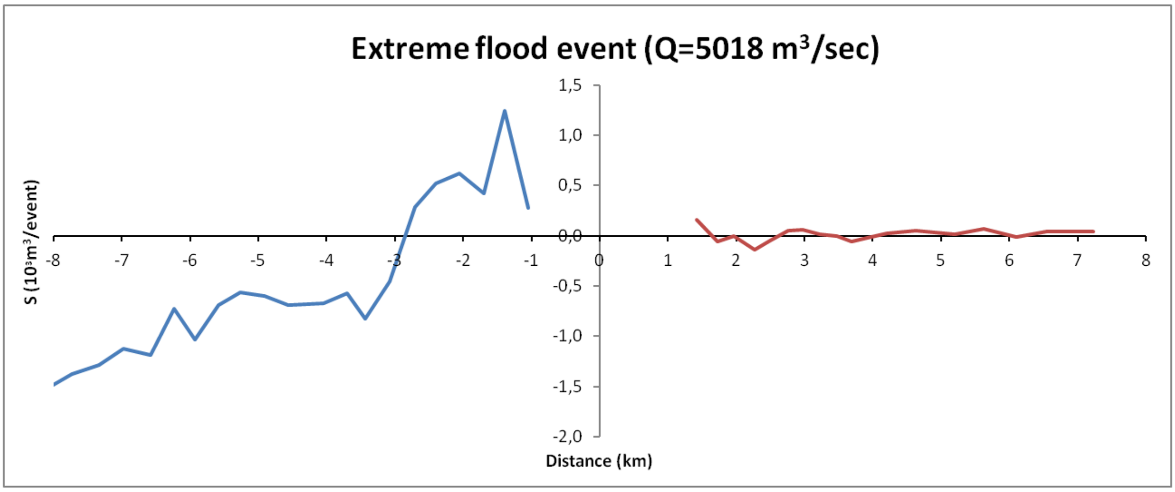


Figure B.19: Alongshore sediment transport pattern during extreme flood event 1 (Q=5018 m^3/sec)

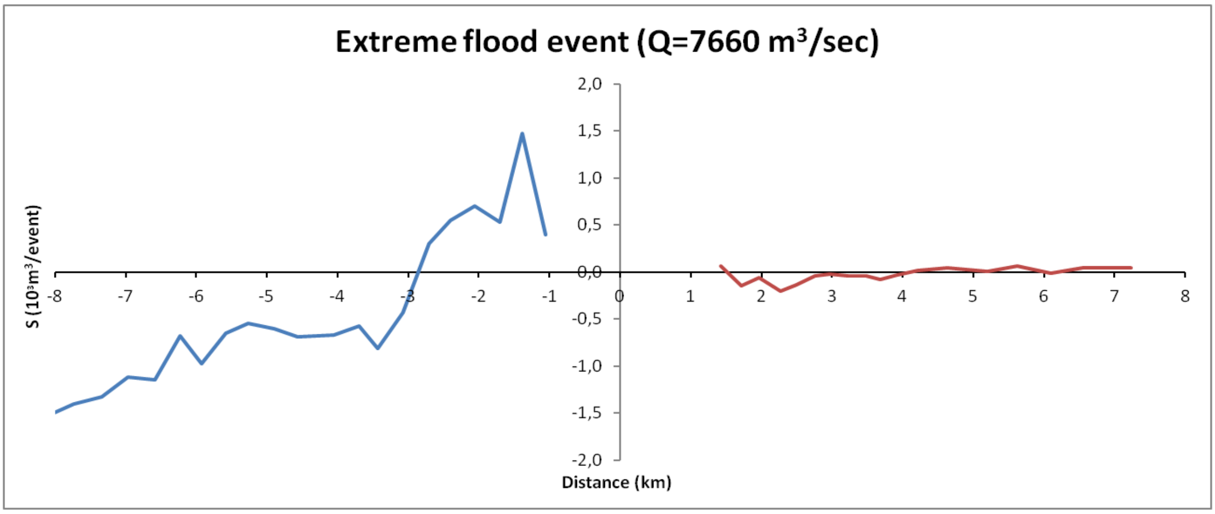


Figure B.20: Alongshore sediment transport pattern during extreme flood event 2 (Q=7660 m^3/sec)

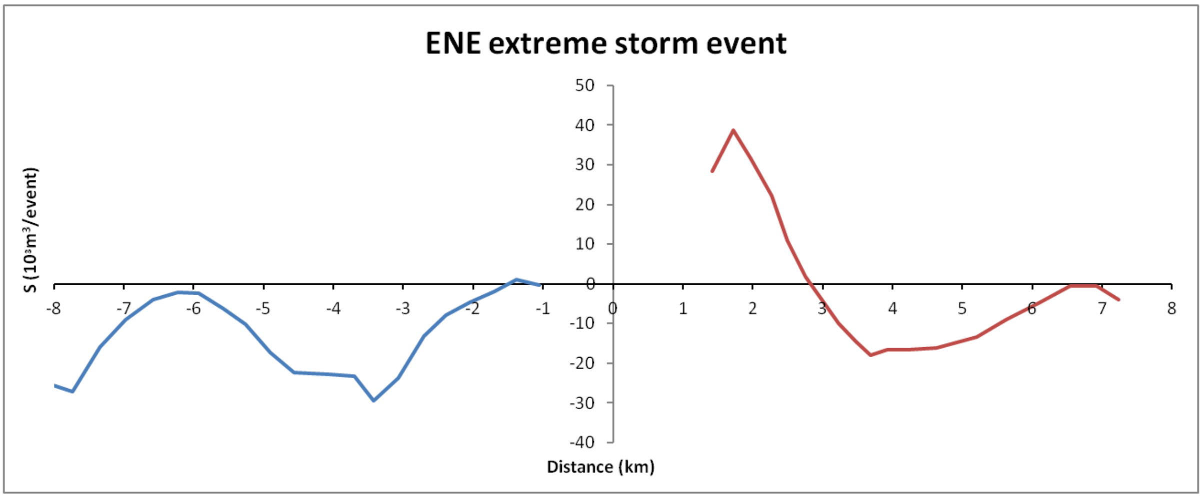


Figure B.21: Alongshore sediment transport pattern during ENE extreme storm event

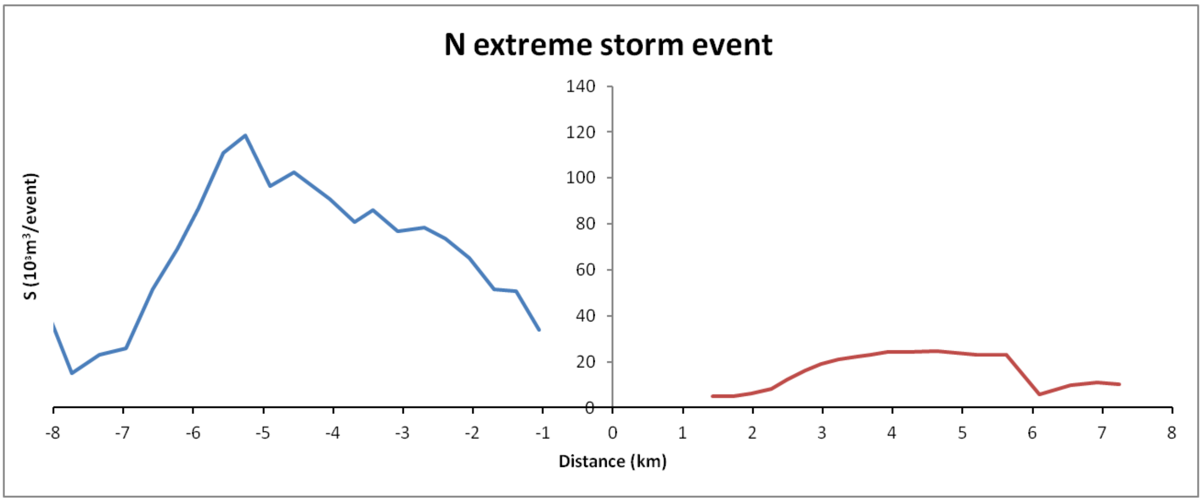


Figure B.22: Alongshore sediment transport pattern during N extreme storm event

C. Appendix: Seasonal trends of design solutions

Design 1

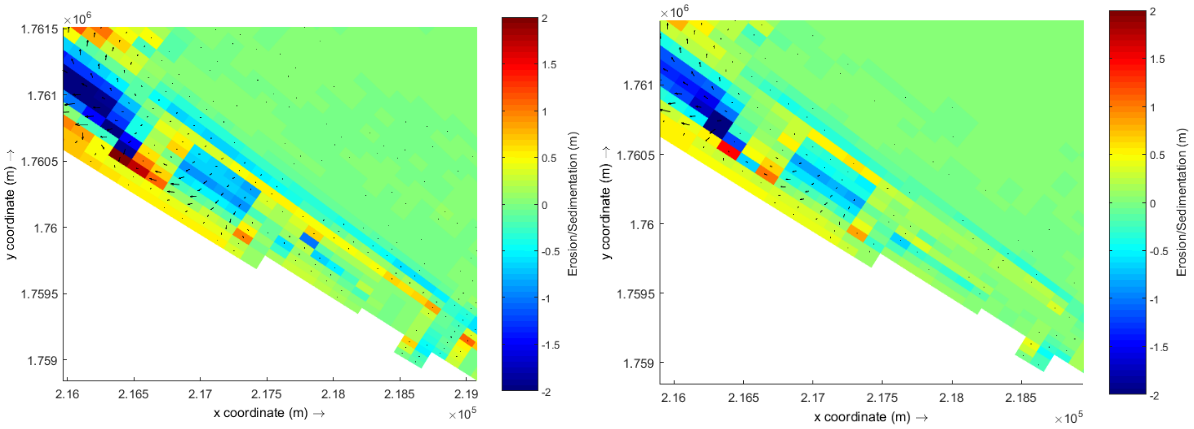


Figure C.1: Morphological changes and transport patterns in Design 1 for (a) winter dry and (b) summer (ENE) seasons

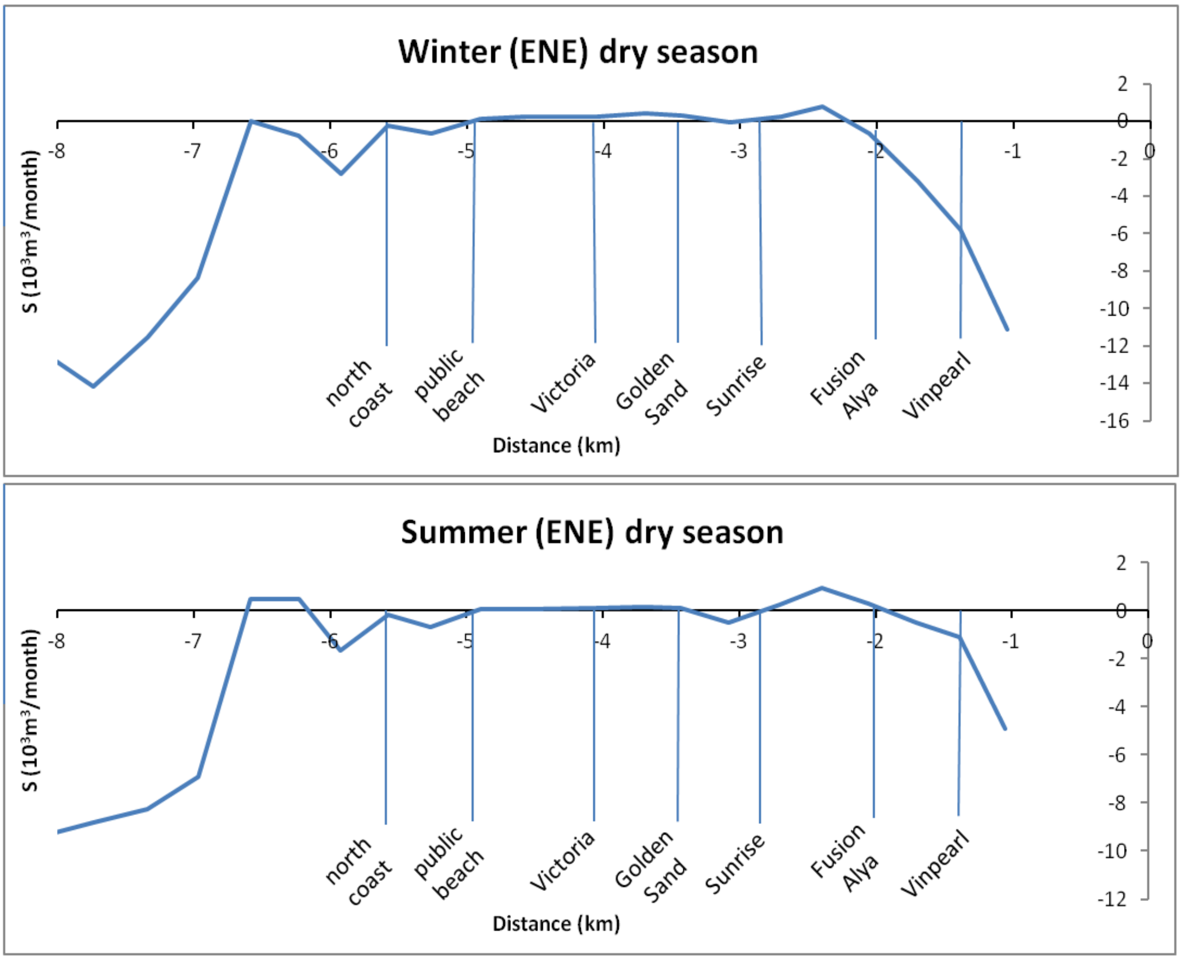


Figure C.2: Alongshore sediment transport trends in Design 1 for (a) winter dry and (b) summer (ENE) seasons

Design 2 - Multiple nourishments

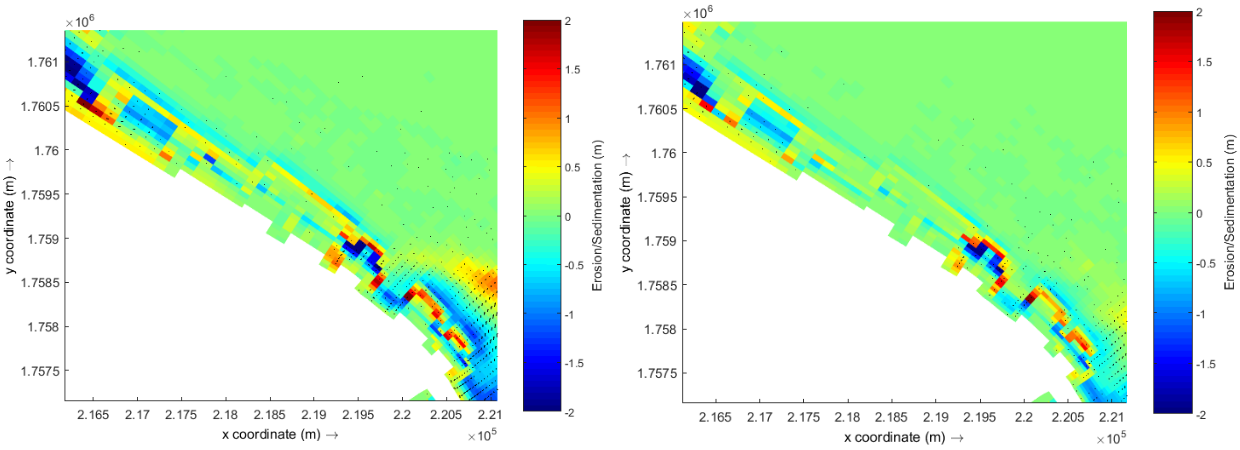


Figure C.3: Morphological changes and transport patterns in multiple nourishments alternative of Design 2 for (a) winter dry and (b) summer (ENE) seasons

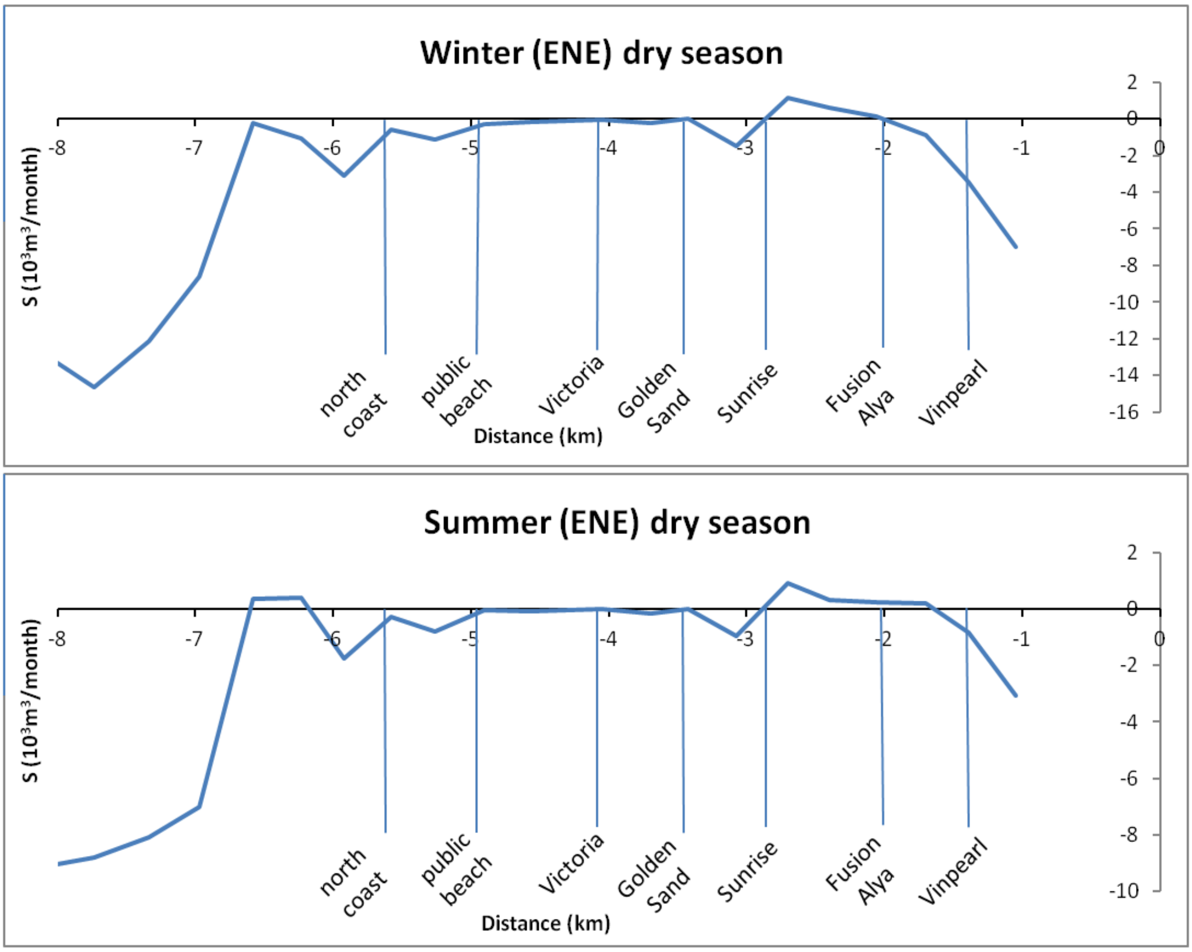


Figure C.4: Alongshore sediment transport trends in multiple nourishments alternative of Design 2 for (a) winter dry and (b) summer (ENE) seasons

Design 2 - Localized nourishment

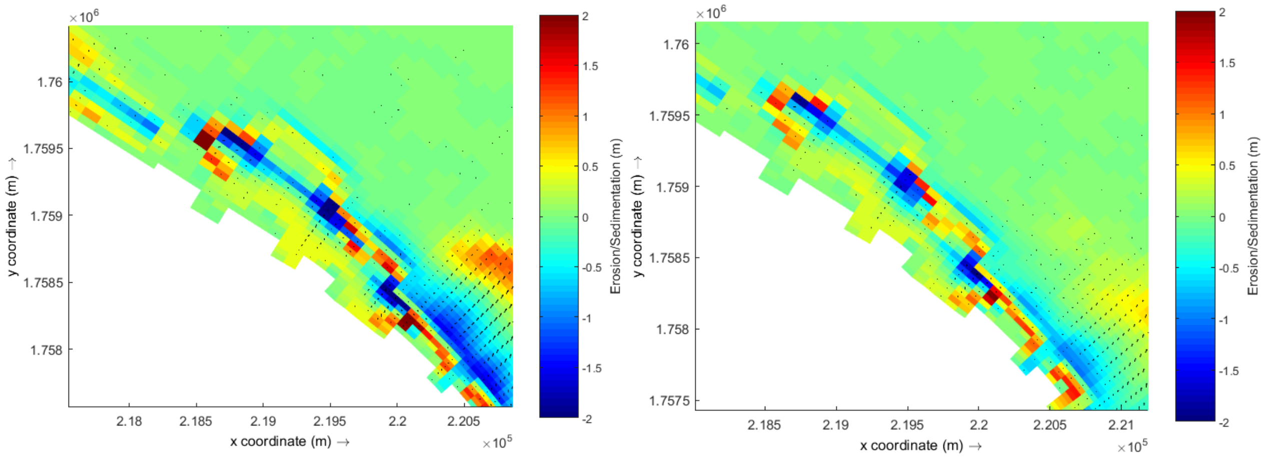


Figure C.5: Morphological changes and transport patterns in localized nourishment alternative of Design 2 for (a) winter dry and (b) summer (ENE) seasons

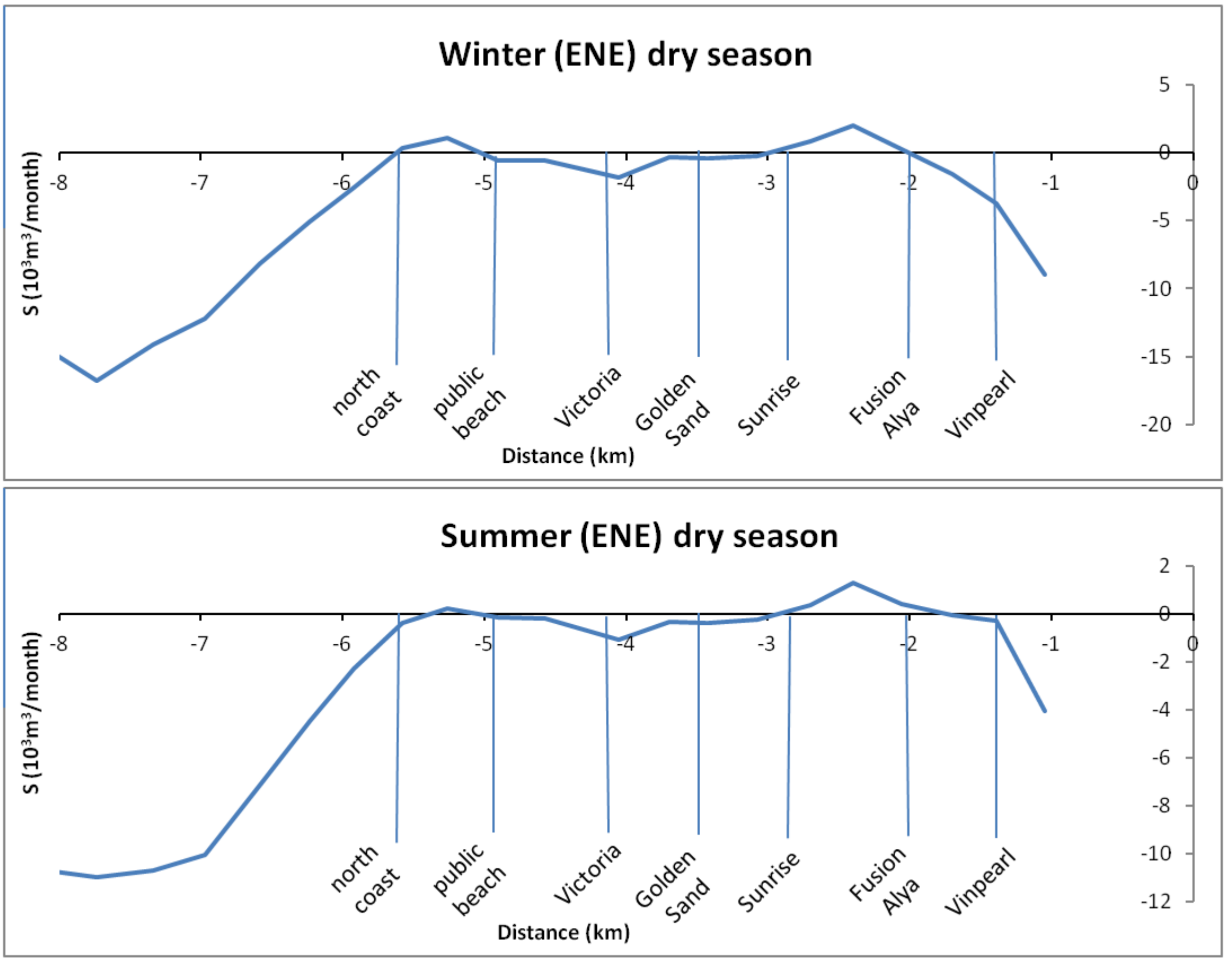


Figure C.6: Alongshore sediment transport trends in localized nourishment alternative of Design 2 for (a) winter dry and (b) summer (ENE) seasons