The Banjaard Breakwaters

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Authors: D. Cuna, J. Diepeveen, P. Janeka, T. Ketting, B. Koole , E. Merks, L. Riemens

Supervisor: Dr. ir. V. Tsimopoulou

Institute: HZ University of Applied Sciences

Location: Het Groene Woud 1-3, 4331NB Middelburg, The Netherlands

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1. Introduction

In October 1986, the Eastern Scheldt storm surge barrier (Oosterscheldekering) was officially opened by Queen Beatrix as a response to the North Sea flood of 1953. Since then, the barrier has been closed 27 times (excluding test runs) in anticipation of expected storms. With a view on (accelerated) sea-level rise, the storm surge barrier may not be able to hold its role in protecting the Zeeland hinterland as only a sea-level rise of 45 cm was assumed in the design of the barrier (Spaargaren, 2018). The accelerated sea-level is a result from the changing climate caused by elevated atmospheric CO_2 levels (IPCC, 2019). The IPCC (2019) specifically predicts that, at the end of the 21st century, sea levels will have risen 0.43 – 0.84 metres. Continuously heightening dikes and dams is not feasible, which is why alternative solutions are being explored. One such solution is using sand nourishments to reduce wave energy, which can be combined with reinforcing Building with Nature techniques, providing long-term hinterland protection and a sound landscape for flora, fauna, and humankind. Additionally, a sand nourishment fits perfectly into the national Delta Programme coastal strategy (see 'Decision on Sand'). Looking offshore, a sandbank known as 'De Banjaard' can be nourished and reinforced to relieve the storm surge barrier. The Banjaard lies just north of Walcheren and southwest of the former island Schouwen, dating back to the 19th century (1815). The sandbank has been slowly disappearing due to changing currents and sea-level rise; despite this, ship navigators must still account for its presence. The aim of this report is to design a sand nourishment, reinforced by nature, in the Zeeuwse Voordelta to contribute to coastal protection.

1.1. Research Questions

Main research question

To what extent can an island in the form of a sand nourishment be designed in the Voordelta, which integrates bio builders to be utilized in protecting the hinterland against sea level rise?

Introduced subquestions

1. To what extent can biobuilders contribute to the protection, reinforcement, and expansion of the initial nourishments?
2. What are the boundary conditions for the engineering design of the sand nourishment?
3. How feasible is the design regarding societal, financial and technical aspects?

2. Theoretical Framework

2.1. Physical process analysis

To produce a good design for the area it is important to gather as much data as possible about the physical processes in the area. The gathered data will be about the influence of the Eastern Scheldt barrier on the area, the tides and waves that are present and the direction of the flow. Another point that is important is the morphology of the area, so when the island is created it will not disappear after a few years.

2.1.1. Eastern Scheldt Barrier

Deltaworks

The Eastern Scheldt barrier is part of the Delta works. The Delta Works is a series of construction projects in the Netherlands that were built to protect the country against high water coming from the North Sea. The Netherlands is very vulnerable to flooding due to its low level and the large amount of water, such as rivers, canals, and the sea. It is therefore important that the Netherlands is properly protected against high water, for the safety of the Dutch and the economy. (Rijkswaterstaat, n.d.-a)

The Delta Works forms a more or less straight coastline from Zeeuws-Vlaanderen to The Hague. As a result, the coastline is only 80 km long, instead of the 700 km before. The advantage of this is that the dikes within the delta works do not have to be excessively reinforced and raised. The disadvantage is that the barriers are essential to protect the Netherlands against the water (Rijkswaterstaat, n.d. -a).

Eastern Scheldt barrier

Initially, the intention was to build a closed dam on the site of the Eastern Scheldt barrier. Part of this had already been realized when there was a lot of criticism of these plans, mainly from fishermen and nature organizations. As a result, construction has been stopped, and it has been decided to build a movable storm surge barrier.

The Eastern Scheldt barrier is the largest storm surge barrier in the Netherlands, and was built to stop the high water from the North Sea in the event of a severe storm. The 62 gates all close at a water level of more than 3.00 meters above NAP. Normally, the Eastern Scheldt Barrier is open, and water can flow in and out of the Eastern Scheldt at low and high tide. On average, the barrier closes about once a year (Ministerie van Infrastructuur en Waterstaat, 2021).

Influence of sea level rise on the barrier

E. van Zanten of Rijkswaterstaat has conducted research into sea level rise and sand hunger in the Eastern Scheldt. The Eastern Scheldt barrier was examined in more detail, and the influence of this on the barrier was calculated in the event of various sea level rises. Figure 1 shows how often the barrier should be closed, based on various measurement data.

ZEESPIEGEL-STIJGING	SLUITINGEN PER JAAR GEBASEERD OP:			PERCENTAGE VAN DE TIJD DICHT GEBASEERD OP:		
	Huidig regime	Golf-over-slag (q_{max})	MHW	Huidig regime	Golf-over-slag (q_{max})	MHW
0,00	0.5	0,1	0,1	0,0%	0,0%	0,0%
0,25	1,7	0,2	0,4	0,1%	0,0%	0,0%
0,50	4,5	0,8	1,2	0,3%	0,1%	0,1%
0,75	22	2	3	1,5%	0,1%	0,2%
1,00	85	3	10	5,8%	0,2%	0,7%
1,25	228	7	31	16,3%	0,5%	2,2%
1,50	418	15	107	32,7%	1,1%	7,5%
1,75	577	31	305	49,5%	2,3%	21,9%
2,00	662	63	522	61,8%	4,8%	39,8%
2,25	674	128	644	69,7%	9,8%	53,5%
2,50	607	261	678	76,6%	20,0%	62,9%
2,75	391	455	652	86,2%	36,3%	70,7%
3,00	123	595	524	95,7%	51,5%	79,7%

Figure 1. Table showing the influence on the Eastern Scheldt barrier during various sea level rises (Zandvoort, 2019).

By taking a closer look at normative high-water levels and wave overtopping, a more specific picture can be formed of how the closing regime of the Eastern Scheldt barrier should be dealt with. In the future, therefore, account will have to be taken of situations in which the barrier will be more closed than open, and the water in the Eastern Scheldt barrier will therefore be refreshed less often, and will have a different water level than now. This can partly be compared with the Grevelingen and the Haringvliet (Zandvoort, 2019).

Erosion Voordelta

To understand the current erosion in the Voordelta it is necessary to understand how Zeeland is formed. In the Roman times Zeeland mainly existed out of a bulk of land with peat which was divided by the Scheldt river. Enhanced drainage of peat both by man-induced causes (peat was a valuable product) and natural processes culminated in a collapse of the land surface and an accelerated transgression by the sea. By AD 800 the sea would have claimed big chunks of land and estuaries were being formed, furthermore, a large-scale network of small channels was dissecting the province. Over time the channels cleared up and disappeared, resulting in the formation of the islands as shown in Figure 2 (de Bruin and Wilderom, 1961).

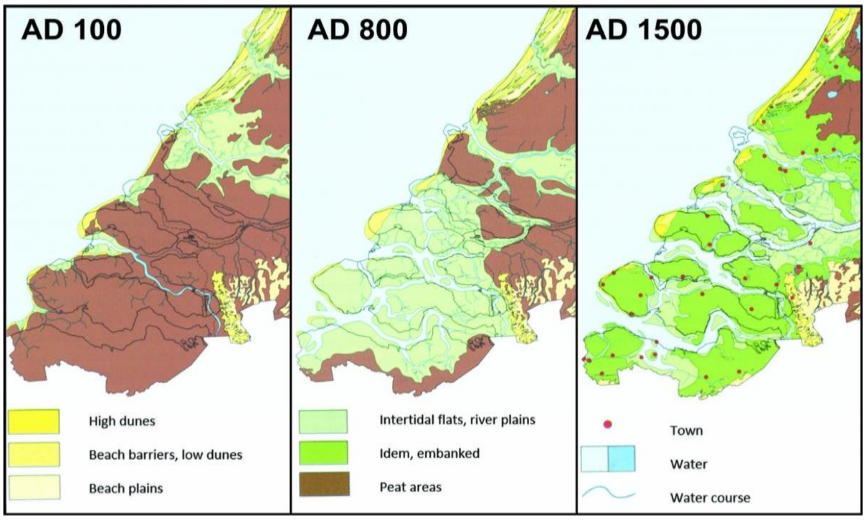

Figure 2. Progression of the delta area 100-1500 AD (Vos et al., 2011).

Location specific

The figure below (3) illustrates the erosion and sedimentation rates of two time periods of the location where the island will be developed. Important to notice is that the sedimentation rates reduced drastically compared to the first period. Before completion of the storm surge barrier sedimentation was dominant. This dominance was created when the Eastern Scheldt got connected to Hollands-Diep. The sedimentation also nourishes the neighboring tidal deltas. The construction of the Eastern Scheldt barrier, the ebb-tidal delta was not really influenced. However, the active cross-sectional area of the tidal inlet got reduced significantly (from 80 000m2 to 17 900 m2). Furthermore, the basin area reduced from 452 km2 to 351 due to sand supplements. This all resulted in a 28% decrease in tidal volume with respect to 1983 (Elias et al, 2017). Louters & Van den Berg estimated that the tidal prism initially increased before the construction of the barrier (from 1130 to 1189 mcm between 1959 and 1980), and reduced to 837 mcm after completion. Moreover, the sediment export of the estuary is blocked completely due to the elevated foundation of the barrier. This elevation consists of large beams which connect the pillars of the barrier with the scour pits located on both sides of the barrier. With no sediment supply and the decreased tidal currents, the waves started to become the dominant transport mechanism in the area. These flow north as a result of the dominating flood tidal current present in the area. This ultimately causes the area to erode. This has an effect on the exposure of the coast as the protective sediments are slowly disappearing which is the reason a sand supplement which would reinforce the coast is necessary.

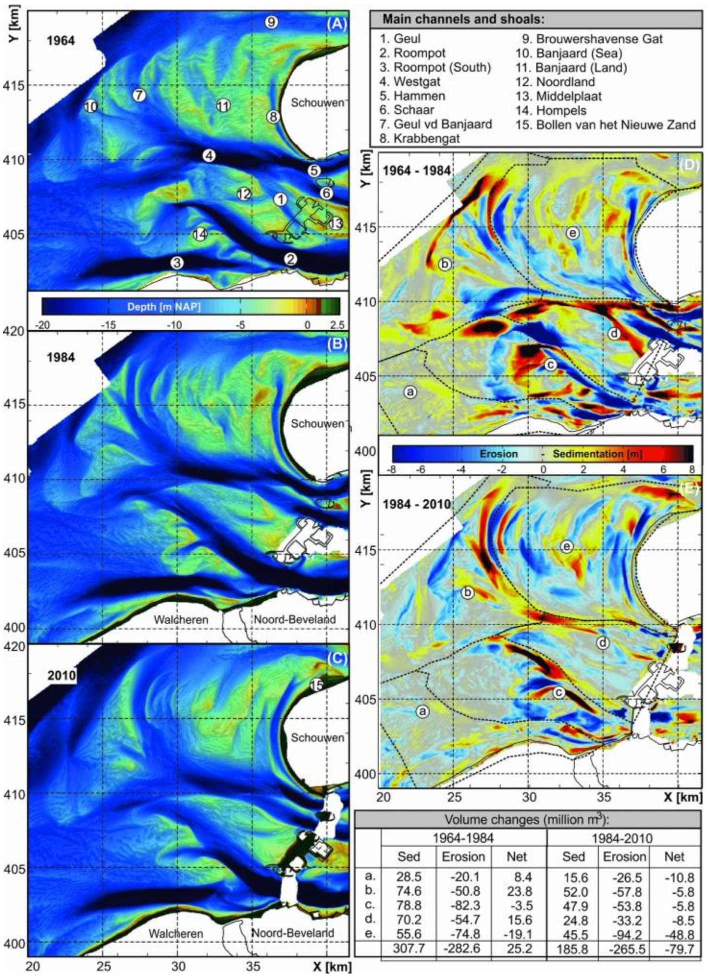

Figure 3. Sediment transport in the Zeeuwse Voordelta (Elias et al, 2017).

2.1.2. Bathymetry of the area

It is important to know what the bathymetry of the area around the Banjaard is. With this information it is possible to find out where the shallow and deep zones are. With the help of EMODnet it is possible to get a clear view of the bathymetry. EMODnet is a website that delivers free satellite data of the waters in Europe to the main public. This is an important and useful tool regarding our project considering volume estimations have to made. Figure 4 shows the bathymetry of the area just in front of the Eastern Scheldt barrier.

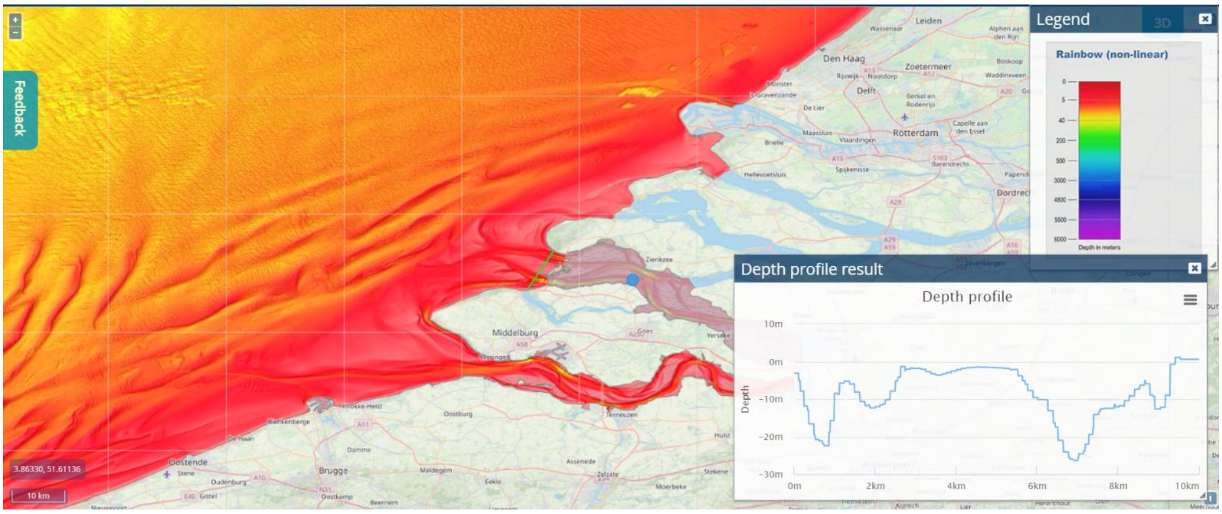

Figure 4. Bathymetric view of the Voordelta (EMODnet, n.d.).

The depth profile on the right side of the picture shows the profile of the Oosterschelde along the green line. The legend explains what the colours in the picture mean, with the red colours showing shallow areas and the yellow/orange area's showing deeper zones.

In order to understand the bathymetry of the area it is important to get a closer look then the picture above. With the help of GEOWEB, Figure 6 is created.

Figure 5. Location of depth profile of figure 4 (GEOWEB, n.d.).

In this map you can see the values that show the depth of the sea, the lines show the area where this depth applies. The smaller shapes inside the bigger shapes show the areas where the sea bottom is deeper.

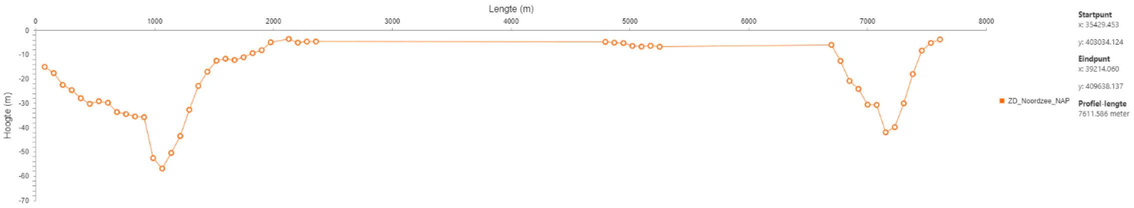

Figure 6. Depth profile of Eastern Scheldt (Geoweb, n.d.).

In this area we are also able to make a depth profile across a line, the figure above shows this depth profile. The depth profile is a bit more detailed as the other profile, in this profile it is possible to see the precise depth at a certain coordinate. But in the profile, there are two long straight lines, in these lines there is no data that shows the depth. The depth profile is taken much closer to the Eastern Scheldt barrier than the first depth profile.

When looking at this data it becomes clear there are three deeper sea channels. These deeper zones are found around the barrier, and in between the islands that are connected by the barrier. In between these channels and further seawards, shallower zones can be found.

2.1.3. Tides and wave height

To get a clear understanding of the area it is important to look at the tides that occur inside the area, tides are dependent on the position of the moon. To get the data of the highest and lowest tide, it is necessary to take the tide data from a whole month. In this case the data from the 2nd till the 30th of September 2021 was taken. Figure 7 shows a tidal difference of 1.5 meters during spring tide with the mean sea level.

Figure 7. Tidal difference of 1.5 meters recorded in September 2021 (Rijkswaterstaat, n.d. -b).

One important factor regarding tidal influence is the construction of the storm surge barrier. This caused the tidal volume to reduce as the barrier was built on a foundation blocking the sediment export. Considering the tidal influence by the barrier did not change and no new sediments are being deposited on the islands the sand eroded and were/still are transported north (Elias et al., 2016).

Water height

Because the Oosterschelde is a big area, data was taken from two measure points, the data from these points is provided by Rijkswaterstaat. The map below shows the two points from which the data was taken. The point near the lock was not chosen, because the data there is measured inside a small bay. The first graph shows the data from the measure point close to the barrier, and the second measure point shows the data from the point further to the sea.

Figure 8. Water height (Adopted from: Rijkswaterstaat, n.d. -b).

When looking at the data of the tides, it shows that at its highest point, the tide will be a little bit more than 200 cm above N.A.P. and at its lowest point the water is 160 cm below N.A.P.

In order to find a solution, it is also important to know what the height is of the waves that could be expected. Therefore, it is necessary to collect data about the wave height. For collecting this data, the same measure points as for the tide is used. The data for the waves will show two graphs, with the first graph showing the data for the point closest to the barrier and the second point showing the data further to the sea.

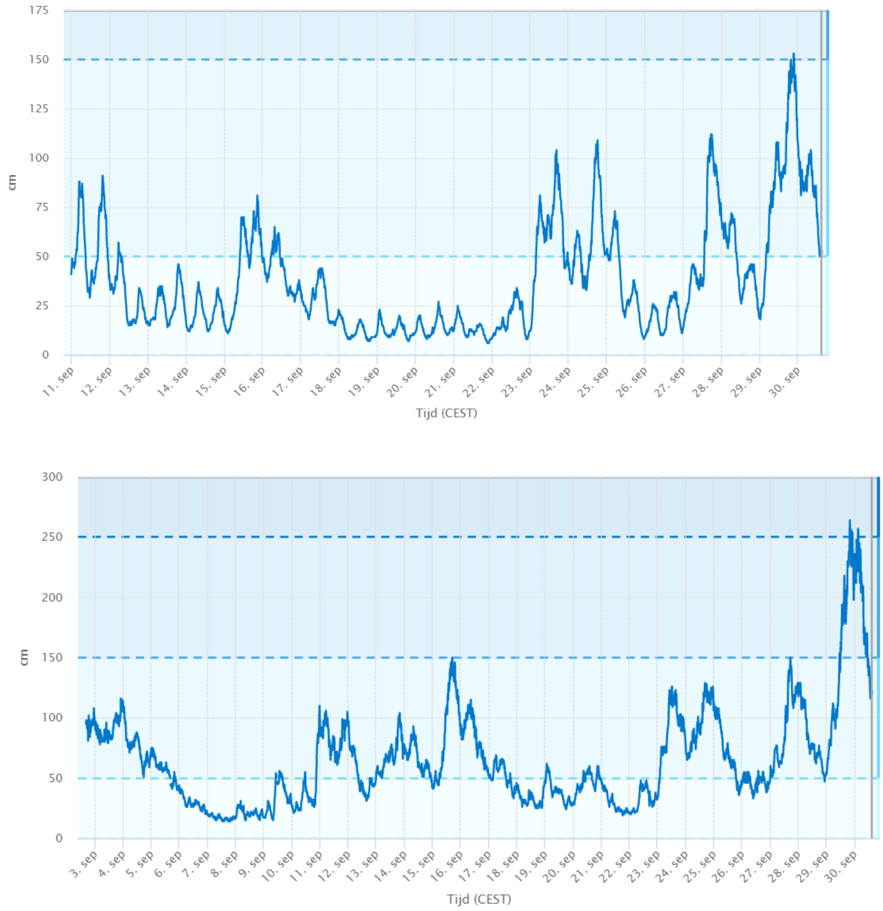

Figure 9. Wave height (Rijkswaterstaat, n.d. -b).

The data shows that the waves seawards are much higher compared to the waves closer to the barrier. With the highest waves at the second measure point reaching heights of 260 cm. The highest wave at the measuring point next to the barrier is just above 150 cm.

Wind

As the Banjaard will be built in the open sea, wind will have a significant influence on the erosion rates considering the waves in the Voordelta are generated by wind (Elias et al., 2016). It is estimated that wind on the open sea has double the speed as wind on land (Janssen, 2021). This can be explained by the fact that on land the wind is blocked by objects and the land itself → altitude. The Netherlands is under the influence of global air currents. These currents are caused by the temperature differences between the poles and the equator considering cold air is heavier and descends whilst warm air is lighter and rises. As a result of this almost 50% of the time the wind comes from the South-West direction (Faber, 2016). The rest of the time the wind usually originates from the southern or western direction. Sometimes the wind switches to the north but this does not happen often as this would have a major impact on the shape of the Netherlands.

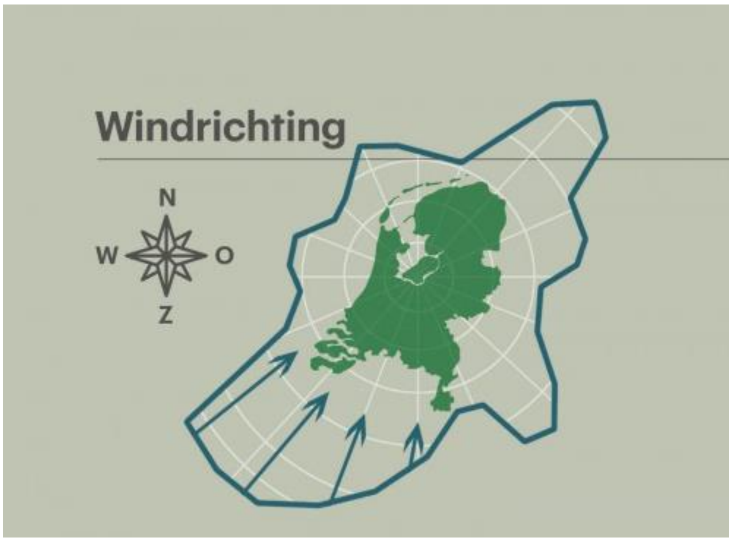

Figure 10. Wind direction in the Netherlands (Faber, 2016)

Sea level rise

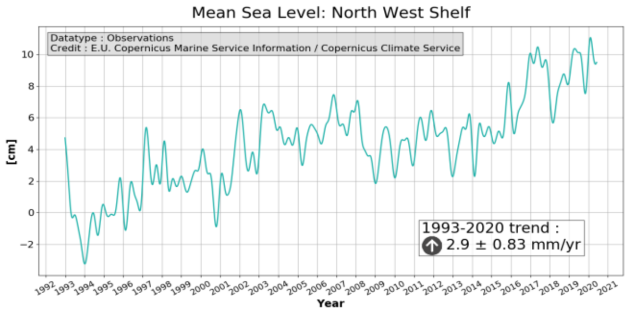

Figure 11. Mean sea level rise 1993–2020 (E.U. Copernicus Marine Service Information, 2021).

As the figure above illustrates, the mean sea level rise shows a clear trend upwards. This has major consequences for the Dutch coast. Considering most of the country is located below sea level and the seasons are fluctuating more (droughts during summer and heavy rainfall in winter (Iglesias et al., 2011) the Dutch coast is already vulnerable. To protect the coast the country is constantly innovating and designing new plans such as 'de Banjaard'.

2.2. Ecological Analysis

The Banjaard is an intertidal area home to many species, depending on the section. The area has been designated as a Natura 2000 area since 2008 under the name 'Voordelta' by the Dutch Ministry of Agriculture, Nature and Food Quality in order to protect its valuable nature. The Natura 2000 area roughly encompasses the shallow sea area from the Maasgeul to Westkapelle (Walcheren), as indicated in gray in Figure 12 (Beheerplan Natura 2000 Voordelta, 2016). The ecological analysis will highlight an ecological perspective on the area in its current situation, divided by biotic and abiotic factors. Furthermore, biobuilders are described for their promising role in maintaining sand nourishments. A sound understanding of the area will lead to informed decision-making, and prevent accidentally destroying essential ecosystems or disrupting important biological processes.

Figure 12. Location Voordelta, marked grey, and surrounding Natura 2000 areas, marine areas marked blue and off-shore areas marked green (Rijkswaterstaat Zee en Delta en Royal HaskoningDHV).

2.2.1. Biotic factors

In the Voordelta Natura 2000 area, conservation objectives apply for the six habitat types and 36 species for which the site has been designated as part of the Natura 2000 network. Every six years a new management plan will be published. For the design of the sand nourishment, it is important to know which species utilize the area and where these species occur to make sure that the organisms are not negatively influenced by the nourishment and to investigate how the nourishment could serve the biotic environment as well.

The designated habitat types assigned to conserve consist of permanent overflowing sandbanks, mud flats and sand flats, saline pioneer vegetation, mud lawns, salt marshes and saline grasslands and embryonic dunes. (Natura 2000, 2016).

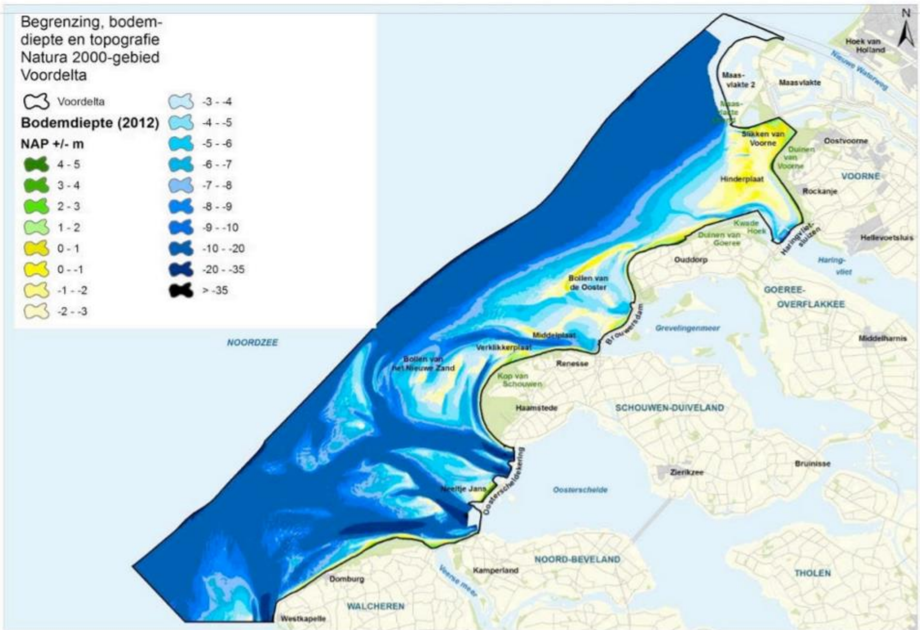

Figure 13. Boundary Natura 2000 area Voordelta, soil depth, plates, and topography.

Figure 13 gives an overview of the area’s morphology, which is important related to the organisms use of the area. The main area consists of permanently submerged sand banks, tidal flats. Tidal area and North Sea coastal area as subtypes and a coastal zone with the habitat type: embryonic dunes. An embryonic dune, precursor to the white dune (‘witte duinen’, habitat type H2120), is a newly-formed ‘pioneering’ dune usually located at the foot of the dune (foredune). Colostrum grass tends to be the only type of vegetation covering the dune, the dune may be periodically submerged by incoming seawater (Natura 2000, n.d.).

A tidal flat is a coastal ecosystem in the intertidal zone, intermittently flooded by the incoming tide (Friedrichs, 2011). Tidal flats provide an important habitat for many invertebrates that live under the sediment, including mollusks, worms, crustaceans, echinoderms, and acorn worms (Balasuriya, 2018). This makes it an essential foraging area for migratory benthivorous wading birds, which rest at stopover points along the migration route (Miththapala, 2013). The sandbanks are mainly utilized by Seals who use the sandbanks as resting ground and to suckle their young, to sunbathe, in order to dry their fur, and for shedding. Tidal flats are furthermore used by crustaceans, cockles, mussels, and shore birds such as the oystercatcher, avocet, and shelduck (Balasuriya, 2018).

Organisms have adapted to the risk of drying out (desiccation), varying levels of salinity, exposure to grazing predators at low tide, and no access to water (food) during low tide. Depending on if the tidal flat consists mostly of soft sediment like sand, or mud, additional characteristics can be observed. For example, soft sediment is harder for organisms to anchor to, and generally shows a decreased number of primary producers. Mud flats, on the other hand, may develop anoxic zones.

The shallow open water area in the tidal zones hosts many bird species, from which the majority are migratory birds who use the area as a feeding ground to gain strength. Fish-eating birds like red-throated diver, great crested grebe, horned grebe, great cormorant, Eurasian spoonbill, red-breasted merganser, little gull, sandwich tern, and common tern (see Figure 14). As well as benthivorous birds like the Greater scaup, common eider, common scoter, and common goldeneye (see Figure 15).

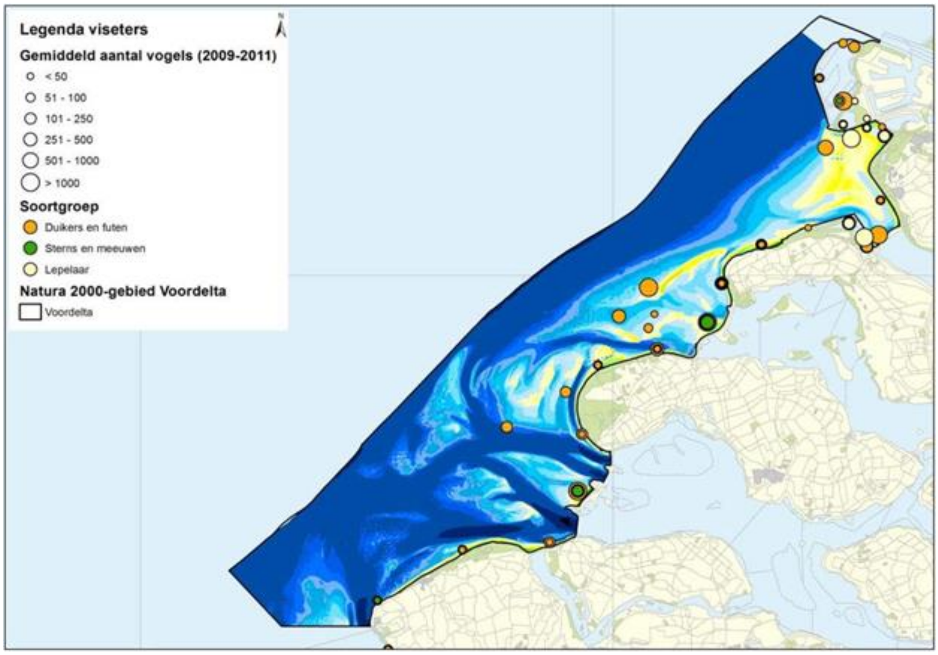

Figure 14. Distribution of fish-eating birds (2009-2011).

Orange circles: divers and grebes are present, green circles: sterns and seagulls, yellow circles: the spoonbill is present (Rijkswaterstaat Zee en Delta en Royal HaskoningDHV, 2016).

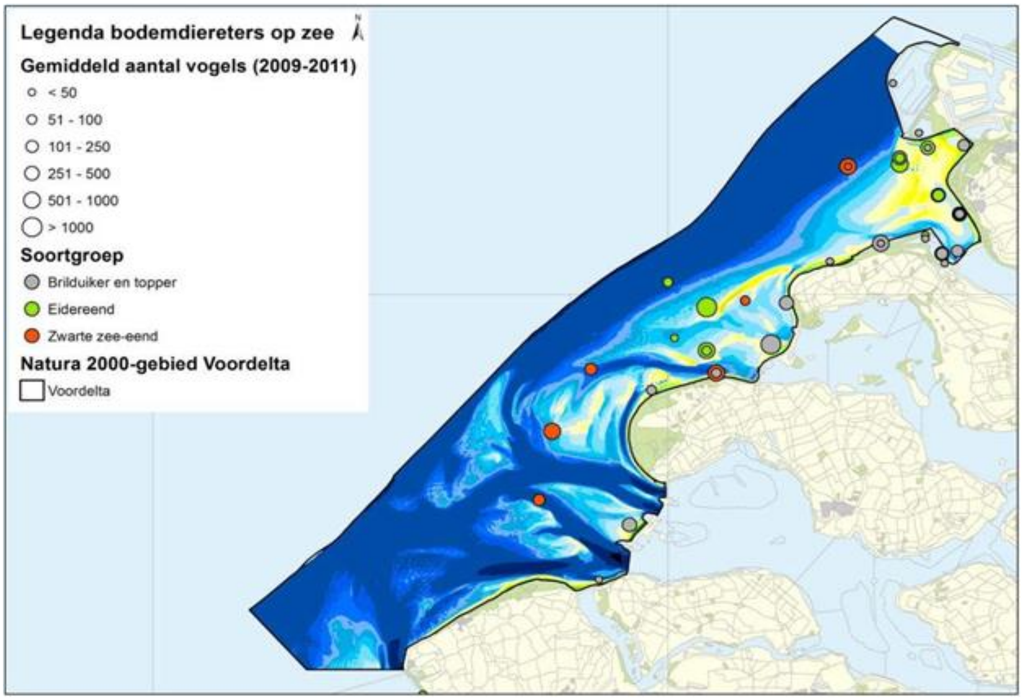

Figure 15. Distribution of benthivorous birds (2009-2011).
Gray circles: greater scaup and common goldeneye are present, green circles: the common eider is present, red circles: common scoter is present (Rijkswaterstaat Zee en Delta & Royal HaskoningDHV, 2016).

As a third category, herbivores, and omnivores like greylag goose, Eurasian wigeon, Eurasian teal, northern shoveler, and gadwall (see Figure 16).

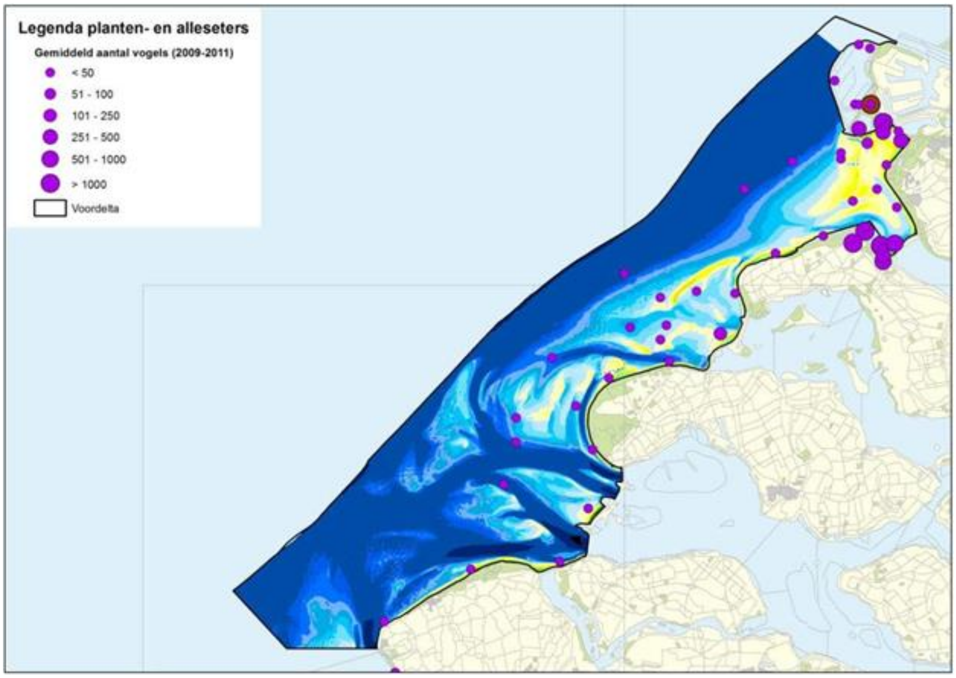

Figure 16. Distribution of herbivores and omnivores (2009-2011).
Purple area size: species abundance (Rijkswaterstaat Zee en Delta & Royal HaskoningDHV, 2016).

The Voordelta has also been assigned as a habit for migrating fish like salmon, houting, sea Lamprey, twaite shad and allis shad. These fish live in saltwater but migrate to freshwater, such as the Rhine River and the Meuse, to reproduce.

Table 1 gives the complete overview of the animals with a conservatory status in the Voordelta.

Table 1.
Overview of species included in the Natura 2000 conservation management plan. (Adopted from Beheerplan Natura 2000 Voordelta, 2016).

Classification	**Common name**	**Scientific name**	**Feeding type**
Birds	Red-throated diver	*Gavia stellata*	Fish-eating birds
	Great crested grebe	*Podiceps cristatus*	Fish-eating birds
	Horned grebe	*Podiceps auritus*	Fish-eating birds
	Great cormorant	*Phalacrocorax carbo*	Fish-eating birds
	Eurasian spoonbill	*Platalea leucorodia*	Fish-eating birds
	Red-breasted merganser	*Mergus serrator*	Fish-eating birds
	Little gull	*Hydrocoloeus minutus*	Fish-eating birds
	Sandwich tern	*Thalasseus sandvicensis*	Fish-eating birds
	Common tern	*Sterna hirundo*	Fish-eating birds
	Greater scaup	*Aythya marila*	Benthivorous birds
	Common eider	*Melanitta nigra*	Benthivorous birds
	Common scoter	*Somateria mollissima*	Benthivorous birds
	Common goldeneye	*Bucephala clangula*	Benthivorous birds
	Common ringed plover	*Charadrius hiaticula*	Benthivorous birds
	Eurasian oystercatcher	*Haematopus ostralegus*	Benthivorous birds
	Sanderling	*Calidris alba*	Benthivorous birds
	Grey plover	*Pluvialis squatarola*	Benthivorous birds
	Dunlin	*Calidris alpina*	Benthivorous birds
	Eurasian curlew	*Numenius arquata*	Benthivorous birds
	Greylag goose	*Anser anser*	Herbivores & omnivores
	Eurasian wigeon	*Mareca penelope*	Herbivores & omnivores
	Eurasian teal	*Anas crecca*	Herbivores & omnivores

	Northern shoveler	*Spatula clypeata*	Herbivores & omnivores
	Gadwall	*Mareca strepera*	Herbivores & omnivores
	Common shelduck	*Tadorna tadorna*	Herbivores & omnivores
	Pied avocet	*Recurvirostra avosetta*	Herbivores & omnivores
	Ruddy turnstone	*Arenaria interpres*	Herbivores & omnivores
	Common redshank	*Tringa totanus*	Insects and small fish
Migratory fish	Salmon	*Salmonidae* family	Carnivores
	Houting	*Coregonus oxyrhynchus*	Carnivores
	Sea lamprey	*Petromyzon marinus*	Carnivores
	Twait shad	*Alosa fallax*	Carnivores
	Allis shad	*Alosa alosa*	Carnivores
Mammals	Common seal	*Phoca Vitulina*	Carnivores
	Grey seal	*Halichoerus grypus*	Carnivores

2.2.2. Abiotic Factors

Water Quality

The conditions of the North Sea are changing as the years pass by. This requires adaptation as nature, which thrived in the past, is not able to keep up with the changes currently occurring in the water. To create a better overview of the area some of the important elements are listed below.

Temperature

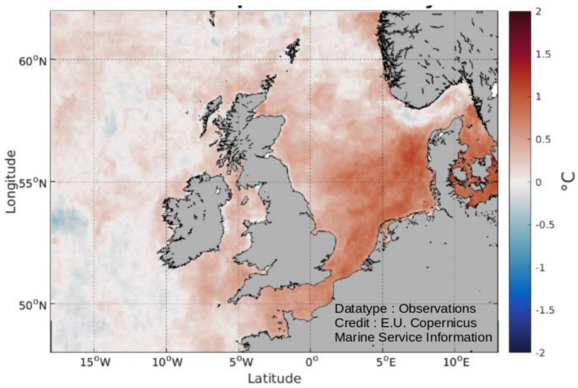

Figure 17. Sea surface temperature anomaly (E.U. Copernicus Marine Service Information, 2019).

The picture above shows the temperature difference compared to the period (1994-2014). The surface water already increased at least 0.5 degrees Celsius, creating difficulties for its local habitants. Shellfish release their eggs when the sea reaches a certain temperature for example and if this temperature is reached too early the new generation is not able to obtain enough plankton to grow.

Salinity
Salinity values of the Voordelta range between 34–35.5 PSU (Swertz et al., 1999). Numbers on salinity are important to investigate if the area of interest meets the bio builders requirements we wish to implement in the build. Additionally, salinity influences the solubility of oxygen, where a higher salinity concentration decreases the amount of dissolved oxygen, affecting present species and biological processes (Sherwood, 1999).

Ocean Acidity & Dissolved Carbon Dioxide

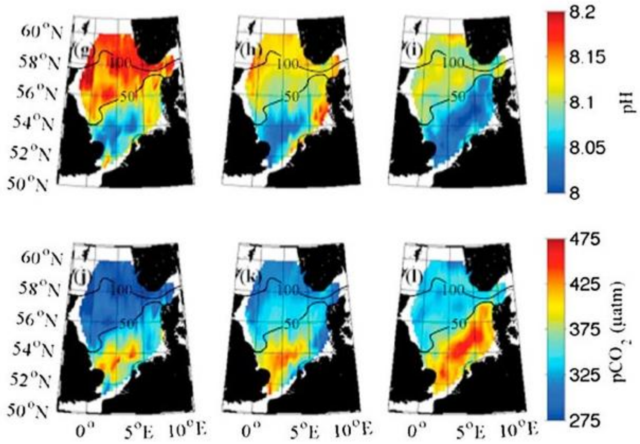

Figure 18. Temporal (2001, 2005, 2008) change in dissolved carbon dioxide (CO_2) and basicity (pH) in the North Sea (Salt et al., 2013).

As seen in the picture above, the pH and CO_2-concentrations in the ocean are changing rapidly. When comparing the 3 different time periods, a clear trend can be observed in which the pH is dropping while CO_2-uptake is rising. In the last four years, a pH range between 6.89–9.27 was measured (Rijkswaterstaat, 2021). Since oceans naturally absorb CO_2 from the air, the uptake of CO_2 increases linearly with the increase of CO_2 in the atmosphere due to climate change. Because CO_2 is an acid the pH is also dropping slowly causing ocean acidification. whereas the changes in Ph seem to be small, the effect it has on calcifying organisms is inevitable. Several studies have shown responses of a decrease in calcification rates in coccolithophores, pteropods, bivalves, foraminifera and more (De Nooijer, L.J. and Reichart, G.J. 2018). However, ocean acidification can also be used as an advantage. For example, some organisms, such as cyanobacteria (Lomas et al., 2012), macro algae and sea grasses (Koch, Bowes, Ross, & Zhang, 2013) have been shown to profit from the ongoing changes in carbonate chemistry.

Nutrients
Eutrophication of coastal areas including the North Sea is considered as a serious problem in Europe and the rest of the world. Various studies observed changes in species composition and phytoplankton density by cause of anthropogenic nutrient loading from airborne and terrestrial sources (Patsch and Radach, 1997; Cadee and Hegeman, 2002). Additionally, changes in benthic communities and an increase in sediment anoxia occur as a result of the higher nutrient loads. In response to this increase the EU applied restrictions in P and N use in agriculture. As you can see in Figure 16 these restrictions are proving to be effective. The figure shows a decrease in the total and external (the difference in external N and P and total can be explained by the fact that the total curve includes internal N and P (e.g., resuspension and remineralization from the sediments)) loading of N and P.

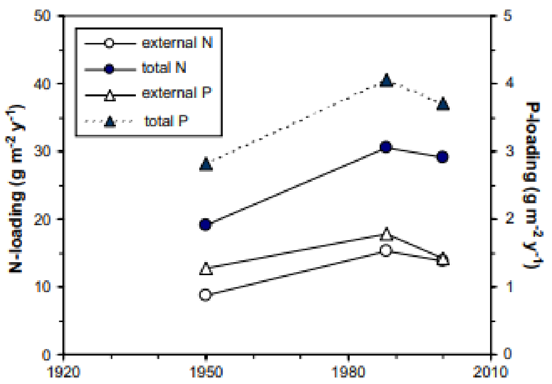

Figure 19. Nitrogen and phosphorus loading in the coastal areas of the North Sea (Vermaat et al., 2008).

However, even with the decrease of the most important nutrients chlorophyll concentrations are still increasing. A paper from Vermaat et al. (2008) claims; "chlorophyll concentrations are more sensitive to temperature and light availability (due to lower turbidity) than by nutrient availability". The complex nature of all of these factors who are interacting with each other makes it difficult to understand the impact of the nutrient fluxes on our area.

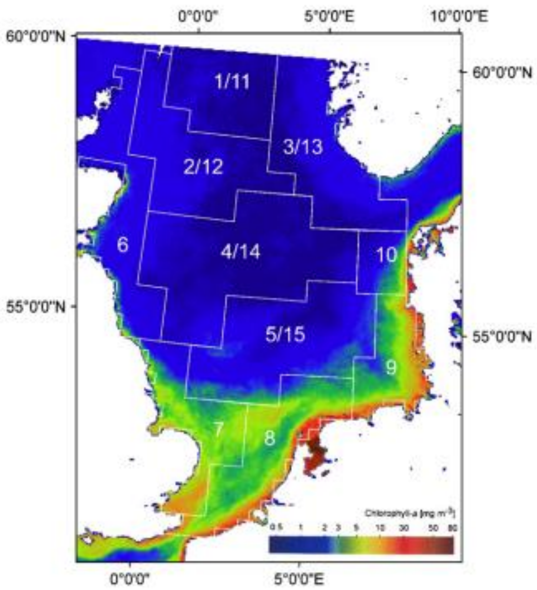

Figure 20. Chlorophyll concentrations in February 2003 (Peters et al., 2005).

To conclude, the Chlorophyll values are quite high near the coast even though the nutrient values are declining. It is expected that this will not have an effect on our area.

2.3. Bio-builders

Ecosystem engineers are organisms that create, maintain, and modify their environment by "changing the distribution of materials and energy via non-trophic interactions with abiotic and biotic components of their respective ecosystem (Eisenhauer, 2010). Ecosystem engineers can substantially influence species richness and habitat heterogeneity, thereby impacting ecosystem function (Wright et al., 2004). When ecosystem engineers are used for human purposes, these organisms may be considered as 'bio-builders'. To define bio-builders: "Bio-builders are organisms with ecosystem engineering characteristics, implemented in such a way that it is beneficial to human area development".

A primary example of utilizing bio-builders is constructing artificial shellfish reefs, these can stabilize eroding coastal areas by entrapping sediment, altering tidal flow and wave action. This results in favourable depositional patterns, research has shown that natural accretion matches pace with sea-level rise (Rodriguez et al., 2017). Functioning as a natural filter, consequently improving the water quality, the reefs simultaneously accommodate many other important species which make for a complex habitat with high ecological value (EcoShape, n.d.). Additionally, once fully developed, shellfish reefs can store substantial amounts of carbon and nitrogen within their shells (Dehon, 2010). The implementation of bio builders in coastal protection is a relatively new, yet promising concept that wishes to function as an ecologically-sound coastal protection measure.

Bio-building Species

Not all bio-builders would thrive in the area of the Voordelta, additionally within the area there could be prefered places. Therefore, it is important to investigate which species could be implemented. Examples of bio-builders previously used in the Dutch coastal areas are plant species and shellfish reefs. Plants covering extensive areas, such as eelgrass (*Zostera marina*) or English cordgrass (*Spartina anglica*), are able to decrease current velocities and reduce wave action, resulting in sediment entrapment and subsequent clarification of the water (Borsje et al., 2011). Cordgrass is also implemented in China as a hinterland protection measure (Chung, 2006). Shellfish reefs, generally consisting of oysters and/or mussels, are described above. Salt marshes also show the ability to dampen wave impact, simultaneously resulting in elevation of the soil (Borsje et al., 2011). Maram grass (*Ammophila arenaria)* can be used as a protection measure on stretches with sand dunes (Borsje et al., 2011). Figure 18 depicts how important the placement of the oyster reef is, by placing further offshore the reef can result in a decrease in orbital wave velocity, improving sediment entrapment. Furthermore, the marsh vegetation gives structure to the sedimentation elevation.

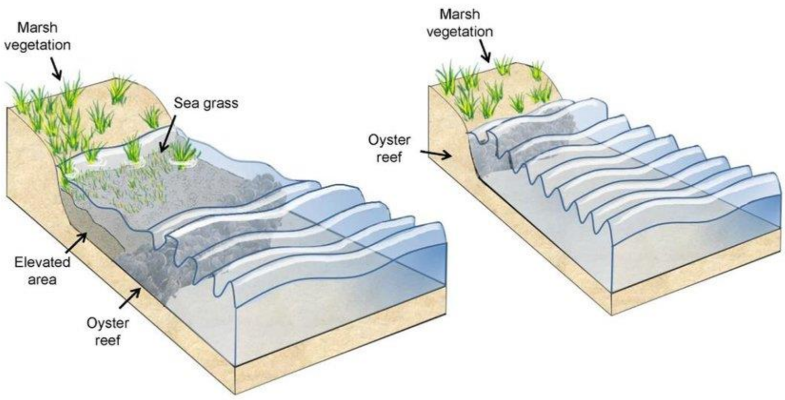

Figure 21. Oyster reef at the edge of marsh vegetation as breakwater to prevent shoreline erosion (Walles et al., 2015).

Local Use of Bio-Builders

Nearly 15 years ago, artificial oyster reefs were constructed in the Eastern Scheldt (mudflat of Viane) as part of a joint research between IMARES, Deltares, Rijkswaterstaat, NIOZ, Van Oord, TUD, and Ecoshape. Initial findings confirmed that the oyster reefs cause local deposition of sediment (EcoShape, n.d.).

Bio-builders requirements

Many shorelines are highly suitable for implementing bio-builders depending on the location, land and water uses, erosion and flood risk, among others. Unfortunately, nature-based approaches are not feasible in some cases, or the risk is simply too high for living shoreline solutions to adequately address shoreline protection.

Criteria for suitable sites for shellfish-based reefs are:

- Evidence of healthy native shellfish population in vicinity, e.g., oyster beds and/or ribbed mussels (Virginia Institute of Marine Science, n.d.).
- Salinity always above 10 ppt; sites with salinity below 5 ppt are not suitable for growing oysters (Virginia Institute of Marine Science, n.d.).
- Water depth at least 1 foot (183cm) at low tide; intertidal reefs are subject to freezing and winter die-off. The density of adult mussels increased between 30-40% exposure time and declined sharply above. Mussel Beds will not be centered above 50% exposure time. (McGrorty, S., et al., 1993).
- Firm bottom, not soft mud. (Virginia Institute of Marine Science, n.d.).
- The wave action (maximum orbital velocity) is the main structural factor. A low orbital velocity is preferred. (McGrorty, S., et al., 1993).

2.4. Stakeholders

Before planning any interventions, stakeholders with a connection to the Voordelta are listed in table 2 below. By this sand nourishment project some of the stakeholders are affected directly and some indirectly in the area.

Table 2.
Relevant stakeholders and their role in the 'Banjaard' project

Sector	Stakeholder	Role
Public	Natura2000	Majority of Voordelta is in Natura 2000 area, they are highly interested in ecological and environmental aspects of the project. Different Natura 2000 nature areas are managed by different provinces of the Netherlands (Natura 2000, n.d.). However, Voordelta is managed by the government. Therefore, Natura 2000 has little influence on the project and has no control in decision making.
Private	Fisheries	Different types of fisheries (industrial maritime, shellfish, trammel, coastal and North Sea) make use of Voordelta (Noordzeeloket, n.d.) . Intense fishing occurs in deeper waters, but the sand nourishment will take place in more shallow locations. Nevertheless, they can be appointed as a sensitive stakeholder group due to recent developments in politics. After Brexit in 2020, European fisheries lost entrances to a large part of the North Sea fishing grounds.
Public	Rijkswaterstaat	The main project stakeholder is Rijkswaterstaat. This governmental organization is doing the management of the area. They are responsible for small as well as big scale developments and shipping routes in Voordelta. Resulting as the most important stakeholder for this project.

Civil society	Recreational users	There are various types of recreation taking place in the Voordelta, see appendix 1. Most activity occurs in the summer period. For certain activities there are guidelines needed to follow regarding the location and time period in which the performance of the activity is allowed, and whether a permit is needed, see appendix 2. Recreational users are considered to have a low influence compared to other stakeholders.
Public	Province Zeeland	The province of Zeeland is responsible for the regional planning. However, this project takes place outside provincial boundaries. Resulting in not having a high influence on the project.
Public	Municipality Veere, Noord-Beveland and Schouwen-Duiveland	Municipalities are responsible for local developments. In this case, municipality interest is in economic developments of the area.
Civil Society	Citizens in Veere, Noord-Beveland and Schouwen-Duiveland	The main community interests are in safety and health, which this project is beneficial for.
Private	Hotels (Duinhotel Breezand, Strandhotel Duinoord, Fletcher Strandhotel Haamstede, BLUE Wellnessresort Zeeland, Amadore Hotel Restaurant Kamperduinen etc.) Restaurants (pavilion Breezand, Strandrestaurant De DAM Vrouwenpolder, Strandpaviljoen VIEW, Sand and Pepper, Brasserie Zeelust etc.)	Private businesses like hotels, restaurants and cafes located in the coastal areas are interested in their business safety against natural hazards (flooding, erosion, heavy storms) and attracting more customers. However, one of their most important businesses selling points is the landscape and its view. Therefore, agreements on the design and construction period are important for mutual agreement.
Civil Society	Zeeland Environmental Federation (ZMF)	ZMF focuses on positive impact creation towards the environment and a sustainable future for Zeeland. They monitor and strengthen the natural and cultural landscape, therefore, projects focusing on nature-based solutions gain their support.
Private	Delta Park Neeltje Jans	Interested in its business safety against natural hazards (flooding, erosion, heavy storms). Additionally, attracting more customers.

To summarize, the main stakeholders need special attention throughout project planning and implementation. The central stakeholder with the highest power and interest is Rijkswaterstaat. The most supportive stakeholder with a very high interest is the non-governmental organization ZMF. On the other hand, with high interest on the opposing side is the fishery sector. It can be seen how the interaction between all stakeholder sectors (public, private and civil society) is happening (Delta Programme, 2011).

2.5. Dutch Coastal Policies

Latest Dutch coastal policies are based on the motto "soft where possible, hard where necessary" solutions for the coastal protection. Furthermore, it is translated into multiple principles for integrated coastal development. In context of this report, the most relevant of them are: the principle of natural dynamics and the principle of spatial quality.

Moreover, looking at National Coastal Strategy, four strategies have been developed by taking into account two different lines of reasoning - one on the coastal safety and land, second on the spatial developments in the coastal zone. These strategies are following:

Smart Exploitation, **strategy 1**: all the investments are kept to the minimum, including the amount of sand.

Sustainable Choices, **strategy 2**: large sand nourishments, where it has an added social, ecological and/or economic value.

Joint Reinforcement, **strategy 3**: focus on creating a safe, attractive and economically viable coast through public – private collaborations.

Prioritizing Land, **strategy 4**: large sand nourishments, where it creates additional space for development, as the Netherlands grow in size.

Dutch use the Adaptive Delta Management, specifically adaptive pathway approach in their planning. It means, by taking smaller steps and building up the measures. In this way, the uncertainties can be easier managed and it is more cost – effective approach than the usual one time, big scale measures. In order to create a successful project, it should fit in the Dutch coastal vision and follow national guidelines.

3. Methodology

This methodology mainly focuses on three aspects: the approach, the data collection, and the data analysis.

Area analysis
A quantitative research approach is being used. Starting with boundary determination and followed by area investigation. The Voordelta is being used for the boundaries of this project, in which physical process analysis is more focused on the historical location of the Banjaard, ecological analysis is more focused on the Natura 2000 area, while stakeholder investigation covers both areas. Furthermore, the requirements for the sand nourishment(s) per discipline have been investigated.

What is the current situation regarding the area of the Banjaard?
This question is an umbrella of several steps that has to be taken to fully understand the current situation of the area. Firstly, with a simple glance in the area, the storm surge barrier can be seen. A literature study of this barrier has to be conducted, considering that the storm surge barrier is a hard structure that serves as a method of coastal protection. Understanding better about its conception and function would be greatly beneficial considering that one of the main objectives with the project is to use the nourished island as a soft method of coastal protection.

Additionally, considering that the main objective of the island is to serve as coastal protection, understanding what the current wave attack and the erosion rate of the coast is of importance. Additionally, knowledge about the bathymetry, astronomical and meteorological conditions would then we achieve by the means of conduction literature studies and analyzing the data that is available online across the different search engines and or programs

*Secondly, f*or a complete ecological analysis on the area a literature study is performed on the biotic and abiotic characteristics of the area. Additionally, literature study is performed on bio-builders, the local usage of bio-builders and their requirements, because the implementation of bio-builders is preferred.

Finally, for a good overview of the stakeholders that are present in the area, a couple steps have been taken. First of all, a spatial understanding of the area is gained by using Google Earth satellite view. It shows societies, governments and private sectors located in Voordelta and surroundings. Furthermore, more information on their relationship with the area is found through online research. The stakeholders with the strongest relation regarding the physical island location are determined. Data on their interference is collected and visualized on a GIS map.

First impression of possible locations
After the completion of the area analysis, the gained requirements from available information online and literature studies have been merged for a multicriteria approach to investigate possible sand nourishment locations. Firstly, the data on these requirements have been displayed on a GIS map and possible locations have been marked.

Data collection
In order to answer the research questions, data is collected and processed using a systemic approach. An overview of the dataset, its source, and collection method can be found in Table 3.

Table 3.
Summary of data collection.

Sub-question	Dataset	Data source	Data collection method
To what extent can biobuilders contribute to the protection, reinforcement and expansion of the initial nourishments?	Literature on area, and design specifications for artificial oyster reefs, dune grass, seaweed implementation. Expert opinion	Ecoshape, J. Wijsman (Wageningen Marine Research, Yerseke), Sciencedirect, E. Hartog (HZ University of Applied Sciences), Rijkswaterstaat, Rijksoverheid	Literature research via Sciencedirect using relevant keywords & Interviews.
What are the boundary conditions for the engineering design of the sand nourishment?	Function of island, cost limitation, bathymetry, volume necessary	Geoweb, Geomod, QGIS,	
How feasible is the design regarding societal, financial and technical aspects?	Existing stakeholders in the area, Dutch coastal policy, expert opinion	Google Earth computer program, online web, government.nl, M. Berrevoets (Natura 2000)	Desk research and interviews.

Data analysis

For the data analysis, content analysis (literature) and narrative analysis (interviews) are combined into an approach for attaining a substantiated sand nourishment design.

The collected data regarding the design will serve as input for GIS layers, which will be superimposed to determine the optimal location for the sand nourishment. All aspects of the sand nourishment, including shape, size, dimensions, biobuilder implementation, construction, regulations, maintenance, recreational usage, will be detailed from collected data. Additionally, design requirements regarding biobuilder implementation will be reviewed and discussed with experts in the field.

4. Outcomes

The desired objective for the sand nourishment is to supply the coast, North to its placement, with sediment brought by waves and tides, natural to the Voordelta. This makes the Banjaard beneficial to a large part of the Dutch coast, which currently undergoes yearly sand nourishment projects. However, first it requires experiments since the sand system dynamics in the area are not studied yet. Additionally, it is planned to persist large part of the sediment by implementing biobuilders. To determine optimal use of biobuilders also experiments in this expertise are necessary. Afterwards, the sand nourishment can be increased to allow for economic activities to take place.
Regarding the Dutch policy, the preferred plan for this project would be start with small steps but at the same time keep in mind the long-term vision.

4.1. Location

Three possible locations are picked based on physical criteria – water depth, Natura 2000 protected zones, shipping routes and finishing areas. All visualized on a GIS map (figure 22) below.

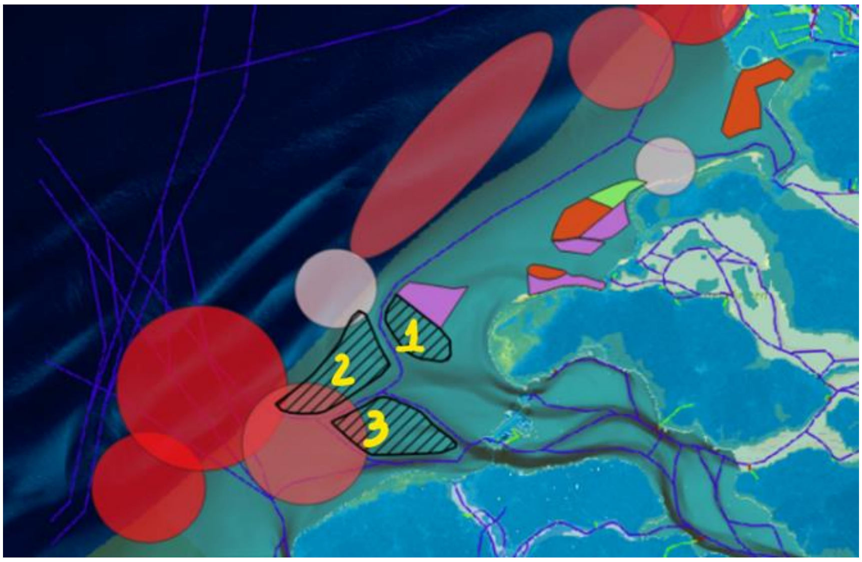

Figure 22: Possible locations based on physical aspects.
Circles displaying fishing areas (light red, non-intense; red, intense). Bird resting areas indicated by purple, orange, and green.

Furthermore, to pick one of the three possible locations the Multi Criteria Analysis (MCA) is conducted by using the following criteria:

Best suiting the desired functions. In Addition to the use of bio-builders, the clients have requested that an extra function is developed on the island. Upon further literature research and consultation with the client, the selected function is nature reserve island. Considering that this function is the selected one to be in any of the islands.

No interference with existing function. One of the criteria used to previously select the preliminary locations was interference with already existing usage of the sea such as the fishery activities, Natura 2000, etc.

Depth. Considering that the island has to be built by the means of nourishment, it is in the client's best interest to choose the island in which the depth is not unreasonably deep that becomes unfeasible.

Wave breaking potential. The primary function of the island is coastal protection. As such, the desired location has to be the one that would break the waves that attack the coast the most.

Sediment transportation. The selected island has to be the one that would create the most sediment transportation since the end goal is to have sediment moving up north from the island.

Based on the criteria importance different weights are assigned and can be visible in the table 4 below. Scores are given to each location, a description of criteria rating can be found in Appendix V.

Table 4.
The criteria weight.

Criteria	**Weight**
Best suiting the desired functions	0,10
No interference with existing function	0,10
Depth	0,10
Wave breaking potential	0,30
Sediment transportation	0,40

The evaluation process is following:

<u>Best suiting the desired functions:</u> for this criterion, locations 2 and 3 score 4 since they are fully suitable to build a nature area. Location 1 will score 2 since this location is adjacent to a Natura 2000 area. Despite the fact that the end goal is to have the island providing nature reserve functionality, Natura 2000 is an already existing and protected area that should not be interfered with. Considering that there is an expectation of re-nourishing the island every so often, this constant re-nourishing would clash with the ideology of protecting the Natura 2000 area.

<u>No interference with existing function:</u> similar to what was explained above, location 1 will score 2 since it interferes with Natura 2000. Furthermore, locations 2 and 3 will score 3 since both of them might slightly interfere with the fishing activity of the area.

<u>Depth:</u> Considering that the island has to be built by the means of nourishment, it is in the client's best interest to choose the island in which the depth is not unreasonably deep that becomes unfeasible. This criterion has a weight of 5%.

island 1→ current Banjaard between 0 and -5 meter

island 2→ between -10 and -15 meter

island 3 → between -5 and -10 meter

When looking at the depth of the three different depths island 1 to the coast would be the most logical option as this area has the lowest depth which means there will be less costs for nourishment. However, if this island is nourished it will have less effect as there is already enough sediment. While island 2 would give the highest nourishment effects, which means that the protection will be better, giving all the island the score of 3.

<u>Wave breaking potential:</u> with regards to this criterion, the islands 1 and 3 will score 2 since both of them are in the sea which naturally will provide some protection for the coast. Location 2 will then score 4 since it is the one that is the most sea wards (the most southwestern) hence breaking the waves much earlier hence attacking less the coast.

<u>Sediment transportation:</u> The main factors that transport sediments are wind and water. Both tidal currents and sea winds, especially during storms, create extremely dynamic environments.

Both tidal and wave influence of sediment transport is north which is beneficial for this project as this provides extra sand nourishment along the Dutch coast which results in a safer coast. However, to get the results it is recommended to pick the island furthest out of the coast considering there is more wave action, and the sediments would spread better and along the entire Dutch coast. Moreover, there is more space for sand nourishments hence, the island could increase in size enhancing the sediment transportation. Considering all that was above described, location 2 will score 4 and locations 1 and 2 will score 3.

The final value for each location is calculated by multiplying the weight by score. Table 6 displays these results and shows that location 2 is being selected for the sand nourishment.

Table 6.
Results of MCA.

Criteria	**Weight**	**Location 1**	**Location 2**	**Location 3**
Best suiting the desired functions	0,10	**2**	**4**	**4**
No interference with existing function	0,10	**2**	**3**	**3**
Depth	0,10	**3**	**3**	**3**
Wave breaking potential	0,30	**2**	**4**	**2**
Sedimentation	0,40	**3**	**4**	**3**
Total	100%	2,50	3,80	2,80

4.2. Sand Supplement

Yearly the Netherlands retrieves around 20 million cubic meters of sand from specific parts of the North Sea. Dredging sand has a major impact on the benthic life as it is dredged. The clouds of sand created are deteriorating the water quality and overall, this activity has a high carbon footprint. The sand is usually dredged between NAP -20 meter and the 12-meter border. This border lies exactly 12 meters from the coast. This area is specifically reserved for dredging activities.

Figure 23: Possible sand extraction locations

Within this area there are specific “search” areas where the sand has to come from. These areas are found in the figure 23 above. The locations are selected by looking at the occupation of the Dutch coast. It can be said that if there is another function (e.g., windmill park, Natura 2000, or oil platforms) the area cannot be used as a dredging area. The blue areas indicate that it is more seaward, while green indicates the area is closer to the coast. For this project the same areas can be used for sand supplementation.

Alternatives
An innovative alternative could be the sand which is dredged in the shipping routes as these routes have to stay deep enough for ships to pass. This would be beneficial for both sides as the sand will eventually be dredged anyway. Moreover, the routes in the Wadden Sea are known to silt rather fast.

4.3. Design

The island is primarily designed to relieve the Oosterscheldekering, and also to protect the coast of Burgh-Haamstede. Additionally, it serves a function of nature reserve. It is possible to design the part of the island that is above sea level as a nature reserve. Planting will take place, such as grasses, bushes and perhaps trees. This will allow not only plants but also various animal species to seek shelter in the nature reserve, to nest and breed here. The nature reserve will also serve as a resting place for (migratory) birds. There is a good chance that the diversity of plants will also be increased, because birds spread the seeds of plants and trees.

Figure 24. Island Texel, the Netherlands (Natuurmonumenten, n.d.).

Grasses and plants in particular, with their fine roots, will have a positive influence on maintaining the island. They ensure that the grains from the soil remain fixed and are not blown or washed away. By applying a nature reserve there is a part of nature with a lot of variation in the North Sea. The island can be seen from land, and many people enjoy seeing this kind of nature.

Benefits

- Positive influence on environment and climate
- Natural areas are seen as positive
- This allows areas of land to be used for other functions
- Positive influence on erosion
- Low maintenance

Disadvantages

- Low quality destination
- Economically not attractive
- Risky, do the various species survive

4.3. Shape and Volume

Based on a client's request two types of sand nourishments are considered. The first shape is a big sand plate (figure 25), and the second shape is a long and thin rectangular sand bar (figure 26). These two different designs provide the minimum and maximum volume as well as the needed costs for the nourishment.

Both islands have a slope of sand as requested by the client which will reduce wave energy before the waves reach the islands. The slope will have an angle of 1 meter of depth per 100 meter in length. The surface area of both islands is calculated by the program which was used (QGIS).

To get the depth of both island raster data of EMODnet was used. This raster data exists out of many pixels who each give different altitude data. When the island was drawn the pixels in the island were clipped and converted into vertex points as can be seen in the figure below. Each point represents the mean depth of that specific location. In the end the average of all these points is taken to calculate the volume of sand needed. As there is a tidal difference of 1.5 meter during spring tide (see Chapter 2.1.3.), and the client wants the island to be around 2 meters above water most of the time, 3 meters is added to the average depth. This means the island is during high spring tide around 1.5 meters above NAP and the rest of the time 2+ meters above NAP. As the island will be designed to reduce wave energy and erode this height will be sufficient to withstand storms.

Big island surface area:
52 082 498.280 square meters = 52.08 km2
Average Depth = -8.16 - 3 = -11.16
The average depth on the outsides of the island where the slope will be built is 13 meters.

Therefore, the volume of the big island is Equation [1].

$$52\ 082\ 498.28\ m^2 \cdot 11.16\ m = 581\ 240\ 680.8\ m^3 \qquad \text{Eq. [1]}$$

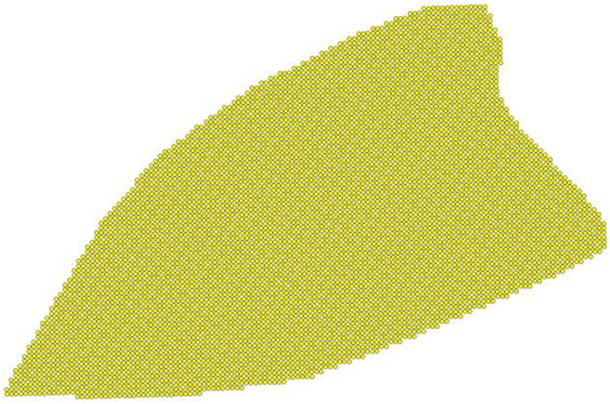

Figure 25. Point data (6226 points).

With the use of the program QGIS it became clear that 17 444 m of the island faces the west and south side. These sides experience the highest wave action and will need a slope. The volume needed for the slope is calculated below. As the island is 13 meters deep on that point (around 14 on high tide) the slope will have to be 14 meters high over a length of 14 * 100 = 1400. As it is a slope the amount has to be divided by 2.

Slope volume big island:
The slope volume of the big island is Equation [2].

$$\frac{(17\ 444\ m \cdot 1400\ m\ \cdot 14\ m)}{2} = 170\ 951\ 200\ m^3 \qquad \text{Eq. [2]}$$

Small island surface area
The same calculations are applied for the small island.

1 901 186.938 square meters (QGIS) = 1.9 km2
Average depth: -13.55 m - 3 = -16.55

Therefore, the volume of the big island is Equation [3].

$$1\ 901\ 186.94\ m^2 \cdot 16.55\ m = 31\ 464\ 628\ m^3 \qquad \text{Eq. [3]}$$

The same slope depth is used for the small island as it is located on the same spot.
Average depth is 14 meter → 100 meter per 1 meter depth = 1400 meter

Length island is 9300, width is 204 m.

For this island 2 slopes and the slope in between as it is a square are calculated and summed up to get the total volume (Equation [4, 5, 6]).

$$\frac{(9300\ m \cdot 1400\ m\ \cdot 14\ m)}{2} = \ 91\ 140\ 000\ m^3 \qquad \text{Eq. [4]}$$

$$\frac{(204\ m \cdot 1400\ m\ \cdot 14\ m)}{2} = \ 1\ 999\ 200\ m^3 \qquad \text{Eq. [5]}$$

$$\frac{\left((\frac{1400m \cdot 1400m}{2}) \cdot 14\ m\right)}{2} = \ 6\ 860\ 000\ m^3 \qquad \text{Eq. [6]}$$

Figure 26. Small island.

Total Volumes

For the big island, a total volume of 752 million cubic meters of sand is needed, whereas for the smaller island a volume is needed of nearly 100 million cubic meters of sand (See Table 7). One cubic meter of sand costs differs from 3 to 10 euros based on the location and distance between the sand mining and nourishment location (STOWA, 2013). For the cost estimation the average 6.5 euro per one cubic meter is used and displayed in table 7.

Table 7.

Overview of formulas used, and volume of sand needed for the big and small island.

Big island	**Formula**	**Volume needed**	**Costs (€)**
Surface area	$52\ 082\ 498.28\ m^2 \cdot 11.16\ m$	$581\ 240\ 680.8\ m^3$	3 778 064 425,2
Slope	$\frac{(17\ 444\ m \cdot 1400\ m\ \cdot 14\ m)}{2}$	$170\ 951\ 200\ m^3$	1 111 182 800
Total	$581\ 240\ 680.8\ m^3 + 170\ 951\ 200\ m^3$	$\mathbf{752\ 191\ 880\ m^3}$	**4 889 247 220**

Small island	Formula	Volume needed	Costs (€)
Surface area	$1\,901\,186.94\ m^2 \cdot 16.55\ m$	$31\,464\,628\ m^3$	204 520 082
Slope 1	$\frac{(9300\ m \cdot 1400\ m\ \cdot 14\ m)}{2}$	$91\,140\,000\ m^3$	592 419 000
Slope 2	$\frac{(204\ m \cdot 1400\ m\ \cdot 14\ m)}{2}$	$1\,999\,200\ m^3$	12 994 800
Slope 3	$\frac{\left((\frac{1400m \cdot 1400m}{2}) \cdot 14\ m\right)}{2}$	$6\,860\,000\ m^3$	44 590 000
Total	$31\,464\,628\ m^3$ + $91\,140\,000\ m^3$+ $1\,999\,200\ m^3$ + $6\,860\,000\ m^3$	**99 999 200 m3**	**649 994 800**

Note. Slope 3 computes the area between slope 1 and 2.

4.4. Ecological Design

Biobuilders will be used to reinforce and sustain the sand nourishment. Seaweed reduces initial wave velocity, with an added effect of vertically-mobile jackknife clams. Additional dune stabilization by dune grass and sediment deposition by the artificial oyster reef. The following section will detail the range of biobuilders proposed.

4.4.1 Shellfish reefs

Viable species
Compared to mussel shells, oyster shells are first choice in the creation of artificial reefs, a benefit to using oysters shells is that these attract oyster larvae, yield high settlement survival, and sustain high growth rates of the oyster larvae (Nestlerode et al., 2007). Moreover, oyster shells are bigger and heavier compared to mussel shells, making it a robust choice that is unlikely to be dislodged. Additionally, by providing a hard substrate, oyster reefs increase local biodiversity. Furthermore, oyster reefs dampen wave energy, and also contribute to lowering the GHG content in the water column, by storing carbon in the calcium carbonate of their shells (Scyphers et al., 2011).

Figure 28. Sketch of the inside view of the *Ostrea edulis* (FAO, 2011).

Figure 29. Sketch of the outside view of the *Ostrea edulis* (FAO, 2011).

The Pacific oyster (*Crassostrea gigas*) has been introduced worldwide to replace stocks of native oysters that have been severely depleted by overfishing or disease, or to create an industry where none existed (Helm, 2005). Figure 30 shows a sketch of the inside and outside view of this type.

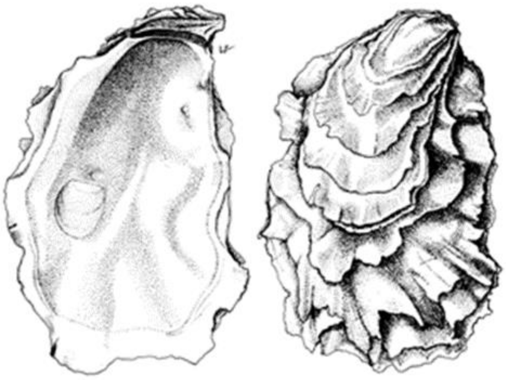

Figure 30. Sketch from the inside and outside view of the *Crassostrea gigas* (FAO, 2011).

Recently, a focus on shellfish reef restoration has emerged, specifically in regard to restoring the ecologically-extinct native European flat oyster *Ostrea edulis* (Beck et al., 2011; Lotze et al., 2006). Remarkably, in early 2016, a natural oyster reef spanning 40 hectares consisting of European flat oysters and invasive alien Pacific oysters Crassostrea gigas was found in the Voordelta (Christianen et al., 2018). Notable is that the invasive Pacific oyster facilitated the native flat oyster in attachment via its shell. The European flat oyster is a key species in its native habitat of the Voordelta (by extension the North Sea), improving biodiversity by increasing species richness, while even fostering several species with conservation interest (Christianen, et al., 2018). To decide on which species to implement a comparison has been made regarding their biotic and abiotic characteristics in the following paragraphs.

Biotic characteristics comparison

Shape

The flat oyster can grow up to 22 cm, but is often smaller. The shape of the shell can be characterized from round to pear or horseshoe-shaped, with one of the two valves being more convex than the other. The flat brim has a scaly sculpture and wavy ribs are also visible on the convex brim (Helm, 2005a) This Pacific oyster can grow up to 23 cm. The shape of the shell is very variable and sturdy. The shell shape is elongated-oval, with one valve being more convex than the other (Helm, 2005b). With regard to the shape the Pacific oyster appears to be more suitable due to the stronger and more robust form.

Reproduction
The flat oyster is a protandrous hermaphrodite, meaning that they change sex several times during their lives, with many animals being female in the third year, but male again the following year. The Flat oyster females lay 1-3 million eggs depending on their size (Oonk, 2014b). The pacific oyster, like the flat oyster, change sex several times during their lives. Although there is also hermaphroditism, where the sex cells of both sexes are active simultaneously. The reproduction of this species mainly takes place in July-August, with the females laying up to 200 million eggs. Because of these huge numbers of larvae and the long time that these larvae float in the water column before spawning, these species can spread over great distances in a short time and colonization takes place quickly (Oonk, 2014a). Considering the substantially higher offspring rate for Pacific oysters, they are considered more preferable.

Growth
Both oysters are filter feeders. Via the gills, palps and the mantle, the oyster absorbs organic material that is dissolved in the seawater (Galtsoff, 1964). The food consists of algae, diatoms, and detritus, which they filter out of the water (Oonk, 2014b).

The extent to which the flat oyster grows depends on the area. Temperature, salinity, and chlorophyll-α content, among other things, play a major role in this. In Marsin Bay, Turkey, in January 2003 through April 2003, semi-grown sized oysters with a total wet weight of 29.46 g (± 8.27) grew to a total wet weight of 41.48 g (± 10.40) (Acarli et al., 2011).

The growth of the Pacific oyster shows an annual cycle. In the Dutch coastal zone, growth occurs from April to October, with a maximum in June. From November to March the oyster does not grow and weight loss can occur (Kater, 2003). Within 18-30 months they can reach a weight of 70-100 grams and dimensions of 8-10 cm at harvest time. The older animals of this species can live for more than 30 years, reach large dimensions and considerable weight (Oonk, 2014a).

It is stated by Hartog (2021) that both species can reproduce in 2-3 years. In optimal conditions, these species can live for at least 30 years and is in principle a long-lived species (Oonk, 2014b). The pacific oyster however grows thicker and quicker, and is therefore considered more favourable.

Habitat
The Pacific and European oyster live rigidly attached to a hard surface, in the tidal area but also below the low water line in depths up to about 40 m. An aspect that is often seen in the Pacific oyster is the formation of oyster reefs. The larvae attach themselves to the shells of older congeners, eventually forming reefs with associated advantages (Oonk, 2014a). The European oyster often lives solitary, but can also form clumps of oysters that have grown together (Oonk, 2014b).

Abiotic tolerance comparison
From table 8 can be concluded that that the Pacific oyster has a wider tolerance range with regard to temperature and salinity.

Table 8.
The abiotic tolerance for the Pacific and European flat oyster for certain parameters.

Parameter	Pacific oyster	European flat oyster
Temperature (in °C)	-5 – 43, optimal between 11 – 34 where growth can take place (Kater, 2003)	3 – 30, optimal between 7 – 14 where growth can take place (Kamermans, et al., 2018)
Salinity (in ‰)	10 – 35, optimal between 20 - 25 (Helm, 2005b)	19 – 35, optimal between 25 and 35 for larvae (Kamermans, et al., 2018)
Stream velocity (m/s)	-	< 0.25 (Kamermans, et al., 2018)
Dissolved oxygen (mg/L)	-	Optimal around 3.5 (Kamermans et al., 2018)

Furthermore, as mentioned above, has the Pacific oyster been introduced into the area because the European flat oyster was struggling to withstand diseases.

Further research suggests mixed species oyster reefs hold a higher net biomass due to the spatial distribution patterns of native and non-native oysters (Zwerschke, et al., 2018).However, it is stated by Hartog (2021) that the flat oyster reproduces earlier in the year than the pacific oyster, because the pacific oyster focusses longer on flesh production. This means that when implementing a mix between the two species there is a threat that the pacific oysters consume the larvae of the flat oysters. This leads to a dominance in pacific oysters in the reef over time.

Considering the above-mentioned characteristics and arguments, the conclusion is drawn that the Pacific oyster is the most suitable for our design.

Requirements
Typically seen in shellfish reef restoration, an area is either ‘recruitment’ limited and/or substrate limited (Brumbaugh and Coen, 2009). Recruitment is referring to the oyster larvae settlement on the reef. The Voordelta presently provides the planned sand nourishment in terms of recruitment, introducing sound substrate to the planned sand nourishment will allow oysters to thrive (Christianen, et al., 2018; Wijsman, 2021).

The substrate used for the shellfish varies from baskets, nets, concrete, Biogrout blocks and gabions (schanskorven). Which substrate accommodates best for oyster settlement and growth strongly depends on local conditions, for instance, wave impact and substrate availability may hinder oyster occupancy on the reef (Ecoshape, n.d.). Additionally, given the dynamic conditions of the Voordelta, it is necessary for the artificial reefs to be fixed (Wijsman, 2021). Ecoshape (n.d.) found gabions to be most suitable in the Eastern Scheldt as these cages are comparatively strong and are able to catch oyster larvae, moreover they can fixate large oyster shells. A sheltered position in the Voordelta simulates the conditions of the Eastern Scheldt (Wijsman, 2021). Furthermore, using gabions is a sustainable option, because these gages consist of galvanized iron, which will start eroding in the sea and be gone after about 3 years. This erosion enriches the sea with iron, which has a positive influence on the ecology (Prifiharni et al., 2018).

As reproduction is required to create and enhance the oyster reef, diploid oysters should be chosen over infertile triploid oysters (Department of Primary Industries, 2016). Furthermore, these oysters are primarily to create strong and fast-growing oyster reefs. Therefore, the so-called ‘zero’ type oysters can be used. These oysters are too big for consumption. One can find these oysters in the nearby area. They can be fished from the Oosterschelde for a small price or gathered around the Wadden Islands in the North of the Netherlands (Ecomare, n.d.). It has shown to be successful behind the barrier to start with gages of 0.5 m high and 2 m wide.

To limit the number of oysters needed and to encourage growth along the nourishment upwards, cages with oysters could be varied by cages with shell substrate. Primarily, Pacific oyster (Crassostrea gigas) shells will be used as substrate for the artificial oyster reef due to its abundance and demonstrated survivability in the Voordelta (Smaal, et al., 2015; Christianen, et al., 2018). Additionally, shell fragments of blue mussels (Mytilus edulis), American razor clams (Ensis leei), and the common cockle (Cardium edule) can also provide substrate for settlement and attachment, especially by the European flat oyster larvae (Christianen, et al., 2018).

A stable dissolved oxygen content is also needed to sustain the reef. Preferably, relatively high-water velocities are maintained to replenish nutrient supply (Dunlop et al., 2017). Younger reefs experience the highest mean growth rate at 20-40% (aerial) exposure, exhibiting a bell-like curve where the optimum aerial exposure is 30%. Decade old oyster reefs show an extended optimum curve between 10-55% (Dunlop et al., 2017). Pilots in the Oosterschelde basin demonstrated lower aspect ratio oyster reefs (long and narrow) to have the strongest sediment accretion patterns (Salvador de Paiva et al., 2018). Additionally, a bed length of ±3 meters significantly reduces wave height, up to 50% far-side of the reef (Borsje et al., 2011).

Placing
The oyster reefs do not need to present a great relief, as they are not in a sediment accumulating area (Fitzsimons et al., 2019). The position of the oyster reef is essential for the survival of oyster larvae and oyster growth (Ecoshape, n.d.). The wave impact is considered too great for the oysters at the seaside of the sand nourishment; hence, the oyster reef is best placed on the side of the sand nourishment facing the coast. The depth at which the oyster reefs are placed may be found experimentally, where an optimal aerial exposure time of 20-40% leads in determining the depth at which the oysters shall be placed.

4.4.2. Seaweed

Seaweeds and marine plants are capable of dissipating wave energy. A study shows that benthic seaweed can reduce the overall wave-energy flux on the shore by 6-18% over 116-131 meters (Denny, 2021). Therefore, they protect the shores from erosion and flooding as well as providing shelter for economically and ecologically valuable animals such as fish, shrimp, and crabs (Denny, 2021). Furthermore, seaweed species themselves can be harvested and possess an economic value by their appliance in different sectors like the food and cosmetic sectors (NIOZ, n.d.).

Viable species
North Sea seaweed species to consider are *Ulva lactuca*, an edible green algae; *Saccharina latissima*, known as the sugar kelp; *Palmaria palmata*, an non-native red seaweed; and *Laminaria digitata*, a large brown kelp species used in some cosmetics (NIOZ, n.d.).

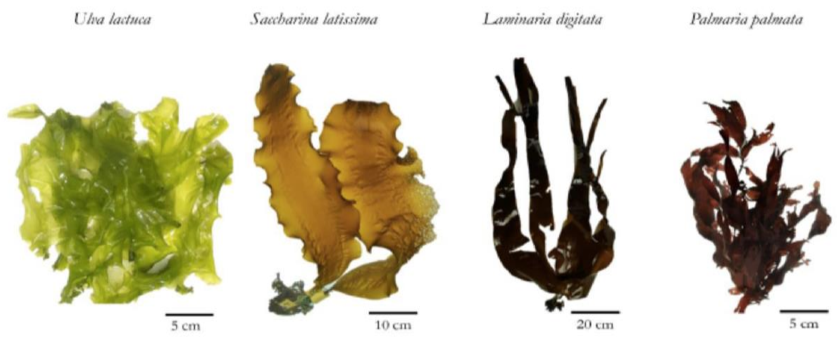

Figure 31. North Sea seaweed species (NIOZ, n.d.)

The main criteria to fulfill is the reduction in wave energy. Strength and height of the seaweed play an important role. *Saccharina latissima*, *Laminaria digitata*, and *Pamaria palmata* are kelp species and therefore very strong compared to *Ulva lactuca* (NIOZ, n.d.). Among these species, Laminaria is the most robust species. The growing period is from September until May, and it has already been cultivated under North Sea conditions. The sugar kelp, Saccharina, grows in the same period and is also to be found robust, see appendix IV for a complete overview of the growing conditions of the North Sea seaweed species. Additionally, sugar kelp is more susceptible to herbivores and a better substrate for Bryozoa and other colonizers than the Laminaria. The Pamaria kelp species has not been cultivated under North Sea conditions (Van den Burg et al., 2013). For the design *Saccharina latissima* has been found to be most suitable. This species can grow up to 4 m long. It lives for 2 to 4 years (White & Marshall, 2006).

Requirements
The *Saccharina latissima* grows in a depth less than 30 m. The maximum depth of the slope is foreseen to be 13 m and therefore suitable. Furthermore, it needs a hard substrate to attach to (NIOZ, n.d.).

E. Hartog from the aquaculture research group of HZ explained that it would be best to work with a vertical net structure, with seaweed planted on, as a first breakwater at the largest depth at the beginning of the slope. After these structures one could place cocosnets seeded in with the seaweed, horizontal on the slope. Seaweed solutions A.S. (n.d.) shows to be successful with vertical farming structures in the North Sea, see figure 32. Additionally, Wageningen Marine Research (2019) has conducted research regarding the ecological development in these North Sea cultures and has stated that a high number of individuals, mostly mussels and amphipods, are attracted and established on the seaweed and the structure, enhancing the area's biodiversity (Bernard et al., 2020) .

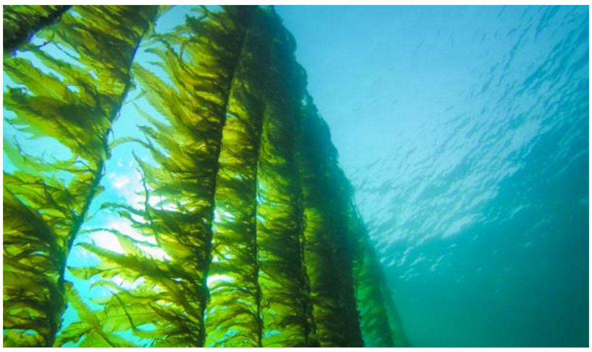

Figure 32. Vertical rope system to cultivate *Saccharina latissima* in the North Sea (Seaweed solutions A.S., n.d.).

Using nets of coconut fiber is an innovative and sustainable method for seaweed cultivation in the North Sea and research concerning the performance is currently taking place (North Sea Farmers, n.d.). This project called 'Wier & Wind' is co-financed by the Interreg programme of the European Union, which will run from July 2019 to June 2022 (Norther, 2020).

4.4.3. Dune grass

Sand dune stabilization is a coastal management procedure designed to prevent erosion of sand dunes (Borsje et al., 2011; Feagin et al., 2015). Part of this principle is using vegetation to stabilize and reinforce the dune, to reduce the impact of wind and water. These plants must withstand saline, nutrient-poor and harsh hydro-sedimentary conditions in the zone between the high-water line and the more stable backshore (Feagin et al., 2015). Furthermore, the vegetation must be able to grow in moving sands, which is done by spanning a broad root system and accumulating sand via their foliage, increasing the overall sand-binding capacity (Bryant et al., 2019; Feagin et al., 2015).

Common species with a high dune stabilization capacity include marram grass (*Ammophila arenaria*), sea sandwort (*Honckenya peploides*), sea rocket (*Cakile maritima*), and cordgrass (*Spartina coarctata*). It is most natural to use native species such as marram grass and sand ryegrass (*Leymus arenarius).*

Requirements/conditions
See Appendix III for the properties of, and requirements for, the aforementioned plant species.

4.4.4. Atlantic Jackknife clam

The Atlantic Jackknife clam (*Ensis directus*) arrived in the Netherlands around 1978. It is to be assumed that it has been transported with the ballast water from America. Nowadays, it can be found along the entire Dutch coastline. This invasive species is only preyed upon by a very few fish and bird species. Mostly it is consumed by bacteria after their death. Therefore, this species holds a strong position in the Dutch marine ecosystem (Philippart, 2020).

Figure 33. The Atlantic Jackknife clam (*Ensis directus*) (Smith, 1874).

The maximum length is about 20 cm over a lifespan of 7-8 years. This species is unique in terms of their mobility. They have muscular feet and thickened mantle structure giving them the capacity to move through their environment. They are commonly found immediately at the sediment surface and in some cases with their posterior end projecting 25 to 50 mm above the sediment surface. They are very sensitive to surface vibrations. When disturbed they dig into the sediment with surprising speed. By doing so, they provide structure to the sand body when velocity is high (Dale, 2013). Therefore, they will be implemented into the design. Due to their preference of shallow waters, it would be best to place them above the seaweed on the slope, where they can move with the tides.

4.4.5. Design

Figure 34 illustrates the side view of the long-stretched sand nourishment design with the above-mentioned bio builders implemented.

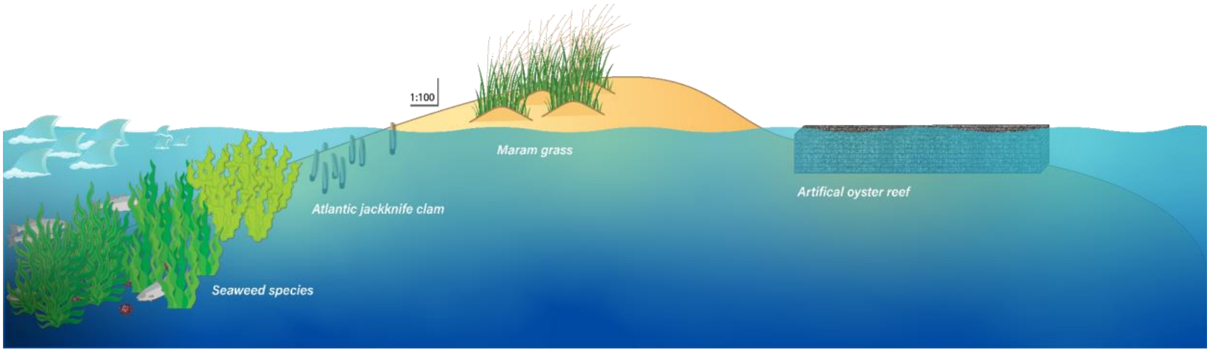

Figure 27: Visualization of biobuilder implementation on the sand nourishment. Seaweed (left) reduces initial wave velocity, with an added effect of vertically-mobile jackknife clams. Additional dune stabilization by dune grass and sediment deposition by the artificial oyster reef.

4.5. Environmental value

Nowadays the environmental value of an area is becoming an important parameter (Agbejule et al., 2004). For example, companies that can provide quality goods or services and produce environmentally friendly products in a sustainable way tend to get bigger shares and returns in the market. Although the environment becomes more important, its value increases simultaneously. To get a valid estimation of the value of an area two different dimensions play a role.

Concept of value

Considering the environment is a common good and not “possessed” by anyone it is impossible to estimate a concrete value. Different stakeholders have different views on the environment which is valued based on their personal beliefs. For example, there is a clear distinction between living- and non-living resources. It is commonly accepted that respect for life is more important than non-living elements. This aspect can be grounded on either religious or philosophical viewpoints (Erikstad et al., 2008).

Analysis of key environmental parameters

The key environmental parameters alter per area. It is essential to evaluate the level of importance and influence in order to estimate the value. For example, biobuilders provide a high biodiversity resulting in a thriving ecosystem. In addition, they contribute to coastal protection as they break incoming waves before they reach the coast. The combination of both functions creates a high environmental value.

When looking at the Banjaard it is preferred to have a relatively high environmental value. Therefore, provisioning, regulating and cultural values of the project are gathered in table 9 below. By creating this value other values are lost, therefore table 10 shows the losses and possibilities to mitigate them.

Table 9.
Different ecosystem services and the created value of the Banjaard.

Ecosystem Service	Value
Regulating	Biobuilders create a new habitat enhancing surrounding ecosystem
	Organisms improve water quality in the area
	Island breaks the wave energy and a result provide security from flooding
Cultural	Educational value. Possibilities for research.
	Restoring the historic Banjaard island
	First biobuilders at the Netherlands coast in the open North Sea.

Table 10.
Environmental and economic loss and its mitigation by realizing the project

Sector	Loss	Loss Mitigation
Environmental	Lost marine seabed environment by placing the sand	A new land environment will be created on top of the island.
Economic	Reduced area for fisheries	Biobuilders and new habitats around it will enhance the ecosystem. Healthier conditions might increase fish reproduction leading to an increase in fishing

4.6. Monitoring

The project aims to allow wind, wave, and current dynamics to form the landscape in the sea and along the coast. It is hard to predict how the morphology will change, therefore, large focus should be put specifically on monitoring these processes. It is preferred to make the maximum use of the natural processes with the assistance of biobuilders or different kind of natural objects to support the sedimentation. The optimal time span for monitoring and evaluating is approximately 10 – 15 years. It can be led by professional organizations, such as, EcoShape or Deltareas, since both of these organizations have experience with these kind of projects along Dutch coast. A partnership between them and research institutes will be necessary, since ecological monitoring should be done in-depth by specialists in this field.

Developmental phase

If the evaluation of the project proves its success, the main phase can start by building up sand in greater extent. Keep monitoring the changes and look for suitable market. In meanwhile, it is possible to start new pilot projects in near locations.

Main focus during this phase is on most suitable economic activities and attracting the market. Some of the possibilities are to focus on energy, aquaculture, recreation etc. More details on possibilities are described below.

Energy Island - Tidal turbines and wind turbines
In order for the island to make a positive contribution to the environment, it is possible to place a tidal turbine on the island. This is a turbine that generates energy as water flows through a channel, which is guided by the difference in water height due to ebb and flow. Several studies have been done on this, and this technique has already proven itself. Locations such as the Eastern Scheldt storm surge barrier are perfect for this technique because the turbine could be placed directly. The water flows through the doors of the barrier, so there is already a kind of a spillway.

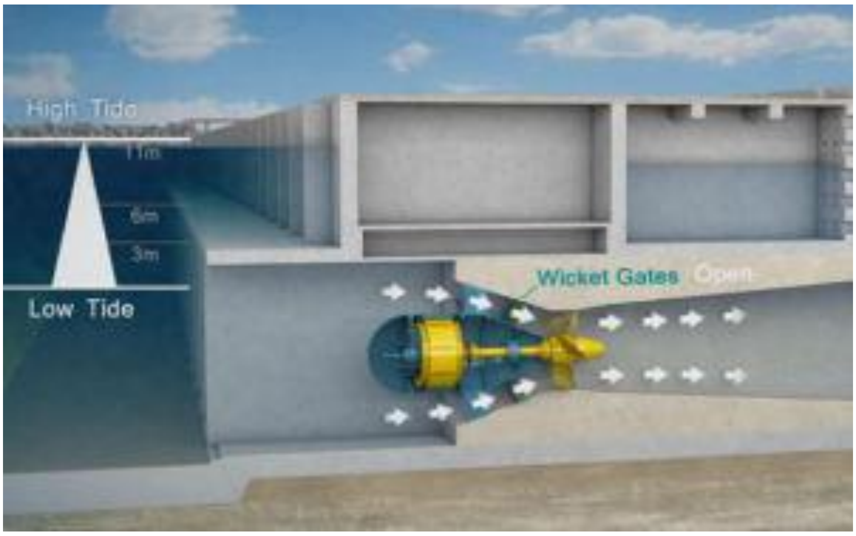

Figure 34. Side section tidal turbine (Deltares, n.d.).

Because the island is placed close to the coast, it is relatively easy to bring the generated power ashore. Because a power channel has to be built, a hard structure is created, which will also have a positive influence on resisting sand erosion. So, there will be less erosion than when there is no support by means of a hard structure.

It is also possible to place wind turbines on the island. In this case, a heavy foundation will be placed in the island to support the loads on the wind turbine. Therefore, a rigid construction will also be applied, which has the same positive characteristics as described above.

Benefits

- A positive contribution to the environment, through blue energy
- Long service life
- Erosion resistant thanks to hard construction
- Economically sound
- Efficient because there is always current and wind

Disadvantages

- Expensive in construction
- Vulnerable to heavy conditions

- Maintenance sensitive
- Windmills spoil the view

Aquaculture - Shellfish
To protect the island from the impact of waves, and thus erosion, it is possible to deploy bio-builders such as oysters and mussels. These occupy certain man-made cages that are placed around the island, resulting in sand entrapment. Besides sustaining the island, it is also possible to give the oysters and mussels an extra function on the island. It is possible to create a plot where the oysters and mussels can be cultivated for consumption. If this function is realized, less fishing area will be lost in the North Sea as a result from the sand nourishment because the area will retain its function or even expand, there is little fishing currently in the area where the island will be constructed.

Figure 35. Oogst Zeeuwse mosselen, Zeeland. (Provinciale Zeeuwse Courant, 2021).

The oysters and mussels require few facilities, making it a fairly simple culture. This is especially true if enclosed plots are used, as would be possible on or around the island. Since the mussels are harvested by ship, no connection to land –other than water– is needed.

Advantages
- Relatively cheap to build
- Easy to expand
- The area will have an interesting function for stakeholders
- Sediment entrapment (accretion)

Disadvantages
- Only interesting for a few companies
- Economic demand uncertain

Recreation
To increase the spatial quality of the newly created land it can serve a public space function. Public space with recreational activities has a potential to increase the value of the area and bring opportunities for economic activities.

Simple recreation

It can be done by simple, nature-based activities. Nature trails, as in Figure 36 below, bird-watching places and towers; the view from the towers could capture the Banjaard and also the Nature 2000 area. Additionally, it is easy to implement a wild camping place.

Figure 36. Trail on new nature island Marken Wadden, Netherlands (Civic Architects, n.d.).

Intercept waste - Catching Plastic

There is a lot of waste, especially plastic, lying around on the ground. If it is not cleaned up, it almost always ends up in the oceans. Because it is difficult to get the plastic out of the oceans, and there are not yet many working systems for this on a larger scale, the amount of plastic in the oceans is increasing. It is possible to build a construction on the island that stops and collects the plastic. There are several options for this. The first option is a design by Boyan Slat. This is a floating tube, which moves across the ocean. This design has already been tested, with positive results. This system has been tested on the open sea, but in our case it will be a more stationary situation, attached to the island.

Figure 37. Floating tube of Boyan Slat, The Netherlands (Recycle Valley, n.d.).

Another option is a relatively new idea. This involves a tube lying on the bottom, which blows air bubbles upwards. The advantage of this is that animals and ships can simply pass through the bubbles, but the plastic remains behind them. This idea is now being applied in rivers. The idea has been tested extensively with successful outcomes. The screen is placed so that it guides the plastic to the bank, from where it can be removed.

Figure 38. The Great Bubble Barrier in action (Voor de Wereld van Morgen, 2018).

Benefits

- Positive for the environment
- Good for image
- Relatively cheap to build

Disadvantages

- Not financially attractive
- Not maintenance friendly, continuous work needed

5. Conclusion

The aim of this report is to design a sand nourishment, reinforced by nature, in the Zeeuwse Voordelta to contribute to protection of the Dutch coast.

The second location (Figure 22) is considered the best island design, based on costs, suitability for desired function, level of interference, depth, wave breaking potential, and sediment deposition. Disregarding construction-related boundaries, a large sand nourishment at this location would require roughly 750 million cubic meters of sand and cost nearly 5 billion euro. Of lower magnitude, a dike-shaped nourishment would need only under 100 million cubic meters of sand, and require a 650-million-euro investment. To reinforce the island using building with nature techniques, artificial shellfish reefs can be implemented consisting of the Pacific oyster (*C. gigas).* Seaweed demonstrates a wave-dampening effect, for this sugar kelp *(S. latissima)* is found to be most suitable. The seaweed can be cultivated on natural nets made of coconut fiber, increasing the overall sustainability of the island. The wave dampening effect from seaweeds can be augmented by the vertically-mobile Atlantic Jackknife clam *(E. directus).* Lastly, dunes can be stabilized by naturally-occurring species such as marram grass *(A. arenaria)* and sand ryegrass *(L. arenarius)*. The island initially assumes a natural function, already provided by local sand banks. Long-term, the island may be assigned extra functions such as aquaculture or energy generation.

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Appendices

Appendix I – Overview of recreation activities in the Voordelta area.

Activity	**Area**	**Period**
Kite surfing	Oostvoorne, Rockanje, Ouddorp, Brouwersdam, Neeltje Jans, Breezand.	All year round, especially in the summer half year
Wind surfing	Brouwersdam, Ouddorp.	All year round, especially in the summer half year
Golf surfing	Domburg, Ouddorp.	All year round, especially in the summer half year
Kite buggyen	Beach of Voorne, Ouddorp, Brouwersdam, Banjaard	All year round, especially in the summer half year
Sailing	Sailing ditch from Stellendam (not within resting areas)	All year round, especially in the summer half year
Motorised sailing	Haringvlietmonding, Brouwersdam, in the Brouwershavensche gat	Summer (June-Aug)
Sport fishing	Ditches in the Sourthern part of the Voordelta at shipwracks	Summer half year
Sport fishing (bigger scale)	Ditches in the Sourthern part of the Voordelta at shipwracks	All year round
Visiting of sandbanks	SvV, HP, BvdO, MP, VP, not outside of BBG	May-Sept
Diving	Spuisluis, Trailerhelling Blokkendam, Duitse landingsboot, at ship wracks	All year round
Sailing in small open ships	In small amounts, haven't been spotted in the resting areas	Un-known
Canoeing, sup and rowing	Brouwersdam and Vissershoek	Summer half year

Appendix II – Overview of recreational activities permit obligation.

Activity	Permission in bottom protection areas	Permission in resting areas	Permission in the rest of the Voordelta
Kite surfing	Exempt from licensing requirement under the condition that men follow the guidelines as recorded in the Nb-law.	No	Exempt from licensing requirement under the condition that men follows the guidelines as recorded in the Nb-law.
Windsurfing, golf surfing	Exempt from licensing requirement under the condition	Limited, with extra mitigation	Exempt from licensing requirement under the condition

	that men follow the guidelines as recorded in the Nb-law.		that men follow the guidelines as recorded in the Nb-law.
Kite buggying	-	No	Exempt from licensing requirement under the condition that men follows the guidelines as recorded in the Nb-law.
Extreme beach sports (beach sailing, flyboarden)	-	No	Exempt from licensing requirement under the condition that men follow the guidelines as recorded in the Nb-law.
Sailing, motorised sailing, sport fishing	Yes with permit	Limited, with extra mitigation	Yes with permit
Diving	Yes with permit	Exempt from licensing requirement under the condition that men follow the guidelines as recorded in the Nb-law.	Yes with permit
Canoeing	Yes with permit	-	Yes with permit
SUP	Yes with permit	Exempt from licensing requirement under the condition that men follow the guidelines as recorded in the Nb-law.	Yes with permit
Visiting of sandbanks	Yes with permit	No	Yes with permit
Usage of the beach	-	No	Yes with permit
Coastal development (beach houses (holiday), beach pavilions, and rescue posts)	-	No	Yes, if Nb-law procedure is applied

Appendix III – Specifications dune grass species

Name (popular name)	Shore protection	Regions	Environmental conditions	Soil type	Propagation	Planting	Other properties
Ammophila arenaria (Marram grass, European beach grass)	Pioneer species with great sand-binding and sand-trapping capacity. Initiates foredune growth on flat beaches. Roots extend one to several meters deep. Stimulates the development of high/steep foredunes vulnerable to erosion and blow-outs.	Native to southern/wester n Europe. Introduced: N. America, S. Africa and Australia. A similar species Ammophila breviligulata (American beach grass) is native to N. America.	Resistant to frost and temperatures up to 50ºC. Tolerates moderate salt spray, drought and low water table.	Well-drained, poor, mobile sandy soils, calcareous preferred. Growth stimulated by sand burial (<1 m/year). Declines in absence of new sand supply.	Rhizomes spreading horizontally and vertically.	Seedlings in dry sand with moist at about 10 cm below surface. Minimum planting depth about 30 cm. Period: late fall, winter, and early spring months; temperature between 0 and 15 ºC.	Invasive species in some countries where it inhibits growth of native plants. Fixes nitrogen. In stabilized dunes, Ammophila is replaced by other species, such as Festuca rubra (red fescue grass).
Cakile Maritima (Searocket)	Pioneer species settling close to the high-water line. Forms low erosion-sensitive hummocky dunes. Single or clumped plants accumulate sand and add organic matter to the soil, thus providing more amenable habitats for the establishment of secondary colonizers.	Cakile maritima native to Europe and N. Africa. Introduced in Australia, New Zealand, Japan. Cakile edentula native to USA.	Resistance to salt spray.	Grows best on moist or wet beaches, alkaline preferred.	Species with seed dormancy. Efficient settling of seedlings, rapid growth, ability to flower under a range of photoperiods. Large numbers of fruits, short life cycle. Seeds can be dispersed by currents.	By seeding or by cuttings.	Invasive species. The plants are sensitive to fungi and are consumed by a variety of phytophagous insects and vertebrates; in response, Cakile manufactures glucosinolates that provides some protection.

Leymus arenarius (Sand Ryegrass, Sea Lyme grass, Lyme grass)	Pioneer species on beach, embryo dunes and foredunes; dune-building grass, stabilizing drifting sands and eroding fronts. Thrives on sand deposition; replaced by other species when sand deposition ceases. Strong similarities with Elymus farctus.	Native to the coasts of northern and western Europe and Iceland. Closely related to Leymus mollis of the northern coasts of North America.	Prefers cool climate but tolerant of hot weather. Highly salt tolerant. Sunny exposure or half-shade.	Grows on low embryo dunes, on a sandy substrate , loam (silt) or clay.	By rhizomes.	Sowing of seeds in sheltered fertilized areas.	Takes up nitrogen into its root system. Changes soil conditions and microclimate, which become more suitable for later successional species. Invasive species in some countries.

Note. Table reference: Dronkers & Hesp (2021).

Appendix IV- Overview of growing conditions of North Sea seaweed species

Group:	Brown algae	Red algae	Green algae
Species:	***Laminaria digitata, Saccharina latissima***	***Palmaria palmata***	***Ulva lactuca***
Growth season	September-May	Presumably summer	Summer
Optimal water temperature	<18	15-20	15-20
Wave conditions		Uncertain whether it can withstand harsh conditions	Uncertain whether it can withstand harsh conditions
Nutrient requirements	During wintertime, it just stores nitrogen in its tissue, to produce proteins during early spring	Uses all nitrogen sources during summer	Uses all nitrogen sources available in warmer water
Grow speed	Up to a daily increase of DM of 20% under optimal conditions	Up to daily increase of 35% of DM under optimal conditions	Up to a daily increase in DM of 50% under optimal conditions
Yield/ha (DM)	15	15-20	20
Vulnerability diseases	Colonised by several organisms, thus hindering its growth during spring and summer	Unknown	It tends to be free floating under harsh conditions
Production risks	Fast degradation in spring (***Saccharina latissima***)	As semi perennial seaweed it is unsure whether the plant will recover after wintertime	Sudden disappearance

Note. Table reference: Van den Burg, et al. (2013)

Appendix V – MCA Criteria Rating

Table 5.
A description of the criteria rating.

Criteria	Ratings			
	1-poor	**2-fair**	**3-good**	**4-Very good**
Best suiting the desired functions	It does not fit the desired function	It slightly fit the desired function	It fits the desired function	It exceptionally fits the desired function
No interference with existing function	It interferes with a lot of the existing functions	It interferes with a considerable number of functions	It interferes with very few functions	It does not interfere with the functions
Depth	It is difficult to find the materials and professionals	It is fairly difficult to find the materials and professionals	It is easy to find the materials and professionals	It is extremely easy to find the materials and professionals
Wave breaking potential	It provides no wave breaking potential	It provides some wave breaking potential	It provides good wave protection	It provides a lot of wave protection
Sedimentation	it will have the least sediment movement	It will have some sediment movement	It will have good sediment movement	It will have the best sediment movement

Appendix VI – Project Planning

			Meeting Vana	Team meeting	Meeting: names	hand-in deliverables	Editors	Teams
Week	Deliverables	Who	Mo	We	Th	Fr	Sa	Su
46	Area analysis	Civil & Socio	Meeting Vana 14:45-15:30		Meeting: Paula & Emily Set up methodology	Meeting: Johan & Emily, continue methodology		Meeting: Johan & Emily, check deliverables, edit and send progress to Vana
46 47	Planning	Johan & Emily						
	Methodology	Civil, Socio & Eco						
	Methodology (edit)	Johan & Emily	Team meeting 12:30-13:00	hand-in deliverables	edit new deliverables in draft & give feedback by editors	opportunity to hand in updates <12:00	Team review draft	Remarks are considered and processed before being sent to Vana by editors.
47 48	Planning	Johan & Emily	Meeting Vana 14:45-15:30		Meeting: Emily, Denisy & Tijmen for Planning and sharing concepts	updates are reviewed in placed in the document by editors > 12:00		
	Data-collection GIS map	Tijmen	Team meeting 15:30-16:00					
	Literature review: shape and functions	Civil						
	Contact experts for interviews	Civil, Socio & Eco	Meeting: Paula, Tijmen, Emily and Johan for planning					

	online data collection analyses	Socio	Meeting: Paula & Tijmen for Socio					
	Prepare interviews	Civil, Socio & Eco	Meeting: Johan and Emily for planning					
	Hold interviews	Civil, Socio & Eco	Meeting: Paula & Tijmen for Socio	hand-in deliverables	edit new deliverables in draft & give feedback by editors	opportunity to hand in updates <12:00	Team review draft	Remarks are considered and processed before being sent to Vana by editors.
	Literature review: erosion	Civil	Team meeting 12:30-13:00			updates are reviewed in placed in the document by editors > 12:00		
	Start calculations	Civil	Meeting Vana 14:45-15:30					
	Process interviews	Civil, Socio & Eco	Team meeting 15:30-16:00					
48 49	Data-collection GIS map	Tijmen						
	Incorporate bio-builders in the design	Eco & Civil						
	Nourishment realization, calculations	Civil						
	Hold interviews	Socio & Eco	Meeting: Paula & Tijmen for Socio	hand-in deliverables	edit new deliverables in draft & give feedback by editors	opportunity to hand in updates <12:00	Team review draft	Remarks are considered and processed before being sent to Vana by editors.

	Nourishment realization, calculations	Civil	Team meeting 12:30-13:00			updates are reviewed in placed in the document by editors > 12:00		
49 50	Process interviews	Socio & Eco	Meeting Vana 14:45-15:30					
	Data-collection GIS map	Tijmen	Team meeting 15:30-16:00					
	Next steps finalisation	Socio & Eco	Meeting: Paula & Tijmen for Socio	hand-in deliverables	edit new deliverables in draft & give feedback by editors	opportunity to hand in updates <12:00	Team review draft	Remarks are considered and processed before being sent to Vana by editors.
	Extra's: sand sources, etc.	Civil				updates are reviewed in placed in the document by editors > 12:00		
	Create GIS map with the final design	Tijmen	Team meeting 12:30-13:00					
50 51	Socio analyses	Socio	Meeting Vana 14:45-15:30					
	Nourishment realization, calculations	Civil	Team meeting 15:30-16:00					
	Finalizing draft report	Editors (/all)						
	Feedback on finalized draft	All	Team meeting 12:30-13:00	hand-in deliverables	edit new deliverables in draft & give feedback by editors	opportunity to hand in updates <12:00	Team review draft	Remarks are considered and processed before being sent to Vana by editors.
51	Process feedback	All	Meeting Vana 14:45-15:30			updates are reviewed in placed		

52						in the document by editors > 12:00		
	Start on presentation	All	Team meeting 15:30-16:00					
	Christmas holiday							
52	-							
1	*Christmas holiday*							
1	-							
2	Presentation	All						
2								
3								
	Monday 17 jan: poster presentation							