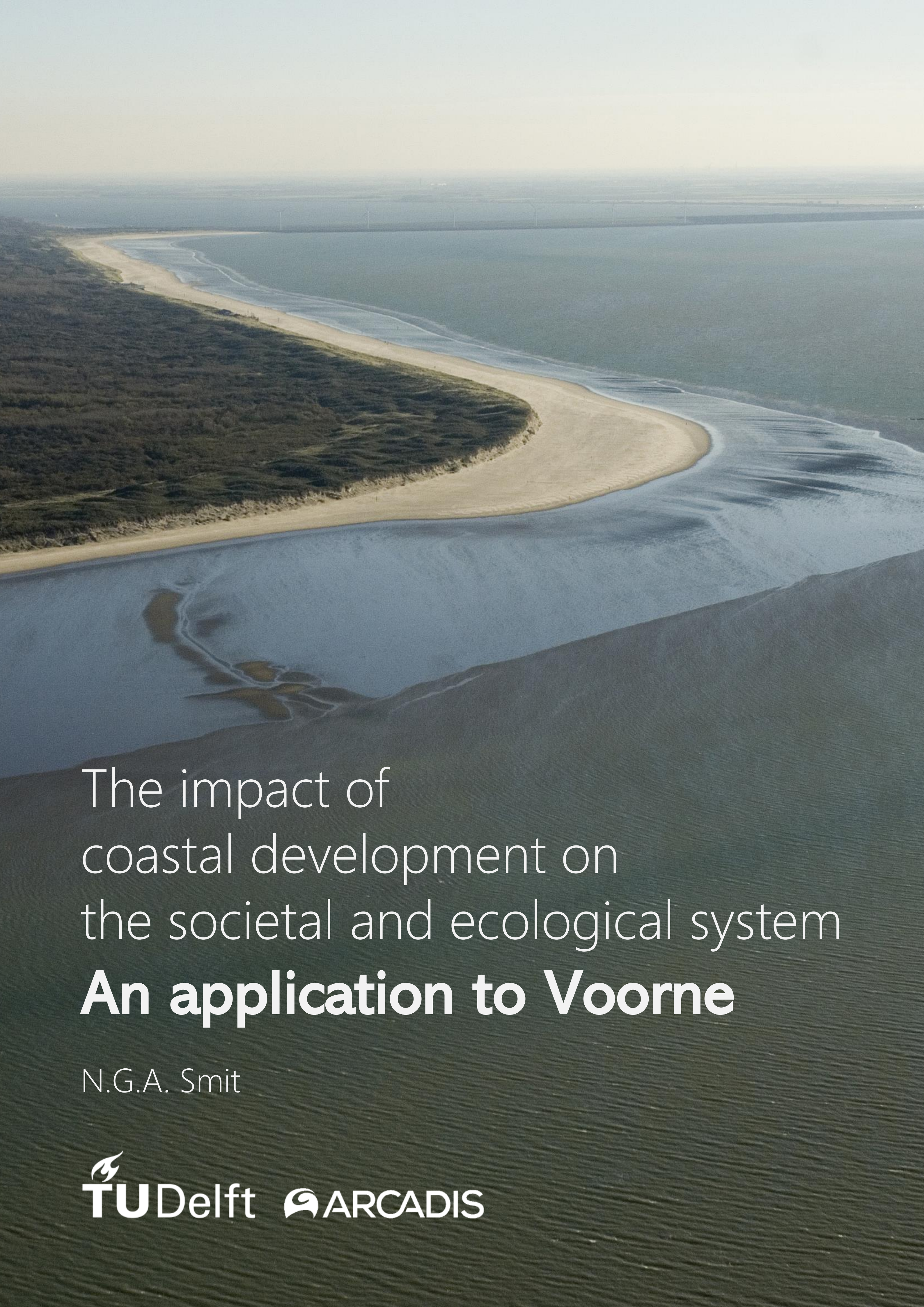

The impact of coastal development on the societal and ecological system

An application to Voorne

N.G.A. Smit

TU Delft ARCADIS

The impact of coastal development on the societal and ecological system:

An application to Voorne

by

N.G.A. (Niels) Smit

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Design & Consultancy for natural and built assets

Summary

Throughout human history deltas attract people and all other sorts of life. Inherent to this increase of delta life is the growth in conflicting values and interests. Coastal systems are not only natural systems, but can also be regarded as societal and ecological systems. Development of the coastal system inevitably leads to changes in these associated societal and ecological systems. Hence, a coast is not only defined by its physical characteristics, but it can also be defined by means of values and interests.

The mouth of the Haringvliet in the Southwest of the Netherlands is a striking example where coastal evolution has its impact on societal and ecological systems. Here, a multitude of anthropogenic interferences triggered a regime shift of the coastal system. While continuously developing towards a new equilibrium, coastal evolution has its impact on societal and ecological systems. When it comes to beach management it is of vital importance to link the changes in the coastal system with values and interest to understand what impact coastal evolution has had and will continue to have on these systems. In this study, an attempt has been made to link the stakeholders values and interests to the physical coastal processes making use of a framework for analysis.

In this study societal and ecological systems are defined by means of stakeholder values and interests. Stakeholder data is obtained from earlier performed stakeholder input sessions to establish such a framework. Stakeholder interests regarding the coast of Voorne are divided over three main interests: 1) safety and Maintenance, 2) economy, and 3) ecology. By combining stakeholder input with a literature study on stakeholder interests related to the coast, a framework is established to link the stakeholder values and interest to the physical coastal processes using a set of relevant indicators. These indicators translate physical processes to assessable parameters, which can be used to quantify the impact on stakeholder interests.

The coastal evolution of the area is assessed by analysing bathymetrical data. From this analysis it was found that the mouth of the estuary has slowly silted up since the damming of the haringvliet estuary in 1970. The foreshore has become steeper and shoals have migrated further towards the coast while growing in height. Secondly, to investigate the impact of this development on the

physical coastal processes, a numerical modeling study has been carried out. Multiple stages in time have been assessed using a process-based 9 layer, Delft3D model.

Model results showed that the wave height along the coast of Voorne has reduced significantly in time. In the most recent years, the waves behind the growing shoals have been reduced to only locally induced wind waves. Moreover, the flow as a result of the tide and sluice discharge is no longer strong enough to induce export of sediment. Right after the closure of the estuary the tidal flow reduced, increasing the residence time in the study area. Since the same volume of discharge is still flushed through the area, water depth reduction due to siltation caused the flow velocities in the area to increase. The area got more flushed and the residence time decreased. However, the associated increase of bed shear stresses is still not enough to induce incipient motion of sediment particles and remove them from the area. Hence, the area has turned into a sediment trap, slowly silting up. When assessing the potential of siltation -the residence time corrected with the particle settling distance- an increase of potential settling is observed in the stages after closure until 2000. However, a trend has been observed in which the potential of siltation decreases in the stages after 2000. From this trend it can be derived that the system seems to develop towards a new equilibrium in which the depth has decreased and flow velocities have increased compared to the situation in 1964 before closure of the estuary. Moreover, due to the accretion of the area, the discharge of the Haringvliet sluices has gained relative importance. The discharged freshwater increasingly reduced the levels of salinity in the area to a more brackish environment. To sum up, it can be stated that the area has turned into a zone with properties that are more alike a lake, with locally induced wind waves, shallow water and low salinity levels.

The evolution of the coastal system has an impact on the values and interest of multiple stakeholders. Using a framework of analysis the impact on the interests of the stakeholders is quantified. The evolution of physical coastal processes, the increase of sediment budget and the decrease of wave exposure, has increased the value of the interest safety and maintenance. Based on the analysis of the physical coastal processes, it is expected that this value will keep increasing in time. When relating the interest of economy to physical coastal processes, a value decrease of this interest is observed over time. The gradually more lake-like area with locally induced wind waves, shallow water and low salinity levels decrease the potential of recreational functions and thus the value of economy. Based on the observed trend of the physical coastal processes, this value is expected to reduce even more in time. At the other hand, the potential value of ecology has increased and is expected to increase even further in time. Despite the lowering of salinity levels, which often does not favour biodiversity, the development of other physical coastal processes such as shoal development, decrease of flow velocities and wave exposure and a decrease of depth has been beneficial to multiple species, enhancing ecology.

To conclude, this study has demonstrated that it is possible to quantify the impact of physical coastal processes on stakeholder interests using a framework for analysis. Applied on the Voorne case, it was found that the interests of safety and maintenance and ecology show an increasing value trend. The interest economy however, shows a decreasing trend. In terms of coastal management it is recommended to look for adequate measures that interfere with coastal evolution and alter the physical coastal processes in order to to enhance the potential value of economy based on the functions defined in this research. Another option is to aim at other functions to enhance the potential value of economy, such as nature recreation.

Preface

This thesis concludes the Master of Science program in Hydraulic Engineering at Delft University of Technology. For the past year, I worked as a graduate intern at the consultancy company Arcadis. I could not have thought of a better working space and learning environment for the past. Therewith, I can genuinely say that I have enjoyed this last year and that I have learned a lot along the way.

This study would not be possible without the support of my graduation committee. Therefore, I would like to thank the committee members, Stefan Aarninkhof, Jan van Overeem, Jos Timmermans, Lies van der Pol, and Jos van der Baan for their guidance during the entire project. First of all I would like to thank Jan van Overeem, for bringing me in touch with Arcadis and for your continues enthusiastic support. You always made time to listen and help me with the problems I faced. Besides, thanks go out to Jos Timmermans for helping out with the stakeholder part of my research. Additionally, I want to thank Lies van der Pol for her support and contagious enthusiasm, it felt like your enthusiasm never ran out of fuel. I truly hope I managed to live up to your expectations and that this research can be of added value to your municipality. I would like to thank Stefan Aarninkhof for his enthusiasm and critical thoughts during the meetings and for opening up my thoughts about integrated coastal management. Finally, special thanks go out to Jos van der Baan. Without you I would not have been able to deliver the work that lies in front of you right now. Whenever I needed, you made time to help me out with the problems I faced. Especially with the modeling related issues, you thought me always to get back up, even when it was as hard as getting out of your chair the second day after leg day at the gym. I have really enjoyed working with you and I cherish the (small) coffee breaks and drinks we had.

Next to my committee, I would like to thank Jessica Bergsma for her enthusiasm and support, your help really has been of benefit to my thesis. Besides, I want to thank Rufus Velhors to help me out with the Python related issues. Furthermore, I would like to thank my colleagues and fellow graduate students at Arcadis for their interest, great advice and especially for the enjoyable times during the coffee-breaks and (small) after work drinks.

I would also like to thank my family, especially my mom and dad, for supporting me throughout my entire student life. This achievement would not have been possible without your love and support. Next to my family, I would like to thank my friends from: P.P., B21 and MDP271 for providing me with happiness, at the moments I needed it.

Niels Smit
Rotterdam, April 2020

Contents

1 Introduction

> *Throughout human history river deltas have attracted people. Today deltas belong to the most densely populated areas in the world and this number is ever growing*
>
> — **IADC** (2009)

1.1 Background and problem definition

The coast of the municipality Westvoorne is located on the seaward side of the island Voorne in the South-West of the Netherlands. The coast of Voorne is part of the mouth of the former Haringvliet estuary. Before the 20th century the Haringvliet estuary was mostly subject to nature. In time, the estuary became more subject to human interventions.

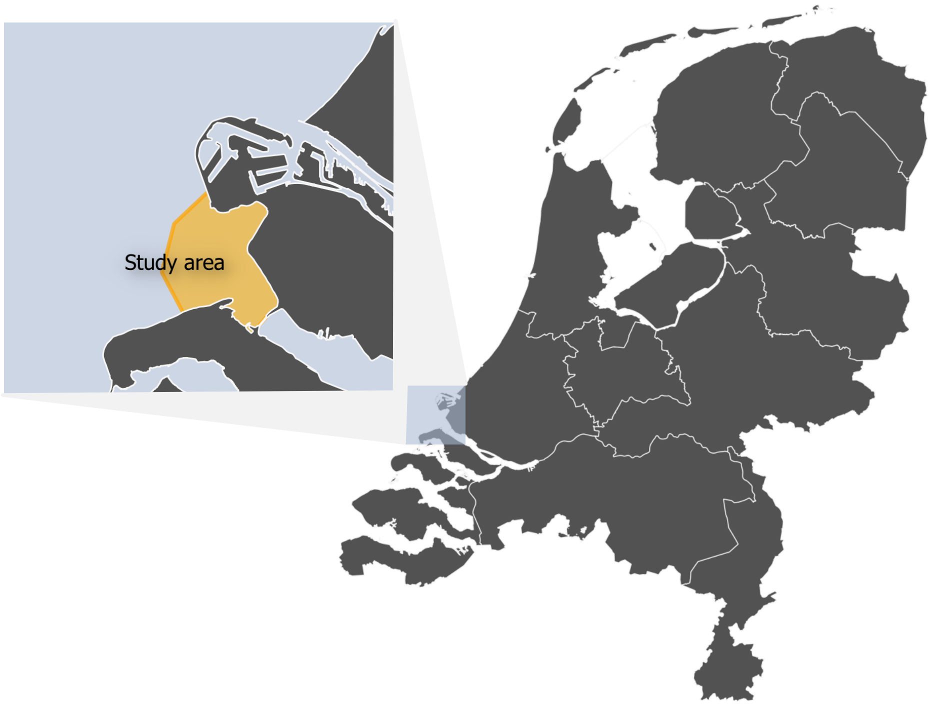
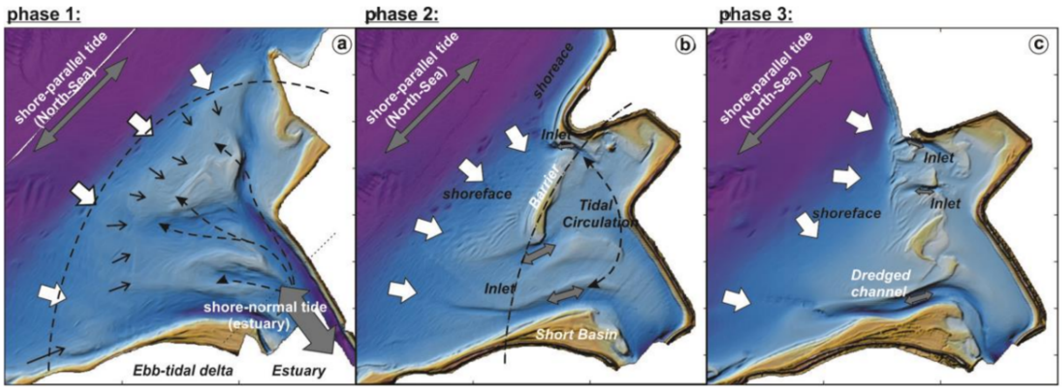


Fig. 1.1.: Location of the study area.

From 1950 onwards, human interventions changed the hydrodynamic characteristics of the estuary, influencing the natural state of the system. This change started by the closure of the Brielse Maas (1950), followed by the closure of the Brielse gat by the Brielse gat dam (1958-

1970) and the construction of the Haringvliet sluices (1970). With the construction of the Haringvliet sluices, the Haringvliet estuary got disconnected from the North Sea. These interventions changed the tidal influence on the ebb-tidal delta due to the decrease of the tidal prism. The dynamic equilibrium of the system was disrupted as schematised in Figure 1.2. Due to the construction of the Haringvliet sluices the outgoing flow decreased by 50 to 90 % (Kohsiek and Mulder, 1988). Changing not only the hydraulics but also the related morphology.

After the closure of the estuary, the tidal flow reduced significantly. As a result, the tide induced flow circulations in the area that are significantly smaller compared to the former estuary driven tide (Elias and Spek, 2014). These flow circulations in the area were initially relatively strong, but not strong enough to counteract the morphological changes of the shoals and channels in the mouth of the Haringvliet estuary. As a result the tide related sediment transport reduced to nearly zero (Elias and Spek, 2014). The erosion on the tidal shoals due to wave influences was not compensated any longer by the tidal driven sediment transport out of the estuary, the shoals were now mainly influenced by the waves. By the lack of a tide-induced flushing effect, the channels slowly silted up with sediment mainly originating from the erosion of the shoals (Kohsiek and Mulder, 1989; Z. B. Wang, Ronde, et al., 2009; Elias and Spek, 2014; Elias and Spek, 2016). From 1950 onwards, after the closure of the Brielse Maas, the individual shoals merged into one large shoal. The dominance of the wave action caused significant erosion of the shoreface, transporting the sediment towards the east and forming the longshore shoal 'Hinderplaat' (Colina Alonso, 2018).



Dynamic equilibrium — *Distorted state* — *Breaching and formation of a coastal plain*

Fig. 1.2.: Morphological development of the study area (Elias and Spek, 2014).

In time, the relative influence of the waves increased. As described by Elias and Spek (2014) the waves have a bulldozering effect on the ebb tidal delta, transforming the shoals and moving it more landwards. Induced by the dominant waves coming from the west, the Hinderplaat propagated in landward direction while increasing in height. The speed of the shoal moving landward decreased from hundred meters per year in 1971 to only ten meters per year in 1978 (Mulder et al., 2010). It was found that in the period after 1978, the location of the shoals has become more or less stable. However, recent studies like Elias, Van Der Spek, et al. (2017) and Colina Alonso (2018) have shown that shoal propagation is still an ongoing process.

In 1986 the Slufter was constructed. Colina Alonso (2018) concluded that this expansion served as an important sediment source for the Hinderplaat directly after construction. Breaking waves coming from the northern direction induced southward directed sediment transport on the Slufter and on the shoal. In Z. B. Wang, Ronde, et al. (2009) it was found that the area at the seaward side of the Haringvliet sluices is relatively large compared to other Delta closures. Therefore the (deep) tidal channels are present on the seaward side of the closure. Addtitionally the area is sheltered by the new constructed Maastvlakte 2 (extension of the Rotterdam port area). As a result, sedimentation in tidal channels is dominating with respect to the shore face erosion, resulting in a positive overall sediment balance (Z. B. Wang, Ronde, et al., 2009). This process is enhanced in the tidal channels due to the reduction of hydrodynamic forcing. Hence, at the sheltered landward side of the shoal, conditions are mild enough for the sediments to settle.

Next to being part of a natural coastal system, the coast of Voorne is part of a societal and ecological system. The coast and its related physical coastal processes provide added values to those systems (e.g. habitat provision for multiple species and recreation for the (local) society). The multitude of anthropogenic interferences as described before triggered a regime shift in the coastal system. Changes in a coastal system inevitably induce changes in the societal and ecological systems. While continuously developing towards a new equilibrium, the evolution of the coast has its impact on societal and ecological systems.

1.2 Objective and research questions

A trend has been observed in accretion of shoals and beaches along the coast of Voorne. An increase in sedimentation is found along the beaches and it is expected that this process will continue in the future, changing the characteristics of the coast. This development of the area has not only an impact on the coastal system, but also on the related societal and ecological systems. This triggers questions about the future development, not only for the interest and understanding of coastal evolution but also for the related societal and ecological system. Change of coastal characteristics will probably have an impact on recreational activities, but also on nature development. When it comes to coastal management it is of vital importance to link the values and interests of the coastal system with the physical coastal characteristics. When understanding whether physical coastal characteristics are perceived as desirable or not, value can be given to certain characteristics. By valuing the characteristics and linking them to stakeholder interests, consideration can be made on which value is appreciated over another and which one is allowed to diminish. Based on these considerations, coastal impact on society and ecology can be quantified and strategic plans can be established.

In order to link the change of the coastal system to changes in the societal and ecological system, quantification of the physical processes is needed. The primary aim of this research is to define stakeholder values and interests and relate them to the physical coastal processes. When assessing multiple stages in time, a trend in coastal processes can be obtained. Based on this evolving trend, future coastal processes can be derived and their impact on the societal and ecological system can be predicted.

1.2.1 Research questions

The primary aim of this research is supported by research questions that form the foundation of the steps required to fulfill the research objectives. The sub-questions are focused on the aspects of the main research question. The main question of this report is:

How does the evolution of the coast of Voorne impact stakeholder values and interest?.

The main research question will be addressed by investigating the following sub-questions:

1. *Who are the stakeholders and what are their associated values and interests related to the coast of Voorne and how can they be linked to coastal processes?*
2. *What are the important coastal processes related to the coast of Voorne and how did they change over time?*
3. *How can the change in coastal processes related to the coast of Voorne be linked to stakeholder values and interest?*
4. *What is the expected future development of the physical coastal processes and how does this affect stakeholder values and interests?*

1.3 Relevance

The mouth of the Haringvliet estuary is a complex area which is influenced not only by nature, but also by large-scale human interventions. These changes have shifted the dynamic equilibrium of the system multiple times. Tönis et al. (2001) concluded that the adaptation timescale T of the largest homogeneous part for the Haringvliet estuary was only 11 years, meaning that the system should have reached a new dynamic equilibrium. However, Colina Alonso (2018) stated that when considering the relation between time and spatial scales of coastal phenomena, these time scales may seem too small since the system is still changing. Hence, it seems that the system is still developing and a new equilibrium has not been reached yet. Coastal evolution continues to impact stakeholder values and interests.

This research gives insight in how (dominant) coastal processes related to the coast of Voorne have changed over time. Change in coastal characteristics lead to a change in societal and ecological systems. In order to assess the impact of this change, it is important to quantify the interests of stakeholders. With a linkage between the coastal processes and interest, the attractiveness of the coast can be assessed. Besides, ecological enhancement can be quantified. Linking coastal characteristics with stakeholder interests is crucial when it comes to future development and decision making. This area of research is relevant, but not exclusive to the coastal area around the mouth of the Haringvliet. The framework applied on the Voorne case can be used to translate beach characteristics to values and interests in other coastal areas as well.

The research is part of "Omgevingsvisie Westvoorne" (Strategy on spatial planning and the environment Westvoorne) and has close points of contact with nature development studies on the 'Hinderplaat' and 'Slikken van Voorne'. It will not only contribute to a better understanding of the coastal processes, but will also have its effect on more local contribution of values and interests, enabling understanding of nature development and local economy and therefore having a far greater importance. Multiple stakeholders, such as for instance the municipality of Westvoorne, the province of South-Holland and the Port of Rotterdam are related to this area, all with their own interest. This research establishes a definition of the beach of Voorne that can be the starting point of future development of a sustainable and joint vision of the coast.

1.4 Methodology and thesis outline

Chapter 2, study area

First a literature study is performed to get an understanding of the evolution of the study area over time. From literature, the study area related coastal characteristics and (dominant) physical processes are obtained. Insight is acquired on how different factors contribute to the development of the study area and how they contribute to the characterization of the coast. However, not all processes can be obtained through literature study. To get a better understanding of the development of the processes that play a role and their impact on the coastal development, a more profound analysis of the study area is needed.

Chapter 3, Stakeholder interests

In this chapter the study performed by Bergsma (2018) is assessed and discussed to obtain insight in the values and interests related to the study area. The derived interests are linked to physical model indicators using a framework. This framework is later on used to assesses the value of different interests in time and to asses future development

Chapter 4, Model set-up

In order to get an insight in the processes and their influence on coastal development a process-based model is used. The model used in this research is a process-based Delft3D model, which is derived from the general model of the Dutch coast; *'Kuststrook-fijn model'* provided by Rijkswaterstaat and Deltares (Simona-kuststrook-fijn-1999-v4). The model set-up and configuration are discussed in this chapter.

Chapter 5, Modelling Methodology

In this chapter the methodology of framework indicators assessment is discussed. It described how data from literature studies and model simulation is obtained and transformed into assessable indicators. The considerations and approaches to perform this assessment are elaborated in this chapter

Chapter 6, Analysis of the model results

By assessing the model results, insight is obtained in the development of the physical coastal processes over time. The analysis of the relevant physical coastal processes is discussed in this chapter.

Chapter 7, Indicator Assessment

After the analysis of the physical coastal processes influencing the area, insight is obtained in the development over time. The development of the physical coastal processes is linked to stakeholder vales and interests by making use of the framework. In this chapter it is discussed what the impact of the indicator development is on the stakeholder interests.

Chapter 8, Discussion

In this chapter the uncertainties and inconsistencies of the study are discussed.

Chapter 9, Conclusions

In this chapter the sub-questions are answered and the conclusion regarding the future development of the coast of Voorne is addressed.

Chapter 10, Recommendations

With the obtained insight from this study, recommendations are given to improve the conducted study and to perform possible future research.

Study area

2

> *Around 80 % of the largest population centres in the world are found in coastal areas*
>
> — **R. Waterman**
> 2008

More and more people tend to move towards the shore, making the importance of coastal management growing. Humans are having an increasingly adverse impact on many beach systems, making questions arise about the attraction of the beach on people. In this chapter the coastal and delta characteristics and processes are discussed.

2.1 Study area

The coast of Voorne is part of the mouth of the former Haringvliet estuary, located in the South-West of the Netherlands. The Haringvliet is a distributary of the combined rivers Rhine and Meuse. The mouth of the estuary is part of a system called the *Voordelta*. The system, as depicted in Figure 2.1, consist of the estuaries located in the South-West of the Netherlands who are separated by the (former) islands that are bounded on their seaward end by coalescing ebb-tidal deltas (Elias and Spek, 2016). The area of interest is located in the most upper part of the Voordelta, the mouth of the (former) Haringvliet.

2.2 Human interventions

The impacts of large-scale engineering works such as channel construction, damming and land reclamation that started already in the late 19th century have changed the geomorphology of the area significantly (Elias and Spek, 2016). Resulting in a new dynamic situation that has not yet reached a new equilibrium. In this section the human interventions and their influence on coastal evolution are discussed to get an understanding of how the coast has developed in time.

2.2.1 Closure works

Plans to interfere with the delta in the south-west of the Netherlands have a long history. Salinization and siltation of the Brielse Maas triggered the plan to close off this distributary in the late 40ties. The increasing saltwater intrusion caused serious problems for agriculture and cattle breeding in the adjacent polders. Additionally, the general idea in the early 20th century was to reduce the length of the coastline by damming the smaller estuaries in the south-west of the Netherlands. This would shorten the length of the dikes needed to protect the hinterland and

Fig. 2.1.: The Voordelta.

would prevent salt intrusion in the low lying polders. Besides, it would create freshwater reservoirs that offered public water supply to approximately three million individuals in the adjacent area (Wijngaarden et al., 2002). In the course of these plans, in 1950, the Brielse Maas was closed off.

A plan to close off the other estuaries was under investigation when in 1953 a huge storm surge hit. Resulting in the adaptation of the Delta project by the Dutch parliament. The plans existed of closing off the Haringvliet with a dam and a sluice complex, damming of the Grevelingen and damming of the Eastern Scheldt. The general idea was to divide the Delta area into two subsystems: 1) The northern basin, consisting of the Haringvliet and Nieuwe Waterweg and 2) the southern basin, consisting of the Eastern Scheldt and its northern tributary Mastgat-Zijpe-Kramer-Volkerak. The Grevelingen was decoupled from the southern system and became a saltwater lake. Eventually, due to observed ecology degradation in the Haringvliet, the Eastern Scheldt was not completely dammed but a storm surge barrier was constructed which allowed water to flow through, ensuring the preservation of the inshore tidal ecosystem.

The northern subsystem was closed from 1957 until 1970 by constructing the Haringvlietdam. To keep its function as a (partly) river runoff branch, a sluice complex was constructed within the dam to be able to discharge the surplus of river water to the sea. The sluice complex was built in such a way that the discharge through the Nieuwe Waterweg, the other river runoff branch connecting the port of Rotterdam with the North Sea, could be regulated in order to keep the salt intrusion constant. With a flow width of 1000 meter the sluice complex has a maximum discharge of 25.000 m^3/s (Aarninkhof and Van Kessel, 1999). The sluice complex was constructed in 1957 by implementing an island of 1400 x 600 m, enabling the realisation of two sluice complexes. After the realisation of these sluices in 1966 it took four years to establish the two dams between the work-island and the mainland. At first the dams combined closed off the estuary completely, but in 1970 the sluice complex opened and became fully operational, making it possible for water to flow through the dam connecting the estuary and the sea again.

2.2.2 Land reclamation

After the closure of the Brielse Maas in 1950, the Port of Rotterdam was expanded further in westward direction with the construction of the Europoort. In 1966 the remaining mouth of the Brielse Maas estuary was further restricted by implementation of the Brielse Gat dam, which was a part of the Maasvlakte construction (Figure 2.2).

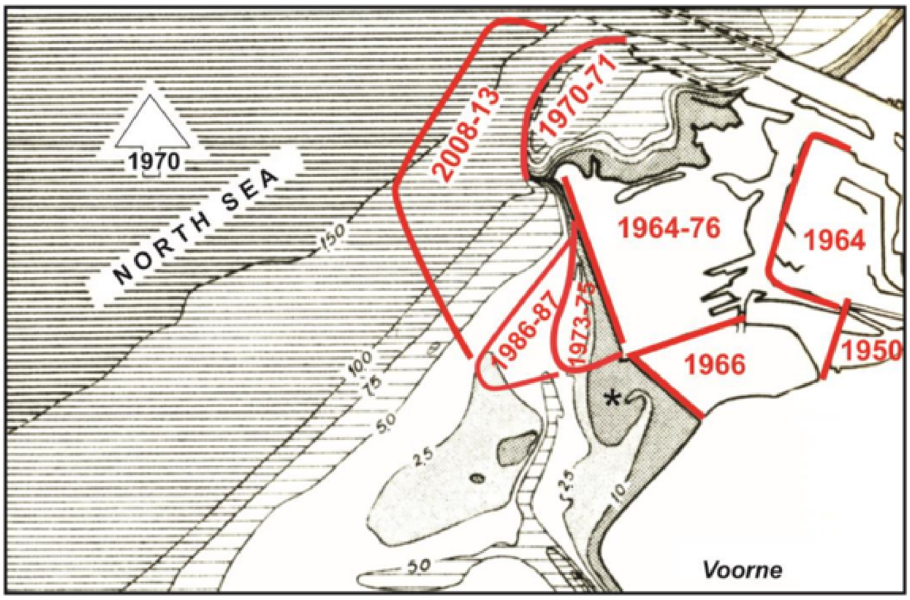


Fig. 2.2.: Expansion of the Port of Rotterdam (Elias and Spek, 2014).

Furthermore, due to the construction of, respectively, Europoort (1964-1966), Maasvlakte (1964-1976), Slufterdam (1986-1987) and Maasvlakte 2 (2008-2013) the shoreline of the northern island Roozenburg shifted 8 km seaward, covering the northern part of the Haringvliet ebb-tidal delta. The Maasvlakte 2 extended further into the sea than the former ebb tidal, causing the mouth of Haringvliet estuary to be sheltered from NW waves. Besides, it forms an obstacle for longshore sediment transport along the Dutch coast.

2.2.3 Kierbesluit

In the former policy (LPH '84, "lozings Programma Haringlvietsluizen 1984") the opening of the Haringvliet sluices depended on the discharge measured at Lobith and the water gradient measured in the sluice complex. The doors of the sluices only opened during ebb tide. As described in Wijsman et al. (2018) the sluice doors opened from a measured discharge of 1100

m^3/s and higher. When reaching a measured discharge of 9500 m^3/s or higher the sluice doors would open completely. When the doors are open, freshwater is discharged directly into the mouth of the Haringvliet estuary, decreasing the salinity levels in the area. Salinity levels decrease due to the opening of the Haringvlietsluices and indirectly due to the outflow of the Nieuwe Waterweg. In Cleveringa (2006c) it is stated that because the channel Nieuwe Waterweg is located at a relatively small distance from the study area, the supply of freshwater is relatively strong. Implying a constant smaller level of salinity in the mouth compared to the North sea. This effect is increased due to the small daily supply of freshwater discharge of the Haringvliet sluices; decreasing the salinity in the study area even more.

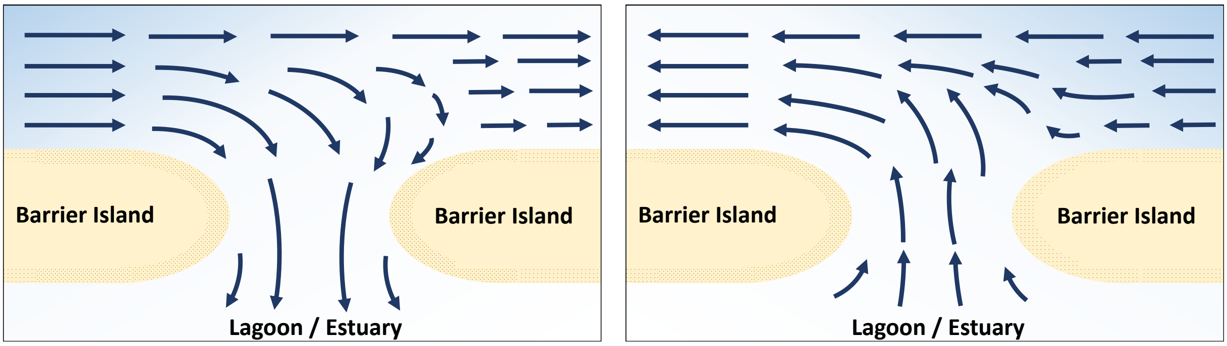
Since the ecological development of the Rhine is enhanced in the most recent years, a new sluice policy is implemented. The Haringvliet sluice caused a blockage for fish to migrate from the sea to the upstream river areas. Therefore, plans were developed to re-open the Haringvliet sluices not only during ebb periods but also during flood periods. This implies that a (limited) flow of saline water is able to penetrate into the estuary. This new policy is called *Kiersbesluit*.

It is expected that due to the implementation of the Kierbesluit policy the possibilities for fish to migrate from the Voordelta to the Haringvliet estuary and upstream river branches will increase (Hop, 2011). With the inflow of saline water the opening of the sluice doors causes an increase in siltation at the west part, within the Haringvliet estuary. The policy implies that east of the imaginary line; 'Middelharnis - Spui', 13 km east of the Haringvliet sluices, freshwater is ensured to provide for the intake of drinking water and agricultural needs.

2.3 Morphology and driving forces

Before human interventions the bathymetry of the ebb-tidal delta was the result of an interaction between the tidal flow and the waves. Because of the vast size of the (former) estuary the duration of inflow and outflow is relatively large. As a result, a phase difference arises between cross-shore tidal flow of the estuary and the longshore tidal wave. This phase difference causes the tidal flow to have a preferred inflow and outflow direction, influencing the shape of the ebb-tidal delta.

The tidal range along the coast of the Netherlands increases significantly from the south to the north. When the tidal wave approaches the inlet from the left, which is the general case on the northern hemisphere because of the Coriolis force, the tidal range on the left side of the ebb-tidal delta generally is somewhat larger than on the right side (Sha and Van den Berg, 1993). At the southern side of the ebb deltas the tidal range is several decimeters more than at the northern side. Before the closure of the Haringvliet, this favoured a more distinct development of southward-bifurcating channels in the mouth as compared to bifurcations to the north (Sha and Van den Berg, 1993). The inflow of the estuary is forced by the incoming flood flow from the south, while the ebb enhanced emptying of the estuary is southward directed Figure 2.3. This results in an asymmetrical development of the channels in the mouth of the estuary. Hence, the geometry of the ebb-tidal delta in the SW Netherlands is slightly asymmetric and directed to the southwest.



(a) Tidal assummetry mid-flood.

(b) Tidal assummetry mid-ebb.

Fig. 2.3.: Tidal asymmetry ebb tidal delta (Redrawn after Sha and Van den Berg (1993)).

As described by Aarninkhof and Van Kessel (1999), the ebb-tidal delta consisted out of two main channels; 1) Rak van Scheelhoek, and 2) Slijkgat. The large shallow area in between would later form the shoal *Hinderplaat*. The shoals in the mouth of the estuary were fully sub-tidal, with gentle slopes towards the North Sea and towards the land. The height of these shoals was determined by the combined action of tidal currents flowing in and out the inlet over the shoals and waves coming in from the North Sea (Kohsiek and Mulder, 1989).

The area has been subjected to human interventions for a long time, but drastic changes in morphology of the ebb-tidal delta occurred since 1950. These changes were induced by damming the river branch Brielse maas with the construction of the Brielse Maas dam (depicted as (e) in Figure 2.4. This damming resulted in a sediment transport in the direction of the tidal channels of the former Brielse Maas. Without the discharge interaction between the river branch and the sea, sediment aggregated in the tidal channels (Aarninkhof and Van Kessel, 1999).

After the closure of the Haringvliet the area changed significantly. Due to almost full disappearing of the cross-shore tide, wave dominance got enhanced. Waves act as a bulldozer on the shoal, eroding the foreshore of the delta. By the absence of sediment transported by the ebb tide, erosion of the foreshore prevailed. The front of the former ebb-tidal delta became deeper and the shoreface became steeper. The sub-tidal shoals on the seaward margin of the ebb-tidal deltas developed into inter-tidal breaker bars on the northern side of the former delta (Cleveringa, 2008). These bars are elongated and narrow, with a gentle slope on the North Sea (front) side and a steep slope on the backside. The intertidal flats bear resemblance to the flats found in tidal basins like the Westerschelde and Wadden Sea (Cleveringa, 2008). The shape of the tidal flats is irregular and determined by the orientation of the flanking channels. The waves coming in from the North Sea break on these bars. As a result, the area behind the shoals consists of either inter-tidal flats or shallow water areas as depicted in figure 2.5.

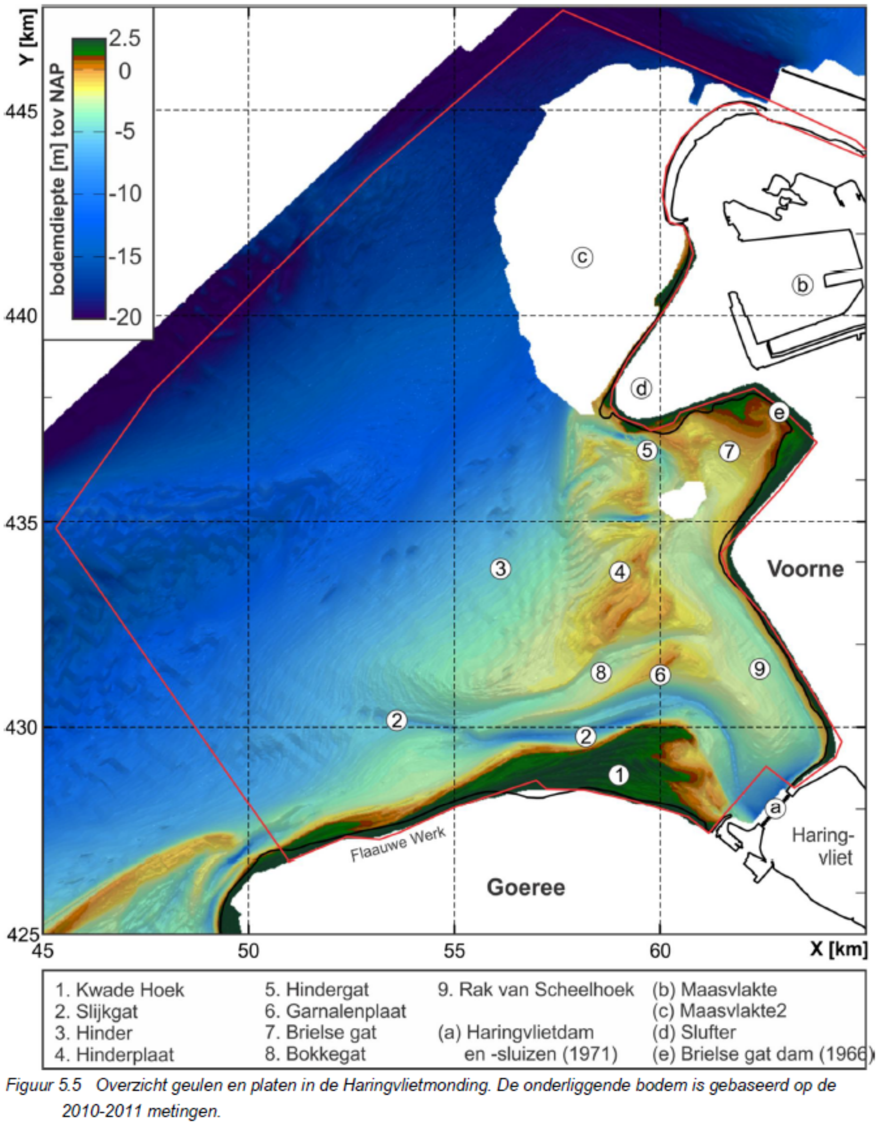


Fig. 2.4.: Overview Channels and Shoals, by Elias and Spek (2016).

In addition the dependence between the estuary and the mouth strongly reduced. The south-north running North Sea tide had started to dominate the current pattern in the seaward part of the mouth after the closure. In the period after the closure of the Haringvliet estuary, the currents around the shoals, as well as the discharge of freshwater through the sluices determines the hydrodynamics of the area. There is no more influence of east-west fill and emptying driven currents due to the closure Steijn et al. (2001). This increased the discharge of Gat van de Hawk during part of the tidal cycle and caused this channel to scour. Other channels changed from sediment transporting conduits to permanent sinks mostly filled in with predominantly mud. (Elias and Spek, 2016).

Sediment imported in the system originated mainly from the coast of Goeree and partly from the northern coast of Voorne. The delta front of Grevelingen ebb-tidal delta and the sand nourishments on the coast of the island of Goeree fed the study area. The transported sediment

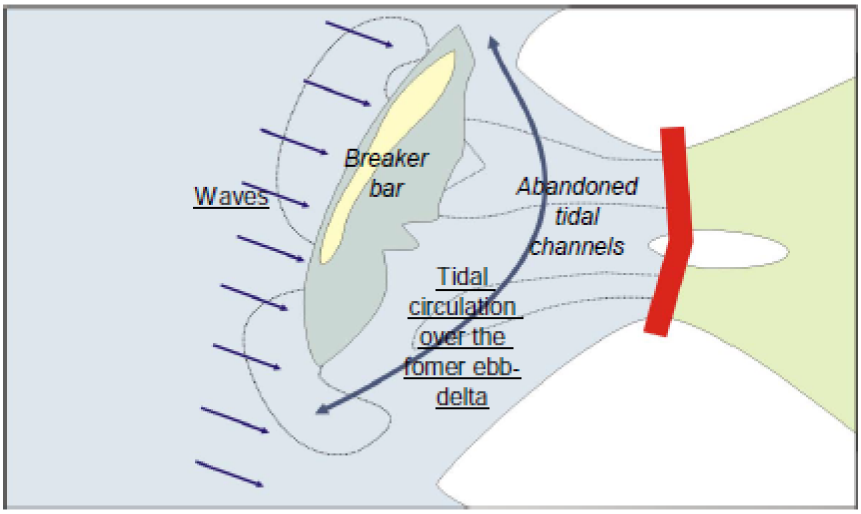


Fig. 2.5.: Schematisation of the Haringlviet after closure (Cleveringa, 2008).

enhances the expansion of the curved spits of *Kwade Hoek* Elias and Spek (2016). During periods with small to average sluice discharges sediment was transported by the eastward directed flood current and settled in the east/north side of the Kwade Hoek.

In 1987 the channel Gat van de Hawk was closed off by the construction of the slufter. The channel was replaced by the channel Hindergat, which was dredged through the Hinderplaat. As a result the coastline change between the south dam of the Maasvlakte and the Brielse gat. The sand dam of the Slufter and the tip of Voorne were maintained with sand nourishment's, both on the beach and at the shoreface (Elias and Spek, 2016). This led to an extra sediment supply, resulting in accretion especially in the area in front of the Brielse Gatdam and the adjacent area around the Slufter (Steijn et al., 2001).

The erosion of the ebb tidal delta continued and the remaining sheltered area behind Hinderplaat silted up. Due to the bulldozering effect of the waves the Hinderplaat moved even further landward. While moving towards the shore, the shoal increased in height and length, but decreased in width. In 1995 an extreme discharge event that lasted 8 days generated large current over the Hinderplaats, causing multiple breaches. The breached channels were maintained afterward by the regular tide Colina Alonso (2018). According to Winter (2014), after the breaching, the smaller shoals merge slowly into one *supershoal*. Finally, without breaching events all shoals will likely coalesce.

2.3.1 Tide

The tidal currents on the former Grevelingen and Haringvliet ebb-tidal deltas follow the tides on the North Sea. The flood currents enter through the tidal channels in the southwest of the former ebb-tidal deltas and leave through the channel or channels in the northeast (Spek, 1987;

Cleveringa, 2006c). The reverse flow path holds for the ebb currents from northeast to southwest, maintaining the circular tidal flow.

The channels of the estuary were flood dominant Tönis et al. (2001) so the maximum flow velocities were in flood direction. Now the current velocities are almost in phase, such that the maximum current velocities in- and outside the estuary occur at almost the same time (Tönis et al., 2001)

The flow pattern of the Mouth of the Haringvliet follows mainly from the flow pattern of the North sea, but is influenced by the discharge through the Haringvlietsluices during low water. As described in Cleveringa (2006c) four phases can be distinguished describing the flow pattern in the former mouth of the estuary as depicted in Figure 2.6.

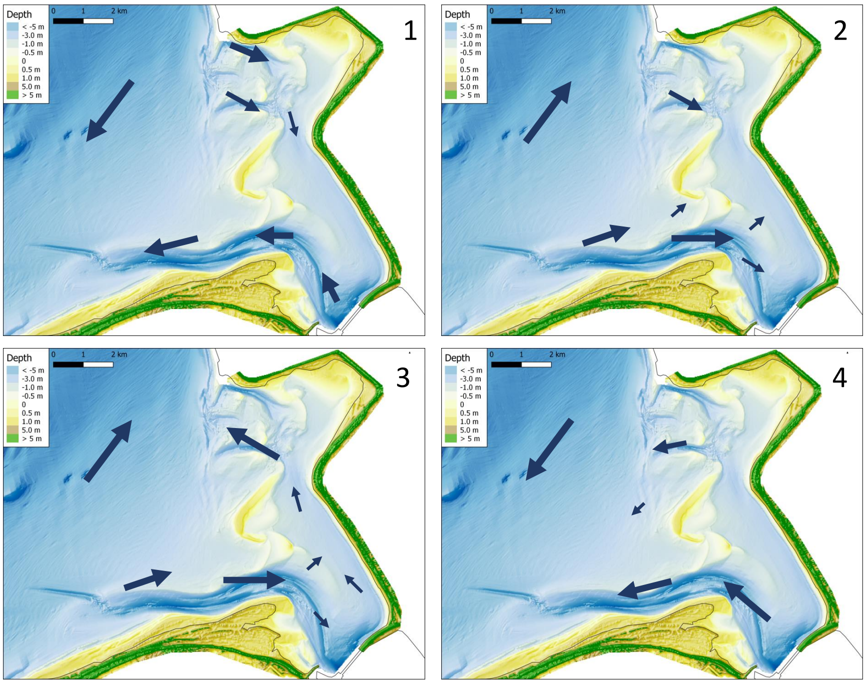


Fig. 2.6.: Propagation of the tide in the study area after construction of the Haringvliet sluice (Drawn after Cleveringa (2006c)).

The four phases shown in the figure can be distinguished describing the flow pattern in the former mouth of the estuary:

1. **Low water, ebb at North sea**
   South west directed ebb flow alongside the Maasvlakte and the Hinderplaat. Through the channel Slijkgat part of the discharged water flows towards the South West.
2. **Flood flow, after tide reversal**
   Flow direction at the North Sea turns towards the north-east, in flood direction. The watersurface rises fast and in the mouth of the estuary high eastward directed flow velocities occur. The duration of this period is relatively short, water storage in the area relatively small.

3. **Highwater, flood at North sea**
   Water flows in through the channels Slijkgat, Middengeul and Bokkegat and flows out through the channel Hindergat. The current velocities are relatively low.
4. **Ebb flow, after tide reversal**
   The total flow of the mouth of the estuary is directed west-ward into the north sea.

2.3.2 Waves

The wave climate of the Voordelta mainly consists of wind waves, locally generated in the shallow North Sea. Since the dominant wave direction in the Voordelta is oriented in south west direction, the dominant wave direction in the mouth of the Haringvliet is also from the South West (Tulp et al., 2019). The average significant Wave height is 1,3m from the west-southwest with a related period of 5s (Mastbergen and Nederhoff, 2012), although waves with longer periods coming from the north west direction arrive frequently in the study area as well. An overview of wave height and direction is depicted in the wave rose of Figure 2.7. During storm conditions, waves can reach heights of 6m with a set-up induced water level rise of more than 2m. The effect of waves from the north west has decreased since the reclamation of the Maasvlakte 1 and the Slufter (Tönis et al., 2001). After the reclamation of Maasvlakte 2, the influence of these waves has decreased even further.

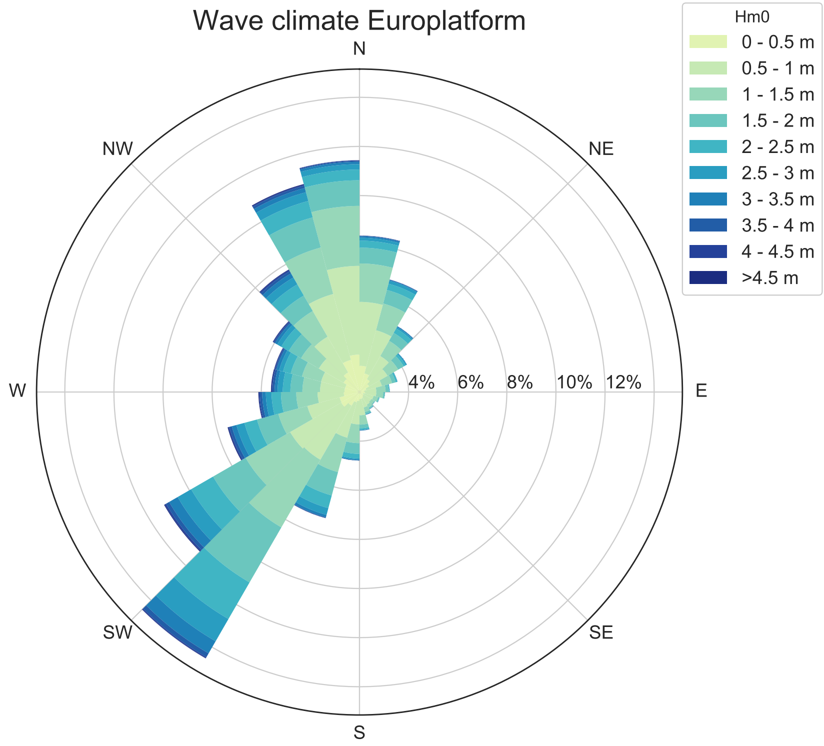


Fig. 2.7.: Wave Climate Europlatform.

As waves approach the study area, the bathymetry becomes shallower and the waves tend to deform due to shoaling, refraction, and wave breaking. The accretion that has been taking place since the damming of the Haringvliet has caused waves to break on the shoals in front of the coast (Tönis et al., 2001). As a result, the influence of waves in the vicinity of the Haringvliet sluice and the coast of Voorne has reduced. The shoals have propagated further towards the coast while growing in height. This leads to a decrease of offshore waves arriving at the coast of Voorne; the largest amount of wave-energy is dissipated on the flats in front of the coast. Waves breaking on the shoals generate currents on the Hinderplaat that govern the residual currents over a tidal cycle (Colina Alonso, 2018). Northwesterly breaking waves induce a higher water level along the seaside of the shoal than at the landward side of the shoal. This results in a gradient that induces cross-shore currents from west to east. In addition, obliquely incident waves also induce longshore currents along the Hinderplaat as well as along the coast of Goeree and the Slufter (Colina Alonso, 2018). In conclusion, waves have gained in importance since the closure of the estuary in 1970. Waves coming in from the north as well as from the south break on the shoals and on the adjacent coast of the study area. The wave energy of the breaking wave is responsible for the increase in sediment transport in the direction of the study area.

2.3.3 Wind

Due to the shoal configuration, the area behind the shoals is relatively sheltered from offshore incoming waves. As a result, wind effects can be of importance for the residual currents in the study area, as the wind forcing is capable of altering the direction of the main flow. In Colina Alonso (2018) it is stated that moderate wind forcing (U = 9.5m/s) show that wind driven currents are capable of changing the direction of the residual currents in the study area. This is mainly in the shallow areas around the shoals.

In the upper shoreface, the wind has its influence on sediment transport. The locally induced wind waves are able to bring the sediment into suspension. The direction of sediment transport in these areas is mostly determined by the wind-driven currents. This does however not hold for sediment transport on the shoals, according to Colina Alonso (2018) sediment transport on the shoals is mostly determined by wave-driven currents.

2.3.4 River discharge

In Colina Alonso (2018) and De Vries (2007) it was found that next to wind and waves, river discharge-forcing has a great impact on the residual currents in the mouth of the estuary. Large river discharges play an important role in the formation of the connecting channels on the Hinderplaat. Predominantly in the areas where the main channels are located.

The river discharge in the mouth of the estuary originates from the rivers Rhine and Meuse. The Haringvliet is a distributary of both rivers Rhine and Meuse as depicted in Figure 2.8. The Rhine has an average discharge of 2200 m^3/s and the Meuse has an average discharge of 230 m3/s Wegman (2015). Making the river Rhine the most important influencing river of the two. The discharge from the river Rhine debouching in the Northsea is divided over two branches; 1) the Waal and 2) the Lek. The discharges trough these rivers is derived from the discharge from the upper Rhine. At the bifurcation near Pannerden the upper Rhine discharge is divided over the Lower Rhine/Lek branch and the Waal.

From the rivers the water flows to the sea via the Haringvliet estuary and the Nieuwe waterweg, the channel connecting the port of Rotterdam with the North sea. The opening of the Haringvliet sluices and thus the runoff through the Haringvliet estuary, depends most of the time on the discharge through the Nieuwe Waterweg. This discharge has to kept stable to prevent extensive salt intrusion in the port. As a result about 550 m3/s flows through the Haringvliet averaged over the time (Stam et al., 2002).

Fig. 2.8.: Rhine and Meuse Delta.

A permanent submersion of the Hinderplaat occurs during extreme discharge events ($Q_{sluices}$ > 7000m3/s), with flow velocities that are four times as high than under regular discharge scenarios. During these events the period over which the flow is in offshore direction almost doubles while the period of onshore directed flow is half as long: this results in strong offshore directed currents on top of the shoal, having a significant impact on the area (Colina Alonso, 2018).

However, these extreme events do not occur that often. Based on historical data it was found that only 1.3% of the time the average discharge through the Harinvliet exceeds 4000m3/s (Colina Alonso, 2018). Smaller discharges, from on average 4000 m3/s to 2000 m3/s only occur about 8.8 % of the time. The largest part of the time, the remaining 89,9%, the flow through the Sluice was on average smaller than 2000m3/s.

2.3.5 Bed composition

The bed of the Haringvlietmouth consists mostly of deposited sediment that originates from the emergence of the Haringvliet estuary. Only a small part originates from the Rhine and Meuse and only a very small amount, mainly consisting of mud originates from the deeper parts of the North Sea (Colina Alonso, 2018).

According to Van Vessem (1998), the sediments of the inlet and tidal delta consists mainly of fine to medium sand particles This is the result of the lowering of the flow velocity, which enables the finer sediments to settle sooner. Despite the limited water depth and the large effects of wave interaction, mud concentration can increase to 90% (Koomans, 2001).

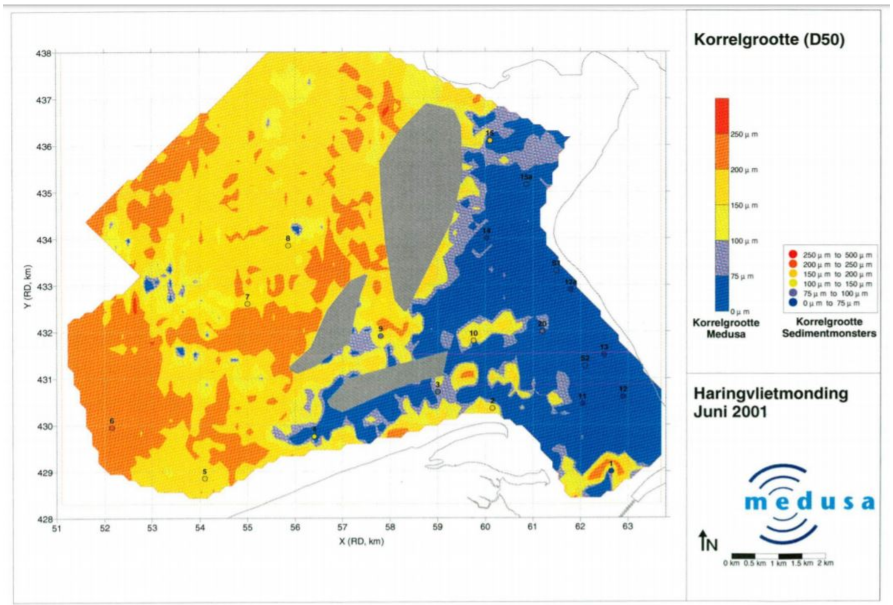


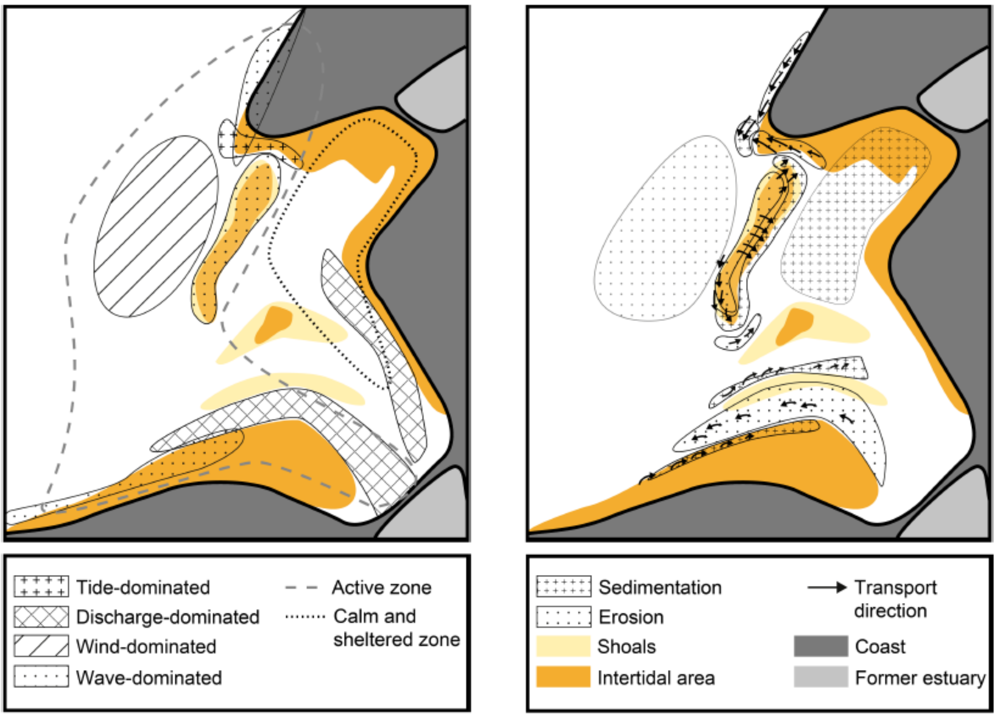
Fig. 2.9.: Sediment distribution by grainsize (Koomans, 2001).

On average the area consists of less than 10% mud in the channels and on the flats (Van Vessem, 1998). It follows that the percentage of mud is larger in the more sheltered areas of the Haringvlietmouth. Since construction of the closure dam, large volumes of mud have accumulated in closed-off channels in the outer delta (Elias and Spek, 2016). In most of the area on average the mud part amounts 5-6%, whereas in the sheltered channels the percentage of mud varies between 10-50% (Koomans, 2001). The distribution of mud is relatively low in the area offshore of the Haringvliet mouth (<20%). In the mouth, landwards of the Hinderplaat mud concentrations are higher. Especially in the north of the Rak van Scheelhoek, here the mud concentrations are the highest compared to the rest of the mouth (>90%). In the Slijkgat concentrations of mud are somewhat lower (~60%), where in the area south of the Slijkgat, near the Kwade Hoek, mud is almost absent. Near the sluices mud concentrations are the lowest at the southwest area in front of the sluices (Koomans, 2001).

More recent analyses of the mud deposits in Rak van Scheelhoek indicate thicknesses of up to 7.5 m (Elias and Spek, 2016). The compaction of the thick mud layers that have been deposited in the cut-off tidal channels, possibly contributed to the gradual loss of sediment volume in the ebb-tidal deltas (Elias and Spek, 2016). From experiments it is found that consolidated fine sediment from the bottom of the Haringvliet is hard to bring in suspension again because of the high cohesive forces of the fine sediment particles(Piekhaar and Kort, 1983). Therefore, it is not expected that the bottom layers get easily eroded, even not during high river discharges.

2.3.6 Summary morphology and driving forces

Within the study area, different regions have different dominant processes. Colina Alonso (2018) mapped the dominant processes in the study area to conceptualised the degradation of the Hinderplaat. The dominant processes are mapped in Figure 2.10. In the active region high flow velocities are taking place and large morphological activity is detected. The calm zone shows much less hydrodynamic and morphological activity due to the area's sheltered location. For a more elaborate description of the evolution of the Hinderplaat it is referred to (Colina Alonso, 2018).



(a) The dominant mechanisms (b) General transport and bed level changes

Fig. 2.10.: Conceptual description of the morphodynamic characteristics (Colina Alonso, 2018).

The conceptual model of the mouth of the Haringvliet describes the most important hydrodynamic en morphological processes in the current situation, which are of influence on the management characteristics at a timescale of 10 to 50 years (Stam et al., 2002).

2.4 Ecology

The study area, as part of the *Voordelta*, is a unique area with valuable nature. The interchange between the freshwater river run-off and the saline north sea makes the area perfect habitat for different kinds of species. The study area a unique area in terms of nature preservation and human activities. Seals rest on the shoals, birds are foraging in the area and humans recreate on the beach and make use of the sea for the fishery. Hence, the balance between human use and nature development in the area is sensitive. Because of this sensitivity and the uniqueness of the area, politics decided to designate part of the area to Natura2000 area. Three natura2000 areas can be distinguished in the study area: 1) Voornese Duin, 2) Kwade Hoek, and 3) the Voordelta Figure 2.11.

Fig. 2.11.: Natura2000 area.

2.4.1 Natura2000

Part of the area is Natura2000 area Figure 2.11, meaning its characteristics should be maintained in such extend that human interference is limited. Natura2000 is a network of nature areas throughout Europe wherein the protection of animal species and nature development is ensured.

The study area is part of a bigger Natura2000 area called the Voordelta. As shown in Figure 2.1 this area stretches out along the south-west coast of the Netherlands. Because of the dynamic hydrological conditions in the Voordelta, the places where bottom fauna can be found fluctuate. When assessed in 2008 the silty mouth of the (former) Haringvliet estuary contained a lot of bottom fauna Delta en Royal HaskoningDHV (2016), however since then a decreasing trend has been observed. The change in bottom fauna can have an influence on the population of birds. In the study area two resting areas are assigned. In these areas -consisting of the shoals as depicted in Figure 2.12- no people are allowed to prevent nuisance of the species resting in these areas. By preventing the disturbance, seals and birds are able to rest on the shoals, some birds can even use the shoals to forage on. It is important to notice that birds locate themselves in the vicinity of foraging areas. So when for example benthic life on the sea bottom relocates or get distinct because of change in physical processes, the birds who depend on those species are likely to relocate as well.

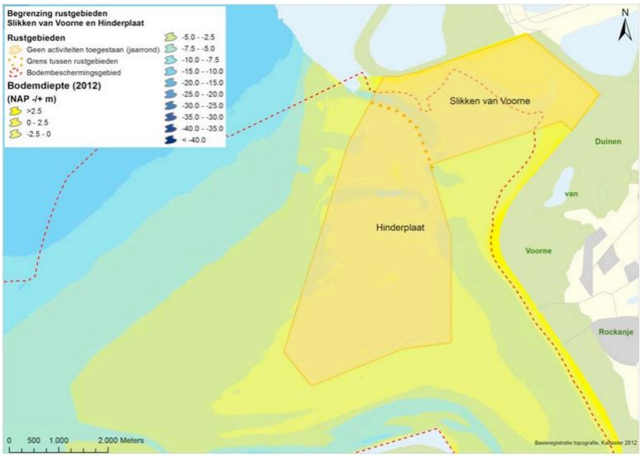


Fig. 2.12.: Resting area slikken van Voorne (Delta en Royal HaskoningDHV, 2016).

Within the study area two other Natura2000 areas are classified. Namely the *Voornes Duin* (Dune of Voorne) and the Kwade Hoek Figure 2.11. The *Voornes Duin* consists of the dune area near Oostvoorne and the salty intertidal area of the Brielse Gat. The area is classified as one of the most precious areas related to flora, containing a large variety of botanical species (Heldt et al., 2016). The Kwade Hoek, in the south of the study area, consists out of dune areas and an inter-tidal area. Due to the low lying shoals the Kwade Hoek is most of the time submerged, resulting in a limited growth of vegetation. Due to its dynamics the dune area consists of older and younger dunes (Delta en Royal HaskoningDHV, 2016). The Haringvliet estuary, east of the sluices is also part of Natura2000, but since the main interest lies on the beach of Voorne, the Haringvliet is out of the scope of this research. In both Natura2000 areas human interference is not allowed.

2.4.2 Saltspray

To preserve the Natura2000 areas the growth of dunes is preferred to be diverse and therewith an increasing amount of vegetation is not wished for. The development of older vegetation needs to be limited in order for younger vegetation to grow. One of the mechanisms influencing the sustainable growth of dunes is salt spray. Due to the dynamics of breaking waves water particles get detached from the waterbody and are released into the air. Under the influence of the wind these particles can be transported in the direction of land. The suspended salt in the water particles gets transported with it. This process is called salt spray.

Since vegetation is vulnerable to salt, the growth of vegetation slows down. Salt levels alongside the coast of Voorne are historically low. Due to the development of the shoals, wave action on the beach reduces and thus the related saltspray reduces with it. Enhancing the growth of vegetation and changing the dune characteristics (Heldt et al., 2016).

Stakeholder interests

3

3.1 Introduction

Throughout human history deltas attract people and all other sorts of life. Inherent to this increase of delta life is the growth in conflicting values and interests. Coastal systems are not only natural systems but are nowadays also correlated with social and ecological systems. Hence, the development of a coast is not only defined by its morphological character, but it can also be described by means of values and interests, referred to as interests in this study. Multiple parties and stakeholders in a coastal area all have interests in the state and development of the coast. Due to the scattered stakeholder interests, preferred morphological developments of the area can become rather contradictory. A striking example of these contradictions is found in the focus area of this research, the beach of Voorne. Here anthropogenic interference in the past created a dynamic area where which seems to develop towards a new dynamic equilibrium, inevitably leading to an impact on stakeholder interests.

In order to link stakeholder interests to the physical development of the coast, a framework is established. This framework divides the main interests over different predefined area (sub)-functions. The area (sub)-functions are linked to physical coastal processes using critical measurable indicators. With the help of measurable indicators, sub-functions can be quantified. By quantifying these sub-functions, the interests of the stakeholders can be valued. In this research, the value of the interests and sub-functions will be compared between different stages in time. Therefore, the quantification of a sub-function will not be exact, but relative to other stages in time. First, the components of the framework are described. Secondly, the different components are discussed.

3.2 Framework

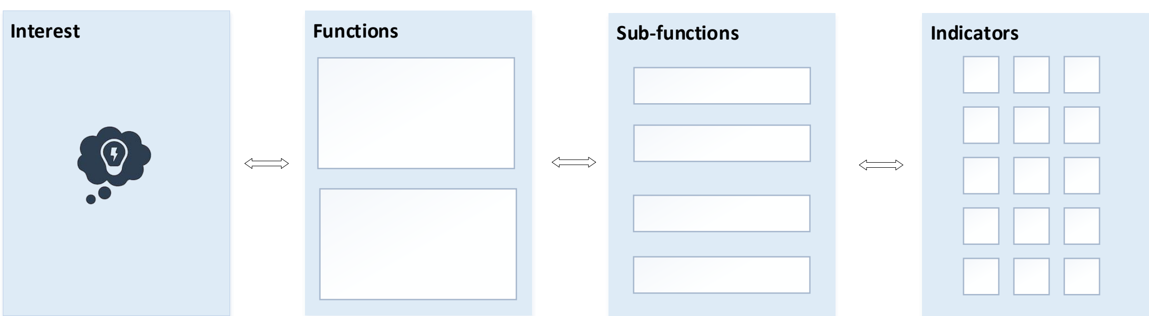


Fig. 3.1.: Framework components (after Van der Moolen (2015).

To associate the interest to physical processes a framework is established. In Figure 3.1 a conceptual format of the framework is shown. The framework consists of four components: 1) interests, 2) functions, 3) sub-functions and 4) indicators. In the next sections these components will be discussed.

The first component of the framework is *Interests*. Interests in the framework represents the various interests of stakeholders in a function of the system. These are different for every stakeholder. The interests of stakeholders are associated with different functions the area provides. These functions give value to their associated interest. e.g. the interest economy can be associated with the function of Recreation. To specify the functions in more detail, sub-functions are defined. Each function consist of one or multiple sub-functions, these sub-functions represent the *potential* of certain activities. Elaborating further on the previous example, the function of Recreation can be divided into the sub-functions sun-bathing, surfing and strolling. These three sub-functions further specify the function recreation.

To quantify the interests associated with the study area, indicators are derived for all sub-functions. Indicators indicate the impact of coastal evolution on the potential of the sub-functions by quantifying the physical coastal processes. Potential of a sub-function is deliberately stated since change in indicators is likely to influence the value of the sub-function, but does not always have to be of influence on the value. The potential of the sub-functions depends namely on multiple indicators and other influences outside the framework domain. Thus, by assessing the indicators, the potential value of the sub-functions can be determined. As shown in Figure 3.2 each sub-function can be quantified with multiple indicators. However the indicators used to quantify the sub-functions can be used to quantify different sub-functions as well. Hence, one indicator can be used to quantify multiple sub-functions. This is illustrated with the lines connecting sub-functions and indicators in Figure 3.2. It once again shows the complexity of the system. However, when assessing the sub-function individually the linkage and quantification with the indicators becomes straightforward (Section 3.4).

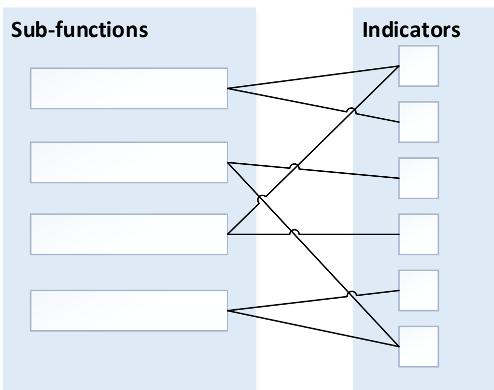


Fig. 3.2.: Relation between sub-functions and indicators.

3.3 Interests

To obtain an overview of stakeholder interests within the study area, a preliminary stakeholder analysis was performed. The first analysis was done by Arcadis by an analyzing QuickScan (Bergsma, 2018). The approach of this stakeholder analysis is further described in Appendix B. The outcome of these sessions will form the base of the stakeholder input within this research. The obtained interests of the stakeholders derived from these sessions could be divided over three main interests: 1) safety and maintenance, 2) economy, and 3) ecology as is shown in Figure 3.3. These interests and their associated stakeholders are further discussed in the following sections.

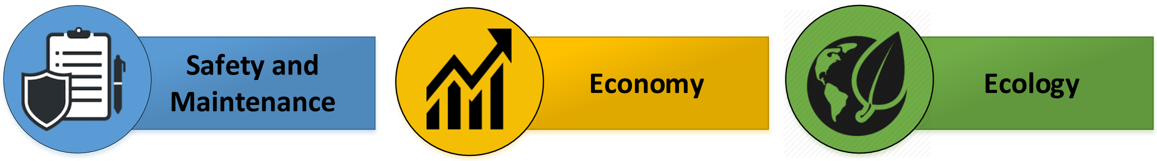


Fig. 3.3.: Main Interests.

Before discussing the main interests separately, the main stakeholders related to all these interests are discussed. The stakeholders that can be related to all interests are the municipality Westvoorne and the province. In 2017 the municipality of Westvoorne established a long term vision regarding the development of the municipality. The aim of the municipality is to create an attractive, sustainable coastal municipality that strengthens and preserves the characteristic landscapes and unique natural features, where visitors and inhabitants enjoy living in (Kuiper-Compagnons, 2017). To fulfill this vision the municipality tries to form a coalition that establishes a common vision on how the coast should develop. Another stakeholder having interests in all of the main three interests is the Province of South-Holland. However, this stakeholder is less involved since the area of interest is only a (small) part of the province. In the following section the main interests and their associated stakeholders are discussed.

3.3.1 Safety and maintenance

When assessing the interest safety and Maintenance the area gives rise to some important stakeholders in the study area. In the area multiple parties need to work together regarding maintenance and management of the coastal area, all parties are responsible for their part of the coast. The upkeeping and cleaning of the beach is carried out by the municipality of Westvoorne. The management and maintenance of the coast regarding flood protection is the combined responsibility of Dutch ministry Rijkswaterstaat (RWS) and Water Authority Hollandse Delta. The interest of RWS is to lower the risk of flooding by limiting the effort to maintain it.

The water authority is the owner of the largest part of the coastal area. Some parts of the areas (about 10%) are private property (Heldt et al., 2016). The private landowners are responsible for the maintenance of their own land, but are always obliged to ensure flood protection.

Other parties having an interest in safety and maintenance are Natuurmonumenten and 'Zuid Hollands Landschap'. These parties are responsible for maintaining the nature areas, especially the Nature2000 sites within the study area. In this research the interest of the nature parties is associated with ecology and is, therefore, further elaborated in Section 3.4.4 and Section 3.4.5.

3.3.2 Economy

In the study area multiple stakeholders have an interest in economy. The main function related to economy in the area is the recreation function the area offers. The other economic function defined in this research is the availability of the waterway *Slijkgat*. This waterway -located in the southwest of the study area- provides shipping access between the North Sea and the Haringvliet.

Recreation

The economy of most coastal municipalities depends mainly on coastal recreation which is without a beach not conceivable (Broer, 2011). The beach of Voorne is no exception and the local economy of Voorne depends essentially on tourism. The coast provides a lot of recreational possibilities for the region such as beach recreation and nature recreation. On windy days the area offers great accommodation space for kite- and wind surfers in the shallow, calm part near the Slikken of Voorne and in the south-east part of the channel Rak van Scheelhoek (Figure 3.7. During warm days the beach of Voorne, near Rockanje (Figure 3.6, attracts large numbers of people from many different places. These visitors can mainly be associated as (sun)bathing tourist, which are mostly families with young children (KuiperCompagnons, 2017). Tourists come from much further than the adjacent area. At first the beach of Voorne provides direct recreational services to the municipality of Westvoorne. It has an important role in the well being and the economy of the municipality. Local owners of beach restaurants and camping owners benefit directly from the recreational function provided by the beach. Making these stakeholders of Westvoorne rather dependent on the sub-functions the beach provides. Thereupon the functions the beach provides are also of great interest to the local economy of the adjacent municipalities. The increased population during the holiday season gives boost to the other local entrepreneurs as well. On the island of Voorne the municipalities complement each other in terms of different recreational possibilities. Combined, they provide a variety in recreation possibilities making the area as a whole even more attractive for tourists.

The municipality of Westvoorne and the neighbouring municipalities Brielle and Hellevoetsluis are important stakeholders, since the beach provides a recreational boost to the island of Voorne. All municipalities have their main interest in increasing local welfare and enhancement of economical growth. Beach recreation plays not only a role in boosting tourism, but it is also of vital importance when it comes to the quality of life in the region. Quality of life is not only favouring tourist but also the inhabitants in the region. People are living in or moving to the area because it provides a lot of special and high valued services which can mostly be correlated to the coastal area (L. van der Pol, personal communication, July 7, 2019). With this quality of life comes a new additional stakeholder, the Port of Rotterdam has the interest to provide a sustainable living area for its employees. Therefore, the port is also favouring the increase of quality of life. The attractiveness of the beach plays an important role in this development. Especially given the fact that the beach is rewarded with internationally acknowledged quality marks: 'QualitiyCoast Gold' and the 'Blue flag award'

Blue flag award

The beach of Voorne is placed in the Top 10 of the cleanest beaches in Europe and is awarded the QualityCoast Gold Award and the Blue flag award. The QualityCoast award is an international quality mark for sustainable coastal municipalities. The iconic Blue flag is one of the world's most recognised voluntary eco-labels awarded to beaches, marinas, and sustainable boating tourism operators. It is annually handed out to the most clean and environmentally recognized beaches, by taking swimming quality and beach services into account.

Waterway

Next to the function recreation, the function of the waterway *Slijkgat* has a high economical value. The waterway provides shipping access between the North Sea and the Haringvliet. The port of Stellendam is one of the biggest fishing ports in the Netherlands and is of vital importance for the town Stellendam. The waterway in the study area provides access to this port. Since the port offers industrial and recreational (sailing) activities, the municipality of Goeree-overflakkee has an interest in the development of the study area. By guarantying the availability of the Slijkgat the availability of the port is ensured, enhancing the potential of economic growth of Goeree-overflakkee.

The port of Stellendam also provides sailing access between the North Sea and the Haringvliet. The lock of Goeree enables ships and vessels to sail from the Haringvliet to the North Sea, making the Slijkgat important for the connection of ports in the Haringvliet with the North Sea. Because the Slijkgat provides this possibility the development of the waterway and thus the development of the study area is of great interest to the port municipality Goeree-Overflakkee but also for municipalities with ports lying inside the Haringvliet such as Hellevoetsluis.

After the construction of the Maasvlakte an arrangement was made with the Port of Rotterdam to guarantee the depth of the Slijkgat at 5.5 meters. The Port of Rotterdam compensates for the cost of the dredging activities which are needed to ensure this depth. With this obligation, the port of Rotterdam also has an economic interest in the study area based on the waterway.

3.3.3 Ecology

The study area is located in the area where the rivers discharge into the sea, meaning a transition zone between fresh and saline water. The inter-tidal system of shoals and creeks in combination with the salinity gradient provides a great possibility for multiple flora and fauna species to flourish. The dynamic area contains functions that can be associated with the interest of ecology. The area is part of the Voordelta which is defined as a Natura2000 area. Within the area two sites are defined as Natura2000, 1) Slikken van Voorne and 2) the Hinderplaat as shown in Figure 2.11 in Section 2.4.1.

Nature preservation is defined as maintaining the state of nature which is originally defined by nature organisations in the Natura2000 management plan. Meaning that a change in the area -whether this is imposed by human interventions or is only the result of natural development- should be brought back to its 'original' state. Hence, the distorted natural state should be adjusted to the degree that the area is reshaped back to its natural state as described in the Natura2000 management plans.

Moreover in Delta en Royal HaskoningDHV (2016) it can be found that an increase in seals is observed in the area since the shoals in the study area are assigned as resting areas of seals. Next to providing a resting place for seals, the shoals provide resting and foraging areas of different species of birds. By assigning these areas, recreation areas got limited by the boundaries of the resting areas. When looking at the function of flora in the study area it follows from Heldt et al. (2016) that a trend has been observed in the growth of vegetation in the dunes. This is to a certain degree the consequence of a decrease of salt spray. Hence, the reduction of wave energy (Section 2.4) influences the preservation of nature areas and as a result the maintenance strategies of nature preservation parties. From this it can be deduced that nature parties most probably are interested in a coastal evolution that maintains the current natural situation as prescribed in the natura2000 management plan. However, in contrast to maintaining the current situation, new developments can potentially be beneficial in terms of area enrichment; e.g.potentially attracting new species or by extending the current potential of nature.

The main stakeholders related to nature management in the area are the Province of South-Holland, water authority 'Hollandse Delta', and the nature parties 'Zuid-Hollands Landschap' and 'Natuur Monumenten'. Furthermore, the nature preservation area in the Voordelta is the result of compensation measures of the Maasvlakte 2 construction. Therefore, the Port of Rotterdam has a great interest in ecology as well. The province is responsible for the management plans of the Nature2000 area, whereas other parties have their responsibility to maintain and develop the nature areas. Zuid-Hollands Landschap ensures the protection and maintenance of nature areas and monuments. They also provide resources for volunteers who share and actively participate in maintenance and up-keeping of the same areas and objects of interest. Natuurmonumenten is an organization that preserves cultural heritage, valuable landscapes, and nature areas. Their main

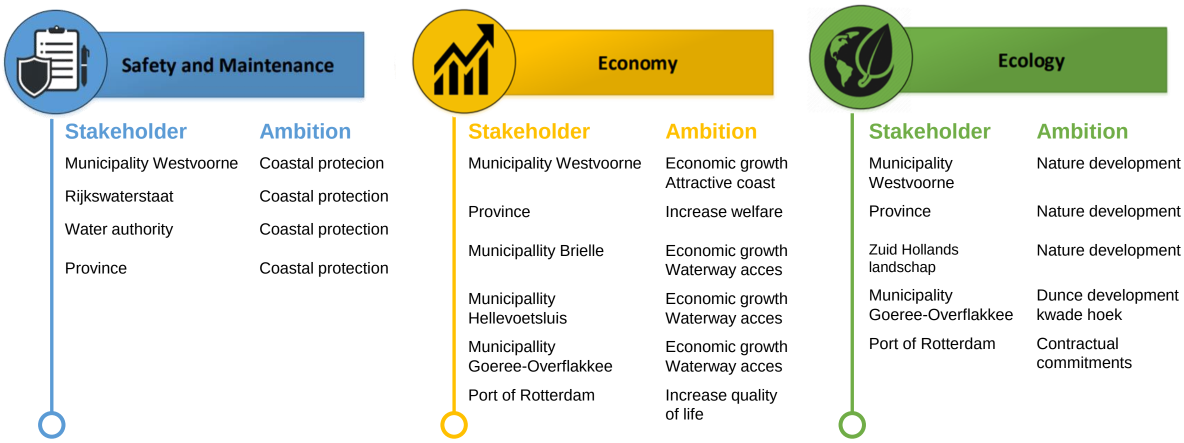


Fig. 3.4.: Stakeholder interests linked to the main interest.

focus in the study area are the Natura2000 areas. As stated in Section 2.4 active maintenance is needed to maintain and preserve the dune landscape in the nature2000 areas.

3.3.4 Summary

Multiple parties have varying interest which can be linked to the main interests derived in Section 3.3. Whether it is because of economical, ecological, or safety and maintenance reasons. These interests are important because they define the potential preferred coastal development for each of the parties involved. By understanding the interests of each stakeholder a combined vision for coastal management may be found. When the interests of the main stakeholders are listed, a wide range can be observed. Figure 3.4 gives a short overview of the various interests of the essential stakeholders. The various interests of stakeholders are related to one of the three main interests.

One should realize that Figure 3.4 only gives an overview of the most essential stakeholders and only summarizes their foremost interest related to the defined three main interests. There are far more stakeholders and parties having interests in the study area and common ground may be found in less pronounced interests. Interest such as economic growth can potentially be achieved by multiple means and with the help of a collaboration of a broad range of stakeholders. However, for this research, the stakeholder input remains to this predefined level.

3.4 Quantification of the effects

Section 3.3 showed the large variety of stakeholders active in a relatively small coastal area. Formulation of a common vision of these stakeholders may Therefore, be a challenge. When it comes to stakeholder management in this area it is of vital importance to link the interests of the beach with the physical coastal characteristics. The identification and assessment of coastal characteristics is critical in analysing the impact of coastal evolution on stakeholders interests.

When understanding how physical coastal characteristics are perceived as desired or not, value can be given to certain physical processes. To be able to compare the state of the coast to the interests of the stakeholders, the interest related to the beach needs to be assessed quantitatively. However, interests cannot always be obtained directly from coastal data or numerical models. Therefore, the interests need to be linked to indicators that can be measured from in-situ data or from numerical models. To do so the framework discussed in Section 3.2 will be used.

In the research conducted by Stam et al. (2002), four main functions can be defined and labeled as important when assessing the coast of Voorne. Stam et al. (2002) linked the functions area with quantifiable indicators, referred to as management parameters in his research. The functions and indicators used in this research are largely based on the management parameters described by Stam et al. (2002). Table 3.1 gives an overview of the defined management parameters as defined by Stam et al. (2002).

Tab. 3.1.: Functions and management parameters study area, from Stam et al. (2002).

Functions	Indicators
1. Flood protection and safety	• Sediment budget • MKL (*Momentane Kustlijn*) • Dune volume
2. Recreation	• Average beach width • Suspended matter in watercolumn • Current velocity • Wave exposure
3. Shipping	• Access channel depth
4. Ecology	• Location shoals and channels • Wave exposure

It is important to understand that interests related to human perception are for the most part subjective. Therefore, in this research, the linkage between interests and indicators is based on the general view of the stakeholders involved. The framework described in Section 3.2 helps to link the interests of the coastal area to the physical and, quantifiable (model) indicators. As described in Van Zanten (2016) it is important to make a distinction between the potential of sub-functions and the actual use of the sub-functions to be described. The actual use of a sub-function is determined by many other factors that are physical, ecological, and social in nature; e.g. factors like weather, infrastructure, and societal influences. Due to this wide range of dependencies the assessment of the functions can become rather complex. To simplify this complexity, the assessment of the functions is based on predefined physical coastal indicators only. Moreover, by assessing the sub-functions only the potential of a sub-function is investigated. Meaning that a value increase or decrease of a function is likely to occur when the potential of a sub-function increases or decreases. Hence, the change in indicators specifies the increase or decrease of the potential of a sub-function.

The interests derived in Section 3.3 are used to construct a framework according to the framework described in Section 3.2. These interests are divided over multiple functions and sub-functions, mainly based on the research conducted by Stam et al. (2002) and using the approach described in Van Zanten (2016). The sub-functions are linked to quantifiable indicators by combining the researches of Stam et al. (2002) and Van Zanten (2016), together with the output of the stakeholder sessions conducted by Bergsma (2018). The researches combined form the base of the framework depicted in Figure 3.5.

Using the framework depicted in Figure 3.5, stakeholder interests can be assessed using the quantified potential of sub-functions. In doing so it is assumed that the interests of stakeholders over time does not change. The (sub)functions and their associated indicators are further discussed in the following sections.

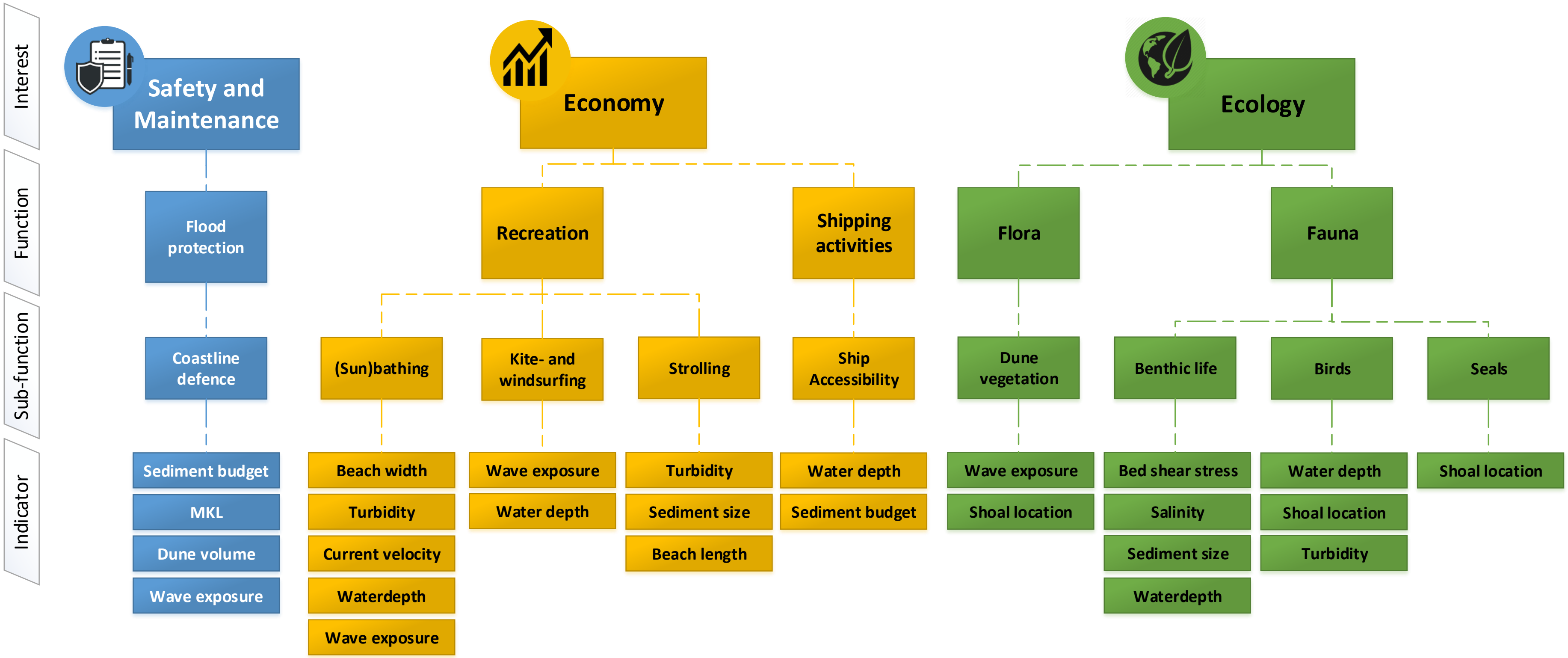


Fig. 3.5.: Value framework (After Stam et al. (2002) and Van Zanten (2016)).

3.4.1 Flood protection

Related to the value of safety and maintenance is the function flood protection. This includes the sub-function coastline defences. To quantify the coastline defence system several indicators are used. First the sediment budget, relating coastline defences to the sediment balance of the defined coastal area. Sediment budget is a measure to identify the magnitude of sediment sources and sinks. When the sediment budget increases, little to no safety issues are expected since dune growth is enhanced. With a sediment deficit measures need to be taken to ensure the adequate level of protection.

Another way to measure the increase or decrease of flood protection is the position of the current coastline position, the MKL (*Momentane Kustlijn*; Position of the current coastline). Rijkswaterstaat measures the position of the MKL yearly and compares it with the BKL (*Basis Kustlijn*; Base Coastline position). This indicator gives insight into the sand volume present in the nearshore area (beach/foreshore). The sand volume influences the wave impact and thus the associated dune erosion during critical conditions. The MKL itself is not directly related to the protection capacity of a dune area, but it can be used as an indicator for flood protection. When the MKL retreats and crosses the BKL, sand nourishments are needed to restore the MKL and ensure the desired level of flood protection.

Another important indicator to assess flood protection is dune volume. By assessing the volume of the dunes and the quantity of erosion during extreme conditions. The dunes need to have sufficient volume to protect the hinterland from flooding. The magnitude of the sediment source predominantly determines dune growth at the Dutch central coast De Vries (2007). Thus, in the absence of a direct dune assessment the sediment budget can be used to evaluate the indicator dune volume.

3.4.2 Recreation

The value of the interest economy is largely linked to the recreation function which the study area provides. This function is mainly provided by the coast and by the beach of Rockanje in particular. The potential for recreation on the beach of Voorne depends for a large part on the state and attractiveness of the beach. The attractiveness of a beach can be determined using multiple factors. According to McLachlan et al. (2013) the factors that determine the potential of an area for recreation are:

- Factors relating to the physical environment, e.g. waves, sediment size and tide;
- Ecological factors, e.g. macrobenthic diversity and abundance;
- Socio-economic factors, e.g. available infrastructure to support the recreation activity, the safety and health status of the beach and the socio-economic environment

.

Thus, to assess the full potential of recreation function, social and economic factors need to be assessed in order to quantify the recreational function of a beach. This research however, focuses on the physical development of the coast. Service, social and economic factors, such as beach restaurants, infrastructure, lifeguards, etc. are assumed to be independent of physical coastal development and are, therefore, not considered in this research. Indicators linked to recreation are related to the physical and natural coastal elements of the beach. As described before, the potential of a sub-functions is assessed based on the impact of physical processes Halbmeijer (2019). In other words, how does the change in a physical coastal process influence the potential of recreation.

This research defines three different recreation sub-functions: 1) (sun)bathing, 2) strolling, and 3) kitesurfing. These types are also used for the sand engine case by Van Zanten (2016). The first and main sub-function of the function recreation is (sun)bathing. This sub-function is defined as people going to the beach for swimming and sunbathing purposes. Sunbathing is related to the indicators describing beach characteristics and swimming is related to indicators describing water characteristics. The second sub-function related to recreation is strolling; walking along the beach. Strolling is assessed by evaluating the indicators describing the beach characteristics such as beach length and sediment size. The last sub-function related to recreation is kite- and windsurfing. This activity is assessed by evaluating the indicators describing the water conditions in the more sheltered part of the study area the *Slikken of Voorne* and in the south-east part of the channel Rak van Scheelhoek; the areas which are currently used as a surf spot. Further elaboration on the sub-functions is given below.

(Sun)bathing

The main sub-function associated with the function of recreation is (sun)bathing. As stated before this sub-function is defined as people going to the beach for swimming and sunbathing purposes. This function is assessed by looking into the beach potential and the (bathing)water potential. The area where the sub-function (sun)bathing applies is indicated in Figure 3.6. The indicators associated are: 1) beach width, 2) turbidity 3) current velocity, 4) water depth, and 5) wave height. The beach width is assessed by the dry beach area. Turbidity is used to assess swim water potential. The indicators turbidity is determined by the residence time and the residual current. Residence time describes the time a suspended particle stays in a predefined control volume. The residual current indicates the potential of mud deposition along the beach. Another indicator to assess (sun)bathing is the current velocity near the beach. This indicator is important to assess swimmer safety. The indicators water depth and wave exposure can also be related to swimmer potential. For the actual attractiveness of the beach, other factors, such as a clean beach, sunny weather, accessibility, facilities, and attractive nature areas (habitat provision) are also important. However as stated before, this research is focused on the physical indicators that can be assessed with real physical data or derived from a model. The indicators for the potential of (sun)bathing are further discussed in the following paragraphs.

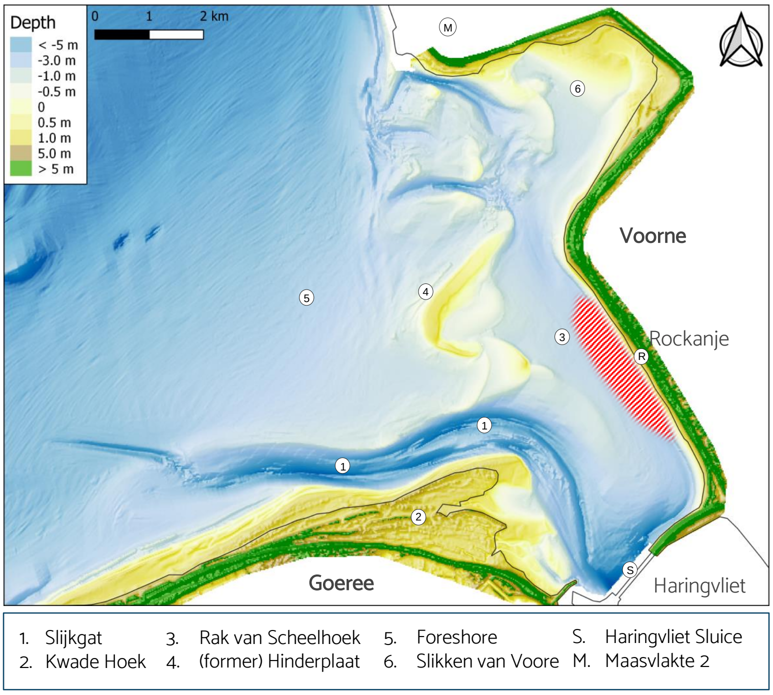


Fig. 3.6.: (Sun)bathing area (marked in red).

Beach width

The potential for sunbathing is defined by the area physically available for people visiting the beach and to use for sunbathing and swimming. To accommodate the recreation potential of the beach, the beach is assessed by its width. The width is defined as the dry part of the beach, between the dune foot and the high water line. The ideal beach width for beach recreation is limited. As described in Broer (2011), it turns out that the first 40 meters measured from the waterline are intensively used for recreation. During extreme crowded days this width increases towards 50 meters (Jiménez et al., 2007). However, in the area beyond these 50 meters, the beach remains (almost) empty. This phenomenon can be explained by understanding the behaviour of people. People prefer to limit their walking distance to the waterline and to citing the fact that sand can get very hot on sunny days, making walking across the beach uncomfortable. In the research conducted by Broer (2011) the beach of Rockanje is characterised as an intensive used beach. Here the minimum beach width in this research is estimated at 60 meters. Not only the minimum beach is relevant, but also the maximum beach width. A beach width that is too large can counteract the recreation potential. From observation by Jiménez et al. (2007) it becomes clear that landward of the crowded zone near the waterline the beach is almost empty. So, for beach visitors the walking distance to the waterline can become too large, consequently decreasing the probability that visitors will take the effort (McLachlan et al., 2013). Therefore, a maximum beach width is determined. According to Van Zanten (2016) this width is 200 meters. To conclude, the minimum beach width to account for (sun)bathing potential is 60 meters and the maximum width is determined at 200 meters.

Turbidity
Turbidity in the water column can be used to evaluate the potential of the (bathing)water. In this research the turbidity is assessed using the residence time of a predefined control volume along the beach and the residual current. Residence time indicates how long certain particles stay in the predefined control volume. Residual current is used to assess the transport potential of fine particles, and especially mud. Transport of small (mud) particles can be associated with a residual current as described in Appendix A.2. Bathing water potential is defined as the level of turbidity in the water column wherein swimmers still enjoy bathing. Naturally clear water is preferred over turbid water when it comes to bathing. By evaluating the indicator residence time -using a predefined control volume- the potential turbidity changes can be estimated. Combining this with the potential of small particle accumulation, the potential of bathing water and also the silt potential on the beach can be assessed.

Current velocity
Safety is an important characteristic of beach management. All beaches present some hazards to the public by breaking waves, rip currents, or variable water depth McLachlan et al. (2013). Current velocity is the main important indicator for swimmer safety. Not only the magnitude important, but also the direction of the flow can be of great influence. A significant current in the top of the water column is far more dangerous than a current directed landward. An important aspect to account for is the likelihood of swimmers present during extreme conditions. During storm conditions, the chance of high offshore directed velocity currents is higher than during calm conditions, but it is less likely that people will be present in the water (Radermacher, 2018). When assessing current velocities one has to be aware of these extreme conditions. Swimmer safety will be quantified by the flow velocities in the bathing area during average calm conditions. An average swimmer can withstand a current of approximately half a meter per second (Halbmeijer, 2019). Current velocities higher than this magnitude are considered unsafe for beach visitors, decreasing the potential of the sub-function (sun)bathing.

Water depth At most locations water depth is not considered an issue when assessing bathing potential. However, since a general trend of accretion has been observed, this indicator might get of importance for the study area. According to the *federation internationale de natation amatuer* (FINA) which is the international body governing competitive swimming, a minimum water depth of 1.2m is necessary for swimming competitions. Although not completely similar this value is assumed to be a representative starting point. Since great depths are a characteristic of the coast it is assumed that this minimum required depth is a little higher. Therefore, the minimum required depth is determined to be at least 1.5 meters for people to enjoy swimming in.

Wave Exposure
One of the variables distinguishing beaches from eachother is the mean significant wave height. One of the first of any study to include wave height, likely to be important for tourism climatology studies on beaches was conducted by Zhang and X. H. Wang (2013). Zhang and X. H. Wang (2013) found that slight wave heights, up to 1.25 m, are most favoured by beach users, but

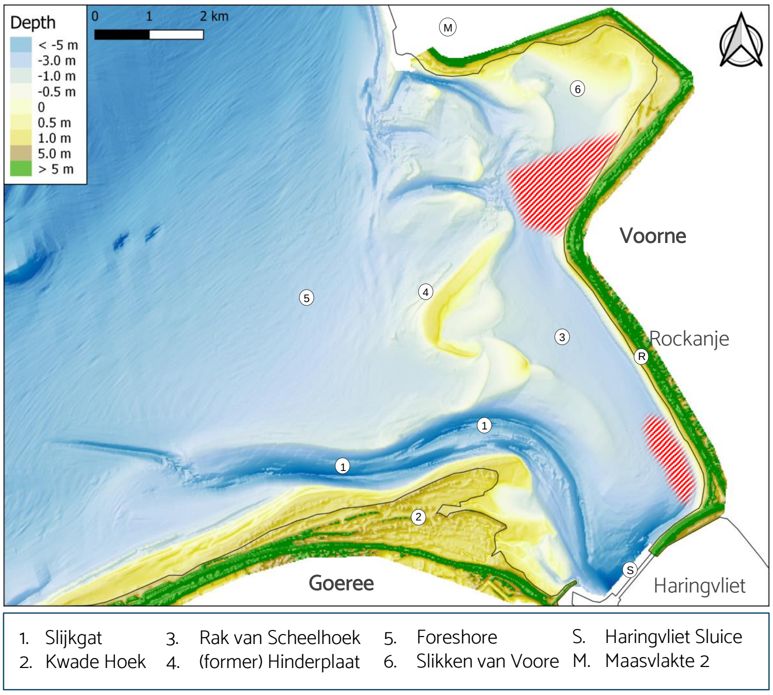


Fig. 3.7.: Surfing area (marked in red).

moderate wave heights, from 1.25 to 2.5 m, are also acceptable. Higher waves are considered to be undesirable for people visiting the beach and thus decreasing the potential of the sub-function (sun)bathing.

Strolling

The strolling potential of the beach is predominantly determined by the dry beach width and beach length. The beach length along the waterline determines the length of the route that is attractive and available for strolling. To account for the strolling potential the length and width of the beach can be assessed. Thereupon sediment size can be used as an indicator to assess the strolling potential of a beach. The accumulation of silt (fine particle) at low energetic areas might cause a nuisance because of the smell of dirt (Van Zanten, 2016). The increase of dirt can become problematic in terms of recreational attractiveness. Problems related to accretion of silt have been found in Ouddorp, south-east of Voorne (Broer, 2011). Here the increase of dirt caused an increase in smell and the accumulation of silt caused safety issues due to the formation of quicksand, making the beach less attractive for recreational use. In addition, when the sediment size is too small, a nuisance to visitors is likely to occur because of blowing and drifting of sand particles by the wind (Van Zanten, 2016). In this research the potential of strolling is assessed by looking into the indicator turbidity which is associated with silt accumulation. The indicators turbidity is assessed based on the residence time and the residual current. A longer residence time has the potential of an increase in fine sediment and the growth of algae, decreasing the positive potential of strolling. The residual current indicates the potential and magnitude of potential fine sediment transport.

Kite- and windsurfing

There are only a few sheltered locations available at the Dutch sea coast where kitesurfing is possible. One of the areas along the Dutch coast is near the slikken of Voorne in the study area the area south-east of the study area as shown in Figure 3.7. The potential of kitesurfing can be quantified with the indicator distinguishing those kitesurf spots; the degree of wave exposure. The conditions need to be mild enough for kite surfing to be possible. Only waves which are smaller than 1 meter are considered to be suitable for kitesurfing. In addition, a minimum depth of 0.5 meters is required to prevent hindrance from local formed shoals (Halbmeijer, 2019). To assess the potential of kite- and windsurfing the amount of wave exposure is evaluated in the areas which are assigned as kite- and windsurf areas and with a minimum depth of 0.5 meters.

3.4.3 Shipping activities

The waterway Slijkgat provides shipping access between the North Sea and the Haringvliet. To use this function the depth of 5.5 meters has to be guaranteed for shipping purposes. The indicator to quantify this function is the water depth in the channel. However, the channel is regularly dredged, maintaining this depth at a constant level. Therefore, when assessing change over time, the dredging quantities need to be considered. This is done using the sediment budget. An increase in accretion means more dredging quantities and thus higher cost. This reduces the potential of the shipping function the area provides. An additional side note must be placed that different stages in time to be considered, had different requirements regarding minimum water depths in the access channel. However, since the impact is relatively quantified, it is assumed that this difference has no significant impact.

3.4.4 Flora

As stated in Section 2.4 the area, which is part of the Voordelta, has great ecological value. The shoals and marshes of the study area and their associated characteristics enable many flora and fauna species to flourish. In this research the interest ecology is divided over the functions flora and fauna. Although the definition of functions and sub-functions can be regarded as arbitrary in terms of ecology, the base of the framework is that functions and sub-functions give value to the interests. The functions giving value to ecology can be seen as the functioning of different species. The functioning of fauna is in this research divided over multiple sub-functions which describes the potential functioning of species.

In this research, the potential value of species is only elaborated shortly. To assess the value of ecology in more depth, a more profound investigation of the functions and indicators is needed. Moreover, the functions associated in this research are only determined by the physical processes acting in the area. One has to keep in mind that species have a great dependency on each other too. For example, birds locate themselves close to foraging areas and certain vegetation species can only flourish without the presence of other species. However, to give a proof of concept of

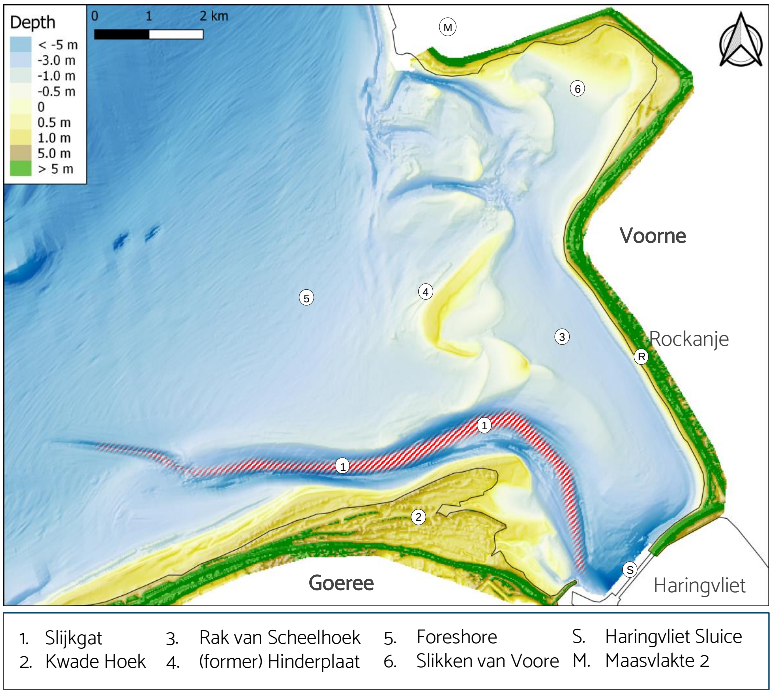


Fig. 3.8.: Access channel Slijkgat (marked in red).

the framework, the assumptions made are representative for the first approach. In this research, the potential value of species is only assessed based on physical coastal processes.

As described in Section 2.4.1 one of the mechanisms preserving the natura2000 areas is saltspray. To determine the amount of saltspray at the coast and especially the dune area, two indicators can be used; 1) the magnitude of the emission and 2) the location of the emission. The magnitude is linked to the dissipation energy of breaking waves. How bigger the dissipation of breaking, how bigger the emission of aerosols (water particles including salt concentrations). The location of wave energy dissipation is important when looking at the travel distance of an aerosol. If this distance is larger than 500m the yearly amount of saltspray will be small since the aerosols can not reach the coast (Steijn et al., 2001). When this distance is smaller the likelihood of particles reaching the coast will be larger and consequently the saltspray potential will increase. Therefore, it is important to assess the positioning and dimensions of the shoals and channels in the area. Higher shoals mean more dissipation, but depending on the location the distance the traveling distance aerosols varies.

3.4.5 Fauna

According to Bouma et al. (2005), the spatial variation of species is mainly determined by the local physical characteristics. The presence and ecological potential of shoals and marshes is mainly determined by the tidal movement, the associated erosion and accretion processes and the inundation period of the areas (LNV, 2008). Bouma et al. (2005) associated the most important physical processes with the following indicators: 1) bed shear stress, 2) salinity gradient, 3) sediment composition and 4) bottom depth.

The level of hydrodynamics is an important indicator in the development of species. The result of waves and currents (induced by tide, waves, and wind) induce bed shear stresses. When bed shear stresses are high enough, sediment can be set into motion. This directly influences the habitat of benthos living in, on, or near the bed. In Van Zanten (2016) it is stated that benthos species need to bury themselves in the bed or find another way to stay in a fixed position. Moreover, according to Herman et al. (2002) the accumulation of sufficient mud at the sediment surface leads to enhanced protection of the benthic microalgae.

Next to bed shear stresses, salinity is a dominant indicator when assessing benthos. It determines whether a certain species are able to grow there in the first place, based on its physiological conditions. According to Bouma et al. (2005) high biodiversity of benthos can be found in freshwater, a minimum diversity in brackish water, and a high diversity in saline water. When looking at sediment composition, the optimum range of the grain diameter may vary per species and can change during the life phases Van Zanten (2016). However, multiple studies have shown a negative correlation between mean grain size and the richness of species Lastra et al. (2006). Hence, smaller grain size enhances the biodiversity of benthic life. Finally the indicator bottom depth can be related to inundation periods, stratification, and light penetration in the photic zone (Van Zanten, 2016). According to Bouma et al. (2005) the depth of the study area is small enough to enable for light penetration and thus this factor can be taken out of consideration. Stratification is influenced by the varying depth, since saline water has a higher density than freshwater and thus seeks to lower areas. The inundation period on shoals determines mainly which type of species is present in that area and does not indicate necessarily a high or low biodiversity.

The potential of birds is quantified with three indicators; 1) water depth, 2) shoal location and 3) turbidity. The potential of seals is only quantified with the indicator shoal location. Note that the potential of both species is dependent on more indicators as described before. Meteorological, ecological and human factors like climate, other species development, and unaccounted human nuisance etc. are assumed to be independent from physical coastal development and are, therefore, not considered in this research. Next to quantification by indicators, a link can be made between sub-functions when considering food provision, e.g the potential of birds is enhanced by the increased benthic life population. This research however, focuses on the physical development of the coast.

The first indicator to assess the potential of birds is the water depth. The water depth can be related to the inundation period of the shoal. A wide range of birds hunts on the surface layers of the water column or uses the intertidal areas to forage on. With a larger intertidal area, the possibility increases for the birds to forage on (Bouma et al., 2005). Moreover, the shoals provide areas for birds to rest. Not only the depth and related inundation period is here of importance, but also the location. If the shoals merge with land, predators are able to enter the shoal, endangering the habitat of the birds. This latter criterion not only holds for birds, but also for seals. For both species it is important to keep a sufficient distance from human activities. To ensure this, the shoals need to be situated at least 500m from human activities (Delta en Royal HaskoningDHV, 2016). By disrupting this distance, the potential of birds and seals decreases. The last indicator determining the potential of birds is the residence time. If the water column is turbid, eyesight hunters have trouble finding food. Therefore, an increase in turbidity can be associated with a decrease in bird potential.

Model Set-up

4

4.1 Model introduction

To assess the hydrodynamic and morphodynamic processes, the process-based numerical model Delft3D will be used. In this chapter the model set-up and the derivation of the boundary conditions is discussed. Two modules of Delft3D are used in this research: Delft3D-FLOW and Delft3D-WAVE. Delft3D-FLOW is the central module that provides the hydrodynamic basis for all the other modules of Delft3D. In this module flow, transport and bottom changes are computed simultaneously. Delft3D-WAVE is used to simulate the evolution of wind-generated waves in coastal waters. It computes wave generation by wind, wave propagation, non-linear wave-wave interactions and wave energy dissipation for a given topography, wind field, water level and current field (De Vries, 2007). In the following sections an elaboration is given on the model modules, settings and input data.

4.2 Grid and bathymetry

The model consist of two grids; a flow grid and a wave grid. The computational grids form the base of the numerical scheme on which the model equations are computed. The size of the computational grids must fulfil two contradicting requirements: on the one hand the extent of the computational grid must be large enough to prevent boundary disturbances entering the area of interest, on the other hand the computational time is preferred to be as small as possible. Another requirement is to have the resolution of the grid fine enough to obtain a better resolution in the area of interest. The preferred resolution is defined as the scale in which the processes of interest can be simulated in sufficient detail.

For this research the computational FLOW grid to be used is derived from the *Kuststrook* model of Rijkswaterstaat as shown in Figure 4.1. The kuststrook model contains the bathymetry of the Dutch coast of 2014 and is driven by astronomical tidal components. Additionally river discharge is schematized in the model by a constant discharge implemented at the river boundaries of the flow grid. The new grid is choosen in such way that it includes all the relevant areas of interest. With this the boundaries are choosen in such way that the grid did not become too large, but also not to small to provide boundary disturbances influencing the area of interest. The boundary conditions for the new smaller FLOW domain are derived by nesting the new FLOW domain in the kuststrook domain, this is further elaborated in Section 4.3.

Bathymetry
The depth contours of the model domain are based on the vaklodingen dataset which covers the whole Voordelta, including the mouth of the Haringvliet, up to about 10 kilometer offshore. As

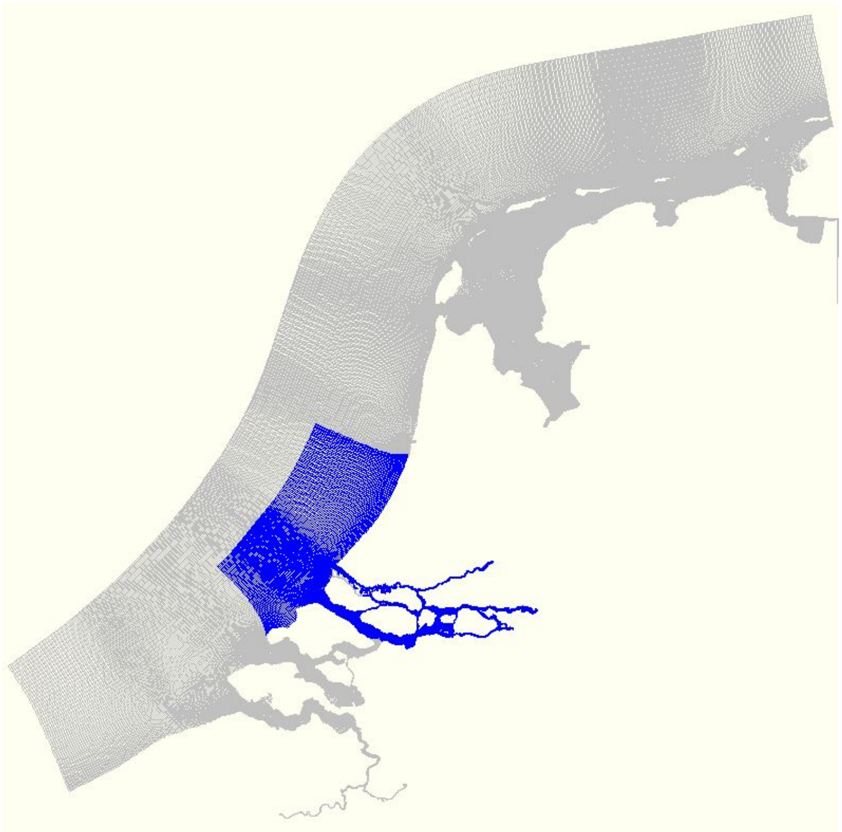


Fig. 4.1.: Flow grid Voorne (blue) nested in the *kuststrook* flowgrid (grey).

described in Colina Alonso (2018) the vakloding dataset has an accuracy that has been estimated between 0.11m and 0.40m **Wiegman2005**. As shown in Figure 4.2 the vaklodingen bathymetry data does not cover the whole model area. To complement the incomplete vaklodingen data set, bathymetry data from the 2014 kuststrook model is used to fill up the missing data. It is assumed that bathymetrical differences offshore between the years have negligible impact on the processes nearshore in the study area. Furthermore bathymetrical changes over time in inland waterbodies are assumed to be significantly small since due to the closure of the Haringvliet hydrodynamic influence on the bathymetry has dropped significantly. The complementing of lacking data with the data from 2014 will therefore have little to no influence on the processes playing a role in the study area. Concluding it can be assumed that by implementing bathymetrical data of 2014 on the data lacking areas of the model domain, will not affect the assessment of the relative difference of processes between years.

4.2.1 3D layers

With the newly implemented Haringvliet policy the doors of the sluices will be opened on regular basis, enabling saline water to flow into the estuary. The interaction between the saline sea water and the freshwater from the rivers causes density driven currents. To account for baroclinic effects due to the density differences over the water column a 3 dimensional approach is needed. By running the model in 3D mode a better insight can be obtained in the vertical exchange

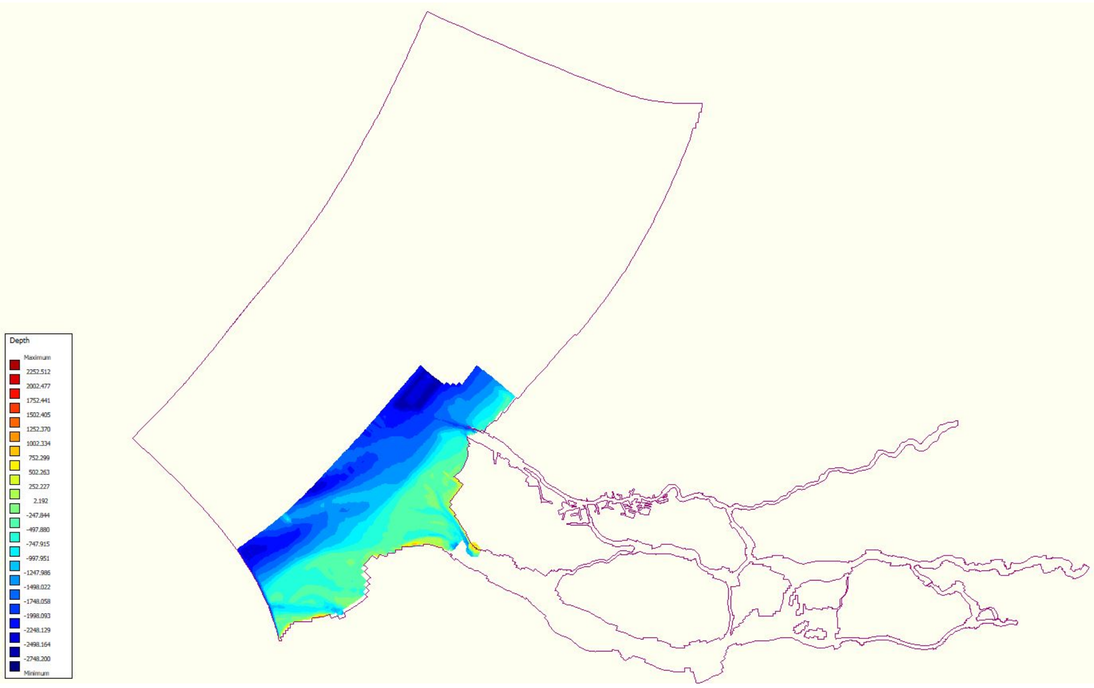


Fig. 4.2.: Covered area Vaklodingen dataset (example 1964).

processes. In Delft3D vertical layers can be implemented by two different layer approaches; using sigma layers or using Z-layers shown in Figure 4.3. Sigma layers are equally distributed over the vertical based on a predefined ratio. Hence, the number of control volumes in the vertical direction is constant over the entire computational domain. The relative layer thickness does not depend on the horizontal coordinates x and y. This allows for more resolution in the zones of interest which can be near the bed to account for more detail regarding sediment transport. However for steep bottom slopes combined with vertical stratification, sigma grids can introduce numerical problems. Due to truncation errors artificial vertical mixing and artificial flow may occur. Since bottom changes are not significantly in the study area, this will not be an issue. In the Z-layer approach the bottom (and free surface) is usually not a co-ordinate line and is represented as a staircase (zig-zag boundary). The number of grid cells in the vertical varies for each horizontal grid point. This layer can be used in cases of steep bed topography and in salinity intrusion models.

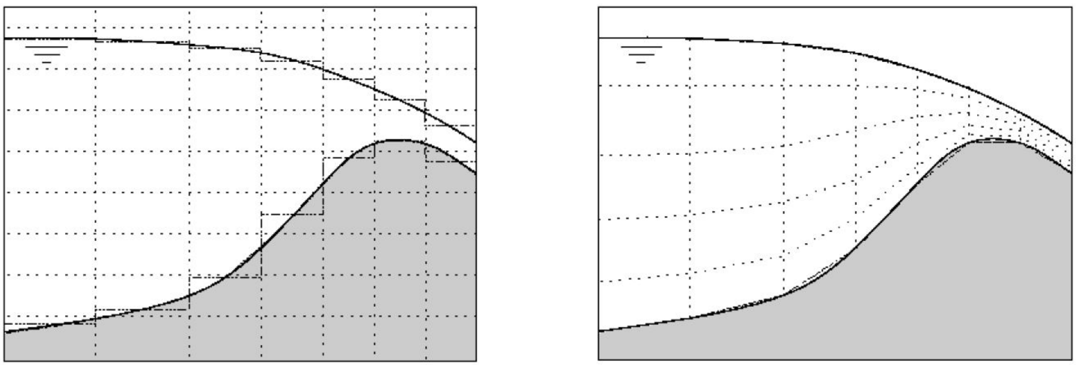


Fig. 4.3.: Z- and Sigma layers, From Bijvelds (2001).

To account for 3 dimensional process the model is computed with 9 sigma layers. Each of these layers is defined based on an percentage of the depth, decreasing in thickness ratio towards the bottom. The bottom layer is the smallest layer and accounts for the last 4% of the water depth.

4.2.2 Courant number

The Courant number is important in descretized models when solving the equations on the numerical scheme. The Courant number is based on the concept of domain of dependence. In the model the full numerical domain of dependence must contain the physical domain of dependence. Meaning that the information computed at a specific position during a specific time step, depends on the former time and spatial step on the line of characteristics, for example the imaginary line on which a wave propagates. The Courant number expresses that the distance that any information travels during a timestep length within the grid must be lower than the distance between grid elements. In other words, information from a given grid cell or mesh element must propagate only within itself or to its immediate neighbors. The Courant number displays the ratio between the propagation speed, the time step and the local domain scales. This criterion can be assessed using the Courant-Friedrechs-Lewy number (CFL), defined by:

$$CFL = \frac{\Delta t\sqrt{gH}}{\Delta x, \Delta y} \tag{4.1}$$

Where Δt is the time step (in seconds), g is the acceleration of gravity, H is the (total) water depth, and $\Delta x, \Delta y$ is a characteristic value (in most cases the minimal value of the grid spacing in either direction).

According to Deltares (2014a) the upper bound for the Courant number of $4\sqrt{2}$ occurs in the most critical situation, namely in case of a narrow channel (width of few grid sizes) that makes an angle of 45 degrees with the computational grid. Generally, the Courant number should not exceed a value of ten, but for problems with rather small variations in both space and time the Courant number can be taken substantially larger (Deltares, 2014a). So satisfy this condition the computational timestep of the model needed to be reduced to 6 second to ensure the stability of the model.

4.3 Boundary conditions

Boundary conditions have to be schematized to solve the non-linear shallow water equations in the FLOW-module model. The boundary conditions represent the processes out of the model domain which have there influence on the processes inside the model domain. To account for the representation of the outer world, all open boundaries in the model need to be described accurately. In this section the model boundary conditions for both the FLOW-module and the WAVE- module are discussed.

4.3.1 FLOW-module

The FLOW-module may be forced using water levels, currents, water level gradients, discharges (total or per grid cell) and the Riemann invariant which is a combination of water level and current (Deltares, 2014a). The hydrodynamic forcing can be prescribed using harmonic or astronomical components or as time-series. For water level forcing the boundary conditions can also be specified in terms of QH-relations (Deltares, 2014a). Seaside boundary conditions for the FLOW-module of this research are derived from the *Kuststrook* model. The tide of the kuststrook model is schematized using harmonic tide components which are forced upon the boundaries. The resulting hydrodynamic conditions are checked and validated. The sea boundary conditions of the FLOW-module are prescribed with boundary support points. These points divide a whole boundary into several segments. By nesting the flow-domain of the new, smaller model into the larger kuststrook model the boundary conditions at these points can be derived. The obtained signal is imposed on the support points as time-series describing Riemann invariants; water level and current velocity. These type of boundary condition are applied on every boundary at the seaside. The points that lie in between two derived support points are calculated by linear interpolation of the forcing at both ends. The Riemann boundaries derived from the kuststrook model describe the spring and neap tidal cycle of the tide along the dutch coast.

On the river boundaries time depended discharges are implemented. These boundaries are defined over several grid cells on which a total discharge is prescribed through the cross-section. A further elaboration on river boundaries is given in Section 4.5.

4.3.2 WAVE-module

One of the governing processes inducing morphological changes found in literature is wave forcing. Colina Alonso (2018) found that waves play an import role in the development of Haringvliet delta. Therefore, in addition to the derived flow module of the kuststrook module, the implementation of a wave grid into the model is required.

To simulate waves accurately it is preferred to orientate the grid in the wave propagation direction. The wave grid is chosen in such way that offshore generated waves can propagate towards the coast by following the grid direction. However, since the area of interest, the coast, is triangle shaped, with the tip of Voorne as the top of the triangle, the wave grids needs to be oriented in the direction of different approach angles. Moreover in former studies it was found that the island of Goeree in the south and the Maasvlakte2 in the north are acting as sources of sediment. Since waves have a significant contribution in sediment transport (e.g. stirring up sediment and inducing currents) it is vital for the accuracy of the model to include these processes. Because of this, the grid is preferably curved towards the coast from northern direction and western direction as much as possible, accounting for the island of Goeree and the Maasvlakte2. However a curved grid increases the risk of growth of disturbances. These disturbances are caused by orthogonality issues that can rise discretization errors. Meaning that the information between cells cannot propagate correctly to the next cell. Therefore the grid is specified in such way that both the island of Goeree and the Maasvlakte2 are still considered with a more rectangular curved grid. This is done by defining the coast parallel boundaries as curved boundaries and the lateral boundaries as straight lines (see Figure 4.4).

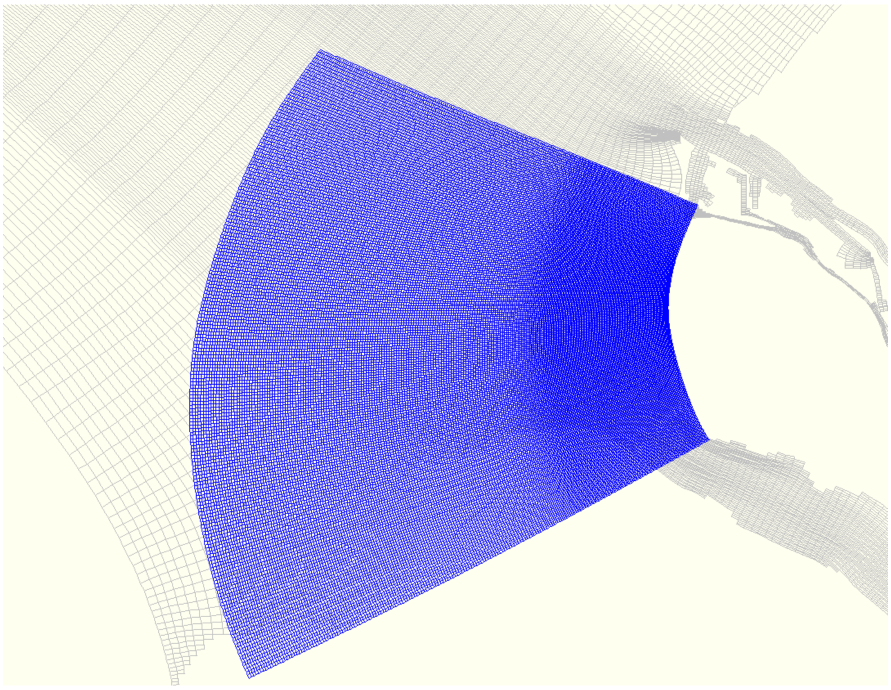


Fig. 4.4.: Wave grid.

To simulate the evolution of random, short-crested wind-generated waves Delft3D uses the model SWAN to compute the evolution of random, short-crested waves in the model domain with deep, intermediate and shallow water and ambient currents. To use SWAN Delft3d has a separated WAVE-module which is linked to the FLOW- module using online coupling. SWAN computes the wave climate by means of iterative simulations of wave conditions. During every iteration it is checked if the required level of accuracy is met, i.e 98%. These accuracy checks are necessary to verify whether the wave conditions forced at the borders of the model are sufficiently spread out over the study area. Within this study the maximum number of iterations in SWAN is set to 15. This means that a maximum of 15 iterations is used to let the wave field develop within the required level of accuracy (De Vries, 2007).

To simulate the waves the WAVE-module requires incident wave conditions at the 'water water' boundaries of the model domain. There are two ways to define the boundary conditions for the WAVE-module. A choice can be made between implementing a wave climate based on orientation or by defining a segment on which the wave conditions are defined. In this research the choice has been made to define the boundaries based on the orientation of the incoming wave climate. This wave climate will be discussed in the next section.

4.4 Wave climate

For the analysis of the governing offshore wind and wave conditions, data from the Europlatform (3.28řE, 52.00řN) has been collected. At this station data is measured every 3 hours. The data has been analysed to assess the directional variations of the wind and wave conditions. The wind conditions at the Europlatform are assumed to be representative for the offshore conditions at the project area.

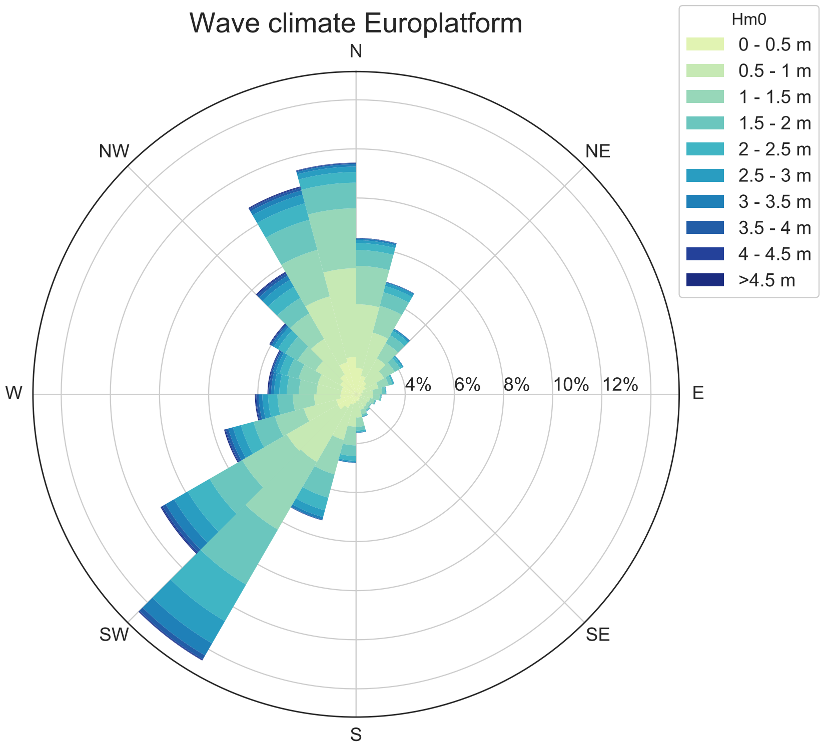


Fig. 4.5.: Wave Climate Europlatform.

The data available at the Europlatform for the wave schematisation consisted of two datasets. One dataset of the period 1979-2001 and one dataset of 2006-2012. However the difference between the two is that the dataset of 1997-2001 contains wind data, where the 2006-2012 data set only contains wave data form station Goeree. In Colina Alonso (2018) it was concluded that using one of the wave climates is sufficient. Because it is important to link wave data to wind data for representing a wave climate the choice has been made to use the 1979-2001 dataset only.

As shown in Figure 4.5 the main wave direction is from the south-east direction. Also the wave coming from the north have a significant contribution in the wave climate. This will be discussed further in the next section.

4.4.1 Wave climate reduction

Hydrodynamic studies and especially morphological studies often come with long simulation times due to the time scales of the relevant processes. To prevent simulations to take up too much time, it is necessary to reduce the wave climate to a schematized wave climate consisting of a relatively smaller set of wave conditions. The criterion of wave climate reduction is that the yearly-averaged sediment transport computed with the reduced set of waves is comparable with the yearly-averaged transport computed with the entire set of wave conditions. For this research a set of five wind conditions is used to schematize the yearly wave climate.

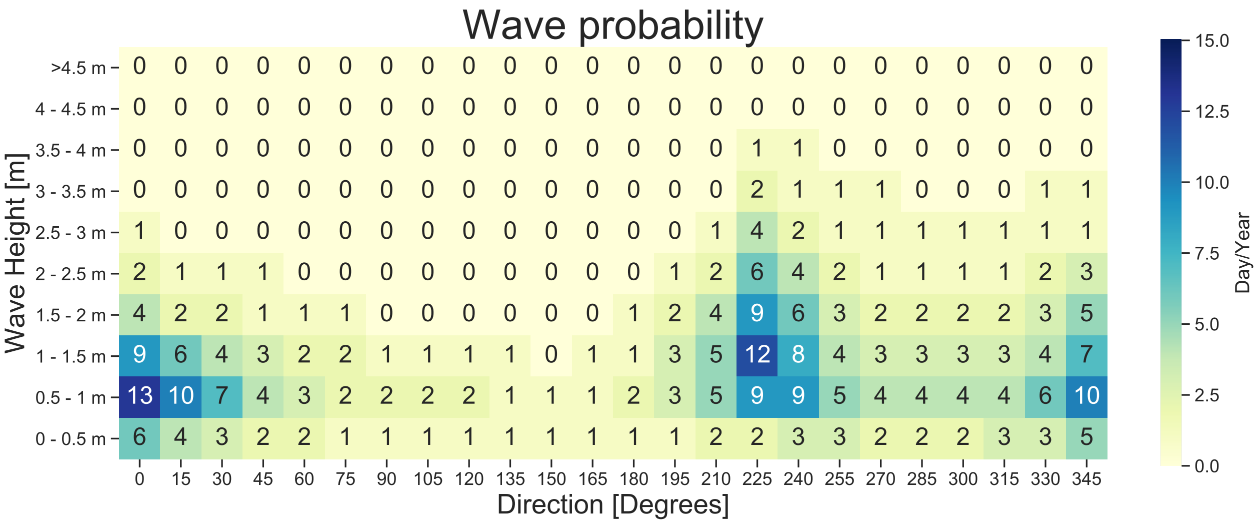


Fig. 4.6.: Wave probability.

Multiple methods have been developed to derive a representative reduced wave climate. In this research the *manual wave class selection* is used. To reduce the wave climate, first the waves are categorised into wave height and wave direction classes (bins). In this research the wave height classes are defined with a limit of 0.5 m per class. Wave heights smaller than 0.25 m and larger than 4.75 m are not considered. To categorize the wave direction classes a directional spreading of 15 degrees is applied per direction class. Waves coming from the South-East (45-195řN) are not accounted for, the waves coming from this side will not have enough time to develop and are assumed to be not representative for the development of the coast of Voorne. This is confirmed by the research done by Colina Alonso (2018), she found that he Haringvliet outer delta is hardly influenced by wave conditions from east-north-eastern to southern directions.

To account for the influence of these conditions to the morphological development, each binned wave condition is scaled by the probability of occurrence and with impact on the sediment transport. Extreme conditions with large wave heights will occur less often but will lead to relative large sediment transports. To account for the relative impact of waves, the wave heights are proportionally weighted using S $\sim H_s^{2.5}$ which is a rough approximation of the CERC formula for longshore transport. This approximation is frequently used as rough estimate of the morphological impact of waves (**Lesser09**).

$$H_{s,rep} = \left(\frac{\sum P(H_{s,bin}, Dir_{bin}) H_{s,bin}^{2.5}}{\sum P(H_{s,bin}, Dir_{bin}} \right)^{0.4} \tag{4.2}$$

Resulting in a weighted contribution of each wave condition to the sediment transport. The corresponding peak period, wave direction, wind speed and wind direction are then computed for each bin, resulting in a reduced wave climate that is represented by 4 wave conditions with associated wind conditions as shown in Table 4.1. The wave conditions are divided based on their wave direction. Note that wind is incorporated in the wave conditions. Therefore, when spoken about wave conditions, both wave and wind forcing are meant. A division is made at 315N (-45N) which is To account for the waves coming from the south/east which are not able to develop into significant waves that influence the morphology an extra wave climate is added which incorporates the wind coming from the south - eastern direction but does not included waves. In this climate only the wind and tide play a role.

Tab. 4.1.: Reduced wave climate.

Wave climate	H_s [m]	T_p [s]	Dir_{waves} [degrees]	U_{wind} [m/s]	Dir_{wind} [degrees]	p [-]	M_c [$m^{2.5}$]
Climate 0	-	-	-	4.01	160.75	0.28	13.68
Climate 1	1.49	4.25	245.78	8.29	275.30	0.43	32.34
Climate 2	3.38	5.80	248.71	15.42	256.53	0.04	24.09
Climate 3	1.17	4.52	358.45	5.79	5.74	0.35	14.35
Climate 4	3.01	5.86	348.59	12.13	346.04	0.04	15.53

The schematized conditions are applied as boundary conditions of the SWAN wave model, from which the model computes the nearshore wave conditions as described in Section 4.4. By schematizing the wave conditions following assumptions are made:

- The wind speed is uniform across the entire grid;
- The wave conditions are uniform along the grid perimeter;
- The wave conditions are described by a JONSWAP spectrum with a spectral peakeness (Y) of 3.3.

An overview of the model settings is given in Appendix A

[]insert Scatter plot between Hsig/peak period etc to show correlation for the purpose of wave climate conditions]

4.5 River discharges

High river discharge can cause large morphological changes. According to De Vries, 2007 the large water level gradients induced by extreme river discharge caused remarkable changes in the development of the shoal Hinderplaat. Representative river discharges need to implemented at the model boundaries to simulate river influence correctly.

Discharge boundaries are schematized as a discharge over a cross-sectional segment of a river branch. This segment is based on the river input cross-sections defined in the kuststrook model. By accounting for bed topography the flow input is divided over the cells and columns. The implemented river discharges are derived from data measured at Lobith and Eijsden which is provided by Rijkswaterstaat (Rijkswaterstaat, 2019). This dataset is used to derive the minimum, maximum and average discharge of the river branches as shown in Table 4.2. Discharges forced on the Waal and Lek boundaries are derived from the obtained data at Lobith. The imposed discharges are divided based on regulation ratios. The derived discharge per branch is then extrapolated and imposed on the river side boundaries of the model domain. The discharge of the Maas is directly derived from the data measured at Eijsden. Resulting in discharge time series, forcing a variable discharge into the rivers based on actual data.

Tab. 4.2.: Discharge rivers Rhine and Meuse.

	Rhine	Lek	Waal	Maas
Minimum $[m^3/s]$	500	150	300	100
Maximum $[m^3/s]$	2800	500	2300	900
Average $[m^3/s]$	1600	350	400	400

4.6 Haringvliet sluice

The Haringvliet sluice is an important construction to manage river runoff and thus of significant importance to the study area. The doors of the sluice can be opened and closed in order to regulate the outflow of river discharge flowing to the Nieuwe Waterweg or through the Haringvliet estuary.

In the scenarios where the Haringvliet sluice is applicable (1970 - 2018), the sluice is represented by dry cells. To represent the discharge through the sluice, the operations discharge function in Delft3D is used. Inlet points are defined on the east side of the sluice and the outlet points are defined on the outer, west side of the sluice. The discharge forced upon the sluice is derived from the research conducted by (Steijn et al., 2001). The simulations will be performed with the normal discharge scenario with a mean discharge of 897 m^3/s is equally divided over the defined discharge points. This discharge has an occurrence percentages of 51% compared to other discharge regime and depends on the water level at sea. When the water level is 0.5m below mean sea level, the operation is active and water is subtracted from the estuary and discharged into the study area. When the water level at sea is higher, no discharge is implemented.

Modelling Methodology

5

5.1 Introduction

This research aims to investigate the main processes in the area and their influence on the different coastal characteristics. To do so the impact of the processes related to beach attractiveness indicators is assessed and compared between different stages in time. In this way the imposed interventions can be linked to the beach parameters defined in Chapter 3 and a possible trend in the development of the indicators can be observed. The framework indicators as described in Chapter 3 and depicted in Figure 3.5 will therefore be assessed over time.

To do so the delft3d model as described in Chapter 4 is used. To assess the development in time multiple stages are elected based on historical interventions. These stages form the base of the model study which is carried out to assess the development of the framework indicators. Every stage in time is therefore regarded as a scenario. The only variable between the scenarios is the bathymetry. The bathymetry for each stage is retrieved from the vaklodingen data set as described in Chapter 4. The overall wave climate is represented by 4 wave climates as described in Section 4.3.2. Each condition is run for a duration of a spring-neap tide (14 days). The wave conditions; wave height, direction and wind forcing are imposed as constants during the whole simulation. Based on these scenarios with wave conditions the development of the framework indicators is assessed.

In this chapter the methodology of the indicator assessment is elaborated. First the different stages in time are discussed and placed on the timeline based on historical interventions. Thereafter the assessment method of the indicators wave exposure and residence time is discussed.

5.2 Simulation scenarios

Using historical bathymetry data, different depth profiles are retrieved and implemented in the model. To assess the different parameters all other model figurations are kept constant. Hence, in the scenarios there is no change in boundary conditions or other processes such as wave and wind climate. By assessing the processes during multiple years the influence of the different parameters can be mapped. The stages to be assessed are based on the historical interventions. These are the biggest changes and are assumed to have the largest impact on the processes playing a role in the area. The stages as shown in Table 5.1 are used for this research.

The stages in time are not based on a constant time frame between stages but they are based on the (human) interventions near the study area.

Tab. 5.1.: Assessment years and related humen interventions .

Years	Interventions
1964	Before closure Haringvliet
1972	After closure Haringvliet
1980	After construction of Maasvlakte 1
2004	Before construction of Maasvlakte 2
2018	Most recent bathymetry after construction of Maasvlakte 2

5.3 Bathymetry development

To get a first insight into how the area develops, the development of the bathymetry, and the movement of the shoal are analysed. From this it becomes clear what changes in the area have occurred. By understanding the change and development of the area, the change in processes can be clarified and linked to the changes over time.

The bathymetrical changes in the area are assessed using the data obtained from the vaklodingen data set. This set contains the measured bathymetry data of multiple stages in time. This data is processed in Gis to get a representative overview of the bathymetry of each stage in time. Using these mapped overviews the development of bathymetry can be analysed.

In Section 6.3.2 the depth profile over a transect is plotted. The transects are positioned in the way they represent the incoming wave development the best (described in Section 5.4.3). Although the transects are not defined considering the bathymetrical changes, they give nonetheless a representative image of the bottom development. The method of positioning these transects is described in Section 6.3.2.

5.4 Wave exposure

As described by Colina Alonso, 2018 waves play an important role in the development of the bathymetry in the study area. In general when waves propagate from offshore to nearshore they start to 'feel' the bottom when depth decreases. When propagating into shallow areas waves become more depth dependent. Hence, bathymetrical changes will induce a change in wave propagation. The stages in time are subject to significant bathymetrical changes, therefore changes in wave exposure are also expected. In this section the set-up of the wave assessment will be discussed. In the next chapter the analysis of wave exposure and its influence on the different indicators will be elaborated.

5.4.1 Wave climate

Each scenario, based on the bathymetry of the stage in time, is exposed to a constant wave climate (derived in Section 4.3.2). The wave climate used to assess wave exposure is established by merging the obtained data of the four wave climate simulations for each stage in time. The four reduced wave conditions are condensed back into one climate. The contribution of each of the separated wave conditions to the merged wave climate is determined using the earlier discussed Equation (4.2) in Section 4.4.

5.4.2 Wave propagation

When assessing the wave propagation characteristics all the wave conditions as described in Section 4.4 are considered. First the mean direction of the four combined wave conditions is considered (combining WC1, WC2, WC3 and WC4). This mean incoming wave propagation direction of this merged condition is from the North-West. Although this direction is according to the wave rose not representative for the study area, it gives a good representation of the combined impact of the derived wave climates.

Next to the merged wave climate, the wave conditions are divided over two main directions. Based on the wave rose Figure 4.5 these main directions are from the north and south-west. The two main directions south-west and North (WC1+WC2 and WC3+WC4, Section 4.4) are taken at high water level and scaled over their 'main' direction. Resulting in a condition coming in from the south-west (WC1+WC2) and one coming in from the north (WC3+WC4). By taking wave conditions from both directions a better understanding of the wave propagation behaviour can be obtained. In this way the dominant direction and influence on the study area can be examined.

5.4.3 Wave height

The change of bathymetry during stages in time will have an impact on wave exposure in the study area. To analyse the wave exposure between stages in time one has to realise that the area is dynamic. Therefore, comparing the wave height at one specific location between the stages in time will not yield a representative comparison. Due to bathymetrical changes, points can fall dry or do not represent the same relative spot on the beach anymore. *For example the point at mean water level, this point changes due to bathymetrical changes.*

To get consistency in the wave analysis, three transects are defined in the area at the same location for each stage in time. These transects are positioned in such a way that wave data is obtained in the most representative way during all stages. This is done by considering the incoming waves, the shore orientation and the area geometry of each stage in time.

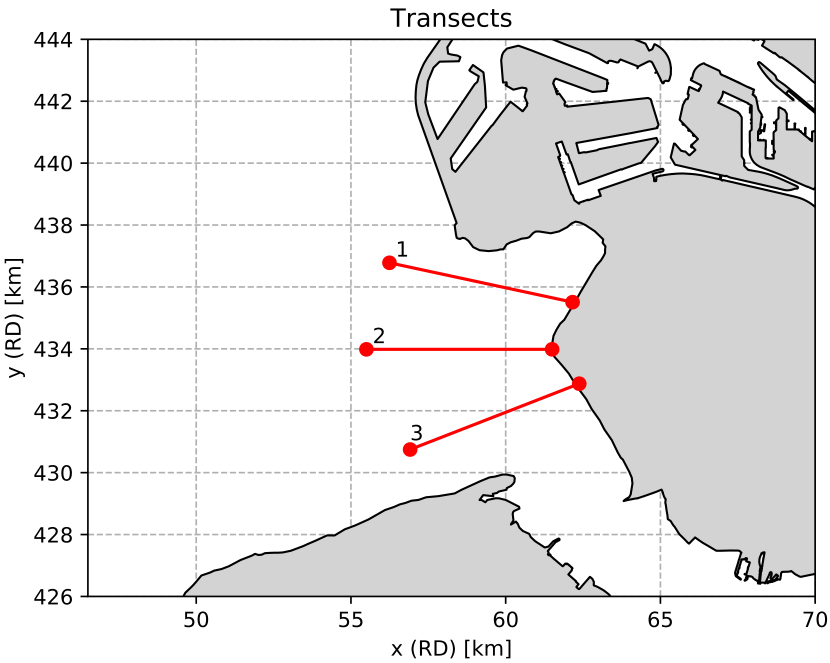


Fig. 5.1.: Wave measurement transects.

To consider the incoming waves the transect lines follow the line of the incoming waves. Under stationary conditions, in the absence of wave generation or dissipation, the energy propagation along the line of propagation keeps constant (Holthuijsen, 2010). This approach is in the ideal case the most convenient way to assess waves. However the shoals in the area affect the wave propagation significantly. The shoals cause and enhance refraction, diffraction, and wave breaking in the region. Moreover in the dynamic changing study area wave aspects will vary significantly between the stages in time, and thus the line of propagation is hard to find. It will, therefore, be even more difficult to compare wave exposure for every stage in time.

To ensure consistency, the transects are positioned in a straight line from a predefined point on the beach to a point further offshore beyond the shoals. Ideally the transects are placed shore normal. The orientation and location of the coast of interest is however not favourable for shore normal transect lines because of the geometry of the region. The coast of Voorne changes from an 'open' coast in 1964 to a more 'sheltered' coast in 2014. To account for this, the positioning of the transects is largely based on the land boundaries of this last stage, which are lying 'sheltered' due to MV2. As a result, the transects are placed under an angle which is a compromise between shore normal and the incoming wave direction as depicted in Figure 5.1.

In theory, the waves plotted over the distance along the transect can have various propagating directions. The same holds for the development direction of bottom topography. The depth profile is only plotted as a 2d profile over a transect, so 3d configurations are not taken into account. Despite these potential inconsistencies it is assumed that these transects give a good representation of the general wave development from a more offshore point to the shore. So based on these transect a representative image can be obtained of the wave exposure development of the years. This will be discussed in the next chapter.

5.5 Residual current and bed shear stress

Next to wave exposure, residual current and bed shear stress are assessed. The residual currents are calculated by averaging the Eulerian velocities over a full tidal cycle. To compare between different stages in time the tidal cycle is chosen in which the Haringvliet sluices discharge freshwater during low water (-0.5m NAP). During this tidal cycle a total amount of 4000 m3 is discharged in the study area.

This tidal cycle is also used to calculate the bed shear stresses in the study area as a result of hydraulic motion without wave forcing. Bed shear stresses are used to assess the likelihood of sediment motion. The 90th percentile is used to see if the water motion during one tide is large enough to induce incipient particle motion. The 90th percentile is used here to prevent the influence of outliers on the results. The color scale in the figures used is chosen in such a way that it can indicate particle motion. The magnitude of bed shear stress lower than the general shields threshold for incipient particle motion (0.3 N/m^2) is plotted from blue to white. In red the magnitude exceeding this limit is plotted.

To assess different sluice policies in the area, three different sluice policies are assessed: 1) With discharge, 2) Sluices closed and 3) Kierbesluit policy (partly opening of the gate). These different policies are assessed with the latest obtained bathymetry (2018) to ensure consistency. All variants are averaged during the same time period over 1 tide. The discharge variant is defined as a sluice discharge active during low water (<-0.5 NAP). In the sluices closed variant, the sluices are closed and no discharge is allowed through the sluices. In the last variant the sluices are partly opened by opening up the 2 layers on the sill of the sluice. Water is now able to flush in out of the estuary through this opened layers (40 cm).

Tab. 5.2.: Sluice policy variants.

Policies	Disharge policy	Closed	Kierbesluit
Waves	No	No	No
Discharge $[m^3]$	4000	-	-
Gate opening $[m]$	-	-	.40

5.6 Residence time

A relevant indicator for the characterisation of the hydrodynamic regime and subsequently for water quality is the residence time. The residence time is defined as length of the time required to evacuate water from the control volume and replace it with new water (Pierini et al., 2019). To assess the residence time the methodology proposed by Braunschweig et al. (2003) as described in Appendix A.3.2 is used. The methodology consist of defining a control volume and calculating the residence time for a potential set of tracers with a volume equal to the control volume. To do so the formula described in Appendix A.3.2 is used. The method is based on multiple boxes, but for this research the method is adopted to suit one control volume with corresponding water mass. The fraction of water mass relative to the initial volume f inside the box at each time step is calculated by the following expression:

$$f_{(t)} = f_{(t-1)} + \frac{V_{in(t)} f_{outside} - V_{out(t)} f_{(t-1)}}{V_{(0)}} \tag{5.1}$$

With $f_{(t)}$ being the fraction of tracers inside the control volume relative to the initial water mass. $f_{(t-1)}$ is the fraction of tracers on the previous time step and $f_(0)$ represents the fraction of tracers outside the control volume which is equal to zero. The fraction of tracers is influenced by the in and outgoing discharges of the control volume with $V_{in(t)}$ being incoming discharge per time step, $V_{out(t)}$ the outgoing volume per time step and $V_{(0)}$ the original volume of tracers contained by the predefined control volume. Since the tracer volume outside the control volume can be regarded as zero, the incoming discharge term V_{in} can be neglected. When $f_{(t)}$ equals zero, the original volume of water has been replaced by new freshwater. The resulting t can be regarded as the residence time of the water mass in the predefined control volume.

The control volumes to be assessed in the study area are one micro and one meso control volume. The micro control volume represents the volume near the coast and the meso control volume represents the whole volume of the mouth of the estuary depicted in Figure 5.2. The control volumes are based on the model grid orientation. The open boundaries can only be positioned over grid lines since measurement cross section are defined on these lines. This dictates the straight open boundary of the Meso volume.

The boundaries of the control volume are kept constant for each stage in time. However, the bathymetry changes over time, and the control volume changes with it. Hence, the size of the control volume during each stage in time changes too. For each year the size of the volume is arranged in Table 5.3 and depicted in Figure 5.3.

Tab. 5.3.: Size of the control volumes for each stage in time.

Stages	**1964**	**1972**	**1980**	**2004**	**2018**
Meso [m^3]	$3.25E^{+08}$	$2.90E^{+08}$	$2.41E^{+08}$	$1.90E^{+08}$	$1.72E^{+08}$
Micro [m^3]	$8.90E^{+06}$	$9.60E^{+06}$	$7.05E^{+06}$	$4.42E^{+06}$	$3.42E^{+06}$

As stated before the model results are based on the four different wave conditions. These four conditions are merged into one representative wave climate. The associated hydrodynamic char-

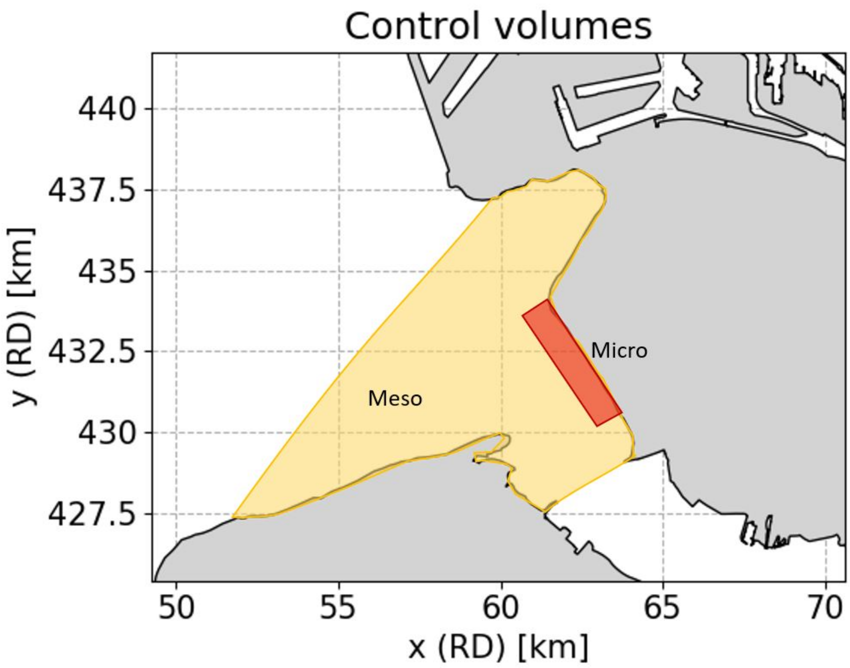
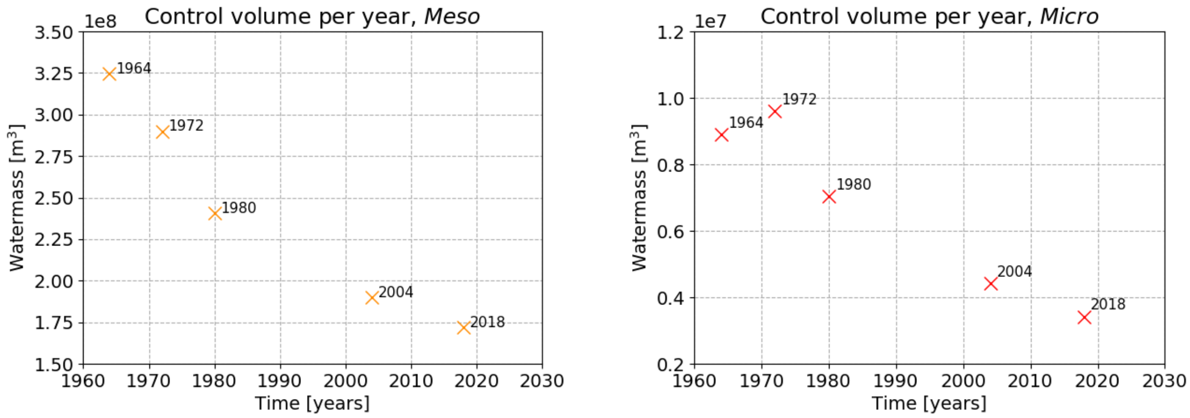


Fig. 5.2.: Predefined control volumes.

acteristics are scaled with it based on the probability of occurrence and form the base of the in and outgoing discharge of the control volume. Using the equation described before these difference are analysed to assess the change in residence time over the stages in time. It is important to notice that when assessing the residence time the analysis is based on the relative difference between the stages in time. As depicted in Figure 5.3 the size of control volume decreases over time.



(a) Meso volume. **(b)** Micro volume .

Fig. 5.3.: Change in size of the predefined control volumes over time.

5.7 Long term developments

To assess the long term development of the study area, a trend will be derived from bathymetrical changes over time. This trend will form the base on which a new bathymetry of the study area will be created. Using the trend in bathymetry development the most recent bathymetry is extrapolated in time to create this new bathymetry. By considering the sources and sinks of sediment the bandwidth of the meso development will be determined. The hydrodynamic processes such as waves and discharges will determine the bandwidth in which the bathymetry elements like shoals and channels will develop.

The newly created bathymetry will be used to assess the indicators as described in Section 3.4. the outcome of the future potential of the sub-functions will be compared to the trend over the years of the indicator potential change.

Analysis of the model results

6

6.1 Introduction

In this section the processes relevant to the indicators derived in Chapter 3 are assessed. This chapter aims to investigate the development of the main coastal processes in the area and relate them to the bathymetry changes in time. The stages in time which are used are discussed in Chapter 5. Since the aim of this research to give a proof of concept of the assessment of the framework, only the processes influencing the indicators are assessed.

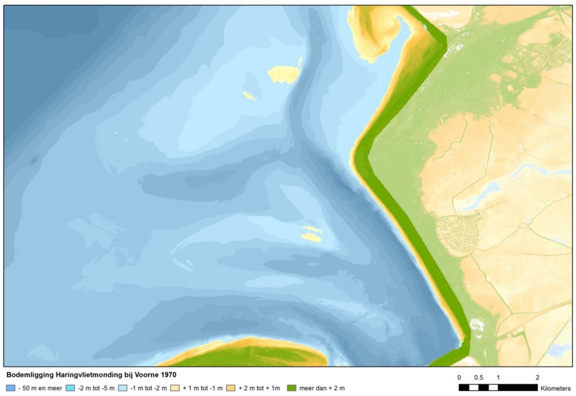
First the general trend in bathymetry development is discussed. After that the indicator wave exposure is discussed. The indicator wave exposure is associated with the wave propagation direction and the mean significant wave height. Wave exposure can be related to recreational activities as described in Chapter 3 but also to sediment transport. After that, the currents without wave influence are assessed to evaluate potential sediment transport. Insight is obtained int the residual flow, the bed shear stresses, and the residence time. Finally, the future development of the area is assessed based on the trends of physical coastal processes observed in the past.

6.2 Bathymetry development

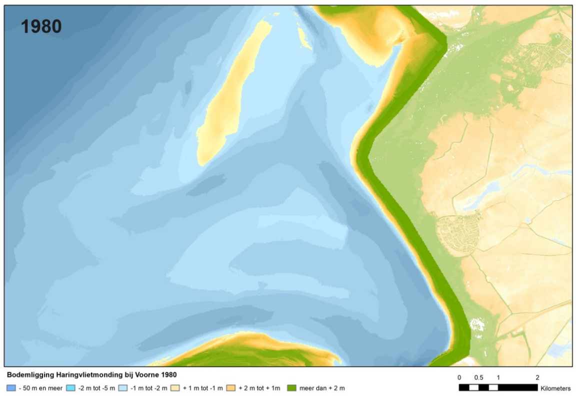
In this section an elaboration is given on the movement of the shoals. By mapping the bathymetry based on measured data sets, insight is obtained in the morphological development of the bottom topography of the (former) mouth of the Haringvliet estuary. Thereafter, the bathymetry development is assessed by analysing the bottom changes over a transect.

First in 1964 when the Haringvliet was connected to the sea, the estuary and its mouth were in dynamic equilibrium. The mouth showed typical characteristics of an ebb-tidal delta. The tidal driven currents created deep channels with sandy shoals in between. After closing the Brielse Maas in 1950, the flats of the mouth evolved into a single flat, the Westplaat. Meanwhile sedimentation took place in the channels Spek (1987). In the period between 1964 and 1970 the remaining part of the Brielse gat and the Haringvliet were both closed. The former tidal channels slowly started to fill up with sediment and mainly with mud. Especially in the area of the Brielse Gat significant sedimentation occurred Colina Alonso (2018)

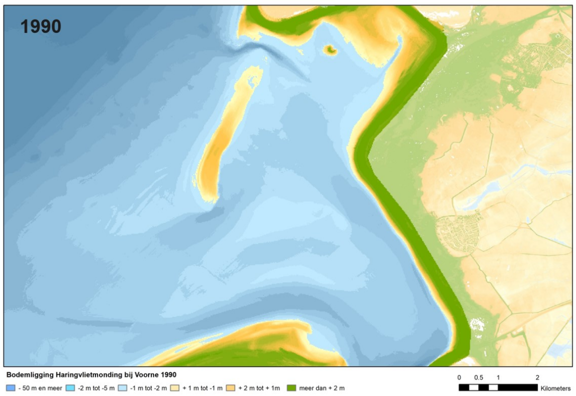
With the closure of the Haringvliet the estuary got cut off from the open sea and the influence of the tide on the system decreased significantly. The relative importance of waves became bigger, enhancing landward driven sediment transport. This caused erosion of the foreshore and growth of the sandy shoals in landward direction. Shoals propagated in a landward direction during which they merged with other shoals. While propagation towards the coast the merged shoal



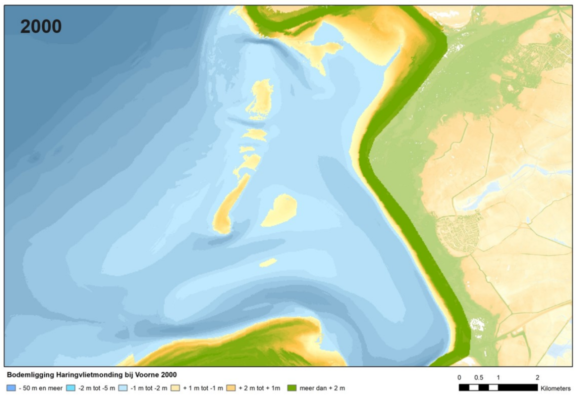
(a) Bathymetry 1970.



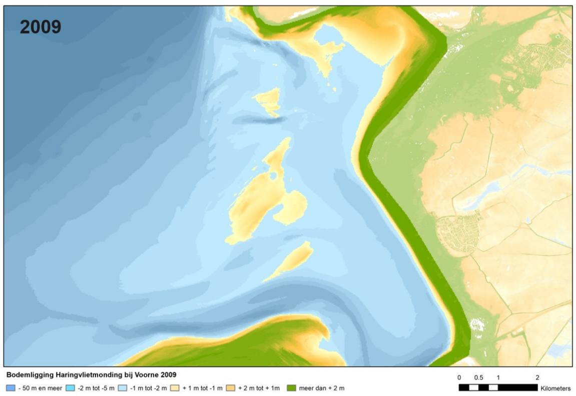
(b) Bathymetry 1980 .



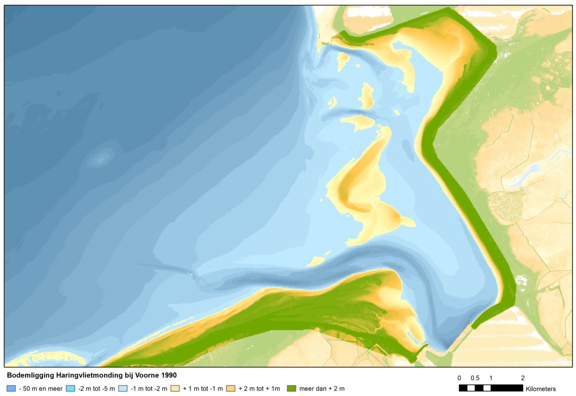
(c) Bathymetry 1990.



(d) Bathymetry 2000 .



(e) Bathymetry 2009.



(f) Bathymetry 2018.

Fig. 6.1.: Bathymetry development over time (after Cleveringa, 2018).

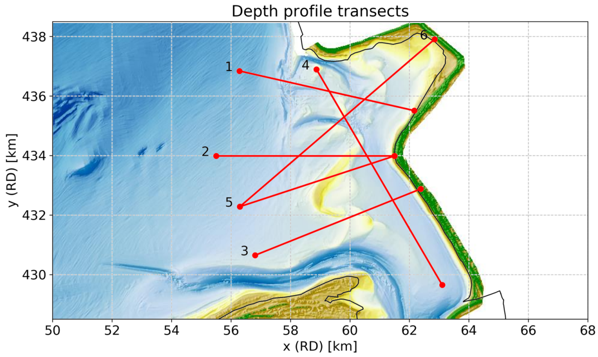
increased in height and length, but decreased in width. Meanwhile the decrease in current velocities in the study area caused the channels to silt up more. This accreting trend of the area can be observed in Figure 5.3, where the water mass of the control decreases. In 1995 the elongated sandbar breached in the north, creating the channel Gat van de Deur through the shoal. This slowly transformed the Hinderplaat into a new dynamic system with several small inlets Colina Alonso, 2018. From that stage on the Hinderplaat is no longer a distinct bar, but it has spread out to the east forming a tidal-flat-like area Elias and Spek (2014).

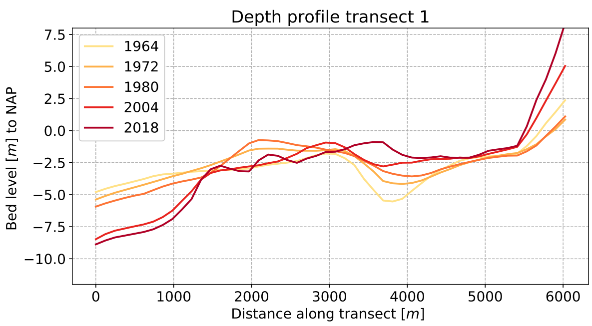
The bottom changes are plotted against a distance along a transect to obtain better insight in the development over time. As described by Elias and Spek (2014), shoals spreading out as a tidal-flat like area can be observed in Figure 6.2e. The area at a distance of 3000m along the transect has accreted significantly in time and the shoal has spread out over a large part of the transect. From Figure 6.2b it can be observed that the foreshore indeed becomes steeper and that the shoal migrates towards the coast of Voorne while increasing in height. This distinct shoal migration is also observed along transects 1 and 3. From Figures 6.2b, 6.2c and 6.2e at a distance of 5000 m along the transect and from Figure 6.2d almost the whole transect, it can be derived that the channel Rak van Scheelhoek silts up over time. However, the speed at which this channel accretes, decreases. What the bathymetry figures already indicated can be confirmed by the figures showing the bed level development over a transect. The foreshore becomes steeper and shoals migrate further towards the coast while growing in height. The area behind the shoals slowly silts up. The channels in the north -between the Slufter and the shoals- are relatively dynamic and depend therefore mostly on extreme events as described by Colina Alonso (2018).

6.3 Wave exposure

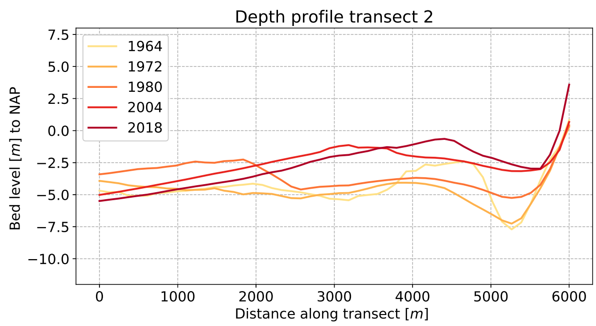
From the previous section it becomes clear that waves have a significant influence on the development of the area. Waves propagating from offshore to the nearshore start to 'feel' the bottom when depth decreases. When propagating further towards the coast waves start to break, mainly on the shoals. By breaking of the waves, wave energy dissipates inducing sediment transport which can cause bathymetrical change. When propagating into shallow areas waves become more depth dependent. Hence, bathymetrical changes will induce a change in wave propagation as well.

The stages in time are subject to significant bathymetrical changes, these changes have their influence on the wave exposure in the study area. In Section 5.4 the assessment method of wave exposure is discussed. In this section the analysis of the wave exposure and its influence on the different indicators will be elaborated. This is done by assessing the development of the propagating behaviour of the waves from offshore to near shore. After that the exposure of the waves on the coast is analysed by assessing the mean significant wave height in time over multiple transects.

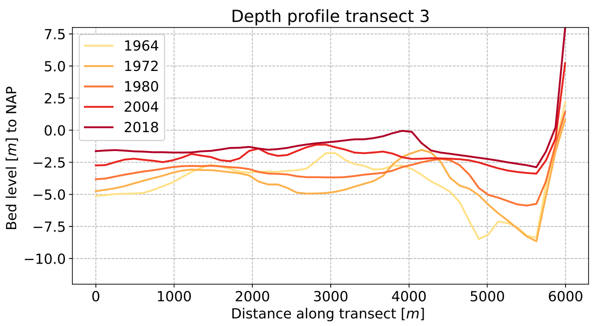




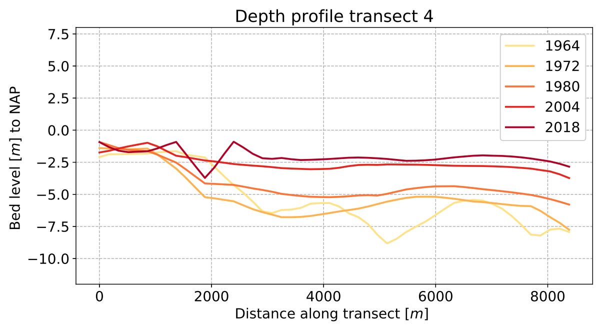
(a) Transect 1.



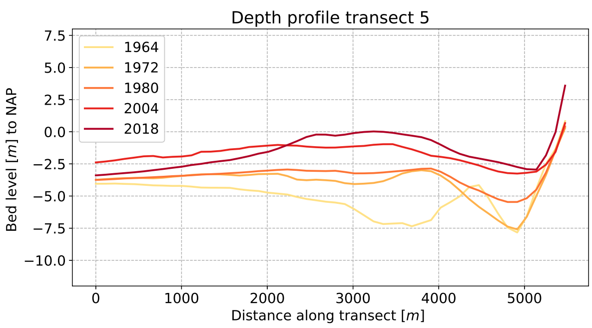
(b) Transect 2 .



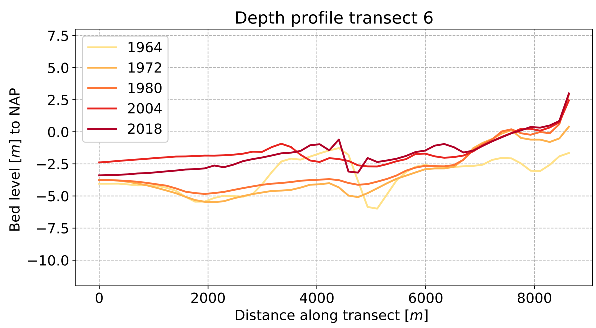
(c) Transect 3.



(d) Transect 4.



(e) Transect 5.



(f) Transect 6.

Fig. 6.2.: Cross-sectional evolution of the study area for 1964-2018, based on the vaklodingen dataset.

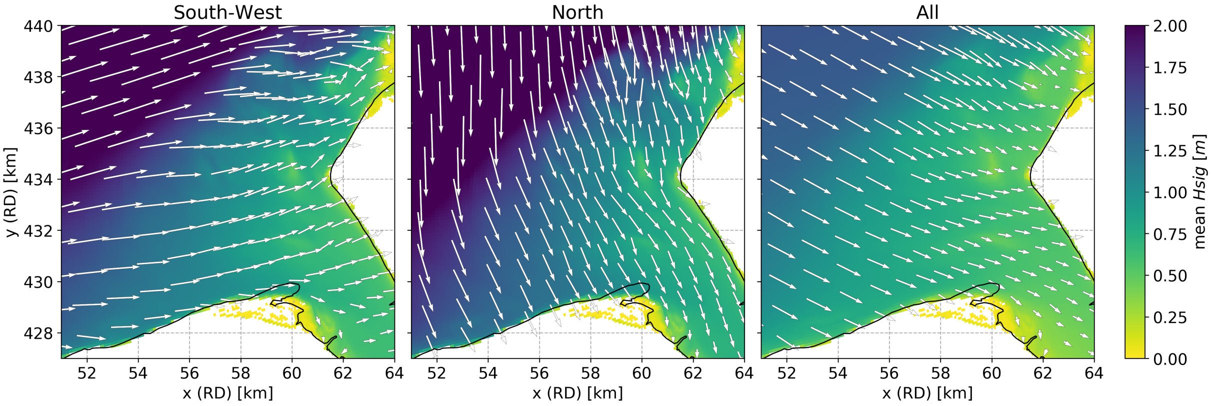
6.3.1 Wave propagation and direction

First the propagation behaviour of the waves is assessed, to assess the wave influence on the study area. The propagation direction of the waves is important when looking into potential wave exposure on the coast. In Section 6.3.1 the mean significant wave height and the mean wave direction are plotted over the study area. The colors indicate the significant wave height as shown in the color bar. The arrows represent the propagation direction of the waves. The propagation direction of the waves is based on the propagation direction during high water. This is done because when averaging the propagation direction over all time steps the results in the areas that fall dry during low water give an unrepresentative outcome. The wave direction is the result of combining two already derived wave conditions and by scaling them back according to the method used in Section 4.4. The wave directions are divided over two conditions main directions according to the wave rose in Figure 4.5. In Section 6.3.1 the results are shown.

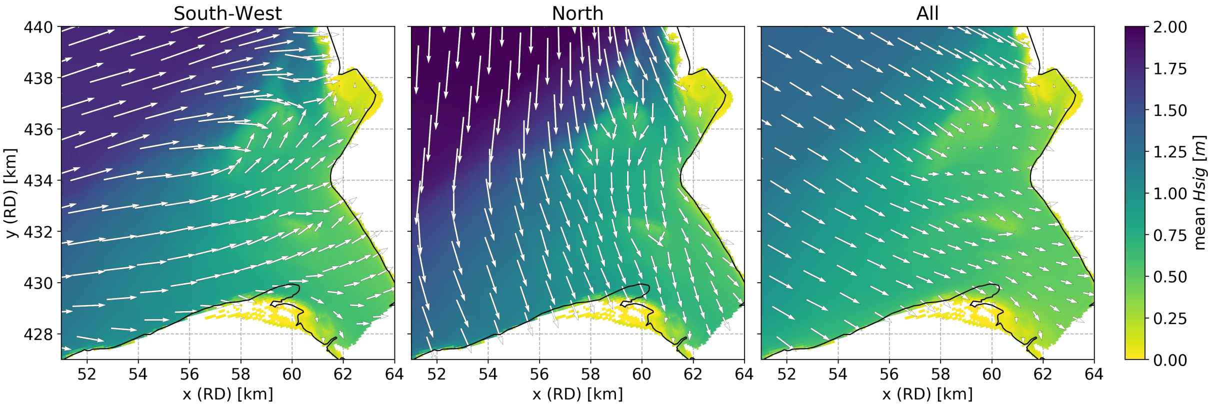
Section 6.3.1 illustrates the propagating direction of the incoming waves. From the figures it becomes clear that the shoals in front of the coast have a significant influence on the propagating behaviour of the waves. In every stage of time waves coming in from the north are deflected towards the east, in the direction of the coast. This is mainly due to the slope of the foreshore. Depth decreases towards the shore, causing refraction of the incoming waves from the north. The waves turn towards the shallow water region, resulting in turning of the waves to the east, in coastal direction.

Already in 1964 waves are influenced by the shoals just in front of the shore and by the in and outflowing tide. Small wave breaking occurs as it can be observed by the rapid decrease in wave height, illustrated with the change in color and decrease in arrow length. The arrows (scaled by the mean H_{sig}) become smaller and the color becomes more yellow. A part of the shoals are high enough to cause incoming waves to break and stop further propagation. In the more shallow part behind the shoals, waves are significantly smaller.

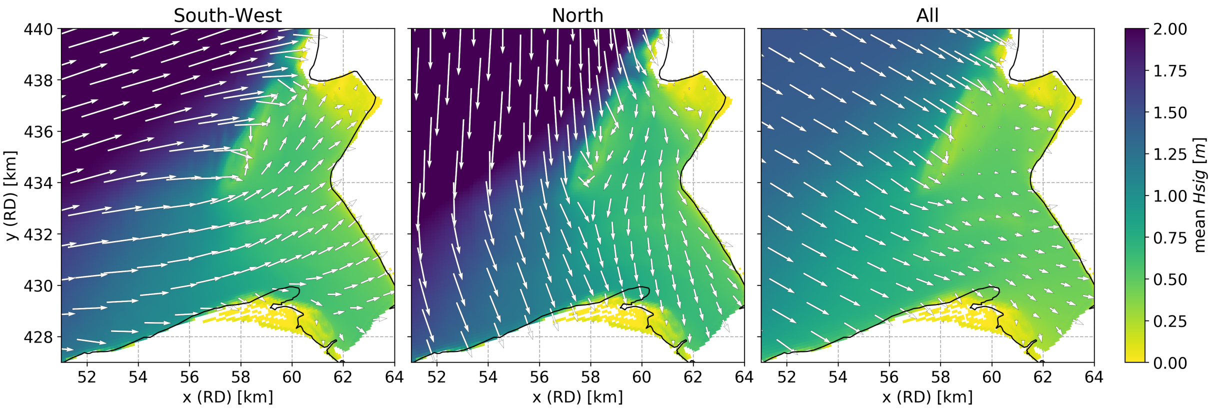
From the direction patterns of the waves in time, shoal migration can be observed. The shoal Hinderplaat grows in size and extends towards the south. Over time less waves are able to propagate towards the coast of Voorne because of this extension. Reducing the wave exposure on the coast. While fewer waves are able to propagate towards the coast, the mean H_{sig} in the study area decreases. The shallow part behind the shoals is then dominated by locally induced wind waves. From 1980 on this becomes more clear. In the overall wave climate the wave height reduces to almost zero and after the construction of the Slufter only waves locally induced by the wind are present in the area. Wave coming from off-shore break on the shoals in front of the coast. After a sensitivity analysis, changing the wind direction, it becomes clear that the area between the shoals and coast is wind dominated. Wave propagation direction mostly depends on wind forcing. Figures to support this are shown in **??**.



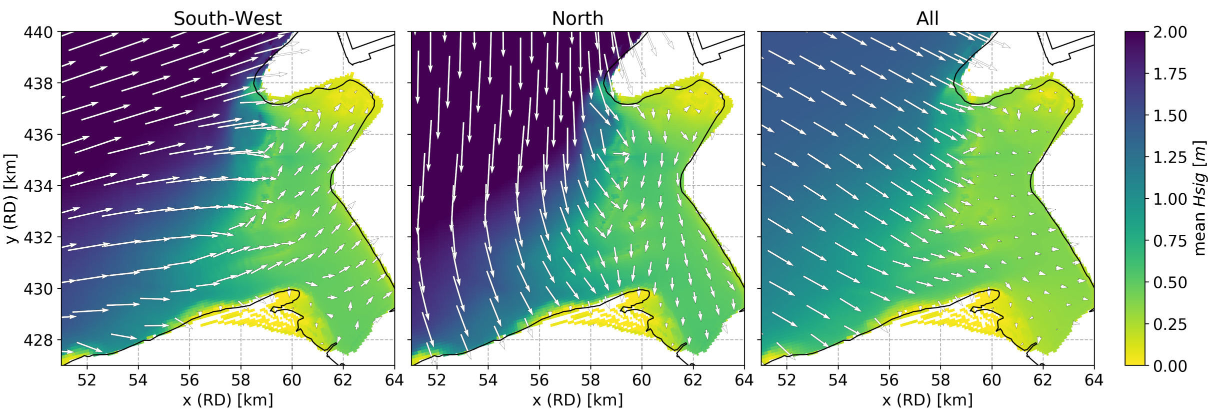
(a) Wave propagation direction 1964.



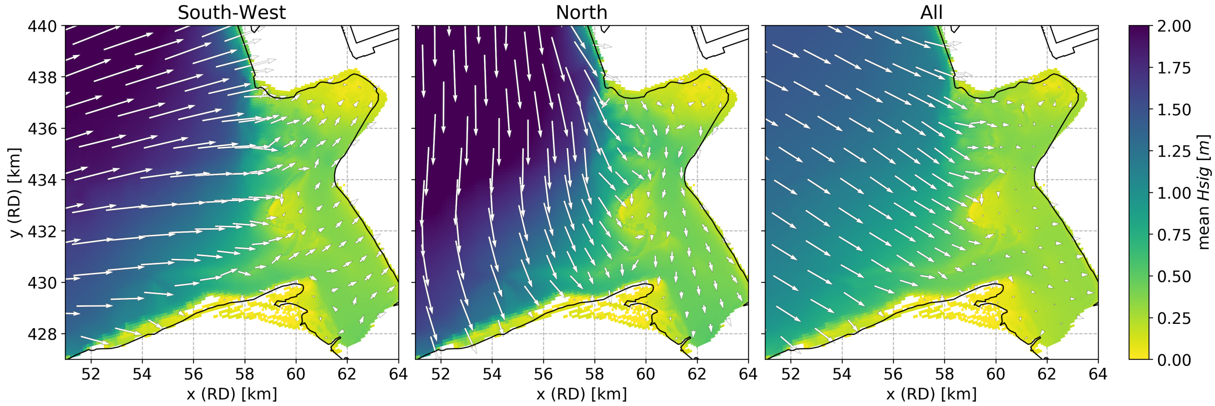
(b) Wave propagation direction 1972.



(c) Wave propagation direction 1980.



(d) Wave propagation direction 2004.



(e) Wave propagation direction 2018.

Fig. 6.3.: Wave propagation direction and mean hsig per stage in time.

With the movement of the shoals towards the coast, the foreshore becomes steeper. This enables waves to remain in height when propagating towards the shore. This can be observed by looking into the area offshore of the shoals, this area becomes darker in time.

As shown in Section 6.3.1 in the earlier stages until 1980, waves coming from the South-West propagate along the coast of Goeree over the channel Slijkgat into the study area. in this area the shoal figuration is less profound and therefore less waves are breaking. Moreover the channel Slijkgat provides large enough depth to enhance wave propagation towards the coast. Following the mean propagation direction of the waves in this area, the waves reach the beach directly. Waves coming from the southwest and reaching the north part of the study area tend to break on the shoals. However, in the latter stages, shoals have developed in such an extent that they break waves coming in from the south-west as well.

To conclude, waves from both directions tend to propagate towards the study area. However, due to the construction of the Maasvlakte and the growth of the shoals, less waves are able to propagate into the area, towards the coast. In the earlier stages waves coming from the South West are able to propagate towards the beach via the south. Here the channel Slijkgat provides large enough depth for propagation and the shoals are less profound. However, in time shoals grew in height and almost all offshore originated waves break on the shoals. This results in a relatively flat region where only waves locally induced by the wind are present. Over time the shoals in front of the coast become more distinct, inducing wave breaking. The incoming waves are unable to propagate further towards the coast. Resulting in a general trend of a decrease in wave exposure on the coast.

6.3.2 Mean wave height over time

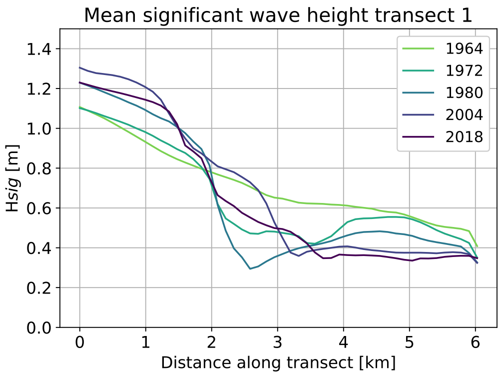
Now that the propagation of the waves towards the coast is analysed, the wave exposure on the coast will be assessed. As described in Section 5.4, transects are defined to assess the wave exposure in the study area. Along the transects wave data is obtained for each stage in time. In this section the wave data to be assessed is the mean significant wave height (H_{sig} mean). The assessed wave field is the result of merging the four derived wind climates back to one representative climate as described in Section 4.4. In Figure 6.4 the mean significant wave height per transect is plotted over the distance along the transect. Since waves are depth dependent in shallow waters it is expected that there will be a dependency between wave height and depth. In order to compare the two, the depth profile of the transect is plotted next to the wave height.

As stated before one has to keep in mind that the waves do not propagate exactly over the transect. The propagation direction of the wave heights plotted can vary over the transect and also between years. Nonetheless, wave development over the transect is assumed to be representative from offshore to nearshore looking at the offshore wave climate in Section 4.3.2. Waves are mainly coming from the North and south-west direction, propagating into the study area.

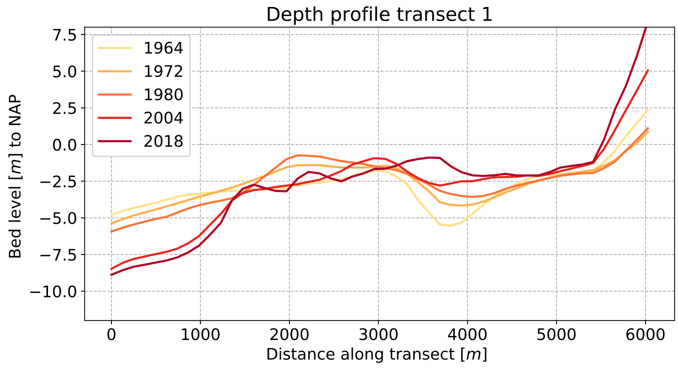
In 1964 when the estuary was open and connected to the sea, the in and outgoing tide had more influence on the waves. The force of the tide could lead to a lowering of the wave height. However in 1964 less shoals were present due to the more open character of the coast. Only the ebb tidal delta was present and was kept in place due to the in and outgoing tide. Without the presence of (high) shoals, relatively higher waves could propagate towards the coast. According to the model results as shown in Figure 6.4 the waves in the 1964 situation are on average higher when reaching the shore than in the latter stages. So the shoals have more influence on the wave propagation near the shore than the in and outgoing tide.

From the figures in Figure 6.4 it follows that the wave height near the coast -at 5 to 6km along transect- is the highest in 1964 for all transects. In this stage the Haringvliet estuary was still connected to the sea. From that point on the main trend is a decrease in wave height near the beach for each stage in time.

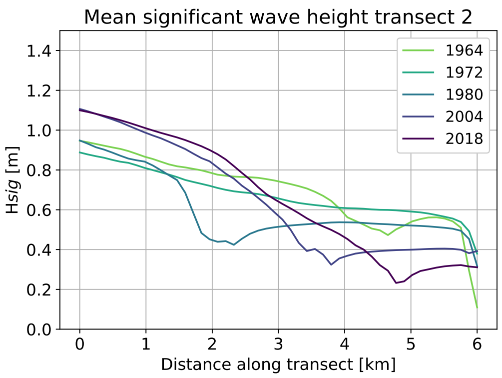
This gradual decrease of wave height in time does not hold for the whole transect. The (relative) wave height difference between stages over the transect varies too. When considering the depth profile most of these changes can be explained directly. Starting with the wave height in 1964. From figure Figure 6.4c it follows that the mean H_{sig} in 1964 in transect 2 is lower in the area just before the shore than the mean H_{sig} of 1972 and 1980. This could be related to the shoal figuration in front of the coast of each stage in time. Namely in 1964 the shoal at a distance of 4 to 5 km along the transect was higher than the shoal in 1972 and 1980. Because of the location and height of this shoal, more waves would break and dissipate due to the decreased depth. Waves propagating towards the shore are too high to propagate over the shoal and the highest waves start to break. The same holds for the H_sig in 1972 over transect 3 (Figure 6.4e). At a distance of 4 km along the transect the mean H_{sig} changes significantly. This change can be explained by the shoal at a distance of 4 km along the transect. The 'wiggles' in the wave height plot can be related to wave breaking. After breaking, waves subsequently grow again.



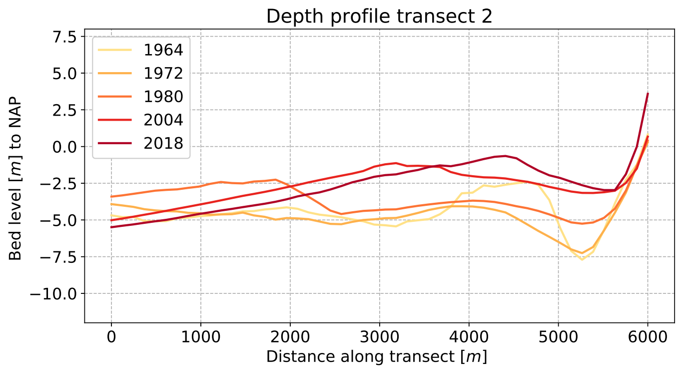
(a) Mean H_{sig} transect 1.



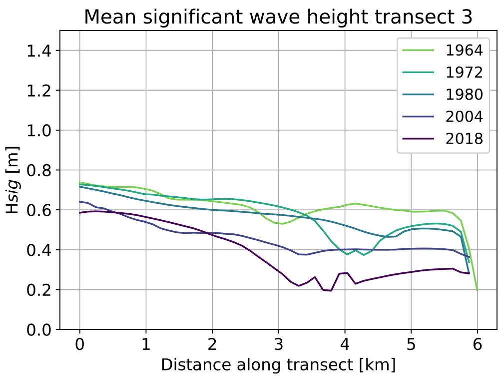
(b) Depth profile transect 1 .



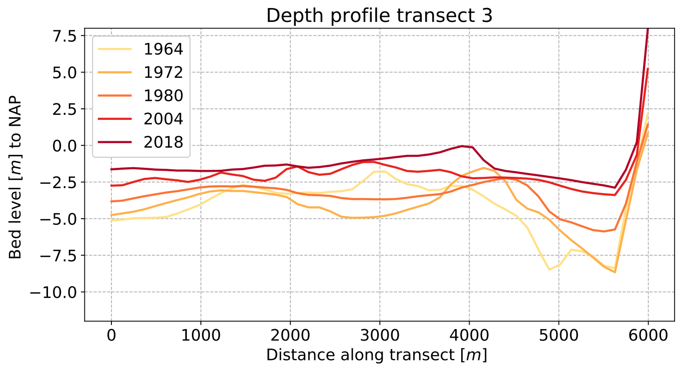
(c) Mean H_{sig} transect 2.



(d) Depth profile transect 2.



(e) Mean H_{sig} transect 3.



(f) Depth profile transect 3.

Fig. 6.4.: Mean wave height and bottom profile per stage in time for each predefined transect.

This growth can be related to wind forcing, or due to omnidirectional effects of waves coming in from other directions.

Another example is the wave height in 1980. The wave height along transects 2 and 3 during this stage decrease significantly around the 2 km point along the transect line. For both transects this decrease can be related to the increased shoal height at the same distance along the transect. The wave height in 2018 shows the breaking of the waves along every transect. At transect 1 the waves break between the 3 and 4 km distance along the transect. Over transect 2 wave breaking occurs slightly before the 5 km distance and over transect 3 it is visible by the wiggles in the wave height plot that waves break at a distance of 4km along the transect. Based on the figures, the breaking of the waves can in all situations be related to the shoals that emerge along the transect.

When looking at the 'off shore' starting point of the transects, the incoming wave heights differ between the stages in time. Waves in this area already 'feel' the bottom and their characteristics become depth dependent. Here too, the wave height can be related to the bottom profile. As follows from the figures a larger depth is associated with a higher mean H_{sig}. Further towards the shore, the mean wave height decreases. This is expected since waves in shallow water are depth dependent.

The foreshore slope of transects 1 and 2 (Figures 6.4b and 6.4d) tends to migrate further in the direction of the shore of Voorne (westward). The foreshore becomes steeper and the shoals propagate towards the coast. From Figures 6.4a and 6.4c it becomes clear that the waves depending on the depth evolve with it. The wave height in the foreshore, at the start of the transect, are higher in the most recent stages in time 2004-2018. Since the shoals increase in height and move further towards the coast the wave field near the shore decreases. The shoals become higher and more waves are breaking. The area west of the shoals is dominated by the wind and derived from the previous section. Here, the wavefield is mostly determined by locally induced wind waves and with some additional smaller waves that were able to propagate over the shoal during high water. Since fewer waves are able to propagate over the shoals over time the mean significant wave height near the shore decreases in height.

Transect 3 on the other hand is not positioned from the shore in offshore direction but stretches from the shore of Voorne to the coast of the island of Goeree. The bottom profile towards the coast is therefore less sloping. Despite the absence of a foreshore slope, shoals develop over the transect. These shoals are not migrating in the direction of the transect but are coming in from the northern direction. The shoals are not migrating in a straight line from north to south but turn from north to east towards the coast of Voorne as shown in Figure 6.1 in the previous section. As can be observed in Figure 6.4e the waves are affected by the depth contours and change with it in time. In the most recent year, 2018, a new shoal propagates into the transect and causes more waves to break, reducing the mean H_{sig} significantly. Compared to the situation in 1972 the slope towards the shoal is less steep. This causes the waves to feel the bottom later, but more sudden. Resulting in breaking of the waves relatively earlier along the transect.

Another interesting development to observe is the wave height above the channel Rak van Scheelhoek near the coast. Illustrated by the lower depth at a distance of 5 to 6 km along every transect. As illustrated in Figures 6.4b, 6.4d and 6.4f the channel becomes more shallow over time, but the relative change in wave height does not follow this line. In the area behind the shoals, the wave height slightly increases to a more or less constant height. from the figures is can be derived that the depth in channel Rak of Scheelhoek has little to no influence on the change of wave height. The area behind the shoal is too limited to have a fetch that can increase the wave height significantly. Therefore, it is expected that mainly the wind locally influence the waves in the area, complemented by waves coming in from direction with less profound shoal heights.

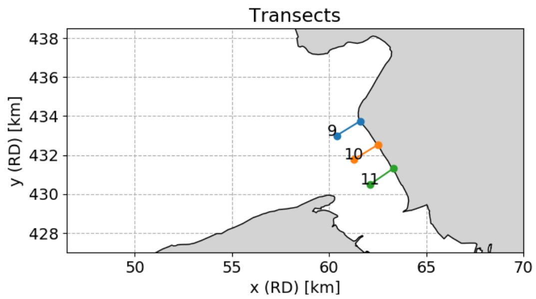
To conclude the gradual decrease can for a large part be linked to the development of the foreshore and in particular the development of the shoals. The height and location of the shoals determine mainly the wave field and the associated exposure on the beach. The wave exposure on the beach has gradually decreased over time. In the most recent stage, almost all waves coming from offshore are breaking on the shoals. The waves near the beach consist mainly out of locally induced wind waves. These locally induced wind waves come with a relatively low wave height. The wave climate acting on the coast of Voorne develops to be less representative for a coast, but more representative for a bank of a lake.

6.3.3 Wave gradient near the beach

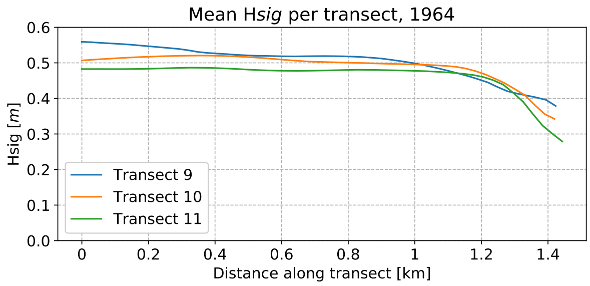
To assess potential transport along the beach of Voorne the wave exposure near the beach is examined with three transects. Note that these transects differ from the ones assessing the mean wave climate. With these transect the wave gradient along the beach is analysed over the years in order to assess potential siltation. To do so, at first three new transects are defined shore normal along the beach as depicted in Figure 6.5a. The mean significant wave height plotted over each of these transects for every stage in time is shown in the other sub-figures of Figure 6.5.

In the figures the difference between the transects of each stage in time is shown. A main decreasing trend in mean significant wave height can be observed from transect 9 towards transect 11. Although the height between the transects is relatively small, for every stage in time the height near the beach decreases gradually from north to south. In 2018 (Figure 6.5f) the wave height over transect 9 is smaller than for transect 10 and 11. This is mainly the result from the shoal just in front of the coast, blocking the waves potentially propagation over transect 9.

The overall gradual decrease from 1964 till 2004 in wave height does not hold for all situations. In 2004 the mean significant wave height at the beginning (offshore side) of the transect increases parallel to the coast from north to south. This difference shifts when following the line along the



(a) Position of the wave gradient transect along the beach.



(b) Mean wave height per transect 1964
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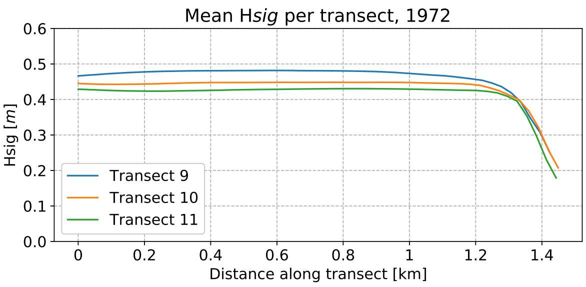
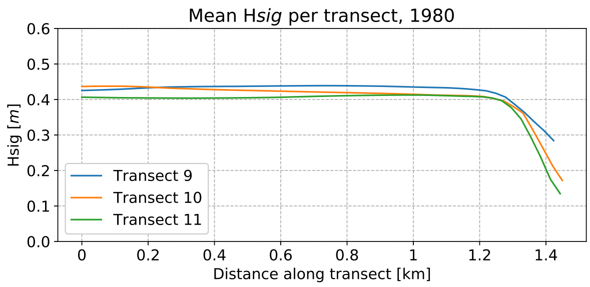
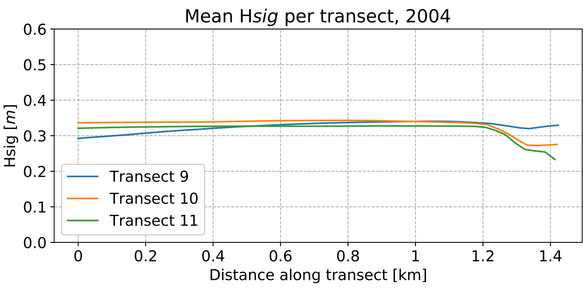


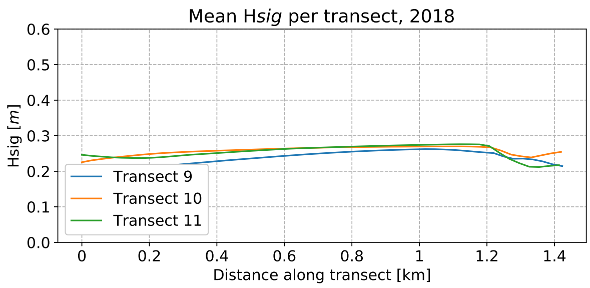
(c) Mean wave height per transect 1972.



(d) Mean wave height per transect 1980.



(e) Mean wave height per transect 2004.



(f) Mean wave height per transect 2018.

Fig. 6.5.: Wave propagation direction.

transect towards the coast. Near the shore the mean significant wave height decreases from north to south parallel to the coast. In both years the wave height on transect 9 is lower at the offshore side of the transect but increases towards the shore, up to an extent that in becomes higher than the mean H_{sig} of transect 10 and 11 (Figures 6.5e and 6.5f). In the stages 2004 and 2018 the wave height has reduced significantly and mainly consists of locally induced wind waves. Here no gradient can be distinguished.

An interesting development that can be derived from the figures is the wave development over transect 9 in 1964. Over this transect the mean H_{sig} near the coast (at a distance of 1.2km along transect) gets lower than the mean H_{sig} of the other two transects. When looking at the bottom profile of transect 9 and comparing it to the other two transects (10 and 11), no significant differences can be observed. In 1964 the ebb channel in front of the coast was more dominant and the area between the channel and the beach was less steep compared to the later stages in time.

To conclude the overall wave height gradient represents a decrease from north to south. Despite the changes in wave height between the different stages in time, the gradient between the wave heights stays more or less constant until 2004. The waves significant wave heights in the north are higher compared to the wave heights in the south. From this it can be derived that the potential of transport along the shore decays along the coast, implying siltation. In the stages 2004 and onward no distinct gradient is observed.

A side note must be placed on the meaning of this potential. Although the wave potential along the beach enhances the potential of siltation, it does not mean there will be actual siltation. This only takes place if there was initially enough wave energy to induce transport from the north in the first place. Also the difference in wave height is almost too small to be of significant influence on siltation.

Next to the wave gradient, the trend in mean wave height along the beach can be observed from the figures. The wave height along the transects is averaged and plotted in Figure 6.6. From this figure it becomes clear that the main trend of wave height along the beach decreases in time. This is in line with the earlier found decrease of wave height in Section 6.3.2.

6.4 Residual current

The presented overview of the wave exposure in the study area contributes to the understanding of the impact of waves during the different stages. However, it is interesting to analyse the hydrodynamic behaviour of the area without wave forcing. From this analysis the impact of the flow generated by the tide and Haringvliet sluices can be derived and linked to potential sediment transport. To analyse these flow patterns the residual current is assessed.

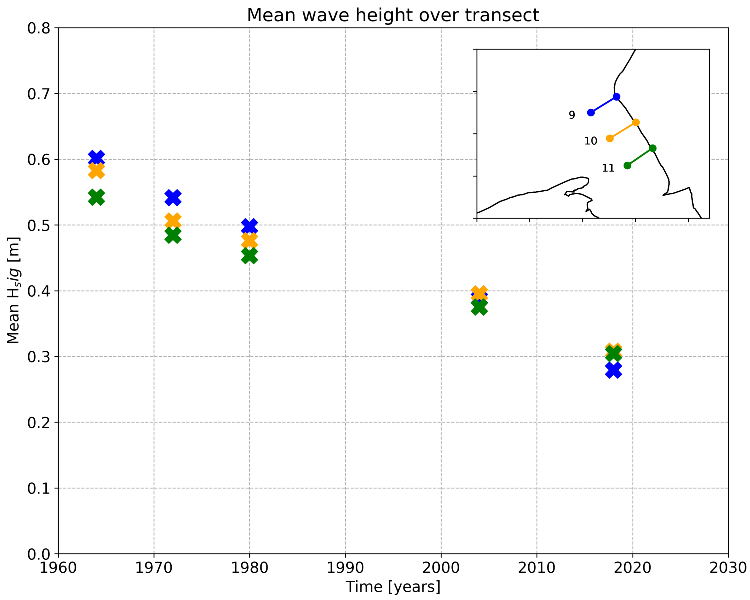


Fig. 6.6.: Average wave height along the beach.

In 1964 when the estuary was connected to the sea, the residual current was dominated by the tidal flow. In the stages after the closure of the Haringvliet the residual flow in the study area was partly generated by the asymmetry in the tidal flow, and partly the result of local discharges. The local discharges were the most dominant process influencing the net flow patterns in the area. The induced offshore directed discharge resulted in pronounced net flow currents through the channels Slijkgat and Rak van Scheelhoek. It is assumed that the residual currents as a result of the tide in these stages were relatively small, which is confirmed by Colina Alonso (2018) for the situation in 2015. However, these relatively small currents do contribute to an average offshore directed current. To analyse the change over time, the residual current over a full tidal cycle is shown per stage in Figure 6.7.

As stated before the residual flow patterns in 1964 are to a great extent dependent on flow induced by the tide. From Figure 6.7 it can be observed that the flow patterns during this stage are more pronounced than the patterns derived for the other stages in time. The arrows indicate a relatively significant offshore directed current. From literature it was derived that in that stage, the tide was more dominated than the waves. Therefore, it can be stated that in this stage the potential of sediment flux is an export of sediment out of the estuary.

In the stages after the closure the derived net flow currents are less pronounced. They are heavily affected by the closure of the estuary. The flow patterns in the channel Rak van Scheelhoek (east in the area) are to a greater extent dominated by the discharge through the Haringvlietsluices (Figure 6.8). In time, it can be observed that due to morphological development the net flow patterns change. In 1972 right after the closure the residual flow velocities are smaller in proportion to eachother than in the most recent stage (2018). The bathymetry in this early stage was mainly the result of the tide and waves induced ebb-tidal delta. The area was relatively open

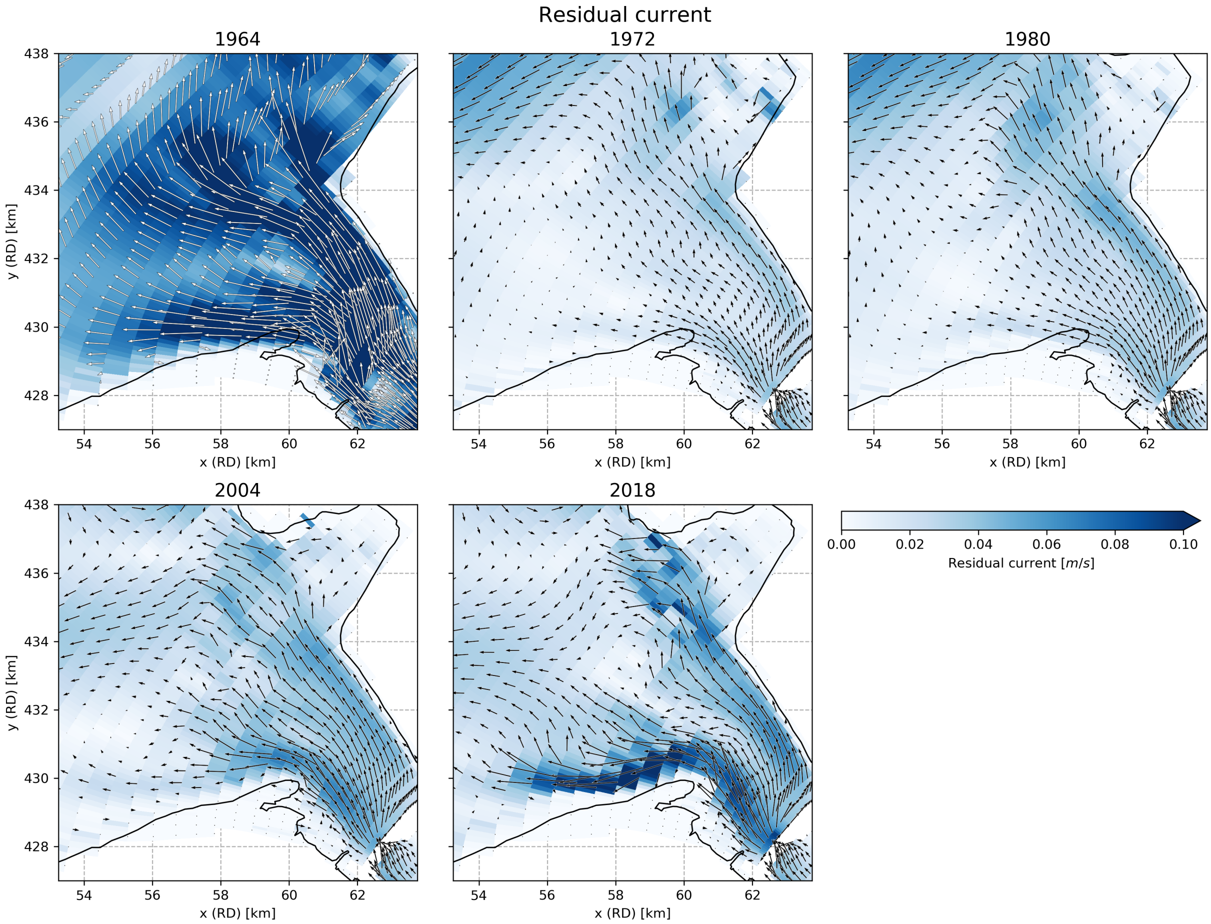


Fig. 6.7.: Residual current per stage in time.

and the shoals present in the area were low. The induced flow by the river runoff through the sluices could easily be discharged over these shoals into the sea. In the stages after the closure, waves enhanced shoal formation and migration of the shoals towards the coast. The migration of the shoals towards the coast resulted in a change of net flow patterns. The increasing shoals forced the outflowing river runoff to the channels Slijkgat and Rak van Scheelhoek. Moreover, in Section 6.2 it was derived that the channel Rak van Scheelhoek silts up in time, reducing the discharge transport capacity of this channel. To transport the same amount of discharge, the flow velocities increase as depicted in Figure 6.7. Since the discharge capacity of channel Rak van Scheelhoek in front of the coast has reduced due to accretion, the relative discharge capacity of the channel Slijkgat has increased. The channels Slijkgat is dredged regularly to maintain the accessibility of the ship, resulting in a more or less constant discharge capacity of this channel. As a result this channel 'attracts' relatively more discharge compared to the former stages in time resulting in an increase of residual current velocity in this area.

Form this developing trend of residual current, changes in sediment transport can be derived. As described in Appendix A.2.1 residual currents can be related to sediment transport. In the study area, the potential of (fine) sediment transport is enhanced in the channels, whereas the residual flow over the shoals shows a decrease of sediment transport potential in time. Although the magnitude of the residual currents has changed in time, the direction of the currents did not alter much in time. From the figures in Figure 6.7 it becomes clear that the main direction of residual current is directed to the coast. From the channel Slijkgat potential (fine) sediment transport towards the shoals can be observed.

To investigate the influence of the sluices and their associated discharge, different sluice policies are assessed. In Figure 6.8 these different policies are depicted: 1) with discharge, 2) closed and 3) kierbesluit (partly opening of the gate). From these plots it can be observed that during the situation with sluice discharge (4000 m^3/s over one tide) distinct offshore directed residual currents are present. In the situation where the sluices are closed the residual flow velocities are significantly lower. These lower residual flow velocities are less pronounced than the situation with discharge. The flow is now mainly induced by the tide and shows a reduced circular flow in the study area. In the last situation in which the Kierbesluit policy is implemented the residual flow velocities have increased significantly compared to the former two situations. Water is able to flow in and out of the estuary and more river discharge is able to get discharged through the sluices. The in and outflowing tide in combination with river runoff leads to an increase of offshore directed residual currents in the channel Slijkgat, but also through the channel Rak van Scheelhoek. This observed offshore directed residual current can be linked to a potential outflow of (fine) sediment.

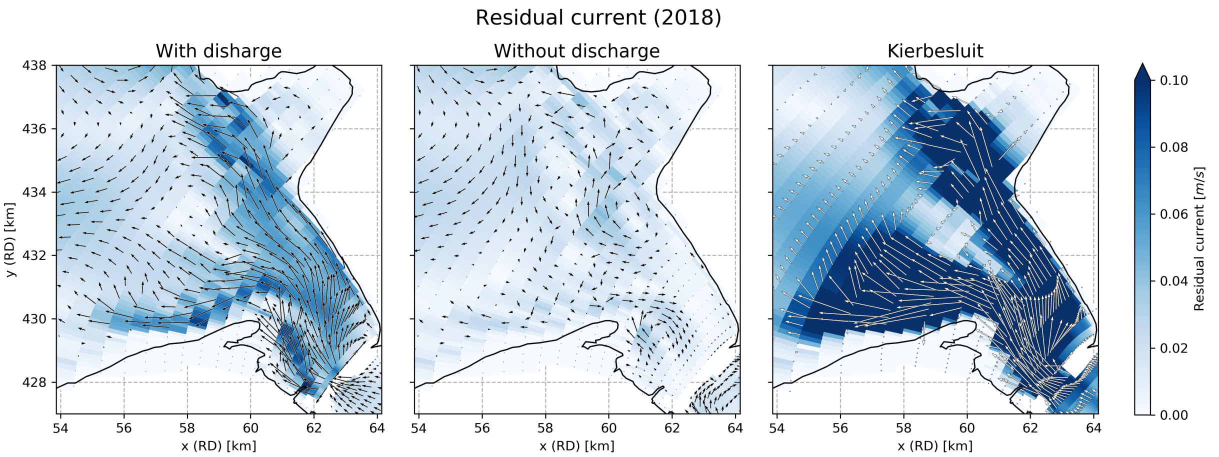


Fig. 6.8.: Residual current during different sluice policies (2018).

To conclude residual current over time has increased in the channels and decreased on the shoals. The associated potential of sediment transport has followed this trend. The potential of sediment transport is enhanced in the channels and when following the direction of the residual current this transport enhancement is directed towards the coast and the shoals. Since the magnitude of the residual flow and thus the sediment transport capacity on the shoals reduces, transported sediment is likely to settle in these areas. Potential accretion is likely to occur when there is a gradient in the magnitude of the residual current. Based on this criterion the coast and the shoals can be associated with potential siltation. Changing the sluice policy will directly lead to an alternation in residual flow velocities and hence, a change in potential (fine) sediment transport. From Figure 6.8 it becomes clear that when the sluices are partly opened, the net current velocities increase. This can be related to the in- and outflowing tide.

6.5 Bed shear stress

Bed shear stress is a crucial parameter for sediment transport processes Ledden (2003). As described in Appendix A.2.1 bed shear stress is the result of the water motion (currents and waves) over the bed and the roughness of the bed surface itself. In this analysis bed shear stress as a result of wave forcing is not taken into account. Here, only the shear stress at the bed as a result of water motion due to currents is assessed. In this way a better understanding of the water motion induced by the tide and sluice discharge can be obtained. Insight can be obtained in the processes in the study area inducing potential sediment export. In the next figure (Figure 6.9 the 90th percentile of the bed shear stress over one tide is plotted for every stage. The 90th percentile is used to see if the water motion during one tide is large enough to induce incipient particle motion and to prevent the influence of outliers on the results. In the figure the magnitude of bed shear stress lower than the general shields threshold for incipient particle motion (0.3 N/m^2) is plotted from blue to white. In red the magnitude exceeding this limit is plotted.

In the first stage in 1964 the tidal channels facilitate the tidal flow between the estuary and the sea. The flow velocities as a result of the moving tide induced large enough bed shear stresses to transport the sediment in these channels. As indicated in the figures the patterns of bed shear stress offshore do not change significantly after the closure. Here, the bed shear stress as a result from the flow is large enough to induce sediment particle motion. However, after the build of MV2, bed shear stresses in the foreshore of the study area decrease. The decrease of tidal flow along this area has decreased the magnitude of bed shear stress.

Inside the study area, the flow patterns are significantly influenced by the shoals. As observed in Figure 6.9 the associated bed shear stress decreased significantly in the east part of the study area. For all stages after the closure, the area around the channel Rak van Scheelhoek is characterised by low bed shear stresses. In this area, the magnitude of the bed shear stress is to low to induce sediment motion. Hence, in the area in front of the coast of Voorne and on the west side of the Haringvliet no transport is expected. Although the discharge through the Haringvliet influences the flow, the water through sluices is discharged at the water surface layer, having almost no effect on bottom shear stresses. In time the area with bed shear stresses under the threshold limit has decreased. Hence, the area where little to no incipient motion is induced has decreased. As derived from the previous section, currents increase because the area accretes. This increase in flow velocities also leads to a shift in bed shear stresses. In the most recent stage it is visible that the channel Slijkgat attracts more flow, and subsequently the bed shear stress increases. Furthermore, bed shear stresses in the north of the study area increase ass well. It is likely that

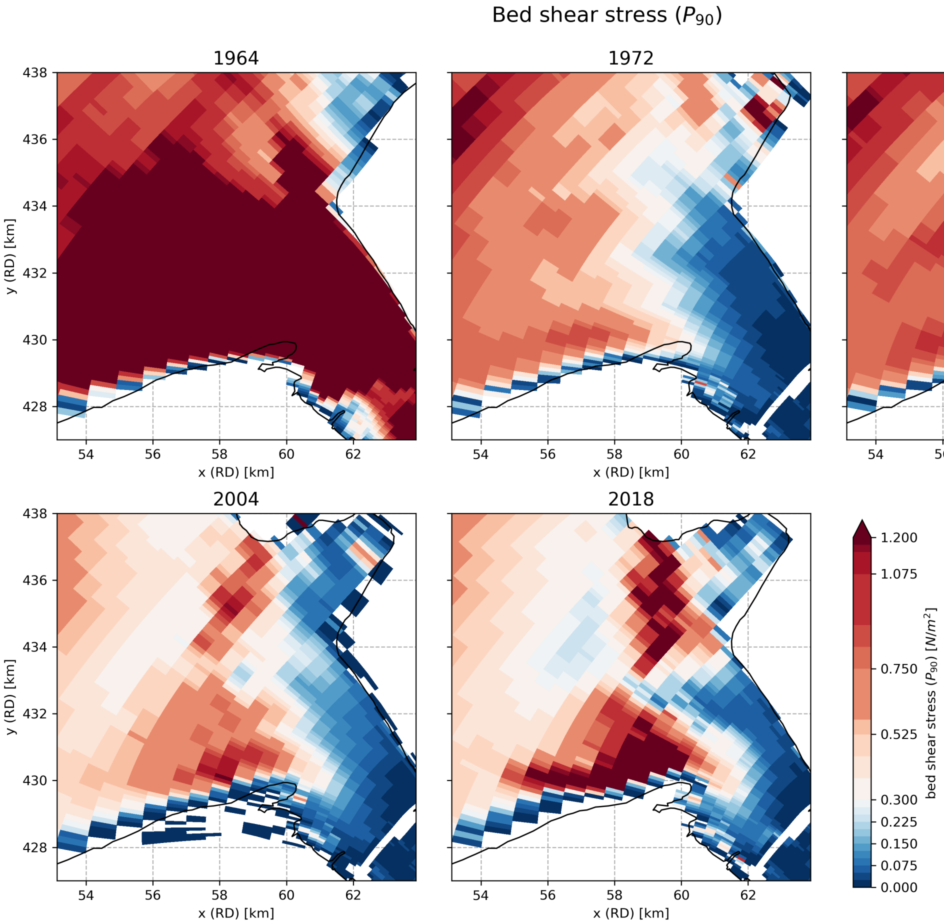


Fig. 6.9.: Bed shear stress per stage in time.

due to the flow the shoals here will erode. On the offshore side of the shoals however, the bed shear stresses decreases to a value below the threshold of incipient motion. Considering the residual flow this implies a flow-induced motion of sediment on the shoals from the landward side of the shoal to the offshore side, enhancing offshore shoal migration. One has to note that this is only the result of the combined effect of the tidal flow and sluice discharge.

The change of sluice policy has its influence on the hydrodynamics in the area and thus also on the bed shear stresses. In Figure 6.10 these different situations -also used for the residual current case- are depicted: 1) with discharge, 2) sluices closed and 3) Kierbesluit policy (Described in Section 2.2.3). From the different sluice policies it can be observed that bed shear stresses at the offshore side of the shoals are mainly induced by the tide. The average discharge through the Haringvliet sluices is not big enough to induce incipient motion of sediments. in the area behind the shoals. When opening the gates, water is able to flow in and out of the estuary. As already observed in the previous section, currents in the channel Rak van Scheelhoek and the channel Slijkgat increase. As a result the bed shear stresses in these areas increase as well. As can be observed in the situation where the sluice doors are open, the flow velocities increase to such extent that they induce bed shear stresses large enough to induce incipient motion of sediment.

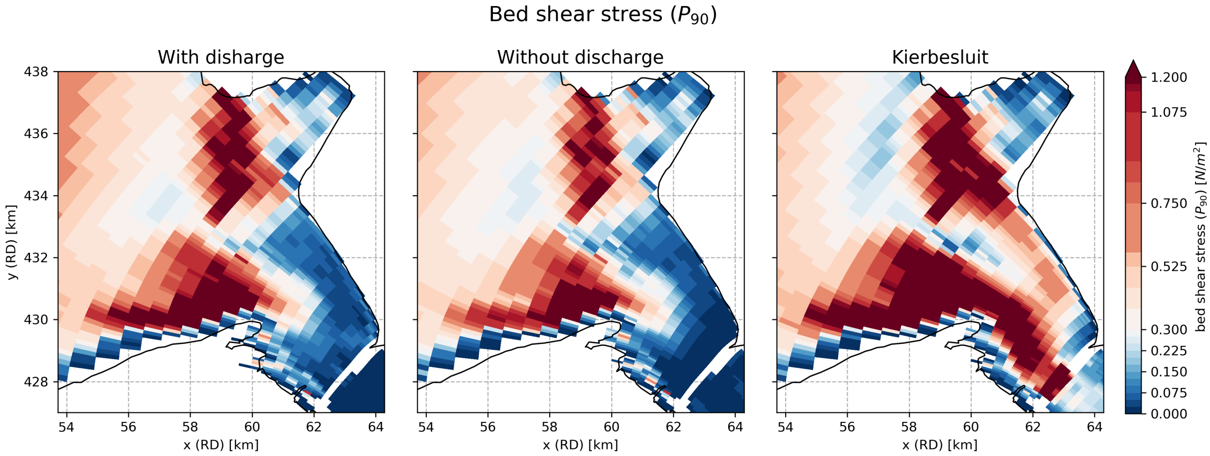


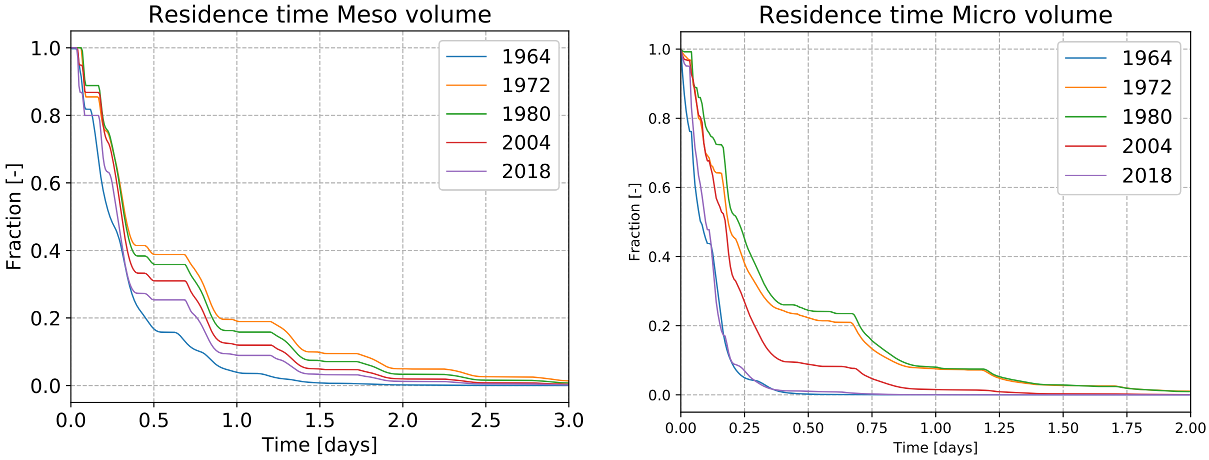
Fig. 6.10.: 90^th percentile bed shear stress during different sluice policies (2018).

It can be concluded that based on bed shear stress the stresses are too low to allow for incipient motion of sediment particles in the area around the channel Rak van Scheelhoek. Since flow velocities are enhanced in the channel Slijkgat and in the smaller channels in the north, the bed shear stresses increase in these areas. By considering the residual flow this leads to an offshore directed sediment flux. So based on the flow only, the shoals show an eroding trend. When opening the Haringvliet sluices by implementing the Kierbesluit policy, the tidal flow velocities increase, inducing an increase in bed shear stress. The increase of bed shear stresses is large enough to set sediment into motion. When considering the residual flow patterns it can be concluded that there is a potential outflow of sediment induced by the flow only. The net transport of sediment however, is also determined by the influence of the waves. Therefore, when assessing sediment transport, wave influence has to be taken into account as well.

6.6 Residence time

Residence time as described in Appendix A.3.2, is the time that suspended particles stay in a predefined control volume. The more time suspended particles remain in the control volume, the more time they have to settle. Hence, the residence time represents the potential of siltation inside a control area but also the potential of turbidity in a volume. The residence time is assessed based on the methodology described in Section 5.6. The initial volume gets flushed and the initial volume fraction decreases due to the water motion. To visualize this, for every predefined stage the decrease of the volume fraction as part of the initial volume is plotted against the time according to the earlier defined Equation (5.1). The result is depicted in Figure 6.11.

From Figure 6.11 it becomes clear that the residence time of both control volumes has increased significantly from 1964 to 1972 after the closure of the Haringvliet. The residence time of the micro volume shows even a little increase towards 1980. This is probably because in 1970 the



(a) Residence time Meso volume.

(b) Residence time Micro volume.

Fig. 6.11.: Residence time control volumes.

estuary got closed off from the sea and the tidal flow reduced. Only the irregular discharge from the Haringvliet sluices contributed in the latter stages to an increase of the flow velocities in the area. As a result the residence time increased and particles stayed longer in the predefined control volume, enhancing the potential of settling. As a result, the area silted up and the size of the water mass (control volume) decreased over time as shown in Figure 5.3. The flow through the area, consisting of the tidal flow and the discharge of the sluices, remained constant. Since the water volume decreases and the discharge through the area remained constant, the flow velocities through the area increased. Hence, the area gets flushed and the residence time decreases. This trend can be observed from 1972 until the most recent stage in 2018. The meso volume is developing towards a new equilibrium, while the micro volume seems to have reached this equilibrium already based on residence time only.

The decrease of residence time implies a decrease in turbidity and a reduction of the siltation potential. However, since the area is silting up at the same time, the vertical settling distance of the suspended particles reduces, and less time is needed to deposit. So, therefore the decrease of residence time does not directly imply that there is less siltation.It is important to compare the time during which particles are able to settle, with the vertical distance over which the particles settle (siltation depth). In other words, the potential of siltation is determined by combining the time the particles spend in the water column (residence time, T_{90}), with the vertical distance that the particles have to settle before they deposit (siltation depth, Sd). The value used to assess the residence time (T_{90}) for each year is the time needed to evacuate 90% of the water mass of the original control volume. Hence, the residence time used of each stage in time, is the time where the graphs of Figure 6.11 drop below the 0.1 fraction. The settling distance is the average depth of the control volume of each stage in time. It is important to note that this average depth is measured below MSL. It is therefore possible that the value of this indicator is larger than the average depth used in this assessment. However, the bandwidth of this error is assumed to be small enough to consider this indicator as representative.

In order to follow the development of both indicators T_{90} and Sd time, use is made of the relative change of the indicators with respect to 1964. To this aim, the indicators relative residence time (R_{T90}) and the relative siltation distance (R_{Sd}) are defined as formulated in Equation (6.1) and Equation (6.2):

$$R_{T_{90}} = \frac{T_{90,[year]}}{T_{90,[1964]}} \qquad (6.1)$$

$$R_{Ds} = \frac{Ds_{\ [year]}}{Ds_{\ [1964]}} \qquad (6.2)$$

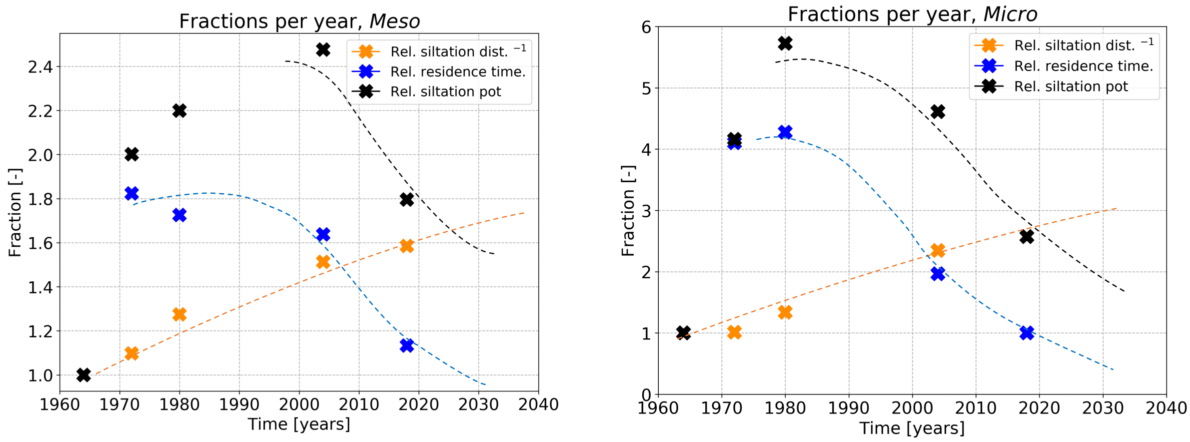
Note that the relative siltation distance R_{Sd} has a negative correlation with the likelihood of siltation. So, when the depth decreases, the likelihood of siltation increases. Therefore, the inverse value of the relative siltation depth is used to assess the siltation potential. The relative indicator R_{T90} and the inverse of the relative indicator R_{Sd} are plotted as a function of time in Figure 6.12

To relate both relative indicators R_{T90} and R_{Sd} to the total siltation potential, a new factor is defined: the relative siltation potential $R_{silt.pot}$. This new factor combines the two relative indicators in one new relative indicator indicating the potential of siltation as formulated in Equation (6.3):

$$R_{silt.pot.} = R_{T_{90}} * R_{Ds}^{-1} \qquad (6.3)$$

This new relative indicator $R_{silt.pot}$ is also plotted in Figure 6.12 together with the relative residence time (R_{T90}) and the inverse of the relative siltation distance (R_{Sd}). In addition, a dashed line is plotted in the figures, indicating the probable trend of the relative indicators. Note that this dashed line is only a representation of a possible trend.

Figure 6.12 shows that the inverse of the relative siltation distance (orange) and the relative residence time (blue) follow the trend line which was observed as described above. The area silts up and as a result the depth decreases. However, the siltation trend decreases, slowing down the decline of depth. The relative residence time follows the derived trend from Figure 6.11. Following this trend, the residence time increases after the closure in 1964 towards 1972 and decreases from 1972 onwards. The relative residence time decreases in such extend that it reaches the same characteristics as the original residence time in 1964. However, as stated before, the siltation potential is determined by both indicators. Therefore, to assess the total siltation potential, the new factor $R_{silt.pot}$ is analyzed.



(a) Relative indicator development Meso volume.

(b) Relative indicator development Micro volume.

Fig. 6.12.: Relative development indicators control volumes: relative settling distance, relative residence time and relative siltation potential.

From Figure 6.12 it can be observed that in the first stage after the closure in 1972, the value of the new indicator $R_{silt.pot}$ (black) is relatively large. This means that the ratio between the residence time and the depth of the control volume is relatively large. This large ratio implies a larger likelihood of siltation; the time particles spend in the water column increases significantly and the siltation distance decreases to a lesser extend. However, in time the relative siltation potential decreases. The relative residence time (blue) decrease, where the decrease of relative siltation distance (orange) slows down. By following the trend in both relative indicators, the ratio between both indicators decreases in the most recent years. Hence, as shown in Figure 6.12, the total relative siltation potential (black) decreases in the most recent years. The system seems to develop towards a new equilibrium where the two indicators keep eachother in balance. In this new equilibrium the residence time has to compensate for the decrease in relative siltation distance to ensure the same siltation potential as in the stage before the closure of the estuary. To compensate for the decrease in depth, the flow velocities through the area have to increase to lower the relative residence time. Meanwhile, the potential of siltation decreases, and therewith also the potential of turbidity in the water column. However, as stated before, this does not imply there will be no siltation and turbidity. It implies at most the siltation and turbidity in the area will not change significantly compared to the stage in 1964 before closure. Finally, from the figures it can be observed that based on the indicators plotted, the residence time has to reduce in order to bring the potential of siltation back to its original value in 1964. Hence, flow velocities in the area have to increase in order to restore the equilibrium situation in 1964, before the closure of the estuary.

6.7 Salinity

Since the study area is located in the transition zone between the rivers and the sea, salinity difference plays a role in the area. Before the closure of the Haringvliet the area was subjected to salinity differences as a result of the in and outgoing tide in combination with freshwater river discharge. After the closure of the Haringvliet estuary, the saline water got flushed out of the estuary by the freshwater river runoff. In time, the estuary became a freshwater basin. The salinity levels in the mouth of the estuary are influenced by the offshore salinity levels, the discharge through the Nieuwe Waterweg and the freshwater discharge through the Haringvliet sluices. To assess the change in salinity levels in time, the salinity levels averaged over one tide are assessed per stage in time as depicted in Figure 6.13. The tide which is assessed, is the same representative tide which is used to assess the residual current and the bed shear stresses, discharging a total amount of 4000 m^3 freshwater into the study area during one tidal cycle. The red color indicates saline water, whereas the color dark blue represents freshwater.

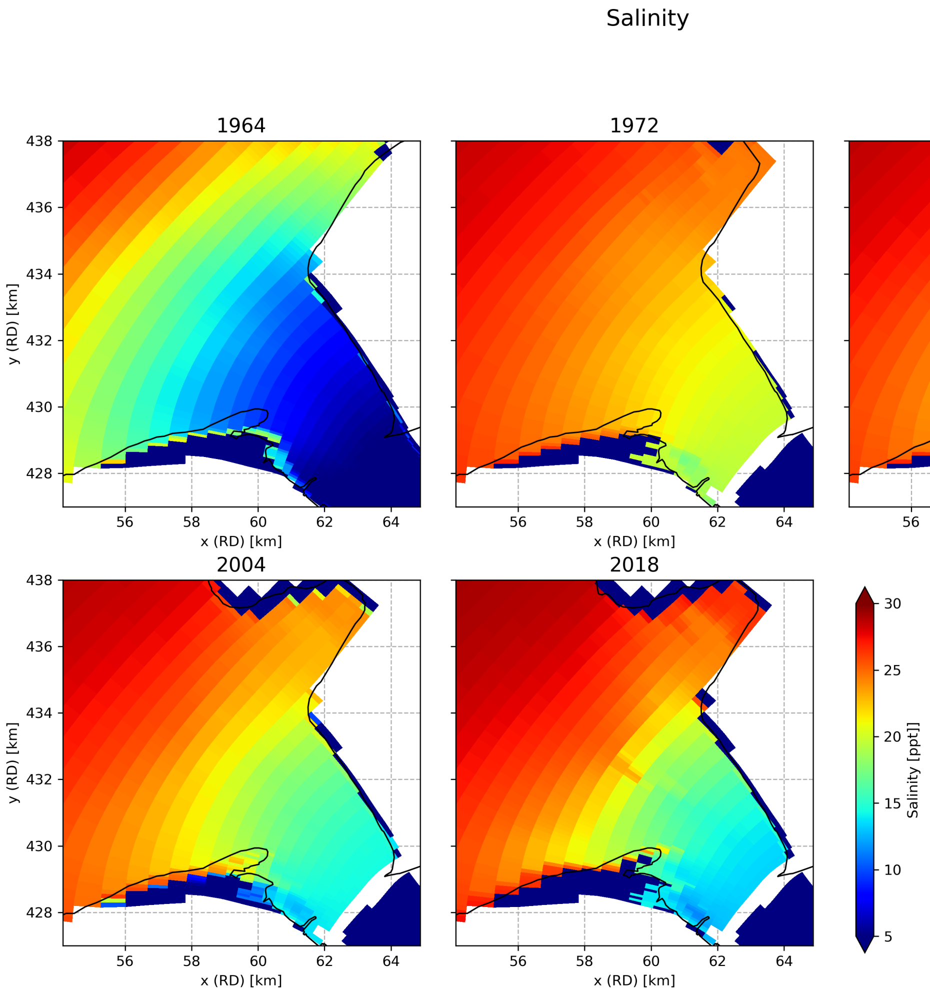


Fig. 6.13.: Salinity levels per stage in time.

From Figure 6.13 it can be observed that directly after the closure of the Haringvliet the salinity levels have changed significantly. Before closure, the study area was located in the zone of the interplay between the saline sea water and the freshwater river discharge. From Figure 6.13 it becomes clear that the salinity levels in that stage were relatively low. A side note must be placed that in the 1964 situation depicted in Figure 6.13, the modeled Haringvliet estuary was already closed of from the Grevelingen estuary, meaning that the main part of the river runoff got discharged through the Haringvliet estuary. Moreover, a constant river forcing is applied, tempering the dynamics of river and tidal interaction. After the closure, the water on the inland side of the sluices became fresh and the seaside of the sluices became more saline. Freshwater river discharge got blocked by the dam and saline seawater was able to penetrate the study area. Only occasional freshwater discharge through the sluices decreased the salinity levels in the study area. After the closure, the freshwater discharge of the Haringvliet sluices gained significant importance in the study area in terms of salinity. Due to the freshwater discharge, the salinity levels in the study area declined. The influence of the freshwater increases within time as depicted in Figure 6.13. One has to keep in mind that the salinity levels observed in the area are still saline. However, the level of salinity decreases towards a more brackish environment. This increase of freshwater influence can be related to the accretion of the area. The reduction of the water volume of the area due to accretion, enhances the relative importance of the sluice discharge. The volume of saline water in the area decreases, but the amount of freshwater discharge remains the same. Hence, the water mass in the area becomes less saline. Especially alongside the beach of Voorne. Here a significant increase of freshwater can be observed during sluice discharge as derived from Figure 6.13. As a result the area has turned into a brackish environment.

6.8 Future development

To assess the long term development of the study area the trend in bathymetry is evaluated and the dominant processes acting on the study area are analysed. When considering the study area as a part of the coastal system Voordelta, a general trend of coastal development can be perceived. After the interventions in the past the system was forced out of (dynamic) equilibrium. The longshore transport of sediment was affected and the gradient in longshore transport became bigger. The system seems to be developing towards a new equilibrium state. To do so the gradient in longshore sediment transport has to decline. Hence, the study area has to import sediment to restore the sediment transport gradient between the island of Goeree and the tip of the Maasvlakte 2.

In time the area has accreted significantly, and its bathymetry is constantly under development. The change over time is discussed in Section 6.2. In Figure 6.14 the change of morphological elements between 2014 and 2018 is depicted. In the study area waves are considered to be the most important drivers of sediment transport. The wave-induced sediment transport along the coast of Goeree and MV2 act as sources of sediment to the study area. In addition, waves acting as bulldozers transport sediment from the foreshore to the emerged shoals (1a). In time, the shoals move further towards the coast while propagating in height. According to Winter (2014) and Elias and Spek (2016) the northern part of the Hinderplaat will continue spreading towards the north, eventually merging with the Slufter. The tidal current in the area decreases and there is no possibility for a circulating flow in the study area. The tidal storage potential reduces and therewith the capacity of the tide to flush sediments out of the area. The only force counteracting the import of sediment is the discharge through the Haringvliet sluice. According to Elias and Spek, 2016 it is expected that the sediments from the shoals will deposit in the channel and fill in the tidal basin completely. From Figure 6.9 it becomes clear that after the closure the bed shear stresses along the coast of Voorne were too small to induce incipient motion of sediment. The flow through the Haringvliet sluice is in extreme situations able to flush the channels in the study area, but in general the force of the outflowing discharge will be too small to counteract the sedimentation. With little to none natural forces to counteract this process, the study area as part of the coastal system tends to silt up further.

The most recent trend of the tidal shoal in the middle of the study area as depicted in Figure 6.14 is a propagating in landward direction (1c). As described in Elias and Spek (2014) the shoals have turned into flat-like area. This can be observed in Figure 6.2e, the shoal has spread out and the upper surface of the shoals lies for a large part around mean sea level (NAP).

As depicted in Figure 6.2d and the channel Rak van Scheelhoek has experienced severe sedimentation over time. The trend of sedimentation is visible considering the increase in bed level, continuing until the most recent stage in time (5).

The channel Slijkgat shows in most recent stages a more meandering behaviour with more curvature in the ebb and flood channels and the development of a natural sill (2). This channel is dredged frequently to maintain its minimal required depth. Because the channel Rak van Scheelhoek silts up more, the channel Slijkgat gains in importance in terms of flow attraction. The water from the Haringvliet mainly discharges through this channel enforcing a positive feedback loop. Flow velocities in the Rak van Scheelhoek decrease and potential siltation is enhanced, favouring the channel Slijkgat as a discharge channel. Hence, the shoal formation turns the study area into a silt trap. The waves breaking on the shoals push the sediment landwards (1b) while the tidal flow in combination with the sluice discharge is not able the transport enough sediment out of the area to prevent accretion. This positive feedback loop can eventually lead to complete accretion of the channel Slijkgat. Hence, the shoals will merge with the shore, leaving the channel Slijkgat as the only discharge channel of the Haringvliet sluices.

The sluice discharge in combination with the morphological changes, causes an increase of freshwater influence in the area. With the absence of larger offshore originated waves, only locally induced wind waves play a role in the area. These small waves stir up the small sediment particles that have settled along the coast, causing increased turbidity of the water column along the coast. The area slowly turns into a small lake-like area with locally induced wind waves, shallow water depth, and lower salinity levels.

The newly implemented Kierbesluit policy enables an increase in tidal flow through the Haringvliet. This tidal flow causes an increase in discharge through the study area. The landward propagation of the shoals will to some extent decrease. However, the sluices are not completely opened and not during the whole year. The sluices are only opened when the river run-off is

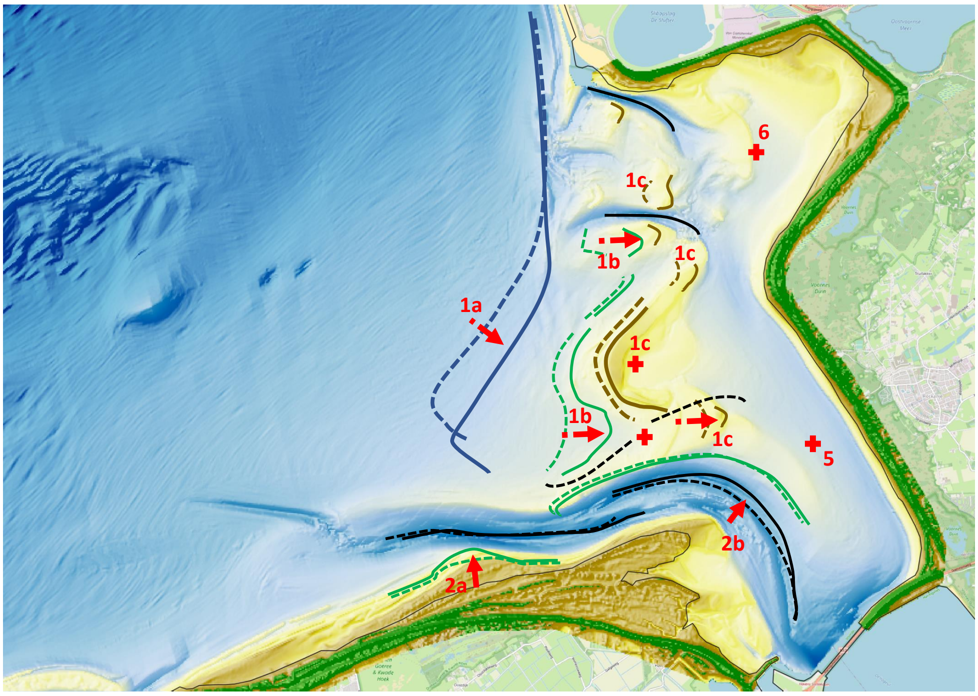


Fig. 6.14.: Development of the morphological elements in the study area, bathymetry 2018. (green: shoals and beach, black: channel axis, brown: emerged shoal, blue; foreshore).

large enough to counteract the salt intrusion in the Haringvliet estuary. Meanwhile, the area has already siltated to such an extent that the shoals have developed into a flat-like area. In addition, siltation of fine particles has made the bed in the channel Rak van Scheelhoek more cohesive. As a result, the increase of tidal flow will be more equally divided over the flat-like shoals and attracted by the channel Slijkgat. The increase of flow velocities in the channel Rak van Scheelhoek will, therefore, be relatively less significant than it would have been in an earlier stage, with a deeper channel Rak van Scheelhoek. Additionally, Piekhaar and Kort (1983) found that consolidated fine sediments from the bottom of the Haringvliet are hard to bring in suspension again because of the high cohesive forces of the fine sediment particle, even during high river discharges. Both trends combined, decrease the potential of sediment export which can counteract the wave sediment supply as a result of wave forcing. To conclude it is expected that the area will slowly silt up if no significant measures will take place.

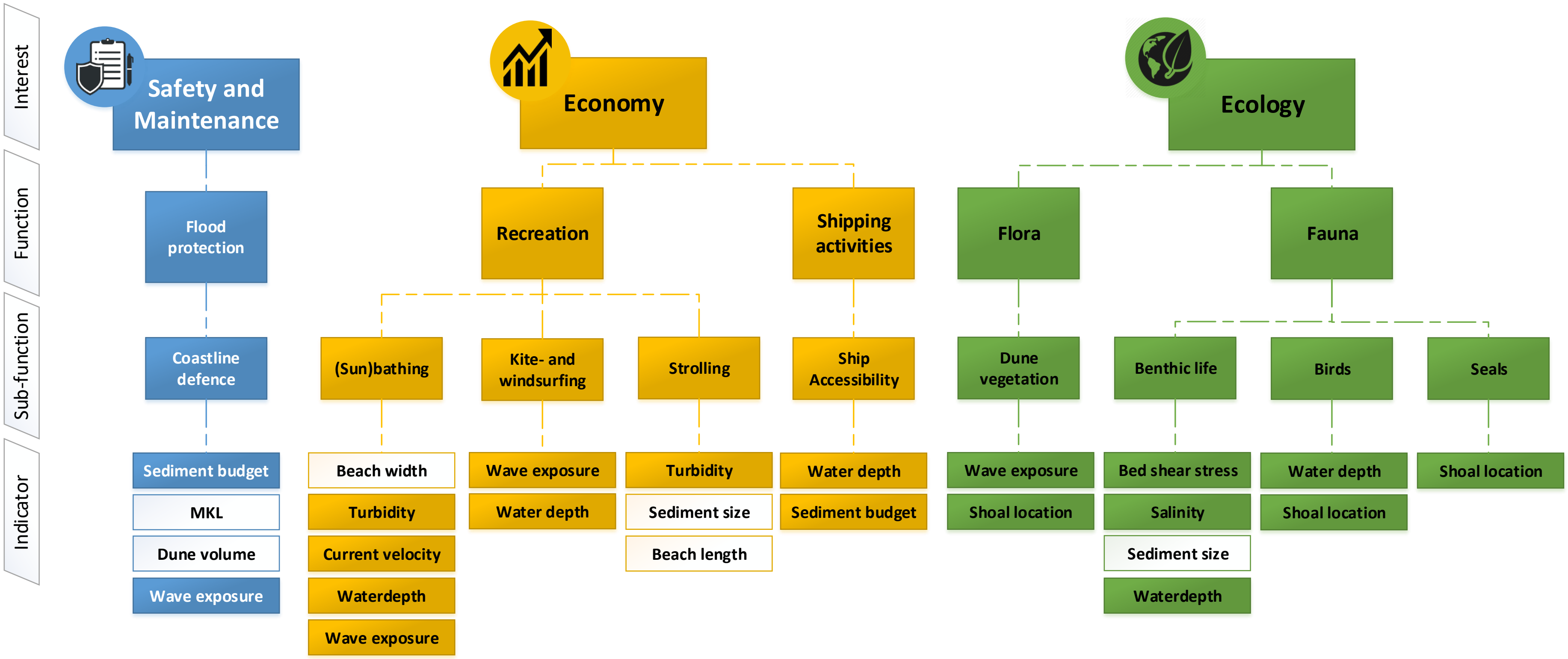


Fig. 6.15.: Stakeholder framework; Highlighted indicators are assessed in this research.

7 Indicator Assessment

7.1 Introduction

In this section the indicators derived in Chapter 3 are assessed based on the model results. The impact of the indicators on the stakeholders interest are assed by making use of the stakeholder framework that is established in Section 3.2. Based on the model results analysis in the previous chapter the different indicators can be evaluated and compared over time. The aim is to investigate the development of the indicators and assess the impact on stakeholder interests. In this chapter a proof of concept of the framework approach is given. Therefore, the defined sub-functions are only assessed based on the indicators highlighted in Figure 6.15. Again, one has to note that the sub-functions can be quantified with multiple other indicators. However, to suit the purposes of this research -giving a proof of concept- only the indicators derived in Section 3.4 are used. In the following sections the impact of the indicators on the sub-functions is assessed per sub-function.

7.2 Safety and maintenance

In this section the impact on the interest safety and maintenance is assessed by evaluating the indicator impact on the sub-function of the interest. The interest safety and maintenance is associated with the function flood protection. The sub-function of the function flood protection is coastline defence.

7.2.1 Coastline defence

As described in Section 3.4.1 the coastline defence system can be quantified with several indicators. In this research the sub-function coastline defence will only be assessed with the indicators sediment budget and wave exposure. The first indicator sediment budget relates the coastline defences to the sediment balance of study area. Hence, sediment budget is a measure to indicate the magnitude of sediment sources and sinks. The second indicator wave exposure determines the likelihood of dune erosion as a result of wave impact.

Sediment budget
As derived from Section 6.2 the sediment volume in the area increases and the area slowly silts up. When assessing the local processes the waves are dominant in terms of sediment transport. Due to wave breaking, the Maasvlakte 2 and the island of Goeree act as sediment sources, feeding the study area with sediment. The counteracting forces are the tidal currents and the discharge of the Haringvliet sluices. As found in the model results, both processes are not strong enough to

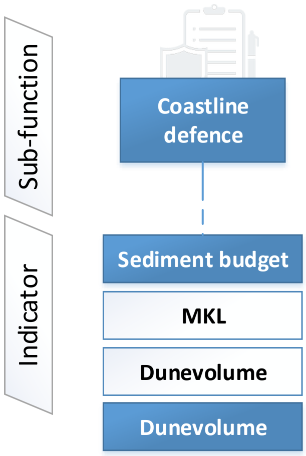


Fig. 7.1.: Indicators regarding safety and maintenance (Assessed indicators highlighted).

set sediment into motion and to export the sediments brought in by the waves out of the study area. Hence, the area slowly silts ups.

When approaching the area from a broader coastal system perspective, the study area can be regarded as a sink in the coastal system called the Voordelta. Hence, the system is importing sediment implying a positive sediment budget. Since the overall sediment budget increases in the study area (Elias, Van Der Spek, et al., 2017), the potential of flood protection increases at most of the sections along the coast of Voorne as well. According to Van Santen (2016) no safety issues are expected at the coast of Voorne until 2030. Based on this indicator, no safety issues related to coastline defence are expected in the study area. Based on this indicator the potential of coastline defence is likely to be enhanced.

Redistribution of sediment

Next to the sediment budget as an indicator for coastline defence it is important to consider the sediment transport along the coast. Insight in sediment transport can be used to get an understanding of the (re)distribution of the sediment and potential erosion spots within the study area.

From Section 6.3.1 the mean wave direction for the derived wave climate is analyzed. In this section it became clear that wave propagation direction offshore hardly gets influenced by the bathymetry. When waves propagate further towards the shore this changes: South-western originated waves are able to propagate into the study area and have the potential to reach the shore. However, in the most recent stages the shoals in front of the coast cause waves to break before they hit the coast. As a result, the area behind the shoals consists of mainly locally induced wind waves. When considering the direction of the waves, the amount of sediment transport is little to none. In addition the wave gradient along the shore is assessed to evaluate the potential of sediment transport. A gradual decrease of wave height along the coast can imply a reduction in potential sediment transport, which means potential siltation. However, as found in Section 6.3.3 the wave gradient along the coast of Voorne is not distinct enough to derive potential siltation along the coast.

Based on the model results the sediment transport potential has decreased over the years. Based on the gradient and propagating directions of the waves this potential from 2018 onward has decreased to an insignificant amount of transport along the beach of Voorne. So it can be concluded that the longshore transport along the beach does not lead to significant redistribution of the sediment. The overall trend is a gradual filling of the channel Rak van Scheelhoek based on Section 6.2.

Wave exposure

Wave exposure is the last indicator to assess the potential of coastal defence. An exposed and energetic wave climate acting on the coast can lead to severe dune erosion. In the stages before the construction of MV2 in 2014, dune erosion occurred at the tip of Voorne as a result of heavy wave exposure. Nourishments were needed to keep the profile of the shore in a sufficient safe shape. But from Section 6.3.2 it becomes clear that the relative amount of wave exposure at the coast has decreased over time. The shoals at the foreshore act as wave breakers for the coast of Voorne, reducing the mean significant wave height of the waves propagating towards the shore. As a result of bathymetry change, the depth in front of the dunes decreases, resulting in a more gentle slope towards the dunes. This gentle slope makes the coast more vulnerable to surges generated by local storms. However, this mechanism shrinks into insignificance compared to the wave reducing effects. In terms of flood protection and safety this potentially leads to less dune erosion and thus increasing the level of safety provided by the dunes.

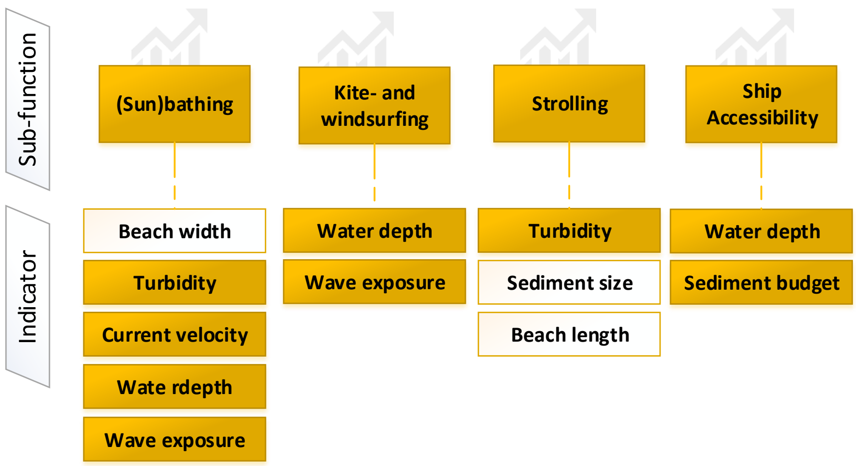


Fig. 7.2.: Indicators regarding economy (Assessed indicators highlighted).

7.3 Economy

This section will discuss the four sub-functions related to the interest economy. Three of the four sub-functions: 1) (Sun)bathing, 2) kite- and windsurfing, and 3) strolling are sub-functions of the function recreation. The fourth sub-function; ship accessibility is a sub-function of the function shipping activities.

7.3.1 (Sun)bathing

As depicted in Figure 6.15 the sub-functions (sun)bathing is assessed based on four indicators: 1) turbidity, 2) current velocity, 3) water depth, and 4) wave exposure.

Turbidity
From stakeholder sessions it was derived that the turbidity of the water column in the study area has increased over time. In this research the turbidity is assessed by evaluating two processes: 1) residence time, and 2) residual current. When assessing the residence time -depicted in Figure 6.11a- the residence indeed has increased in the period right after closure of the Haringvliet. In the stages after the closure of the estuary, the residence time decreases again. Hence, the replacement of the water mass happens faster than in the stages before. When combining the residence time with the average depth in the area, it was found that the potential of siltation in the study area indeed has increased in the period till 2000. However, in the period after 2000 the potential of siltation has decreased (Figure 6.12). As described in Section 6.6 this does not imply that there will be no siltation and turbidity. It implies at most the siltation and turbidity in the area will not change significantly compared to the stage before closure in 1964.

The analysis of the residual current shows that over the years the net currents in the area are directed towards the beach. Additionally it was found that the current velocities as a result of the tidal flow and sluice discharge are not significant enough to set sediment into motion and to remove the sediment out of the area. Hence, the study area has turned into a silt trap. Sediment particles that have accumulated over time are still present in the study area since no force has removed them out of the area. The fine particles in the shallow area in front of the coast are stirred up by the locally induced wind waves, causing an increase of turbidity in the water column in the area along the coast. The turbidity in the deeper parts of the area is most probably less severe, since the wind waves do not affect the bottom here. However, beach visitors mainly observed the turbid water column alongside the coast. Hence, perceiving the study area as a turbid.

To conclude, according to the hydrodynamic analysis turbidity does not increase in time. However, based on the analysis it can be concluded that at most the siltation and turbidity in the area will not change significantly compared to the stage in 1964 before closure. Therefore, it is assumed that the indicator turbidity has no explicit impact on the sub-function (sun)bathing.

Current velocity

As can be derived from Figure 6.7, the current velocities have decreased significantly after the closure. From 1972 until the most recent stage a slight increase trend of flow velocities can be observed. Local shallow areas can of high danger since the flow velocity can suddenly increase. However, the magnitude of these flow velocities is still too low to cause serious swimmer safety. To conclude, this indicator has no, to little effect on the potential of sunbathing since it does not significantly change the potential danger.

Water depth

From Section 3.4.2 it becomes clear that at least a depth of 1.5 meter is preferred by people visiting the beach. When assessing the evolving bathymetry in time it can be observed that the depth decreases. Directly after closure this trend did not influence the potential of (sun)bathing. However, in the most recent stage some zones along the coast have decreased to a depth under the minimum preferred 1.5 meter Figure 6.2. In this last, most recent stage, the decrease in depth has a negative impact on the potential of (sun)bathing.

Wave exposure

From Section 3.4.2 it can be derived that the significant wave height potentially affects the people visiting the beach. Light wave heights, up to 1.25 m, are most favoured by beach visitors (Zhang and X. H. Wang, 2013). From the model results it becomes clear that mean significant wave heights near the beach do not exceed this value in all stages. Therefore, every stage in time can be regarded as a situation with 'light wave heights'. As stated in Section 3.3.2 a different amount of wave exposure leads to different types of recreation. Where situations with higher exposure attract different people than milder wave conditions. A part of the people visiting the beach favours a more exposed wave climate. Since waves are a characteristic of the coast, it is assumed that offshore originated waves are preferred over locally induced wind waves. To conclude, the further decrease of wave height -given the fact that all the stages already can be regarded as a mild climate- has a negative impact on the potential of (sun)bathing.

7.3.2 Kite- and windsurfing

Another important sub-function of the function of recreation is kite- and windsurfing. The area is one of the main spots of surfers to go to along the Dutch coast. The sub-function kite- and windsurfing is assessed based on the indicators wave exposure and water depth (Figure 6.15.

Wave exposure

When assessing the indicator wave exposure for the sub-function kite- and windsurfing the mean significant wave height is assessed. Based on the change of this indicator over time a possible change in recreation potential can be observed. In Section 6.3.2 the change of mean significant wave height development is discussed. The wave height development of each defined transect decrease over each stage in time. Moreover, from the plotted figures in Section 6.3.1 the decrease in height over the area can be derived from the change in color and the length of the plotted direction arrows. Over time, the color shifts from blue towards yellow and the length of the arrows become smaller. This indicates a reduction of the mean significant wave height over time.

As stated in Section 3.4.2 the potential of sub-function kite surfing can be quantified with the factor distinguishing surf spots; the degree of wave exposure. Only waves which are smaller than 1 meter are considered to be suitable for surfing. When looking at the trend of wave height development a wave height decrease is favouring the potential of kite surfing in the study area. The shoals in front of the coast break the wave sufficient enough to ensure a mild enough wave climate for visitors to surf on. The main trend during the years is a decrease in wave height, implying an increase in kite- and windsurf potential.

Water depth

Next to wave exposure, the indicator water depth is used to quantify the potential of sub-function kite- and windsurfing. As stated in Section 3.4.2 a minimum water depth of 0.5 meter is required for surfing to be possible. Based on the vakloding dataset the mean water depth is assessed using this criteria. The depth which is smaller than the minimum water depth is shown dark red in Figure 7.3. In orange-red the area is indicated for which the depth can become critical during low water (1.0-0.5m to NAP).

From figure Figure 7.3 it can be observed that during the years shoals evolve and grow larger in size. From 1980 the shoals in front of the coast enhance a sheltered area from the waves, favouring surfing activities. However, in time the shoals migrate further towards the coast and the area Slikken van Voorne in the north east of the study area silt up. Where the availability of surf area already was limited due to nature conventions, accretion causes the reduction of the available surf area even more.

Additionally, the areas indicated in orange-red show the area just under the treshold of 0.5 meter. These areas can already be regarded as a 'danger zone' during low water, limiting the potential of available surf area. Moreover, these areas have the potential to silt up further, increasing the area where surfing is not possible. Based on the previously discussed sediment budget, it is assumed that accretion will continue in the future. To conclude, the potential of kite- and windsurfing is enhanced based on the observed trend in the stages assessed. However, in the long term this potential might decrease due to bathymetrical changes.

7.3.3 Strolling

The last sub-function to assess the function recreation is strolling. The sub-function strolling is in this research assessed based on the indicator turbidity. Although turbidity is mostly related

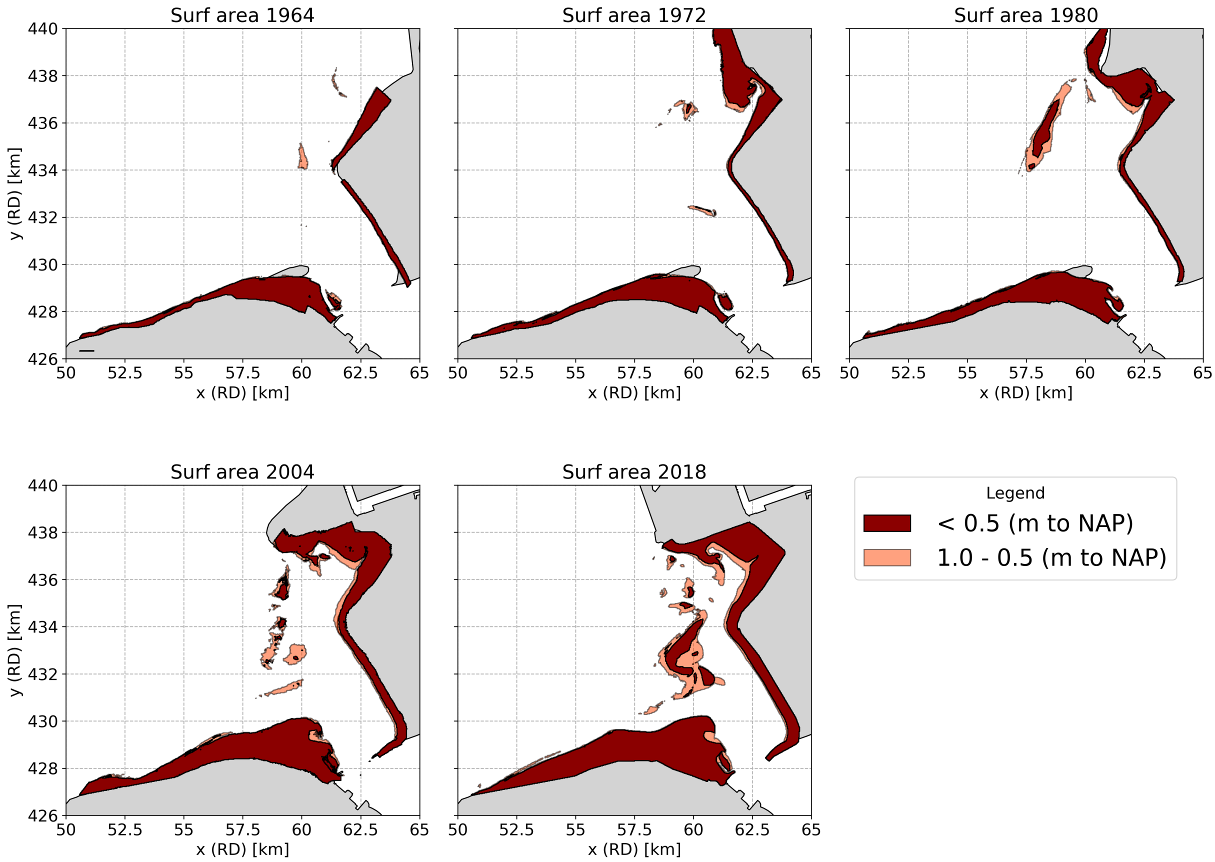


Fig. 7.3.: Available kite- and windsurf area.

to the quality of the water column, it can also be related to potential smell and nuisance on the shoreline.

Turbidity

Turbidity is in this research assessed based on residence time and residual current. in Section 7.3.1 it already became clear that at most the turbidity in the area will not change significantly compared to the situation in 1964 before closure. Additionally for every stage in time the direction of the net current in the area is directed towards the beach. The potential of smell and nuisance of accumulated fine particles and algae are does not change significantly compared to the situation in 1964. Therefore, it is assumed that the indicator turbidity has no explicit impact on the sub-function strolling.

7.3.4 Ship accessibility

Ship accessibility is a sub-function of the function shipping activities. In this research it is the only sub-function and therewith this sub-function directly quantifies the function shipping activities. The sub-function accessibility is quantified by the indicators water depth and sediment budget.

Water depth
A minimum water depth of 5.5 meters is necessary to ensure the passing of ships through the channel Slijkgat. However, this depth is maintained at this minimum criteria by dredging. Therefore, the indicator water depth remains constant for every stage in time and does not lead to an increase or decrease of the potential of shipping activities.

Sediment budget
Sediment budget is the main indicator quantifying the sub-function ship accessibility. As described in Section 3.4.3 the sediment budget can be related to dredging activities which have an impact on the potential of shipping activities. As found in Section 6.2, the sediment budget in the area is for every stage in time positive, meaning an increase of sediment in the area. As found in Figure 5.3 the observed trend of accretion slows down, resulting in a less severe decrease of the potential of shipping activities. Although the general trend of siltation in the area slows down, the siltation in the channel Slijkgat is assumed to increase since the relative depth compared to the surrounding area becomes larger. Therefore, for every stage in time, the indicator sediment budget reduces the potential of shipping activities.

7.4 Ecology

The interest ecology is associated with 2 functions: 1) flora, and 2) fauna. The function flora is in this research linked with the sub-function dune vegetation. The function fauna is related to three sub-functions: 1) benthic life, 2) birds, and 3) seals. In the following sections the indicators are assessed and their impact on the sub-functions is evaluated

7.4.1 Dune vegetation

Dune vegetation is a sub-function of the interest ecology as described in Section 3.3.3. In this research dune vegetation is assessed by evaluating the indicators related to saltspray; 1) wave exposure, and 2) shoal location (Figure 6.15.

Shoal location
As depicted in Figure 6.4 the shoals propagate towards the shore. Most waves break on these shoals. With the migration of the shoal towards the coast, the location of breaking moves also closer to the shore. The distance that a saline water particles has to travel to the dunes becomes shorter. Hence, the potential of saltspray is enhanced. However, the distance from the shoals is too large to have a significant effect. Therefore, this indicator is considered to have no effect on the sub-function dune vegetation.

Wave exposure
Wave exposure can be related to the amount of wave dissipation. As stated before, the change in H_{sig} can be related to the change of wave energy. When the height of the breaking waves

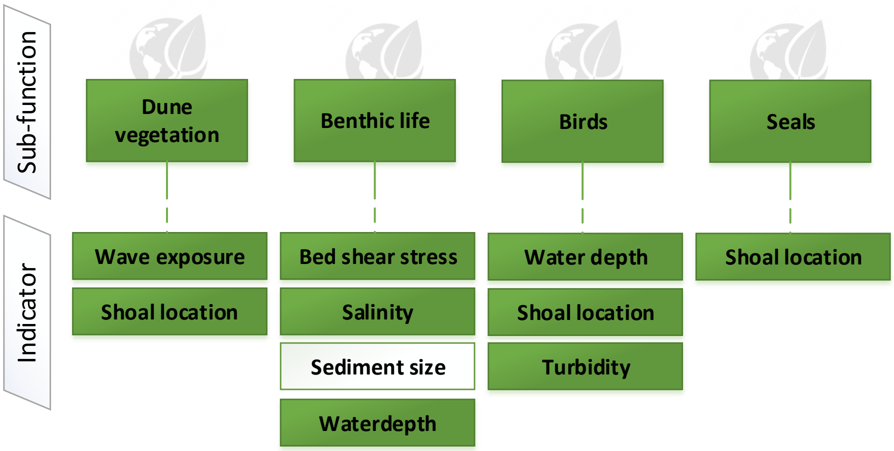


Fig. 7.4.: Indicators regarding ecology (Assessed indicators highlighted).

increases, the energy dissipation of breaking waves increases. By considering the trend in bathymetry change with a steeper foreshore migrating to the coast, the potential of higher waves breaking closer to the coast continues. From Figure 6.4 it can be derived that in time, the incoming (offshore) wave height increases. This is the result of bathemetrical changes; the foreshore becomes deeper and steeper. As a results the potential wave dissipation energy increases and thus saltspray increases. However, the waves breaking close to the shore are still smaller waves. The effect of a shift of breaking waves from offshore to the more nearshore can then be neglected

By considering the place of breaking and the intensity of breaking, it is expected that the effect of wave exposure on saltspray does not change in time. Based on both indicators no effect on dune vegetation is expected.

7.4.2 Benthic life

Benthic life is the first of the three sub-functions of the function fauna. The sub-function benthic life is assessed with four indicators as described in Section 3.4.5; 1) bed shear stress, 2) salinity, 3) sediment size, and 4) water depth. However, in this research sediment size is taken out of the assessment.

bed shear stress

As described in Section 3.4.5 a decrease in bed shear stress enhances mud accumulation in sheltered areas and therewith favours the growth of benthic life. When assessing the stages in time the bed shear stress decrease directly after closure. In front of the coast of Voorne, in the channel Rak van Scheelhoek, the bed shear stresses are significantly low, enhancing the potential of benthic life. In the areas around the foreshore and in the channel Slijkgat, flow velocities and wave action cause significant bed shear stresses which diminish potential benthic life in these areas. Therefore, the main area of interest is the area Slikken of Voorne and the area Slijkgat. In the area Slikken van Voorne a little increase of bed shear stresses is observed. In the most recent stage in time (2018) the stresses have slightly increased in the area Slikken of Voorne. The bed shear stresses in the channel Rak van Scheelhoek keep significantly low. To conclude based on this trend the indicator bed shear stress has no significant impact on the potential of benthic life. However, in the long term the increase in bed shear stresses is likely to decrease the potential of benthic life.

Salinity
The study area lies in the transition zone between fresh and saline water. As found in Section 3.4.5 a high biodiversity can be found in freshwater and saline water. A minimum diversity is found in brackish water (Bouma et al., 2005). As found in Section 6.7, during the first stage in 1964, the Haringvliet estuary was open and the water was inside the estuary was mostly fresh. The transition zone between saline and freshwater was located in the study area. Therefore, the water in the area can be regarded as brackish in this stage in time. Following Bouma et al. (2005) brackish water is associated with a low biodiversity. Directly after closure the area became more saline, meaning that the biodiversity would have increased. However, in time the area became less saline and more brackish as found in Section 6.7. This implies a potential reduction of the biodiversity and a decrease of the benthic life potential.

7.4.3 Birds

The potential of birds is assessed with three indicators as described in Section 3.4.5. These are: 1) water depth, 2) shoal location, and 3) turbidity.

Waterdepth
Based on the indicator water depth the potential of birds has increased in time. With the decrease of depth, more areas became available for birds to settle and to forage on.

Shoal location
The shoal location has propagated in time as observed in Section 6.2, however, this propagating has not lead to significant changes for the birds. The shoals are still disconnected from the mainland, keeping predators away. Therefore, shoal location is considered to enhance the potential of birds

Turbidity
Turbidity in the water column can hinder the bird species hunting on eyesight. As discussed before, the study area has turned into a silt trap, and turbidity is not expected to decrease significantly. Since the change in turbidity is expected to be insignificant, turbidity is considered to be of no influence on the potential of birds.

7.4.4 Seals

The last sub-function of the interest ecology is the seals potential. As described in Section 3.4.5 the potential of seals is quantified with the location of the shoals.

Shoal location

When assessing the potential of seals, human activities must keep situated at a minimum of 500 meter from the resting places of seals as described in Section 3.4.5. In time, both merging of the shoals with the mainland and shoal propagation closer than 500 meters to human activities are not under discussion in the assessed stages. Therefore, it can be concluded that shoal location is enhancing the potential of seals.

7.5 Overview indicator impact on sub-functions

In this section an overview is given of indicator impact on the sub-functions as discussed in the previous sections. The main interest are represented by their symbols on the left side, the associated sub-functions are shown in the interest associated colored box. The green arrows indicate that the observed indicator trend enhances the potential of the sub-function. The red arrows indicate a diminution of sub-function potential based on the observed trend of an indicator. In cases where the indicator had no direct influence on the potential of a sub-function the results in the table are indicated with a blank stripe (provided that the indicator has a relation with the sub-function).

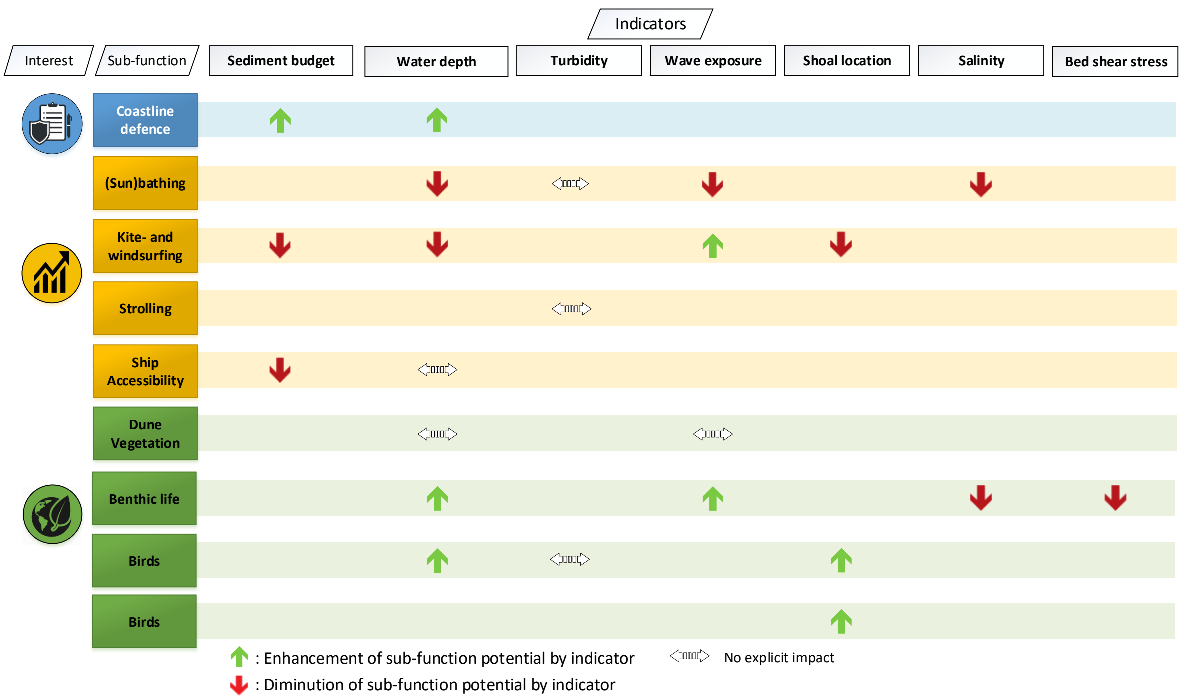


Fig. 7.5.: Overview indicator impact on sub-functions.

8 Discussion

Before presenting the main conclusions that follow from the analysis of data and model results, first a critical reflection is required on the conducted research. In the setup of this research, several assumptions and simplifications have been made to capture the complex problem into a concise scope. The reasoning behind the choices will be explained in this chapter, together with the limitations that arise from them. This chapter provides a discussion on the methodology, the framework, and the future development of the study.

8.1 Framework limitations

When linking the main characteristics of the coastal, societal and ecological systems to eachother, simplifications are necessary. Although a dynamic area such as the coast of Voorne is subjected to many interests, only three main interests are considered in this research. To account for all concerns in the region, more interests and associated (sub)-functions need to be defined. However, it is not within the scope of this research to assess all those interests with their (sub) functions. This research aims to give a proof of concept of the use of a values and interest framework. Therefore, a choice has been made to address only the main important interest with their associated sub-functions which is derived from the stakeholder meeting performed by Bergsma (2018).

When establishing the framework to connect the sub-functions in the area to physical indicators, a distinction was made between the potential of a sub-function and the actual use of the function. The results of this study is an analysis of the physical capacity of the sub-functions, the actual use of sub-functions depends on multiple other factors. Moreover, a value increase of one function can lead to a value decrease of another function: e.g. a value increase of surfing can lead to a value decrease of ecology. When assessing the results more qualitatively, these additional factors should be evaluated and the relationship to the sub-function should be validated.

Not all indicators could be assessed correctly based on the the model results. Some indicators -e.g. dune volume- can be assessed more accurate with other models. Moreover, due to time restrictions not all indicators could be evaluated. Therefore, the choice has been made to only assess the indicators which could be assessed with the Delft3d model. As stated before, this research aims to give a proof of concept of the framework. Based on this it is assumed that the analysis done gives a representative evaluation of the framework and the development of the potential of the sub-functions. The next list gives an overview of the missing indicators and the effect on sub-function potential.

- **Coastline defence**
  The indicators MKL and dune volume are not assessed in the analysis. Especially dune volume is a critical indicator in the assessment of coastal safety. By assessing the coastline safety, it is therefore important to consider the possible impact of this missing indicator. Sediment budget alone does not suffice to give a representative assessment of the potential of coastline defence
- **(Sun)bathing**
  For this sub-function the indicators beach width is not assessed. From the model no direct derivation of beach width is possible since the landward border of the beach is not defined. Nevertheless, it is assumed that this indicator does not influence the potential of (sun)bathing since the width of the beach remains fairly constant in time.
- **Strolling**
  Considering the sub-function strolling, the indicators beach length and sediment size are missing in the analysis. The length of the coastline does not change significantly as already stated in the section about beach width. The indicator beach length can thus be considered constant. Hence, the indicator beach width does not effect the potential strolling in this research. The sediment size cannot be retrieved from the model since morphology is not included in the model. The shoals in front of the shore make is hard to get an indication of the sediment size based on the slope of the shore. Moreover, no sufficient data was available to assess this indicator. Although the former two indicators are not applicable, the indicator residence time in combination with residual current can give an adequate estimation to assess the potential of strolling.

Indicators in this research are chosen based on model assessment applicability. In reality far more indicators can be applied to assess the potential of the sub-functions. Especially for the interest of ecology. When considering different species of flora and fauna, this interest consists of far more sub-functions than established in the framework. These sub-functions all come with additional indicators. However, the aim of this research is to give a proof of concept of the framework approach. To include all the sub-function and associated indicators related to the interest of ecology, more research is needed.

8.2 Modeling methodology limitations

In general, the use of a model inevitably leads to inaccuracies when representing reality. To set up a model, assumptions need to be made when defining the boundary conditions and physical parameters. The physical parameters were adopted from the calibrated and validated MV2 model by Adema (2016). This model was validated for the hydrodynamics in the area of the Maasvlakte2. Since, the new model used for this research uses a different grid different new bathymetry data, it is not sure whether the data from the MV2 model can be adopted without a new validation. Therefore, the model results should be applied in a qualitative way.

The bathymetric analysis is based on echo soundings made by Rijkswaterstaat, collected in the Vaklodingen dataset. The measurements and processing of these datasets sometimes lead to inaccuracies and uncertainties in the data. Years with abnormal changes in the dataset are therefore excluded from the analysis. Bathymetry data of the stages that are assessed are assumed to be representative to evaluate the coastal processes for that stage in time. Moreover the vaklodingen data was only available for the Voordelta. The bathymetry further offshore and north along the Dutch coast were all based on the data provided by kuststrook model of 2014. Although these issues lead to inaccuracies, it is assumed that they are not of large significance for the quantitative comparison of the processes.

With the increase of sediment budget in the study area, the average depth decreases and the discharge through the Haringvliet gains in relative importance. However, the daily discharges through the sluices are represented by an average discharge derived from an older study. The discharge is regularly enforced by the sluices, creating a constant flow in the study area. The influence of extreme and low discharge regimes are therefore not taken into account. Moreover, the seasonal variability of the discharge is not considered either. To obtain better insight into the year round influence of different discharge regimes, further research is needed.

Waves are considered the most dominant forcing mechanism and a large part of the analysis is based on the offshore imposed wave conditions. The wave climate has been schematized to the two most frequently occurring wave directions using a manual schematization technique based on wave induced longshore transport. In this research, this wave climate was also used or other processes not related to wave induced littoral drift. Nonetheless, this approach is considered to be sufficient for a first quantitative analysis of the processes. To get more accurate results, expansion of the wave climate and other wave climate reduction techniques need to be considered.

8.3 Future development

The future development of the Haringvliet outer delta is uncertaint. New human interventions can alter bathymetrical changes and even anthropogenic events can have a significant influence in the development of the area. Nevertheless, the major part of the development of the system is determined by the natural and regular hydrodynamic forcing. This consideration is taken into account when assessing the long-term development of the area.

Evolution of the coastal system inherently induces changes in societal and ecological systems. The perspective of stakeholders changes over time, which can lead to a new quantification approach of the indicators. Moreover, the value of some functions can be depreciated in such amount that its potential reduces to zero; e.g. the area can silt up in such extend that it is no longer possible to surf in the area. Subsequently that function can be left out of the framework. But also the opposite is true, due to coastal development certain functions, such as ecotourism, can arise and give extra value to certain interests. For this research it is assumed that the framework with its functions remains constant over the assessed period. However, when assessing future development, framework modifications need to be considered.

Finally, this research does not take the effect of sea level rise on the development of the coast system into account. The average absolute sea level rise along the Dutch coast over the period assessed (1964-2018) was in the order of 9 to 10 cm (Leefomgeving, 2018). Although small, this relative increase has its effect on the hydrodynamics and thus on the development of the outer delta of the Haringvliet. When qualitatively assessing the processes over time this effect should be considered. Although this is a slowly ongoing process, it will have a significant impact on the long-term morphodynamics of the area (Passeri et al., 2015).

Conclusions

9

The objective of this research is to link stakeholder values and interests to physical processes along the coast of Voorne and assess the impact of coastal development on the societal en ecological system over time. In this chapter, the main research question is answered by presenting the answers and conclusions to the sub-questions as defined in Chapter 1. Finally, the answer is given to the main research question.

9.1 Research sub-questions

In this section answer is given to the sub-questions defined in Section 1.2.

1. Who are the stakeholders and what are their associated values and interests related to the coast of Voorne and how can they be linked to coastal processes?

In the dynamic area such as the study area, many stakeholders are present. The main stakeholders associated with the study area are the municipalities Westvoorne, Hellevoetsluis, Brielle and Goeree-overflakkee, the province of South-Holland, the water authority 'Hollandse Delta', Rijkswaterstaat, the port of Rotterdam and multiple nature parties. The values and interests related to the coast are referred to as interests in this report.

The interests regarding the coast of Voorne can be divided into three main categories: 1) safety and maintenance, 2) economy and 3) ecology. These main interests can subsequently be divided over multiple functions and sub-functions, which give value to the interests. To quantify the functions, indicators are defined. Indicators are quantifiable parameters that can be measured in practice or assessed by model results. Based on criteria, these indicators specify whether the potential of a (sub-)function is enhanced or diminished. To get consistency in the analysis, a governing framework was established to link interests with functions, sub-functions and indicators.

The sub-function associated with the interest safety and maintenance is coastline defence. This sub-function can be assessed based on the indicators sediment budget, MKL (Current Coastline) and dune volume. The interest economy is divided into four sub-functions: 1) (sun)bathing, 2) kite- and windsurfing, 3) strolling and 4) ship accessibility. The indicators linked to (sun)bathing are beach width, water residence time, current velocity and water depth. The sub-function kite- and windsurfing is quantified by the indicators wave exposure, and water depth. Strolling can be assessed with the indicators turbidity, sediment size, and beach length. The final sub-function of the interest economy is ship accessibility which is quantified with the indicators water depth and sediment budget. Finally, the interest ecology can be related to multiple functions and sub-functions. In this research the functions of ecology are flora and fauna, the associated sub-

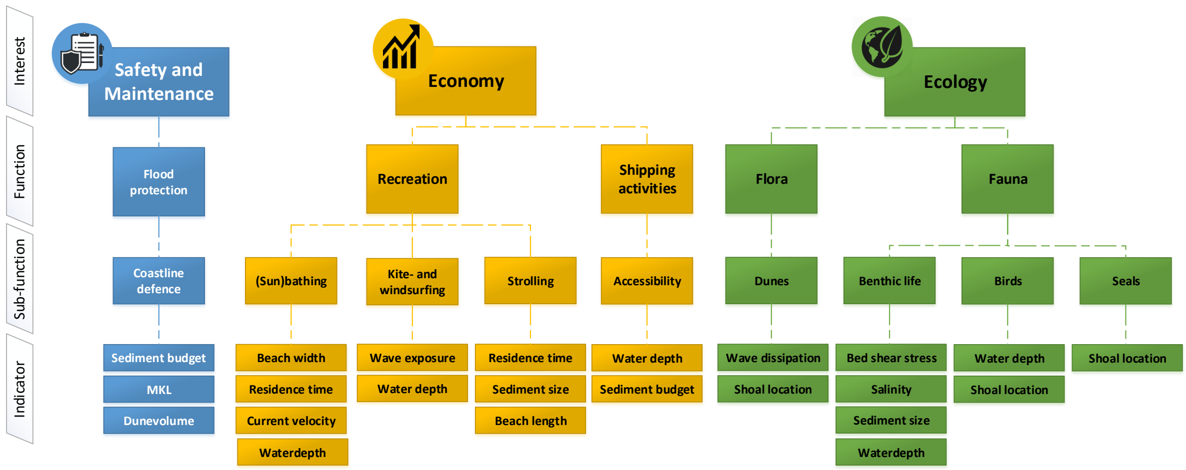


Fig. 9.1.: Stakeholder framework.

functions are: 1) dune vegetation, 2) benthic life, 3) birds and 4) seals. The sub-function dune vegetation can be linked to saltspray, which can be quantified with the indicators wave dissipation and shoal location. Benthic life is quantifiable with bed shear stress, salinity, sediment size and water depth. The potential of birds can be linked to water depth and shoal location. Finally, seals are quantified with the indicator shoal location. To conclude stakeholder interests can be linked to coastal processes using (sub-) functions and indicators. The connection between the interests and the indicators are incorporated in a stakeholder framework as depicted in Figure 9.1.

2. What are the important physical coastal processes related to the beach of Voorne and how did they change over time?

The dominant processes are assessed by analysing various stages in time. In this way the development over time is evaluated. In the first stage in 1964, the estuary was still connected to the sea. The system was in a dynamic equilibrium in which the tide was dominant. The mouth of the estuary, consisted of a dynamically stable ebb tidal delta. During this stage, the coast of Voorne had an 'open' character with high flow velocities and relatively high wave exposure along the coast. When in 1970 the estuary was closed off, the tidal current velocities reduced significantly and the relative influence of the waves increased.

The relative increase of wave exposure induced shoal development in front of the coast. The shoals grew higher and migrated further towards the coast. Although the relative importance of the waves increased, the absolute wave height along the coast decreased. The development of the shoals caused more waves to break, reducing the mean significant wave height of the waves acting on the beach. In the most recent stages in time, almost all waves propagating from offshore to the coast tend to break on the shoals. As a result, the area behind the shoals mainly consists of locally induced wind waves.

The influence of the tide decreased after closing off the estuary, the magnitude of the associated current velocities decreased with it. However, after closure of the Haringvliet, the system tends to develop towards a new equilibrium. While the shoals propagate landward as they grow in height, the (former) mouth of the estuary area silts up. With the decreasing depth, the relative influence of sluice discharge in the study area increases. In time bathymetrical changes induced a shift in flow patterns. The flow got repelled by the developing shoals and attracted by the channels. This shift caused the flow velocities to increase in the channels and decrease over the shoals. The channel Slijkgat, as opposed to the channel Rak van Scheelhoek, is dredged frequently. This artificially maintained constant depth increases the relative importance of this channel as a discharge channel. As a result, the net current in the channels -mainly the channel Slijkgat- increased over time. The general direction of the residual currents remained the same over the years. The net currents in the channels is mainly directed to the shoals and towards the coast of Voorne. The direction of the residual currents flowing over the shoals is offshore directed. The associated magnitude of the residual currents decreases over time.

3. How can the change in coastal processes related to the coast of Voorne be linked to stakeholder values and interests over time?

The impact on stakeholder interests is assessed by linking the indicator analysis to the potential of the defined sub-functions. The decrease of the indicator wave exposure has its effects on the potential of sub-functions coastline defence, (sun)bathing, kite- and windsurfing and benthic life. A main trend of mean significant wave height decrease along the coast of Voorne has been observed. This decrease favours the sub-functions coastline defence and kite- and windsurfing. The potential of coastline defence increases since the decrease in wave exposure leads to less dune erosion. Moreover, a positive sediment budget means further accretion, favouring coastal safety. When assessing the sub-function kite- and windsurfing the decrease in wave height enhances the potential of the sub-function since waves are more often mild enough to surf on. However, the decrease in wave height is unfavourable for the sub-functions (sun)bathing and saltspray. The lack of waves potentially withholds people from visiting this specific beach, decreasing the potential of the sub-function (sun)bathing.

The change of the residual flow in time shows an increase of flow velocities in the channels and a decrease of the flow velocities over the shoals. Relating the residual currents to sediment transport, the increasing currents in the channels cause a trend in sediment flux towards the beach of Voorne and towards the shoals. Based on this trend it is expected that more mud and dirt -which is present in the water column- will settle on the beach. Locally induced wind waves stir up the sediment close to the coast, causing a turbidity of the water column along to the beach. This process is perceived as a nuisance for beach visitors. Hence, the potential value of the sub-functions (sun)bathing and strolling decreases.

When looking into the interest ecology, further decrease of wave height along the coast would also have its impact on dune vegetation. Landward moving shoals cause offshore originated waves to break closer to the shore. The height of waves breaking on the shoal increases over time, because the foreshore of the shoals become steeper. However, when assessing the impact of wave exposure on the sub-function dune vegetation, the location of wave dissipation is located too far away from dune vegetation to have a notable effect; The waves behind the shoals only consist of locally induced wind waves, which have limited to no effect on dune vegetation. The potential of benthic life is favoured by the decrease of wave exposure since the dynamics in the area decrease. Besides, the potential of benthic life is enhanced by the decrease of depth since it favours the biodiversity. However, as opposed to the latter two trends, the decrease of salinity levels decreases the potential of benthic life. In a brackish environment less biodiversity is expected than in a saline environment. It is assumed that salinity differences have no notable effect on the potential of the other fauna species, birds and seals. When assessing the indicators of both these species, both the potential of birds and the potential of seals are likely enhanced. The emerged shoals provide resting places for both species. Furthermore, the decrease of depth favours the potential of birds; the shallow areas fall dry more often, providing more foraging area for the birds. Concluding, the change in physical coastal processes is enhancing the net potential of ecology.

4. What is the expected future development of the physical coastal processes and how does this impact stakeholder values and interests?

The former mouth of the Haringvliet is developing towards a new equilibrium. Based on the observed trends, the study area is likely to further accrete. The shoals migrate further towards the shore to restore the gradient in longshore transport. The channel Rak van Scheelhoek is likely to silt up further since there is no significant force counteracting the accretion. The area in between the shoals and coast will get the characteristics of a lake-like area. Offshore originated waves break on the shoal and are not able to reach the coast. As a result, waves near the coast only consist of locally induced wind waves.

The tidal flow reduces further since shoal development limits the possibility of a circular flow through the area. The channel Slijkgat is frequently dredged, maintaining a constant depth. This alters the development towards a new equilibrium. The area has already accreted to such an extend that the shoals have developed into a flat-like area. The channel Slijkgat attracts relatively more flow compared to the channel Rakvan Scheelhoek inducing a positive feedback loop. The flow velocities in the channel Rak van Scheelhoek reduce and the flow velocities in the flow attracting channel Slijkgat increase. When relating flow velocities to sediment transport, the Channel Rak van Scheelhoek is likely to silt up further. In addition, siltation of fine particles have made the bed in the channel Rak van scheelhoek more cohesive. The increased cohesive bed requires higher bed shear stresses to set sediment into motion. Hence, the cohesive bed reduces the likelihood of erosion.

Finally, a decrease of salinity levels is expected since the relative importance of the Haringvliet discharge increases. The shallow, saline area is easily flushed by the freshwater sluice discharge. Due to density difference the discharged freshwater favors the water surface layer. As a result, the freshwater lens will be relatively dominant on the shoals and in the (shallow) area near the coast. To lowering of the salinity levels enhances the lake-like perception of beach visitors.

The development of the coastal system inevitably induces changes in the societal and ecological system, influencing stakeholder perspective. When assessing the sub-function coastal safety this future trend favors flood protection. The sediment budget increases and wave exposure decreases. Considering the interest economy all sub-functions are expected to decrease in value. The decrease in water depth and wave height results in a decrease of the potential of (sun)bathing; beach visitors prefer deeper bathing water and higher waves.

In time the area has turned into a silt trap. The lack of forces counteracting the waves cause sediment particles to accumulate in the area. The particles alongside the beach are stirred up by the locally induced wind waves. This causes a nuisance for beach visitors and decreases the potential of (sun)bathing and strolling. The potential of kite- and windsurfing is likely to be affected by shoal migration and accretion of the area. The decreasing depth causes a further reduction of surf area, decreasing the potential of the sub-function kite- and windsurfing.

In contrast to the interest economy, ecology is likely to be enhanced based on the trend observed in physical coastal processes. The potential of dune vegetation is expected to remain as it is. Offshore originated waves are breaking closer to the shore, but are not breaking close enough to be of significant effect on dune vegetation. Following the trends in siltation and wave exposure, it is likely that the potential of benthic life will increase. It is presumed that the decrease of salinity levels will not have a significant impact on this potential. Moreover, the potential of birds and seals is likely to increase further since more shoals will emerge. However, a note must be placed that when the shoals will propagate too far landward, possible nuisance by human activities can lower the potential of both species.

To conclude, the coastal system of Voorne is a very dynamic system that has been subjected to many changes. The system is developing towards a new equilibrium, inherently changing the societal and ecological systems. While developing towards this new equilibrium, the societal interest safety and maintenance and the ecological interest ecology will increase in value. However, following this autonomous development, it is expected that the value of the interest economy will only decrease.

9.2 Main research question

The main research question as defined in Section 1.2 is answered in this section.

How does the evolution of the coast of Voorne impact stakeholder values and interest?

After the closure of the estuary in 1970, the mouth of the estuary was forced out of dynamic equilibrium. The influence of the tide on the system decreased significantly and the relative importance of the waves became increased. This shift enhanced landward driven sediment transport, causing erosion of the foreshore and growth of the sandy shoals in landward direction. Meanwhile the decrease in current velocities turned the study area into a silt trap; There is no force strong enough to counteract the sediment input induced by the waves. The bathymetrical development of the study area lead to a decrease of the wave height along the coast. Besides, the salinity levels along the coast decreased, while siltation continued to proceed.

This development of the coast has its impact on stakeholder values and interests. The interest safety and management is enhanced since the sediment budget increased and wave exposure decreased. The interest economy, which is mainly based on recreational activities, is negatively impacted. The decrease of wave height, salinity levels and depth, in combination with a turbid water column turns the area into a lake-like area. This alternation of the area is not desired by the beach visitors, negatively impacting the interest economy. Finally, the interest ecology is enhanced by the evolution of the coast. The dynamics and the water depth decrease, creating larger nursery, resting and foraging areas and thus enhancing the potential growth and flourishing of multiple species.

10 Recommendations

In this thesis a first step is taken towards quantification of the interests associated with the coast of Voorne. Nonetheless, several recommendations can be made regarding the set-up of the framework and the numerical model study which is performed to support this quantification.

10.1 Framework approach

The assessment of stakeholder values and interests comes with a wide spread of uncertainties. Simplification and generalisation are made that lead to recommendations for future research.

- The first recommendation is to further validate the indicators that quantify the potential value of sub-functions. Although a linkage between indicators and sub-functions is has been established, it is important to know how strong these connections are and how the indicators really influence the potential of sub-functions. More field data is needed to obtain the correct relation of each linkage. Once established, quantification of the sub-functions can be realised using weighted indicators.
- In addition to the previous recommendation, the validation of indicators can give insight more in potential new indicators. On the other hand, one may hit upon certain indicators that can be neglected in the quantification of sub-function potential. From this an updated framework can be established that makes a stronger translation of the impact of physical coastal processes to stakeholder interests.
- Lastly, the current framework is specifically developed to suit the Voorne case. Although the core of the framework is widely applicable, some features included in the framework are case specific. For other coastal areas, other sub-functions or indicators may be needed. To make the framework more widely applicable, further research -e.g. surveys or assessment of nature development plans- and development of the framework is needed.

10.2 Numerical model

A model will always remain a schematization adhering to a certain level of detail and, as a result, will never fully represent reality. Model studies invariable require assumptions, inherently come with simplification and therewith uncertainties. The numerical model used for this study was set-up with adequate care and its accuracy was subsequently validated. It is therefore the opinion that the model was applicable for this study. Nonetheless, recommendations can be given to increase the reliability and applicability of the model. In this subsection recommendations are given for model improvement and future use.

10.2.1 Model improvement

- Model calibration is required to obtain a better quantification of the impact of physical processes. This research is aimed at assessing the development of indicators based on their change over time. By using a calibrated model not only the relative change can be assessed, but also the absolute change. Moreover, model refinement is needed to obtain more detail in the areas of interest. In the current model the grid in the area of interest is too coarse to obtain the right level of detail. Especially when assessing the nearshore processes. Here, flooding and drying has a big impact on the development of processes along the coast. However, the model fits the purpose of this research, assessing physical coastal processes and link them to stakeholder values and interest. When continuing with this model, it is highly recommended to reconsider the grid which has been used for this research. Although it has proven its functionality in the research conducted, it lacks area specific detail and computation times can become rather large. Grid consideration that can be taken is a further local refinement of the grid along the coast of Voorne. A better option when looking to hydrodynamic forcing only, is to convert the grid and its properties to Delft3D-Flexible Mesh, allowing for a greater degree of freedom when refining the computational grid.
- In the study conducted, a simplification of river system is made. The river boundaries are enforced on the model as a relatively high constant discharge. Sluice discharge is modelled as a constant discharge as well. In reality the delta system is far more complicated and the flow distribution depends on multiple factors. River runoff fluctuates and differs per river branch and the distribution of river runoff depends on different factors, e.g. (mainly) the salt intrusion in the Nieuwe Waterweg. To investigate the impact of these simplifications, a sensitivity analysis is needed. The magnitude of river runoff can be varied to assess the effect of river runoff. This can be done using a time series. Different sluice policies can also be implemented as discharge time series at the place of the sluice in the model grid. Moreover, RTC-tools can be used to simulate different sluice policies. In this way the opening of the sluices can be made condition dependent. Hence, the effect of different policies be assessed in more detail.
- The morphological response of the system is in this study evaluated by assessing the change in hydrodynamic conditions. Although this gives a good first impression of morphological response, morphology processes can be incorporated in the model itself to get a better insight of morphological response. Especially to get a better insight in area specific shoals and channels. When doing so, it is important to distinguish sediment fractions. In other studies (Colina Alonso, 2018; Ledden, 2003) it was found that the accumulated mud particles in the area influence the erosion and siltation patterns, affecting the morphological response.
- The assessment used for all indicators is based on the derived wave climate to represent longshore sediment transport. To assess the impact of each indicator in a more representative manner, the indicator specific boundary conditions should be derived. To assess the impact of wave height along the beach on beach recreation, the wave height does not have

to be scaled. In addition, different scenarios with these newly derived boundaries should be tested to get a better assessment of the indicators.

10.2.2 Future use of the model

- The model incorporates a large part of the Dutch river delta and a part of the North Sea to make it is suitable for the study of the interaction between river runoff and certain Haringvliet sluice policies. As stated before, RTC-tools can be implemented to represent different sluice policies. Although the model is still relatively coarse, it can be used to get a first impression of the large scale processes.

- When model calibration is improved, the model can be used to study the salt intrusion in the estuary. Moreover, a more detailed assessment of the freshwater plume in the mouth of the estuary can be obtained. To do so, it is recommended to use a Z layer approach instead of sigma layers which are used in this study, as described in Section 4.2.1. The assessment of salt intrusion can be put to use on different aspects: e.g. the assurance of drinking water provision in the estuary and the ecological response within the estuary, also in relation to the new behaviour of the system as result of the Kierbesluit.

- This study focused on the coast of Voorne. Since the model is not only refined in the area of interest of this research, it can also be applied to other areas of interest within the model domain: e.g. to assess the impact of human interventions on hydrodynamic conditions per stage in time in the Nieuwe Waterweg or in the areas further up north along the coast.

- Lastly, when morphological processes are added to the model, the trend in morphological response can be derived in more accurate. With this increased insight, future development and the associated time scale can be derived in more detail. In addition, potential measures to alternate to autonomous development can be implemented in the model to investigate the response of the system on these measures.

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Appendices

Literature background

A

A.1 Delta's and tidal basins

Delta morphology and geology are primarily the product of an interplay between fluvial sediment input and reworking of sediment by marine or lacustrine processes (Galloway, 1975). Deltaic progradation is modified primarily by tidal currents and wave surge. Coastal systems can be described based on the relative importance of wave versus tidal energy and sediment transport to characterise a prograding or transgressive coast. Following Galloway, 1975 marine deltas can be classified into three types: 1) fluvial (river)-dominated deltas, 2) wave-dominated deltas, and 3) tide-dominated deltas. These classes are depicted in Figure A.1.

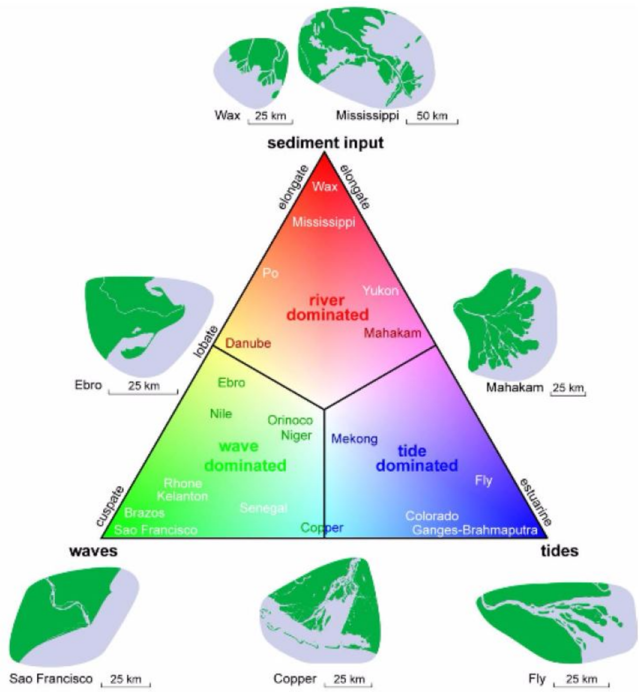


Fig. A.1.: Delta classification by Galloway, 1975.

The overall morphology of marine deltas depend on the combined action of waves and tides. Tides fill and empty the basin via channels that cut through lower and higher tidal sand and mud flats, while the waves coming from the sea interact with the tide and delta morphology to act as a 'bulldozer' pushing the offshore directed sediment flow back to the shore. River influence determines the availability of sediment which can be seen as a building material to enable the growth of the delta. One of the features of a delta is the tidal inlet. A tidal inlet can be characterised as an opening in the shoreline which connect bays or lagoons to the open sea or ocean (Bosboom and Stive, 2015). Based on the entrance characteristics and the influence of freshwater run-off three distinct types of tidal basins can be classified:

Tab. A.1.: Basin classification.

Type of Basin	Characteristics
1. **Tidal lagoons**	• Enclosed by wave-shaped barrier islands or spits • High level of wave dissipation • Limited freshwater run-off
2. **Tidal bays**	• Absence of barriers; open to deep water • Low wave energy due to depth-limited breaking • limited freshwater run-off
3. **Estuaries**	• Development of spits, shoals or barriers near the mouth • Tend to be tide dominated, limited wave influence • Freshwater run-off

The development of inlets is linked to the tidal range. The surface area of the basin, in combination with the tidal range defines the tidal prism; the volume of water that flows in and out through the tidal inlet during one tidal cycle. An empirical relation holds between the cross-section of the entrance channel and the tidal volume. How bigger the tidal volume, how bigger the flow area needed. When the tidal volume increases, the area will move towards a new equilibrium, resulting in erosion of the cross-section channel. For a short basin, the tidal prism is usually estimated by multiplying the mean surface area of the estuary by the mean tide range in the estuary, however, this is only valid in cases were river discharge can be neglected.

As Colina Alonso, 2018 already discussed in her research, some relations hold between the characteristics of a tidal inlet. LeConte, 1905 discovered the relation between the cross-sectional area of a tidal inlet and the tidal prism. This relation was later modified by O'Brien, 1969, he found that the equilibrium minimum flow area of an inlet is controlled by the tidal prism which leads to the following relation:

$$A_{eq} = CP^q \tag{A.1}$$

In which:
- A_{eq} = Minimum equilibrium cross-section of the entrance channel, below MSL $[m^2]$
- P = Tidal prism $[m^3]$
- C = Empirical coefficient $[m^{2-3q}]$
- p = Empirical coefficient [-]

Eysink, 2012 found that not only a relation holds for the tidal prism and the entrance of the channel, but also between the tidal prism and the total channel volume of the tidal basin:

$$V_c = C_v P^{3/2} \tag{A.2}$$

In which:

- V_c = Equilibrium total channel volume, below MSL $[m^2]$
- P = Tidal prism $[m^3]$
- C_v = Empirical coefficient $[m^{-3/2}]$

The relationships can be helpful to determine in what way the coastal system will respond to changes in the existing dynamic equilibrium of tidal inlets. When applying the relation of the tidal prism on the Haringvliet estuary, the changes in the mouth after human interventions can be analysed and explained.

A.1.1 ebb-tidal delta

The ebb-tidal delta is a morphological dynamic area, which develops under the relative influence of waves compared to the tide as described in (Aarninkhof and Van Kessel, 1999). The ebb-flow out of the tidal inlet, combined with river discharge reduces in speed when the flow spreads out in the open sea. The deceleration of the flow causes a gradient in current velocity and therefore a gradient in the related sediment transport. A decrease in sediment transport capacity enables sediment to settle, resulting in the growth of the outer delta, also called the ebb-tidal delta.

The tide forces the flow of water through the opening of the estuary which results in high current velocities in the mouth of the estuary. Outgoing currents slow down to the interaction with slower moving ambient water and the forcing of onshore waves. The waves move sediment onshore and limit the area over which the ebb-tidal delta can spread out (Bosboom and Stive, 2015). Hence, the ebb-tidal delta morphology is generally determined by the balance between a net offshore directed sediment flux induced by the inlet currents and a net onshore directed sediment flux induced by offshore waves (Bosboom and Stive, 2015). The driving forces behind the development of the delta are further elaborated in Section 2.3.

The morphology of well-developed ebb-tidal delta is characterised by a large seaward the protrusion of the delta front. Hence, the development of the ebb-tidal delta can be defined as the ratio of protrusion to inlet width. The value of this protrusion index will be large in case of a well-developed outer delta. As shown by Walton and Adams, 1977. This suggest that the ebb-tidal delta protrusion is positively related to the ratio of tidal prism and wave action. In order define the morphological developments of delta's, empirical relation can be used based on a dynamic equilibrium of the outer delta and the volume of the tidal prism.

The following empirical relation was found by Walton and Adams, 1977 for the sand volume of the ebb-tidal delta and the tidal prism:

$$V_{od} = C_{od} P^{1.23} \tag{A.3}$$

In which:

- V_{od} = Sand volume stored in the outer delta $[m^3]$
- C_{od} = Empirical coefficient $[m^{-0.69}]$
- P = Tidal prism $[m^3]$

Where the empirical coefficient depends on the wave climate. It ensures that the relation still holds for a wave dominant situation compared to a mild wave climate. With this formula changes in Tidal prism (e.g. land reclamation, sealevelrise) can be related to changes in the ebb-tidal delta.

A.2 Sediment

A.2.1 Net transport

Tidal basins are classified as flood or ebb dominant, enhancing import or export of sediment. Net sediment transport is the difference between the import and export of sediment. Since sediment transport is related to flow velocities, net sediment transport is induced by a gradient in flow velocities. The maximum flow velocity can be different between the flood and ebb flow due to distortion as a result of bottom friction and other non-linear effects. The degree of asymmetry between the flood and ebb flow velocity peaks can be related to the residual transport of sediment because of the non-linear dependency of sediment transport on the local flow velocity. This feature is called tidal asymmetry. Following Z. B. Wang, Jeuken, et al., 1999 the asymmetry of the horizontal tide may be associated with:

- An asymmetry in the magnitude of maximum flow: for instance if maximum flood velocities exceed maximum ebb flow a flood-dominant transport (bed load and suspended load) is likely to occur, as the sediment transport non-linearly increases with the velocity.
- An asymmetry in the duration of slack water: if the duration of slack water before flood exceeds the duration of slack water before ebb an export (ebb-dominance) of fine suspended sediment is favoured. When the period of slack water before flood lasts shorter the period of slack water before ebb and import of fine suspended sediment is likely to occur.

It is important to distinguish sand (coarse sediment) and mud (fine sediment) when looking at sediment transport. A small volume of mud already reduces the degree of sand erosion. Important mechanisms influencing horizontal sand-mud patterns are tidal asymmetry, spring-neap variations, gravitational circulation, and seasonal variation (Ledden, 2003). Moreover, the refreshment time of the watercolumn plays an important role in the import and export mechanism

Coarse sediment transport can be regarded as bed load transport and is largely induced by the hydrodynamic conditions and sediment properties. However, fine sediment transport depends not only on the local instantaneous flow velocity, but also on the flow conditions upstream and in the past (Bosboom and Stive, 2015). The characteristic that causes an essential difference in the tidal dynamics of fine sediment compared to coarse sediment is the timescales of erosion and sedimentation. Where coarser sediments settle fast, fine sediments need time to respond.

In contrast to a coarse sediment, the availability of fine sediment is often limited and the flow conditions do not govern the transport capacity of mud. Mud is transported as suspended load. fine sediments can still be transported in suspension, while coarse sediment is already deposited at the bed surface. The net transport of fine sediment is mainly determined by the settling time and the current asymmetry around slack water. **groen1967** explains the basic mechanism behind the so-called ' settling lag effect' using a detailed analysis Figure A.2

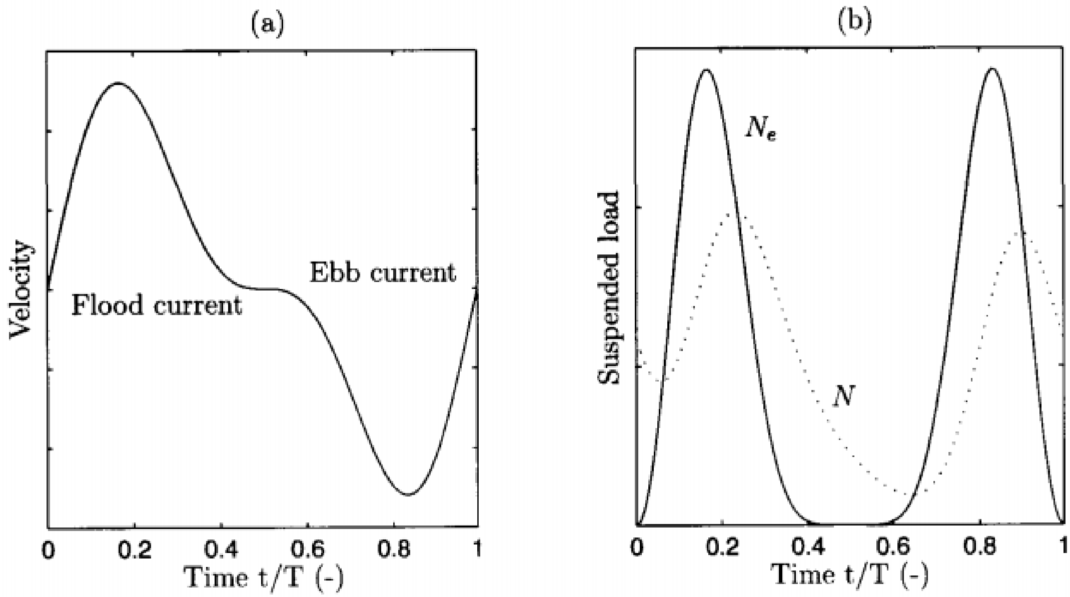


Fig. A.2.: Settling lag effect.
Time variation of the current velocity (a) and the equilibrium suspended load Ne and actual suspend load N (b) during a tidal cycle on a arbitrary scale (from Ledden, 2003)

Fine sediment particles do not adapt instantaneously to changing flow conditions, but lag significantly behind the flow. If the slack water period at high water is much lower than at low water, the particles have a longer time to settle during high water and the suspended sediment concentration after the high water period is lower than after the low water period. Therefore, less suspended sediment is transported backward during the ebb period and a residual flux in flood direction during one tide occurs.

Horizontal variations in bed shear stress, which is related to roughness and the combination of currents and waves, induces differences in erosion patterns of fine and coarse sediments. Resulting in sand and mud segregation. Wave and storm surges can cause a strong erosion of the bed by increase the bed shear stress and stirring up the fine sediment from the bed and thus enhancing the export of sediment. The effect of waves on the bed is bigger for smaller water depths than for a larger. So during low water levels stirring up of the (fine) sediment will happen more easily. Resulting in an increase of fine sediment concentration in the initial ebb phase, and thus in an enhancement of ebb-transport of fine sediments. Interaction between fine sediment (mud) and coarse sediment can, therefore, have a significant influence on the erosion patterns.

However, Ledden, 2003 found that when comparing the long-term morphological development of a reservoir and a tidal basin with sand and mud to the situation with sand only gives rise to two opposing observations:

1. The morphological adaptation time scale decreases, due to the extra availability of sediment and the high mud deposition near the head of the basin.
2. The bed level profile in the equilibrium situation is quite similar to the equilibrium bed level profiles for sand only.

A.3 Estuarine processes

In this section processes found in the estuary environment are elaborated. Since the study area is located in the (former) mouth of the an estuary, the processes described in this section are all relevant in describing the hydrodynamics and other processes in the area. These processes have been subjected the different anthropological events, changing their impact in the area.

A.3.1 Currents

The currents in the vicinity of a tidal inlet are partly tidal, partly wave-driven, and partly wind-driven. The tidal currents are primarily concentrated in the main channels, the wave-driven currents in areas where waves are breaking. Wind-driven currents occur in the more sheltered parts of tidal inlet. These currents are rather episodic because they occur mainly during storm events, but are nonetheless still important.

Waves and currents encounter a very complex bed topography, with length scales that are not much larger than the wavelength of wind waves or swell via refraction, diffraction, and reflection, this can lead to complex wave patterns with a strong spatial variability. In the meandering channels, these induced flow circulations play an active role in the morphological development of channel meanders and of ebb and flood chutes Bosboom and Stive, 2015. Straight channels are almost always unstable; a small irregularity in the channel tent to grow. Likewise, the shoals are maintained by curvature-induced secondary flow components.

Relevance
From this section it can be derived that bathymetry and currents interact with eachother. Currents influence the morphological changes and the changes in morphology has its impact on the current patterns. This interaction is called morphodynamics. Since the area has been under influence of large morphological changes the morphodynamics in the study area have also changed significantly.

A.3.2 Residence time

Due to the mixing of fresh and saline water, water budgets and salt budgets are very important to assess the flow dynamics. To get an insight into the volume changes of those quantities the residence time of a volume can be used. The parameter residence time is commonly used for representing the time scale of the physical transport processes within a waterbody such as sediments or salinity. Hagy et al., 2000 defined residence time as the required time to reduce the total mass in a control volume of a theoretical pulse of a conservative material by 37% of the original total mass. Pierini et al., 2019 defined the residence time as the time where 90% of the original volume has flushed out of the control volume.

From the ecological point of view, for example, estuaries with a short transit time will export nutrients from upstream sources more rapidly than estuaries with longer transit times. On the other hand, the domain average residence time average residence time of water parcels inside the estuary determines if microalgae can stay long enough to generate a bloom (Braunschweig et al., 2003).

The average residence time of water parcels inside the estuary characterize the exchanges between the water column and the sediment: deposition of particulate matter and associated adsorbed species depends on the particles settling velocity, water depth and particle residence time (Pierini et al., 2019). This is particularly important for the fine fractions with lower settling velocities. The residence time of an estuary can also be used to determine the bloom of micro-algae, by comparing the residence times of an estuary with the doubling time of algae. If the doubling time of algae cells is shorter than the residence time, flow conditions would inhibit formation of algae blooms (Kierstead and Slobodkin 1953; Lucas et al. 1999;USEPA 2001).

In a water budget, the total volume transported out in a unit of time is the sum of the volume transported in by tides plus the volume of the freshwater inflow transported into the estuary from the rivers. Thus, the residence time is the volume of the estuary $V_{estuary}$ divided by the rate of flow of water leaving the estuary or predefined control volume T_{out}:

$$T_r = \frac{V_{estuary}}{T_{out}} \tag{A.4}$$

The residence time is very important because it controls the carrying capacity of wastes, the residence for fresh water, the residence time by tidal action, the effects of mixing, and it can be affected by coastal up-welling and down-welling. Thus, the residence time is a key variable that controls nearly all estuarine processes. (**montagne 2013**)

Box models

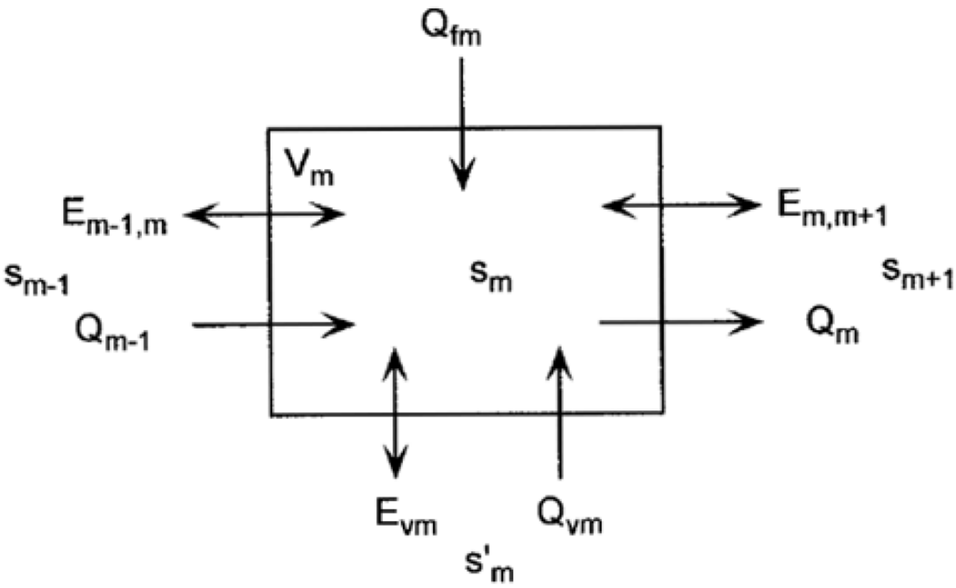


Fig. A.3.: Schematization of salt water exchange for a two layer estuarine box model (Hagy et al., 2000).

To estimate the residence time and related bulk physical exchanges of water bodies, a box models can be used. With the box model the exchange of advective and non-advective transport between volume and surroundings can be estimated. Here salt is taken as an example, the generic volume based on Figure A.3, results in the following salt balance equation:

$$V\frac{ds_{in}}{dt} = Q_{in}s_{out} - Q_{out}s_{in} + E(s_{out} - s_{in}) \tag{A.5}$$

In which

- V = volume of the control volume
- Q_{in} = Advective transport into the control volume
- Q_{out} = Advective transport out of the control volume
- s_{in} = Salinity inside the control volume
- s_{out} = Salinity outside the control volume
- E = non-advective exchange between the control volume and the surrounding environment

The residence time was calculated as the time required to reduce the mass of tracer in the entire estuary to e-1 times (37% as described by Hagy et al., 2000 the initial mass. Exchange coefficients are kept constant through the simulation so that estimated residence times can be compared to multiple situations in time.

The water fraction (f) inside the box at each time step is calculated by the following expression:

$$f_{i;j}(t) = V_{i;j}(t)/V_{i;j}(0) \tag{A.6}$$

With V$i;j$(t) being the volume of tracers from box j contained in the box i at a time t, and Vi;j(0) the original volume contained by the box i, which sums the total volume of the estuary. When Vi;j(t) equals to zero implies that all the original volume of water has been replaced by new water and thus t would be the residence time of that water mass.

Relevance
From this section a method is described which can be used to assess suspended particle matter in the water column. With the help of control volumes dynamic processes can be quantified. By this quantification for a specific area different stages in time can be related to eachother.

Stakeholder session

B

The input for stakeholder values and interest in this research is derived from an previous conducted study performed by Arcadis (Bergsma, 2018). The aim of this study was to form a coalition of stakeholders which would work together on defining a long-term vision for the coast by considering the best interests and values for the multiple parties involved. Multiple sessions were organized to inform and consult the (local) stakeholders about the coastal development.

The study involved an interview round with different stakeholders to map their interests. After the interview, interactive sessions where held to set weight to the different values and interest of the parties involved. During these stakeholder sessions, the most crucial parties present were asked to think along about the future development of the coast. The development of the coast and the position of values and interest in this development was discussed. Their main aim; how should the coast evolve in time and how can it be adjusted to suits everyone's best interest. Therefore, different stakeholders where asked to indicate their preferred interest and the points on where they think collaboration on shared interest is possible.

The most important interests discussed during these meetings were listed:

- Nature (shoals, dunes)
- Flood protection
- Recreation (beach, nature, sports)
- Fishery (local)
- Economy
- Energy
- Climate change
- Morphological development
- Quality of life
- Ship accessibility

Next to the obtained interests, possible opportunities were formulated. However the opportunities varied to form a base of multiple different outcomes. This indicates once again how dynamic the system is. Opportunities vary from energy generation to nature development and flood protection. However during the sessions the first urgency to act was lacking by the different parties. Except for the municipality of Westvoorne. As a result, the sessions were used as an input to seek common ground among the involved stakeholders involved and will form the base for a long term coastal vision.

C Main model settings Delft3D

Tab. C.1.: Summary of the main model parameter settings, adapted from Colina Alonso, 2018.

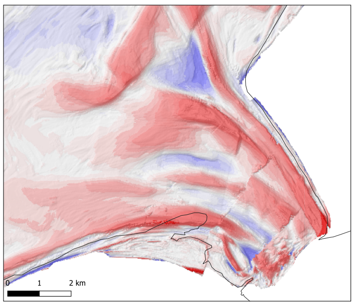
Model	Parameter	Value	Description
Flow	Kmax	9	Number of computational layers [-]
	Δ t	0.1	Computational time step [min]
	ρ_w	1000	Density of water [kg/m^3]
	ρ_a	1.205	Air density [kg/m^3]
	Roumet	M,Manning	Type of bottom friction formulation [-]
	Ccofu	from file	Uniform bottom roughness in u-dir [m1/2/s]
	Ccofv	from file	Uniform bottom roughness in v-dir [m1/2/s]
	Vicouv	from file	Uniform horizontal eddy viscosity [m^2/s]
	Dicouv	from file	Uniform horizontal eddy diffusivity [m^2/s]
	ROUwav	FR84	Bottom stress formulation due to wave action [-]
	Dryflc	0.1	Threshold depth for drying and flooding [m]
	barocp	yes	Baroclinic pressure [-]
	denfrm	Eckart	Equation of state [-]
Wave	Spectrum	Jonswap	Shape of the wave spectrum [m]
	PeakEnhancFac	3.3	Peak enhancement factor in case of jonswap spectrum [-]
	Setup	false	No wave related setup [-]
	WaveForces	dissipation 3d	Method of wave force computation [-]
	GenModePhys	3	Generation mode of physics [-]
	Breaking	true	Include wave breaking, B&J model [-]
	BreakAlpha	1	Alpha coefficient for wave breaking [-]
	BreakGamma	0.73	Gamma coefficient for wave breaking [-]
	Triad	false	Include triads [-]
	BedFriction	0.067	Bed friction coefficient [-]
	Diffraction	false	Include diffraction [-]
	WindGrowth	true	Include wind growth [-]
	WhiteCapping	Komen	Formulation for white capping [-]
	Quadruplets	true	Include quadruplets [-]
	Refraction	true	Include refraction [-]
	FreqShift	true	Include frequency shifting in frequency space [-]

Additional plots

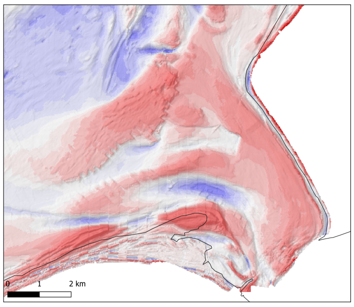
D

D.1 Area change over time

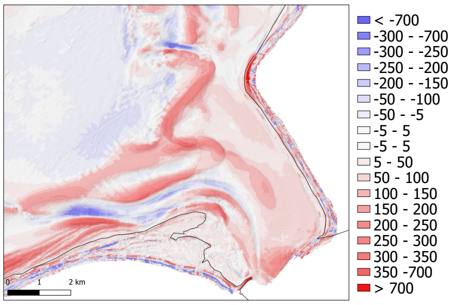
In this section the bathymetrical changes between different stages are plotted



(a) Bathymetry difference 1964 - 1980.



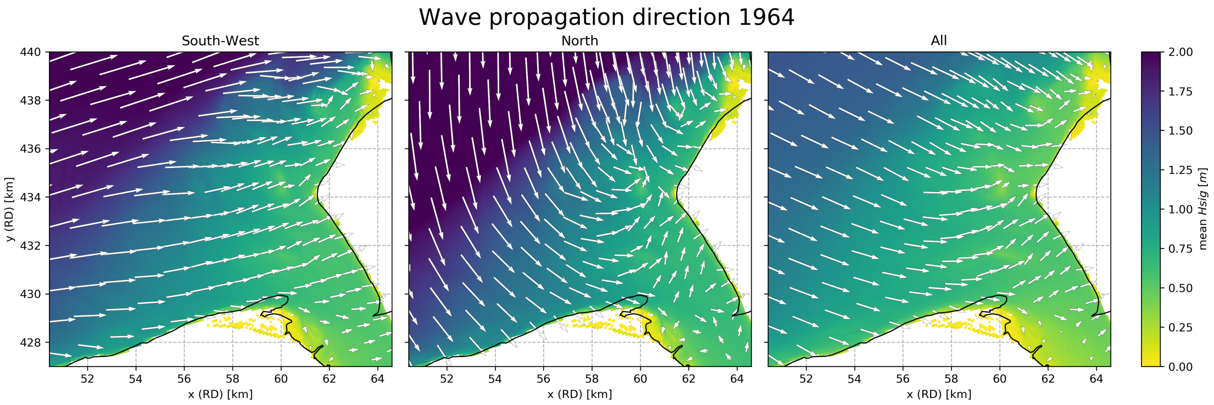
(b) Bathymetry difference 1980 - 2004.



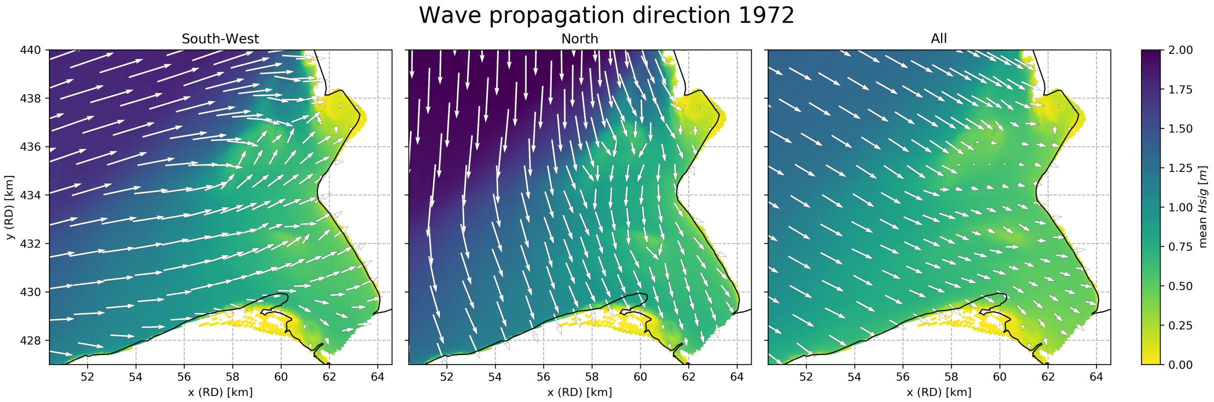
(c) Bathymetry difference 2004 -2018 .

D.2 Sensitivity analysis wind influence on wave propagation direction

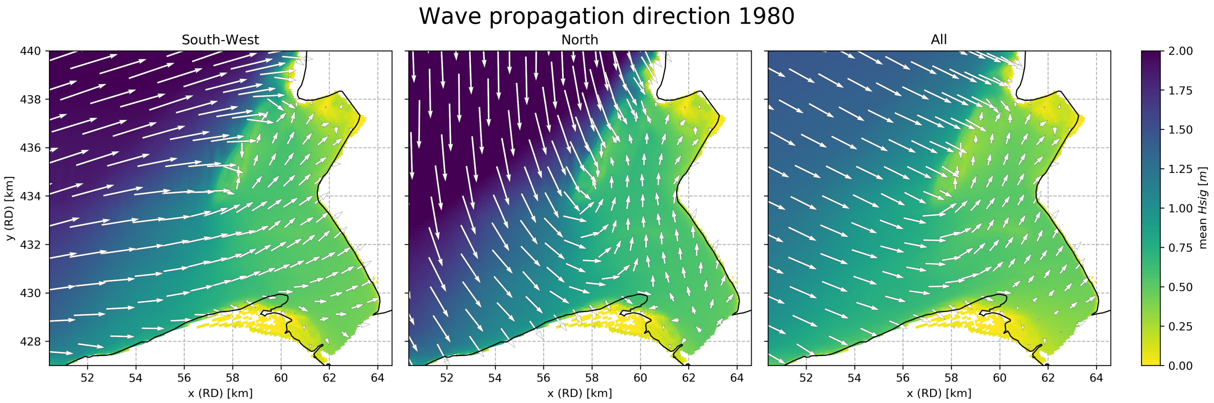
In this section additional plots are shown of the sensitivity analysis regarding the influence of wind direction on wave propagation.



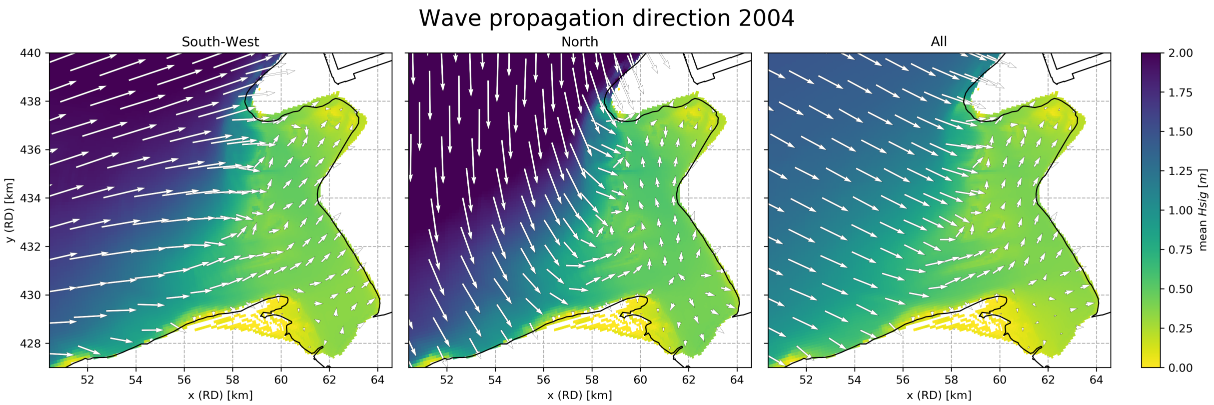
(a) Wave propagation direction 1964.



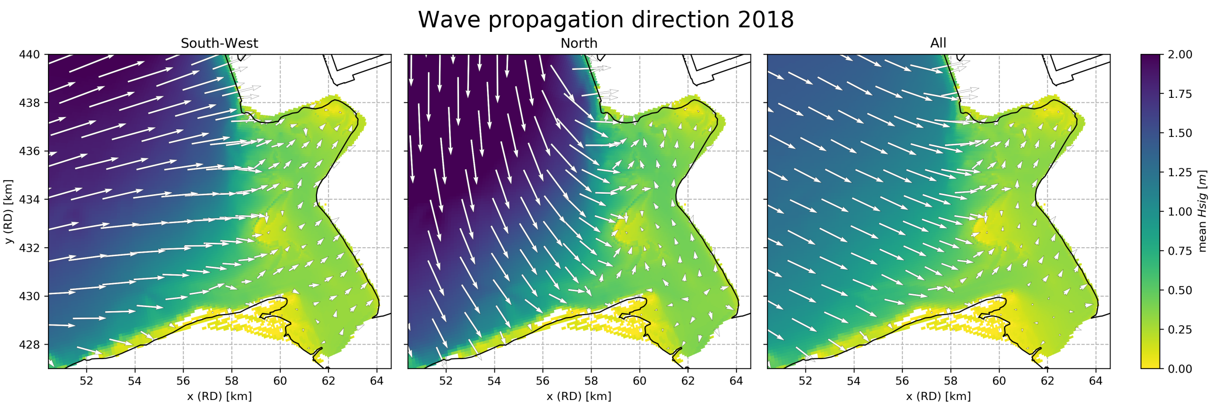
(b) Wave propagation direction 1972.



(c) Wave propagation direction 1980.



(d) Wave propagation direction 2004.



(e) Wave propagation direction 2018.

Fig. D.2.: Wave propagation direction and mean hsig per stage in time, with wind coming from southern direction.