Breakwater barrier island 'De Banjaard'

Developing a barrier island on the eroded Banjaard sandbar as dynamic coastal protection through Nature-Based Solutions

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Vocabulary list

- **Bathymetry:** “the study or measurement of the depth of water in a sea” (Cambridge University Press, n.d. a)
- **Biobuilder:** See **Ecosystem engineer**
- **Biogenic reef:** Biogenic reef habitats are raised, hard, complex structures created by the activity of animals (Zu Ermgassen et al., 2020).
- **Critical width:** “Critical width is the smallest cross-shore dimension that minimizes net loss of sediment from a barrier island and thus reduces migration of the island over periods of decades to centuries. The concept of critical width is important for large-scale barrier island restoration, in which islands are reconstructed to optimum height, width, and length for providing protection for estuaries, bays, marshes and mainland beaches.” (Rosati & Stone, 2007, p. 12).
- **Deltawerken:** Dutch famous water flood defences in the Southwest of the Netherlands (Zeeland.com, n.d.).
- **Ecosystem engineer:** “Ecosystem engineering species are organisms that change biotic or abiotic materials, thereby controlling availability of resources to other organisms” (Borsje et al. 2011). This research project focuses on the ecosystem engineers that stabilise sediments and reduce wave energy.
- **Intergovernmental Panel on Climate change (IPCC): ''**the international body for assessing the science related to climate change.'' (IPCC, 2021)
- **Kreekrakdam**: Dam that decouples the Oosterschelde from the Westerschelde.
- **Nature Based Solutions (NBS):** According to the International Union for Conservation of Nature (IUCN) NBS are “actions to protect, sustainably manage, and restore natural or modified ecosystems, that address societal challenges effectively and adaptively, simultaneously providing human well-being and biodiversity benefits”. (IUCN, 2016)
- **Normaal Amsterdams Peil (NAP):** “Dutch ordnance level which is about mean sea level” (Elias et al., 2016)
- **Ocean sprawl:** the proliferation of artificial structures in marine and coastal environments, and the subsequent modification and loss of natural substrata" (O’Shaughnessy et al., 2020)
- **Oosterschelde:** Eastern Scheldt delta.
- **Oosterscheldekering:** Eastern Scheldt storm surge barrier.
- **Sandbar:** “a long-raised area of sand below the surface of the water, especially where a river enters the sea, usually formed by moving currents” (Cambridge University Press, n.d. b).
- **Seagrass:** Seagrasses are flowering plants that are fully submerged in shallow marine waters. (Himes-Cornell et al., 2018)
- **Sea level rise (SLR):** increasing volume of the oceans, predominantly caused by thermal expansion and melting of the glaciers (Church et al., 2013)
- **Semi-diurnal tidal currents**: there are “two high and two low tides of approximately equal size every lunar day” in an area (National Oceanic Service, n.d.).
- **Shore-normal tidal flow**: tidal current is perpendicular to the coast.
- **Spatial configuration:** “particular spatial arrangement of something” (Cambridge University Press, n.d. c), in this research project spatial configuration refers to a three-dimensional shape and position.
- **Tabby:** Construction material consisting of sand, lime (from shells and wood ash), water and sometimes whole shells (Lee, 2014).
- **Tarra: “**anything that does not belong to bivalve molluscs, tunicates, echinoderms, marine gastropods or crustaceans such as loose shells, starfish, mud mussels, slippers, smallpox, clods of mud, stones, waste, dead or broken molluscs and is unfit for trade for human consumption as well as anything released or left over during the cleaning, processing or processing of the batch of bivalve molluscs received” (Provincie Zeeland, 2017).
- **Voordelta**: The seaward side of the Deltawerken. It is characterized by tidal and deeper sandbanks with deeper channels in between.

Executive summary

The consequences of climate change heavily threat the coast of Schouwen (Zeeland, the Netherlands); the strong relative SLR, which is predicted to range from +0.54 to +1.21 metres in 2100 in the most scenario (KNMI, 2021) or even more, extreme events, and ocean acidification (IPCC, 2019) challenge us to rethink our coastal protection systems. Therefore, we aim to assist Shared Concepts with a development plan for a dynamic breakwater system with coastal protection as its main function. The use of NBS is in strong contrast with the conventional management strategies. This project will be approximately located on the eroded Banjaard sandbar, which disappeared after the establishment of the Kreekrakdam and the Deltawerken. This changed the Oosterschelde (Eastern Scheldt delta) from a mixed energy system into a wave dominated system and redirected the net transport of sediments towards the northeast (Elias et al., 2016).

In Ch. 3, we based the analysis for the position and shape of the future barrier island on the following five criteria: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities. This analysis resulted in two potential spatial configurations, respectively the Crescent and the Hook design. Although both designs have a similar seaside, their leesides strongly differ; the Hook design has a curved shape and thereby has a stronger potential for the reduction of forcing by the currents. Therefore, this design will probably lead to a stronger ecological development than the Crescent design. However, future research and management decisions should determine how the Banjaard barrier island will look like in the future.

Erosion and sedimentation processes in the open sea have a complex origin and pose difficulties for the creation of the barrier island. Ecosystem engineers (as discussed in Ch. 4) can attenuate wave energy and capture sediment. Hard structures enhance wave attenuation and sediment retainment by creating conditions favourable for ecosystem engineers to settle, and by the ability of these structures to attenuate waves and retain sediments by the structure itself. These structures can be artificial, biological and/or biodegradable. In Ch. 4 we introduce habitat types based on Natura 2000 with high potential to protect, sustain and stabilise the barrier island. We discuss if, how and where we can realise the habitat types on both the Crescent and Hook design. Since the Hook provides a larger gradient in ecological dynamics, more habitat types can thrive on the barrier island, resulting in a higher resilience of the barrier island.

There is still limited research available concerning the construction of a barrier island and about which role ecosystem engineers can play in this process. In the development pathway (Ch. 5), we give suggestions for follow-up research during the six phases of the development of the barrier island, respectively: 1) the finalisation of design, 2) research on the sediment, 3) financial aspect and stakeholder analysis, 4) preparation for monitoring, 5) experimenting and monitoring and 6) development of future barrier islands. The first four phases should take place prior to the sediment suppletion, the fifth and sixth phase afterwards.

We strongly believe that investing in elaborative research during the pre-suppletion phases will increase the capacity for providing coastal protection and the ecological value of the future barrier island. Hence, we advise to adjust the moment of the sediment suppletion to the timespan needed for the recommended research. Prior to the suppletion we recommend research about; the optimalisation of the barrier island spatial configuration; the origin and quantity of the sediment; the stakeholders, legislation, and finances; and the establishment of a monitoring framework. After the suppletion we recommend; the monitoring of ecosystem engineers, applied hard structures, and environmental conditions on and around the barrier island; analysis of the coastal protection performance of the barrier island; and analysis on how other barrier islands can be developed.

Chapter 1: Introduction

Climate change is likely to have a strong, severe impact on the marine system; increasing temperatures cause melting of icesheets and thermal expansion of the seawater. These processes together cause SLR (IPCC, 2019). The Intergovernmental Panel on Climate Change (IPCC) projected this global mean SLR in the range of +0.63 m to +1.01 m compared to preindustrial levels in the most extreme Representative Concentration Pathway (RCP8.5) by 2100 (Arias et al., 2021). Moreover, frequency and severity of extreme events, such as coastal floods and storm surges, are likely to increase (Arias et al., 2021). The Dutch coast is vulnerable to erosion, due to the loose and sandy sediments (Borsje et al., 2017). The impacts of climate change and sediment properties make low-lying coastal areas, such as the province of Zeeland, highly vulnerable to climate change.

This research project focuses on a part of the Voordelta (Zeeland, the Netherlands), which is situated off the coast of Zeeland. The area provides habitat to many species, e.g., the grey seal (*Halichoerus grypus),* benthic fish species, and migratory birds, and is thereby recognised as ecologically valuable by Natura 2000 (Ministerie van Infrastructuur en Milieu, 2016). The soils in this part of the Rhine-Meuse-Scheldt River delta have a high peat content and are drained for agricultural purposes. This, together with climate change-induced heat stress, causes peat compaction and oxidation and subsequently results in subsidence of the soils (Van Asselen et al., 2018). Besides, geological land subsidence occurs due to glacial isostatic movements of the Earth crust. Annually, those glacial isostatic movements cause a subsidence of the soils of approximately 0.02 cm (Deltares, 2018). Together, the global mean SLR, land subsidence, and local coastal sea currents (KNMI, 2021) result in a relative SLR for the Dutch coast which is larger than the global mean SLR. This relative SLR is expected to be +0.54 m to +1.21 m by 2100 for the extreme SSP5-8.5 scenario (KNMI, 2021).

Currently, the protective measures in Zeeland are not built for the extent of the predicted relative SLR for the Dutch coast. For example, the Oosterscheldekering (Eastern Scheldt storm surge barrier) next to the coast of Schouwen was built for 0.10 m land subsidence and 0.20 m increasing sea levels (Verbrugge et al., 2012; Witteveen+Bos, 2017). Therefore, this storm surge barrier is built for a relative SLR of 0.30 m, which is far below the expected value. The storm surge barrier and the dikes will face increasing wave heights and wave pressures in the future caused by SLR, increasing storm strength and frequency, and erosion of sandbars in front of the dikes (Verbrugge et al., 2012). For the coast of Schouwen, the effects of eroding sandbars are already emerging since the eroding 'Banjaard' sandbar caused an increasing coastal wave attack (Vermaas et al., 2015). Therefore, to continue the protection of Zeeland residents, the Oosterscheldekering should be closed more frequently in the future (Zandvoort et al., 2019). Higher sea levels and increased wave heights could also negatively impact the stability of the Oosterscheldekering and the current erosion problems around the base of the Oosterscheldekering could become more severe (Verbrugge et al., 2012). Hence, improvement of the coastal protection is needed to reduce impacts of relative SLR on both the Schouwen coast and the Oosterscheldekering in the future.

Due to the expected increase in relative sea levels, it has been postulated that the conventional management of heightening dikes will no longer be sufficient. Therefore, this project focuses on dynamic NBS to decrease the pressure on the coastal system of Zeeland. A breakwater barrier island is visualised at the approximate site of the eroded 'Banjaard' sandbar off the coast of Schouwen. This barrier island will henceforth be referred to as 'barrier island', 'future barrier island', 'future Banjaard' or 'Banjaard barrier island'. Following the vision of the commissioner of this project; Shared Concepts, the future barrier island is engineered with sediment nourishments after which these sediments are stabilised with different ecosystem engineers. The ecosystem engineers are implemented on the barrier island to promote dune formation and within the marine environment. Engineering such a barrier island on the eroded Banjaard sandbar as well as the implementation of ecosystem engineers can be considered as nature and habitat creation, which could improve the ecological value of the area.

The aim of this research project is to assist Shared Concepts in the development of an eco-engineering plan for a self-supporting dynamical breakwater system with coastal protection as its main function. This development plan should be well-performing, realistic, and in line with the Natura 2000 regulations. The breakwater system should also be achievable within approximately 30 years, which is in line with the vision of Shared Concepts. This research project assists Shared Concepts in developing an action plan which can be applied to the eroded Banjaard sandbar from 2025 onwards. The outputs of this research project consist of a report, a development pathway, and several sketches, which are obtained with literature studies and three expert interviews which we used as additional sources. The following three experts were interviewed; (I) N. van Rooijen, ecologist WUR, (II) M. Eelkema, hydrologist Voordelta, (III) A. den Oudenhoven, related to the project Zandmotor.

The research questions addressed in this research project are the following:

1) *What is the optimal positioning, shape and profile of the Banjaard barrier island to protect the coastline of Schouwen?*
2) *What are optimal ecosystem engineer options and positions to stabilise the sediment supplements?*
3) *What is a feasible development pathway with recommendations for future research for development of the barrier island?*

Before we will move on to answering these question, Ch. 2 will dive deeper into the theoretical background that has been touched upon in the introduction. It will discuss the interactions between the ocean and the climate system that are relevant to the context of the Banjaard, as well as the history of the Voordelta area and the Banjaard sandbar. In Ch. 3, the first research question is analysed, in which criteria are used to establish the optimal spatial configuration of the future barrier island off the Schouwen coast. Subsequently, in Ch. 4 information is provided about potential optimal ecosystem engineers and their habitat positions in the marine and dune environment on the barrier island, thus answering question 2. In Ch. 5, research question 3 is addressed and a feasible development pathway is presented.

Chapter 2: Theoretical background

2.1 Climate – ocean interactions

In this chapter, the impact of climate change on the ocean and the role of oceans in climate change mitigation will be discussed. The ocean interacts with the climate in many ways (Kaiser et al., 2011). This chapter will focus on the mechanisms deemed most relevant in the context of the Banjaard, namely SLR; oceanic uptake of carbon from the atmosphere and the resulting ocean acidification; and deoxygenation.

2.1.1 Sea level rise

Global warming is caused by anthropogenic emissions of greenhouse gases, such as carbon dioxide (CO_2), due to the burning of fossil fuels (Arias et al., 2021). Consequently, global mean SLR is caused by melting of glaciers and ice sheets, and by thermal expansion of the seawater (IPCC, 2019). The ocean is heated from the top and therefore, warming of the sea water mostly takes place in the upper ocean layer. Nevertheless, it is likely that deeper ocean layers are also heating up. Generally, warming of seawater has been the largest contributor to SLR, however, climate change has increased the SLR contribution of melting glaciers and ice sheets. There is already observable evidence that SLR is accelerating as well as the melting of ice sheets in Greenland and Antarctica. The impacts by 2100 will depend on the amount of greenhouse gases that will be emitted in the meantime (IPCC, 2019).

Regarding the predicted global mean SLR of 0.63 m-1.01 m by 2100, it should be considered that SLR is not expected to stop in 2100. Instead, this process will continue over centuries or even millennia (Arias et al., 2021). Furthermore, this rate of SLR comes with a lot of uncertainties and will probably be much higher, due to the limited understanding of feedback mechanisms (Siegert et al., 2020). Spatial variations resulting from land subsidence and isostatic movement, as mentioned in the introduction, also contribute to this uncertainty (Nicholls et al., 2014). Those spatial configurations result in a predicted relative SLR that is ranging from +0.54 m to +1.21 m for the Dutch coast, which is larger than the global mean SLR (KNMI, 2021).

2.1.2 Carbon uptake

Climate change also affects the balance between the number of CO_2 molecules in the atmosphere and the number of dissolved CO_2 molecules in the ocean. Due to higher CO_2 emissions, the partial pressure of atmospheric CO_2 increases, and this causes the ocean to take up more CO_2. The ocean functions as a large carbon sink and therefore it is a large contributor to climate mitigation. In the past, the oceanic CO_2 uptake was approximately 30% of the anthropogenic emissions (Kaiser et al., 2011).

The oceans also function as reservoirs for heat. Subsequently, climate change will result in warmer ocean water (IPCC, 2019). Since less gas can be dissolved in warmer liquids according to Henry's law (Goosse, 2015), the capacity of the oceans to take up CO_2 gas from the atmosphere decreases (IPCC, 2019). As a consequence of decreased oceanic uptake, more CO_2 will remain in the atmosphere. This will contribute to the further progression of climate change which, as a positive feedback mechanism, results in further oceanic warming.

The oceanic CO_2 uptake also affects the chemistry in the oceans because CO_2 molecules react with water molecules (H_2O). Due to this interaction, hydrogen (H^+) particles can be detached via the following reactions (Goosse, 2015):

$$CO_{2(gas)} + H_2O \leftrightarrow H_2CO_3$$
$$H_2CO_3 \leftrightarrow H^+ + HCO_3^-$$
$$HCO_3^- \leftrightarrow H^+ + CO_3^{2-}$$

The detached H^+ particles decrease the pH value of the ocean water and hence the ocean acidity is higher. According to Guinotte & Fabry (2008), the pH of the seawater has already dropped from a pre-industrial value of 8.16 to 8.05 and the pH value is forecast to decrease by another 0.3-0.5 by 2100. Note that since the pH is measured on a logarithmic scale, this decrease is equivalent to a H^+ increase of 100-150% (Kaiser et al., 2011).

A higher ocean acidity impacts the ocean ecology and mainly calcifying organisms are affected. Shells and skeletal structures consist of calcium carbonate ($CaCO_3$), formed in a precipitation process through the chemical reaction $CO_3^{2-} + Ca^{2+} \leftrightarrow CaCO_3$. More oceanic CO_2 uptake, results in more conversion of CO_3^{2-} to HCO_3^- which is more stable. When the seawater is undersaturated with CO_3^{2-}, organisms are unable to biomineralize their $CaCO_3$ structures. Temperature, salinity, and pressure also determine the stability of $CaCO_3$ (Feely et al., 2004). Together, these factors determine the depth of the saturation horizon (Kaiser et al., 2011) and below this depth the calcifying marine organisms are vulnerable to dissolution. Over the past 200 years, the saturation horizon has already moved upwards by 50-200 metres, and it is expected to rise even more (Kaiser et al., 2011).

2.1.3 Deoxygenation

Warmer oceans also result in less oxygen (O_2) uptake according to Henry's law, leading to deoxygenation of the ocean due to climate change (IPCC, 2019). This process is exacerbated by increased stratification of the ocean. Since the ocean is heated from the top, the warmer upper layers have a lower density than the colder deeper layers, causing less mixing between the layers. This stratification process leads to a thinner ocean surface layer that is in contact with the atmosphere and therefore O_2 dissolves less easily in stratified oceans (Kaiser et al., 2011).

Deoxygenation can also be exacerbated by eutrophication. High fertiliser and manure runoff from agricultural land towards the ocean can severely increase the nutrient content of coastal waters. These nutrients can facilitate rapid growth of biomass, especially when the temperature is also sufficiently high, leading to algal blooms. When this plankton dies, it sinks and is decomposed by microbes which consume O_2. With lots of decomposition taking place the water can get depleted of O_2, resulting in a dead zone where hardly any organisms can survive (Kaiser et al., 2011).

2.1.4 Effects on marine ecology

The above-mentioned processes can have large effects on marine ecology: water temperature is a major factor in determining the spatial distribution of organisms, the timing of spawning, the growth rate of fish, and the survival of larvae. Deoxygenation can lead to dead zones and acidification reduces the habitat of calcifying organisms by rising the saturation horizon. While an organism may be able to cope with one form of environmental stress, this could decrease their adaptability to another environmental stress factor (Kaiser et al., 2011). Hence, the synergistic effects of climate change and other anthropogenic factor such as habitat destruction and overfishing could be drastic.

These effects should be considered in planning the development of the future Banjaard. The ecosystem engineers that will be chosen to stabilize and capture the sediment should be able to survive in present and future environmental conditions in the Voordelta.

Main Message

- Anthropogenically induced climate change will affect the pH, O_2 content, and temperature of the sea water.
- SLR caused by climate change will continue over centuries or even millennia and the rate of SLR comes with lots of uncertainties due to the limited understanding of feedback mechanisms.
- The Banjaard barrier island should be able to withstand the expected SLR and the (introduced) species on the barrier island should be able to survive in present and future environmental conditions.

2.2 History of the Banjaard sandbar and the Voordelta

In the time of the Romans, the Rhine-Meuse-Scheldt River delta area in the present-day South-Western Netherlands was mostly peat bog, protected from the sea by dunes (Elias et al., 2016). Due to increasing intrusion of the sea, peat accumulation in this area was greatly reduced around 100 AD. Furthermore, the dike embankment of land stopped the deposition of new silt and improved drainage caused the peat layers in embanked areas to subside. Additionally, many river delta areas were stripped of peat for the extraction of salt (in Dutch: moernering) and therefore the local population actively caused land subsidence. Lastly, tectonic processes also contributed to the lowering of the local land (Van den Berg, 1986). This land subsidence, along with other factors, led to the formation of new inlets and channels. Up until the 14th century, the Oosterschelde (Eastern Scheldt) was the main branch of the Schelde (Scheldt). However, over time the Honte, which was one of the newer inlets, broke through into the Schelde around Antwerp, after which it gradually took over as the main outlet of the Schelde and became known as the Westerschelde (Western Scheldt). The Westerschelde and Oosterschelde remained connected through two shallow channels named the Kreekrak and the Sloe, which silted up over time. Eventually, during the 19th century, both the Kreekrak and the Sloe were dammed up, blocking natural flow of water between the Oosterschelde and Westerschelde in its entirety (Van den Berg, 1986; Elias et al., 2016).

Although an extensive ebb-tidal delta has formed in front of the Oosterschelde over time, it is also suggested that neither the Maas, the Schelde, nor the Waal contributed a significant supply of sand to the Voordelta. Instead, the proposed source of sand is the relocation from within the Oosterschelde and its shores to the Oosterschelde part of the Voordelta (and to places beyond) via erosion (Elias et al., 2016). Part of the Voordelta that was fed by this relocation of sediment was a large sandbar, The Banjaard (Fig. 1). The Banjaard was attached to the beach of Schouwen in the east and bound by the Roompot channel in the south, as indicated in reports from the 16th century. At this point, there were supposedly no channels crossing the sandbar. Towards the end of the 16th century, charts reported that the Banjaard sandbar had become separated from Schouwen by a channel. In the decades that followed, this initial channel split into other channels, which started to divide the Banjaard sandbar into smaller sandbars. A posited cause is that the Hammen channel, flowing along the southern shore of Schouwen, initially fed into the Roompot channel, but became separated during the 17th century. Before this separation, water flowing through Hammen would have been transported along the Banjaard through the Roompot. After the separation, water flowing through Hammen would instead be sent north towards the Banjaard, where a Banjaard channel system had started to develop around this time and started feeding the developing Banjaard channel system instead (Eelkema, 2013).

From the year 1800 onwards, clear sources are found that indicate the development of the Banjaard sandbar. At the start of this period, the Banjaard sandbar was intersected by the following three channels mentioned from west to east: Westgat, Hondengat, and Krabbengat. Over time, the Westgat started straightening and shifting in southern direction until 1910, changing its direction from nortwest to southwest. In 1933, a new channel, Geul van de Banjaard (Banjaard Channel), started forming where the Westgat ended in 1827. Two decades later, this channel had almost reached the seaside and caused the splitting of the Banjaard into a seaward and a landward section, which is still the present-day situation. Furthermore, around 1933 Hondengat became abandoned and silted up to the depth of the surrounding area. Additionally, over this period nearly all the intertidal area in the Banjaard area disappeared (Eelkema, 2013). The erosion of the Banjaard sandbar is considered to be caused by a combination of many different human and natural causes, including construction of the Deltawerken and the Kreekrakdam. The erosion of this sandbar was caused by an interplay of blocked sediment supply, decreased tidal currents, and the physical impacts of waves (Elias et al., 2016).

Main Message

- The Banjaard is an eroded sandbar lying in the Voordelta west of Schouwen.
- The Banjaard sandbar became completely submerged as a result of erosion induced by an interplay of both man-made and natural changes.

Chapter 3: Spatial configuration of the Banjaard barrier island

In this chapter we answer the following research question: 'What is the optimal positioning, shape, and profile of the Banjaard barrier island to protect the coastline of Schouwen?'.

For the construction of the barrier island sediment nourishments are needed, which should comply with the sediment characteristics present off the Schouwen coast. Hence, we first shortly discuss the sediment conditions off the Schouwen coast and possible sources for the sediment nourishments in Ch. 3.1. Furthermore, the Banjaard barrier island should be placed at a sufficient distance from the coast to also retain its coastal protection function in the future. Therefore, in Ch. 3.2 the minimum distance between the future barrier island and the coast is discussed and this distance is used as a foundation for the location of the future Banjaard. In Ch. 3.3, the abovementioned research question is answered by analysing the following five criteria agreed with commissioners: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities. This criteria analysis results in an optimal spatial configuration for the future Banjaard.

3.1 Sediment availability

The eroded Banjaard sandbar consists of a landward and a seaward part which are separated by the Banjaard channel (Fig. 1). The envisioned barrier island will be developed at the approximate location of the landward Banjaard sandbar (location B closest to the Schouwen coast in Fig. 1). Due to the establishment of the Deltawerken, the Voordelta changed from a mixed energy system into a wave dominated system. This wave dominance results in a net sediment transport towards the northeast (Elias et al., 2016).

The sediments in the Voordelta area are in the 'moderately coarse' (210 – 420 µm) to 'coarse' (420 µm) grain size range (Bos et al., 2011; Rijkswaterstaat, 2011). We expect that it would be favourable to use sediments in this same grain size range for the construction of the barrier island.

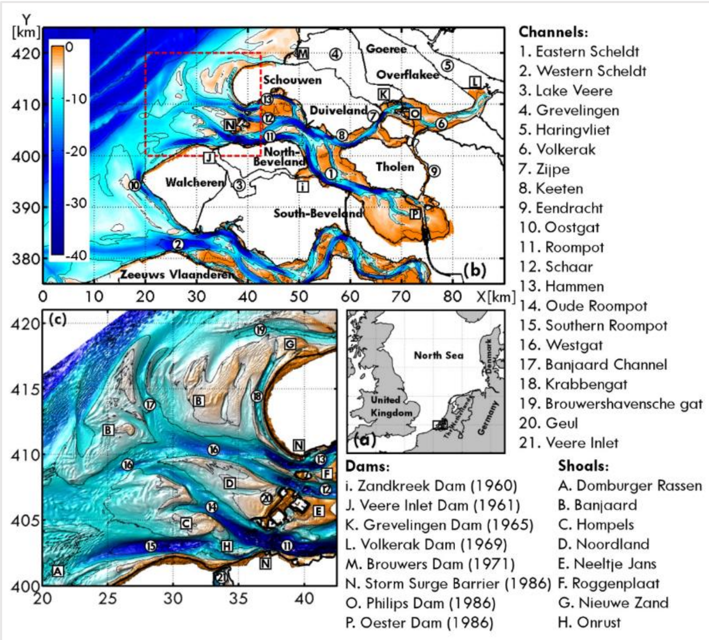

Figure 1: Map of the Voordelta (upper figure) and a zoomed in map of the Oosterschelde basin (lower left figure); on the right side the names of the channels, dams and shoals are displayed. Figure retrieved from Eelkema (2013). This figure shows the ebb-tidal delta 2008 in which the Banjaard sandbar is still noticeable.

The relation between erosion and grainsize is illustrated in the Hjulström-diagram (Fig. 2) which is based on riverine systems (Hjulström, 1935). This diagram has been modified to respectively include different levels of cohesion and differentiation for consolidated and unconsolidated soils (Miedema, 2013). Fig. 2 shows for 'moderately coarse' to 'coarse' sediments, the maximum flow velocity at which the particles will settle is in the approximate range of 2.1 cm/s (0.021 m/s) to 4.8 cm/s (0.048 m/s). Furthermore, the minimum flow velocity at which erosion takes place is approximately 10.7 cm/s (0.107 m/s; Fig. 2). These flow velocities only serve as indications here since there are some limitations regarding the application of the general Hjulström-diagram to the future Banjaard location (Ch. 5.1). However, with future research into the specific flow velocities at the barrier island location, a site-specific Hjulström-diagram could be developed to further determine an optimal sediment grainsize for the Banjaard barrier island (Ch. 5.1).

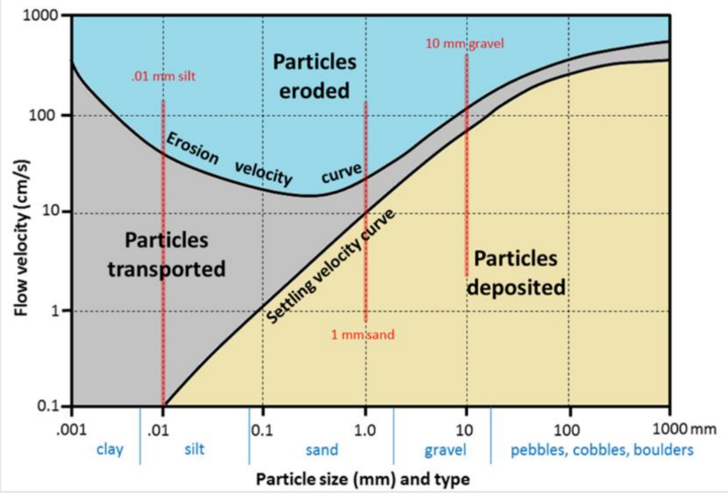

Figure 2: Hjulström-Sundborg diagram; a modification on the Hjulström-diagram: it shows the relationships between grainsize and the tendency to be eroded, transported, or deposited at different current velocities Adapted from figure 6.3.1. From *Dynamic Planet: Exploring Geological Disasters and Environmental Change* (section 6.3), by Estrada, C., Michel, C. L., Wilson, M. & Simpson, J., n.d. Copyright by Steven Earle

The type of sediment used for construction of the Banjaard is very important since the grain size, chemical, and physical characteristics of the sediments determine whether the environmental conditions are optimal for an ecosystem to thrive (A. van Oudenhoven, personal communication, May 11th 2022). The following three potential sediment sources were proposed to us by Shared Concepts and are therefore shortly discussed below:

Option 1: Dredged sediments from the Rotterdam harbour access channel

The first option is the use of dredged sediments derived from the access channel of the Rotterdam harbour. Considering the high siltation rates, frequent dredging of this area is required (Winterwerp & Van Kessel, 2003). However, the application of dredged sediments is associated with high costs in the long run (Davis et al., 2022). Additionally, shipping activities in the harbour create a risk of deposition of contaminants (Bocchetti et al., 2008). Using contaminated sediments could have a strong negative impact on the ecological quality of the barrier island. Moreover, the largest fraction of sediments in this area has a very small grain size. Therefore, use of those sediments would be transported easily towards the coast due to the hydrodynamic transport mechanisms mentioned in Elias et al. (2016). It would also create low opportunities for settlement of ecosystem engineers and increase erosion of juvenile bivalves (Hunt, 2004).

Option 2: Extracted riverine sediments

By digging secondary river branches and widening riverbeds, the adaptive capacity to climate change induced extreme rain events in the river landscape can be increased (Sijmons et al., 2017), this method is already applied in the Netherlands. These extracted riverine sediments can potentially be used for the development of the barrier island. However, contaminants and nutrient excesses derived from anthropogenic activities are stored in those sediments of the rivers (Wohl, 2015), which could negatively affect ecosystem engineers on the future barrier island.

<u>Option 3: Restoration of original sediment dynamics</u>

During the late 19^{th} century, the Oosterschelde was decoupled from the Westerschelde by the Kreekrakdam and the Sloedam, after which erosion of the Banjaard became clear. However, it is unlikely that this has a direct causal link to the disappearance of the Banjaard. Firstly, Elias et al. (2016) suggest that the Schelde did not supply a significant amount of sediment to the Oosterschelde system (Ch. 2.2). Secondly, since at least the 13^{th} century, many other changes have also taken place in the Oosterschelde basin; it has repeatedly grown and shrunk due to large floods and gradual land reclamation. Once such changes take place in a basin, the system adjusts to the new situation over time, which can take decades to centuries depending on the size of the change (Eelkema, 2013). These two points indicate that the disappearance of the Banjaard is very complex, and probably linked to the adaptation of the basin to a long series of changes. Simply 'restoring' river flows is therefore unlikely to result in a restoration of the former Banjaard. This is further supported by a comment of M. Eelkema: "Tidal prism is much stronger. Where the Rhine has a flow rate of two to three thousand m^3/s on average, a tidal prism can have flow rate of up to eighty thousand m^3/s" (M. Eelkema, personal communication, April 29^{th} 2022), so the added influence of restored river flow will be minimal compared to the ongoing tidal prism that shapes the basin.

Main Message

- A site-specific Hjulström-diagram for the barrier island location can determine suitable sediment grain sizes regarding the site-specific hydrodynamics (Ch. 5.1).
- The sediment suitability for the construction of the barrier island is also dependent on the preferences and characteristics of ecosystem-engineers.
- The proposed sediment nourishment sources for sediment nourishments are: (1) dredged sediments from the Rotterdam harbour access channel (2) extracted riverine sediments; (3) restoration of original sediment dynamics.
- These proposed sediment sources have significant disadvantages. We advise to do more in-depth research into suitable sediment sources for the Banjaard barrier island (Ch. 5.1).

3.2 The distance from the coast

To achieve the goal of the future Banjaard – reducing the present and future wave pressures on the Schouwen coast, the space in between the barrier island and the Dutch coast should be maintained over time. However, increasing sea levels can create a receding barrier island towards the coast, which can be estimated by the Bruun Rule (Ranasinghe et al., 2007). The Bruun Rule; $R = \frac{S\,L}{\mathrm{h+B}} = \frac{S}{tan\beta}$ includes recession of the shoreline (R), sea level rise (S), length of the profile (L), depth of the closure (H), dune height above sea level (B), and average slope (β) (Cooper & Pilkey, 2004). In literature the Bruun Rule is often criticised because, amongst others, it is oversimplified, relies on relationships which do not exist in nature, and it neglects important factors (Cooper & Pilkey, 2004). According to Ranasinghe & Stive (2009, p. 467) the Bruun Rule should only be used for "broadly indicative estimates that are not suitable for direct use in coastal planning and management". Hence, the Probabilistic Coastline Recession (PCR) model is proposed to be a more suitable method than the Bruun Rule (Ranasinghe et al., 2012; Ch. 5.1). However, due to its simplicity, the Bruun Rule is mentioned in this research project to illustrate the general coastal retreat mechanisms due to relative SLR.

The Bruun Rule indicates that the distance from the coast to the barrier island must be greater than the recession of the barrier island towards the coast. The barrier island must not move too close to the current coastline, as it will then lose its aim for coastal defence. For the Dutch coast the sea level is expected to rise with +0.54 to +1.21 m by 2100 (KNMI, 2021) and since the Bruun Rule provides a rule-of-thumb recession between 50xSLR and 100xSLR (Ranasinghe et al., 2007), an indication for the minimum distance between the barrier island and the Schouwen coast should be in the range of 27 m (0.54 m SLR x 50) to 121 m (1.21 m SLR x 100). Therefore, a minimum distance of 121 m is used as foundation for the location of the future Banjaard, however, we emphasize the uncertainty of +1.21 m SLR on which the minimum distance of 121 m is based. Also, note that the Bruun Rule recession relies on the assumption that the slope of the barrier island is in the range of 1:50 to 1:100 (Ranasinghe et al., 2007). To prevent the future barrier island growing close to the coastline the coming 80 years, the future Banjaard should be located according to the criteria described in the following paragraphs.

Main Message

- The Bruun Rule is not suitable for direct use in coastal planning and management. However, due to its simplicity, we still use the Bruun Rule to indicate the minimum distance between the Banjaard barrier island and the coast.
- According to the Bruun Rule, an indication for the minimum distance between the Banjaard barrier island and the Schouwen coast is in the range of 27 m to 121 m.
- Based on a predicted SLR of +1.21 m by 2100, a minimum distance of 121 m to the coast is used as foundation for the location of the future Banjaard in this research project.

3.3 Spatial configuration of the future Banjaard barrier island

The properties related to the spatial configuration of future Banjaard are based on the following five criteria: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities. These criteria were agreed upon with Shared Concepts at the start of this research project. Our criteria are used to determine the initial placement and shape of the barrier island. However, since nature-based solutions are dynamic, they can change e.g., their position due to environmental influences (Davis et al., 2022). Most of the criteria mentioned above are chosen because they provide information on how the coastal protection performance of the barrier island can be optimised and how coastal erosion can be mitigated. Environmental properties related to waves, currents, and coastal bathymetry are also used by Davis et al. (2022) to evaluate the coastal protection of a restored barrier island. Furthermore, the nautical activities criterium is selected in this research project since the barrier island should not obstruct shipping routes considering the risk on ship damage and subsequently massive oil spills (Hong & Amdahl, 2011). Prevention to obstructed shipping routes was also incorporated in the design of the Zandmotor project in the Netherlands (Oost et al., 2016). The chosen criteria are related to site specific spatial characteristics and determine the suitability for specific ecosystem engineering species as shown in the Belgian pilot project 'Coastbusters' for NBS (Sterckx et al., 2020).

To identify the most suitable shape and position of the future Banjaard, a simplified method from Gelan (2021) is used. In the article of Gelan (2021), a map analysis was done for multiple criteria to determine the highest suitability for urban green areas when the different criterium maps were overlaid. Similarly, to this methodology, we analysed each chosen criterium and the resulting potential spatial configuration of the barrier island is presented in a criterium map. For the final spatial configuration of the barrier island, all criterium maps are overlaid to identify the highest suitability for the position and shape of the barrier island.

3.3.1 Wind direction and wind velocity

At the location of the future Banjaard, the dominant wind direction is southwest (Prins et al., 2020) and could incidentally reach wind velocities up to 17.49 m/s (weather station Renesse-West; Windfinder, 2022). However, in the month of April the wind is predominantly northwest oriented (weather station Renesse-West; Windfinder, 2022). Off the Dutch coast, winds coming from this north-western direction are associated with the largest fetch and thereby with the highest potential for generation of large waves and storm surges (De Winter et al., 2013; Prins et al., 2020).

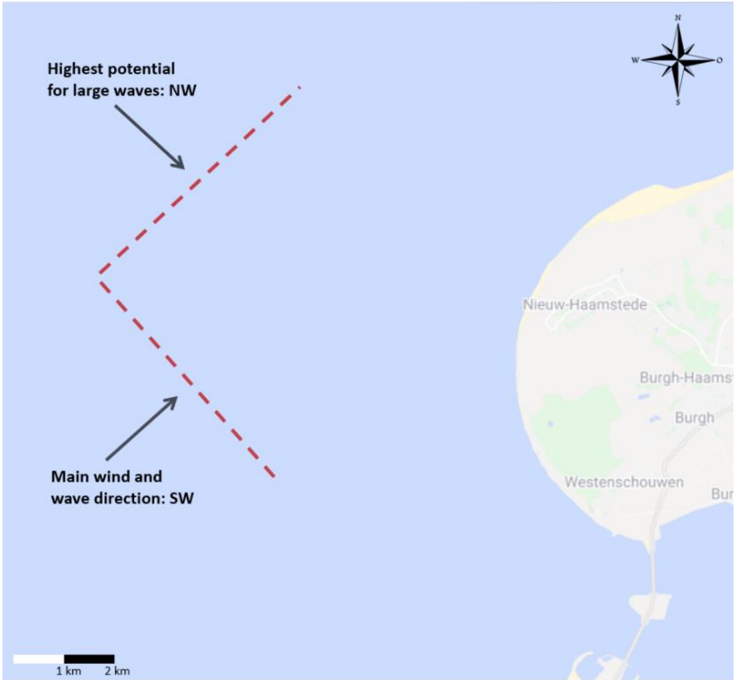

Figure 3: Approximate placement of the Banjaard barrier island with regard to the current main wind direction (SW = southwest) and the wind direction that will become more dominant in the future (NW = northwest) that generates the highest waves.

In the context of coastal protection, the barrier island should be resistant to strong winds from the southwest and northwest directions (Fig. 3), which would result in a curved shape. Because of its curved shape the proposed barrier island has a long leeside, which will provide a sheltered environment from the dominant wind direction and the wind direction that generates the largest waves. Often, the highest biodiversity is found on the leeward side, since the deposition of the smallest fraction of the sediments takes place here (Perkins et al., 2015).

However, this spatial configuration based on wind direction and speed comes with high uncertainties. Those uncertainties are partly caused by climate change. Due to climate change, the dominant wind direction is likely to shift from southwest to northwest (Beniston et al., 2007) and extreme wind events are likely to occur more frequently (Van den Hurk et al., 2007). The development of the barrier island with dune formation also contributes to this uncertainty. Vegetated dunes are likely to decrease the windspeed locally (Durán & Moore, 2013) and change the direction of wind fluxes (Livingstone et al., 2007). Therefore, further research should be done on the interaction between the barrier island development and larger wind fluxes, and on the vegetation-sediment interaction after the establishment of the dune system (Ch. 5.1).

3.3.2 Wave direction and wave energy

In the Voordelta the waves are mainly created by the forcing of the wind (Elias et al., 2016) and since the main wind direction is southwest, this is also the main wave direction (Prins et al., 2020). Although the average wave height is 1.3 m, the wind-generated waves can become more than 6 m high under stormy conditions (Elias et al., 2016). Wave height can be used as a proxy for wave energy, since wave energy is proportional with the squared wave height (Holthuijsen, 2007). Therefore, an increase in wave height will increase wave energy quadratically.

Currently, the coast of Schouwen encounters an increased wave forcing due to the erosion of the Banjaard sandbar resulting in a reduced deceleration of the waves (Vermaas et al., 2015). Therefore, a barrier island engineered on the location of the eroded Banjaard sandbar, can mitigate the wave forcing on the coast of Schouwen and reduce coastal erosion. As mentioned in Ch. 3.3.1, the main wind direction will shift from southwest to northwest (Beniston et al., 2007) in the future and the north-western wind has the highest potential for large waves (De Winter et al., 2013; Prins et al., 2020). Therefore, in the future it is possible that the main wave direction, influenced by the wind, will also shift to the northwest and that the mean wave height could increase. Hence, the barrier island should provide protection against waves from the dominant southwest direction and from high waves from the northwest direction. The placement of the barrier island following the wave criteria is similar to the placement of the Banjaard following the wind criteria in Fig. 3.

3.3.3 Tidal currents

Due to the construction of the Oosterscheldekering, resulting in partial occlusion of the Oosterschelde, the shore-normal tidal flow decreased. According to M. Eelkema, "the currents change more or less instantaneously after such interference" (M. Eelkema, personal communication, April 29th 2022). The storm surge barrier increased the dominance of tidal currents parallel to the coast of Schouwen (Elias et al., 2016) and it decreased the tidal current velocity in the Voordelta (Prins et al., 2020). During high tide, the semi-diurnal tidal current moves along the coast towards the north, whereas during low tide, the current moved towards the south (Lazar et al., 2017). Under semi-diurnal tidal conditions, either during low tide or high tide, the currents experience the highest velocities (Nichols, 2009).

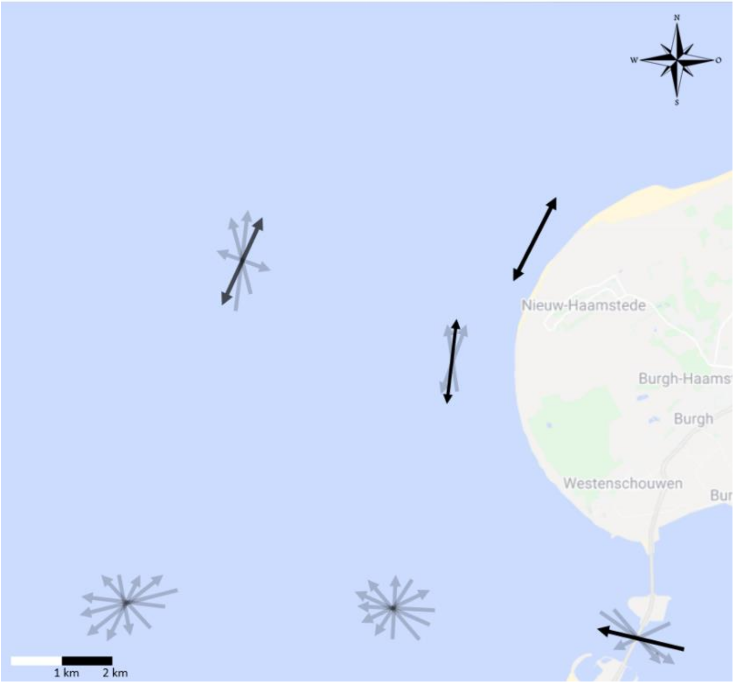

Figure 4: Approximate directions of the tidal currents off the coast of Schouwen for one tidal cycle on 21/11/21. Data is retrieved from HP33D - NLTides, see also Appendix A.1.

During high tide, the water level can rise by approximately 2 m respective to NAP (Rijkswaterstaat, n.d.). Hence, for engineering the barrier island, extra height for the large tidal fluctuations should be considered. The velocity of the tidal currents is in the approximate range of 0.16 m/s to 0.87 m/s (The Netherlands Hydrographic Services of the Royal Netherlands Navy, 2022) and the approximate direction of the currents off the coast of Schouwen can be seen in Fig. 4. The tidal currents in Fig. 4 are for the date of 21/11/21. However, it is assumed that these tidal movements are representative for the average tidal movements off the Schouwen coast (for an explanation, see Appendix A.1). Overall, it should be noted that the velocity and direction of the tidal currents presented are spatially averaged, since tidal currents can vary strongly due to differences in bathymetry and hence the currents can be unpredictable (Dienst der Hydrografie van de Koninklijke Marine, 1992).

Tidal movements off the Schouwen coast provide information on how the Banjaard could grow in the future. The main tidal currents occur to the north-north-east or to the south-south-west, hence, the Banjaard could grow along these directions under the force of the tides. After the construction of the barrier island "the currents will not change very much [in the future], of course also because the Banjaard [sandbar] is already quite shallow." (M. Eelkema, personal communication, April 29th 2022). Hence, the current tidal conditions are assumed to be representative for future currents.

3.3.4 Bathymetry

After the Oosterscheldekering was constructed, the network of channels in the ebb-tidal delta remained similar to what it was before due to sufficient tidal current forcings (Elias et al., 2016). However, the bathymetry shows a slow response to interference since “the [seabed] morphology takes decennia to adapt” (M. Eelkema, personal communication, April 29th 2022). For the Banjaard sandbar, a net trend of sediment volume erosion has taken place in the period of 1984-2010.

Figure 5: Approximate area that displays depths in the range of -6 m to +0.1 m respective to NAP. This area is suited for the position of the Banjaard barrier island regarding the criterium for bathymetry. Data is retrieved from Rijkswaterstaat (2017), see also Appendix A.2.

It is likely that the eroded Banjaard sandbar will not encounter large changes in the future, although the sandbar will probably become deeper (Prins et al., 2020). Since it is uncertain how the Voordelta depths will evolve over time, the current bathymetry of the eroded landward Banjaard sandbar is used to determine the spatial configuration of the barrier island. Off the coast of Schouwen there is an area with depths ranging from approximately -6 m to +0.1 m respective to NAP (Rijkswaterstaat, 2017) (Fig. 5), which contains part of the eroded Banjaard sandbar. Around the shallow area, the depths can quickly plummet to approximately 10 m below NAP (Rijkswaterstaat, 2017) as can also be seen in Appendix A.2. The shallow area is suitable for the placement of the future barrier island because a limited amount of sediment would be needed for the construction of the barrier island. This is beneficial from a financial perspective since large sediment nourishments come with high costs at 5 to 10 euros per cubic m of sediment (Stronkhorst et al., 2018). Additionally, it is ecologically favourable because large sediment nourishments can have a large negative, disruptive impact on the habitats already occurring in the area (Peterson & Bishop, 2005). Furthermore, “the natural development [at the location of the Banjaard sandbar] led to a shallow area, which could increase the chance that such a [barrier] island will remain in place” (M. Eelkema, personal communication, April 29th 2022).

3.3.5 Nautical activities

The Oosterschelde is a busy shipping route with approximately 45,000 vessels per year and the route has a high economic importance (Nationaal Park Oosterschelde, n.d.). The future barrier island should not interfere with nautical activity and hence should be positioned in an area with minimal nautical activities (Fig. 6). The term 'nautical activity' includes the movements of: cargo vessels, tankers, passenger vessels, tugs, crafts, fishery, recreational or pleasure crafts and navigation aid (Marine Traffic, n.d.). Around the area with approximately no nautical activities, displayed in Fig. 6, the shipping routes are in the range of 5 to 521 routes/km^2/year (see also Appendix A.3). The main shipping route is approximately 6.7 km offshore and the smaller Krabbengat channel is approximately 0.8 km from the coast of Schouwen (estimated from Google Maps). The very large vessels can be found further offshore (Marine Traffic, n.d.) and these do not seem to interfere with the positioning of the future barrier island.

Figure 6: Approximate area that displays shipping routes in the range of 0 to 1 routes/0.08km^2/year. This area is suited for the position of the Banjaard barrier island regarding the criterium for nautical activity. Data is retrieved from Marine Traffic (n.d.), see also Appendix A.3

Nautical traffic, especially larger vessels, affect sediment transport and seabed topography by eroding the channels and resuspending the seabed sediment (Xue et al., 2021). The increased turbulence in the water caused by nautical activities can result in changed seabed sediment conditions and increased turbidity in the water column, which can affect marine species (Xue et al., 2021). The disturbances can also affect species living on the water surface. E.g., common scoters are disturbed by nautical activities at a distance of 1 kilometre, which resulted in the establishment of rest areas in the Voordelta (Prins et al, 2020). Therefore, the future Banjaard should have sufficient distance from navigation channels. However, determining the minimum distance is outside the scope of this research project and can therefore be investigated with future research (Ch. 5.1). For ecological reasons a rough measure of approximately 1 kilometre has been used as a sufficient distance between the future barrier island and the major shipping routes in Fig. 6.

3.3.6 The final spatial configuration of the Banjaard barrier island

We combined the criteria maps of previous paragraphs to determine a feasible output-area which is suitable for constructing a barrier island off the coast of Schouwen. These maps illustrated the position and shape of the future Banjaard according to the wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activity. The combination of the criteria maps (Fig. 7) results in the optimal 'Crescent' design sketch for the spatial configuration of the Banjaard barrier island (Fig. 8; see also Appendix A.4). The shape of the future barrier island follows the general shape of the coast (Fig. 8), which was also suggested in the interview with M. Eelkema (M. Eelkema, personal communication, April 29th 2022). A sidenote to the Crescent design is that the part of the barrier island that is underwater at high tide (dark dotted line in Fig. 8) is not compliant with the nautical activities criterium (Appendix A.4). This is because in some places the (underwater) barrier island is situated in an area with 5-10 routes/0.08km^2/year (Appendix A.4) instead of the 0-1 routes/0.08km^2/year used in the nautical activities criterium. However, we consider 5-10 routes/0.08km^2/year as relatively limited nautical activity and hence we foresee no nautical difficulties with the Crescent barrier island spatial configuration. Another sidenote is that the Crescent spatial configuration of the future barrier island (Fig. 8) is situated in an area that experienced net erosion from 1984 to 2010 (Elias et al., 2016). Nevertheless, as mentioned before, it is uncertain how the construction of the barrier island will affect e.g., the future hydrodynamics and, as a result, the erosion or sedimentation processes in the area. After the Banjaard barrier island is constructed, these processes can be monitored as mentioned in Ch. 5.2.

To preserve the optimal position of the Banjaard barrier island over time and hence prevent migration towards the coast, the future Banjaard should have a certain critical width. This critical width can be determined when the site is in its end-conditions (Rosati & Stone, 2007). Since the critical width is case-specific and the end-conditions of the barrier island are uncertain, it is not yet possible in this research project to determine a specific critical width for the future Banjaard. Therefore, we propose that the Migration, Consolidation and Overwash model (MCO) of Rosati & Stone (2007) could be used in further research to estimate the specific critical width of the Banjaard (Ch. 5.2). As a starting point, we use a barrier island width of 200 m estimated from the following research findings: Leatherman (1976) found a critical width in the range of 122 to 213 m for a barrier island at the northern end of Assateague Island in Maryland; Jiménez & Sánchez-Arcilla (2004) found a critical width of 225 m for a barrier island in the Elbro-delta; and Stone et al. (2004) found a width of 220 m for four barrier islands in Santa Rosa Island in Florida. Therefore, is seems valid to use an above-water-width of 200 m as a rough estimate of the future barrier island under high tide conditions. We estimate that the part of the barrier island that is below the waterline at high tide has a width of 500 m on all sides of the barrier island (dark dotted line in Fig. 8).

Fig. 9 displays a simple cross-section sketch of the Banjaard barrier island. Due to varying water depths on the location of the future barrier island (Ch. 3.3.4), we assume a uniform water depth of approximately -5 m with respect to NAP. Hence, the barrier island height regarding the bathymetry

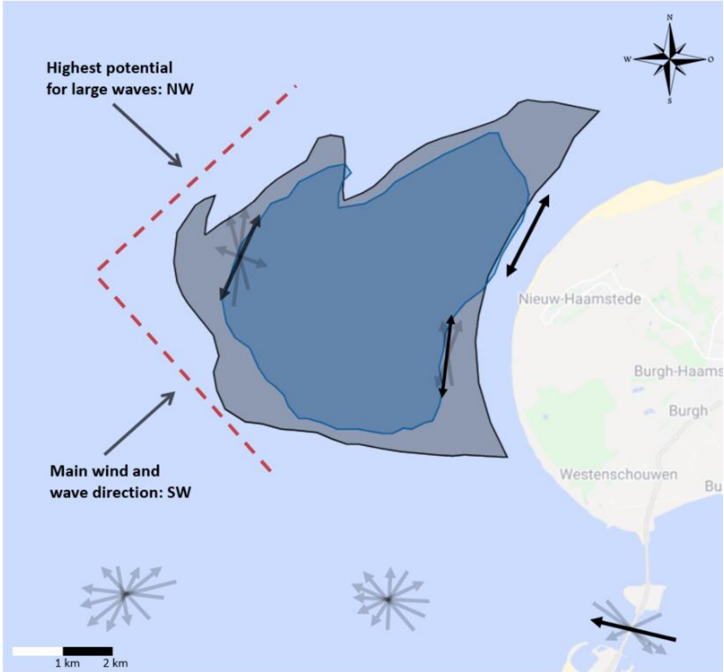

Figure 7: Final map in which all criteria maps are overlaid to identify the suitable spatial configuration of the future barrier island. The red dotted lines show the optimal protection against waves and wind. The tidal currents are represented with arrows, with black arrows indicating the dominating tidal current direction. The grey area approximately shows depths in the range of -6 m to +0.1 m with respect to NAP. The blue area approximately displays shipping routes in the range of 0 to 1 routes/0.08km²/year.

Figure 8: Optimal spatial configuration of the Banjaard barrier island according to the combined final criteria map. The solid yellow line represents the part of the barrier island above the waterline at high tide, this part has a width of approximately 200 m and a minimum distance to the coast of approximately 4 km. The dark yellow dotted line represents the part of the barrier island under the waterline at high tide, this part has a width of approximately 500 m on all sides of the barrier island.

should be 5 m measured from the seafloor (0 m). Furthermore, the barrier island is subject to a tidal fluctuation of approximately 2 m (Ch. 3.3.3) and therefore the barrier island height should be at least 7 m (starting from the seafloor) to prevent flooding of the future Banjaard (Fig. 9). In addition, the barrier-island should withstand large 6 m waves under stormy conditions (Ch. 3.3.2) even under high tide conditions, resulting in a total barrier island height of at least 13 m when starting from the seafloor (Fig. 9).

On average, 'nearshore beach' slopes are in the range of 2:100 and 1:100 (Ranasinghe et al., 2007). Hence, we estimate the slope to be 1.4:100 for barrier island heights of 0 m to 7 m (measured from the seafloor at 0 m; Fig. 9). This slope allows for the aforementioned width of 500 m on all sides of the barrier island below the waterline at high tide (Fig. 8 and Fig. 9). From a height of 7 m to 13 m we estimate a slope of 6:100 (Fig. 9). Dune-angles can vary roughly between 100:100 (after storm surge) to 8:100 and the angle of dry sand below a dune can have shallow angles of around 5:100 (Van de Graaff, 2007). The 6:100 slope is used in this research project because this slope is within the range of dune angles, and it enables the barrier island width of 200 m that was mentioned before.

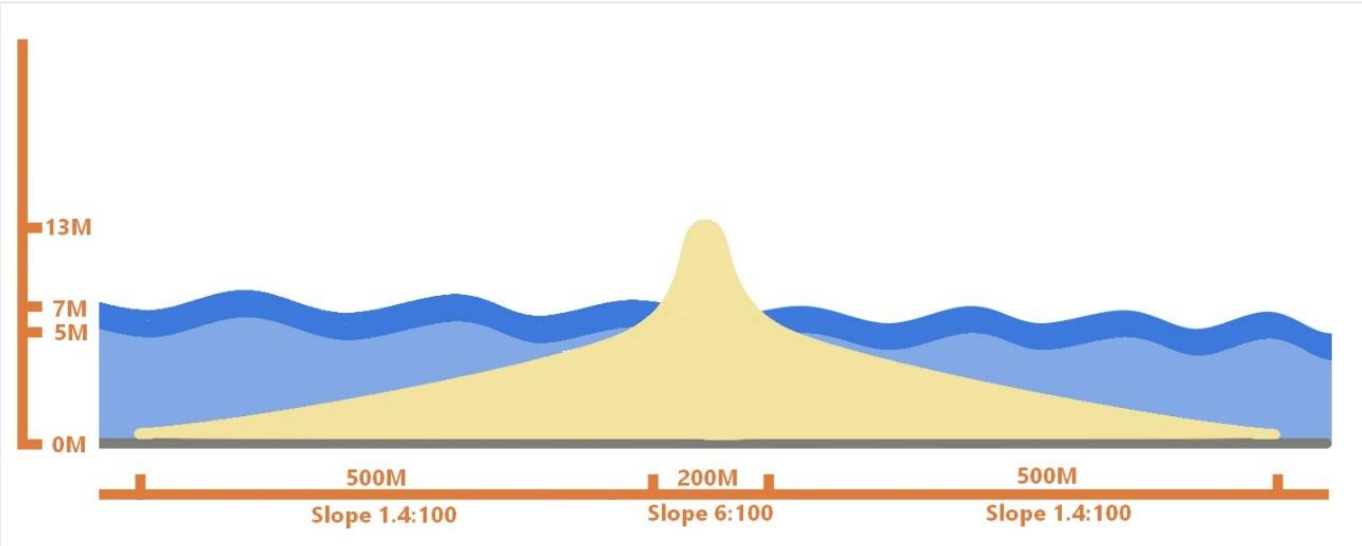

Figure 9: Cross section of the Banjaard barrier island. The blue area represents water, and the yellow area is the barrier island. The water depth is 5 m in between low tide and high tide, and the water depth is 7 m at high tide. The dark blue line between 5 m and 7 m depth represents the high tide. The above-water-part of the barrier island should be 200 m in width under high tide conditions and the height of the barrier island is 6 m at high tide.

Main Message

- The estimated above-water-width is 200 m for the barrier island at high tide.
- The estimated under-water-width is 500 m (on all sides) for the part of the barrier island that is underwater at high tide.
- Composition of the barrier island height:
    - Considering the bathymetry: height is 5 m measured from the seafloor (0 m).
    - Considering tidal fluctuation of approximately 2 m: height is at least 7 m measured from seafloor (0 m).
    - Considering stormy conditions with 6 m waves: height is at least 13 m measured from seafloor (0 m).
- Hence, the estimated total barrier island height is at least 13 m measured from the seafloor (0 m). This minimum height will enable the barrier island to withstand storms under high tide conditions.
- The estimated slope is 1.4:100 for the barrier island between 0 (seafloor) and 7 m in height.
- The estimated slope is 6:100 for the barrier island between 7 and 13 m in height.

The Crescent spatial configuration (Fig. 8) is recommended for the future barrier island and this barrier island should host a varied, stable marine ecosystem and a dune system. However, this Crescent design is not stimulating the development of favourable ecological conditions for most ecosystem engineers (N. van Rooijen, personal communication, May 6th 2022). In the interview with N. van Rooijen, it was therefore suggested that the ecological component should also be considered for the barrier island spatial configuration (N. van Rooijen, personal communication, May 6th 2022).

As already mentioned in Ch. 3.3.3, the currents will not change much after the Crescent barrier island is constructed (M. Eelkema, personal communication, April 29th 2022) and hence the envisioned 'leeward side' in this design still endures the strong forcing of currents. This results in a "very low chance for small particles to settle [and] therefore you will not obtain a development of salt marshes in the end" (N. van Rooijen, personal communication, May 6th 2022). For the development of a sheltered side of the barrier island where sediment can settle "a huge difference in currents between the west and the east of the [barrier] island" is needed (N. van Rooijen, personal communication, May 6th 2022). Hence, when also considering the ecological component, the Banjaard design should be adjusted to create a leeward side which is sheltered from both strong currents and waves. To adjust the spatial configuration, the "dune arch" on the coastline of Schouwen should be mimicked to provide a more "stable structure" (N. van Rooijen, personal communication, May 6th 2022). We emphasize that the resulting sketch of the 'Hook' design for the barrier island (Fig. 10) is an indication, hence, the red part in Fig. 10 can also be shortened.

The Hook spatial configuration has the advantage over the Crescent design that it could provide more shelter from the currents on the leeward side of the barrier island, which is favourable for the formation of salt marshes. Hence, it could result in a more biodiverse ecosystem on the leeward side of the future Banjaard and both the ecosystem and the barrier island could have a higher stability compared to the Crescent spatial configuration. A disadvantage of the Hook spatial configuration is that the barrier island design is not in line with both the bathymetry and nautical activities criteria (Appendix A.4). Furthermore, the Hook barrier island is closer to the Schouwen coast (minimum distance is approximately 2.6 km) compared to the Crescent design (minimum distance is approximately 4 km) and there are limited opportunities for the barrier island to 'grow' parallel to the coast. For the Crescent design, both the further distance from the coast and the growth opportunities along the coast are therefore advantages. Additionally, the Crescent spatial configuration requires less sediment suppletion, which reduces the costs and therefore provides an advantage over the Hook design.

Figure 10: Sketch of the Hook design for the optimal spatial configuration of the Banjaard barrier island, including the ecological component. The solid yellow line and the dark yellow dotted line is the Crescent spatial configuration according to the initial criteria; the solid red line and the dark dotted red line is the addition to the initial spatial configuration design due to the ecological component.

A sidenote is that the quantity of sediment nourishments for the final Hook barrier island can be reduced since the leeward side can also be made steeper and narrower compared to the Crescent design. This is because there are alleviated wave and current conditions on the leeward side of the Hook barrier island, which could result in a natural sediment settlement. Therefore, the steeper and narrower leeward side could reduce the extra costs of the larger sand nourishments needed for the initial construction of the Hook barrier island.

Another sidenote for the Hook design is that the additional red part in Fig. 10 can also be constructed using different materials than sediment. Hard structures, such as wooden poles and hard blocks (see Ch. 4.4.3), can also be used for the construction of the additional red part shown in Fig. 10. Future research is recommended to determine the effectiveness of a Hook design in which the red part is solely constructed with hard structures, compared to the effectiveness of a Hook design in which the red part is solely constructed with sediments (Ch. 5.1).

Since the Crescent design and the Hook design have advantages and disadvantages, it is clear that both designs require further research to find the optimal spatial configuration for the barrier island (Ch. 5.1). This research project continues considering both the Crescent and Hook design.

Main Message

- The Crescent barrier island design results from analysing the following criteria: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities.
- The Hook barrier island design results when we also include an ecological criterion, which likely increases the stability of the barrier island. The additional red part in the Hook design can be constructed with sediments or hard structures, such as wooden poles.
- For the Hook design the minimum distance is approximately 2.6 km to the coast and for the Crescent design the minimum distance is approximately 4 km to the coast.
- Both designs have advantages and disadvantages. We recommend determining the optimal spatial configuration of the Banjaard barrier island with further research (Ch. 5.1).

Chapter 4: Protecting, sustaining and stabilising the Banjaard

In this chapter, we will answer the following research question: "What are optimal ecosystem engineer options and positions to stabilise the sediment supplements?"

After the sediment supplements have created an island, the island will mostly be left to natural processes. We expect this will lead to the formation of certain habitats as described in this chapter. The presence of natural succession, erosion and sedimentation will lead to the creation of gradients on the island that allow for biodiversity. However, to protect, sustain and stabilise the barrier island directly after creation, some intervention is advised. Specifically, the application of ecosystem engineers, that capture and retain sediment, and attenuate incoming waves. In this chapter, the habitats and fitting ecosystem engineers for the Banjaard barrier island are described.

According to the European Habitat Directives, habitat types are distinguished. Every European country determines which habitat types are relevant for their nature areas in order to protect and manage these areas (Natura 2000, 2014b). We use the Natura 2000 habitat types for determining which ecosystem engineers are suitable for the future Banjaard. Natura 2000 gives us a clear description of habitat types, including characteristic species and the environmental conditions that suit the habitat type best. Characteristic species prefer a certain habitat type over others, though they may still be present in the other habitat types, albeit in lesser numbers. With environmental conditions is meant the preferences for pH, salinity, nutrient load, temperature, and depth. Species also have their preferences regarding grain size. In this chapter we want to present realistic habitat types that all suit the environmental conditions in the Voordelta, i.e. the habitat types used in order to protect, sustain and stabilise the future barrier island, all occur in relative low pH, saline, and temperate areas like the Voordelta.

Next to the capture and stabilisation of sediments, reducing the flow velocity/wave energy is the most important function of vegetation on the barrier island. Because of the lack of research on this topic, Koch et al. (2009) describe the use of biomass as a proxy for wave attenuation. Note that wave attenuation by biologic factors is drastically limited in case of abrupt interference of these habitats by structures as dikes, or the disruption by channels (Stark et al., 2016). The wave attenuation by biomass is not a solid measure, but will vary across plant, communities and even over seasons (Lara, 2016;

Koch et al., 2009). In this report we used biomass as proxy for wave attenuation and by that for sand capture capacity.

In this chapter, the habitats and fitting ecosystem engineers for the Banjaard barrier island are described. We do this by describing all potential habitat types from the east to the west side of the barrier island. For the east side of the barrier island the analysis of possible habitat types is divided corresponding to the two spatial configuration designs (see Ch. 3); Hook (Ch. 4.1) and Crescent (Ch. 4.2). Subsequently, the middle part will be discussed in section: Dunes (Ch. 4.3). We complete the description of habitat types on the barrier island all the way on the west seaside of the barrier island (Ch. 4.4).

4.1 East side; the Hook design

According to the Hook design, on the east side of the barrier island a salt marsh ecosystem is formed due to the intensively flow inhibited leeward side. This leeward side of the barrier island is highly dynamic and therefore the biodiversity is higher. A sketch of the cross-section of the Hook design is shown in Fig. 11 in which the different habitat types are included.

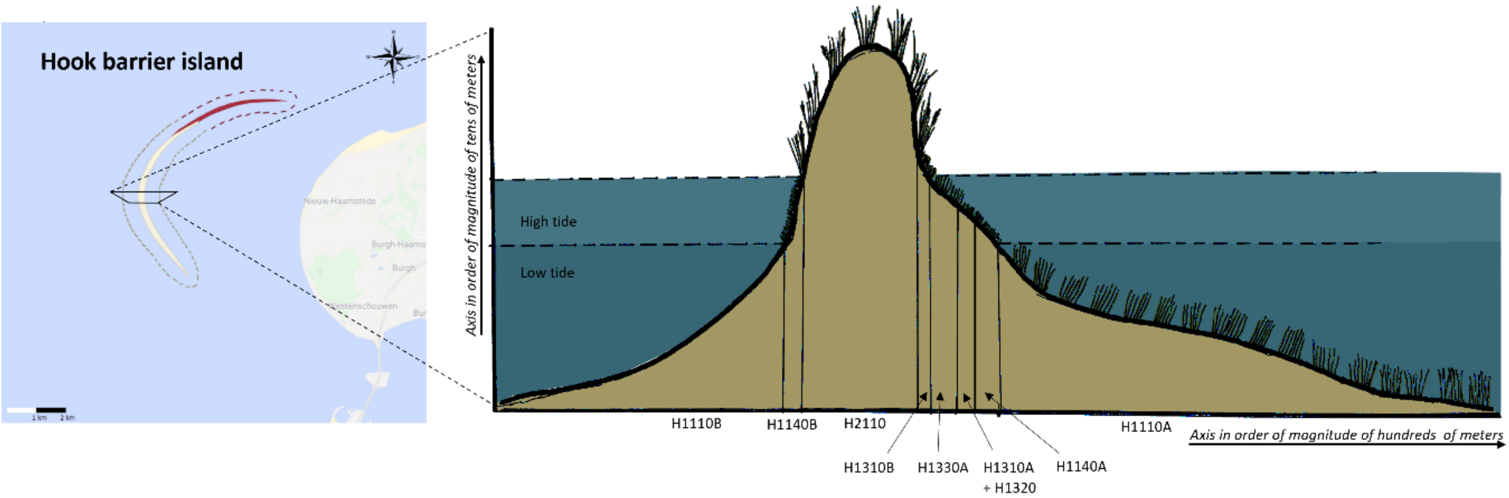

Figure 11: Sketch of the cross-section for the Hook scenario. The scale is indicative. The height will be in the order of magnitude of tens of metres, the width will be in the order of magnitude of hundreds of metres, depending on the actual wave attenuation and silting.

4.1.1 Sandbanks which are slightly covered by sea water all the time (H1110: Permanent overstroomde zandbanken; A: getijdengebied)

One of the most important goals of creating the future Banjaard is to shelter Schouwen's sea coast from wave action. Therefore, we predict that the future Banjaard will create a sheltered zone between the future barrier island and Schouwen's west coast in which H1110A can develop (see Appendix B.2 for more detailed description of habitat type A).

Seaweed and algae can be present in this habitat type (Natura 2000, 2014a). Without other vegetation types, a diverse pioneer ecosystem can still be present consisting of seaweed, algae and species feeding on these. Furthermore, (Natura 2000, 2014a) also mentions that before the 40's large growths of *Zostera marina* (a seagrass species) occurred in permanently submerged parts of De Waddenzee. The submerged vegetation results in sediment capture capacity and wave attenuation. Seaweed can reduce the threshold velocity for sediment transport by one order of magnitude (0.3 m s^{-1} versus 3.5 m s^{-1} (Frey & Dashtgard, 2012).

4.1.2 Mudflats and sandflats not covered by seawater at low tide (H1140: Slik- en zandplaten; A: getijdengebied)

Closer to the barrier island, the seabed will gradually rise until it is high enough to fall dry during low tide. This is where H1110 ends and H1140 begins. Habitat type H1140 is defined as the part of the seabed that lies between high and low tide (Natura 2000, 2008e). For H1140, we again expect that subtype A (tidal dominated; see Appendix B.2, B.3 for additional information) will develop on the leeside of the island. This habitat type is the start of what in Dutch is called 'kwelder' or in English saltmarsh (some additional information on saltmarsh can be found in Appendix B.1).

In this habitat type the following vegetation is present: *Ruppietum maritimae*, *Zosteretum noltii*, *Zosteretum marinae,* algae and seaweed (Natura 2000, 2008e). Furthermore, H1140A is the habitat for mussels (*M. edulis*), cockles (*C. edule*), sand mason worms (*L. conchilega*) and lugworms (*A. marina*) (Natura 2000, 2008e).

Vegetation in this habitat type results in wave attenuation, for the duration of the tidal cycle in which they are submerged. This is because the physical hinderance and long morphology of the plants slows the waves down. The vegetation serves the ecosystem by sheltering the mussels, cockles and worms that enhance wave attenuation and sediment capture capacity.

Sediment is stabilized by the root mats of these grasses. The stiffer cordgrass dampens hydrodynamic energy with its stems, while the more flexible seagrasses bend their shoots to inhibit currents (Temmink et al., 2020). A characteristic for ecosystem-engineer grasses is the ability to grow along with a rising sea level: the vegetation captures the sediment and continues to grow at greater heights (Borsje et al, 2011).

4.1.3 *Salicornia* and other annuals colonising mud and sand (H1310: Zilte pionierbegroeiingen; A: zeekraal (*Salicornia*), B: zeevetmuur (*Sagina Maritima*))

This habitat type consists of two subtypes. Firstly, *Salicornia* (Zeekraal/Salicorn) is represented by vegetation habitat type H1310A. This habitat type consists mainly of the *Salicornia procumbens* and *Salicornia* europaea species. *Salicornia* can be found in the transition zone where mud flats run dry (H1140) and the higher salt marsh vegetations starts (H1330) (Natura 2000, 2008g). *Salicornia* is submerged during high tide, whereas *Sagina maritima* is only submerged incidentally during storms, thus for wave attenuation *Salicorna* is more useful.

Secondly, *Sagina maritima* (Zeevetmuur, sea pearlwort) is abundant in this habitat type (H1330B). *Sagina maritima* grows on the dryer parts of the saltmarsh where the saltmarsh gradually changes in an embryonic dune system (H2110) (Natura 2000, 2008g).

Because of the status of pioneer species, we assume *Salicorna* and *Sagina maritima* will colonise the salt marsh area of the future Banjaard without the need to plant these species. Because *Salicorna* and *Sagina maritima* are annual pioneer species, the amount of biomass produced in one year is relatively high (Natura 2000, 2008g). Especially in the first period of the creation of the future barrier island, fast growing biomass is beneficial. In the first vulnerable period of the Banjaard barrier island, little species are settled on the barrier island, this means there is also a small capacity for wave attenuation. Hence, annually fast-growing biomass as these *Salicorna* and *Sagina maritima* are beneficial in this period to stabilise the island when not a lot of species are already abundant on the future Banjaard. Secondly these species are favourable for the capacity to capture sediments. Taking the morphology of the species into account, both species are small but have a lot of branches that can capture sediments by aeolian and/or wave transport.

4.1.4 *Spartina* swards (H1320: Slijkgrasvelden)

This habitat type consists of the characteristic pioneer species *Spartina anglica* (cord grass/Engels slijkgras) (Natura 2000, 2008d). *Spartina anglica* is a pioneer in the upper tidal zone, effective in accretion of sediments (Nehring & Hesse, 2008) and absorbing wave energy (Bouma et al., 2005). Currently, *Spartina anglica* is the most important invasive species in the Wadden sea and probably its settlement is still increasing because of increasing temperatures in spring due to climate change (Nehring & Hesse, 2008).

Initially, you could think *Spartina anglica* could be considered not suitable for the future Banjaard because of the high potential of becoming invasive, resulting in low vegetation biodiversity. Although it is expected that *Spartina anglica* will colonise the whole barrier island, this species also brings benefits, its effectively accretion of sediments and attenuation of waves. These benefits might weight more than the biodiversity of many vegetation species (N. van Rooijen, personal communication, May 6th 2022). N. van Rooijen (personal communication, May 6th 2022) also explained small crabs and bivalves live in between the roots of *Spartina anglica* making the invasive species a favourable habitat for a diversity of other organisms.

4.1.5 Atlantic salt meadow (H1330: schorren en zilte graslanden; A: Buitendijks)

Interesting pioneer and/or eco-system engineer species for this habitat type are several rush, reed, and grass species: *Puccinellia maritima* (kweldergrassen), *Zostera*-species (seagrasses), *Cyperaceae* (cypresgrassen), *Phragmites australis Asteretea* (riet) and *Scirpetum tabernaemontani* (ruwe biessoorten) (Natura 2000, 2008c).

In addition to the vegetation types, there are also bivalve species of interest: *Ostrea edulis* (flat oyster), *Crassostrea gigas* (Japanese or Pacific oyster). In colonies bivalves can be seen as an ecosystem engineer: by filtering the water, they create an environment beneficial for other species (Zu Ermgassen et al., 2020). The hard bivalve shells increase the seafloor roughness, attenuating wave energy (Carss et al., 2020).

Ostrea edulis (flat oyster) can be seen as natural reef builder in the North Sea with potential to colonise the Banjaard. In general, bivalves need hard substrate and low dynamics for initial establishment (N. van Rooijen, personal communication, May 6th, 2022). The hard structure may evolve in later stadium into soft sediment (Van Duren, 2017).

In the 1960s *Crassostrea gigas* (pacific or Japanese oyster), was introduced in the North Sea as consequence of the endangered status of *Ostrea edulis* due to overfishing, diseases, pollution, and cold winters (Kamermans, 2018; De Vriend, 2012). Although *Crassostrea gigas* is a non-native species, it can be of interest to further examine its potential for reef development at the open seaside (see Appendix B.4 for more information about bivalves). Because of the high abundance of *Crassostrea gigas*, this species will colonise the barrier island whether we introduce the species from the beginning or not. C*rassostrea gigas* does brings advantages for the habitat type: it provides shelters and hard substrate for settlement of *Ostrea edulis.* Another advantage: in reefs of native and non-native oysters combined the biodiversity is also higher than in monocultures (Christianen et al., 2018).

4.2 East side; The Crescent design

The leeside of the barrier island in case of low stream inhibition is expected to become less biodiverse than would develop on the leeside following the Hook variant (4.1). Because of less dynamics as consequence of the shape of the barrier island, according to the Crescent design, less habitat types will be able to settle on the leeside of the barrier island, resulting in a lower biodiversity. For the Crescent design, the following habitat types are still expected to be feasible: H1320, H1310 and H1140.

The habitat types in the Crescent variant are already discussed in previous chapters, therefore not explained in this chapter again. In Fig. 12 a sketch is shown for the cross-section of the Crescent design, which also includes the habitat types for this barrier island design.

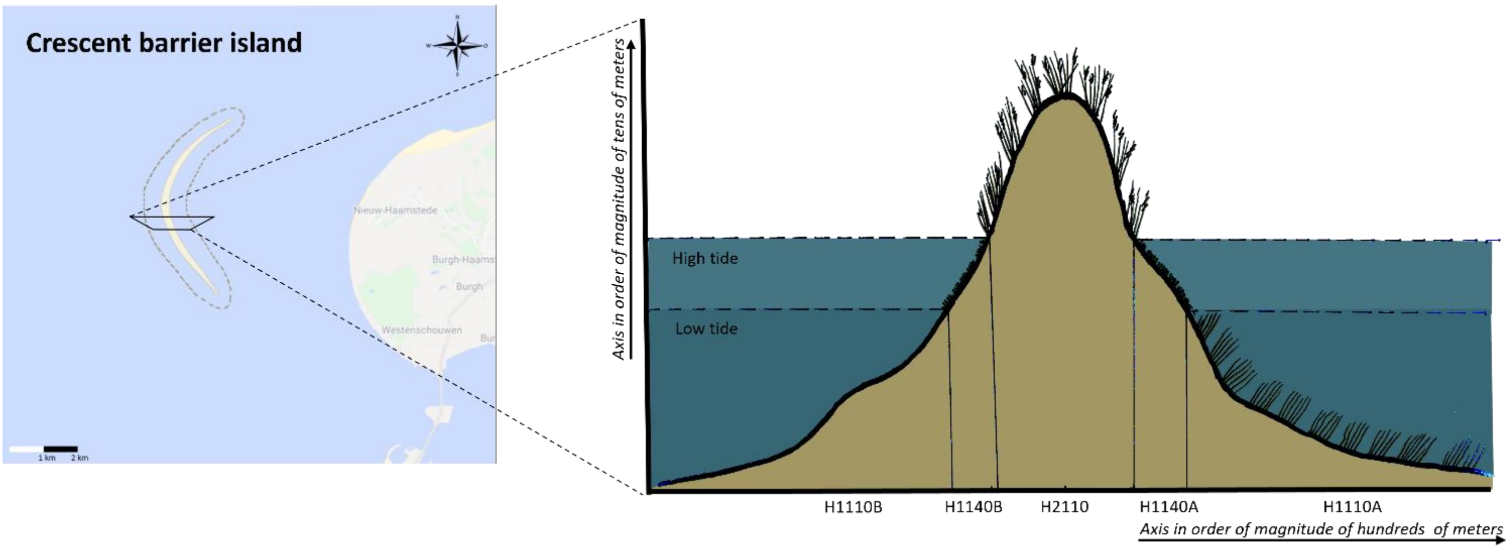

Figure 12: Sketch of the cross-section for the Crescent scenario. The scale is indicative. The height will be in the order of magnitude of tens of metres, the width will be in the order of magnitude of hundreds of metres, depending on the actual wave attenuation and silting.

4.3 Dune

The main function of the barrier island is to protect the coast. In order to protect the coast also during heavy storms we described in Ch. 3 the minimal height of the barrier island above sea level should be 6 metres at high tide. The dune is the highest part of the barrier island and therefore very important to fulfil the barrier island's function. For an overview of the habitat types discussed in this section, see Ch. 4.1.

4.3.1 Embryonic shifting dunes (H2110: Embryonale wandelende duinen)

To reach the height of the 6 metres, the very fast in height growing habitat type Embryonic shifting dunes (H2110) is used (Natura 2000, 2008a). According to the Natura 2000 profile description of embryonic shifting dunes (2008a), the dunes occur on several dune systems including wash-overs (lower dune formations that occasionally flood) and floodmarks. *Elytrigia juncea* (Sand Couch/Biestarwegras), can be found as most typical vegetation in the embryonic shifting dunes habitat type.

When there is no storm, the top of the barrier island, the dunes, won't be flooded. In this case, Ely*trigia juncea* has two functions (Bryant et al., 2019). The belowground biomass of vegetation binds and thereby stabilises the sediment. When the Embryonic dunes are (partly) flooded because of a storm, *Elytrigia juncea* reduces the flow energy because of the biomass of this species.

Like the name describes, embryonic shifting dunes are non-permanent forms of a beginning larger dune system (Natura 2000, 2008a). *Elytrigia juncea* is one of the first species to be able to colonise the bare sand that will form the first dunes on our barrier island, this explains why this habitat type is often called pioneer dunes. After supplementing the sand of the barrier island, *Elytrigia juncea* will naturally colonise the island, but this will take some time. *Elytrigia juncea* will be planted on the barrier island right after the sand is supplemented. By doing this, we prevent sediments blown and flown away by wind and waves in the first weeks of the realisation because of the lack of vegetation that holds the sediments.

Embryonic dunes have high potential to transform into dune ecosystems with higher biodiversity. In this chapter we describe the habitat types present just after the Banjaard is created, therefore we do not include dune succession in the habitat descriptions. In Appendix B.5 potential dune succession stadia are described more elaborate.

4.4 West side

The seaside of the barrier island is a harshest environment on the Banjaard. The habitats on the seaside must be resistant to disturbance (Natura 2000, 2008e). Immediate stabilisation after the first sand supplements is important to prevent the supplements being washed away instantly. Sediment stabilising species should be introduced directly, rather than waiting for species to colonise the seaside.

In the North Sea there is no natural reef; no native habit type H1170. Reefs protect, sustain and stabilise the barrier-island, therefore we introduce the options for artificial reefs in Ch. 4.4.3. For an overview of the habitat types discussed in this section, see Ch. 4.1.

4.4.1 Mudflats and sandflats not covered by seawater at low tide (H1140: Slik- en zandplaten; B: Noordzeekustzone)

Descending from the dunes towards the seaside, the next habitat type encountered is H1140B. This habitat type is described in Ch. 4.1.1, in contrast to the leeward side the waves on the west side are not dominated by the tidal influence but instead are fully exposed to the influences of the open sea (additional information on this in B.2, B.3).

The only vegetation type listed for H1140B are marine weeds (Natura 2000, 2008e). Furthermore, species of *L. conchilega* (schelpkokerworm) characterise this habitat type. *L. conchilega* is an ecosystem engineering worm species. It builds tubes that protrude out of the sea floor. These tubes have been found to slow down flow velocity of sea water around the tubes, which leads to settling of the sediment and its stabilisation. The worms build the tubes upwards as sediment is captured, resulting in mounts that vary in height over the year, but can reach up to 80 cm above the sea floor around it (Borsje et al., 2014).

4.4.2 Sandbanks which are slightly covered by sea water all the time (H1110: Permanent overstroomde zandbanken; B: Noordzeekustzone)

Moving out further, the area below low tide is defined as the start of H1110. Though in parallel with Ch. 4.4.1, this variant is not sheltered from the North Sea by the island, and therefore considered as subtype B, H1110B (more information in Appendix B.2).

H1110B is currently the dominant habitat type in the Voordelta region, which means that species should have no trouble spreading from the surrounding unaffected area to the newly placed sediment. The list of typical species is long, and three potential ecosystem engineers were identified; *L. conchilega* (Ch. 4.4.1.) and *S. bombyx*, and *Magelonidae papillicornis.* Seaweed is present in this habitat type (Natura 2000, 2014a).

S. bombyx builds vertical tubes that protrude from the sea floor. *M. papillicornis* builds flimsy tube-structures (Fauchald, 1977). This is expected to reduce flow velocity around the seabed, allowing sediment to sink. However, it is difficult to find information about *S. bombyx* (Dauer et al. 1981) and *M. papillicornis* (Fauchald, 1977).

4.4.3 (Sub)structures for artificial reef creation

Hard structures could be helpful for several aspects; (I) as wave damping object itself; (II) improvement of local conditions and niche creation; (III) and as surface for attachment and settlement of species (Koch et al 2009). Artificial structures are often dominated by a mix of invasive and opportunistic species (O'Shaughnessy et al., 2020). The created shelters and rough surfaces are attractive for settlement of plant and animal species, but artificial objects will not necessarily perform the same ecological function as natural reefs. The introduction of alien structures should therefore proceed with caution and monitoring (Van Duren, 2017). It should also be noted that hard structures can also have a negative impact on wave attenuation by biomass: a hard structure next to a salt marsh can limit the wave attenuation capacity of that marsh; due a rapid hard cut-off of the meadow (Stark et al., 2016).

4.4.4 Examples of non-biodegradable and/or engineering (sub)structures

Boulders are a solution for sides where NBS are not feasible due to major storm impacts or insufficient space (Table 1).

1. Hard blocks: artificial and natural variants

Rocks are frequently used for coast defence and can initiate and/or enhance the local ecosystem and its biodiversity. Natural rocks like granite and basalt can be used, but also imitations of these natural rocks to make the materials more stable, durable, cost-efficient, and practicable. Structures like quattro blocks and basalton columns are interesting for the future Banjaard (Rijkswaterstaat: de afsluitdijk, n.d.). At Chesil Beach, UK, Gabions are used to protect the crest from sand erosion during a storm. Layers of Gabions can create a wall or staircase to amplify the protection even more and break high wave energy waves (Dorset Coast Forum, n.d.).

Macarthur et al. (2020) developed an *EcoRock scoring matrix* for selecting the most ecological suitable rock materials for coastal engineering. This scoring is based on chemistry / composition, positioning of the blocks / spaces, surface structure and porosities. *EcoRock scoring matrix* might help in selecting the best suitable structure for the Banjaard.

2. Grind and gravel

Next to rocks, larger grainsize could also be an option. Next to the gabions, Chesil beach is an example of a storm surge barrier of gravel sand at open sea. It is an elongated gravel bank of 18km long for the coast of Portland and is largely studied. It mainly contains of gravel and has a top layer of sand (Dorset Coast Forum, n.d.).

3. Artificial oyster or mussel reefs

There are several recovery projects known in the Dutch sea for example the Borkumse Stenen: this a project that uses artificial reefs, covers it with oysters and let it sink. Several times researchers take out the cages and monitor the development of the oysters. Bureau Waardenburg investigates the further development of biodiversity; "the first results show a well development of the biodiversity in the Voordelta" (Kamermans, 2018). Artificial structures could be of use for the development of bivalve reefs at the future Banjaard (table 1).

4. Shipwrecks

There are shipwrecks located off-coast of Schouwen. These obstacles block the wave and could be used for the growth of bivalves (Van Duren, 2017, Fig. B7). There are shipwrecks known to contribute to biodiversity; housing specific native species; housing entirely wreck-dependent species, for example *Ctenolabrus rupestris (*goldsinny wrasse) and *Thorogobius ephippiatus* (leopard-spotted goby) in sea wrecks at Dutch sea (Van Duren, 2017).

4.4.5 Examples of biodegradable engineering (sub)structures

1. 3D biodegradable plastic reef structures

The Royal Netherlands Institute for Sea Research (NIOZ) in collaboration with the University of Utrecht investigates the use of biodegradable, 3D-printed plastic reef structures for establishment of bivalves (oysters in this case) and seagrasses. This summer (2022) the first tests will follow. The temporary structures should provide roughness and lee necessary for settlement (NIOZ, 2022).

2. 3D printed Calcium carbonate-reefs

Currently there is an EU-funded project going on: 3DPARE (2020), that uses 3D printed calcium carbonate structures as reef creating structures (Fig. 13). The first objects are installed in June 2020 and are being monitored ever since. Although there are no results yet, this project can be of interest for the future barrier island (Kennedy, 2021).

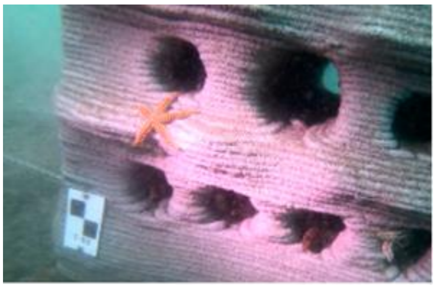

Figure 13: showing an applied 3D printed Calcium carbonate structure at Matosinhos beach (3DPARE, 2020).

3. BESE (structures & pasta)

BESE biodegradable mats are used in a project of several Dutch universities (Radboud University, NIOZ, Bureau Waardenburg, Wageningen University, and the University of Groningen). These structures are made from potato starch and will dissolve in ten years (Govers & Reijers, 2021). It turned out they were useful for restoration of seagrass meadows, salt marshes and other coastal ecosystems (table 1). There were experiments done across (sub)tropical and temperate seagrass meadows. The base elements mimicked suppression of waves or sediment mobility: by usage belowground it mimics seagrasses, aboveground usage mimics cord or marsh grasses (Temmink et al., 2020; Teunis, 2021).

4. Wooden poles or fences

Reed and willow branches can be used for collection of sand and creation of dunes. Rowes of posts can also be used to direct marine sedimentation in salt marshes (Govers & Reijers, 2021). The direction, height and form of wooden structures may be interesting for a future experimental approach on the leeside of the island (table 1).

5. Tarra (shell remains)

Tarra, in short shell remains (Provincie Zeeland, 2017), can be used for sediment capturing (Govers & Reijers, 2021). It can also be used as concrete in the form tabby, a kind of lime which you get after burning the shells (Lee, 2014).

This chapter described the possible habitat types that could thrive on the future Banjaard. The table below summarizes all habitat types and provides an overview of the performance on wave attenuation, sediment capture capacity, species introduction strategy and appliance structures for both the Crescent and Hook designs.

Table 1: Overview of habitat types for both designs. Plus signs ('+') in column 'performance' indicate the level of wave attenuation and sediment capture capacity. Range of plus signs is between 0 and 3 signs: 3 signs indicating high performance, 0 signs indicating no performance. Column 'intervention' describes whether vegetation should by introduced naturally (natural dispersal) or with helping hand by humans (planting, introduction by humans).

	Design		**Performance**		**Intervention**	
Natura 2000 Habitats	**Crescent**	**Hook**	**Wave attenuation**	**Sediment capture capacity**	**Species introduction strategy**	**Option for appliance structures/ H1170**
H1110B	x	x	+++	+++	Planting marine weeds and algae Introduction by humans *L. conchilega* Depending on research: (1) *S. bombyx* and (2) *M. papillicornis*	Wave attenuation & shelter for weeds and bivalves
H1140B	x	x	+++	+++	Planting marine weeds and algae Introduction by humans *L. conchilega*	Wave attenuation & shelter for weeds, bivalves
H2110	x	x		+++	Planting dune grasses	Application of wooden fences
H1310B		x	Only during storm: ++	Only during storm: ++	Natural dispersal of pioneers	
H1330A		x	Only during high tide: ++	Only during high tide: ++	Introduction by humans *O. edulis* Natural dispersal (invasive) C. gigas	As support in initial growth phase for marsh grasses As shelters for bivalve reefs initiation
H1310A		x	Only during high tide: ++	Only during high tide: ++	Natural dispersal of pioneers	
H1320		x	Only during high tide: +++	Only during high tide: +++	Natural dispersal (invasive)	
H1140A	x	x	+	+		
H1110A	x	x	++	++		

4.5 Overview: protecting, sustaining and stabilising the Banjaard

While the expected habitat types are discussed above, it is also important to note that nature is already present in this area. As the Banjaard will be located on the previously eroded sandbar, we expect that this area is currently H1110 (Sandbanks which are slightly covered by sea water all the time) and H1140 (Mudflats and Sandflats not covered by sea water at low tide). The expectations for habitat development for the west side is expected to have fewer options compared to the east side due to the strong currents and wave energy, though this is similar than the current occurring habitat types. The expectations for habitat development for the westside is expected to have fewer options compared to the east side due to the strong currents and wave energy, though this is similar to the current occurring habitat types.

Ecosystem engineers protect, sustain and stabilise the barrier island by wave attenuation and sediment capture capacity. The wave attenuation by biomass is not a solid measure, but will vary across plant, communities, over seasons and influenced by how its boundaries end. Hard structures enhance wave attenuation and sediment retainment by creating conditions favourable for ecosystem engineers to settle, and by the ability of these structures to attenuate waves and retain sediments by the structure itself. The more dense and solid an artificial structure, the larger its capacity for wave attenuation is expected. Another distinction in structures is the artificial versus natural and/or its biodegradability; the less invasive/less unnatural the better prospects for initiating a natural environment.

From this can be concluded, that the future Banjaard has possibilities for the usage of ecosystem engineers and nature development in combination with wave attenuation, but there is much uncertain and unknown. It is therefore recommended to carry out future experiments (Ch. 5).

Main Message

- Ecosystem engineers help protect, sustain and stabilise the Banjaard barrier island by wave attenuation and sediment capture capacity.
- The Banjaard barrier island has potential for harbouring diverse environmental gradients.
- The east side has better prospects for settlement of a diverse population; this is especially the prospect for the Hook spatial configuration design.
- Environmental conditions determine ecosystem-engineer selection for the Banjaard.
- Invasive species as *S. anglica* and *C. gigas* are assumed not preventable, though they also bring benefits for wave attenuation and sand retainment.
- Substructures can be used for the following three goals: (I) wave attenuation; (II) niche creation; (III) surface for attachment. However, substructures can also have limiting effects.
- Introduction strategies may be beneficial for kickstarting ecosystem-engineers settlement.
- The future currents and the development of lower tidal dynamics at the leeward side determine selection for artificial structures and ecosystem-engineers and consequently the selection of the desired grain size.
- Future experiments should focus on the selection of structures and species for specific sites and the related grain sizes. Scoring matrices, such as the *Eco rock* scoring matrix, may be helpful for determining the best structures.

Chapter 5: Development pathway with recommendations

In this chapter we answer the following research question: 'What is a feasible development pathway with recommendations for future research for development of the barrier island?'.

To answer this research question, we provide a pathway of research recommendations for the development of the barrier island. We structured the pathway into phases (Fig. 14) instead of absolute time indicated intervals, since the exact duration of each point is uncertain. Note that the phases are not strictly consecutive in order and hence they can have some overlap. These pathway phases have been subdivided into two sets. The first set contains four phases of preparations taking place before the barrier island is constructed, these phases are needed to further shape the design and the construction plans, and to create a monitoring plan. The second set takes place after the construction of the barrier island and this set contains two phases. These phases focus on; experimenting on the future Banjaard; monitoring on and around the future Banjaard; and investigating the creation of more barrier islands. It is important to note that, since limited information is available for relevant modelling and experimental setups, research on the future barrier island will emphasise the principle of Learning by Doing (Reese, 2011). In the case of wave breaking habitats for example, there are limited research studies that present input for model validation or experiments representative of natural circumstances (Lara, 2016).

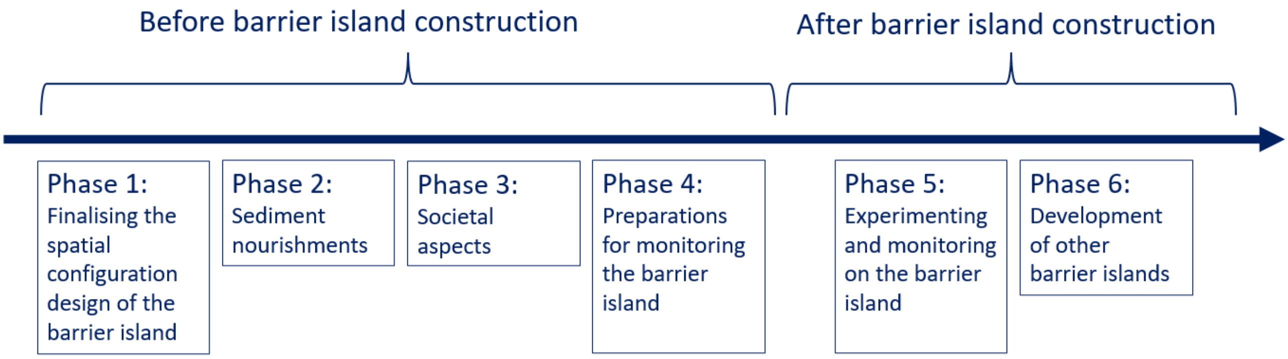

Figure 14: Development pathway with six consecutive phases; four phases take place before the barrier island construction and two phases are after the barrier island construction. Note that the phases can partly overlap.

5.1 Research recommendations prior to barrier island construction

In these phases, different types of research should be done to prepare for the eventual construction of the barrier island. This preparation consists of e.g., modelling studies, laboratory experiments, literature studies, and site-specific research. To increase the effectiveness and efficiency of the project, we recommend to clearly specify the primary goals and functions of the barrier island in advance. This is in line with what was mentioned in the interview with A. van Oudenhoven (personal communication, May 11th 2022). Furthermore, the vision of Shared Concepts is that the construction of the barrier island would already take place in 2025. However, given the extent of the preparation research phases described below, we would like to emphasise that it might be best to consider a later starting date of the Banjaard barrier island construction.

Phase 1: Finalising the spatial configuration design of the barrier island

In Ch. 3, we provided a foundation with the Crescent and Hook designs for the spatial configuration of the barrier island and further research can build on this foundation. Therefore, we recommend the following research actions:

- Analysis of sufficient distance between the coast and the barrier island with Probabilistic Coastline Recession (PCR) model, which is a more suitable alternative to the Bruun Rule to determine the coastal recession caused by SLR (Ranasinghe et al., 2012). This would build further on the distance indication between the future Banjaard and the Schouwen coast provided in Ch. 3.2.
- Analysis of the sufficient distance between the barrier island and the navigation channels from an ecological perspective. The species on the barrier island should encounter as little disturbance as possible by nautical activities (mentioned in Ch. 3.3.5).
- Research on the interaction between the development of the barrier island and the larger wind fluxes, and on the vegetation-sediment interaction after the establishment of the dune system (mentioned in Ch. 3.3.1).
- Analysis of the sea currents off the Schouwen coast for both the Hook and the Crescent spatial configurations. The chosen design should provide a side that is sheltered from strong currents and wave forcings allowing the development of a biodiverse ecosystem (mentioned in Ch. 3.3.6).
- Analysis if the Crescent or the Hook design is more suitable for coastal protection off the coast of Schouwen by weighing both the advantages and disadvantages of the designs (mentioned in Ch. 3.3.6). For the Hook design, the effectiveness can be analysed and compared for a design when the additional red part (Fig. 10) is solely constructed with hard structures; and for a design when the red part (Fig. 10) is solely constructed with sediments (Ch. 3.3.6).

Phase 2: Sediment nourishments

- Research on potential sediment sources for the sediment suppletion needed for the barrier island construction (mentioned in Ch. 3.1). The sediment properties should be suitable for the hydrodynamics off the Schouwen coast and for the (introduced) ecosystem engineers on the barrier island. Considering the hydrodynamics at the future Banjaard location, the Hjulström-diagram can be used (Ch. 3.1). However, because of restrictions relating to the usage of a general Hjulström-diagram for the Banjaard project, a site-specific Hjulström-diagram can be developed, following the example by Frey & Dashtgard (2012). A site-specific Hjulström-diagram can help to determine the suitability of sediment sources for the barrier island construction.
- Analysis and calculations for determining the quantity of the required sediment. The quantity analysis should include that the substrate nourishments should be larger since the substrate sediment can be (partly) lost from the barrier island. Furthermore, the sediment with which the barrier island is constructed can consolidate, or the sediment that is underlaying the constructed barrier island can consolidate (Harris et al., 2020).
- Analysis of what time of the year is optimal for the construction of the barrier island, and in which season the ecosystem engineers should be introduced for optimal survival (Ch. 4 introduction).

Phase 3: Societal aspects

Apart from the physical and biological aspects of the Banjaard barrier island, an equally important part will be to investigate the societal aspects of this project.

- Stakeholder analysis and stakeholder involvement in the barrier island project. As was also mentioned by A. van Oudenhoven; “you should first ask yourself which stakeholders will execute this and what their primary goals are” (A. van Oudenhoven, personal communication, May 11th, 2022). The stakeholder analysis should include the power relations between stakeholders. During the communication with stakeholders about the barrier island, the following question should be addressed; “can we guarantee that the [envisioned] functions [of the barrier island] can be generated?” (A. van Oudenhoven, personal communication, May 11th, 2022).
- Legal analysis for the barrier island project. Since Shared Concepts aims to construct the Banjaard barrier island in the near future, the existing (Natura 2000) legislation should be considered.
- Financial analysis of the barrier island construction and maintenance; estimation of the economic costs and benefits of this coastal protection measure. To do this properly, the uncertainty of the barrier island functioning should be evaluated.

Phase 4: Preparations for monitoring the barrier island:

As with any large project, constant monitoring of the Banjaard barrier island before, during, and after its construction is important to know when management interventions are needed, either to speed up desired processes or stop/adapt to unwanted processes. To properly prepare monitoring activities on and around the barrier island, we propose the following steps:

- Creation of a conceptual model of the system and its interactions (as is also done in Davis et al., 2022) for detailed understanding of the system.
- Evaluation of important parameters according to the conceptual model. These parameters (the metrics) should be monitored in the barrier island area, both before and after the construction of the barrier island (as also mentioned in Davis et al., 2022). The monitoring before the construction allows for the evaluation of the effects on the system caused by the introduced barrier island.
- Creation of a decision framework to evaluate the stability of the barrier island, the stability of the ecosystems on the barrier island, the coastal protection performance of the barrier island, and the potential of the barrier island to grow with sea level rise. The decision framework should include

various metrics, performance thresholds and adaptive management actions, following the coastal protection monitoring methods of Davis et al. (2022) for barrier islands. The frequency and the method of monitoring should be established for each of the metrics.

5.2 Research recommendations after barrier island construction:

During the phases after the barrier island is constructed, the research focus is especially on doing experiments on the Banjaard barrier island and monitoring the barrier island and its surroundings.

Phase 5: Experimenting and monitoring on the barrier island

- Monitoring how the artificially introduced ecosystem engineers are adjusting to the environmental conditions on the barrier island and if the ecosystem engineers are placed on an optimal location for sediment stabilisation and wave attenuation. Evaluation of natural dispersal and reproduction of both artificially introduced species and naturally introduced species in the barrier island area. Analysis of the functioning and survival of those species in correlation with climate change impacts on the marine environment (Ch. 2 & Ch.4.4.4).
- Monitoring the applied (sub)structures and their contribution in creating optimal environmental conditions for species on the barrier island. The possibilities for applying artificial structures are; as addition wave attenuation; to provide shelter for seaweeds and seagrasses; wooden fences for addition sand capturing; as surface for bivalve-attachment (Table 1, Ch.4.4.4).
- To kickstart the ecosystem-engineers the next introduction strategies are desired: planting seagrasses, marine weeds, and dune grasses. Application of bivalves (attached to artificial structures), introduction *of Conchilega species* (Table 1, Ch.4.4.4). The further succession or development of a balanced ecosystem needs to be monitored.
- Monitoring of the change in tidal currents and waves around the barrier island over time (Ch.3.3.6 & Ch.4.5). These parameters can already be monitored before the Banjaard is constructed. In addition, the water quality on the leeward side of the barrier island should be monitored. In this calmer environment, where limited forcing of waves and currents takes place, climate change induced heating of the water increases the risk of severe algae blooming (Gobler, 2020). An analysis can be done on the effect of potential adaptive management actions (Ch. 2.1).
- Monitoring of barrier island growth towards the coast and parallel to the coast. An analysis can be done on the performance of the barrier island as coastal protection. Furthermore, the effects of potential adaptive management actions can be evaluated.
- Monitoring of erosive locations on the barrier island and the scope of erosion. Analysis of the frequency, amount, and effectiveness of sediment nourishments to retain the barrier island as coastal protection measure.
- Monitoring of barrier island resilience and natural adaptive capacity regarding relative SLR and extreme events such as heavy storms.
- Analysis of the specific critical width of the constructed barrier island using the Migration, Consolidation and Overwash model (MCO) of Rosati & Stone (2007) (mentioned in Ch. 3.3.6). This analysis of the critical width can also be useful for other barrier island engineering projects.
- Analysis of advantages and disadvantages of the barrier island as NBS for protection of the Dutch coast. Evaluation if the barrier island can provide more resilience for the Dutch coast regarding SLR and climate change.

Phase 6: Development of other barrier islands

Ultimately, Shared Concepts is aiming for the development of multiple barrier islands along the Dutch coast to create an interlinked protection system. Therefore, the Banjaard barrier island is considered an experimental project, which generates knowledge for the development of more barrier islands. The information generated by monitoring the Banjaard barrier island before and after its construction can hence be used in the development phase of other barrier islands off the Dutch coast.

- Research regarding the position of another barrier island, considering e.g., monitoring information retrieved from the Banjaard about erosion rates and transport of the sediment alongside the Dutch coast.
- Research on the shape and the slope of other future barrier island, by evaluating the erosion rates and critical width found for the Banjaard. Ecological information about the dispersal, settlement, and survival of ecosystem engineer species can also be used.
- Analysis on how the sediment nourishments can be minimised for another barrier island, by looking at volume growth of the Banjaard over time.
- Research on how to maximise ecological functioning for other future barrier islands by considering information related to settlement and survival of flora and fauna retrieved from the Banjaard. Ecological experiments on the Banjaard will provide information on which ecosystem engineer species work well and display a high resilience on a constructed barrier island in a Dutch climate.

Main Message

- Our development pathway provides in total six research phases that give insight in how future research can build on the results from this research project.
- Four of these research phases take place before the Banjaard barrier island is constructed. These further prepare the design and the construction of the barrier island. Also, a monitoring plan is created in these preparatory phases.
- The last two research phases take place after the barrier island is constructed. These phases focus on; experimenting on the future Banjaard; monitoring on and around the future Banjaard; and investigating the creation of more barrier islands.
- Given the extent of the preparation research phases provided, it might be best to consider a later starting date for the Banjaard barrier island construction.

Chapter 6: Discussion

The Banjaard barrier island is both a large-scale experiment (Ch. 5) and a coastal protection investment for the Schouwen coast. To continue the coastal protection function in the future, the Banjaard barrier island should remain at a sufficient distance from the Dutch coast, and it should grow with SLR over time. Although the Banjaard barrier island could be a dynamic and sustainable coastal protection measure, it is important to emphasise various uncertainties. These uncertainties include the uncertain future development of the environmental conditions off the Schouwen coast as well as uncertainties in the Crescent and Hook barrier island designs in this research project.

Therefore, the question might arise if developing a barrier island is an adequate solution for future coastal protection, not only because of the uncertainties, but also because it involves creating a barrier island on a location with severe erosion. Also, it should be considered that the active creation of nature can conflict with legislation as well as with ethical values. Do we as humans have the right to interfere so drastically with nature, especially if the primary goal is to protect ourselves? While it is important to ask this question, this was not within the scope of this research project.

In this discussion chapter we identify critical sidenotes to the findings presented in this research project. First, we discuss the methods and results limitations regarding the spatial configuration research in Ch. 3. Afterwards, the limitations regarding Ch. 4 are discussed.

6.1 Sidenotes on the methods and results in Chapter 3.

During the research project we discovered that the construction of a barrier island by NBS for coastal protection has been explored to a limited extent in scientific research. Methods to determine the optimal spatial configuration of the Banjaard barrier island were therefore scarce. Consequently, we chose criteria roughly supported by scientific literature and visualised our criteria in maps which provided a suitable spatial configuration when overlaid. This method was derived from existing research methods used to determine suitable areas for urban greenery (Ch. 3.3).

In this research project we based the Crescent spatial configuration of the Banjaard barrier island on the five criteria that were initially considered relevant: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities (Ch. 3.3). We came up with those criteria in accordance with our commissioners. Note that the selection of different criteria would probably have led to different results in spatial design: perhaps closer to shore, or a different shape. However, in the interview with N. van Rooijen in a later stadium of the research, we discovered that an ecological component should also be included for the spatial configuration (Ch. 3.3.6). This criterium resulted in the significantly different Hook spatial configuration. Hence, a sidenote to our research method is that possibly also other relevant aspects for the development of an optimal spatial configuration for the barrier island are not represented in our criteria. Moreover, we derived our criteria and method roughly from other scientific literature and we had limited resources, as a result, our research method shows room for improvement.

In addition, we also used alternative methods to create the criteria maps in Ch. 3. This was especially the case for the tidal currents criteria map, since it required information about averaged tidal currents over time on and around the location of the eroded Banjaard sandbar. However, recent information about the averaged tidal currents near Schouwen was not readily available to us. Therefore, we used the most recent HP33D – NLTides stroomatlas to create the tidal currents criteria map. An important side note here is that it remains unclear if the tidal currents in HP33D – NLTides are based on observed data or modelled data (The Netherlands Hydrographic Services of the Royal Netherlands Navy, 2022). This limited information about the workings of the HP33D – NLTides restricts us in drawing clear conclusions about the tidal movements, since modelled tidal currents can differ from observed tidal currents if the model is not frequently validated with observed data. The Ch. 5 recommendation to monitor the tidal currents should provide more validation of the tidal currents criteria map.

Finally, a sidenote for the estimated slopes of the barrier island is that the 1.4:100 slope (for a height of 0 m (seafloor) to 7 m) and the 6:100 slope (for a height of 7 m to 13 m) of the future Banjaard mentioned in Ch. 3.3.6 were only roughly based on scientific literature. Therefore, these estimated slopes serve as general guidelines for initial construction of the barrier island since afterward the slopes will be reshaped by the dynamical marine forces. These forces combined with the influences of ecosystem engineers will ultimately provide the barrier island with slopes that show spatial and temporal variations. In addition, this research project is working with different habitat types, instead of pinpointing specific locations for certain ecosystem engineers. Hence, the Ch. 4 results of this research project are not dependent on specific slopes of the barrier island designs.

6.2 Sidenotes on the methods and results in Chapter 4

In this report we discussed habitat types, based on Natura 2000, that protect, sustain and stabilise the barrier island. The list of habitat type species given by Natura 2000 is one of ‘typical species’ (Natura 2000, 2014b). In this research project all species, except for *Modiolus modiolus,* were based on these Natura 2000 profile descriptions. However, since the ‘typical species’ list excludes trivial species that are not easily measurable or not sufficiently indicative of good habitat quality, it is possible that useful ecosystem engineering species were not included in our analysis.

Another sidenote to the 'typical species' list is that 'typical' species are meant to give an indication of habitat quality, i.e. their presence indicates that the habitat is in a good state. Nevertheless, it could be that the habitat areas cannot support all these species directly after the construction of the Banjaard barrier island. This situation might be the case when the ecosystem engineers are not (yet) supported by the environmental conditions. Therefore, before using any of the listed species, follow up research should investigate what conditions are needed to support each of them.

Besides the importance of determining which ecosystem engineers should protect, sustain and stabilise the Banjaard barrier island, we should also consider the density of these ecosystem engineers. This is because some species are only able to function as an efficient ecosystem engineer when the density of ecosystem engineer is optimal (Koch et al., 2009). In this research project this density of ecosystem engineers is not discussed and hence for a more reliable vegetation plan this should still be considered.

Another sidenote is that the sediment stabilisation ability of ecosystem engineers differs throughout the year, since the seasonal variability in biomass results in variable wave attenuation by vegetation (Koch et al., 2009). The variability in biomass is especially high in temperate regions where seasonal differences are larger. At present, the Banjaard barrier island would be located in such a highly variable temperate region. It should be kept in mind that due to climate change the climate could alter drastically. Note that at present, winter conditions cause a reduced biomass of most vegetation, whereas storms have the largest impact during this time of year and increase the need for wave attenuation to protect the Dutch coast.

Overall, this research project provides good indications for the spatial configurations and the habitats of the future barrier island, despite the research limitations mentioned above. With this research project we provided a starting point on which future research can build, supported by the development pathway phases provided in Ch. 5.

Chapter 7: Conclusion

This research project is an exploration towards the development of a climate robust barrier island on the location of the eroded sandbar the Banjaard off the coast of Schouwen. The analysis for the position and shape of the future barrier-island was based on the following five criteria: wind direction and velocity; wave direction and energy; tidal currents; bathymetry; and nautical activities. This analysis resulted in two optimal spatial configurations of the future barrier island: the Crescent design and the Hook design. Both design options are approximately located on the original position of the eroded Banjaard sandbar. This spatial analysis resulted in an estimation of an above-water width of 200 m and an underwater-width of 500 m (on all sides) at high tide. The initial total barrier island height is at least 13 m measured from the seafloor (0 m). This minimum height will enable the barrier island to withstand storms under high tide conditions. The Hook design is characterised by a curvature, allowing for a reduced forcing by currents. This will lead to better environmental conditions for ecological development and hence better ecological prospects. In fact, the biology can be seen as an additional or sixth criteria for the design of the Barrier Island. However, in our Hook design the minimum distance to the coast is approximately 2.6 km whereas for the Crescent the design the approximate distance is 4 km.

To create a barrier island, sediment must be retained, and the wave energy must be attenuated, which is a big challenge at open sea. Ecosystem-engineer species can contribute to wave attenuation and sand capturing; they have a strong capacity to protect, sustain and stabilise the barrier-island. In addition, hard structures can reduce wave energy and increase species settlement, especially on sites where currents are extremely strong. Each ecosystem engineer has its own preferences for abiotic conditions, such as grain size of the sediments. Hence, we advise to first select which ecosystem engineers should settle on the barrier island, after which additional structures and desired sediments can be determined. The selection of ecosystem-engineers and additional hard structures should be based on the tidal currents. These structures will attract both pioneer and invasive species. This is a risk for invasive species overgrowth, but it can also lead to a unique species community. It is worth kick-starting the desired ecosystem-engineers by applying different introduction strategies; this will boost their chances to coexist next to invasive species and promote biodiversity.

During this research project it became clear that there is still limited research available regarding the construction of a barrier island and the use of ecosystem engineer species to stabilise the sediment nourishments. We therefore developed a pathway of six phases of research recommendations: (1) Finalising the spatial configuration design; (2) Sediment nourishments; (3) Societal aspects; (4) Preparations for monitoring; (5) Experimenting and monitoring; and (6) Development of other barrier islands. Although the creation of a barrier-island with NBS is not conventional, the Banjaard barrier island should be viewed as a living laboratory. Hence, the project should be monitored and tweaked during all development phases. Given the extent of the preparation research phases, we advise considering a later starting date than the envisioned 2025 for the Banjaard barrier island construction.

Nature-based seaward solutions have good prospects for coastal protection in combination with conventional coastal management strategies. This research project provides a foundation on which future research can build further. The Banjaard barrier island is certainly a challenging project, however, this project has potential to be very rewarding in the future. Whereas conventional engineering measures focus on coastal protection only, the future Banjaard can offer a solution to protect the coast to future climate change effects, while multiple purposes are served in a sustainable way.

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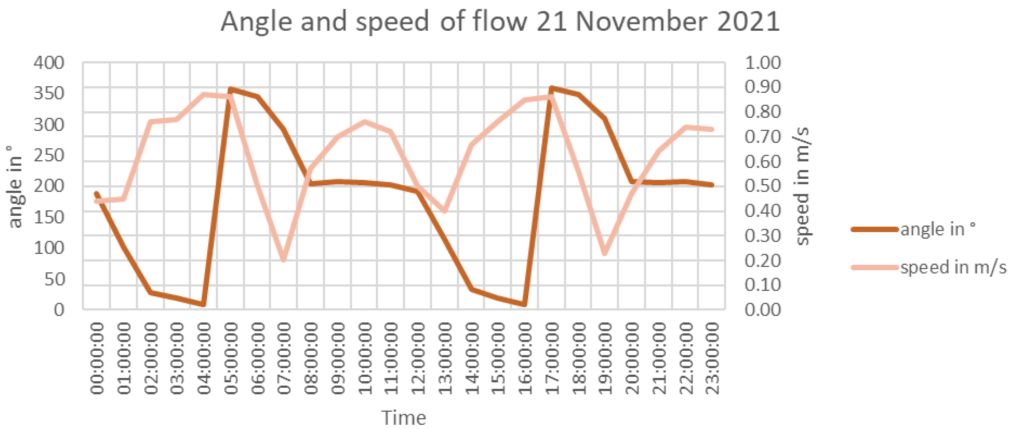
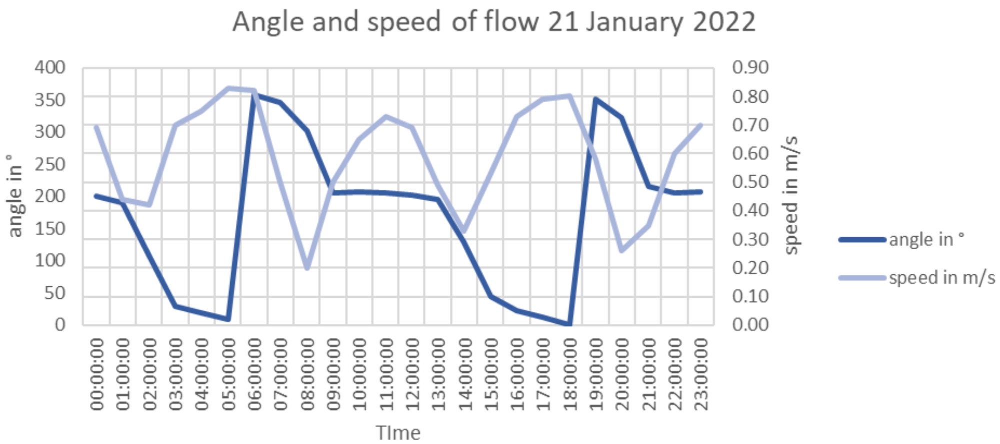
Appendices

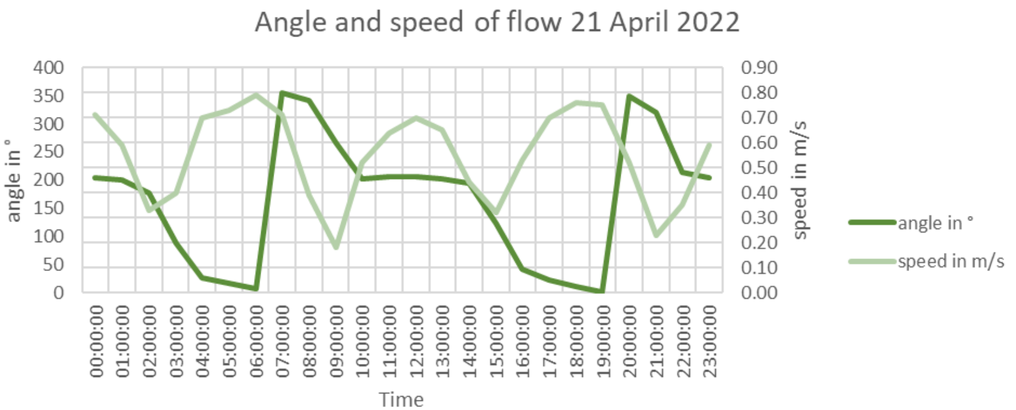
Appendix A: Supporting information for Chapter 3

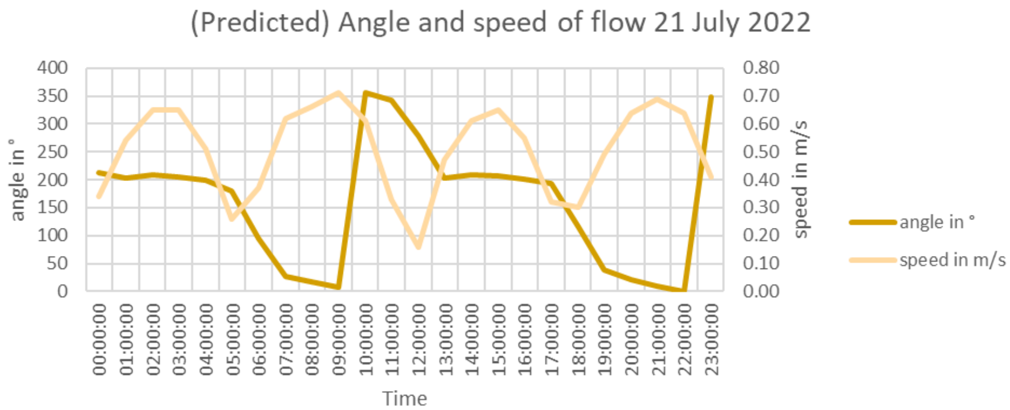
A.1: Tidal currents

In Ch. 3.3.3. we depicted a tidal criteria map with arrows indicating the general tide direction and speed. To obtain this map we used data from the NL Tides stroomatlas (HP33D – NLTides). The stroomatlas consists of data on speed and angle of flow every hour for last and coming year. The tidal criteria map is only based on the tidal cycle of 21/11/21 because of feasibility and limited time for the project. To check whether the tidal cycle of 21/11/2021 is representative for the general tidal movements, the tidal currents in HP33D – NLTides were analysed for each hour of the following four dates; 21/11/21 (NH autumn); 21/01/22 (NH winter); 21/04/22 (NH spring); and 21/07/22 (NH summer). The data of these four days are displayed in the graphs below. Since these four dates have similar tidal trends, we assumed that the tidal currents criteria map of 21/11/21 is sufficiently representative for the average tidal movements in front of Schouwen.









The actual map with arrows showing the direction of the currents is based on maps from the HP33D - NLTides too (Fig. A.1). Stroomatlas offers maps from every hour, for coming and past year. By putting layers on each other with the upper layer edited with a transparency of 50%, we could eventually see arrows on top of each other from the 12 hours in total representing one tidal cycle. To increase readability of the map and to compare this tidal map with the other criteria for location of the Banjaard, we decided to edit the arrows on another base map (see Ch. 3.3.3).

Figure A.1: HP33D - NLTides map showing the direction of the currents off the Schouwen coast for one tidal cycle on 21/11/21.

A.2: Bathymetry

Fig. A.2-1 shows the bathymetry of the sea bottom off the coast of Schouwen and the data is retrieved from Rijkswaterstaat (2017). To estimate the approximate area that displays depths of -6 m to +0.1 m with respect to NAP, the coordinates along the edge of the light blue area (Fig. A.2-1) were inserted in Google maps. Note that if there was doubt about the depth that was displayed on a certain location, the depth was checked on the OpenLayers map preview from the rwsprojectarchief[1] which displays the specific depth when you click on a location. These coordinates together created an approximate area in which the depth varies between of -6 m to +0.1 m with respect to NAP (Fig. A.2-2).

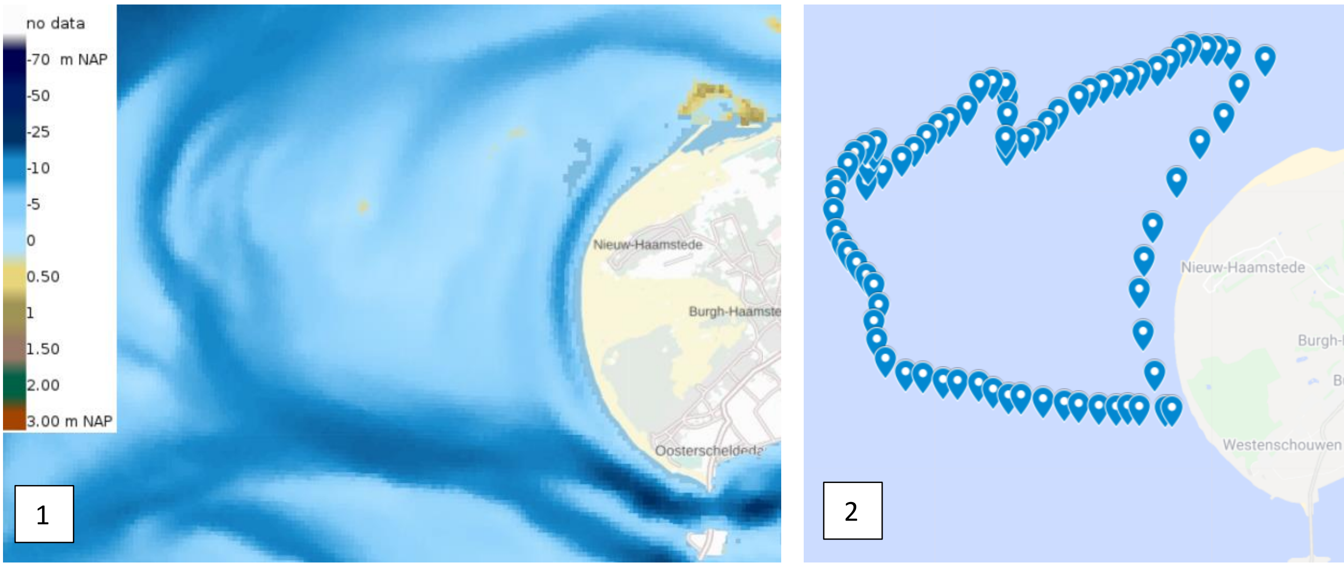


Figure A.2: The bathymetry of the sea bottom in front of Schouwen-Duiveland (retrieved from Rijkswaterstaat, 2017) (1) and the coordinates along the edge of the shallow area (2).

1 https://rwsprojectarchief.openearth.nl/geoserver/rws_coast/wms?service=WMS&version=1.1.0&request=GetMap&layers=rws_coast%3Abathymetrie2017&bbox=468193.5351%2C5662997.0338%2C783093.5351%2C6179897.0338&width=467&height=768&srs=EPSG%3A3043&format=application%2Fopenlayers

A.3: Nautical activities

Fig. A.3-1 below displays the density of ships on the shipping routes in the North Sea near the Schouwen coast (data is retrieved from Marine Traffic, n.d.). To estimate the approximate area without nautical activities off the Schouwen coast, the coordinates along the edge of the purple area (0-1 routes/0.08km^2/year) (Fig. A.3-1) were inserted in Google maps. These coordinates together created an approximate area in which almost no nautical activity takes place (Fig. A.3-2).

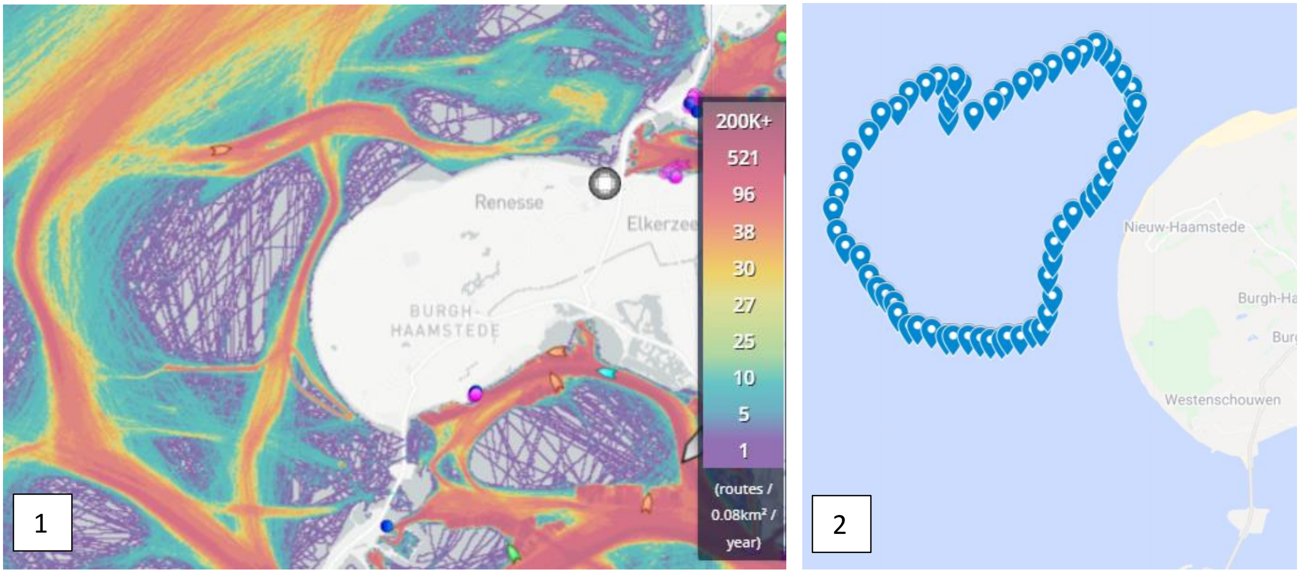


Figure A.3: The nautical activities in front of the Schouwen-Duiveland coast (retrieved from Marine Traffic (n.d.)) (1) and the coordinates along the edge of the area with almost no nautical activities (2).

A.4: Spatial configuration barrier island

The optimal spatial configuration of the future barrier island is visualised in the combined map of all criteria (Fig. A.4). The barrier island is positioned as far from the coast as possible and it follows the coastal outline of the Schouwen coast, however, the barrier island has a slightly narrower curve to provide a perpendicular plane for optimal obstruction of the wind-generated waves. The barrier island is positioned within the suitable area with almost no nautical activities and a suitable bathymetry of -6 m to +0.1 m with respect to NAP. The part of the barrier island that is above the waterline at high tide is situated approximately 4 km from the coast of Schouwen and it is approximately 200 m in width. The Hook design that includes the ecological component in the spatial configuration of the barrier island is shown in Fig. A.5, part of the red addition in the figure is situated in areas with a depth of -8 m to -7 m with respect to NAP. Furthermore, part of the red addition is placed in quite busy shipping routes.

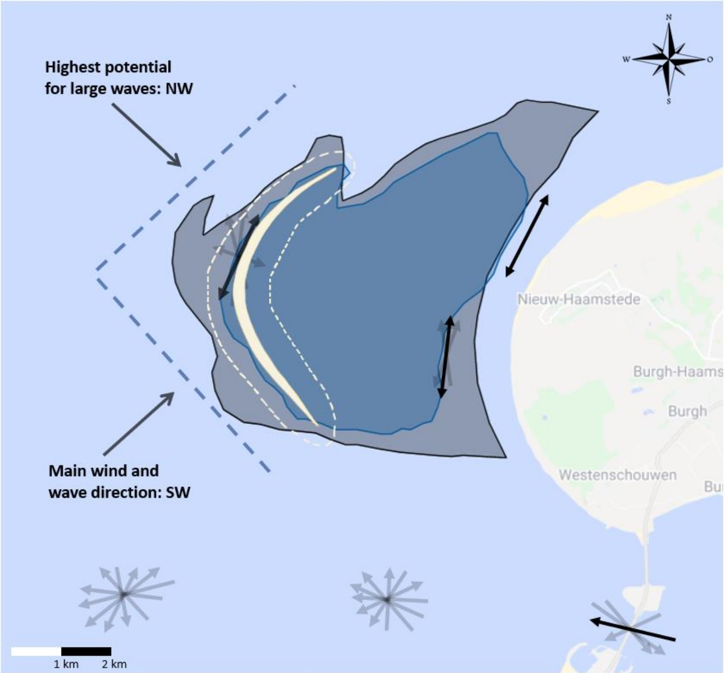


Figure A.4: Combined map of all overlaid criteria maps, resulting in the optimal spatial configuration for the barrier island. Note that the solid light-yellow line displays the part of the barrier island that is above the waterline at high tide, whereas the dotted light-yellow line displays the part of the barrier island that is under the waterline at high tide.

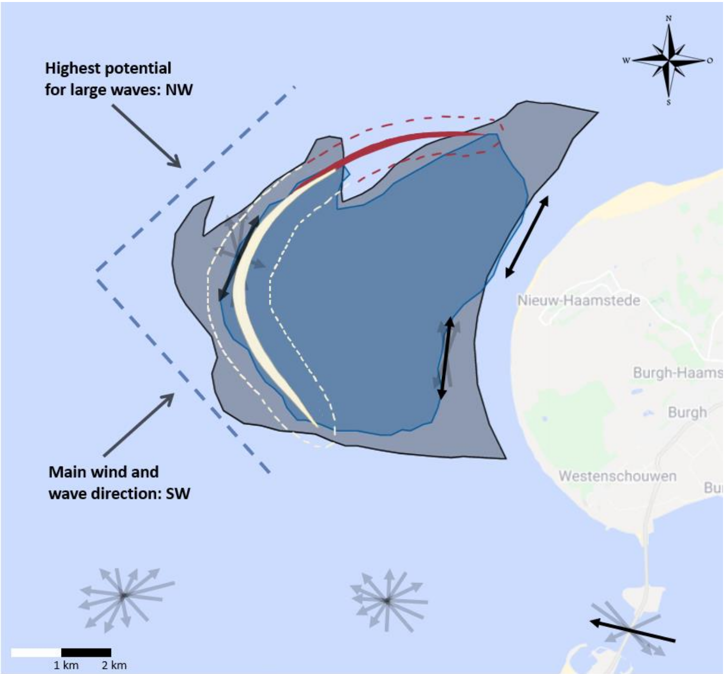


Figure A.5: Combined map of all overlaid criteria maps including the ecological component, resulting in the Hook design for the spatial configuration for the barrier island. The solid yellow line and the dark yellow dotted line is the Crescent spatial configuration according to the initial criteria, the solid red line and the dark dotted red line is the addition to the initial spatial configuration design due to the ecological component.

Appendix B: Detailed description of habitat types

In this appendix, we give some further information on some of the habitat types that could need some extra explanation. The information in this appendix is used as reference, therefore is not decisive in understanding Chapter 4, but can be useful when research on this topic is proceeded.

B.1: Additional information on leeside (Hook design)

Facing the risk of a rising sea level, there is a growing interest in tidal wetlands as a combined nature-based coastal defence combined with more common engineered coastal defence structures as dikes (Stark et al., 2016). Salt marshes can grow with rising sea levels by capturing sediment; in this way they can act as a vegetated foreshores by reducing the wave energy (Vuik et al., 2016). Extensive stretches of salt marsh can already be found in between the Dutch coast and the Wadden Islands. There these salt marshes form a vegetated transition zone between land and water that function as wave breaking system (Van Loon-Steensma, 2015). Under the influence of the tide, a salt marsh has a clear vegetation zoning with corresponding decrease of salt tolerance.

B.2: Additional information H1110A

Starting the furthest away from the Banjaard shore, the H1110 habitat type is designated to the areas with sandy substrate, which are covered by water all the time. While the name says they are 'slightly' covered, the actual definition of this habitat type indicates that the 'slight' cover of water might be a column of up to 20 metres (European Commission DG Environment, 2013). Even then, this document also mentions that sand banks can extend deeper than that, and as such even deeper areas may be designated to this habitat type if the right biota is present.

In the Dutch interpretation of these habitat types, both H1110 and H1140 (which follows in the next subheading) have two subtypes defined. Subtype A is named 'tidal area' (getijdengebied) and is used to indicate parts of H1110 and H1140 that are sheltered from the North Sea's wave action by islands or sand banks. Thus, in subtype A tidal action is more important than wave action (Natura 2000, 2014a; Natura 2000, 2008e). This contrasts with subtype B titled 'North Sea coastal zone' (Noordzee-kustzone), which is fully exposed and is dominated by the waves of the North Sea. The difference between these subtypes is important for both H1110 and H1140, as different vegetation communities and fauna thrive under these differing circumstances.

B.3: Additional information H1140A

In its definition there is an exception: if species of salt marshes or meadows (Habitat types H1310/H1320/H1330) are colonising below the high tide, this area is not considered as H1140. Thus, around the future Banjaard, H1140 will be the area that lies between the average low and high water marks, unless salt marsh and meadow species are colonising the area. If so, these colonising species form the upper limit (Natura 2000, 2008e). H1140 forms a mosaic of different ecotypes, e.g. because of difference in height of the sand/mudflat or differences in grain size.

Different species prefer different of these ecotypes. As such, the habitat- and biodiversity that follows is an important measure of H1140's quality. Furthermore, because many characteristic species of H1140 will spend part of their life cycle in adjacent habitat types, permanently flooded sandbanks (H1110) and salt marshes and meadows, its continuity with these habitat types is important. Like mentioned in the subheading about H1110, H1140 too is divided into a tidal dominated and a wave dominated subtype.

B.4: Additional information H1330

The Northern horse mussel prefers depths below 20 metres (Van Duren, 2017), where it will only be up to 6 metres around the Banjaard. Therefore, this bivalve is not assumed to show itself here. This species is mentioned to keep in mind as potential species in case of future sea level rise and or the creation of local depths by erosion.

Modiolus modiolus is a bivalve mollusc which is found throughout the world, in deeper waters on ridges of a gravel and coarse seafloor (Wilson et al., 2021). In the Dutch sea this is an endangered species (Van Duren, 2017). It is a relatively large bivalve and is thereby known by its extremely large capacity for filtering the water column by 1 to 4 litres per hour (Kent, 2015).

Mytilus edulis- North Sea species blue mussel
This mussel is commonly found at large amounts on artificial structures in the North Sea: wind turbines, platforms etc. It can be seen as a key stone species; a species with a disproportionately large effect on its natural environment in relation to its abundance. It has a large depth range of occurrence, therefore this species can be of interest in case gullies occur due to erosion around the future Banjaard (Coolen & Jak, 2017).

B.5: Dune succession stadia

Embryonic dunes will potentially be succeeded by White dunes (H2120: Witte duinen). When *Elytrigia juncea* have retained enough sediments so the vegetation is out of reach of the saline sea water, White dunes with *Ammophila arenaria* (helmgras/marram grass) will suppress the embryonic vegetation (Natura 2000, 2008f; Natura 2000, 2008g).

When the White dunes create areas in the dunes covered from the impact of the wind, soil development can start to take place. This means herbs and mosses will be able to colonise the dunes. Additionally small shrubs will be able to settle on the so called Grey dunes (H2130: Grijze duinen) (Natura 2000, 2008b).

Other habitat types that can eventually succeed on the Embryonic dunes can be: Decalcified fixed dunes with *Empetrum nigrum* (H2140: Duinheiden met kraaihei); Atlantic decalcified fixed dunes (H2150: Duinheiden met struikhei); Dunes with *Hippophaë rhamnoides* (H2160: Duindoornstruwelen); Dunes with *Salix repens ssp. argentea* (H2170: Kruipwilgstruwelen); Wooded dunes of the Atlantic, Continental and Boreal region (H2180: Duinbossen); and Humid dune slacks (H2190: Vochtige duinvalleien).

It is likely the White dunes will successfully succeed on the Embryonic dunes because of the suitable environmental conditions (Natura 2000, 2008f). Whether the other above-described habitat types actually will colonise barrier island the future Banjaard is very unclear. This depends a lot on the development on the island, the introduction of animals, the accessibility of humans to the island and weather conditions (Van Puijenbroek et al, 2017).

We chose to set up a plan for initialising vegetation on the barrier island right when it is created, to limit sediments being removed from the island. Our priority is to give the ecosystem a head start for natural development of the dune system on the island. Therefore we will not discuss ecosystem engineers of succeeding habitat types in detail here.

Appendix C: About the authors

Our research project team consists of six highly motivated students. We are all following the MSc programme Climate Studies at Wageningen University and Research and this project is part of the course Design of Climate Change Mitigation and Adaptation Strategies.

The MSc programme Climate Studies is very broad, giving students the possibility to choose a specialisation in the direction they like the most. This, and the added value of the very different backgrounds of our team members results in a diverse availability of skills and knowledge. A short overview of the individual team members and their team roles is given in the table below.

Group members	BSc background	Team role	Skills
Christian Menheere	Biomedical Technology	Planner	Physics, mathematics and chemistry Modelling and programming Critical thinking
Freek Engel	Environmental Sciences	Team manager	Planning Writing Working out of ideas
Renske Schouwink	Liberal Arts and Sciences, including social sciences and environmental sciences		Leadership Interdisciplinary skills Maintaining an overview
Noortje Janssen	Dentistry Environmental Sciences	Contact person to N. van Rooijen	Out of the box thinking Generating of ideas Maintaining an overview
Rosanne Erhardt	Spatial Planning	Notetaker, Contact person to M. Eelkema	Multidisciplinary thinking Out of the box thinking Creativity
Sara Almeloo	Landscape Architecture	Contact person to commissioner and supervisor, Contact person to A. van Oudenhoven	Creativity Writing Visual representation

+ Renske!