(Re)construction of the Marker Wadden:
an example of applying land reclamation for nature restoration

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Abstract

Vegetation plays a key role in diversity and structure of ecosystems throughout all trophic levels. To develop specific marshland habitats from newly reclaimed land using mostly mud and silt instead of sand is still poorly understood, yet achievable. The Marker Wadden is proof of that.
Using a retrospective study of the island's construction and a field study, we reveal how the Marker Wadden turned from a silty barren wasteland to the vegetated nature reserve it is today, and document what steps were taken to achieve that and how these activities finally resulted in the desired reed marsh (although not everywhere). In addition, we take an in-depth look at two dynamics that the Marker Wadden and its vegetation is subject to: water-wind and elevation.
We document how the islands were built in a phased manner, starting with the main island (comprising of islands A and B) and island D1 that were finished in 2017 and subsequently the other nature islands C, D2 and D3 that were finished in 2019/2020. Reed marsh development was stimulated through reed sowing, exclosure placement, willow removal and water management. Reed sowing on its own was found to be not very effective towards developing a reed marsh. However, reed sowing in combination with strategic exclosure placement to reduce grazing pressure from graylag geese strongly increased successful reed bed establishment after at least two years. Regarding the water-wind dynamics, we found that the water in the Markermeer behaves according to Bretschneider's equations. However, this behavior is not possible within the Marker Wadden as the maximum fetch length there was found to be lower than 2 km. Therefore, the Marker Wadden islands are sheltered from wave action. In our elevation analysis, we found that the six most major vegetation types appear in the following elevational gradient from lowest to highest: *S. congestus*, bare ground, *Typha sp.*, *Salix sp.*, *E. hirsutum* and *P. australis*. In addition, we found that willows occupy a wide niche.
These findings elucidate that a reed marsh can be developed on freshly reclaimed land but it takes a significant amount of time (>5 years) and intervention effort. The Marker Wadden are still in an early developmental stage. Reed marshes did not spontaneously develop, but reed material sowing with exclosure placement are effective ways to produce one. To maintain the reed marsh though, requires careful consideration and insight in changes in biogeomorphological processes that the Marker Wadden are subject to. As of now, the Marker Wadden compartments are sheltered from wave action and they are at a preferable elevation for reed marsh development. However, especially taking climate change into consideration, it will be a necessity to carefully monitor wind tide mechanics and expected soil subsidence to sustain reed marsh development in the future.

1. Introduction

Habitat suitable for various wildlife species is declining worldwide at an alarming rate to make room for uses such as agricultural intensification or infrastructure. Fortunately, many restoration efforts aim to revert such trends. One such initiative is the Marker Wadden, an artificially constructed island archipelago in the Markermeer (Netherlands) that aims to develop novel breeding and foraging habitat for marshland birds.

Land reclamation is not an unknown concept in the Netherlands but it was generally used for agriculture, housing and industry. The Marker Wadden is the first land reclamation effort with nature as the main subsequent use. The Marker Wadden story starts at the end of the 19th century when plans were made to close off the Zuiderzee estuary by constructing dikes and draining the water to produce land from the former sea floor. These plans were collectively called the Zuiderzee Works (NL: Zuiderzeewerken). In 1932, the Afsluitdijk was realized which permanently separated the Zuiderzee - henceforth known as the 'IJsselmeer' - from the Noordzee. From this point on, several land reclamation projects were realized in the IJsselmeer which notably resulted in the creation of the province Flevoland (combination of the North-East-, East- and Southern Flevopolder) and the Wieringermeer in North Holland (figure 1). In 1975, the Houtribdijk was completed separating the IJsselmeer into a northern and a southern part. The northern part would remain to be known as the IJsselmeer, whereas the southern part was supposed to be reclaimed as the 'Markerwaard'. The latter plan, however, was never realized due to doubts in desirability and feasibility. In addition, the area had already become an important feeding area for shorebirds and over time, the contribution of the lake to nature was valued over the original intended use of the Markerwaard. Thus, the southern part came to be known as the Markermeer (Van Lier and Steiner 1982).

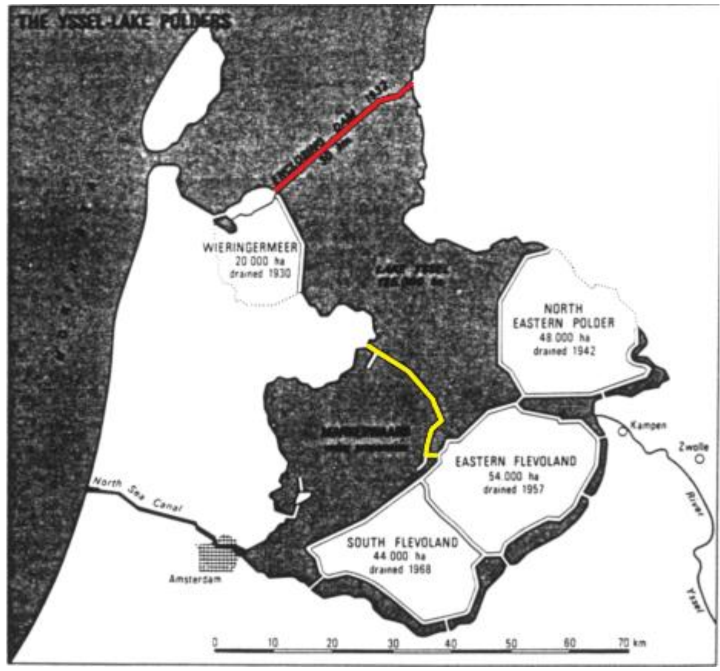


Figure 1. The Zuiderzee Works. Highlighted are the Afsluitdijk (red) and the Houtribdijk (yellow). Above the Houtribdijk is the IJsselmeer, below is the Markermeer. (van Lier et al)

With the Markermeer remaining an aquatic environment, it also remained an important foraging area for shorebirds. However, the ecological value and water quality of the Markermeer declined over the years. Because the lake lost most of its natural shores to land reclamation and flood protection measures, sediment is unable to be deposited in shallows. As a consequence, a thick layer of silt covers many areas of the lake bottom, suffocating benthic organisms. Additionally, wave action increasingly causes sediment to be churned up and float in the water, leading to increased turbidity which obstructs light from reaching the lake bottom. The resulting reduction in amount and quality of primary production by water plants and algae restrict trophic transfer in food webs (Noordhuis 2010, 2014, de Lucas Pardo et al. 2013, de Lucas Pardo 2014).

To cope with these problems, the Marker Wadden initiative was developed, an archipelago of artificially constructed islands built from the excessive silt and sand in the Markermeer. The project is an initiative of the Dutch nature conservation organization “Natuurmonumenten” to improve the ecological value of the Markermeer. The islands are developed in order to improve the water quality of the Markermeer as well as provide additional habitat for birds and fish to forage and breed, but they are also partially opened for recreational purposes and research.

The public tender for the construction of the Marker Wadden was won by Boskalis, commissioned by Natuurmonumenten and Rijkswaterstaat (the Dutch Directorate-General for Public Works and Water Management). Boskalis is a Dutch dredging company involved in construction of maritime and freshwater infrastructure. The Marker Wadden was built in the east section of the Markermeer, about 3 km away from the Houtribdijk and 5 km from Lelystad (figure 2). The definitive design of the Marker Wadden phase I was completed in December 2015 (appendix A). In phase II, more islands will be built to the northeast of the phase I Marker Wadden islands, though construction of the phase II islands would only commence in 2021. For convenience, we will refer to the Marker Wadden phase I simply as “Marker Wadden” in this thesis, since the phase I Marker Wadden islands are the only existing islands by the time this thesis was written.

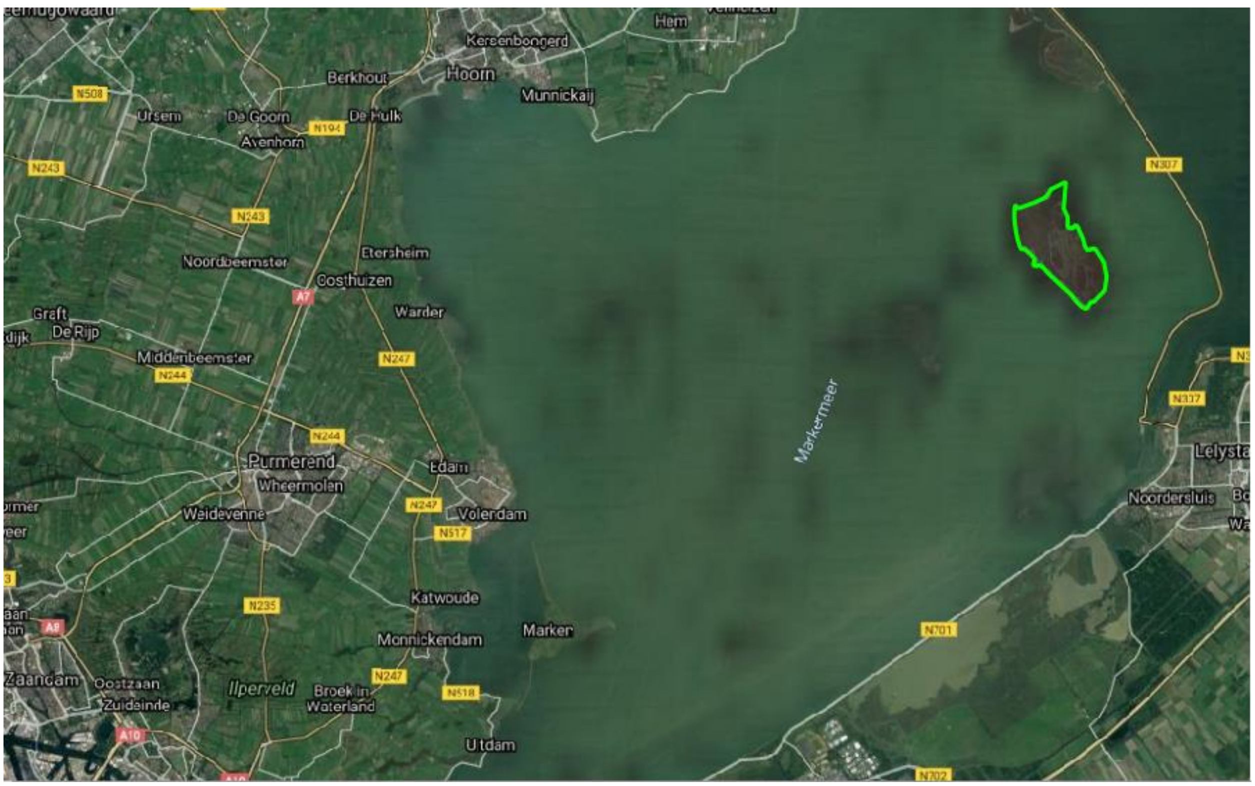


Figure 2. *Position of the Marker Wadden (outlined in green) in relation to the Markermeer. Directly to the east of the Marker Wadden lies the Houtribdijk, connected to Lelystad.*

The design of the Marker Wadden was, as the name suggests, based on the Wadden islands found in the North of the Netherlands. On the Wadden islands, sandy beaches and dunes protect the inland from wave action in the south- and northwest. In the lee behind it lie the marshes and mudflats. As is clear from the position of the Marker Wadden in relation to the contour of the Markermeer, the distance that a wave can travel is greater from the southwest than from the northeast. This distance is called a fetch length. Generally speaking, the higher the fetch length, the more waves can accumulate energy and become higher (Saville 1954). This means that the Marker Wadden will endure the fiercest of waves from the southwest much like the Wadden islands. This has been accounted for in the design of the Marker Wadden, as the islands are protected by two straight sandy shores on the northwest (N1/N2 in figure 3) and southwest (R1/Z1 in figure 3), further reinforced by a stone dam connecting the two on the most compromised side. Behind the shores, the marsh landscape is built in silt as an island archipelago separated by water from the Markermeer (figure 3).

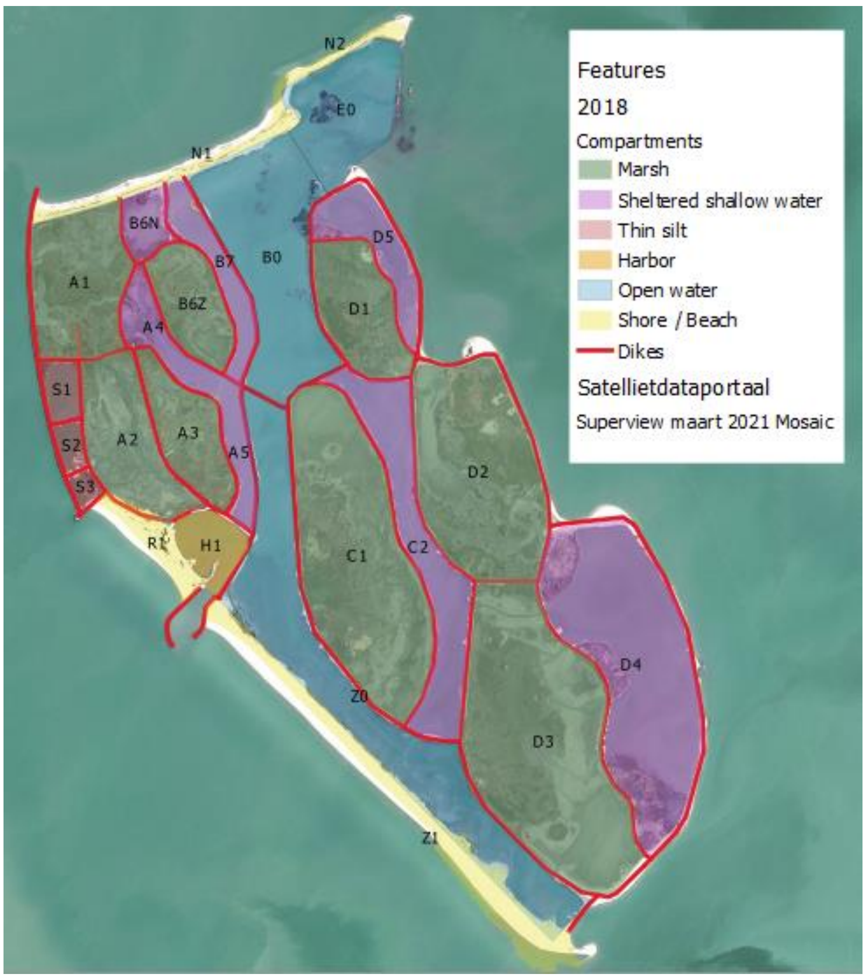


Figure 3. *Division of the Marker Wadden into its compartments and their nomenclature*

The construction of the Marker Wadden was finished by 1 January 2021 when ownership was carried over from Boskalis to Natuurmonumenten. On that date plus an additional 15 months of warranty period, the Marker Wadden had to meet a number of design specifications requested in the tender by Natuurmonumenten and Rijkswaterstaat. The most important demand was the elevation, more specifically the elevation of the ground level for all the marsh compartments. The ground level of the marsh compartments is required to be between 0 and -40 cm NAP, around the water level of the Markermeer with the intention of keeping the soil moist enough that woody species are unlikely to establish. Exceeding the boundary would result in too high of a risk for willow establishment while undercutting would result in excessive flooding. The elevation specifications for the marsh compartments are listed in table 1.

Table 1. *Elevation specifications for the Marker Wadden to be met by January 2021 plus additional 15 months warranty period (Boskalis 2020)*

Specification	Requirement
Ground level elevation wetland	The ground level of the marsh compartments is required to be between plus and minus 20 cm in relation to summer level (summer level NAP-0.2m, requirement: NAP+0m - NAP-0.4m) **Elucidation:** ground level 20 cm above summer level poses too high of a risk for willow establishment
Allowed margin of error	Allowed maximum area 20 cm above summer level is 20%
Area above summer level	At least 50% of total marsh area must be above summer level (summer level NAP-0.2m, requirement: 50% NAP+0m - NAP-0.2m “high marsh”, 50% NAP-0.2m - NAP-0.4m “low marsh”)
Adjustment elevation	Prognoses are made based on consolidation data gathered from monitoring surveys. These prognoses are judged by an expert who compares them with the definitive design of the Marker Wadden.

The physical background of the surface elevation decline over time is called soil consolidation. This is a process in which sediments and soils shrink as a result of their own weight and because of water evaporation. This leads to gradual sinking of the soil surface, also known as subsidence. The process is visualized stepwise in figure 4. The red dotted lines represent the margins of the required elevation. During a deposit with holocene sediment (1), the resulting soil-water mixture rises above the margins. Because the holocene sediment does not dissolve in water and is also more dense, it will sink to the bottom (2). This sedimentation process makes the sediment more dense and increases the pressure, resulting in more water being repelled from the sediment layer. As more water is repelled, the pressure increases once again in a self-reinforcing feedback. This is the underlying mechanism of consolidation (3). Important to mention is that the pressure on the original soil also increases, leading to the same processes occurring on this layer as well, thereby further increasing subsidence. To accelerate crust forming on the top layer, the compartment is drained (4) by means of water level management in the summer. The top layer dries as a result of consolidation, water evaporation and vegetation (that absorb water) and forms a crust (5). The goal is to ensure that subsidence occurs to such an extent, that the ground level falls within the margins by the time ownership is transferred plus a 15-month warranty period and the soil is sturdy enough for geese to walk upon (6,7) (Boosten 2016, Boskalis 2020).

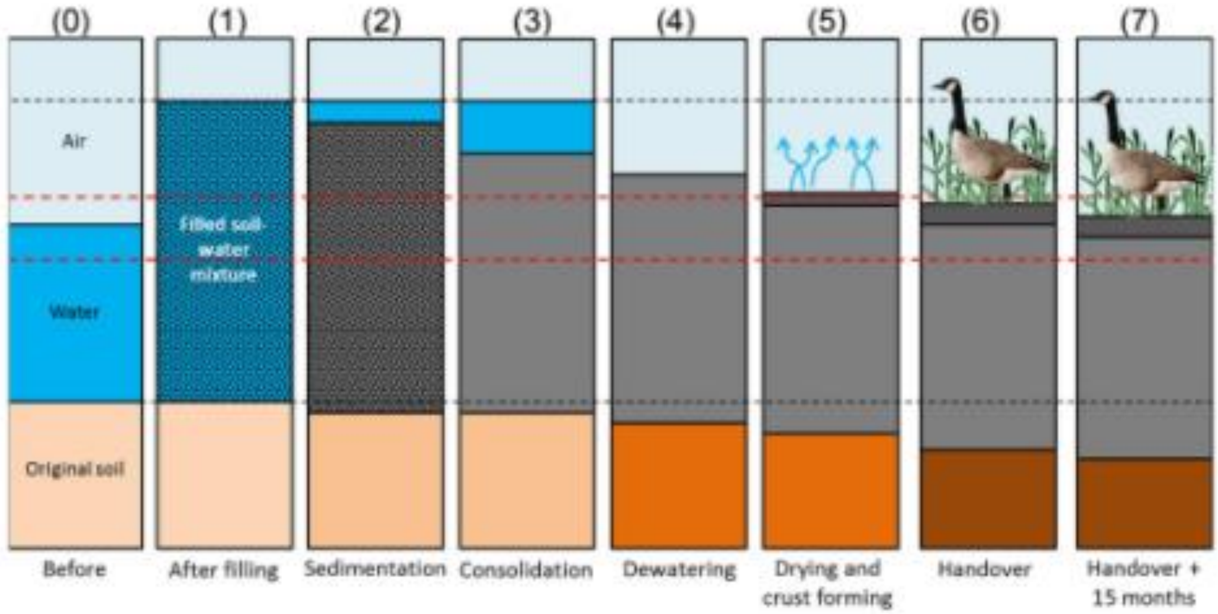


Figure 4. *Principle of the elevation development on the Marker Wadden schematically illustrated in seven steps (Boskalis 2020)*

The silty bare soil then becomes the foundation for many plants to grow on. Vegetation forms key aspects of the habitat of birds and fish. In the first place, vegetation provides an immediate food source for grazing species such as for graylag geese and the silver carp (Datta and Jana 1998, Montràs-Janer et al. 2019). However, vegetation also provides a food source in an indirect manner for insectivorous and piscivorous birds. Many insects are dependent on plants as their main food source (in the form of nectar found in flowers or as herbivory) and as hosts for their eggs and larvae. Fish are dependent on aquatic vegetation in the same manner - for grazing species it provides an immediate food source while some species lay their eggs on them or in the vicinity. This use of external fertilization for reproduction is called ovuliparity and is found in species such as trout *Salmo trutta* and three-spined sticklebacks *Gasterosteus aculeatusv*(Lodé 2012). This mode of reproduction is often found in toads and frogs as well, whose larvae (tadpoles) also provide a food source for some birds (Gontijo et al. 2018, Crump' and Vaira 2021). Also, fish larvae found a refugium in dense vegetation against predators. Finally, birds also directly interact with vegetation as a form of shelter. Some birds depend on vegetation as their breeding grounds, though ultimately even those who do not may also profit from vegetation as base material to build their nests with (Collias 1964, Goldstein et al. 1986). On the other hand though, birds may also use this form of shelter to escape from predators (Beisiegel 2006). In conclusion, vegetation - whether terrestrial or aquatic - plays a highly significant role in the survival of animals in all trophic levels.

Natuurmonumenten aims to mainly develop nature type N01.03 "Riparian and marsh landscapes". This nature type is described as being directly determined by the water dynamics of the river and succession (whether or not dependent on grazing) for areas around river banks, but also for peaty and silty areas more distant from rivers being directly determined by fluctuations in water level, differences in elevation and grazing (in)dependent succession (BIJ12 n.d. p. 12). Strictly speaking, the Marker Wadden are not under direct influence of a river as it is located in a lake. However, the design of the Marker Wadden is quite similar to a riparian and marshy landscape because the water from the lake is freshwater and can be transported through the gullies around all the marsh compartments, and fluctuates in level due to wind and water management. This may create riparian-like areas near the banks of the gullies and silty areas more distant from the gullies.

Riparian plant communities are generally very species rich and of high conservation interest(Valk 2005, Keizer-Vlek et al. 2014). On one hand, we can expect to find mudflat pioneers in areas that fall dry in the summer as a result of water fluctuations. These are usually annual and biennial species such as *Senecio congestus, Chenopodium rubrum* and *Rumex maritimus.* On the other hand there are the helophytes; plants that grow in shallow waters and bare mudflats whose submerged buds are able to survive winter. These communities are dominated by tall emergent perennial species such as *Phragmites australis, Typha latifolia* and *Epilobium hirsutum*. Together, they make up an important habitat for many birds, fish, mammals, amphibians and macro-invertebrates (Ter Heerdt 2016).

Natuurmonumenten aims to develop the Marker Wadden into a reed marsh by intervening in the expected spontaneous hydroseres. A hydrosere is a form of ecological succession in which open shallow waters and wetlands gradually turn into forested land over time. Pioneer species are initially the only ones capable of settling in the water or wetland. These plants strongly transpire water, accelerating the hydrosere by drying out the soil and making it more suitable for intermediate species. The pioneers will either die off by unsuitable conditions (winter) or competition from intermediate species in the next growing phase, and their dead plant material will turn into humus and slowly fill up the puddle. The piling up of peat, which is rich in organic material, creates conditions suitable enough for intermediate species (helophytes) to establish in these lands. Over time, the soil will become sturdy enough that woody structures can settle here, completing the hydrosere as a woodland ecosystem (Van Donselaar-ten Bokkel Huinink 1961). A hydrosere starting from an open body of water until forested land as described above takes a very long time. Natuurmonumenten starts the vegetation development on the mudflats, therefore the vegetation present now is a result of a strongly accelerated hydrosere. Establishment of species from hydroseral communities at this point is the result of the soil already being feasible enough to grow on as well as external efforts to develop the vegetation, as peat formation is far from happening right now.

Natuurmonumenten has decided to try to retain the intermediate phase of hydrosere where helophytes are dominant (creating the typical marsh landscape) and where succession to forest is prevented. This is visible from her strategy in nature management. Starting from 2017, efforts have been made by Boskalis in consortium with Witteveen+Bos and later on Natuurmonumenten to develop the reed marsh. Central to this development are stimulating reed growth and countering the factors that limit their development the most. These limiting factors are grazing by geese, deposition of holocene sediment, water level and competition from willows. Four measures to develop the reed marsh stand out: sowing of reed, exclosures, willow removal and water management.

Our research

This thesis was written after the construction of the Marker Wadden was finished and ownership was carried over to Natuurmonumenten. To properly manage the Marker Wadden, it is important to have a good overview of the construction details to interpret future developments. The problem is that prior to this thesis, the documentation on the construction of the Marker Wadden was scattered over various files from different parties involved and thus not accessible in one place. Coupled with demand from researchers for a centralized database, this led to the initiative in this thesis to develop a logbook in which the construction activities are recorded from start to present. Using a retrospective study, we looked at how the Marker Wadden was built up from the start of the construction and we recorded the activities in detail in an online database. At the start of the results section of this report, we tell the story of the construction based on the recorded data.

Moreover, we take an in depth look at the measures that were taken to develop the reed marsh and examine to what extent they led to vegetation change, through a vegetation mapping field study during the summer of 2021. In particular, we investigate the effectiveness of sowing and exclosures on the development of the reed marsh.

Finally, we investigated how water-wind and elevation dynamics can predict the vegetation, which may be useful for Natuurmonumenten to consider in their future management. As mentioned, the Marker Wadden may be subject to tremendous wave action. Intense wave action poses a threat to the vegetation development, as most of the desired vegetation is not able to withstand such forces (Nilsson 1987, Roberts and Ludwig 1991). For this reason, the compartments where the marsh will be developed are sheltered from the waves by sandy shores and dikes. Open waters connected to the Markermeer are, however, present in the Marker Wadden, though we expect that wave action in these waters can never be high enough to affect the marsh development because fetch lengths are too low within these waters.

We also expect there to be an elevational gradient between vegetation of the different hydrosere stages. Pioneer species such as *Senecio congestus, Chenopodium rubrum* and *Rumex maritimus* will likely be found on lower elevation. These soils are often wet, too unfavorable for intermediate species. Over a growing season, pioneer species will absorb a significant amount of water from the soil and die off. These occurrences lead to compaction and fertilization of the soil. In this stage the soil is solid enough for helophytes such as *Phragmites australis* and *Typha latifolia* to establish. We expect that *Typha latifolia* will occur at slightly lower elevations than *Phragmites australis* and *Epilobium hirsutum* due to its preference for submerged areas (Coops and Velde 1995). We expect the latter two to be found at similar elevation (Clevering and van der Toorn 2000). As hydrosere progresses, the elevation rises too, making the soil more favorable for the final successional stage which is characterized by woody species such as *Salix alba*. Therefore, we expect willows to be found at the highest elevations of all major vegetation types.

2. Material and Methods

Logbook Marker Wadden

Data on the construction of the Marker Wadden was collected from several sources who were involved in the construction, and entered into a Google sheets database dubbed the “Logbook Marker Wadden”. Each activity contained a description of the activity itself, some activity-specific details and a spatial (where the activity took place) and temporal dimension (when the activity took place). In addition, a source is cited for each activity with a link to the referenced document. These documents form the base informative sources of the construction, water management and vegetation development throughout the first five years of the Marker Wadden.

The spatial data in the logbook database was linked to a map created in QGIS 3.16.7, which contained all the associated vectors. These include polygons for the various compartments of the Marker Wadden, line vectors for the dikes, hiking trails and boardwalks and point vectors for the bird hides and watchtower. Additional vector data include sowing areas of reed, exclosure locations and other vegetation development activities, and locations of research instruments.

Vegetation mapping in the field

Vegetation mapping on the Marker Wadden was performed during a double 6-day visit in May-June 2021. As base map, we used a 0.5 m resolution Superview satellite image of 1 March 2021. Each vegetation polygon was determined and represented by only its most dominant species, since the vegetation development is still in its early stages leading to strong dominance of only a few species. This does not eliminate the possibility of other species occurring within a certain defined patch, but for our research it was the most practical to determine based on dominance. A patch is defined as a 10 m^2 or larger area covered by vegetation with a density of at least 10 plants per m^2. Vegetation type determination of each polygon was tracked using a water-proof Samsung Galaxy Tab Lite with QField installed, which was provided with satellite imagery of the Marker Wadden gathered from the Satellite Data Portal from the Netherlands Space Office. The patches and their borders (if necessary) were designated with point vectors in the field. Subsequently, the vegetation polygons were drawn in QGIS 3.16.7 Desktop as polygon vectors using the add polygon tool, split feature tool, vertex and clipper.

After vegetation mapping was completed, we performed calculations and statistical analyses on our data. Field calculations were performed using QGIS 3.16.7. Statistical analyses were performed in RStudio 3.16.7 using the packages “tidyverse”, “ggplot2”, “waver” and “sf”.

To evaluate vegetation change, we generated 200 random pixels in QGIS, spread out among the area where reed was observed in May-June 2021. These points were compared with satellite imagery from June 2020, June 2019, June 2018 and June 2017 and determined for reed presence. The resolution of the satellite imagery was 0.25 m^2 per pixel, therefore the total area of the pixels in 2021 was 50 m^2. We visualized the data in a bar plot using Rstudio.

The effect of reed sowing and exclosures was calculated using an overlap analysis in QGIS. This calculates what percentage of a (multi)polygon overlaps with another polygon, for example what percentage of the observed reed cover overlaps with the sowing area in 2017. We visualized the data with bar and box plots using Rstudio.

Wind and water analysis

Wind and water data of the Markermeer was provided by the Service Desk Data of Rijkswaterstaat. The data was gathered from three stations in the Markermeer: Edam, Markermeer midden and Marker Wadden (figure 5). The data gathered from there consisted of the water level in cm compared to Amsterdam Ordnance Datum (Dutch: NAP), wave height in cm compared to NAP, wind direction in degrees compared to true North and wind speed in m/s every ten minutes during the period 1 Jan 2016 until 14 Jul 2021. Additionally, hourly water level data from within the Marker Wadden was provided by the “Natuur in Productie” project, gathered from three stations located in compartment B6N, the harbor (H1) and near the southern shore (Z1) (figure 5).

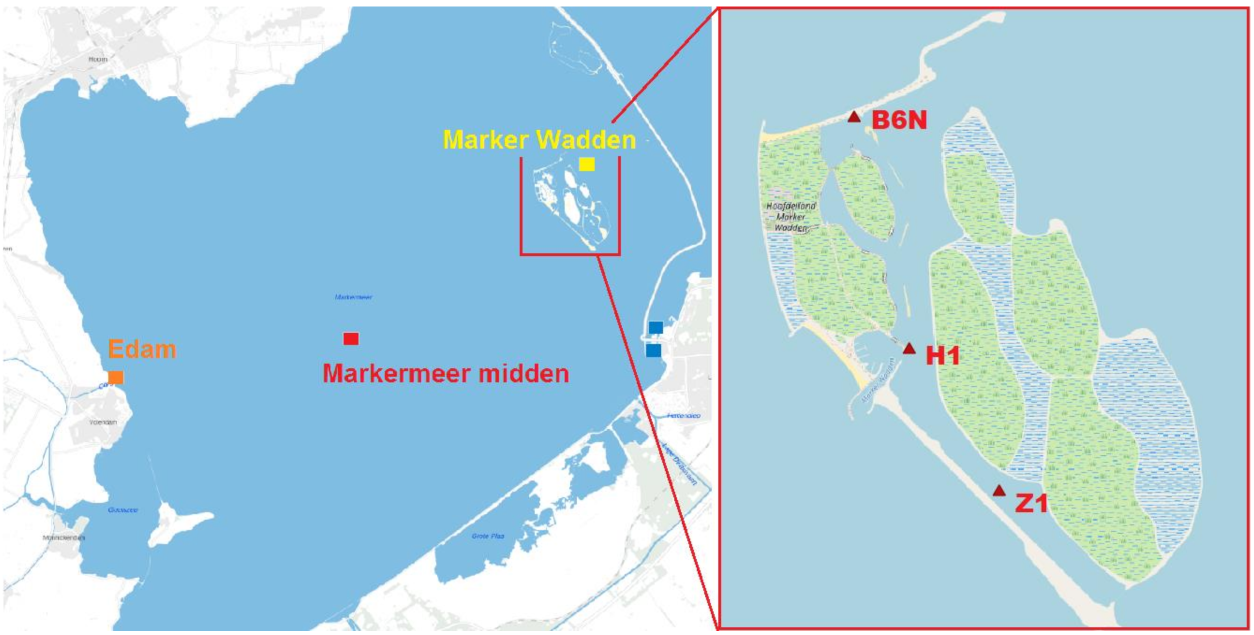


Figure 5. *Locations of the three measuring stations of water level, waves and wind data from Rijkswaterstaat in the Markermeer (left) and the three measuring stations of water level from the Natuur in Productie project in the Marker Wadden (right).*

Spatial objects for fetch length calculations were drawn in QGIS. For the Marker Wadden calculation in relation to the Markermeer, we created a SpatialPoints object at the centroid of the total Marker Wadden area and a SpatialLines object of the Markermeer shorelines. For the fetch length within the Marker Wadden, we created a SpatialPoints object located in the Marker Wadden open waters at coordinates X:154701,Y:510276 and a SpatialLines object of the Marker Wadden shorelines from within. We chose these coordinates because the potential fetch length from this point is maximal within the Marker Wadden.

With the fetch lengths and wind speeds from each direction, we also made estimations of the expected wave heights in the Markermeer using the Munk-Sverdrup-Bretschneider nomogram in figure 6 (Rodolfo, 2014) and the Bretschneider equation (Calderon et al., 2016):

$$\underline{H} = 0.283\, tanh\, (0.530\underline{d}^{\ 0.75})\, tanh \left[\frac{0.0125\underline{F}^{\ 0.42}}{tanh(0.53\underline{d}^{\ 0.75})} \right]$$

$$\underline{H} = \frac{H_S\, g}{u^2},\ \underline{d} = \frac{d\, g}{u^2},\ \underline{F} = \frac{F\, g}{u^2}$$

Where:
g = gravity acceleration [m/s^2]
u = wind speed at 10m height [m/s]
d = water depth [m]
F = fetch length [m]
H_s = Significant wave height [m]

Finally, we visualized the water level in the Markermeer and Marker Wadden as a line graph, and the fetch lengths (from Marker Wadden to Markermeer and from point within Marker Wadden), wind direction frequency, wind speed, expected wave heights and observed wave heights with circular plots in Rstudio.

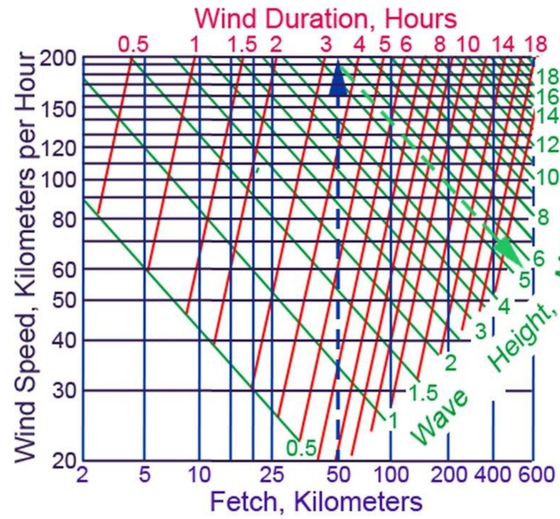


Figure 6. Munk-Sverdrup-Bretschneider nomogram which shows the relation between fetch length, wind speed, wind duration and wave height. (Rodolfo, 2014)

Elevation analysis

The elevation analysis on the vegetation was done using zonal statistics in QGIS, which calculates an average elevation for each vegetation patch, with an elevation raster layer from July 2020. First, we expressed elevation for the most prominent vegetation types in m relative to NAP, directly from the elevation raster layer. We call this the absolute elevation. The obtained data was then transformed, analyzed and visualized with density plots in Rstudio.

We then expressed elevation for the most prominent vegetation types in m relative to the low water mark in July 2020. This is what we will refer to as the relative elevation. First, we obtained the low water mark for each compartment by drawing a terrain profile (linked with the elevation raster layer) along a waterline within each compartment. From the resulting terrain profiles, we calculated the mean low water mark elevation specific for each compartment. Then, we acquired the mean elevation of the vegetation per compartment by performing a zonal statistics analysis of the vegetation per compartment. Subsequently, we imported the data into Rstudio and subtracted the low water mark elevation of the corresponding compartment from the elevation of the vegetation per compartment. This results in the relative elevation of the vegetation per compartment. Finally, we grouped the observations by vegetation type and calculated the overall mean, resulting in the relative elevation for our elevation analysis. We visualized the data with density plots in Rstudio.

3. Results

3.1 Logbook results

3.1.1 Construction of the Marker Wadden

Figure 7. Enclosing dam of the main island is built (left) prior to filling the island with holocene sediment (right)

In February 2016, a final plan was drafted so that construction of the first island could commence in the next month. The Marker Wadden would be constructed in six islands: A, B, C and D1, D2 and D3 in that order (figure 3). Islands A and B are aggregated, so we may refer to them as the "main island" subsequently. The main island would be accessible to the public, with recreational facilities such as a harbor, hiking trails and bird hides. The C, D1, D2 and D3 islands would strictly become "nature islands", inaccessible to the public. Each island is divided into so-called compartments (or basins), where the first letter corresponds to the island it belongs to. This applies if the first letter is A, B or C with the exception of B0 (figure 3). For D1 and D3, there is a distinction between "island" and "compartment". When we refer to island D1, we refer to the assembly of compartments D1 and D5. The same applies for island D3, which is the collective name for compartments D3 and D4. Island D2 solely consists of compartment D2, thus these terms may be used interchangeably depending on the context.

The islands' foundation is made of fine organic mud and marine clays that were dredged from the Markermeer. These silty sediments are henceforth conglomerated as "holocene sediment". This term was widely used by the construction workers of the Marker Wadden to refer to these sediments. The dikes that form the basins for holocene sediment fillings are made of sand.

Construction Main island (island A / B)

In March 2016, construction of the main island started. Conceptually, only the island A was supposed to have been built before starting island B. In reality, an excess of building material was dredged up so that islands A and B could be constructed simultaneously. Before the holocene sediment foundation can be built, the contours of the island must be erected in sand as enclosing dikes (NL: "ringdijk", figure 7). This is to prevent the holocene sediment from flowing outside the desired borders. Both holocene sediment and sand are mined from dredging pits (NL: "zandwinputten") around the Marker Wadden (appendix A), where the holocene sediment layer lies on top of the sand. Because of this, it was not possible to build the enclosing dike of the main island from the dredging pits. The sand for the first enclosing dike was brought in from the IJssel river near Olst, where it was dredged to promote shipping. From then on, the main island was built up from holocene sediment and sand from dredging pit 1 in an alternating manner. The first enclosing dike was built up to above water level (+0 m NAP), which was reached at the end of May 2016.

From June until August 2016, the surrounding dike was reinforced with sand and on the west side also with stones (from dredging pit 1). Stones were used to enforce the three washovers on the stone dam. Their objective is to allow water from the west into the island, but slow it down enough to prevent flooding of the compartments. In addition to working the surrounding dike, inner dikes were created. These inner dikes constitute the edges that separate the main island into its compartments. Most of these inner dikes would later serve as the basis for all the hiking trails and boardwalks (figure 8). The marsh compartments A1, A2, A3 and B6Z would be filled with holocene sediment to above water level and allowed to eventually develop into a marshy landscape. The sheltered shallow water compartments A4, A5 and B6N would be filled with holocene sediment to just below water level to create shallow waters for fish to thrive in and waders to forage. This distinction in filling height between marsh compartments and sheltered shallow water compartments would apply for all future construction activities of this sort.

Figure 8. Overview of the boardwalks and hiking trails on the Marker Wadden main island with nomenclature

The third and last fillings of holocene sediment took place in August 2016 and March 2017 respectively, with reinforcement of the existing dikes and addition of the harbor dikes happening in between.

Construction Nature islands (islands C, D1, D2 and D3)

Shortly after the last holocene sediment deposit on the main island in March 2017, construction already shifted towards the nature islands. On March 23rd, four days after the last deposit, construction of the underwater enclosing dike of island D1 already began. Conceptually, island C was supposed to be constructed after A/B, but since island D1 was smaller, priority shifted to the latter. Holocene material and sand for the construction was dredged from dredging pit 2 as the first had been depleted. Holocene sediment deposition for island D1 took place in four bouts in 2017 from April to June. During the reinforcement of the enclosing dike in between the holocene deposits, an inner dike was constructed as well that divided the island in two halves. The western half would become the marsh compartment D1 whereas the eastern half would become the sheltered shallow water compartment D5.

The second nature island to come to the surface was island C, of which construction of the underwater enclosing dike began on April 24th 2017. Holocene material and sand for the construction of island C were dredged from dredging pit 2 in 2017 and pit 3 in 2018. As island C is significantly larger than island D1, the holocene sediment was deposited in six major bouts from May 2017 to April 2018. The last small deposit on island C was done in July 2019. Similar to island D1, an inner dike was constructed during the reinforcement of the enclosing dike of island

C in between holocene sediment deposits. The western half became marsh compartment C1 and the eastern half became sheltered shallow water compartment C2.

Island D3 was the third island to be built. The contours of the enclosing dike and the inner dike of island D3 were built in sand from May to September 2017. Holocene sediment deposition happened in six bouts from May 2017 to April 2018, three in 2017 and three in 2018. It is unclear when this island was filled for the last time, as another company (Van Oord) assisted in the dredging activities for island D3 too. It is suspected that their activities lasted until early 2020, but this cannot be verified. Building material for all activities in 2017 were extracted from dredging pit 2 and for 2018 from dredging pit 3. Van Oord used their own dredging pit directly to the south east of the Marker Wadden. Because the island is split by an inner dike in a similar fashion as the previous nature islands, it would produce the marsh compartment D3 and the sheltered shallow water compartment D4.

Immediately after raising the dikes of island D3 to their end profile in September 2017, the west and east dam of D2 were built in sand connecting the enclosing dikes of islands D1 and D3. These dikes were finished in February 2018 and created the contours of what would become the last nature island D2. Holocene sediment was deposited from February to April 2018 in six major bouts. The final smaller deposit was done in January 2019. Building material for all activities in 2017 were extracted from dredging pit 2 and for 2018 from dredging pit 3. The foundation of island D2 was the last to be finished and it separates itself from the other nature islands by not having an associated sheltered shallow water compartment. Rather, this island was filled to a marsh compartment (D2) as a whole.

3.1.2 Vegetation development

3.1.2.1. Reed sowing

Every year in July since 2017, the sediments in the compartments are sown with seeds of *Phragmites australis* (common reed). In 2017, the fresh bare sediment of compartments A1, A2, A3, B6Z and D1 was sown with two mixtures: *P. australis* rhizome and a mixture of *P. australis, Typha latifolia* (broadleaf cattail) and *Typha angustifolia* (narrowleaf cattail) seeds. The decision to use seeds instead of exclusively rhizomes was due to budgetary restrictions and the low priority of vegetation development for Boskalis. Seeds are less expensive than soil with rhizomes, therefore they formed the majority of reed material applied on the soil in 2017. However, since some budget was freed up for vegetation development, it was possible to partially cultivate the rhizomes. The seed mixture was applied by driving a hovercraft to the center of a compartment and spraying the seeds around in a circular motion (figure 9a). The rhizome material was limited, therefore it was applied in either small planes or long thin strokes with the hovercraft (figure 9b). Both reed materials were applied at a density of 1 kg/ha, with total area sown being 47 ha (Princen 2017).

Figure 9a. (left) *Sowing areas with P. australis and Typha sp. seeds* in 2017. **Figure 9b. (right)** *Sowing areas with P. australis rhizomes (right) in 2017.*

In 2018, the foundation of all phase I islands was established so that reed material could be applied on all marsh compartments of the Marker Wadden. Moreover, different types of reed material was used this year: *Phragmites australis*, *Typha latifolia* and *Typha angustifolia* seeds from peatlands in Weerribben-Wieden national park, *Phragmites australis*, *Typha latifolia* and *Typha angustifolia* seeds from inorganic soil in the Zwarte Meer near Kampen and *Phragmites australis* rhizomes from inorganic soil in Lelystad. Seed materials were applied by dispersal by wind from a hovercraft like in 2017, though not necessarily in the same fashion since dispersal locations were limited to places that the hovercraft could reach. Because elevation development at the start of 2018 was uncertain, the water in the compartments of the main island was drained maximally to perform an elevation survey. It was found that the holocene sediment was locally sprayed to a relatively high elevation. This caused the higher elevated sections to fall dry, making it impossible for the hovercraft to reach. In addition, the local high elevation made it impossible to increase water level to the desired level, leaving those areas completely exposed to drought and therefore willow establishment. To counteract this, an additional sowing round was done in April on the main islands before the planned round in July with the intention of making helophytes already dominant before the germination period of willows (May-June). For the main islands, a total of 121 kg seed material was applied over an area of 44 ha (2,75 kg/ha) in April and July combined. For island C, a total of 40 kg was applied over an area of 40 ha (1 kg/ha) and for island D1, D2 and D3 combined, a total of 119 kg was applied over an area of 94 ha (1,26 kg/ha) (Figure 10a). This adds up to 178 ha of area sown this year. The nature islands were only sown in July (Princen 2018a, 2018b).

Rhizomes were deployed exclusively on the main island due to additional budget being made available for vegetation development. The extra budget was also invested in exclosures, which were placed around the locations where reed rhizomes were applied (figure 10b). It is crucial to understand that reed rhizome deployment was almost always paired with exclosures. In total, 20,000 rhizomes were applied on the mudflats over an area of 2 ha and along the harbor at a density of 3500 rhizomes over 0.25 ha (Princen 2018a, 2018b).

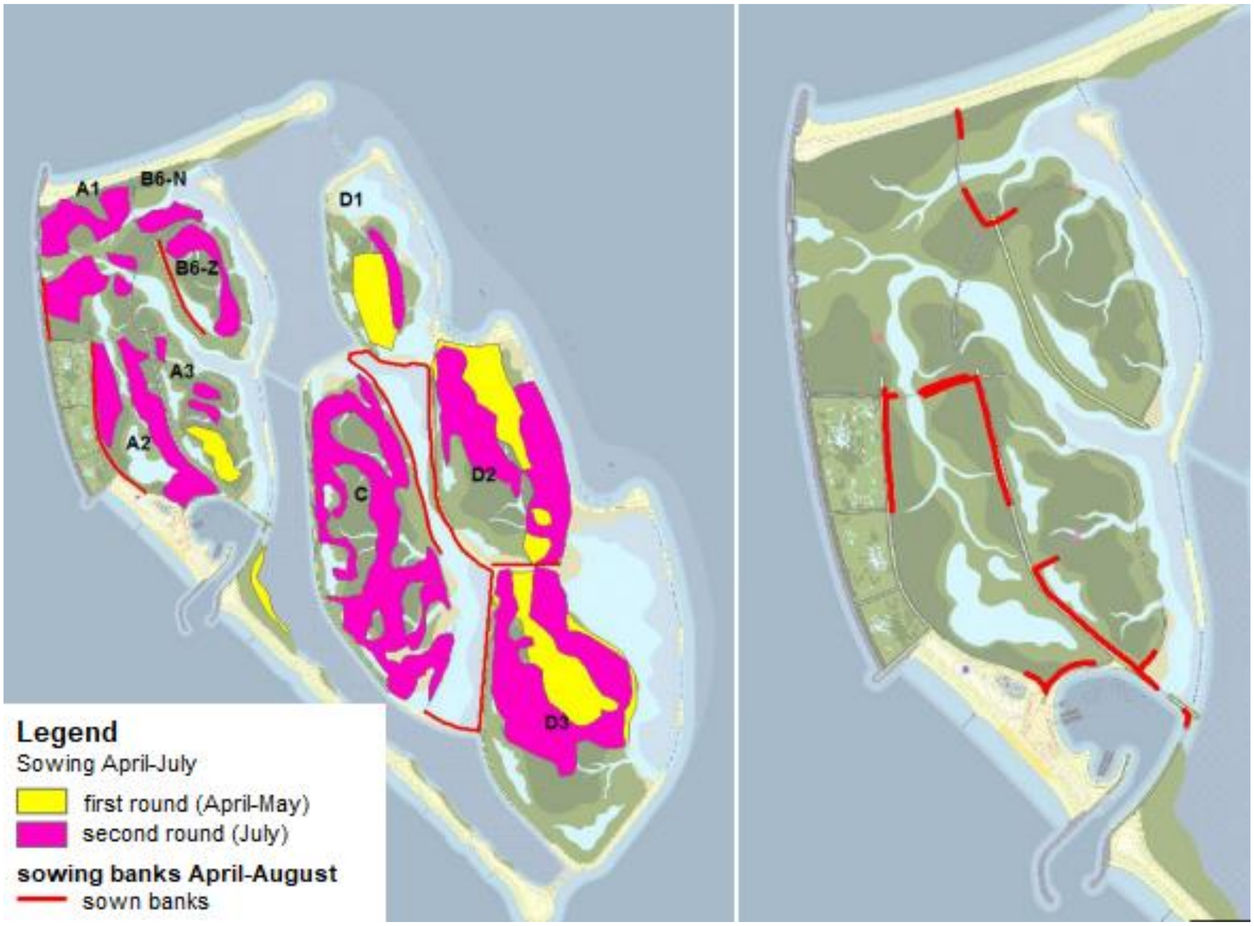


Figure 10a. (left) *Sowing areas with Phragmites australis and Typha latifolia seeds in 2018*. **Figure 10b. (right)** *Application of Phragmites australis rhizomes in 2018.*

In 2019, two new approaches to the sowing of reed were used. First, a segment of *P. australis* seeds were sown accompanied with seeds of *S. congestus.* One of the limiting factors to the vegetation development turned out to be grazing by geese. Young reed, if left exposed, will be consumed by geese to such an extent that a reed bed can no longer develop (Temmink et al., 2021). However, geese do not eat *S. congestus*. It is probable that they do not find it as palatable. The aim is to use *S. congestus* to fend off geese from the places where reed is sown. A total of 53 ha was sown over islands A/B, D1 and D2, of which 40 ha with *P. australis* alone and 13 ha with *P. australis* and *S. congestus* (figure 11a) (Princen 2020).

The second measure taken is the investment into "robust cores" of reed rhizomes. In the previous year, rhizomes were spread over long thin strokes along the edges of the mudflats. This year, the rhizomes were planted in smaller, dense planes (robust cores). Creating a strong fundament of reed like this increases their chance of surviving a grazing attack or a holocene sediment filling. In the first place, the rhizomes were manually inserted into the soil but this proved to be a time consuming task. The insertion method eventually developed into scattering the rhizomes over the robust core area and pressing them into the soil using a large steel plate, followed by outlining them in an exclosure. In total, 100,000 rhizomes were used over islands A/B, D1 and D2, in 2019 over an area of 6 ha (figure 11b) (Princen 2020)**.**

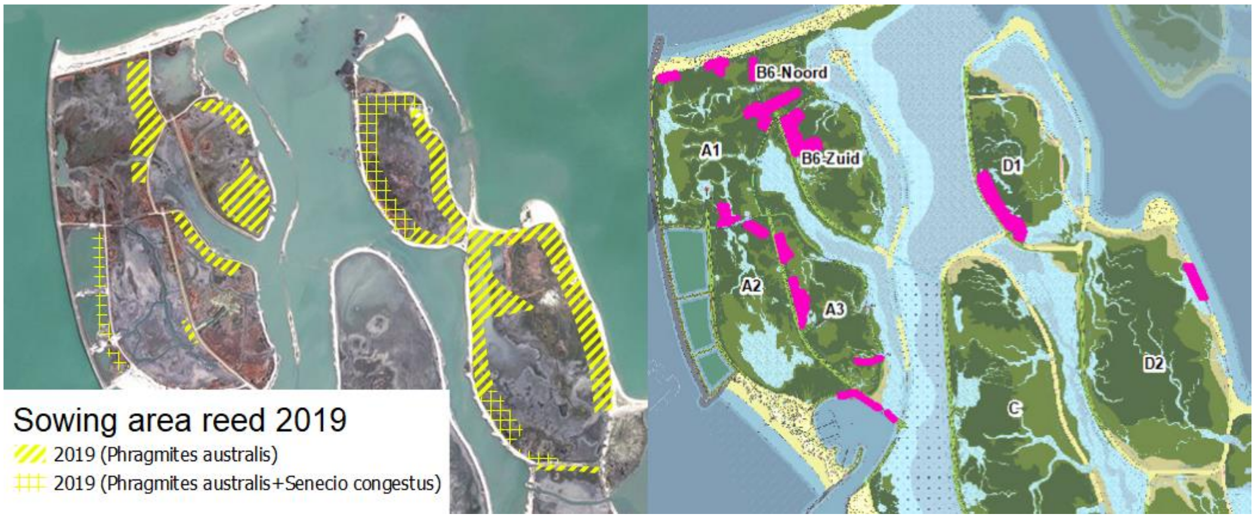


Figure 11a. (left) *Sowing areas with Phragmites australis seeds alone and Phragmites australis accompanied with Senecio congestus seeds in 2019.* **Figure 11b. (right)** *Application of Phragmites australis robust cores in 2019.*

In 2020, no new measurements were introduced. Instead, the measurements from the previous year were continued on the remaining islands C and D3. That includes only reed sowing without *S. congestus* and investment in rhizome robust cores (figure 12). Reed was sown over a total area of 62 ha and robust cores were applied over a total area of 1.5 ha.

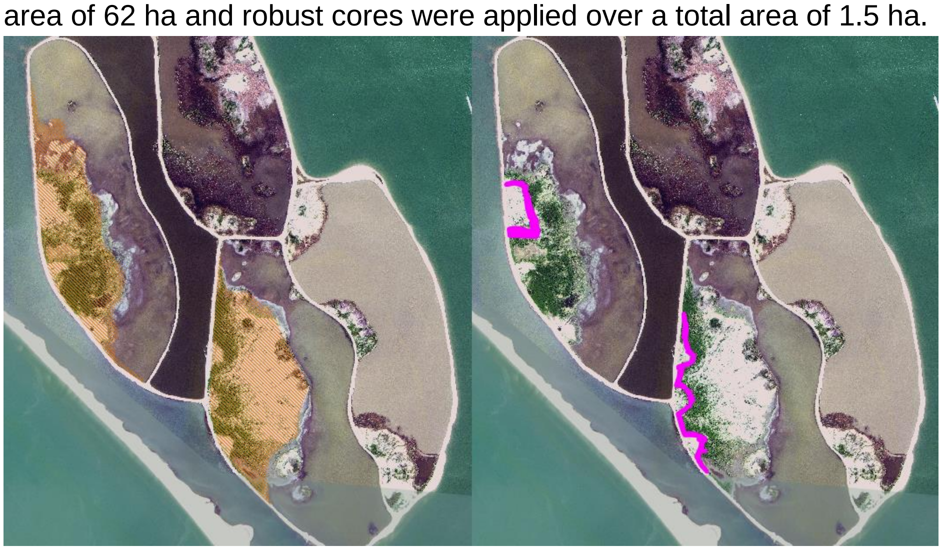


Figure 12a. (left) *Sowing areas with P. australis seeds in 2020.* **Figure 12b. (right)** *Application of P. australis robust cores in 2020.*

3.1.2.2. Exclosures

Exclosures were placed around soil where reed rhizomes are applied to fend off geese and reduce grazing pressure. Since 2018, they have been placed selectively around these areas by Boskalis to stimulate reed dominance. From 2020, Natuurmonumenten has taken over nature management responsibilities including the exclosures. Natuurmonumenten aims to monitor the reed development in the exclosures and remove those where reed is dominant enough to maintain on its own, but also to add new ones where reed growth must be stimulated. Overall, we can categorize the exclosures into six types: exclosures placed by Boskalis in 2018 and removed, exclosures placed by Boskalis in 2019 and removed, exclosures placed by Boskalis in 2018 and still present, exclosures placed by Boskalis in 2019 and still present, exclosures placed by Natuurmonumenten in 2020 and exclosures placed by Natuurmonumenten in 2021. The locations of the exclosures and their types are shown in figure 13. Notice that most of the exclosures overlap exactly with the area of rhizome robust cores in figure 11b and figure 12b. That is because these two measures were not mutually exclusive (Princen 2017, 2018a, 2020 p. 20).

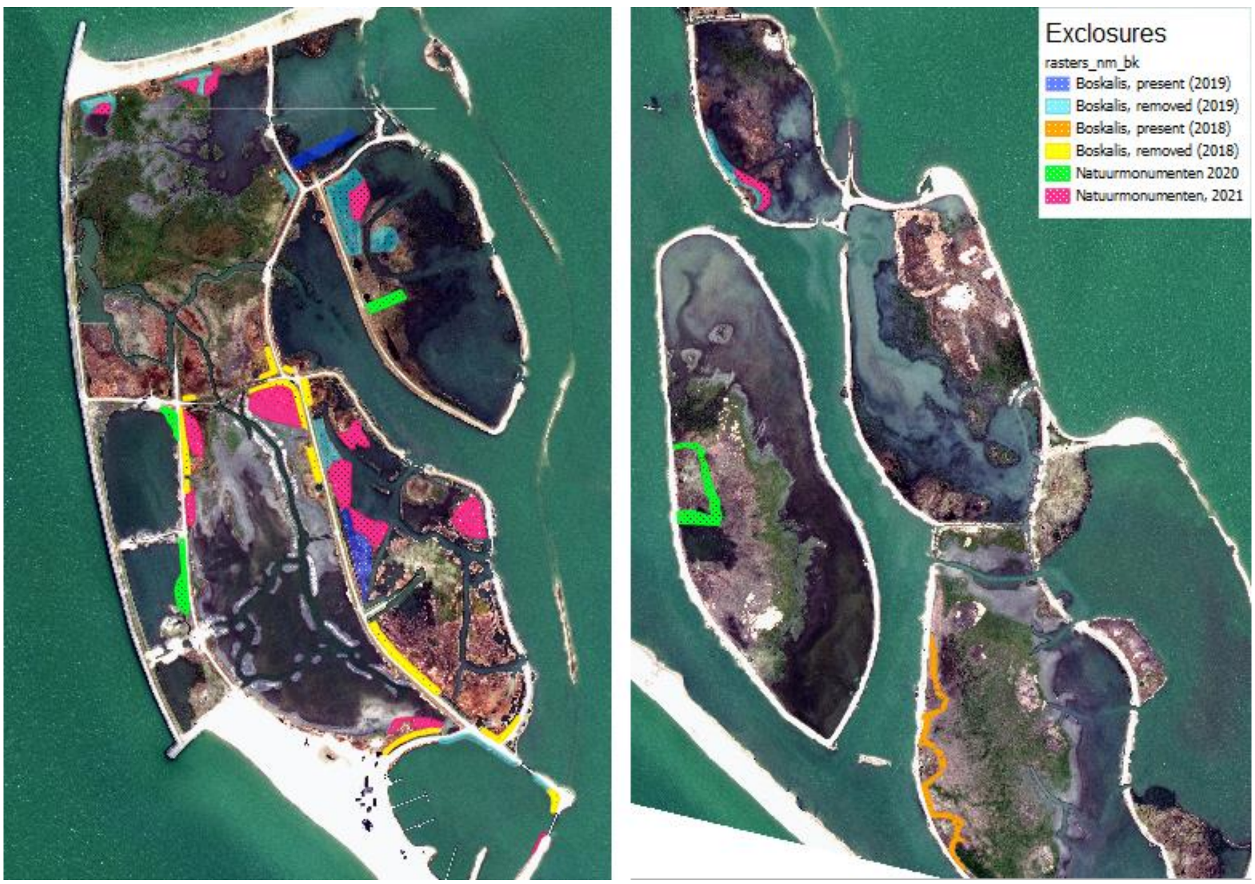


Figure 13. *Locations of the exclosures placed throughout the Marker Wadden.*

3.1.2.3. Willow removal

Willows have the undesirable property of outcompeting reed from the perspective of the current management plan. After willows have already been established, there is no choice than to remove them by hand or machine. This has been done during autumn and winter since 2018. To be effective, the plant must be removed in its entirety. Initially, this task came at the expense of Boskalis. However, from 2019 and on, this responsibility was taken over by Natuurmonumenten on the condition that Boskalis would invest the money that is saved in robust cores of reed in 2019-2020.

This method is undesirable because it is very labor-intensive. In the summer of 2019, Natuurmonumenten even ceased manual removal of willows because the task was deemed too heavy to be performed by volunteers (Princen 2020). Therefore, Natuurmonumenten and Boskalis aimed to minimize removal efforts by not allowing willows to germinate in the first place. They did so by inundating the soil during the period where willows are most likely to germinate. In other words, by managing the water levels. The willows that managed to persist the water level management were mechanically removed.

3.1.2.4. Water management

The water management of the Marker Wadden mainly serves two purposes: to prevent germination of willows and to create suitable conditions for germination and growth of helophytes. In the first years, the water level was adjusted using a system of pumps and drainpipes while constantly being monitored with gauge rods (figure 14). The eventual goal is to break open the outer dikes and connect the Marker Wadden waters with the Markermeer, so that the water level of the Markermeer determines the water level throughout the whole Marker Wadden. At that point, water level management is ceased.

Water level is expressed in one of two ways: in m relative to NAP or in m relative to ground level (which in this case is the mean elevation of the sediment in a compartment). The first way of expression is related to a normalized standard (constant) whereas in the other case, it is related to the mean elevation of the relevant Marker Wadden compartment (variable). Not only does the ground level change over time due to subsidence, but there will also be variance between the ground level of each compartment. The targeted water level of the Markermeer in the summer is 20 cm below NAP (summer level). During the winter, the target level is 40 cm below NAP (winter level).

In 2018, the washovers on the stone dam became operative, allowing water from the lake to flow into the main island compartments. In that same year, the east dike of B6N was breached to allow flooding in this compartment. In 2020, the rear dikes of the D islands were breached as well, leaving compartment C as the only one not connected to the lake by 2021 and therefore the only compartment where the water level is still dictated by management.

Figure 14. *Locations of objects used for water level management on the Marker Wadden (Boskalis 2019)*

The current water management aimed at reed vegetation development on the Marker Wadden is a constant battle between serving the two goals. On one hand, willows (*Salix*) form a significant threat to the reed marsh development as they are able to outcompete reed before the latter is able to become dominant. Willows spread their seeds during the spring which are most likely to germinate in the period May-June on bare, wet soil. An experiment performed by Koen Princen MSc. (Witteveen+Bos) in 2018 showed that by halfway through June, the two most common willow species on the Marker Wadden (white willow *Salix alba* and eared willow *Salix aurita*) had already distributed most of their seeds (Princen 2018b). Willow seeds, however, are not able to germinate when they are inundated (Stromberg et al. 1991, Castro-Morales et al. 2014). Boskalis' strategy to utilize water management against willow germination is based on these findings. On the other spectrum of the scope, water level management should also facilitate helophyte development. Seeds and seedlings cannot survive any form of inundation whereas adult helophytes are dependent on periodic inundation (Coops et al. 1999). However, excessive inundation may lead to increased inhibition of root growth and increased root mortality, and should therefore be prevented (Kozlowski 2002). Thus, inundation is both beneficial and detrimental to reed development and it is the interplay between the two goals that gives the most beneficial effect to helophyte development.

The water management strategy by Boskalis during the construction of the Marker Wadden summarized is to inundate the soil during the germination period of willows and drain the water during the germination and growth period of helophytes. Despite the germination period of willows being May-June, the decision was to inundate the soil sooner because of breeding season. As per law, Boskalis is not allowed to disturb the breeding birds on the islands by raising the water level. However, it is possible to make an area brood free. That is, to create circumstances so disadvantageous that birds are not able to breed there in the first place. Thus, every year until 2021 (except 2018), the water level is actively raised around halfway March with the intent of achieving the desired water level (0-20 cm above ground level, henceforth referred to as spring level) halfway in April to create a brood free zone. This spring level was actively monitored and maintained until around the 1st of July. Because reed is sown around this period, the water level should be lowered to facilitate their development. Thus from July until October, the water level is actively lowered to summer level (20 cm below ground level). Starting from October, the water level will be lowered to winter level (40 cm below ground level) and maintained at that level until March next year and the cycle starts over again (Boskalis 2019). The annual water cycle is schematically illustrated in figure 15.

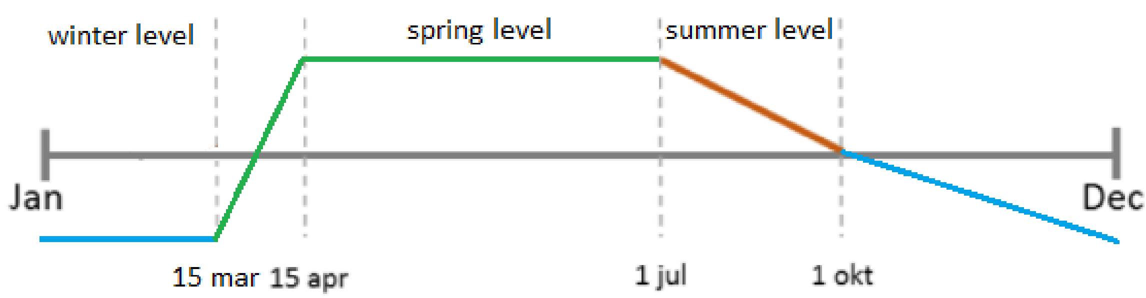


Figure 15. *Annual cycle of water management on the Marker Wadden (Boskalis 2019)*, *where the gray line represents the soil surface*

Though water management was mainly used to steer the vegetation development, it is critical to understand that vegetation is not the main priority for Boskalis. The construction of the Marker Wadden by Boskalis was bound to elevation requirements from Natuurmonumenten. In short, the goal was to raise the final soil surface to within a certain margin in relation to the Markermeer average water table (appendix B). This ensures that the marsh compartments never flood completely and prolongedly. Boskalis must meet these requirements as per contract. However, Boskalis was only required to make an effort in developing the desired vegetation composition. This was especially visible in 2018, when there was uncertainty over the elevation requirements being met. Normally, the water level would be lowered gradually from July to October, so that the soil still remained inundated for an extended period outside the germination period of the willow. In this case, the water level was drained maximally in July so that halfway through the month, the water level was already 10-20 cm below ground level in some compartments. This increased the risk of willow establishment. So even though some water management was partially steered by the desired vegetation development, the elevation development was prioritized (personal communication Koen Princen).

3.1.3 Elevation development

Elevation was monitored by periodical drone surveys at a frequency of four times per year. During such operations, high resolution images are made to differentiate crust, water and vegetation while elevation of the new ground level is measured with photogrammetry. This method does provide a few obstacles. Since elevation is measured specifically for the crust only, reflections from vegetation and water are not usable. This data is filtered from the raw data, meaning a survey never covers the whole area in its entirety. Moreover, certain activities and conditions during the construction may also hinder elevation surveys. During times when water levels are high in compartments (e.g. summer, after holocene sediment filling of the basins), the amount of usable area for surveys is reduced. Moreover, as time passes, subsidence will constantly take place causing more and more areas to fall under the water level. In addition, vegetation also develops over time, taking more area that was otherwise usable. These problems make it so that the measured area can never be the same as the total area of the compartments. Thus it is very difficult to relate the measured elevation to the demands in table 1 (Boskalis 2020).

Despite the difficulties faced in obtaining elevation measurements, a conclusion had to be made using the available data in late 2020. The data was used to make a prognosis of the expected elevation development. First, the raster data was divided into grids of 10x10 m. Per island (A, B, C, D1, D2, D3), the grids were filtered for those that provide usable data. Only the filtered grids were used for analysis.

It was found that the elevation development can be divided in two categories (figure 16). The first category are the islands that were finished relatively early (A, B and D1). The last deposit with holocene sediment was in 2018. For this category, the average subsidence was found to be 5-10 cm per year. It is expected that the ground level for these compartments will meet requirement number one (table 1) during the warranty period of 15 months. The other category comprises the islands that were finished relatively late (C, D2, D3). These compartments were last filled in 2019. The average subsidence was estimated to be 20-25 cm per year, significantly more than the compartments of the other category. Expected is that these compartments are too high by the time of ownership transfer, however they will likely subside to “high marsh” levels during the warranty period. Therefore, it is expected elevation requirements 1 and 2 will be met. For requirement 3, the proportion will likely tend more towards high marshes instead of 50/50 (Boskalis 2020).

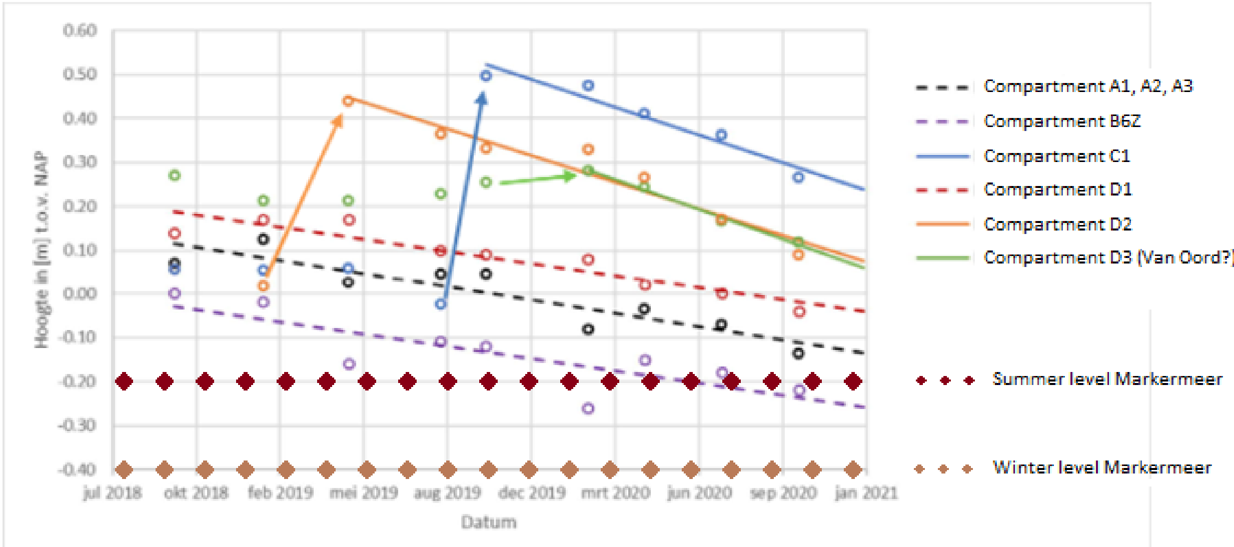


Figure 16. *Mean soil surface elevation development of the Marker Wadden compartments since their last deposits with holocene sediment, based on drone elevation measurements (Boskalis 2020).*

3.2 Vegetation analysis

3.2.1 Vegetation mapping

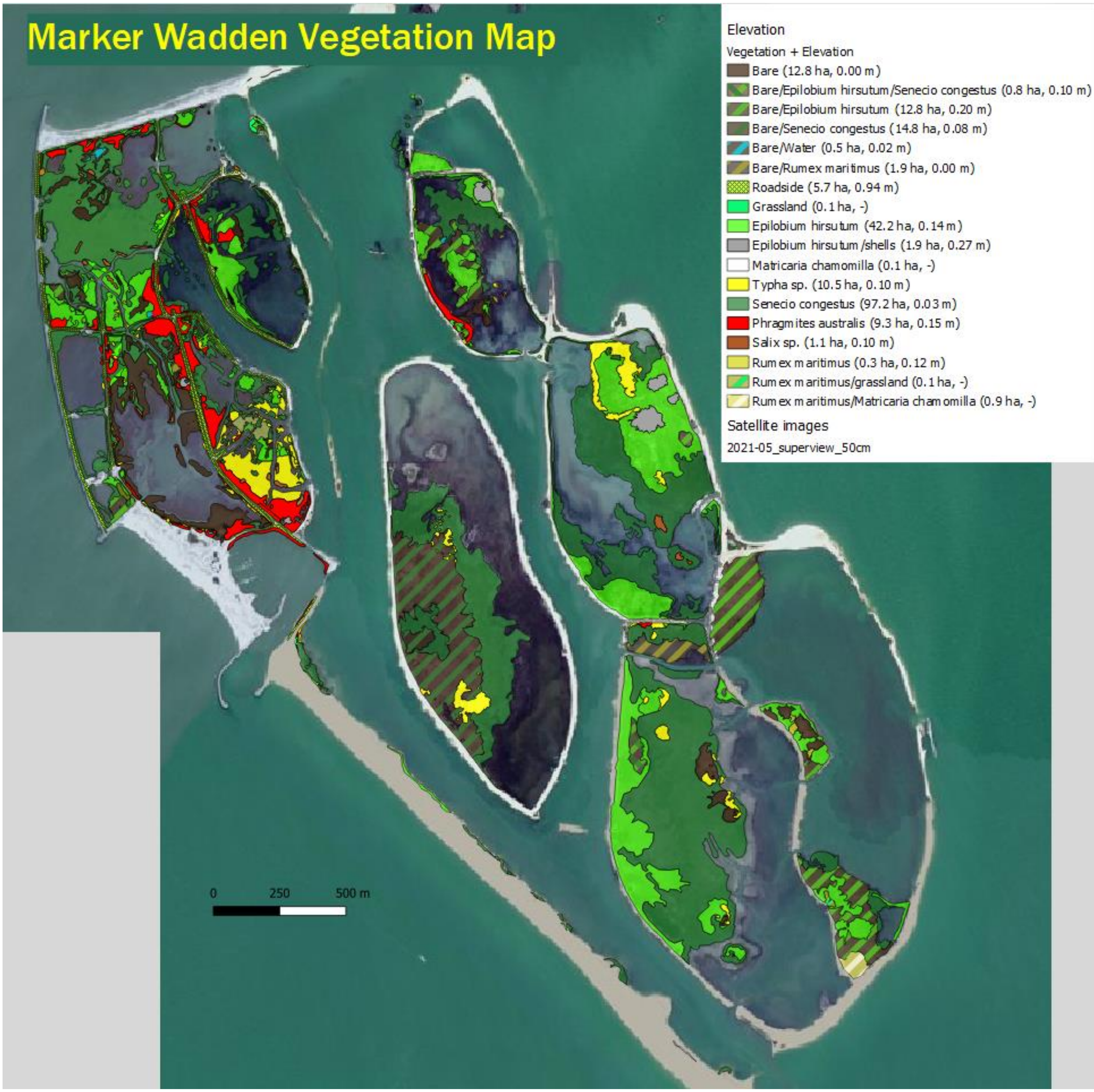


Figure 17. *Mapping of the Marker Wadden vegetation as determined in summer 2021, with total area in ha and mean relative elevation to ground level in m shown for each vegetation type.*

A total area of 220 ha on the Marker Wadden has been characterized by vegetation type (figure 17). By far the most abundant vegetation type is *S. congestus* (97.2 ha + 15.6 ha), followed by *E. hirsutum* (42.2 ha + 15.5 ha), *Typha sp.* (10.5 ha) and finally *P. australis* (9.3 ha). A substantial 12.6 ha of soil is characterized as bare ground. *Salix sp.* locally appear around the Marker Wadden, comprising a total area of 1.1 ha. That would yield the following estimated proportions of the six most major vegetation types: *S. congestus* (51.3%), *E. hirsutum* (26.2%), *Typha sp.* (4.8%), *P. australis* (4.2%), *Salix sp.* (>0.0%) and bare ground (5.7%).

3.2.2 Reed development over the years

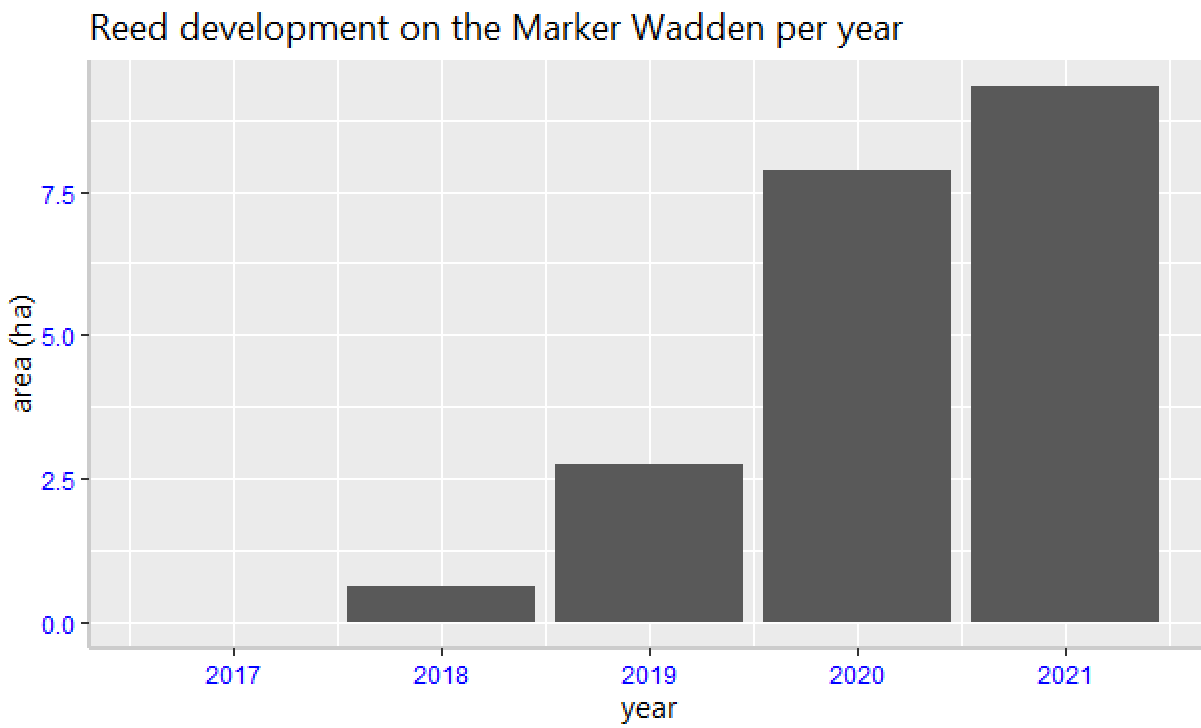


Figure 18. *Reed development on the Marker Wadden from 2017 to 2021.*

In 2017, no reed was observed. This increased by 0.6 ha reed in 2018, then by 2.1 ha reed in 2019, 5.2 ha reed in 2020, and finally by 2.1 ha reed in 2021 to reach a total area of 9.3 ha of dominant reed beds at the time of our study (figure 18).

3.2.3.1 Vegetation development activity: Reed sowing

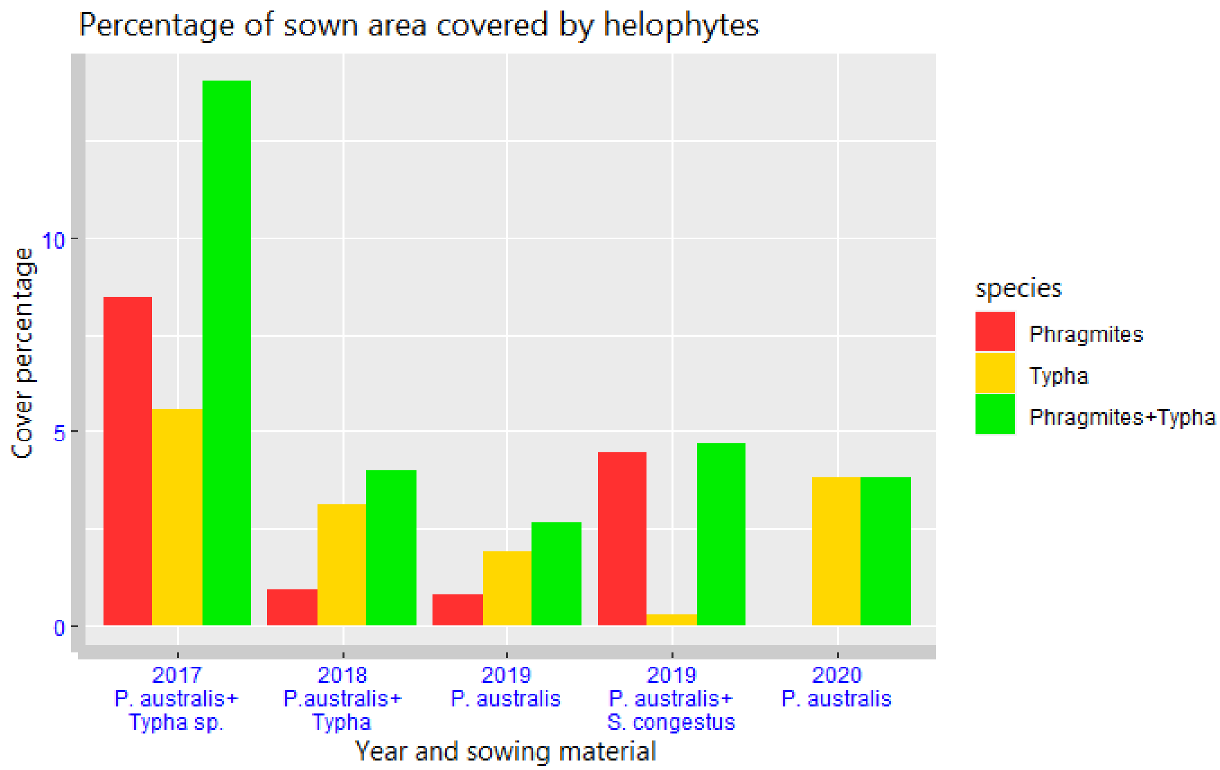


Figure 19. *Percentage of sown area each year overlapping with P. australis and Typha sp. dominant patches in 2021.*

Of the total 47 ha of reed sown in 2017, 6.5 ha eventually became helophyte dominated in 2021. This amounts to 14% of effectively sown area. Relative to the total area sown, this is the highest of all years. 8.4% of the helophytes were *P. australis* dominant (3.9 ha) and the remaining 5.6% being *Typha sp.* (2.6 ha) (figure 19).

Of the total 176 ha sown by reed in 2017, 7 ha became helophyte dominant in 2021. In absolute terms, the effectively sown area was the highest of all years. However, this amounted to only 4% of the total area sown. 0.9% of the helophytes were *P. australis* dominant (1.5 ha) and the remaining 3.1% was *Typha sp.* (5.5 ha) (figure 19).

In 2019, two seed mixtures were sown independent of each other. The first mixture contained seeds of *P. australis* exclusively. 1 ha of the total 39 ha where this mixture was sown became helophyte dominant. This comes down to only 2.7%. *P. australis* dominated in 0.8% (0.3 ha) of that and *Typha sp.* in 1.9% (0.7 ha) (figure 19).
The second mixture was *P. australis* seeds accompanied by *S. congestus* seeds. 0.65 ha of the total 39 ha sown with this mixture became helophyte dominant, which is an effectivity of 4.7%. *P. australis* dominated in 4.5% (0.62 ha) and *Typha sp.* in the remaining 0.2% (0.03 ha) (figure 19).

In 2020, 2.3 ha of the total 60 ha initially sown was dominated by helophytes. This is 3.8% of the total covered area. The helophyte dominant areas were exclusively *Typha sp.* There was no overlap with *P. australis* dominant patches (figure 19).

3.2.3.2 Vegetation development activity: Exclosures

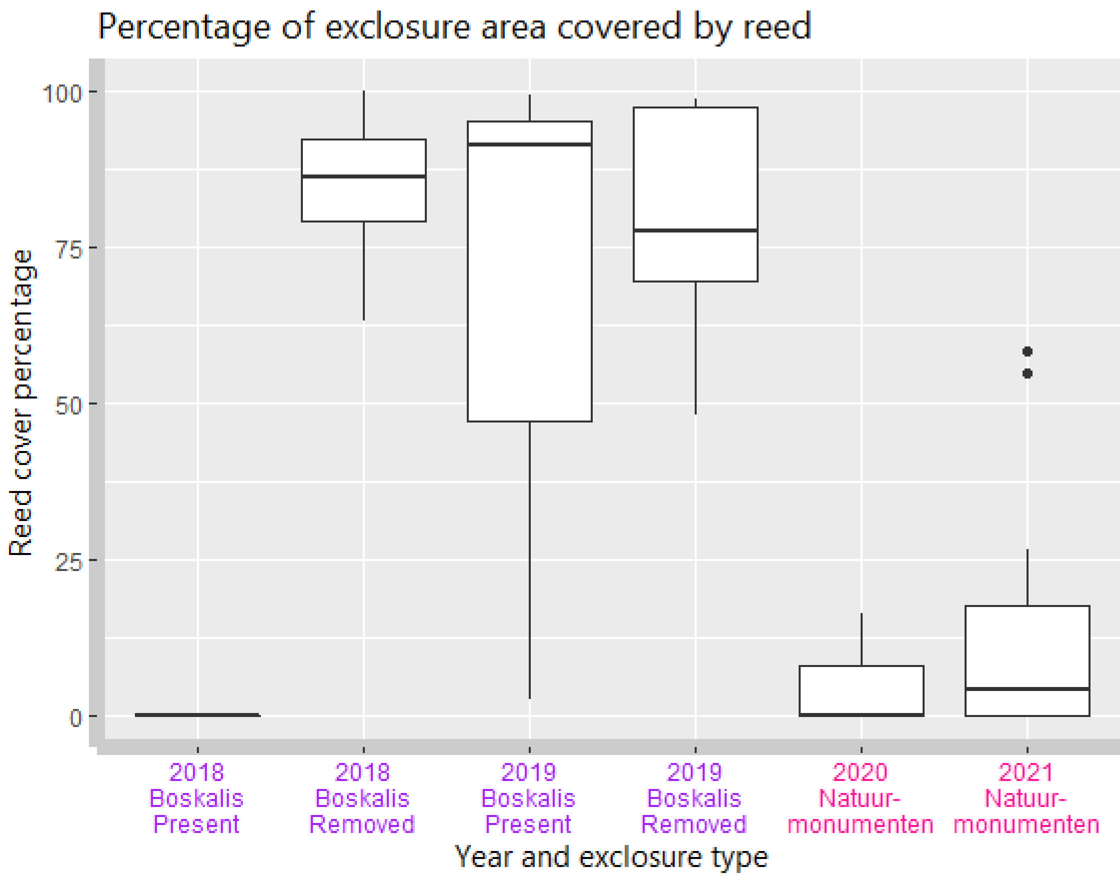


Figure 20. *Boxplot of cover% with reed in six exclosure types. From left to right: exclosures placed by Boskalis in 2018 that are still present (median: 0.0), exclosures placed by Boskalis in 2018 that were removed (median: 86.2), exclosures placed by Boskalis in 2019 that are still present (median: 91.3), exclosures placed by Boskalis in 2019 that were removed (median: 77.4), exclosures placed by Natuurmonumenten in 2020 that still exist (median: 0.0) and exclosures placed by Natuurmonumenten in 2021 that still exist (median: 4.0). Other parameters to these boxplots can be found in appendix B.*

The effectiveness of the exclosures can be divided into two categories (figure 20). The category low effectiveness is characterized by a median below 25 and comprises three types: 2018 Boskalis Present, 2020 Natuurmonumenten and 2021 Natuurmonumenten. The category high effectiveness is characterized by a median above 75 and comprises the other three types: 2018 Boskalis Removed, 2019 Boskalis Present and 2019 Boskalis Removed.

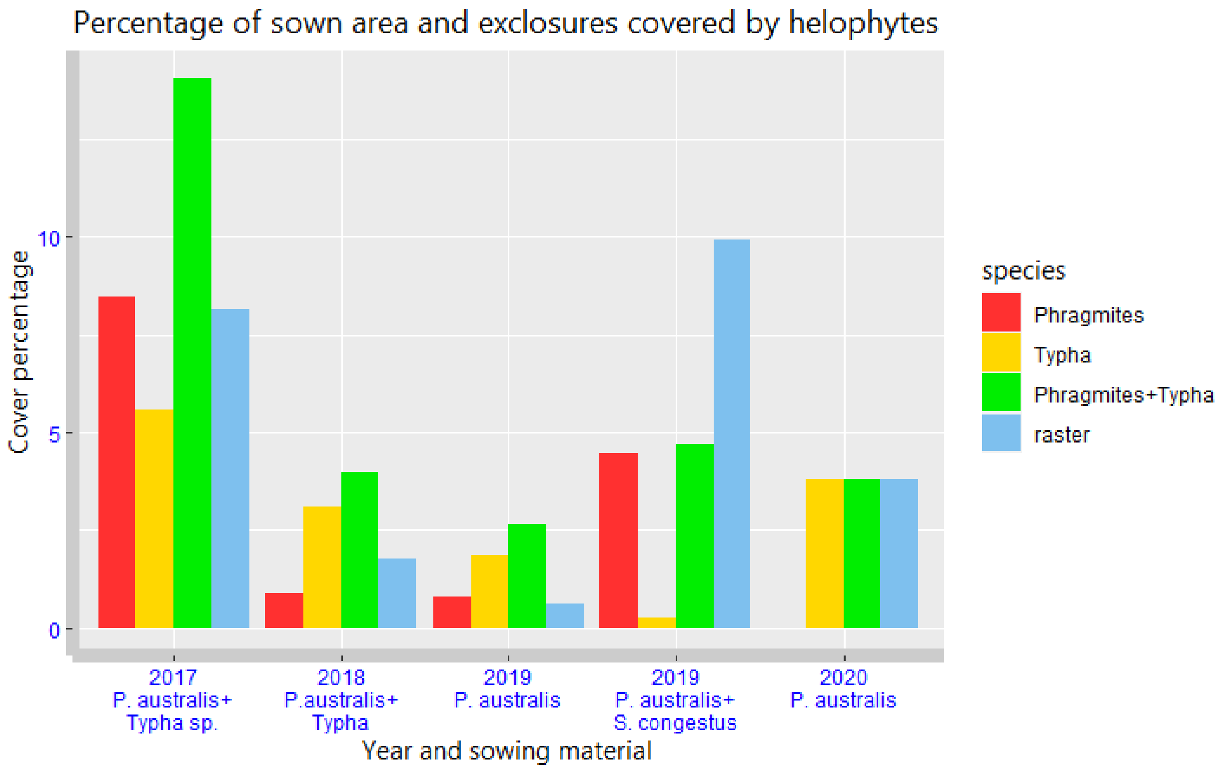
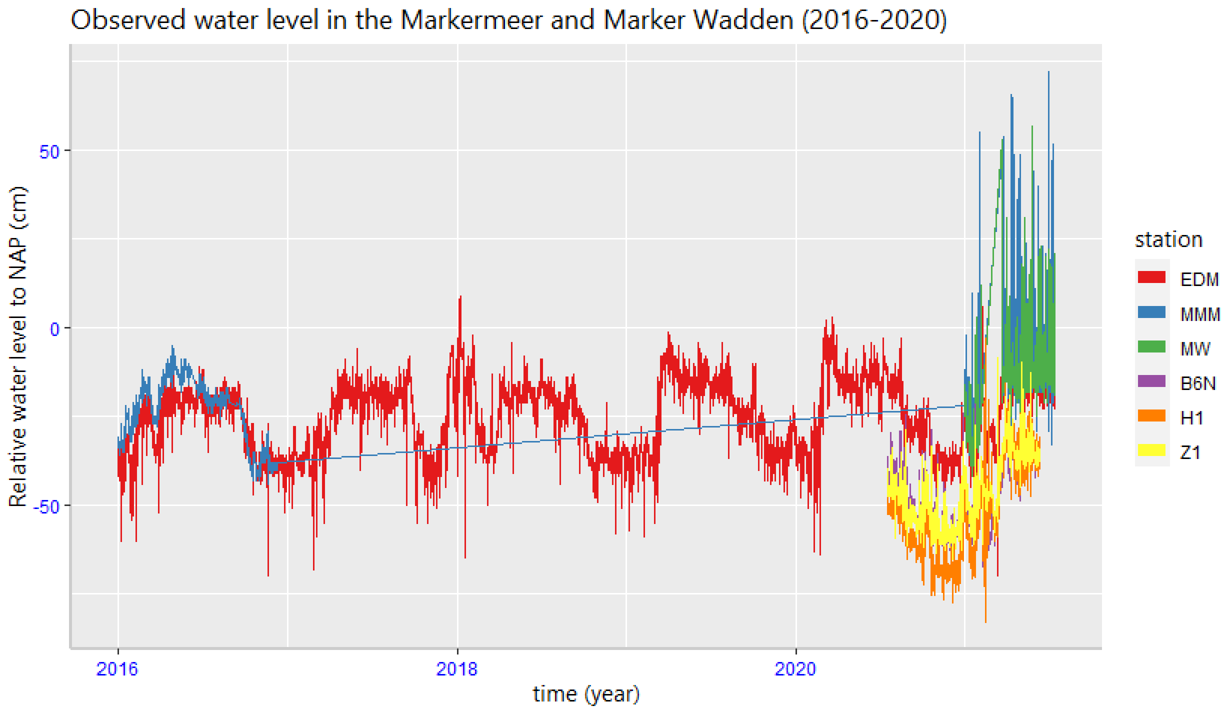


Figure 21. *Percentage of sown area each year overlapping with P. australis and Typha sp. dominant patches and with exclosures in 2021.*

In figure 21, we added the amount of overlap between the sown areas and the exclosures (without taking into account which category). The overlap between sowing and exclosures for 2017 was 8.1%, for 2018 it was 1.7%, for 2019 it was 0.6% without and 9.9% with *S. congestus*, and for 2020 it was 3.8%.

3.2.4 Water-wind



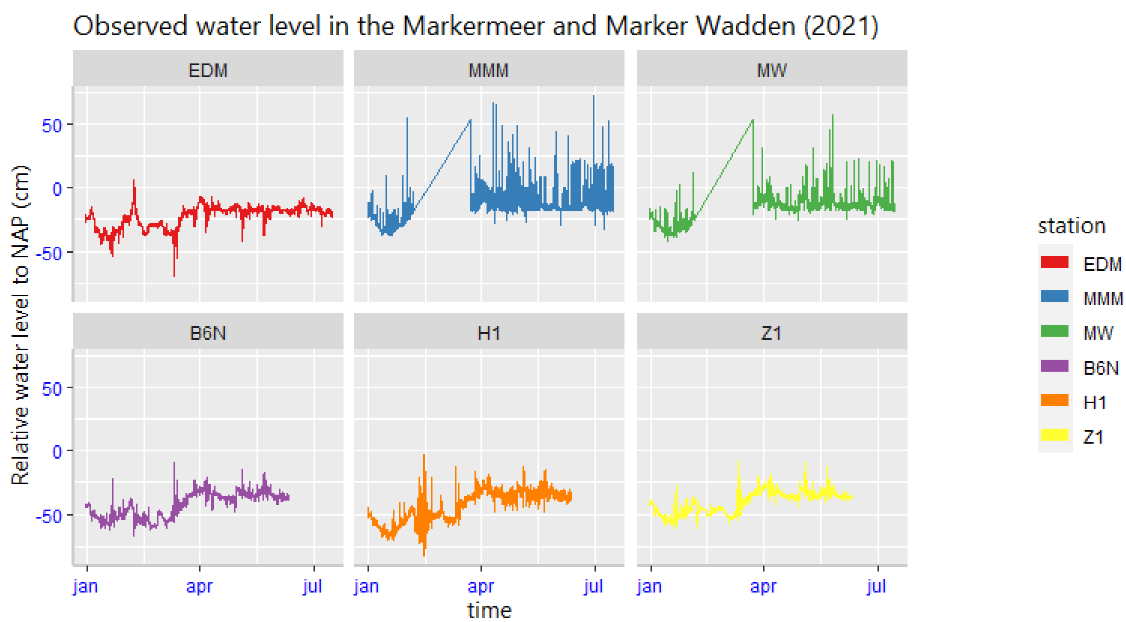


Figure 22a. (above) *Observed water levels from 1 Jan 2016 until 15 Jul 2021 of three stations within the Markermeer (EDM=Edam, MMM=Markermeer midden, MW=Marker Wadden [locations: see figure 5]) and three stations within the Marker Wadden (B6N=B6 North, H1=Harbor, Z1=Southern shore). For MMM, no data was available from 8 Dec 2016 to 30 Dec 2020. The stations around and inside the Marker Wadden (MW, B6N, H1, Z1) only started measuring from 2020/2021 because they were only installed since then.* **Figure 22b. (below)** *Observed water levels from 31 Dec 2020 to 15 Jul 2021 in the same stations, shown separately.*

Station Edam in figure 22a shows the seasonal variation of the water level in the Markermeer as a result of the management by Rijkswaterstaat. The water level fluctuates to around -20 cm NAP during the summer and around -40 cm NAP during the winter.
However, variation is also visible on a decaminutely scale (every ten minutes). These differences are generated by variation in wind, which causes water levels to constantly fluctuate.
Furthermore, figure 22b shows that there is a gradient in the water level of the Markermeer, which gradually increases towards the east. The west station of Edam measured an average water level of -23.7 m relative to NAP over the period 31 Dec 2020 until 15 Jul 2021. The middle station Markermeer midden and the east station Marker Wadden respectively measured -18.6 m and -16.9 m relative to NAP during the same period.

Also visible from figure 22 is that the water level within the Marker Wadden is structurally lower than the water level in the Markermeer with B6N measuring an average -42.5 m, H1 measuring -43.8 m and Z1 measuring -40.4 m relative to NAP during the same period.

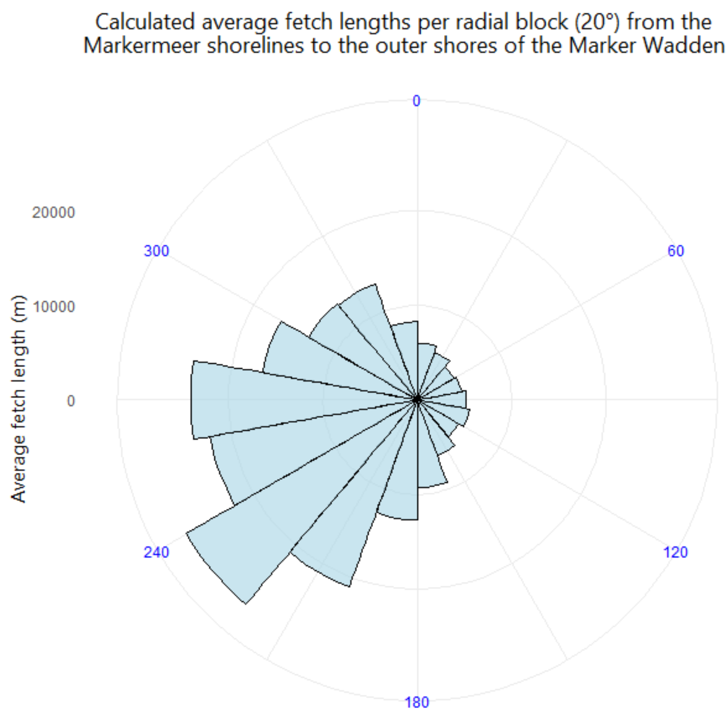


Figure 23. *Calculated average fetch lengths from the Markermeer shorelines to the outer shores of the Marker Wadden, split into radial blocks of 20°* ***.***

The most significant fetch lengths are found in the southwest, between 180° and 270°. The highest possible fetch length belongs to the radial block 220°-240°. Fetch lengths in the west (180°-360°, mean=17724 m) in general are higher than in the east (0°-180°, mean=5813 m) (figure 23).

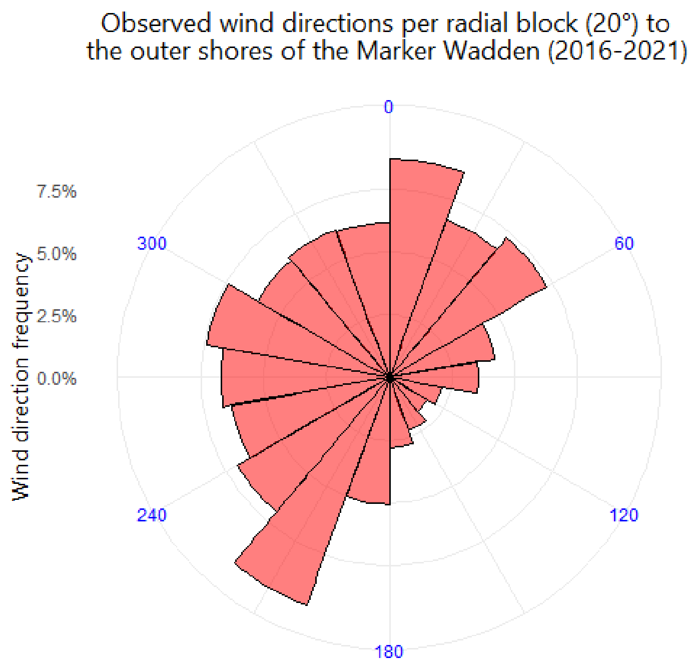


Figure 24. *Observed wind directions towards the outer shores of the Marker Wadden (2016-2021) split into radial blocks of 20°.*

The wind direction is most frequent from the southwest, with the absolute most frequent direction being radial block 200°-220° (10.5%). Overall, 60% of the wind direction frequency originates from the west and 40% from the east (figure 24).

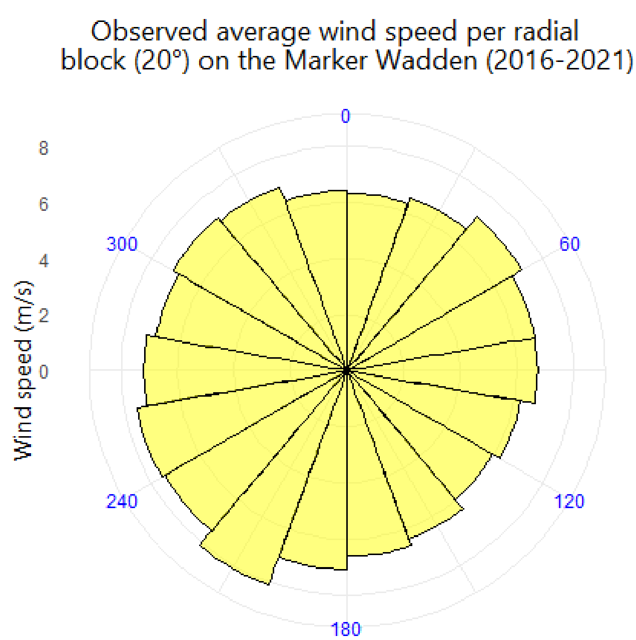


Figure 25. *Observed average wind speeds on the outer shores of the Marker Wadden (2016-2021), split into radial blocks 20°*

The observed wind speeds are slightly higher from the west than the east, with an average of 7.20 m/s (25.9 km/h) compared to 6.52 m/s (23.5 km/h) respectively. The highest average wind speed was observed from radial block 200°-220° (figure 25).

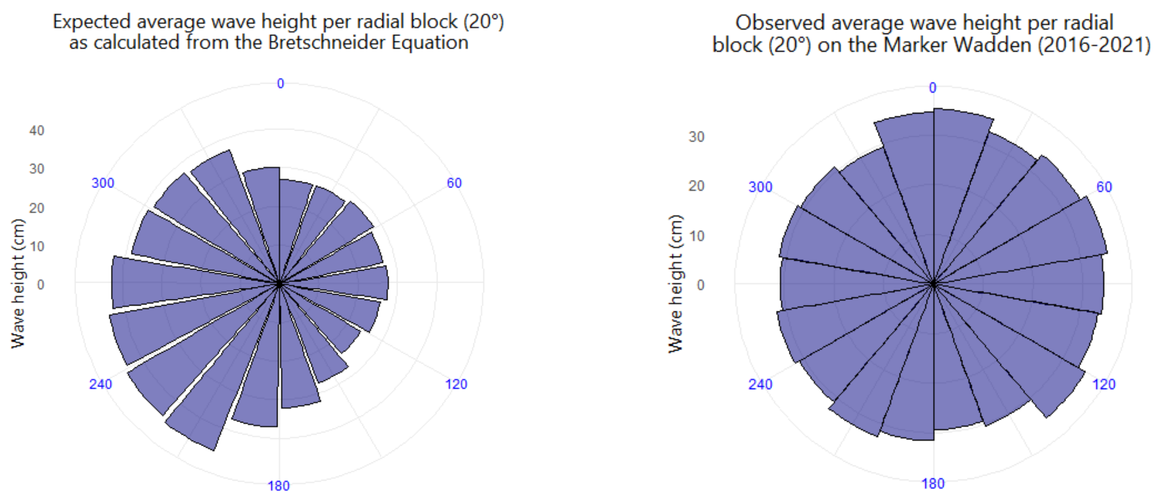


Figure 26a. (left) *Expected average wave heights around the Marker Wadden, split into radial blocks 20°.*
Figure 26b. (right) *Observed average wave heights around the Marker Wadden (2016-2021), split into radial blocks 20°.*

Figure 26a shows that the wave height is expected to be superior coming from the west (mean=39.8 cm) compared to the east (mean=27.3 cm), based on calculated fetch lengths and measured wind speeds. The mean expected wave height overall is 33.6 cm. Figure 26b, however, shows that this pattern does not emerge from the observed wave heights, with wave heights from the west (mean=31.6 cm) being slightly lower than waves from the east (mean = 33.3 cm). The mean observed wave height overall is 32.4 cm.

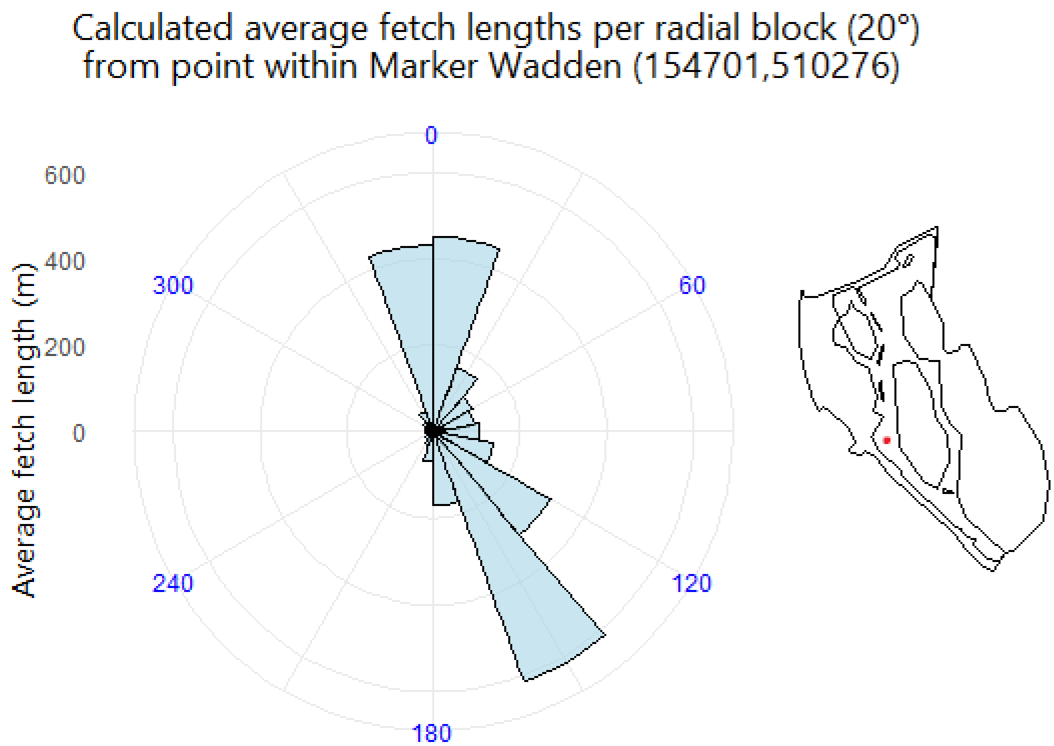


Figure 27. *Calculated average fetch lengths from a point within the Marker Wadden (location highlighted in red on the right) to the first encountered inner shoreline, split into radial blocks of 20°.*

Figure 27 demonstrates that the maximum possible fetch length from within the Marker Wadden is 614.6 m, along the southern shore Z1. Another major fetch length possibility is through the open water between the main island and the nature islands, north of the selected point. The average fetch length of the northern radial blocks 340°-0° and 0°-20° is 440.7 m.

3.2.5 Elevation

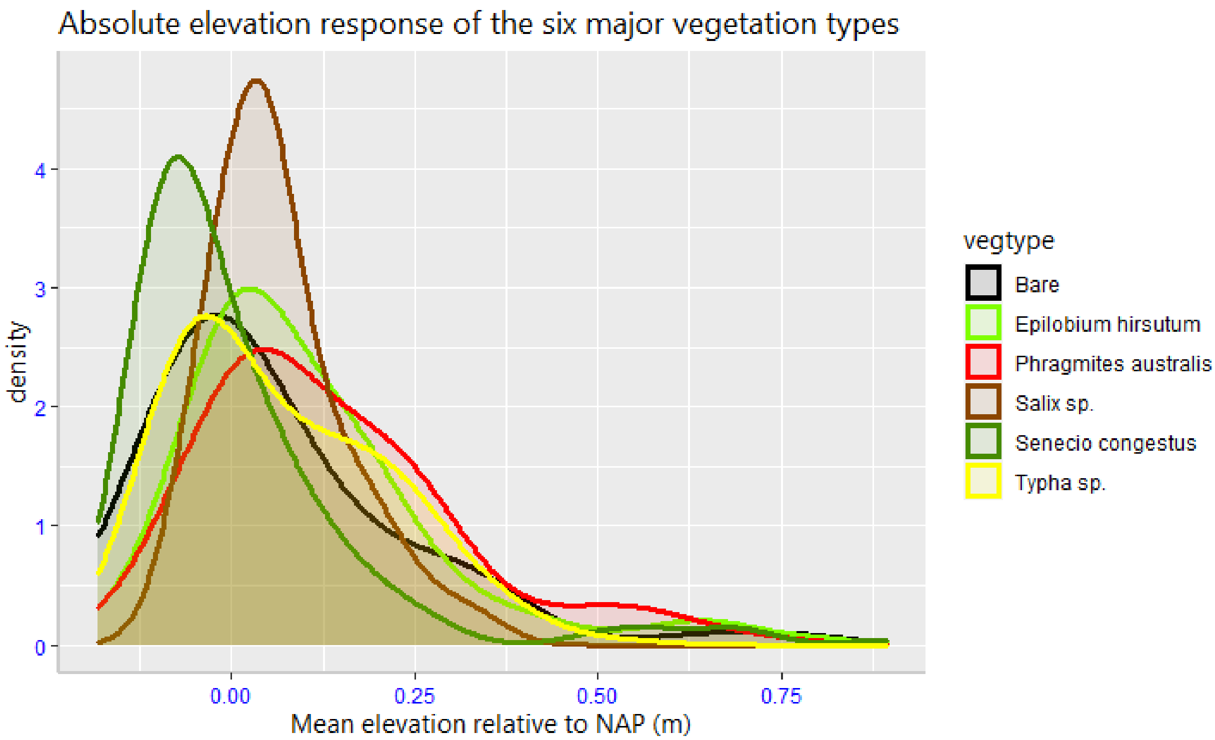


Figure 28. *Elevation density plot of the seven most major vegetation types, with absolute elevation in m relative to NAP on x-axis and density on y-axis. Peak average elevation levels of the vegetation types are: bare ground (-0.0311 m), E. hirsutum (0.0161 m), Typha sp. (-0.0473 m), S. congestus (-0.0800 m), P. australis (0.0329 m), Salix sp. (0.0399 m)*

Table 2. *Median absolute elevation of the six major vegetation types extracted from figure 28.*

Vegetation type	Median absolute elevation (m)	n
Bare	-0.0311	65
Epilobium hirsutum	0.0161	124
Typha sp.	-0.0473	153
Senecio congestus	-0.0800	188
Phragmites australis	0.0329	74
Salix sp.	0.0399	35

Table 3. *Relative elevation of the marsh compartments*

Compartment	Elevation of low water mark relative to NAP (m)
A1	0.0311
A2	0.0088
A3	-0.0591
B6	-0.0890
C1	0.2584
D1	-0.0948
D2	-0.1333
D3	0.0352

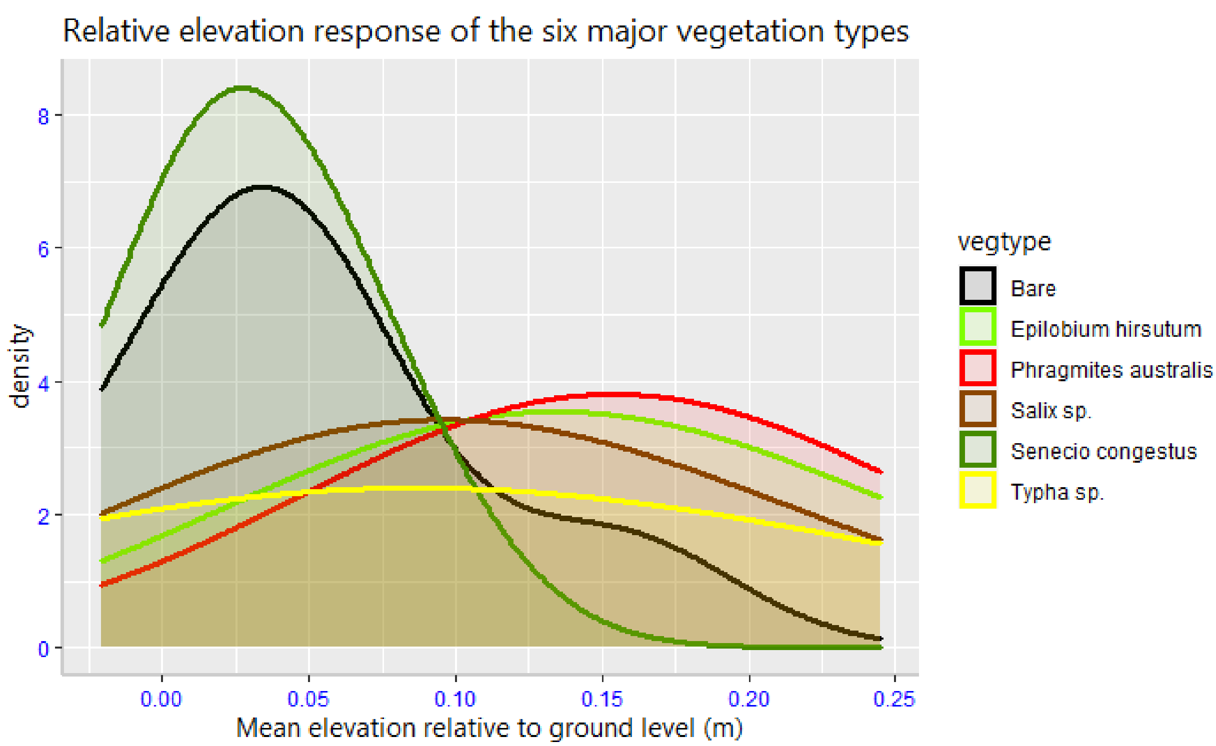


Figure 29. *Elevation density plot of the seven most major vegetation types, with mean elevation relative to low water table of each compartment in July 2020 in m on x-axis and density on y-axis. Peak average elevation levels of the vegetation types are: bare ground (0.0431 m), E. hirsutum (0.1131 m), Typha sp. (0.0533 m), S. congestus (0.0216 m), P. australis (0.1337 m), Salix sp. (0.0689 m)*

Table 4. *Median relative elevation (to the soil surface of each basin) of the six major dominant species, calculated from the zonal statistics for the different polygons (n) dominated by each species*

Vegetation type	Median relative elevation (m)	n
Bare	0.0413	65
Epilobium hirsutum	0.1131	124
Typha sp.	0.0533	153
Senecio congestus	0.0216	188
Phragmites australis	0.1337	74
Salix sp.	0.0689	35

First, the absolute elevation was assessed by comparing the median absolute elevation of each vegetation type in table 2. *S. congestus* on average appears on the lowest elevation (n=188) followed by *Typha sp.* (n=153) and bare ground (n=65). Above sea level, the first type of vegetation to occur is *E. hirsutum* (n=124). On higher elevations, we may find *P. australis* (n=74) and *Salix sp.* (n=35) at similar average elevation levels though *Salix sp.* is found slightly higher.
Subsequently, the relative elevation was assessed by comparing median relative elevation of each vegetation type in table 4. *S. congestus* on average appears on the lowest elevation (n=153) followed by bare ground (n=65) and then *Typha sp.* (n=188). A little higher than that is occupied by *Salix sp.* (n=35). At higher elevations of +10 cm above low water mark, we may find *E. hirsutum* (n=124) and *P. australis* (n=74) in that order.

4. Discussion

4.1 Construction

We chose to focus on the construction of the marsh compartments, since these are the only places in the Marker Wadden where reed is found, the focal vegetation type. We did find it important to mention the construction of the dikes, as these were essential in shaping the marsh compartments and regulating the water level within them.
The shores, beaches and dunes of the Marker Wadden were built simultaneously with the construction of the marsh compartments. However, the shores were built in a much more gradual fashion than the marsh compartments. Most of the days, sand has been deposited on the shores in some quantity. Therefore, one could state that the shores have been in construction all the time from 2016 till 2020. For this reason, as well as the fact that reed does not grow on the shore, we chose to exclude their construction in our results.
Quantities of holocene sediment and sand deposited in the Marker Wadden were not mentioned because we felt the amount of missing data is so significant, that it was impossible to tell a coherent story from it. Moreover, the quantity of sediment was not very relevant to our research, therefore we chose to omit it.

4.2 Vegetation

4.2.1. Vegetation mapping

There is no doubt that *S. congestus* was the most abundant species found on the Marker Wadden, comprising more than half of the total vegetation cover at 51.3% (figure 17) in 2021. This suggests that most of the vegetation cover is still in an early stadium as *S. congestus* is a pioneer species in marshy wetlands that tends to dominate the first year after soils fall dry (Clevering and van der Toorn 2000). The proportion of *P. australis*, which typically dominates in later stages of the hydrosere, being a mere 4.2% reinforces the argument that the vegetation development is still in its early stage.

Moreover, woody species such as *Salix sp.* are still found at very low densities over the Marker Wadden (figure 17). This fits the narrative that the vegetation development is in its early stages, but it may also imply that measures taken against woody species encroachment have been effective. Unfortunately, we have no historic data on woody vegetation presence and removal, thus we were not able to make an assessment on the effectiveness of water level management and willow removal on woody species encroachment.

4.2.2. Reed development over the years

In five growing seasons (2017-2021), a total area of 9.3 ha (4.2% of the total vegetation cover) has developed into dominant reed beds on the Marker Wadden. In this preliminary investigation, we related the total area of reed in the previous years starting from 2017, to the total area of reed in 2021. That means, however, that lost reed beds from previous years are untraceable. Therefore, we cannot rule out that reed area from previous years was not larger than we observed in our analysis.

After the first growing season (2017), no reed patches were observed (figure 18). Considering that the Marker Wadden were still in the midst of construction, and that efforts to develop the vegetation had not started yet, this is an expected result

After the second growing season (2018), 0.6 ha of land had developed into reed beds (figure 18). This suggests that sowing with reed seeds and rhizomes in the previous year was successful in promoting a relatively small reed bed.

After the third growing season (2019), an additional 2.1 ha of land had become reed beds (figure 18). This increase may be attributed to additional sowing activity with reed seeds and rhizomes, and placement of exclosures in 2018. However, it may also simply be the fact that sowing material of 2017 was given more time to establish. Indeed, the possibility that the activities of 2017 and 2018 have stacked cannot be excluded.

After the fourth growing season (2020), reed beds had established on an additional 5.2 ha of land (figure 18). This is the highest relative increase in reed area of all five growing seasons. Considering the difference compared to last year’s increase, this result suggests that the new measures taken in the previous year had an additional effect. The new measures were sowing reed with *S. congestus*, application of robust cores and additional exclosures. Once again however, the fact that activities in previous years were given more time cannot be ruled out.

After the last growing season in our analysis (2021), an increase of 2.1 ha of reed cover was observed (figure 18). Measures taken in the previous year remained the same as the year before, except that sowing reed with *S. congestus* was omitted. Interestingly, the increase observed after this growing season is similar to the increase two years ago, in 2019. If we compare the measures from last year to the measures in 2018, we find that they were actually quite similar, with the exception that rhizomes were applied in more robust cores in the later year. However, the passing of more time should again not be overlooked.

Though we cannot draw conclusions yet on which measures were the most effective in the vegetation development, we can say from this preliminary investigation that reed has developed throughout the years since the start of the vegetation development. The most significant increase was seen in 2020, which suggests the most effective measures were taken in 2019.

4.2.3. Vegetation development activities

Establishment success of the helophytes was largest for the areas sown in 2017 (figure 19). This number is consistently lower in the following years except 2020. These findings suggest that it takes a significant amount of time for helophytes to become dominant. However, there may be other explanations as to why reed seeds did not germinate as much as the first growing season. One possibility is that geese had not found the Marker Wadden yet during the first growing season. As a result, their seedlings did not have to endure high grazing pressure. Another explanation could be the extreme weather events after 2017. In particular, we highlight the heat waves that occurred in the summers of 2018, 2019 and 2020 (KNMI n.d.). Heat waves can decrease the germination rate of reed seeds by eliciting drought through increased evaporation (Orsenigo et al. 2015). However, there is also evidence that heat waves provoke seeds to take up bet-hedging strategies and remain ungerminated, causing a lower germination rate (Ooi 2012). Finally, we consider that increased passage of time also increased likelihood of willow establishment, which may have outcompeted reed seedlings.

In figure 20, a pattern is visible that shows reed establishment in older exclosures is higher than in newer exclosures. The observation “2018 Boskalis present” is an exception to this pattern, caused by an interference in the construction. This observation is a collection of nine exclosures found on compartment D3. This compartment was filled most recently somewhere in late 2019 / early 2020. The seedlings that grew within these exclosures became buried in holocene sediment and died as a result. In addition, since only a small portion of *P. australis* seeds germinate in their second year (ter Heerdt, 2016), the yield of second-year germinants from sowing in 2018 was not likely to establish a dominant reed bed. Since the next sowing moment on compartment D3 was in 2020, most of the clones that were visible during the field analysis could only have been one year old.

The older exclosures (“very effective” category) have over 75% reed dominance. Considering that the reed clones here were 2-3 years old max and the expected duration of reed dominance is four years, the growth within these exclosures is relatively fast. In the newer exclosures (“not very effective” category), we found less than 25% reed dominance. The most obvious explanation for this difference is that the older exclosures simply exist longer, thus the reed plants profited from the growth facilitation of the exclosures for a longer time. The reed plants in the newer exclosures were two years old at best, because these exclosures were placed around the sowing area of 2019. However, since the effectiveness of the exclosures has a similar relationship with time as

the effectiveness of reed sowing, the effect of exclosures may also be explained by the same grazing, extreme weather events and willow arguments given for the reed sowing.
A limitation to studying multiple activities with an overlap analysis is that it is not possible to conclude if an effect is fully attributable to one activity if there is overlap between activities. In other words, quantifying the effectiveness of reed sowing for example becomes unreliable when the sowing area overlaps with exclosures. This limitation is demonstrated in figure 21, where exclosures may explain half of the reed sowing effect in 2017. Because of this limitation, it was not possible to conclude whether sowing reed accompanied with *S. congestus* was more effective than sowing reed alone. Moreover, this applies too between sowing years as there is significant overlap in sowing area between years. In general, this implies that quantifying the effectiveness of reed establishment is not accurate with this method. However, we can make qualitative conclusions.

Both reed sowing and exclosures can contribute towards developing a dominant reed marsh. Our results demonstrate, however, that each activity alone cannot warrant the same effectiveness. Reed sowing alone lead to dominant reed establishment in only 14% of the total sown area in the best year. Exclosures on the other hand only serve to facilitate growth for seedlings. However, if the reed material is not applied beforehand, it would be irrational to expect an established reed bed within five years.

Reed dominance was expected after four years under semi-natural conditions from previous studies that were done in the Oostvaardersplassen (Clevering and van der Toorn 2000, Ter Heerdt 2016). However, we found that exclosures can accelerate this process by one or two years. Since the exclosures are mainly intended to reduce grazing pressure, our results also suggest that reed development is highly susceptible to grazing. This was also expected from the preliminary research that was conducted on the Marker Wadden and in nature area Loenderveense Plas (Bakker et al. 2018, Temmink et al. 2021).

4.2.4. Water-wind effects
In figure 22a, station Markermeer midden in 2016 corresponds well with Edam in the same period, except for a small period in the summer where the Markermeer midden level appears consistently higher. The pattern emerges again in 2021, but now both the Markermeer midden and Marker Wadden water levels are structurally higher than Edam. We found indeed that the water level of the Markermeer is higher in the east than in the west.
This observation is explained by the circular plots of the fetch length, wind direction and wind speed. Figure 23 demonstrates that the fetch length is undoubtedly the most significant from the southwest, meaning wave action from that direction is potentially the most severe. This effect is further reinforced by figure 25 as wind speeds from the southwest (radial block 200° - 220°) are the highest on average at 8.12 m/s. Moreover, figure 24 shows that the most frequently observed wind direction is from the same radial block at 10.5% of the total observations. This all adds up to a net effect of winds being structurally more severe and more frequent from the southwest. As a result, the water of the Markermeer is “pushed” more towards the east, creating a lateral skew in the Markermeer surface level with the east at a higher level than the west. This is exactly what

figure 22 demonstrates, as the water level of Edam in the west is structurally lower than the water levels of Markermeer midden and Marker Wadden in the east.

In figure 26a, we plotted the expected wave heights per radial block of 20° that were calculated using the Bretschneider equation. Expected was that wave heights are highest coming from the west, where fetch lengths are higher. The mean expected wave height according to the Bretschneider equation is 33.6 cm. In figure 26b, we plotted the observed wave heights per radial block of 20° from the data supplied by Rijkswaterstaat. The observations show us that the wave height from the west is not superior to wave height from the east, rather they are quite similar. The mean observed wave height was 32.4 cm. A t-test performed on the expected and observed wave heights yielded a *p-value = 0.5445,* meaning the observed wave heights are not significantly different from what we expected. This suggests that the Bretschneider equation is more precise than it is accurate for the Markermeer, as the means are not significantly different from each other even though the distribution of observations is very different.

Since the mathematical clarification of wave height by Bretschneider in 1964, the calculations have become more complex. It has for example yielded the Munk-Sverdrup-Bretschneider nomogram in figure 6, which takes into account the wind duration. As an example, the arrow at a 50 km fetch length estimates that a 200 km/h wind stretching over 50 km of sea for 3.5 h will yield waves of between 5-6 m (Rodolfo 2014). If we take for example the radial block with the largest fetch length (200° - 220°), we can apply a fetch length of around 28 km and a wind speed of around 30 km/h to the nomogram. We would then conclude that this input will yield waves of around 0.6 m (60 cm) if the wind was allowed to blow for two hours. The observed average wave height at this radial block was 31 cm, about half of what was expected from the nomogram. This might suggest that wind duration is also important for predicting wave height and should be taken into account in future studies.

A more important insight we can gather from figure 6 is that the origin of the x-axis is 2. This was done purposefully, as it indicates that a fetch length below 2 km is unable to generate high waves. Significant wave action can affect vegetation in different ways, including physical removal of the plant or plant parts as well as substrate type and stability (Roberts and Ludwig 1991). Figure 23 indicates that the fetch length from all radials is above 2 km, meaning the Marker Wadden is subject to wave action from all directions. For that very reason, the Marker Wadden is sheltered with dikes from all outside directions. Within the Marker Wadden, we can find open waters as well. However, figure 27 shows that the fetch length inside the Marker Wadden can never be higher than 2 km, meaning high waves can never be generated from the inside. Therefore, even if the marsh compartments were not reinforced with flood protection, wave action can never be high enough to pose a threat for the vegetation.

Of note, for the Bretschneider calculations, we used a water depth of 4 m for the Markermeer. We chose this value because the mean average water depth of the Markermeer is between 2 and 6 m (Rijkswaterstaat n.d.). We did not have the water depth data for any of the Markermeer stations, thus we could not relate the water-wind data to the water depth nor calculate a mean water depth from measured data. However, we did perform the calculations with the minimum and maximum water depth of the Markermeer and concluded that the calculated wave heights do not differ very significantly from each other. Nevertheless, it should be accounted for in the future.

4.2.5. Elevation effects

We used two ways of expressing elevation in our analysis: absolute elevation and relative elevation. We found two substantial differences between them.

First of all, the order in which the vegetation occurred on an elevational gradient was different. In absolute elevation, *Typha sp.* appears below bare ground whereas in relative elevation, it appears above bare ground. Moreover, *Salix sp.* appears at the highest elevation in absolute elevation, but it does not in relative elevation.

Secondly, expressing in relative elevation lead to higher values for all six vegetation types than expressing in absolute elevation. To add to that, three vegetation types (*S. congestus, Typha sp.,* bare) were found below sea level when expressed in absolute elevation. When expressed in relative elevation, however, we found none below water level. This suggests that the water level in the marsh compartments is lower than NAP, which is expected. Since the water level of the Marker Wadden is supposed to mimic the water level of the Markermeer, the low water mark should structurally be below 0 m NAP.

Since the differences between expressing in absolute or relative elevation are so substantial, we decided to only use relative elevation for our general elevation analysis. We chose this way of expressing the elevation because it directly relates the vegetational presence with the actual local water level, which is the main driving factor in the development of a riparian vegetation landscape. Any subsequent usage of “elevation” will refer to the relative elevation unless specified otherwise.

Consistent with our hypothesis, *S. congestus* appears on the lowest elevation (0.0216 m) below bare ground (0.0413 m), indicating that it is quite capable of surviving submerged conditions or at the very least moist soils. In the field, this was clearly visible as *S. congestus* was found abundantly in the center of compartments, where elevation is relatively low. Moreover, *S. congestus* was also commonly found as belts on river banks, standing directly between water and land as the first line of vegetation.

Bare ground is found next along the gradient followed by *Typha sp.* (0.0533 m) at a one cm increment. We had indeed expected *Typha sp.* to appear as the first helophyte along the elevational gradient as it prefers submerged conditions and dominates earlier in the hydrosere than other helophytes (Clevering and van der Toorn 2000). We had, however, expected *Typha sp.* to appear below bare ground but this was not the case. We assume that bare ground manifests as such because it is submerged for such a significant portion of the time, that barely anything can grow here. Apparently, submersion at that magnitude is unfavorable for *Typha sp.* germination. Considering the small increment though, we may conclude that *Typha sp.* can grow on soils that may be subject to moderate submersion.

Furthermore, we found an elevational distinction between helophyte species. *Typha sp.* appears on the lowest elevation, followed by *E. hirsutum* and then *P. australis*. This demonstrates a parallel between the elevation and the expected successional cycle. In the first phase of succession,

pioneer vegetation such as *S. congestus* starts to colonize the bare soil. In the next two years, *Typha sp.* is expected to outcompete *S. congestus* and become dominant. In later years, *E. hirsutum* and eventually *P. australis* are expected to adopt that behavior (Ter Heerdt 2016).
Salix sp. (0.0689 m) was found after *Typha sp.* along the elevational gradient at an increment of 1.5 cm. We did expect *Salix sp.* to be found at higher elevations, however we did not expect it to be found lower than *E. hirsutum* (0.1131 m) and *P. australis* (0.1337 m). This conflicts with our hypothesis that woody species such as *Salix sp.* would dominate the highest elevational plane where soils contain increased amounts of organic matter and the water table is low. Figure 29 suggests that willows can establish along a wide range of elevation. A study by Southall *et al* on willow carr forests discussed that some species of willows are able to establish along a moisture gradient due to a more complicated root system (Iremonger and Kelly 1988, Southall et al. 2003). This would allow for increased respiration and detoxification, increasing their tolerance (Talbot et al. 1987). Therefore, willows can be found much closer to streams at lower elevational zones than we expected (Amlin and Rood 2001). Additionally, a review on forest succession by Finegan *et al* in 1984 found that willows behave more as pioneer tree species compared to other woody species such as the oak (Finegan 1984). We were most likely wrong to assume that willow establishment is indivertibly the next successional stage of a reed marsh. Willows can definitely dominate in the final stage of a hydrosere (Penfound 1952), but they do not necessarily have to succeed a reed marsh.
We think too, however, that time is another factor which has not been considered. Though we found no studies that specifically studied the duration of a willow carr hydrosere, we did find a study by Penfound in 1952 on American swamps and marshes that claimed it took between 30 and 50 years for a body of open water to transform into a red mangrove swamp, *Rhizophora mangle* (Penfound 1952). Of course, the two species are very different and occur in different geographical habitats, but they are both woody species that pose as an end stage species in a hydrosere. Considering the magnitude of time that it takes for a mangrove hydrosere to reach such a stage, it is likely too early to observe afforestation on the Marker Wadden.

If there is indeed a positive correlation between hydrosere and elevation, the expectation is that all land now dominated by *S. congestus, Typha sp.* and *E. hirsutum* will eventually turn into *P. australis* if given enough time. How much time it takes is of course dependent on which vegetation type dominates at the moment. It is expected that a *S. congestus* dominant area will take longer to become *P. australis* dominant (through natural processes) than it will for an *E. hirsutum* dominated area. However, this process does not have to start with *S. congestus* as pioneer vegetation. Some areas are naturally at a high elevation, such as the spray points from where the compartments are filled with holocene sediment. These areas were predominantly colonized by *E. hirsutum* already, which may accelerate the development of the reed marsh. The new insight we gathered, however, is that willows are able to establish as an intermediate species between pioneer vegetation and reed marsh, thus it is important to maintain the countermeasures against their spread.

Another process relevant for the future management is the anticipated subsidence of the marsh compartments. This decrease in elevation may lead to vegetation regression instead of succession, reducing further woody species establishment at least in the short-term. It is expected that subsidence will gradually reduce over time, thus it should not be relied on in the long-term. In the meantime it is expected that during 2021, the absolute elevation of the main island and island D1 will descend 5-10 cm and on the other nature islands 20-25 cm (figure 16). Since the average elevation difference between *P. australis* and *Salix sp.* is around seven centimeter, the subsidence in or within a year may be severe enough to make elevation more favorable for willows rather than reed or worse, the subsidence may be so severe that plains become permanently inundated so that both species cannot establish.

Increased subsidence will result in increased inundation of the soil. An already established reed bed would be able to survive under these conditions using their intricate developed root system, but reed seedlings can not (Mauchamp et al. 2001). For systems that are yet in an earlier successional stage of a reed marsh, the subsidence will most likely slow down succession to reed marsh even more. Conditions might become so unfavorable that only pioneer vegetation can settle, provided that the soil falls dry every now and then. However, for areas where the reed marsh is already established, the subsidence is less likely to eradicate it while succession to willow forest is impeded. This is, however, provided that subsidence is not too large. Despite their more developed root system, long term and deeper inundation increases the chance of root destabilization and subsequently vegetation regression.

What consequences does this have for the reed marsh development of the Marker Wadden? In general, we can create two scenarios that are based on the subsidence categories of the marsh compartments. The main island and island D1 are expected to subside 5-10 cm during the year 2021. On these islands, we may find reed marshes locally near the dikes while the center of the compartments are predominantly colonized by earlier successional stages (figure 17). This is expected, since the soil around the dikes is at a higher elevation than around the center. Most willows are found in the center of the compartments, where the elevation is lower. In this case, the subsidence will contribute to the reed marsh in two ways. First, since the subsidence is not that severe, the likelihood of an established reed marsh to survive the inundation increases. Moreover, this hampers succession in those areas, maintaining the reed marsh for a longer time. Second, the subsidence will lead to more land inundation which in the long run may prevent establishment of willows. The mild degree of subsidence will probably not be enough to eradicate the willows that have already established though. Removal of willows should probably be continued on these islands.
The other scenario applies for the nature islands C, D2 and D3 that were last filled more recently. These islands are expected to descend by 20-25 cm during 2021, a considerably more severe subsidence than other islands. Overall, these compartments are categorized mostly by pioneer and intermediate vegetation. Reed marshes are not found here. Willow vegetation is found locally in small quantities. The subsidence possibly has the following consequences for the reed marsh development. First, because a reed marsh has not developed here yet and the subsidence is quite severe, establishment of a stable reed marsh will require more time. Apparently, the elevation was not suitable in the first place for reed development but the expected subsidence will only reinforce this. At the same time however, willow establishment and expansion will become very unlikely on these islands. In principle, the same effect applies as for the main island and island D1, but in this case the effect is exaggerated making it even more difficult for willow

colonization. Whether the already established willows can survive the resulting conditions is unsure as their roots are known to be quite stable (Iremonger and Kelly 1988, Southall et al. 2003). Nevertheless, considering the relatively low area of willow vegetation and the extremely unfavorable conditions in the future, it is probably worth the effort to remove them on these islands.

5. Conclusion

In this thesis, we set out to document in detail and in one database, the construction of the Marker Wadden from the initial land reclamation in the Markermeer to the characterization of the vegetation structure that would establish from that activity.

We found that the Marker Wadden foundation was created in a phased manner, starting with the main island and island D1 (finished 2017) to the nature islands C, D2 and D3 (finished 2020). The reed marsh was developed by Boskalis and Natuurmonumenten through the following activities starting from 2017: reed sowing, exclosure placement, willow removal and water management to prevent establishment of woody species. We saw an increase of reed presence on the Marker Wadden starting from 2018 in our vegetation change analysis, meaning the sowing activities were at least effective. The effectiveness of the sowing activities alone proved to be limited. However, combining reed sowing with strategic exclosure placement was very effective in developing the reed marsh.

In addition, we found a water-wind dynamic in the Markermeer that is predicted by fetch length and wind speed. This dynamic is able to create a skew in the water level, which we found in the Markermeer where the water level in the east is higher than in the west. We, however, concluded that the fetch length within the Marker Wadden can never be significant enough to create high waves that may disrupt the marsh vegetation. But the wind effects may lead to a wind tide that can affect the future biogeomorphological dynamics of the area. Finally, we quantified the elevation zonation of the dominant plant species, relative to the low water mark in July 2020. However, we found that willows did not necessarily occupy the stage after a reed marsh which may make nature management more complicated. We predict from our analysis that the reed marsh on the main island and island D1 can withstand the expected subsidence and that willow germination will decline. Additionally, we predict that the subsidence on islands C, D2 and D3 (where no reed marsh has developed yet) will delay the development of a reed marsh and at the same time effectively counter willow establishment. Main uncertainties around the expected ecological change are related to the future dynamics of the graylag geese population, and the further development of the soil subsidence process.

6. Literature

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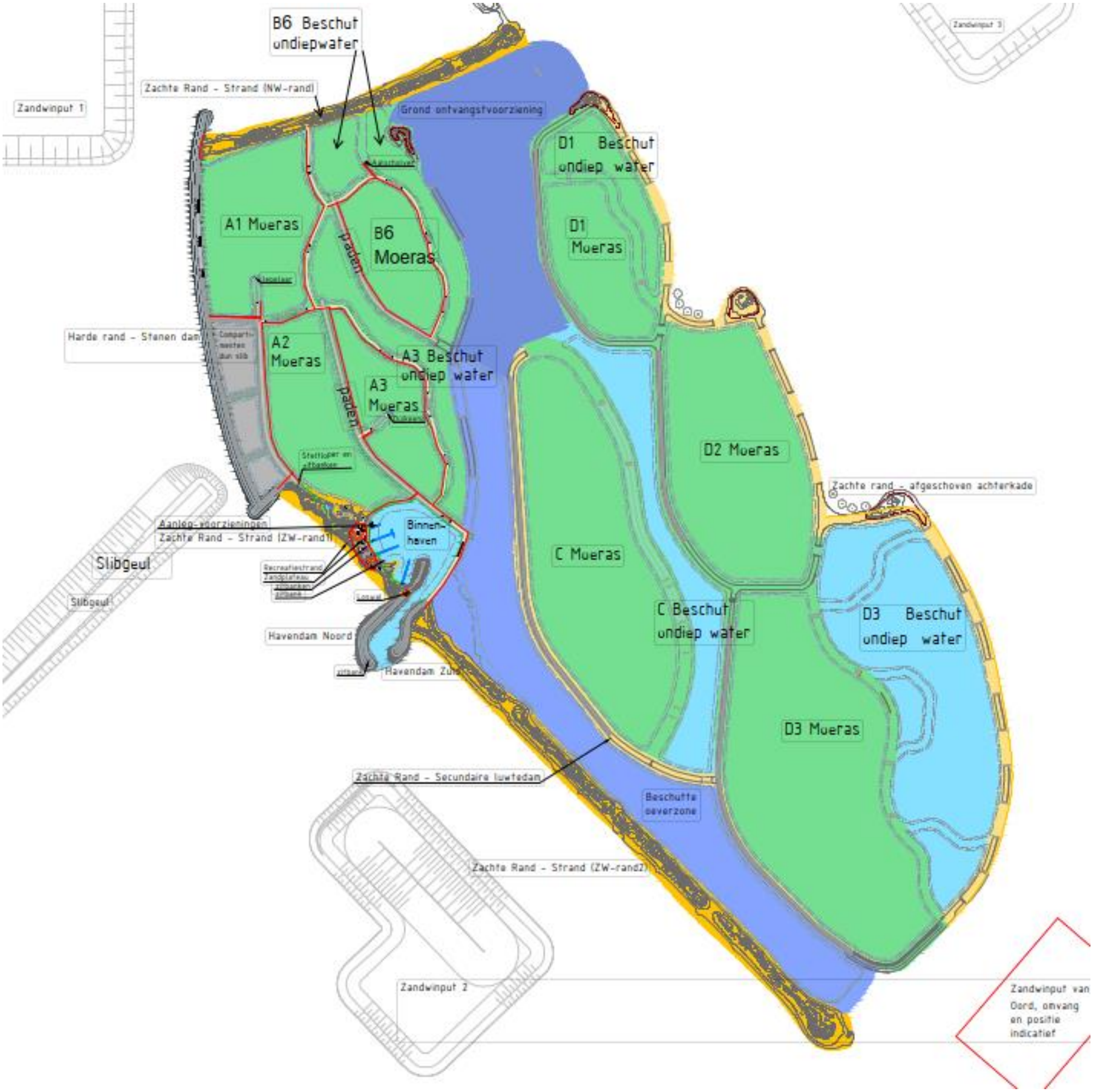
7. Appendix

Appendix A. Original design of the Marker Wadden as drafted by Boskalis (Boskalis, 2015)



Appendix B. Visualization of the elevation margins (red dotted lines) for the final soil surface (in brown). Margins are not relevant for the sand dikes (yellow). The illustrated margins are not precisely proportionate to the actual elevation in relation to the Markermeer.