10-years evaluation of the Sand Motor

Results of the Monitoring- and Evaluation Program (MEP)
for the period 2011 to 2021

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Summary

In 2011 the large-scale sand nourishment 'The Sand Motor' was constructed (21.5 million m^3) with the aim of gaining experience with innovative nourishments that combine recreational, natural and coastal maintenance functions and strengthen the Delfland coast. Unique about the Sand Motor is that it can freely reshape over time as a result of natural coastal processes. Waves, tidal currents and wind redistribute the sand along the coast and to the dunes.

The development of the Sand Motor in the period from 2011 to 2021 was evaluated for Rijkswaterstaat. The objectives in the Environmental Impact Assessment (EIA), that were set prior to the realization of the Sand Motor, are leading for this evaluation. These are:

I. Stimulate natural dune growth at the coast of Delfland for the benefit of safety, nature and recreation;
II. Develop knowledge and innovation;
III. Add attractive (temporary) recreational and natural area.
IV. Management objectives, aiming at recreational safety (e.g. for swimmers), impact of recreational use on nature and effects of the Sand Motor on groundwater, vegetation in the existing dunes and infrastructure.

I : Stimulate natural dune growth

The Sand Motor has created natural dune growth at the Delfland coast. The first dune row was growing gradually with 14 $m^3/m/year$, contributing to long-term protection of the Delfland coast. Since 2016 also new small dunes ('embryonal dunes') developed at the Sand Motor. The growth of these embryonal dunes was less substantial than anticipated (especially in the first years after realization), which is due to the catchment of wind-blown sand in the dune lake and lagoon. The high level at which the peninsula was constructed also resulted in a lower sand supply to the dunes. So, a mega sand nourishment, such as the Sand Motor, promotes natural dune growth, but the design has a large influence on the rate of dune growth. If quick dune growth is desirable, it would be better to design the peninsula of the Sand Motor with a lower crest height and without a dune lake or lagoon.

II : Development of knowledge and innovation

A large number of research programs were initiated because of the presence of the Sand Motor. This has substantially advanced our understanding of the physics of large-scale nourishments, has kicked-off new innovations in measurement techniques (e.g. with drones) and provided the right setting for the development of generically applicable numerical modelling techniques. The new knowledge is already applied in other projects, such as for the Hondsbossche Dunes. Also the measurement data can still be used for years to strengthen the knowledge base of the coastal system, and to provide the opportunity to prepare ourselves for the future challenges, especially in relation to an accelerating sea level rise. The Sand Motor is therefore not just aimed at protecting us from the current coastal safety threats, but moreover to ascertain long-term coastal safety. The international attention that was raised by the Sand Motor is beneficial for the coastal engineering sector.

III : Addition of attractive recreation and nature area
The Sand Motor adds extra recreational options to the Delfland coast. Hikers, runners, bathers and kitesurfers are the most important users. They appreciate the Sand Motor more than regular nearby beaches. Remarkable was the unforeseen use of the Sand Motor, such as artists making sand sculptures, cultural groups organizing meetings and archeologists and paleontologists collecting historic items. These spontaneous developments show us that the absence of planning did not hinder, and may even have created the required room for these types of societal use of the Sand Motor.

Over time the landscape at the Sand Motor got a high degree of naturalness. The marram grass promoted the growth of new (embryonal) dunes at the Sand Motor. The vegetation growth was, however, very limited in the first five years. Since 2015 the vegetation growth accelerated substantially. The relatively slow vegetation growth in the first years is especially due to the impact of driving with cars on the beach and cleaning of the beach.

The number of benthic animals increased after the realization of the Sand Motor. It is not clear whether the Sand Motor is responsible for these changes. It is clear though that the Sand Motor introduced more variation in the environmental conditions (e.g. sediment and flow velocities) which led to an increase in the diversity of the benthic communities. A large number of birds used the Sand Motor for resting and foraging, but only a few breeding birds were observed due to the disturbance by beach users. In conclusion, the Sand Motor developed into an attractive natural and recreational area. In the design phase, decisions can be made about the prioritization of these natural and recreational functions.

IV : Management
Management had to take place at and around the Sand Motor to sustain the recreational safety and to regulate the effects of recreation on nature development (such as vegetation growth on the beach). Management is also required to mitigate the potential effects of the Sand Motor on the nature in the existing dunes, the groundwater and sedimentation of nearby harbor entrance channels.

The swimmer safety at the Sand Motor was well manageable thanks to the work of the lifeguards. The risks of rip currents were even lower at the Sand Motor than for the surrounding coastline, although currents with high flow velocities did exist occasionally. These high flow conditions occurred predominantly on sections of the Sand Motor with a larger distance from the beach entrances (such as at the peninsula) or during extreme weather conditions. Therefore, the number of beach users was small during these conditions which limited the risks for swimmer safety. Nature management on the Sand Motor has been very limited, because the Sand Motor was meant as an open area without a mandatory delineation of natural and recreational areas. Vegetation and embryonal dunes on the Sand Motor therefore developed at a lower rate than anticipated, especially because of the driving with cars. Also the cleaning of the beach with tractors has slowed down the vegetation growth.

The conditions in the dunes of Solleveld, landward of the Sand Motor, are somewhat influenced by the Sand Motor. The sand and salt spray were reduced, which enhanced the growth of sea buckthorn. This was counter-acted by applying dune management in Solleveld, such as the removal of sea buckthorn and the creation of blowout zones in the dunes. The Sand Motor has had no impact on the groundwater level in the dunes, because drainage tubes were placed. A significant accretion of the navigation channels of Scheveningen and Rotterdam could not be found in relation to the Sand Motor.

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1 Introduction

1.1 Background of the Sand Motor

The 'Sand Motor' sand nourishment was placed on the Delfland coast in 2011. This large sand buffer was aimed at protecting the coastline as well as providing a co-benefit for other coastal functions (Figure 1.1). The coast between Ter Heijde and Kijkduin has been shifted seaward by up to 1000 meters over an alongshore length of two kilometer. In total about 21.5 million m^3 of sand was nourished on the coast. The sand of the Sand Motor will be redistributed along the coast over time as a consequence of the reworking by the waves and currents, which will result in a strengthening of both the adjacent coast and the dunes.

Figure 1.1 Sand Motor after realization in 2011 (Rijkswaterstaat / J. van Houdt)

About 128 hectares of land were added with the realization of the Sand Motor, which were meant for recreation and nature. A lagoon is present at the northern side of the Sand Motor just landward of the hook-shaped peninsula. The lagoon is sheltered from the waves and currents, which creates a different ecological habitat than the unprotected coast.

1.2 Aims of the Sand Motor & Evaluation questions

The aims of the Sand Motor were formulated in the Environmental Impact Assessment (DHV, 2010a), resulting in the following objectives:

I. Stimulate natural dune growth in the coastal area between Hoek van Holland and Scheveningen. This dune growth should provide a benefit for the safety, natural and recreational functions;
II. Development of knowledge and innovation. To answer the questions to what extent coastal maintenance can be of added value for recreational and natural functions, and whether these can be realized together;
III. Addition of attractive (temporary) recreational and natural area to the Delfland coast.

The fourth objective is to evaluate the 'management of the Sand Motor and its surroundings'. The focus is on recreational safety (e.g. swimmer safety, cliffs and quicksand), ability to combine recreational and natural goals and prevention of adverse impacts on groundwater, natural values of the existing dunes of Solleveld and port entrances.

Questions were formulated to concretize the actual assessments of the impacts of the Sand Motor in this evaluation (see Table 1.1). The answers are described in this document in relation to changes in the environmental conditions, nature development and recreation. A concise answer to the questions can be found in Appendix A. The following questions are discussed :

Table 1.1 Overview of the evaluation questions and chapters

Chapter :	3	4	5	6
EIA 1 : Dune safety				
1-1: Does the Sand Motor contribute to long-term preservation of the coastal foundation and basis-coastline between Hoek van Holland and Scheveningen? To what degree will this lead to natural dune growth?	■			
EIA 2 : Knowledge development and innovation				
2-1: Does the Sand Motor create new physical system knowledge on the realization of coastal maintenance with an added value for recreation and nature?	a		b c	
2-2: What is the added value of a mega-nourishment, such as the Sand Motor, for nature when compared to regular nourishments? And which aspects are creating this added value?	a	b		
2-3 : What spin-off is created for knowledge and innovation?				■
EIA 3 : Nature and recreation				
3-1a: Does the Sand Motor add attractive natural area on the Sand Motor and in the young foredunes seaward of the existing dunes?		■		
3-1b: How does the temporary new nature develop in the intertidal area and the lagoon of the Sand Motor?		■		
3-2: How did the appreciation of the coast between Hoek van Holland and Scheveningen change as a result of the Sand Motor?			■	
Management :				
4-1: Are there adverse impacts of the Sand Motor for recreational safety? Can these effects be mitigated with management measures? Was the management protocol sufficient?			■	
4-2: To what degree can recreation and nature development goals be united on and around the Sand Motor?			■	
4-3: Is it possible to prevent adverse impacts of the Sand Motor on the groundwater?			■	
4-4: Are there adverse impacts on the natural values of the existing dunes? Can they be prevented? How can they be mitigated?			■	
4-5: What adverse effects of the Sand Motor can be present for the wet infrastructure, such as navigation channels and outfalls? Can these effects be mitigated?			■	

Rijkswaterstaat, the Province of Zuid-Holland and Dunea made a covenant wherein they agreed to jointly carry out the monitoring of the Sand Motor as well as the assessment of the evaluation questions (i.e. the questions from the Environmental Impact Assessment and the management questions). The evaluation of the morphological and ecological development of the Sand Motor, related to the dune growth and the spreading of the sediment, are the responsibility of Rijkswaterstaat. The Province of Zuid-Holland is responsible for the questions with respect to recreation (in relation to nature) and management (e.g. swimmer safety and impacts on dunes of Solleveld). The impacts of the Sand Motor on groundwater are monitored by Dunea.

1.3 Context

This report provides an overview of the findings of the monitoring and evaluation program (MEP). In this document the development of the Sand Motor is described in relation to safety, nature and recreation for the period from 2011 to 2021. The information from the monitoring is used as a basis for the evaluation (DHV, 2010b; Tonnon et al., 2011). Also, the knowledge development and innovations that were generated from the project are described. Reference is made to the previous evaluation of the first 5 years of the Sand Motor (Taal et al., 2016), which is used as a base for this study.

Detailed information on the measured parameters and analyses can be found in the underlying reports for each of the monitoring parameters (e.g. Ecorys, 2020; Wijsman et al., 2020; of donk et al., 2020; WUR, 2020; Arens, 2021; Huisman et al., 2021; IJff et al., 2021; Vertegaal, 2021). The emphasis in this report is on the presentation and evaluation of physical developments in the subregions of the Sand Motor. No judgment is given on the Sand Motor project as a whole.

Besides this 10-year evaluation report of the physical changes at the Sand Motor, also a governance evaluation was carried out in 2021

(Rebel Group, 2021). That report judges the degree to which the three policy aims (from the EIA) and the management goals have been achieved, using this report as a reference for the evaluation of changes at the Sand Motor. Attention is also paid to the more project related aspects of the Sand Motor program, such as the realization of the project and the collaboration between stakeholders.

1.4 Readers guide

This report is structured as follows:

- Chapter 2 explains the background of the Sand Motor, the Dutch water policies, and the decisions that were made to select the location and the design of the Sand Motor.
- Chapter 3 contains information on the landscape development, which encompasses coastal changes, dune growth, cliff development, and changes in tidal currents, bed sediment composition and the sediment balance.
- Chapter 4 describes the nature development at and around the Sand Motor, which encompasses the impacts of the Sand Motor on benthic species in the shoreface and lagoon, vegetation and dune growth at the beach and in the dunes, and effects on birds, fish and mammals.
- Chapter 5 discusses the appreciation of the Sand Motor by beach users, the societal functions, the recreational management and environmental impacts of the Sand Motor.
- Chapter 6 provides an overview of the spin-off of the Sand Motor for knowledge and innovation.

2 Background of the Sand Motor

2.1 Protection from the water

For centuries the Dutch coast had to be protected from the water. In Roman times the terps, small mounds in the landscape, were used as shelter from the rising water. Over time the protection of these terps diminished as the sea level was rising while the land subsided. Dikes were therefore constructed from the 11^{e} century onwards to protect the agricultural areas. Many thousands of kilometres of dikes were constructed especially along the primary rivers and inland lakes. Dikes were also necessary for the protection from the sea at tidal basins, such as the Zuiderzee (after closure this water body is now referred to as the IJsselmeer) and Waddenzee. These protecting structures were, however, not necessary on the sandy coasts of the North Sea where the beach and dunes provide a natural water defense.

The dunes on the Dutch coasts therefore provided protection for the hinterland, but slow but persistent retreat of the shoreline did take place due to reworking of the beach by waves and currents and ongoing rise of the sea level. Very narrow dune sections remained at some of the coastal sections providing minimal protection from the sea. At some of the seaward extending sections of the Holland and Zeeland coasts the erosion was so large that villages and harbors had to be abandoned. In the 17th century the construction started of seaward extending groynes at the Holland coast which were made of heavy basalt rocks or wooden poles (Figure 2.1). Sixty-eight of these rock groynes were built on the coast between The Hague and Hoek van Holland, where the Sand Motor was later constructed. These measures did slow down coastal retreat, but were seldom able to stop the ongoing erosion. The causes for the erosion of the coast were not mitigated. One of the main reasons for the erosion was the net northward transport of sand by the waves which could still erode the lower sections of the beach profile. This created an increasing sediment deficit over time. It only takes time before a storm exposed the shortage of sand, as the dunes are eroded by the storm waves while recovery is not possible due to the lack of sand under water.

Figure 2.1 Beach groynes and wooden poles along the Dutch coast (source: Rens Jacobs/Beeldbank Rijkswaterstaat)

The ongoing battle against the water was still not decisively won in the beginning of the 20^{e} century. A lack of attention for the quality of the dunes and dikes created conditions in which the large flood of 1953 could take place (‘watersnoodramp’), wherein large parts of the Province of Zeeland and Zuid-Holland were flooded. Although the flooding’s were especially due to breaches in dikes, a critical situation also formed in 1953 due to storm erosion in the dunes of ’s-Gravenzande at the Holland coast, which nearly triggered a dune breach. The sediment present in the profile was barely enough to accommodate the natural eroding processes during this storm.

It was decided by the Dutch government that coastal flooding’s needed to be prevented with all means, which resulted in the drafting of the

‘Deltaplan’ for the Dutch coast. The Dutch coast was strengthened over a period of 30 years in the so-called ‘delta works’ project. These construction works aimed in the first place at improving the dikes to withstand the water and secondly to reduce the extreme high-water levels inside the tidal basins by closing them off with dams. The responsibility for coastal maintenance was also anchored in Dutch legislation (the ‘Waterwet’). The dune defenses are also part of this legal framework and have to be re-assessed regularly on water safety. If required, the dunes or the beach are replenished with sand.

Sand availability

It turned out that the amount of sediment in the coastal profile was one of the most important aspects for coastal maintenance. If too little sediment is present then the coast will retreat, while the coast will stabilize or even build seaward when sediment is added. Substantial shortages of sand are present at some sections of the Dutch coast even in the natural situation, which implies an ongoing local coastline retreat. The main cause is the lack of natural supply of sand from the rivers and marine sources. The supply by the rivers has declined substantially over the last centuries due to (partially anthropogenic) changes in the catchment area of the Rhine and Meuse. While also the supply of sand by the wave-driven onshore transport from the sea has come to a standstill, as the seabed has now become relatively deep due to a combination of onshore transport and sea level rise. In the meantime, the waves are carrying the sand northward along the coast of Holland, which leads to erosion. Coastal areas with a relatively large seaward extent compared to the surrounding coast are especially vulnerable, which is the case for older towns along the Dutch coast (e.g. Egmond aan Zee, Ter Heijde and Domburg). From the 70’s onward, sand was nourished on the dunes at Ter Heijde to prevent erosion. After 1990 the maintenance of the coastline has become part of Dutch legislation. Typically, a part of the nourishment sand is blown to the foredune by the wind, where the sand is captured by quickly growing marram grass. In this way the dunes also benefit from the sand nourishments that are carried out.

Future challenges

In the beginning of this century, it became apparent that future storms would be more severe than was assumed previously. Dune reinforcements needed to be carried out on weaker sections of the Dutch coast between 2009 and 2011. Rijkswaterstaat and the Hoogheemraadschap Delfland worked on this project, which is referred to as “Zwakke Schakels” (DHV, 2007). An extra dune row was created on the Delfland coast as a buffer against future storms.

It is the expectation that the natural retreat of the coastline will further increase as a result of enhanced sea level rise and possible changes in the wave direction due to climate change (Oppenheimer et al., 2019). The melting of polar ice sheets, on especially the southern half of the globe, will most likely result in a considerably larger pace of sea level rise than we have today. Currently, the sea level rises at a relatively mild rate of approximately 2 to 3 mm per year, but this can increase to 2 cm per year in the coming decades (Figure 2.2). A rate of sea level rise of about 2 cm per year may not seem like a lot, but it will have a large impact on sandy coasts.

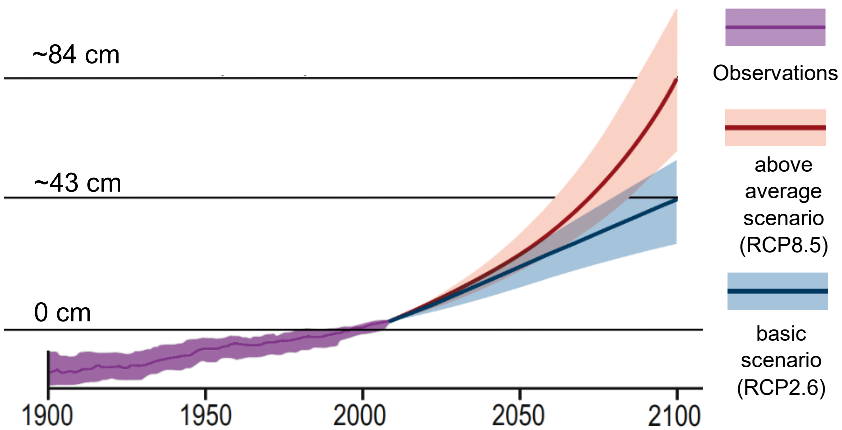


Figure 2.2 Expected sea level rise (Oppenheimer et al., 2019)

The expectation is that the coast will retreat approximately one meter for every centimeter rise of the sea. In this scenario, an additional 10 to 20 million cubic meters of sand will be required solely to maintain the sandy coast in the Netherlands, which does not yet account for the large sediment deficits that will be created at the Dutch lower shoreface, in the Waddenzee and in the Western Scheldt. A considerable challenge is posed for the maintenance of the Dutch coast in the coming century.

2.2 Approach of Dutch coastal maintenance

Management of the sediment balance of the dunes, the beach and the lower shoreface has been at the core of the coastal maintenance policy in the Netherlands over the last 50 years. This policy is described in detail in the Dutch National Water Directive (‘Nederlands Waterplan’, Rijksoverheid, 2015), the legislation (‘Waterwet’, Rijksoverheid, 2009) and the vision document on infrastructure and planning (‘Structuurvisie Infrastructuur en Ruimte’, Rijksoverheid, 2012). Through this policy a sustainable coastal maintenance can be achieved, which not only accounts for the safety of the hinterland against floods, but also preserves the quality of the coastal zone. In practice, actions are taken to preserve the coast at three different time scales (current situation, over a few years or the long-term decadal stability):

- The first action is to maintain the safety of the primary water defenses (e.g. dunes) in order to withstand high water levels during storms;
- The maintenance of the basis-coastline position, which was determined in 1990;
- Compensating the sediment volume in the coastal foundation for sea level rise. This coastal foundation is the region stretching from the inner dunes to the lower shoreface, which is approximately from the MSL -20 m contour up till the dunes.

Dunes need to have sufficient strength to withstand an extreme storm, preventing flooding of the hinterland. The Dutch water legislation (‘Waterwet’) prescribes the safety norms for the dikes and dunes (primary water defenses). For the dunes this means that a sufficiently large sand buffer needs to be present to resist the expected storm erosion. The dune defenses are evaluated every six years. Strengthening of the dunes will take place if the required safety-level is not achieved. If possible, sand will be used to realize the strengthening of the sea defense, while hard structures are only used when they are indispensable (‘soft where it can be done, hard where it is necessary’). Using sand is a scalable way to preserve long-term protection of the hinterland, beach recreation and naturalness of the coastal system.

The coastline position itself is also preserved with sand nourishments since the year 1990 with the aim of compensating deficits in the sediment balance of the nearshore coastal zone on the medium term. Structural erosion of the coast and dune water defenses is prevented in this way. A minimum coastline position was set for this in 1990 (the basis-coastline).

The maintenance of the coastal foundation is intended to make sure that the coastal zone of the Netherlands keeps pace with the rising sea level, which is a long-term aim. The preservation of the coastal foundation is a part of the Dutch coastal policies since 2001. Approximately 12 million m^3 sand is nourished yearly at the Dutch coast, which is the volume required to let the whole Dutch coastal foundation keep up with the current sea level rise of 18 cm per century. The yearly nourishment volume can be increased in case sea level rise accelerates in the future.

2.3 Methods for nourishing sand

In the Netherlands, we add sediment to the coastal system by means of ‘sand nourishments’ to sustain the coast. A borrow area is designated at some distance from the coast where a hopper-suction dredger can collect the sand and bring it to the shallow nearshore coastal zone. The borrow areas are typically outside the coastal foundation at a depth of more than 20 meter to prevent an impact on the coast itself. Sand that is nourished will be redistributed along the coast by the wind, waves and tide. A part of the sand can be blown into the dunes, where it contributes directly to coastal safety. The sand in the surfzone is, however, also useful as it reduces the dune erosion during storm events. The dunes will recover much better after a storm if sufficient sand is available in the surfzone and at the beach, which would not be the case if there is a deficit of sand in the nearshore zone.

A few decades ago, the nourishment sand was always placed on the beach or in the dunes, which provides a direct contribution to the sea defenses and coastline. However, since the 90's these beach nourishments are less common, as most of the nourishment sand is now added to the nearshore breaker bar (at approximately 4 to 8 meter water depth; Figure 2.3). This approach has a clear cost advantage over the direct nourishments to the beach and dunes. The wave forces will eventually push the sand up the profile in landward direction. This prevents coastal retreat and will on the longer-term lead to a buildup of the dunes, because the wind will transport part of the sand in the inter-tidal zone to the dunes. The forces of nature are effectively used to redistribute sand in the direction of the beach and the dunes. Over time the size of the applied sand nourishments has increased substantially, and effort is spent to make the nourishing process more efficient.

The Province of Zuid-Holland has presented an innovative plan in 2008 which aims at co-creating natural and recreational functions with a large-scale sand nourishment (referred to as the 'Sand Motor'; PZH, 2015). In cooperation with Rijkswaterstaat and representatives from the Dutch water sector, this plan was realized in 2011 (Figure 2.3). A large sand buffer is placed on the Delfland coast which is allowed to freely deform as a result of natural processes. This results in a lower of disturbance of the coastal nature, as the more typical smaller nourishments would have required a higher frequency of interventions. The expectation was that the natural processes (waves and tidal currents) would move the sand to the surrounding coast and dunes. The Sand Motor has economy of scale benefits, with lower costs per cubic meter of the nourished sand than for regular nourishments.

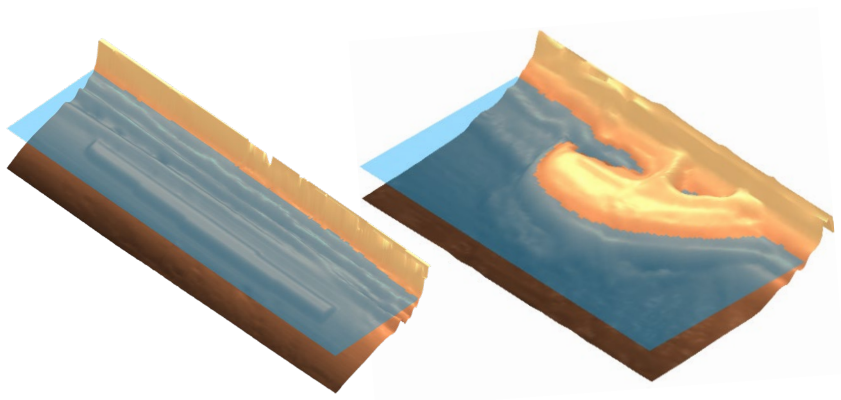


Figure 2.3 Shoreface nourishment at Noordwijkerhout (2002) and the Sand Motor nourishment at Ter Heijde (2011). source: Huisman (2019).

The practical experience with the construction of large coastal reinforcements, such as the Sand Motor, is also of importance for the future protection of the Dutch coast, as we know that the required volumes for maintenance of the sandy coast are likely to grow considerably (Stronkhorst et al., 2017). In the first place it is essential to know how a large-scale dynamic sand buffer such as the Sand Motor can be created. To be able to efficiently design such a measure, it will also be crucial to create a knowledge base, which makes it possible to already account in the design-phase for the spreading of the sediment and the impact on the nature of the dunes and shoreface. The Sand Motor is a pilot of a new type sand nourishment which is meant for the long-term maintenance of the coastline, through which we prepare ourselves for future challenges of climate change.

2.4 Location of the Sand Motor

The Sand Motor was realized at the Delfland coast near Ter Heijde. This coastal section is located in-between Wassenaar and Hoek van Holland, and is managed by the Waterboard ('Hoogheemraadschap') of Delfland (Figure 2.4). This was a logical location for the Sand Motor from both the governance perspective as well as from practical considerations, since a considerable amount of coastline maintenance is expected for this coast. This will require large quantities of sand. In addition, the region has a shortage of natural and recreational areas. Creating additional room for recreation and nature development, as a co-benefit of coastline preservation, was therefore an important reason for the realization of the Sand Motor.

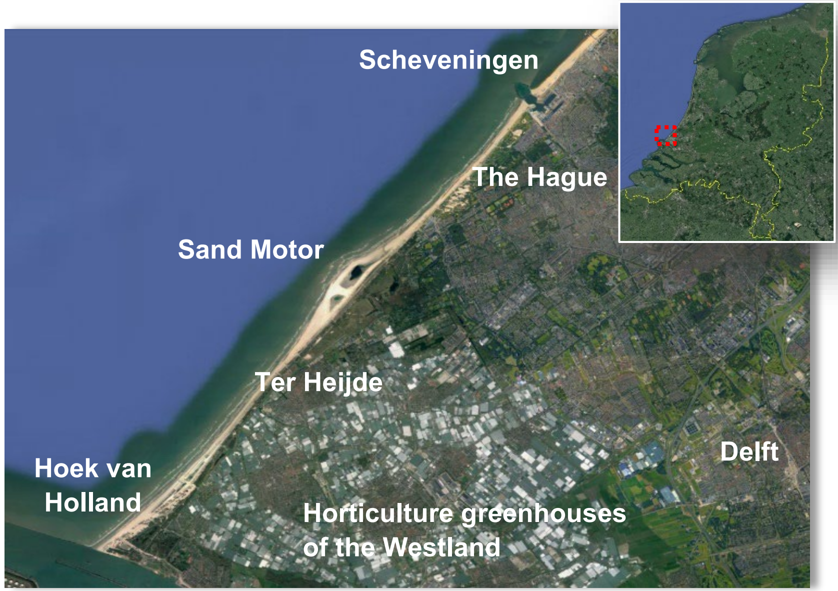


Figure 2.4 Location of the Sand Motor along the Dutch coast

The dunes at Ter Heijde are amongst the narrowest of the Dutch coast. The coastal zone consists of just a few dune rows with a width of approximately 200 meter, which contrasts with the relatively wide dunes at the more northern and southern sections of the Delfland coast. The relatively narrow dune defenses do, however, protect a densely populated hinterland. Approximately 1.4 million people are living here behind the dunes of the Delfland coast. They also protect the historic heritage of cities like Delft, Schiedam, Vlaardingen, Rotterdam and The Hague. The horticulture of the Westland is also a capital-intensive industry that is protected by the dunes. The Sand Motor is seen as an insurance for the water safety in this area.

The beaches and dunes of the whole Delfland coast have a relevance for natural and recreational functions. The dunes are protected as Natura-2000 areas, which means that a strict protection needs to be maintained based on the European Habitat directive and the Dutch Environmental regulations, not only against measures in the region itself, but also from the adverse impacts of measures taken in the adjacent regions. The dunes of Solleveld are a protected area in the vicinity of the Sand Motor. This area consists of so-called 'Old Dunes'. The relatively young dunes at the seaward side of Solleveld were created as a result of the dune reinforcements of 1987 ('Foredune 1987') and 2010 ('Zwakke Schakels').

2.5 Design

The design of the Sand Motor consists of a hook-shaped sand buffer, or peninsula, that encloses a lagoon (Figure 2.5). A dune lake was constructed at the location where the Sand Motor connects to the beach. Directly after realization, the Sand Motor had a length of approximately 2.5 km and a cross-shore width of 1 km, creating a land area of 128 hectares. Most of the peninsula had a height of approximately 3 meter above sea level, which increases in landward direction to 5 meter above sea level. At the centre of the Sand Motor, the highest point ('The top') had a height of 7 meter above sea level.

The western part of the lagoon had a depth of 4 to 5 meter below sea level, with gradually decreasing depth in landward direction. Before construction, a spit was expected to grow at the northern side of the peninsula of the Sand Motor as a consequence net northward sediment transport by the obliquely incoming waves. The spit would grow in northward direction until it attaches to the coast north of the Sand Motor.

Additional sand buffers where placed north and south of the Sand Motor as elongated underwater berms (referred to as 'shoreface nourishments'). These were aimed at preventing erosion in the early phases after realization of the Sand Motor. It was considered a possibility that sand from the beaches just north of the Sand Motor would be transported into the lagoon during a northwestern storm event. The northern shoreface nourishment was therefore placed almost at the same time as the Sand Motor, while the southern shoreface nourishment was constructed mostly in November 2011.

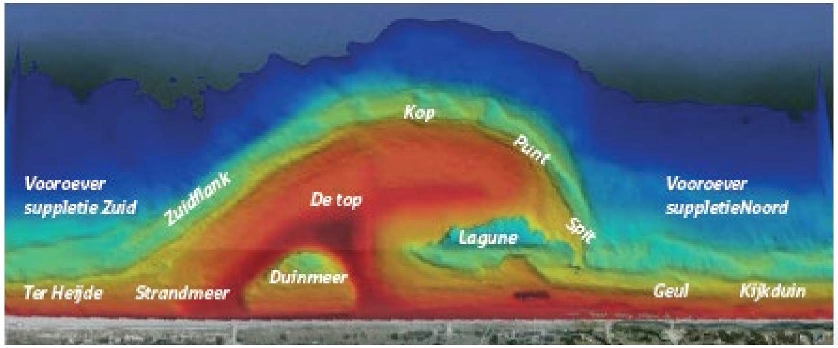


Figure 2.5 Overview of the subregions of the Sand Motor

Realization of the Sand Motor

Sand was nourished on the beach for the Sand Motor from March 2011 till July 2011 using large dredging vessels. The sand was dredged from a borrow area in deep water about 10 kilometers seaward from the coast of Delfland. After sailing to the coast, the sediment was disposed at the Sand Motor construction site by opening the valves underneath the dredging vessel. In this way the underwater section of the Sand Motor was constructed in intermediately deep water (up to 5 meters water depth). In shallower water a method called 'rainbowing' was used which sprays a mixture of sand and water from the vessel onto the coast. The dry beach was constructed from sand that was transported through pressurized pipelines and subsequently spread by bulldozers.

In total, a volume of 21.5 million m^3 of sediment was nourished to create the Sand Motor. Most of this sediment was used for the peninsula (approximately 19 million m^3) while the rest of the sand was used for the 'shoreface nourishments' that were located just North and South of the Sand Motor. These had a volume of respectively 0.6 and 1.7 million m^3. It is noted that a large dune reinforcement project (the so-called 'Zwakke Schakels') was realized before the Sand Motor, which created an additional dune row (or foredune).

2.6 Monitoring

Monitoring was carried at the Sand Motor, providing a basis for the evaluation of the Sand Motor (Figure 2.6). These measurement data were used in statistical and computer models, which further analyse the actual changes in the morphology and ecology of the Sand Motor and adjacent coast. The monitoring was defined in the 'implementation program' (DHV, 2010b; Tonnon et al., 2011). The end-goal was to verify the Sand Motor objectives arising from the EIA, to obtain information on effective coastal management and to evaluate the requirements that come with the permits.

The coordination and execution of the monitoring is performed by Deltares, Wageningen Marine research (WMR) and the foundation 'Zuid-Hollands landschap'. Various other bureaus have contributed to the monitoring and analyses, such as SHORE monitoring, Arens consultancy, Vertegaal ecological advice, Bureau Waardenburg and Ecoresult.

Figure 2.6 Overview of the monitoring of the Sand Motor

Environmental conditions, such as water levels, wind speeds and ground water levels, were monitored by Rijkswaterstaat, SHORE monitoring and the dune water company Dunea. Subsequently, these data were analyzed by Arens consultancy and Deltares. This encompassed, for example, the computation of the impact of the waves and currents, which were measured at some distance seaward from the Sand Motor. Dunea installed ground water gauges in the dunes of Solleveld, which are located landward of the Sand Motor.

The changes in the landscape (morphology) of the Sand Motor and the driving processes are analyzed by Deltares on the basis of bathymetric surveys. For this purpose, SHORE has carried out two-monthly to half-yearly measurements of the bathymetry at the Sand Motor (both on the beach and in the water up to 10 meter water depth). In addition, the regular yearly topography measurements (JARKUS) of Rijkswaterstaat were used for the evaluations, as these measurements cover a larger alongshore area. Half-yearly laser-altitude measurements (LiDAR) were available for the monitoring of the dunes, and in later years also to capture the development of the new (embryonal) dunes at the beach. These data were essential for the description of the development of the landscape of the Sand Motor, adjacent beaches and dunes.

Vegetation growth at the Sand Motor has been monitored by Bureau Waardenburg to obtain an overview of the ecological development of the Sand Motor beaches and nearby dunes of Solleveld. The changes in vegetation and their relations with the morphology were analyzed by Vertegaal ecological advice. Aerial photos of the Sand Motor have been used to map the vegetation at the Sand Motor for a selection of years prior to and after the realization of the Sand Motor, which were verified with in-situ inspection of the plant species. The plant species on the beach and vegetation in the dunes were also assessed in detail for small patches (2x2 meter) on five cross-shore transects into the dunes. The sand and salt spray were also measured at these five transects, as the wind-blown supply of sand and salt is very relevant for the development of dune vegetation. Dunea performed the measurements and analysis were made by Arens consultancy.

Benthic animals in the shoreface and on the beach were monitored two-yearly by WMR, while observations of shells were made regularly along the edges of the lagoon. Monitoring of the fish in the lagoon was carried out in the first years after construction by WMR. Furthermore, monthly bird counts were carried out at the beach of the Sand Motor by Ecoresult and analyzed by Vertegaal ecological advice.

The province of Zuid-Holland carried investigated the added value of the Sand Motor for recreation (by Wageningen University research), while the economic value for the region was assessed in a study by Ecorys for Rijkswaterstaat. Other societal functions of the Sand Motor (e.g. art, culture and archeology) have been studied by Deltares making use of interviews.

3 Coastal dynamics and dune growth

3.1 Expectations and aims

The Sand Motor is a unique coastal engineering project, as the forces of nature can freely deform the landscape. This is very different from coastal protection with hard static structures which has been common in the past and at other places around the world. These structures were effective in protecting the coast but were not beneficial for other coastal functions such as nature development and/or recreation.

The inherent dynamic nature of the Sand Motor needed to be taken into consideration already in the planning phase of the Sand Motor. The expected changes in the landscape were therefore predicted in advance before the construction phase to allow proper decision-making. For safety of the coast, it was essential to know whether the dunes would grow as a result of sand supply from the Sand Motor by the natural processes. The rate of sediment redistribution along the coast was also an important question, while the landscape development was considered very relevant for nature development. Detailed computer models were therefore used to provide inside into the expected morphological and ecological developments.

A very dynamic area was expected to develop, which would then reshape over time (Figure 3.1). Waves and currents would transport sand from the peninsula to the adjacent coast, predominantly in northward direction. As a result, the Sand Motor would become more elongated over time. A sand spit was expected to grow at the northern side of the peninsula and would attach to the coastline North of the Sand Motor after some years, resulting in the closure of the lagoon. Only a shore-parallel entrance channel was expected to remain as a connection with the sea. The Sand Motor would supply sediment to the adjacent beaches of Kijkduin and Ter Heijde, with the largest supply rates during storm conditions. Over time the Sand Motor would elongate, yielding a smooth coastline on the long-term (decades).

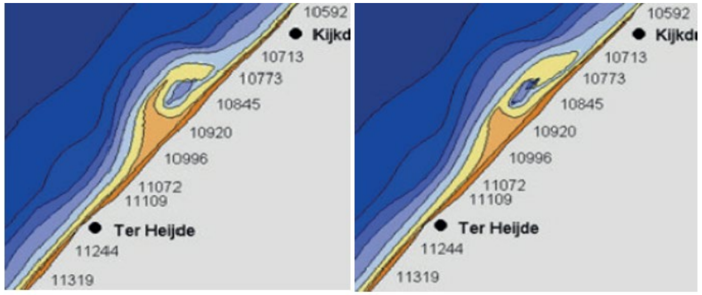


Figure 3.1 The a-priori predicted morphological development of the Sand Motor as computed for the EIA. Left: the computed development after 5 years. Right : the computed morphological change after 10 years.

In this chapter the focus is on the capability of the Sand Motor to promote natural dune growth, the way in which sediment can be beneficial for maintaining the basis-coastline and whether the Sand Motor sediment can be preserved in the active coastal zone from MSL -20m to the dunes, referred to as the ‘coastal foundation’ (EQ1-1; see Table 1.1). Lessons were learned on the planning and design of (mega)nourishments with a co-benefit for natural and recreational functions (EQ2-1). In addition, also a knowledge basis is created for the evaluation of the nature goals and recreation at the coast. The sediment composition of the shoreface is, for example, important for the habitat of benthic species in the shoreface (EQ2-2a and EQ3-1b1) while large-scale currents can impact recreational safety (EQ4-1).

Frequent measurements of the bathymetry were carried out to identify the changes to the dunes, beach, surfzone and lower shoreface. Computer models were used to identify the responsible forcing conditions for the spreading of the sand. Information that is essential for learning the required lessons for future nourishments.

3.2 Landscape dynamics of the Sand Motor

3.2.1 Alongshore redistribution of sand

The developments in the last 10 years show that the sediment of the Sand Motor mainly spreads alongshore under the influence of waves and tide (Figure 3.2), which cause coastal retreat of the Sand Motor peninsula and accretion on the adjacent coast (De Schipper et al., 2016). Shortly after realization, the Sand Motor took on a gaussian shape which gradually elongated in alongshore direction and narrowed in cross-shore direction. The length of the Sand Motor increased from 2.5 km in 2011 to about 5 km in 2021 (Figure 3.3).

Especially in the first years a very strong retreat of the coastline was observed at the hook-shaped peninsula. This retreat was approximately 100 meter in the first half-year. In total a retreat of 500 meter took place on the most seaward point of the Sand Motor from 2011 to 2021 (Huisman et al., 2021; Figure 3.4). Erosion was strongest in the first years after construction. During the first 3 years, the erosion amounted some tens of meters per year. Most erosion took place in the winter during storms. The coastal retreat and spreading of sand to the adjacent coast is, however, decreasing over time as the cross-shore extent of the Sand Motor is getting smaller. While transport also reduced slightly after a few months due to a less steep beach slope.

A spit with a length of over 500 meter has been growing at the northern side of the Sand Motor in the first five months after construction, which enclosed the lagoon (Figure 3.2). The spit area in the North then has further accreted, locally with up to 300 meter at the northern flank in 2021. The coastline at Kijkduin did, however, move slightly landward in the period 2011 to 2019 (2 m/year), but since 2020 the coast is also accreting in this region (~10 m/year) as a result of sediment supply from the Sand Motor.

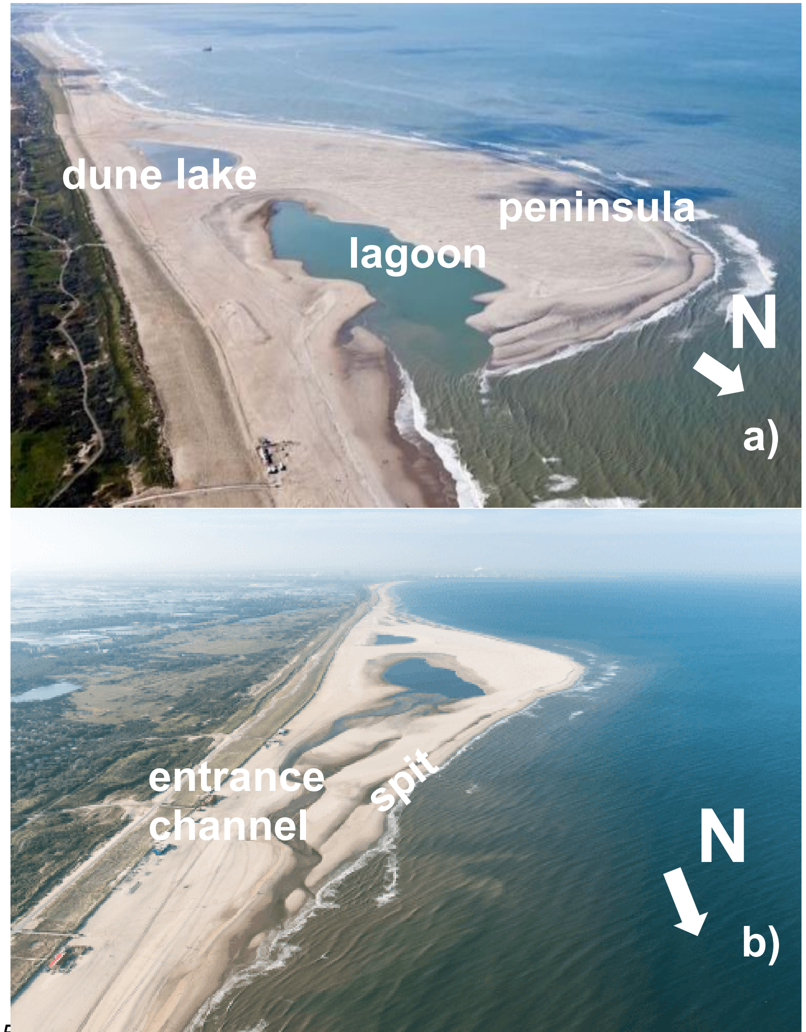


Figure 3.2 The Sand Motor during low tide on a moment shortly after construction in 2011 (a) and in October 2013 (b)

A wide accretion area also developed just South of the Sand Motor with shallow channels ('zwinnen') which get flooded during high water. The accretion was about 200 meter and mainly took place in the first 2 years after construction of the Sand Motor. Regions further South of the Sand Motor were hardly impacted (e.g. Van Dixhoorndriehoek, 's Gravenzande and Ter Heijde), and only a limited impact of the Sand Motor is expected here in the coming years as most of the sediment is transported towards the North.

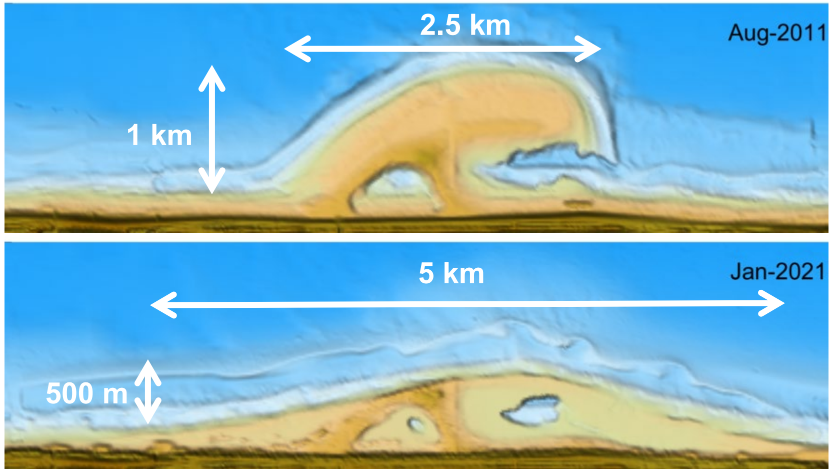


Figure 3.3 Development of the Sand Motor from 2011 to 2021.

Erosion also takes place in deeper water on the lower shoreface of the Sand Motor (Figure 3.4), but this happens at a much slower pace than the changes in the shallow nearshore zone (approximately half the rate at 5 to 8 meter water depth). A plateau therefore developed at 5 meter water depth at the head of the peninsula, as the coast retreated more quickly in shallower water. Erosion was small beyond the toe of the Sand Motor nourishment at a water depth of about 10 meter. A vertical erosion of a few centimeters per year was measured here. The lower shoreface does, however, act as a source of sediment for the coast. So, in principle there is a sand buffer present on the lower shoreface in front of the Sand Motor which slowly feeds the nearshore area with sediment.

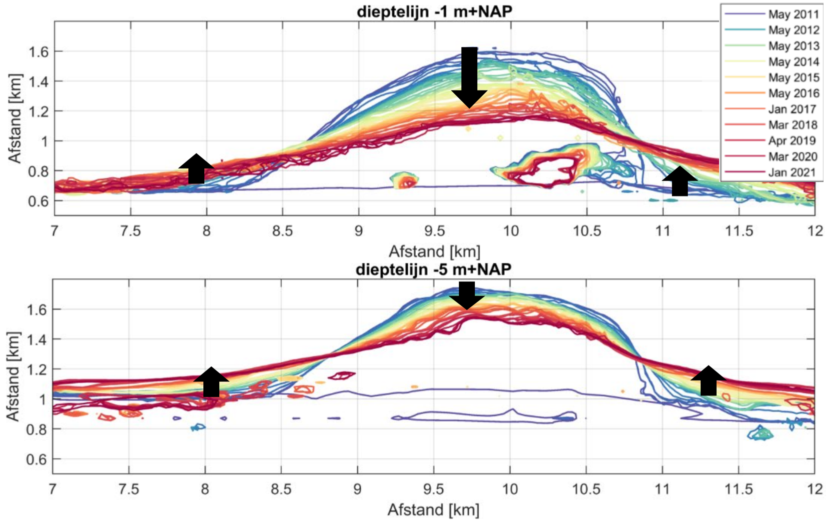


Figure 3.4 Coastline changes at the 1 and 5 meter depth contour of the Sand Motor (Huisman et al., 2021).

3.2.2 Waves as driving force

The surfzone is the most energetic zone of the coast, where breaking waves and tidal currents are very strong. The reshaping of the Sand Motor is determined mainly by the amount of sand that is transported in the surfzone, which is the shallow water zone with a depth of up to 5 meter. In this region the waves are breaking, causing strong alongshore currents (Figure 3.5).

Calculations of the development of the Sand Motor show that the waves are the dominant factor for the redistribution of sediment in the surfzone. Approximately 74% of the sediment transport was caused by the waves (Luijendijk et al., 2017). Waves will cause a strong current when they approach the coast under an angle. These currents can move sand along the coast to more quiet locations. These quiet locations are especially present at the flanks of the Sand Motor (Figure 3.5), where accretion is taking place.

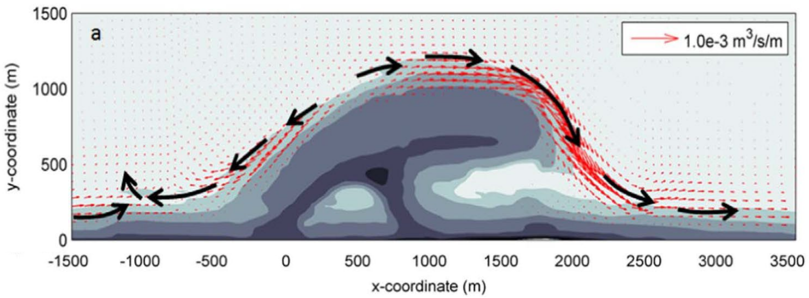


Figure 3.5 Computed year-averaged redistribution of Sand Motor sediment as a result of the obliquely incoming waves (Luijendijk et al., 2017).

Storms contribute considerably to the redistribution of sediment along the coast. A single storm in December 2013 transported as much sand as all conditions in the four months prior to this event (Luijendijk et al., 2017). Almost all storms in the winter period had a distinguishable impact on the Sand Motor. The incoming wave direction did not really matter that much for the expected life span of the Sand Motor (Tonnon et al., 2018), which is remarkable given that obliquely incoming waves lead to larger sediment transports. The transport in northward direction will increase when waves approach more from the South-West, which means that more sand is moved away from the Sand Motor to the North. On the other hand, also more sand is coming in from the South-West, meaning that the net balance of erosion and sedimentation of the Sand Motor is not changing much when waves come in more obliquely. The benefit of the acquired understanding of the sediment transport is that it allows us to more efficiently design future large-scale nourishments.

3.2.3 Influence of tidal currents

The sheer size of the Sand Motor also has an impact on the tidal currents along the coast. An acceleration of the tide takes place just seaward of the Sand Motor, because of the obstruction that it poses to the tidal flow (Huisman et al., 2016). Consequently, the tidal currents and forcing on the bed are increased in the area seaward of the peninsula. The actual change is relatively small, but still sufficiently large to result in sorting of bed sediment in this deeper section of the shoreface (see also paragraph 3.4.3).

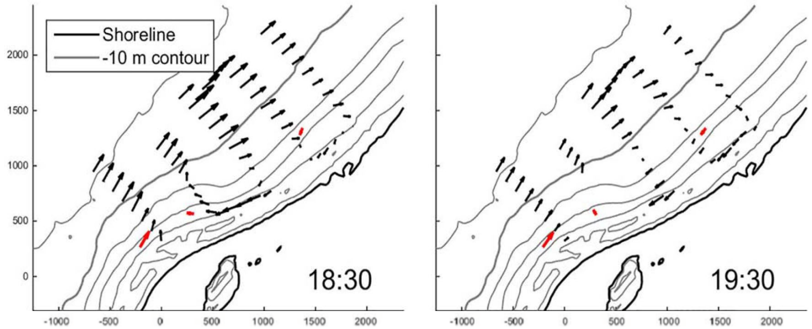


Figure 3.6 Tidal currents on the northern flank of the Sand Motor during the flood phase as recorded with a ship-mounted ADCP (Radermacher et al., 2017)

The local contraction of the tidal current can create a large-scale circulation (a ‘gyre’) at the northern flank during the flood phase, and most likely also on the southern side during ebb (Figure 3.6). This effect on tidal currents is decreasing over time though, as the cross-shore extent of the Sand Motor gets smaller, which is a result of the redistribution of sediment to the adjacent coast.

Tidal currents do, however, have only a limited impact on the sediment transport in the shallow nearshore zone and subsequent reshaping of the Sand Motor (Luijendijk et al., 2017). The tidal currents are slightly stronger during flood (i.e. in northward direction), but the net difference in transport still remains small. The vertical tide is important though for the rate of retreat of the waterline of the peninsula. The volume of eroded sediment is not influenced by the vertical tide, but the water level variations (due to tide) allow for the pick-up of sediment from the deeper sections of the coastal profile (during low water) and therefore a relatively smaller erosion rate near the waterline.

3.2.4 Sand bar dynamics and currents

A more complex pattern of sand bars was observed at depths of approximately 4 meter after construction of the Sand Motor (Figure 3.7). It is striking that this pattern differs so much from the pre-construction situation. It is in fact a new step in a long-term trend of increasingly pronounced sand bars at the Delfland coast. Hardly any sand bars were observed at the Delfland coast 40 years ago (Radermacher et al., 2018), but the sand bars are more numerous now as a result of the added nourishment sand. Initially, a single sand bar was present, while a double sand bar was present after construction of sand nourishment in the 90's. Even more complex alongshore varying sand bars are now observed at the Delfland coast due to the Sand Motor.

After construction of the Sand Motor the type of sand bar regularly changed from typical elongated alongshore uniform sand bars to irregular shapes with more alongshore variation. For example, in the first years after construction of the Sand Motor (2012 to 2014) an elongated alongshore bar was observed on the southern flank of the Sand Motor, while the bar pattern at the northern flank was much more irregular (Figure 3.7). Especially the angle of incidence of the waves during storm events has been shown to be important for the changes in the bar patterns (i.e. shape, depth and distance from the coastline). These bars became more alongshore uniform after events with strong wave-driven alongshore currents at a considered flank.

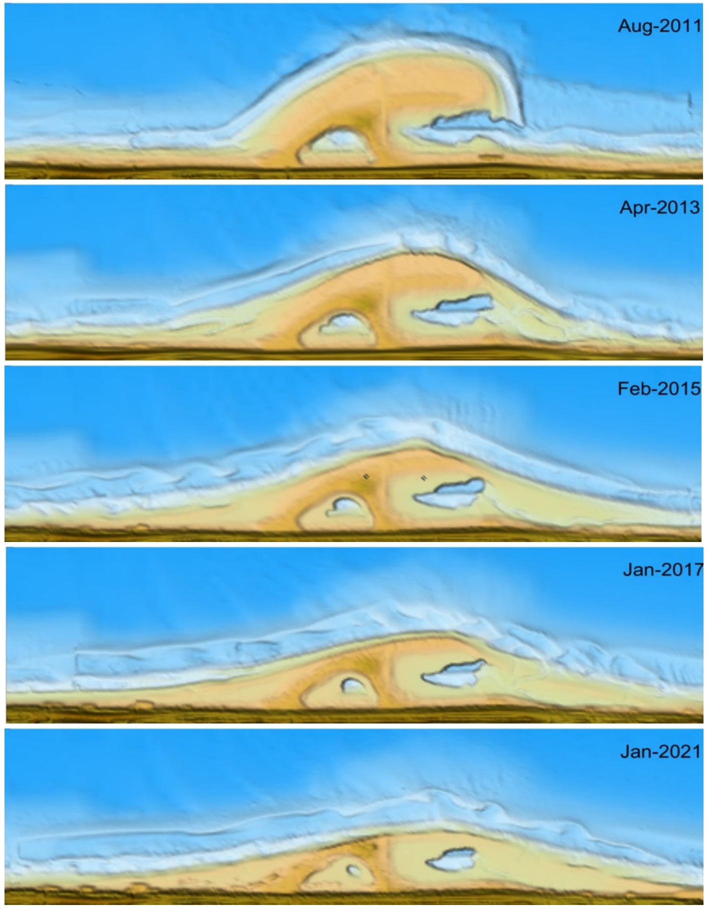


Figure 3.7 Development of the shape of the sub-tidal sand bars for the bathymetries of August 2011 till January 2021 (Huisman et al., 2021).

These sand bars can also affect the currents in the nearshore zone which is a part of the Sand Motor that is also used by bathers. A seaward directed current (also referred to as a 'rip current'), which can be dangerous for swimmers, can develop under specific conditions. The swimmer safety risk of these rip currents has been investigated by releasing GPS-drifters at the Sand Motor. The measurements show that dangerous rip currents can occur when intermediate to high waves (H_s of about 1 m) approach relatively perpendicular to the coast. These conditions do, however, often coincide with bad weather conditions, meaning that only a small number of beach users will be present at these specific moments (Radermacher et al., 2018). Measurements with drifters showed that the situation at the Sand Motor is definitely not worse than at the regular nearby beaches, because a smaller number of rip currents was observed at the Sand Motor. At the regular beaches the rip currents are predominantly found in the vicinity of local groynes, which were covered in sediment at the site of the Sand Motor.

3.2.5 Development of the lagoon and the dune lake

The lagoon and the dune lake are located landward from the peninsula of the Sand Motor (Figure 3.2a). Initially, the lagoon had an open connection with the sea, with diurnal in and outflow of the tide. The closure of the lagoon by the spit did, however, substantially change the situation here (Figure 3.2b). Only a narrow channel remained as a connection between the lagoon and the sea. Every tide the emptying and filling of the lagoon now takes place through this channel, implying that considerable currents can develop in the flood and eb phases. These currents then keep the connecting channel open. Attempts were made in the first year to reduce the flow velocities by placing rocky material in the entrance channel, but this had little effect as a bypass quickly developed. Nature eventually chooses the shortest route.

Initially, in the first year after construction, the channel was rather narrow, deep and relatively short, but over time the channel elongated as a result of the migration of the channel entrance towards the North (Figure 3.8). The entrance channel length was about 1200 m in October 2012, 1500 m in March 2015 and 2000 m in July 2018. The main cause for the migration of the channel entrance was the redistribution of sediment from the peninsula of the Sand Motor which had the tendency to block the southern side of the channel entrance and thus push it northward. The elongation of the channel did, however, also reduce flow velocities which made the channel shallower and less capable of filling and emptying the lagoon. It was therefore a matter of time before a short-cut channel was created. Such a shortcut was created by storms in December 2012 and March 2016 (Figure 3.8) as a result of the overwash of water over the spit, which eroded the spit locally. Afterwards the migration to the North and lengthening of the entrance channel resumed.

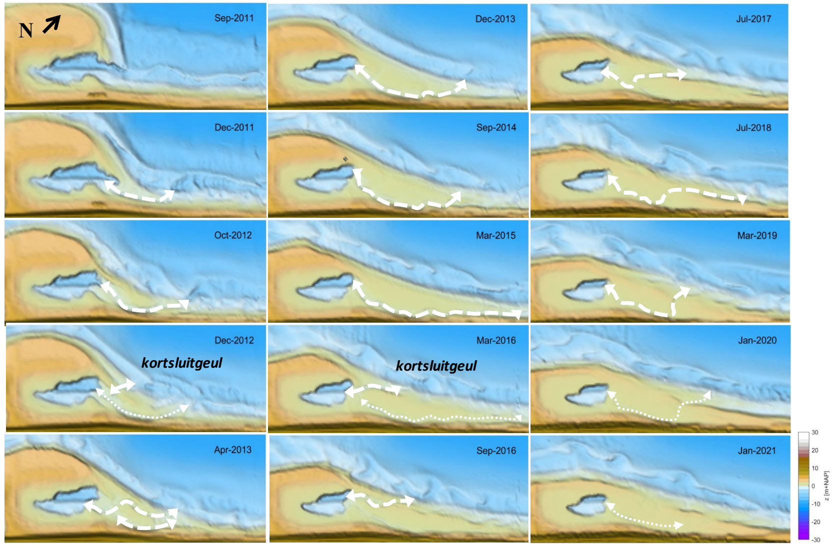


Figure 3.8 Development of the entrance channel at the northern flank of the Sand Motor in the last 10 years. Contour lines show the high-water mark (Huisman et al., 2021).

The currents in the entrance channel and the tidal variation in the lagoon do, however, decrease over time. This is partly due to the infilling of the lagoon and partly the result of the lengthening of the channel, making it more difficult for the tide to fill and empty the lagoon (Figure 3.8). Tide induced water level variations in the lagoon have strongly decreased over time, meaning that the water levels are determined not anymore solely by the tide, but also (to a lesser extent) by the precipitation. In 2020 the lagoon was even completely deprived of any exchange of water with the sea, and only received water as a result of overwash during high-water events. This has had a large impact on the conditions in the lagoon for benthic species (see Paragraph 4.3). The area is, however, very dynamic and in 2021 a new opening to the sea toe was created by natural forces.

The area and depth of the dune lake and lagoon are decreasing over time (Figure 3.8), especially at the southwestern side. Winds from the South-West transport sediment from the beach to the lagoon and dune lake. Approximately 200,000 m^3 of sand was blown into the lagoon in the first four years after construction of the Sand Motor (Hoonhout & the Vies, 2017). About 60% of this sand originates from the beach South of the Sand Motor, while the other 40% comes from the erosion of the dry beaches of the peninsula (Hoonhout & De Vries, 2017). The wind-driven supply from the intertidal zone South of the Sand Motor is in-turn related to the high accretion rates at this beach due to alongshore transport in the surfzone. Over time the proportion of the sand coming from the dry beach of the peninsula has decreased, because the top-layer of the sediment has coarsened substantially here. The remaining material is made up of shells and coarser sand grains which are more difficult to further erode by the wind. Still the height of the peninsula has decreased by approximately 50 cm as a result of the wind erosion.

Despite the general tendency of a reduction of the area of the dune lake and lagoon, there can be periods in which the area increases as a result of etiher storm surges of the sea water or when abundant precipitation takes place. The original total area of the lagoon of approximately 210,000 m^2 has reduced to only 100,000 m^2 in 2021 (Huisman et al., 2021). For this reason, less water needs to flow in and out of the lagoon every tidal cycle, which in-turn reduces the flow velocities in the entrance channel.

3.2.6 Formation of cliffs on the peninsula

Strong erosion takes place at the beaches of the peninsula of the Sand Motor during storms. This sediment is then transported away by the waves and currents along the coast. This can result in a rather even retreat of the coast, or effectively a ‘lowering’ of the beach. A special situation does, however, play out when a storm occurs during low water. In this case the erosion can only develop on the lower part of the beach, while the higher part of the beach remains unaffected (De Schipper et al., 2017; Van Bemmelen et al., 2020). Cliffs can then develop on the seaward side of the peninsula of the Sand Motor (Figure 3.9) of which the height can vary from a couple of decimeters to 1.5 meter. Incidentally, the cliff can be two to three meters in height.

Figure 3.9 Cliffs on the Sand Motor (De Schipper et al., 2017; Aerial photo : Rijkswaterstaat - Joop van Houdt)

These cliffs develop especially during summer storms, which are typically the situations wherein the waves have insufficient run-up height to erode the upper section of the beach profile. The cliffs will last until a storm condition takes place during high water or with sufficient wave energy to run up the beaches. Sometimes the cliffs may also partially collapse in dry periods.

An overview of the cliffs at the Sand Motor is shown in Figure 3.10, indicating the relevance of the rather mild storm conditions for the development of the cliffs (shown in green), while the more extreme conditions with more wave run-up reduce the cliffs (shown in red). The actual presence of the cliffs is caused by the relatively high design height of the dry beach of the peninsula with respect to wave run-up height. The cliffs could not have been present if the design height would have been lower than the average run-up height. Besides this, also the steepness of the beach profile is of importance, because cliffs can only develop if erosion takes place on the upper side of the beach.

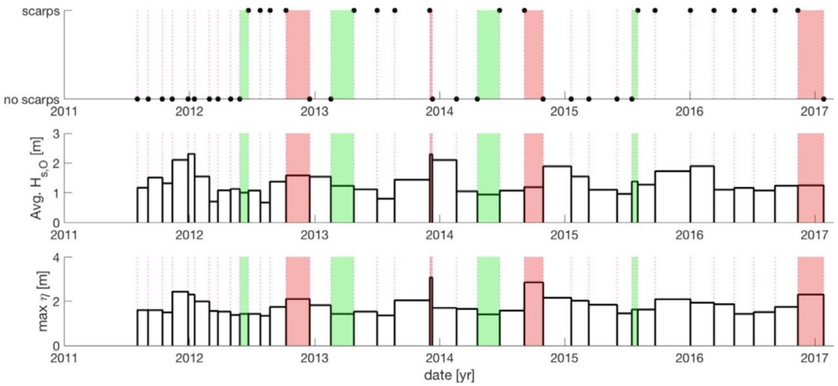


Figure 3.10 Occurrence of cliffs on the Sand Motor in relation to the average wave height ($H_{s,o}$) and wave run-up height (η). Green : developing cliffs; Red : erosion of cliffs (De Schipper et al., 2017; Van Bemmelen et al., 2020).

3.3 Dune development

The wind is not only taking sand to the lagoon and the dune lake, but also builds the dunes. Sand is picked up on the wet beach of the peninsula and is then transported landward. The most of this sand was captured in the first dune row ('dune reinforcement of Delfland') which has been growing strongly in both height and width (Huisman et al., 2021). The more landward dunes did, however, receive only a small amount of sand.

The first dune row landward of the Sand Motor (approximately 2.5 km of the centre of the Sand Motor) has been growing with 700,000 m^3 between 2011 and 2021 (Huisman et al., 2021). This agrees with an average growth of 14 m^3/m/year. Dune growth has been rather constant over the considered period, which is related to the sediment that gradually becomes available for wind transport in the intertidal areas. The impact of the Sand Motor on the safety of the dunes is not directly measurable, as the 'dune reinforcement' in 2010 widened the dunes with 40 to 80 meter and therefore already provided the required safety buffer. The Sand Motor does, however, supply the beaches of Delfland with sediment which can promote dune growth and therefore preserve dune safety for an extensive period of time.

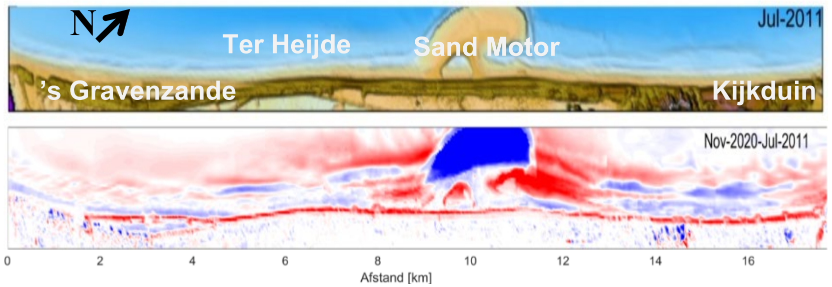


Figure 3.11 Difference in bed level of the Delfland coast between November 2020 and July 2011 (Huisman et al., 2021).

The rate of growth of the dunes at the Sand Motor is not very different from the rest of the Delfland coast, where the dunes have been growing 13 m^3/m/year. The relatively limited increase of dune growth at the Sand Motor is the result of the capture of a part of the wind transport in the dune lake and in the lagoon (Van der Weerd & Wijnberg, 2016). If this catchment of sediment is taken into account, then the net wind transport at the Sand Motor would be much larger than for the rest of the Delfland coast (~27 m^3/m/year; Hoonhout & De Vries, 2017). It is expected though that this relatively fine sand, which was captured in the lagoon and the dune lake, will become available for wind transport again in the future (within 10 to 20 years) as soon as the peninsula of the Sand Motor is eroded. This sediment can be picked up again by the tides and waves and become available in the intertidal area.

Figure 3.12 Growth of the foredune (left) and new 'embryonal dunes' on the Sand Motor (right).

In the first years after construction, the aeolian sediment was transported predominantly to the first dune row. Embryonal dunes started to grow after the first 5 years, which then captured a large share of the aeolian sediment supply (Figure 3.12; Arens, 2021). The first small embryonal dunes were formed already in 2013, but the actual large-scale embryonal dune growth started only in 2016. The main trigger for the development of these new dunes was the growth of vegetation on the beach (most often marram grass or sand couch). These plants need somewhat stable sediment in order to survive, and it also took years before the groundwater level could rise sufficiently. The rate of growth of the new dunes was not very high initially, but in 2021 some of the new dunes reached a similar height as the foredune (i.e. a few meters higher than the beach). In the meantime, these dunes are very valuable as a refuge for breeding birds (see paragraph 4.4).

Besides wind speed and direction, also the grain size is of relevance for the eventual destination of the wind-blown sediment. The finest grains are fully carried by the wind, and do not touch the ground at all, due to which these grains can be blown over the existing dunes. While the intermediate and coarser sand grains saltate or roll over the beach, which means that these grains will more easily be captured by vegetation. The coarse sand grains and shell fragments hardly move at all and remain at their location. A consequence of this preferential transport of sand grains was that a protective armor layer formed at the dry beach of the peninsula, consisting of coarser sand grains and shells, as they can resist any further erosion from the wind (Figure 3.13). The volume of sediment that was eroded by the wind from the dry beach of the peninsula was initially large (about 0.5 m in the first 2 years), but then became very small in later years. In later years, the wind transport originated from the intertidal areas of the beach where the water regularly sorts the sediment and makes finer sand grains available for pick-up by the wind.

Figure 3.13 Beach section with an armoured top-layer of the bed with shells and coarse sand on the peninsula of the Sand Motor

3.4 Shoreface of the Sand Motor

3.4.1 Change of the shoreface

The lower shoreface (deeper than 8 meter) of the Delfland coast also changes over time, which is partly due to the Sand Motor and partly due to existing long-term trends. A long-term trend of erosion takes place at the lower shoreface (blue areas marked with A in Figure 3.14). The shoreface lost about 100,000 m³/year in the depth region of 8 to 12 meter water depth over the last 10 years. A part of the sediment has been transported landward by the waves and recirculation currents which are created by the freshwater plumes from the Rhine. Also, a net northward directed transport is present in deeper water as a result of the asymmetry of the tidal velocities. An effect of the Sand Motor can be seen locally, as some erosion took place just seaward of the peninsula, while accumulation took place in deeper water just North of the Sand Motor.

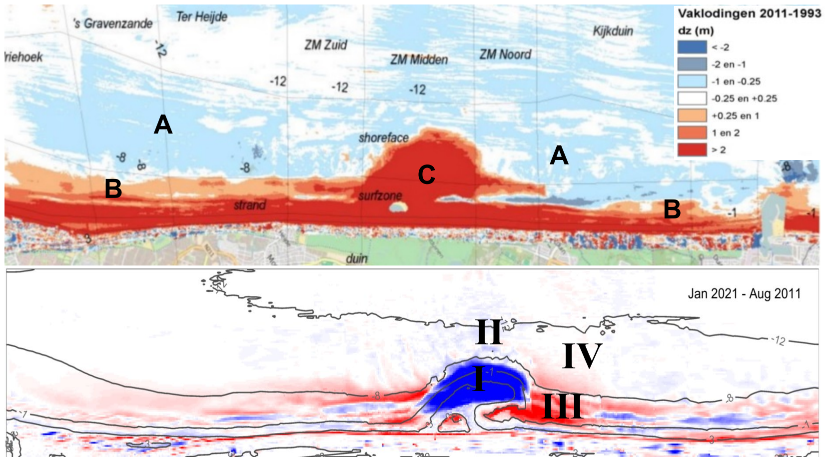


Figure 3.14 Measured bed level change in the period 1993 to 2011 and for the period 2011 to 2018. Accreting areas are shown in red, and erosion in blue.

A large amount of sand has been added to the shallow regions of the Delfland coast by means of sand nourishments. These shoreface nourishments can even be distinguished as elongated red lines in the plot (see B) and the Sand Motor is also clearly visible (see C).

3.4.2 Shoreface nourishments

Two 'shoreface nourishments' were constructed in 2011 at the northern and southern side of the Sand Motor (see Figure 2.5). These shoreface nourishments are effectively sand buffers that are placed just seaward of the sub-tidal bar (Figure 3.15). The northern shoreface nourishment had the aim to prevent erosion on the northern side of the Sand Motor in the first months after construction. The nourishment North of the Sand Motor was constructed with the aim to mitigate potential erosion at the Kijkduin coastline. A-priori it was perceived a possibility that sediment would be transported to the lagoon in case of persistent waves from the North, which may locally have led to a (temporary) shortage of sand. These persistent conditions from the North and subsequent temporary erosion have not taken place though.

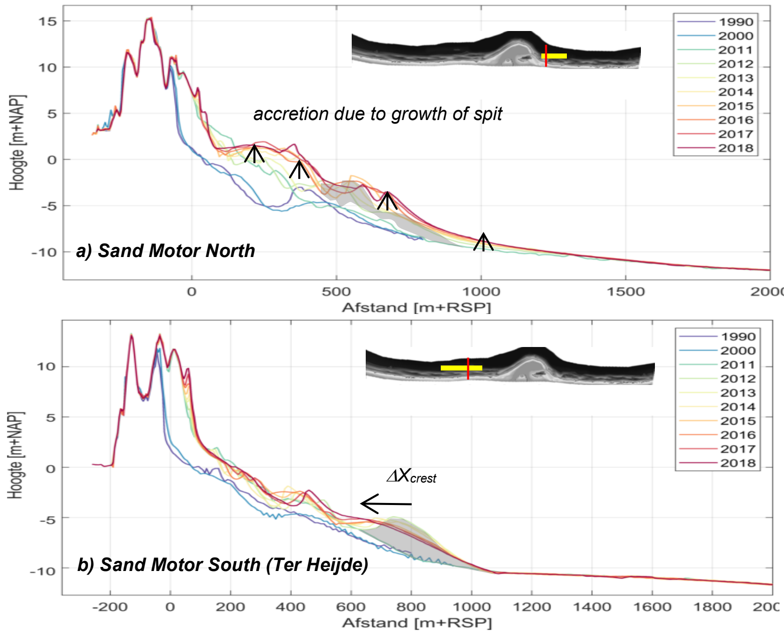


Figure 3.15 Measured cross-shore profiles at the shoreface nourishments close to the Sand Motor. Grey areas demarcate the nourishments (Huisman et al., 2021).

The shoreface nourishments have behaved differently from each other. The northern nourishment was covered within the first year with sediment that originated from the peninsula of the Sand Motor (Figure 3.15a). In fact, this northern nourishment created a shallow zone which allowed the spit of the Sand Motor to grow more quickly in northward direction. The southern shoreface nourishment could develop much more freely. Over time the crest of the nourishment and the existing bars are pushed in landward direction by the waves (see Δx_{crest} in Figure 3.15b). This is in agreement with the experiences at other shoreface nourishments along the Dutch coast (Huisman, 2019).

3.4.3 Sediment composition of the shoreface

The bed sediment composition of the Sand Motor is important for the coastal nature. For vegetation is the easier to settle in sediment with finer grains than in the coarser sand. Sediment is also very relevant for benthic species (such as worms, shellfish and crustaceans), since these animals move over the bed, adhere to the grains or excavate corridors that should not collapse. Specific flatfish take shelter in the bed. They use a thin layer of sediment as camouflage against predators (Post et al., 2017). The bed sediment composition therefore provides insight in the impact of the Sand Motor on the habitat for benthic animals.

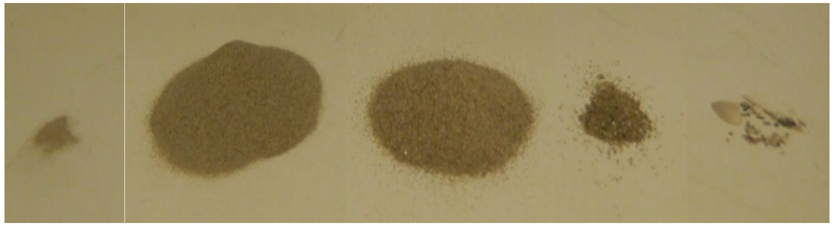


Figure 3.16 Different grain sizes and shells in a sand mixture

The sediment of the Sand Motor consists not just of a single type of sand grains, but comprises a variety of sand grains with different sizes and shapes (i.e. more square or round; see Figure 3.16). Typically, most of the grains range from 0.1 to 0.5 mm, but much finer grained material with a grain diameter of less than 0.06 mm (silt and clay) can also be part of the mixture. The fine material can clog the pores of the sand, resulting in a muddy bed (with sand and silt or clay), but the fine grains have little resistance against the forces exerted by the wind, waves and currents, and will therefore not settle in energetic regions such as the surfzone.

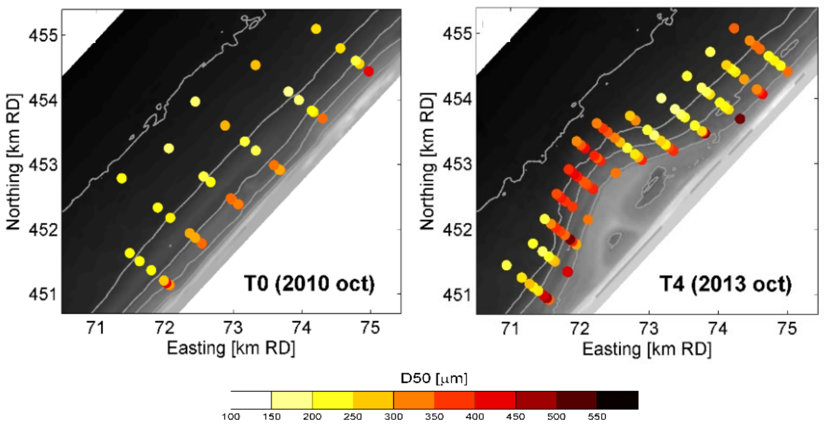


Figure 3.17 Measured median grain size (D_{50}) for the situation before and after construction of the Sand Motor.

A seaward directed fining of the sediment was in place prior to the construction of the Sand Motor. Coarser sand was present at the waterline with a median grain size (D_{50}) of about 0.4 mm, while the sediment in deeper water consisted of fine sand with a D_{50} of 0.1 to 0.2 mm (see Figure 3.17). After construction of the Sand Motor this changed considerbaly (Huisman et al., 2016), showing the following:

1) Coarser sand was used for the construction of the Sand Motor than the sediment that is naturally present here, on average sediment was used with a D_{50} of 0.28 mm. This is in fact a direct impact of the selection of the nourishment sand at the borrow location at sea.

2) The spatial variation of the grain sizes has increased, which is due to the impact of the Sand Motor on the tidal currents. An effect is especially seen in deeper water seaward of the peninsula, where the sediment has become twice as coarse as the natural sediment (with a D_{50} of up to 0.4 mm). A fining of the sediment took place North and South of the Sand Motor (up to 50 μm finer).
3) Fine sand, silt and organic matter have accumulated in the lagoon. The finer sediment can settle in the relatively calm conditions. Rather coarse sediment is found in the entrance channel that connects the lagoon with the sea, where flow velocities can be considerable.

Computer models show that tidal currents are the main cause of the sorting of the bed sediment on the lower shoreface (Huisman et al., 2018). The underlying mechanism is that the tidal currents have sufficient energy to mobilize the finer grains, but cannot fully mobilize the larger grains. Remarkably, storms were not causing the sorting of bed sediment at the lower shoreface, which was an a-priori expectation. Instead, the storms mobilize all sediment grains resulting in a decrease of the bed sediment sorting. The seaward extent of 'Sand Motor' type nourishments is the most determining factor for the impact on the tidal currents, and consequently also for the change in bed sediment composition at the lower shoreface. The width of the Sand Motor does, however, decrease over time as a result of the redistribution of sand by the waves and currents, meaning that the effect of the Sand Motor on the tidal forcing, and subsequently on the bed sediment, is likely to decrease. It will, however, take many years before the bed composition is again comparable to the situation prior to the Sand Motor.

A number of distinct subregions (or 'habitats') with different sediment composition have developed as a result of the Sand Motor. Wave and tide conditions also vary per region. It is expected that that each of these habitats will have their own distinct types of benthic animal populations (see paragraph 4.2).

3.5 Sediment balance

The coastal retreat at the peninsula of the Sand Motor is the most prominent morphological development in the region (see I in Figure 3.14). Sediment is, however, also eroded from the bed seaward of the Sand Motor (see II in Figure 3.14). This is related to the increase in the local tidal currents. Accretion is taking place in the vicinity of the Sand Motor (see III in Figure 3.14) as well as in deeper water just North of the Sand Motor (see IV in Figure 3.14). Computations were made of the sediment volumes near to the Sand Motor (i.e. within 2.5 km from the centerline) to allow for a quantification of the morphological changes (Figure 3.18).

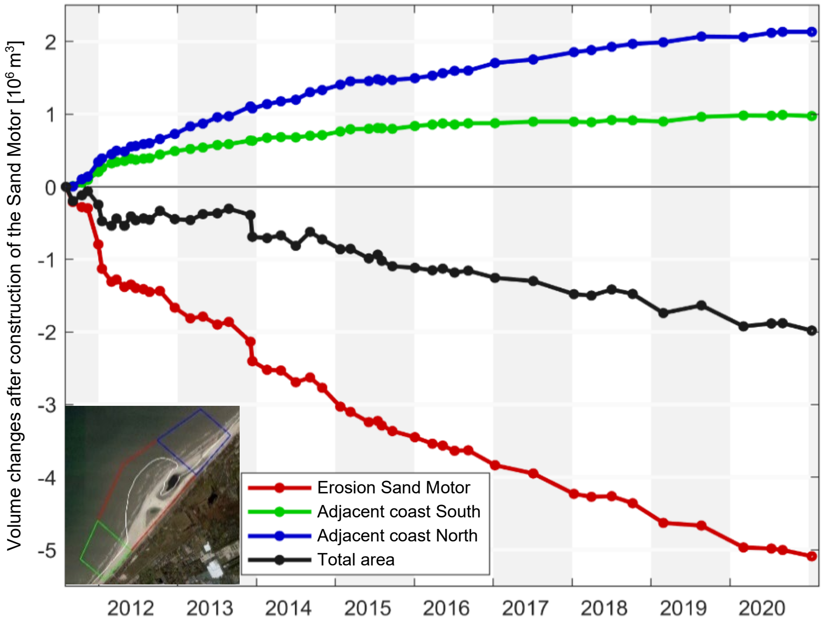


Figure 3.18 Changes in the measured volume of sediment in the first 10 year after construction of the Sand Motor (Huisman et al., 2021).

Changes at the Sand Motor

The sediment volume at the peninsula of the Sand Motor has decreased with about 5 million m^3 over the considered 10-year period (see the red line in Figure 3.18; Huisman et al., 2021), while the sediment volume increased with 3 million m^3 at the adjacent coastal sections North and South of the Sand Motor (see green and blue lines). About 60% of the sediment was found in close proximity of the Sand Motor after 10 years (within 2.5 km of the centreline). In 2016 this was still 95% of the sediment. The remaining part of the sediment is, however, still available within other sections of the Delfland coast. Especially the coastal zone and dunes North of the Sand Motor have received a substantial amount of sediment.

The rate of erosion and sedimentation at the peninsula of the Sand Motor is decreasing over time. This is directly related to the decreasing cross-shore protrusion of the Sand Motor. The difference between the incoming waves and the coast angle has decreased resulting in smaller wave-driven currents and longshore sediment transport at the flanks. Over time the rate of change will further decrease. The total growth of the foredunes at the Sand Motor was 700,000 m^3 over the considered alongshore stretch of about 5 km, which means that the average dune growth was 14 m^3/m/year.

Sediment balance of Delfland

A tighter sediment balance can be achieved when the whole Delfland coast is considered (Huisman et al., 2021). An increase of 1.2 million m^3 of sediment is found over the considered 10-year period (see black line in Figure 3.19). However, the sand nourishments, that were carried out in this period, should be distracted from the balance. In total a volume of 2.8 million m^3 of sediment was nourished at the Delfland coast in the 10-year period. About 1.3 million m^3 was nourished in the fall of 2011 for the shoreface nourishments North and South of the Sand motor, while 1.5 million m^3 was nourished in 2013 at Ter Heijde and Hoek van Holland. After the correction, a net volume loss of 1.6 million m^3 is obtained for the whole Delfland coast. It is expected that this sediment has been moved northward of the harbor of Scheveningen by the natural wave-driven alongshore current. Most sediment was therefore preserved within the Delfland coast, while a small part was beneficial for the Rijnland coast.

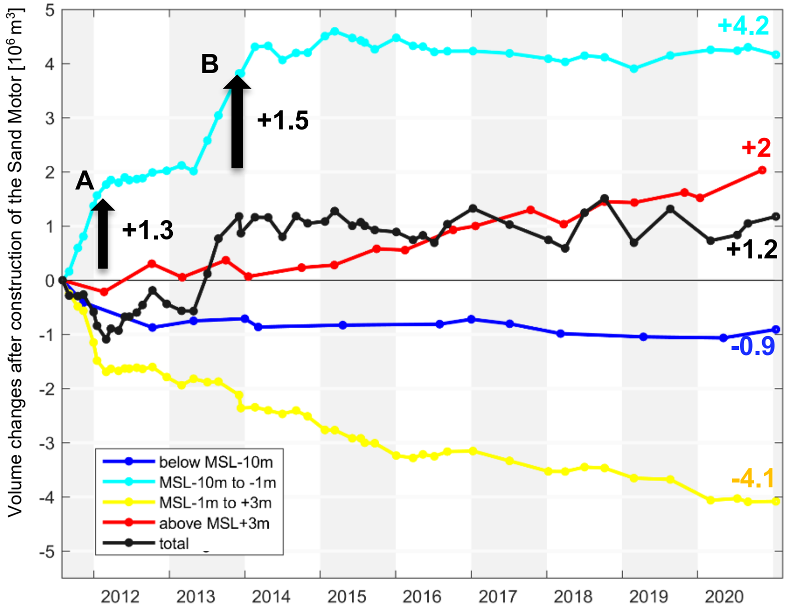


Figure 3.19 Volume changes within the Delfland coastal cell since 2011
A : nourishment +1.3 million m3 (second part of nourishment at Ter Heijde)
B : nourishment +1.5 million m3 (Hoek van Holland – 's Gravenzande)

The dunes and the surfzone have increased substantially in volume (see the red and light blue lines in Figure 3.19), while the beach (especially of the Sand Motor) has decreased in volume (yellow line in Figure 3.19). The changes on the lower shoreface were not very substantial compared to the other regions, but a retreat has likely taken place as a result of the erosion of the lower shoreface at the Sand Motor (darker blue line in Figure 3.19). It is expected that sediment was transported from the lower shoreface either cross-shore to the surfzone or alongshore in northward direction by the tide.

Yearly variations
Calculations of the sediment transports at the Delfland coast show that a net northward directed natural transport is present at the port of Scheveningen, but this transport can vary substantially per year. In some years the transport was 300,000 m^3/year, while it was only some tens of thousands of cubic meters in other years. The average net transport at the port of Scheveningen is estimated at 150,000 m^3/year based on numerical models (Huisman et al., 2021). This agrees with the computed net loss of sediment from the Delfland coast of 1.6 million m^3 for the considered 10-year period.

Expectations of the future developments
The Sand Motor will become more and more elongated on the longer term as a result of alongshore redistribution of sediment (Luijendijk et al., 2019). The cross-shore width of the Sand Motor will decrease, while the beaches at Ter Heijde and Kijkduin will get wider. The coastline orientation will get more straight over time. These changes will, however, take many years, meaning that the Sand Motor will be recognizable for another ten to twenty years as a seaward protrusion of the Delfland coast. It is expected that the Sand Motor will be about 400 meter wide in the year 2040.

In a few years from now, a new entrance to the lagoon will develop (Luijendijk et al., 2019), which is expected to take place quite abruptly as a result of a storm that coincides with high water. Sand from the peninsula will then be transported into the lagoon, which may quickly fill up. Effectively, the Sand Motor is then split into a northern and southern part.

The dunes at the Delfland coast will continue to grow in the coming decades with sediment from the Sand Motor. A large amount of sediment will become available from the lagoon in the coming years. The fine sand that has accreted in the lagoon will become available for transport as soon as the hook of the peninsula is fully eroded. The Sand Motor will deliver a long-term contribution to the safety of the whole Delfland coast. Especially the regions of Ter Heijde and Kijkduin will benefit.

The new dunes on the beach of the Sand Motor will also continue to grow as a result of vegetation growth and aeolian sand transport, which will make the landscape more natural. Sand will also be blown into the lagoon and the dune lake, which will create a new area with a relatively wet beach plane. Possibly, vegetation will settle there in the coming years, resulting in a wet dune valley at the Sand Motor.

3.6 Evaluation of coast and dune development

This chapter provides an overview of the development of the coastline, dunes and the coastal foundation at the Sand Motor. The content in this chapter was used to answer the evaluation questions related to natural dune growth, coastline development and sediment composition of the Delfland coast. It is noted that a, sometimes shortened, answer to the (sub)evaluation questions can be found in Appendix A.

Natural dune growth and long-term preservation of the coast
The question with respect to natural dune growth, the first objective of the Environmental Impact Assessment, can be answered as follows:

- *EQ1-1: Does the Sand Motor contribute to long-term preservation of the coastal foundation and basis-coastline between Hoek van Holland and Scheveningen? To what degree will this lead to natural dune growth?*
  The Sand Motor has created a very dynamic area where natural forces can freely form the contours of the beach and dunes. This fits well with the Dutch coastal policies which have a preference for working with dynamic sandy solutions. Both the embryonal dunes on the beach and existing foredunes, which act as primary water defenses, have been growing substantially due to the

supply of sand via aeolian transport. The safety against flooding was already sufficient for the Delfland coast, but is now sustained on the long-term as a result of the Sand Motor through the placement of this large sand buffer.

Sediment accumulation has taken place in the dunes landward of the Sand Motor with a rate of 14 m^3/m/yr. This sand mostly ended up in the first dune row. The dune growth at the Sand Motor is slightly larger than the average dune growth of the Delfland coast (13 m^3/m/yr). Even though much more sand was available for aeolian transport at the Sand Motor, a large part of it was captured by the lagoon and the dune lake. If this accretion in the dune lake and the lagoon is taken into account, the windtransport at the Sand Motor would have been considerably larger (~27 m^3/m/yr). The growth of vegetation and embryonal dunes on the Sand Motor is essential for the nature development at the Sand Motor, but did not contribute to the coastal safety, as less sediment is now provided to the primary water defenses of the foredune. Aeolian sediment that is captured by the lagoon, the dune lake and the embryonal dunes, will, however, become available for wind transport as soon as the erosion of the Sand Motor progresses.

The Sand Motor does not only protect the area directly behind it, but also the adjacent coast. The supply of sediment from the Sand Motor to the adjacent coast will be largest during extreme conditions, which means that the Sand Motor also contributes to the safety of the dunes at the adjacent coast (e.g. at Ter Heijde and Kijkduin). The safety of a large part of the Delfland coast is sustained in a very natural way by the Sand Motor. Almost all of the nourished sediment of the Sand Motor is still present in the 'coastal foundation' of the Delfland and Rijnland coast (stretching from MSL -20 meter to the dunes). Redistribution of sediment has, however, taken place within the coastal foundation. Approximately 150,000 m^3/yr was transported northward to Rijnland in the considered 10-year period.

Lessons about morphological development

Lessons were learned from the assessment of the morphological development of the Sand Motor that are relevant for future large-scale nourishments (EIA objective 2):

- *EQ2-1a: Which lessons were learned about planning and design of (mega)nourishments from the morphological development of the Sand Motor, in particular for the nourishments that also aim at an added value for nature and recreation?*
  The reshaping at the Sand Motor is different from the behavior of regular (shoreface) nourishments. Shoreface nourishments deform predominantly in the cross-shore direction, whereby the crest gradually moves onshore. While redistribution at the Sand Motor takes place especially in alongshore direction as a result of the wave-driven transport. The dominance of this process makes it possible to relatively quickly (i.e. without complex cross-shore processes) gain insight in the expected future development of a large-scale nourishment (or a sandy dune reinforcement). The sand bars became more pronounced and dynamic as a result of the addition of Sand Motor sediment to the coastal system.

  Tidal current velocities have increased seaward of the peninsula as a result of the Sand Motor, and in addition also a recirculation of the currents takes place at the flanks. For this reason, erosion takes place at the lower shoreface seaward of the Sand Motor and accumulation just North of the Sand Motor (on the lower shoreface), which also results in local sorting of the bed sediment.

  The dunes were strengthened by the supply of sand from the Sand Motor, which was rather constant over time. Not only the wind conditions and size of the nourishment were relevant for the aeolian transport rates, but also the intertidal area is of great importance for the supply of aeolian transported sand. Furthermore, catchment of sand takes place in the lagoon and the dune lake, which has a large impact on the supply of aeolian sediment to the dunes. Accretion took place at the western side of the dune lake and lagoon. On the long-term, the development of vegetation and new dunes on the beach will result in a decrease of sediment supply to the existing dunes. Only a small amount of sediment becomes available for wind transport at the higher sections of the dry beach, because a protective armor layer of coarser sand and shells is developing here through selective transport of the finer sand. The peninsula is effectively too high for the waves (and wave runup) to rework the bed.

The number of sand bars on the Delfland coast has increased as a result of the nourished sediment from the Sand Motor. Both alongshore uniform and rhythmic sand bars were observed at the Sand Motor. The alongshore variability of the sand bars was largest when waves approach the coast relatively shore-normal, while the sand bars on the lee side of the Sand Motor (where waves approach more obliquely) are typically more alongshore uniform. The increase in the number of alongshore variability of the bars is, however, a development which also took place earlier at this coast due to other nourishments.

Sediment composition of the shoreface

The measurements at the Sand Motor also provide very useful information on the sediment composition of the wet beach and shoreface (EIA objective 2):

- *EQ2-2a: Which mechanisms may cause changes in the sediment composition of the Sand Motor (i.e. grain size distributions and organic content) on the wet beach and the lower shoreface?*
  Large-scale nourishments, such as the Sand Motor, influence both the waves and the tidal currents. The wave forcing and resulting wave-driven currents create a strong erosion in the surfzone of the peninsula, because of which the bed sediment composition will get slightly coarser. The biggest impact on the bed sediment composition is, however, found on the lower shoreface (>6m water depth), where the Sand Motor creates an enhancement of the tidal currents. Areas with a finer bed sediment composition developed at the adjacent coastal sections (at the lower shoreface) just North and South of the Sand Motor. The impacts on the bed sediment composition extend further than the initial construction area of the Sand Motor (up to 3 km from the coast). The seaward extent of a nourishment determines the impact on the tidal currents, and consequently also the changes in bed sediment composition.

4 Nature development

4.1 Expectations and aims

The Sand Motor adds a large new area to the Delfland coast where nature can develop (Figure 4.1). New environments were added with very different characteristics from the regular beaches, such as the lagoon and the dune lake. The lagoon and the dune lake experience far less energetic conditions than the surfzone of the coast where the waves and currents can act freely. The development of the nature and naturalness of these areas is one of the main points of attention in the monitoring of the Sand Motor.

Figure 4.1 Overview of the subregions of the Sand Motor

Aims
The aim of this chapter is to answer the questions related to the added value of the Sand Motor for nature development (EQ2-2), with special attention for the benefits of placing a one-off large-scale sand nourishment instead of repetitive small nourishments for the benthic species. A description is given of the development of attractive nature in the dunes (EQ3-1a), the lagoon, the dune lake and in the shoreface. Considering also the birds, fish and sea mammals (EQ3-1b).

Expectations
Prior to construction of the Sand Motor, it was expected that the Sand Motor would impact the environmental conditions (e.g. currents, bed dynamics, bed sediment and aeolian transport) which can affect the habitats at the beach, in the dunes and underwater (see Chapter 3).

The benthic community composition in the shallow coastal zone is an important indicator for the impact on the ecology. The species living in and on the bed, such as small crabs, shellfish, worms and crustaceans, are also a food source for birds and fish. Fish, such as sole and plaice, live close to the bed and feed themselves with worms and shrimps. Even birds, such as the black scoter, dive to the bed for shellfish, while other bird species forage on the intertidal beach. The large area and relative remote location of the peninsula for visitors creates a calm environment for the birds and sea mammals.

The one-off placement of a large volume of sand, such as at the Sand Motor, was expected to effectively yield a reduction in the burial of benthic animals compared to regular more repetitive shoreface nourishments (which are placed every 5 years). This is supposed to have a positive impact on especially the longer living species of benthic animals, which would typically recover at a slower pace from the burial with nourished sediment. It was also expected that the coastal environment would become more diverse, since spatial variations in environmental conditions can create different types of habitats for benthic animals. The sheltered lagoon would, for example, show some similarities with tidal flats of the Waddenzee, but at a much smaller scale. Young fish could grow up in these quiet waters.

The beach of the Sand Motor was expected to have strong dynamics of the bed. Plants, such as marram grass and sand couch, would settle and alter the landscape and dunes. Thus, making the area suitable for breeding birds. The sediment transported over the beach by the wind would be trapped by the vegetation, creating a positive feedback for dune growth. Also, the presence of rare plants had attention in the monitoring of the Sand Motor, because some may settle at the still pristine beaches.

The dunes consisted of a first rather unvegetated dune row (or 'foredune'), that was constructed as part of the dune reinforcement of 2010, and the more landward located (older) dunes of Solleveld. These two subregions are in principle located outside the Sand Motor area, but were investigated in order to see whether an impact of the Sand Motor would also be present here. An expectation was that the vegetation in the dunes could change because of Sand Motor induced changes in salt and sand spray. This holds especially for the dunes of Solleveld, as this is a protected nature reserve with various types of dune habitats with their own characteristic vegetation.

4.2 The habitat in the shoreface

A large number of bed samples were collected at the shoreface and on the beach to monitor the developments of the benthic communities (Wijsman et al., 2020; Figure 4.2). These samples were taken with both a bed slicer and a Van Veen grabber (Wijsman et al., 2021). The bed slicer is pulled over the seabed and collects the benthic animals in and on the sediment (up to a depth of 10 cm) in an area of approximately 15 square meters. Larger benthic animals, such as shellfish and crustaceans, are separated out from the bed slicer samples with a 5 mm sieve, while the smaller worms and crustaceans are filtered out with a 1 mm sieve. The Van Veen grabber does collect smaller local samples (0.1 m^2) of the bed sediment, digging slightly deeper into the bed. These samples are sieved out in the laboratory, which makes it feasible to determine the benthic species in more detail. An analysis is made of each of the samples to determine the number of species (taxa), biomass per specie (in gram per m^2) and density (number of individuals per m^2).

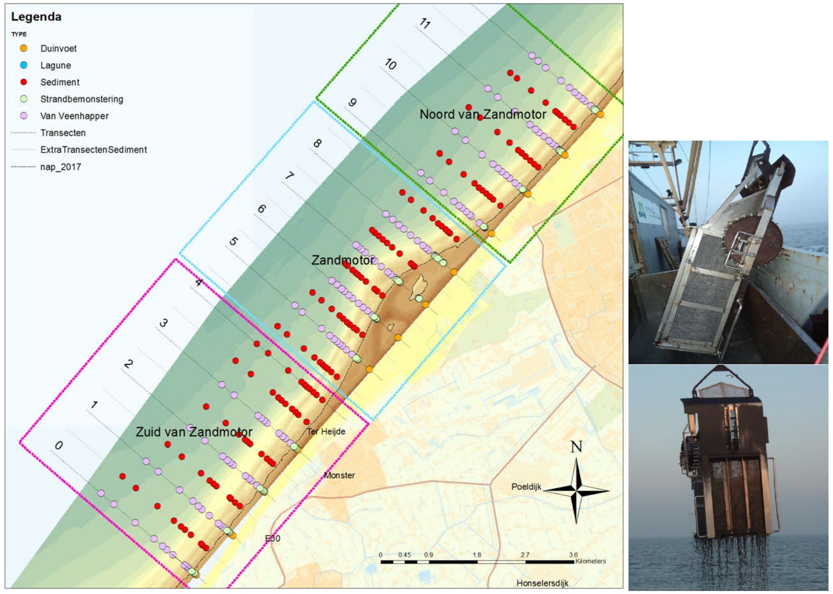


Figure 4.2 Overview of the sampling locations (Wijsman et al., 2018)

The monitoring of the macrobenthos was started in 2010, before construction of the Sand Motor, after which a number of follow-up surveys were carried out in the fall of 2012, 2013, 2015, 2017 and 2019. The sampling locations are located on twelve cross-shore transects which are spaced 800 to 1000 meter apart. Ten samples were taken on each of the transects. The grain size distribution was determined for each of the benthic sample locations, and from 2013 onward also for transects that are placed halfway in-between these benthic sample transects.

Changes in the benthic communities

The number of species, the density and the biomass were substantially higher after construction of the Sand Motor compared to the pre-construction survey in 2010 (Figure 4.3; Wijsman et al., 2020). A large biomass of benthic animals was found especially in 2019 and 2017, while the number of species was largest in 2019 (8 species per sample). The first years after construction (until 2015) had a much smaller biomass than the two most recent surveys, but still a much larger biomass was found than for the reference year (2010).

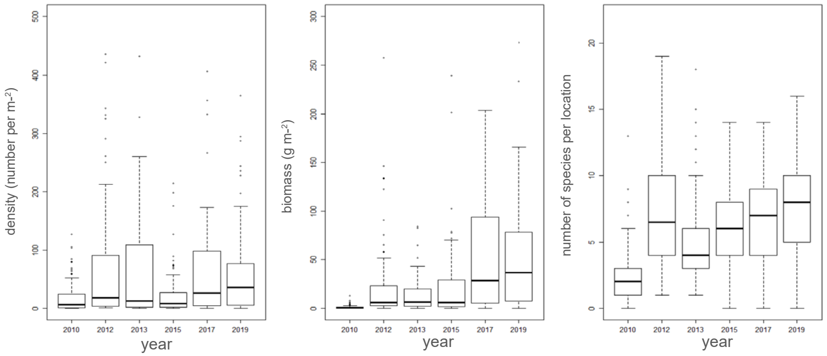


Figure 4.3 Density, biomass and number of species of benthic animals for each of the surveys, as measured with the bed slicer (Wijsman et al., 2020)

The benthic communities in the Dutch coastal waters can change substantially year over year due to natural variability, which means that observed changes in the benthic species may not always be related to the Sand Motor. For example, the moment and location at which the larvae of shellfish sink and settle at the bed and the predation on these shellfish in that particular period are super-relevant for the population of particular shellfish species. This moment and the location can differ per year, because of which some species can be unsuccessful for a few years.

Spatially there are large differences in the distribution of the benthos. Typically, their numbers increase considerably at larger depths (Figure 4.4), where the environmental conditions are very different from the nearshore zone with breaking waves. The most important environmental factors affecting the presence of populations of benthic species are the waves, currents, bed sediment and the duration of drying and flooding (Ysebaert et al., 2016; Tulp et al., 2018; Herman et al., 2021). It is possible to distinguish the environments that are most beneficial for benthic animals, which is illustrated for a couple of species in Figure 4.5.

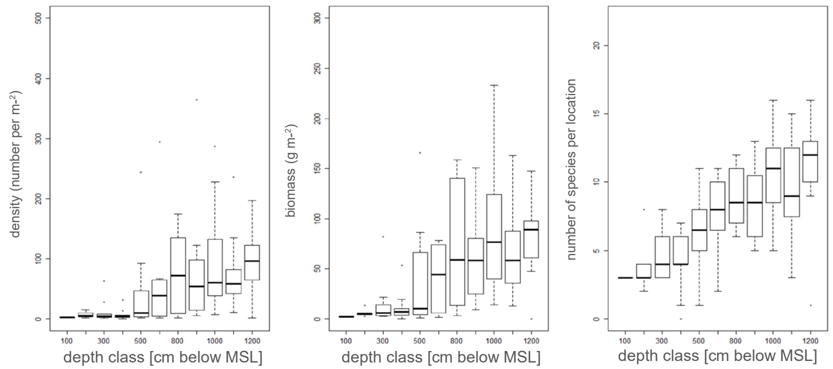


Figure 4.4 Density, biomass and number of species of benthic animals in relation to water depth, as measured with the bed slicer (Wijsman et al., 2020)

The shallow breaker bar zone is a difficult habitat for most of the benthic species, because of the wave forcing and large sediment dynamics. Also, the beach, with the regular drying and flooding and strongly fluctuating temperatures, has very hostile conditions for many benthic species. Only a few benthic species can therefore survive in the shallow breaker bar zone (both in number of species and total biomass). Only specialised species, such as the Pennant's Swimming Crab (*Portumnus latipes;* see Figure 4.5) and the gemshorenworm (*Scolelepis squamata*), are doing well here. Other species were only found in the intertidal area of the spit of the lagoon. The average density of the benthos on the beach was the lowest in 2017 and 2019, but the number of benthic species was also low in the other years, definitely when their numbers are compared to the abundance of benthos in the lower shoreface.

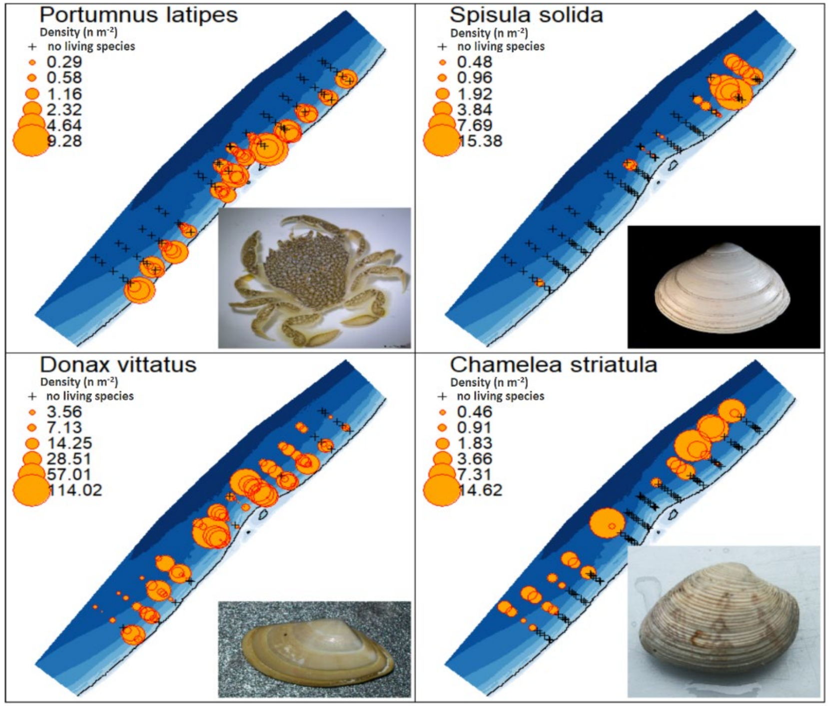


Figure 4.5 Spatial overview of the redistribution of the species Portumnus latipes, Spisula solida, Donax vittatus and Ensis spp. in 2017 on the basis of the measured density with the bed slicer (Wijsman et al., 2020)

More benthic animals were found at larger depths (deeper than -6 m NAP) both in biomass and number of species, with the most being found at depths of 11 meter or more. The venus shell clam (*Chamelea striatula*) prefers somewhat deeper water (Figure 4.5). The tidal currents and the sediment are of relevance in deeper water, as the tidal currents supply nutrients to the benthos (algae's), while the sediment is relevant for the settling of the benthic species. The surf clam (*Spisula solida*) rather settles in the intermediate to coarse sand, while the banded wedge shell (*Donax vittatus*) does better in finer sand. In general, more species of benthic animals can be found (and in larger densities) in places with finer sand (smaller than 0.25 mm) than in places with coarse sand (Herman et al., 2021). For this reason, a lot of benthic species were found in the finer sand just North and South of the Sand Motor.

Habitat for benthic animals

One-off placement of a large volume of sand
It could not be determined based on the measurements whether there is a benefit of the one-off placement of a large volume of sand, and subsequent less frequent burial of benthic species. Instead, an increase was observed of the biomass, diversity and the number of benthic species. The effects of burial of the benthos by the Sand Motor were limited due to the presence of benthic species with a high degree of adaptation to the hostile breaking wave conditions and sediment dynamics, which have therefore quickly recolonized the shoreface. The expectation is that the benthic life would revert back to the situation prior to the Sand Motor over the coming decades, when the Sand Motor sediment has been redistributed fully along the coast.

4.3 Nature development in the lagoon and dune lake

The lagoon and the dune lake have rather tranquil conditions, which means that birds can stay there and forage in the intertidal area. A more explicit expectation was present for the lagoon than for the dune lake. The increase in intertidal area as a result of the lagoon was expected to provide favorable conditions for benthic animals, because of which a habitat can develop that has similarities with the intertidal areas of the Waddenzee (Figure 4.6).

Figure 4.6 Photo of the intertidal area of the lagoon on Augustus 2018 at the end of a very dry period (photo : L. van der Valk)

Development of the lagoon

The lagoon has reshaped considerably over time (Van der Valk, 2019; Arens, 2021; Huisman et al., 2021). Especially the aeolian transport of fine sand from the beach causes siltation at the western side of the dune lake and lagoon. In addition, a lot of fines and organic matter were deposited at the bed of the lagoon, which were brought into the lagoon through the entrance channel. Occasionally, also an influx of medium sand takes place as a result of storm overwash over the spit during storms. This creates sandy deposits at the northern side of the lagoon. Effectively, a layered bed is formed in the lagoon as a result of the fines/silt from the entrance channel, wind-blown fine sand from the beach and intermediate to coarse sand from the spit (Figure 4.7).

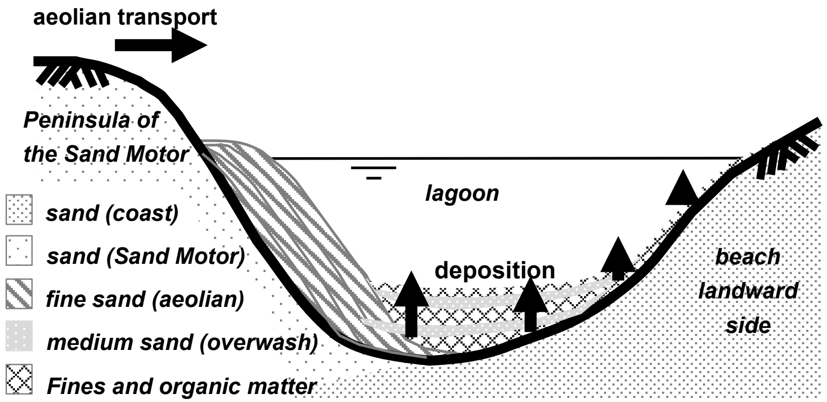


Figure 4.7 Interpretation of the changes in bed sediment composition of the lagoon (Interpretation : B.J.A. Huisman and L. van der Valk).

The bed composition of the lagoon has therefore changed considerably over time. Especially the finer sediment is relatively rich in organic material and can serve as food for the benthic animals. The high organic content in the lagoon may, however, lead to deoxygenated conditions, which is further aggravated by the limited exchange of water through the entrance channel. These de-oxygenated conditions can be unfavorable to many benthic animals. In later years we see algae-blooms along the perimeter of the lagoon and black-colored sediment just under the surface of the bed, which are also indicating a limited availability of oxygen. The main cause is the limited exchange of water with the sea via the relatively long entrance channel and the oxygenation of organic material.

Two surveys were carried out within the lagoon in 2013 and 2015 to obtain an overview of the local benthic populations, for which they used a Van Veen grabber. The survey found larvae of mosquitoes and small worms in the bed of the lower sections of the lagoon, which are also indicative of relatively oxygen deprived conditions.

Figure 4.8 Selection of washed-up shells that were found at the perimeter of the lagoon (left : cockle (Cerastoderma edule), baltic clam (Limecola balthica), sand gaper (Mya arenaria) and razor clam (Ensis leei); right : Manila clam (Ruditapes philippinarum) which were found in march 2018; photo : L. van der Valk)

In addition, regular surveys were made of the washed-up bivalve shells at the edge of the lagoon, which provide a proxy for the benthic animals living in this area (Van der Valk, 2019). Other benthic species were found in the lagoon than for the outer rim of the Sand Motor (e.g. the beaches of the peninsula and spit). The most common shells found in the lagoon were the cockle (*Cerastoderma edule*), the baltic clam (*Limecola balthica*), the sand gaper (Mya arenaria), the razor clam (*Ensis leei*), the peppery furrow shell (*Scrobicularia plana*) and the Manila clam (*Ruditapes philippinarum*; Figure 4.8). In addition, a large number of benthic species were found at the lagoon which were also found at the seaward side of the Sand Motor, such as the otter shell (*Lutraria lutraria*) and the cut through shell (*Spisula subtruncata).* They may have been washed into the lagoon during the storm season.

The composition of the shells found at the rims of the lagoon changed considerably over time (Figure 4.9). The number of species of washed-up shells has increased from two species in 2012 to seven species in 2019. In the last years the number of washed-up clams has decreased substantially.

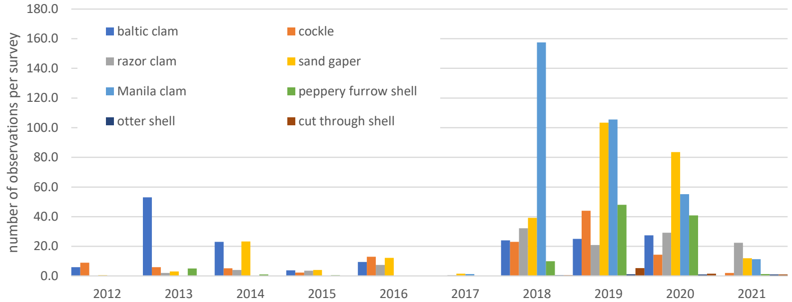


Figure 4.9 Average number of shells that were found on the edges of the lagoon per year per measurement survey (Van der Valk, 2021).

A large number of cockles and baltic clams were found in the first years, but hardly any were still observed in 2018. While the sand gaper, Manila clam and the razor clam were very plentiful in later years. These species could be found both in the lagoon as well as in the entrance channel. The razor clam was also found in the nearshore zone of the coast outside the lagoon, but the razor clam shells found at the lagoon were wider and much darker than the shells found at the shoreface, which is expected to be an effect of the differing environmental characteristics. Their epidermis are often quite well preserved, which is not the case for shells that are brought in from the North Sea coast. The protected environment of the lagoon hosts a very different benthic community than the intertidal areas of the open coast.

The lagoon developed into a region that provides shelter from the waves of the North Sea, and with limited in and outflow of sea water. Especially, the increasing length of the tidal entrance channel over time has played an important role in the development of the environment of the lagoon. Only the high tide is now regularly flushing the lagoon, and on the long-term the exchange may only consist of the overwash over the spit during storm conditions and precipitation. This has resulted in a lagoon that is rather sensitive to temperature fluctuations and supply of nutrients. De-oxygenated conditions may therefore develop in the summer season, making the summer-conditions rather harsh for benthic animals in the lagoon (e.g. in 2018). A period with stench even occurred as a result of high concentrations of organic material and low oxygen levels. This will most likely last until a breach will occur in the peninsula of the Sand Motor as a result of the ongoing erosion, thus creating a new opening from the lagoon to the sea.

The western side of the lagoon has developed into a relatively shallow zone as a result of the influx of fine wind-blown sand and fines/silt from the sea. This wet beach plain is considered a special region (and possibly later a habitat when plants start to grow) which is rather uncommon for the Holland coast.

Development of the dune lake
The habitat “dune lake” is also new for the Holland coast. It can be described as an enclosed very wet beach plain with initially relatively deep water. A rare plant species, snavelruppia (*Ruppia maritima*), was growing in the brackish dune lake in 2018. This is a characteristic plant species that attracts waterbirds. No information is available on the water quality of the dune lake, but it is expected that it has been quite good quality water conditions (especially when compared to the lagoon), because the dune lake is filled with rainwater.

The dune lake gradually decreases in size (both volume and area), and will most likely disappear on the long-term as a result of the influx of wind-blown sand. A beach plane with a high ecological quality may, however, be created as soon as the dune lake has filled with wind-blown fine sand. As such the “dune lake” and “lagoon” are new dynamic habitats for the Delfland coasts, and can be considered as unique habitats where higher nature values can develop over time.

4.4 Dune formation on the beach and foredune

Prior to the construction of the Sand Motor it was expected that strong vegetation and dune growth would take place on the beaches and in the dune reinforcement. A positive feedback of vegetation and dune growth was expected, starting off with vegetation growth, which then captures the wind-blown sediment in the vegetated regions, which would be a stimulus for the vegetation. Quiet zones would develop which are suitable for (breeding) birds. An important question was, however, how quickly and to what extent these natural and dynamic dune regions would develop. And an additional point of attention was the impact of recreation on the nature development of the beach.

Vegetation and dune growth on the beaches of the Sand Motor
Vegetation on the Sand Motor was expected and also desirable. It creates a more diverse landscape and nature, with hiding and breeding spots for birds and other animals. Plants were observed on the Sand Motor after a few years (Van Puijenbroek, 2017; Vertegaal, 2021). In the first three years this concerned mostly sea rocket (C*akile maritima*) at the beach of the peninsula, while sand couch (*Elytrigia juncea*) and marram grass (*Ammophila arenaria*) are sowed along the foredune and at the southern side of the Sand Motor (Figure 4.10).

Marram grass was typically the primary dune former, which is remarkable given that the classical knowledge is that sand couch will settle first on the beach before the marram grass, because it is more tolerant to salt. The vegetation creates a sheltered region which captures the wind-blown sand, stimulating further growth of the marram grass. Also, sand rye grass (*Leymus arenarius*) is present at the Sand Motor and acts as primary dune creator. New dunes developed at the beach with a height of a few meters (referred to as ‘embryonal dunes’).

Figure 4.10 Embryonal dune growth at the southern side of the Sand Motor (upper left), pioneering plants such as sea rocket (lower left) and sand couch (right).

The number of plant species, mosses and lichens on the Sand Motor is still quite small which is most likely the result of the large sand dynamics and some relatively dry years (Arens, 2021). It also takes time before the groundwater reaches a level that is sufficient for the plants. The high dynamics of the bed at the Sand Motor are not an advantage for all plant species. The sea holly (*Eryngium maritimum*) was observed in many surveys at the Sand Motor, which is listed as an endangered species, but not too many rare plant species were found.

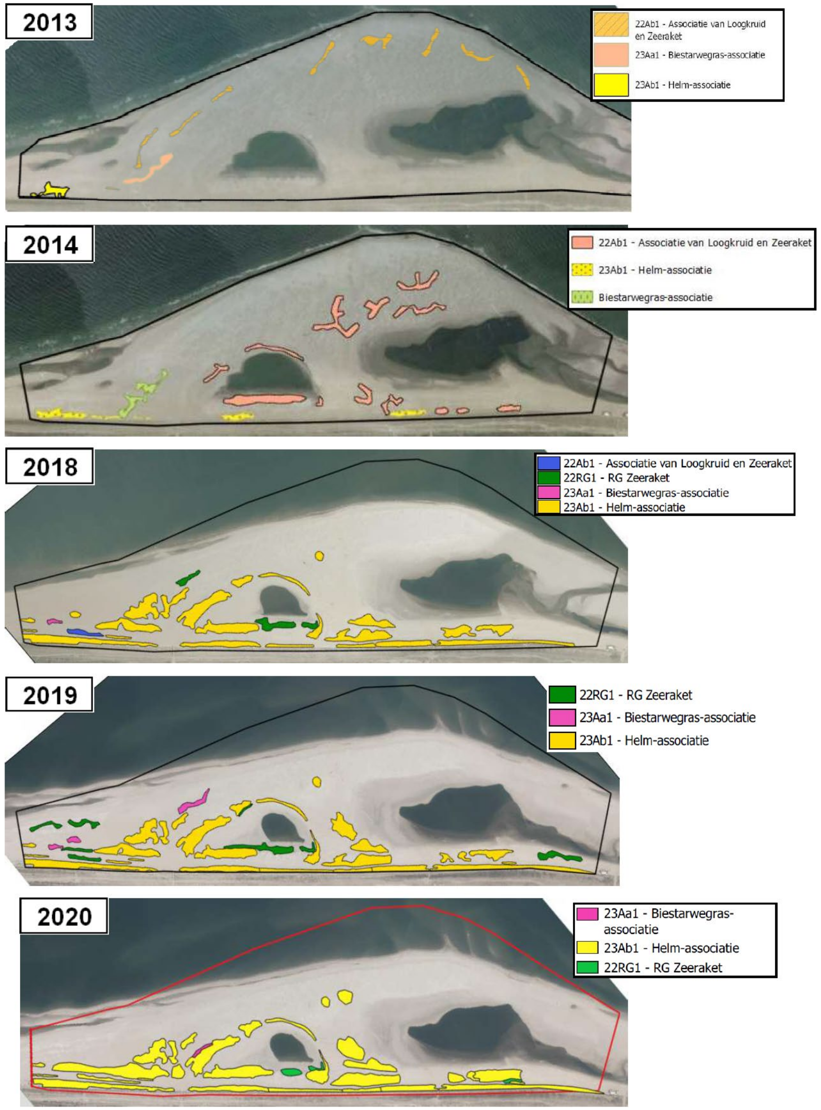


Figure 4.11 Overview of the vegetation of the Sand Motor and related dune growth in places with marram grass vegetation (Vertegaal, 2021).

The development of new dunes at the Sand Motor was initially much slower than anticipated, but a clear acceleration took place since 2016 (Figure 4.12). Approximately 6 hectares of embryonal dune were created up till 2018, which increased to an area of 13 hectares in 2020.

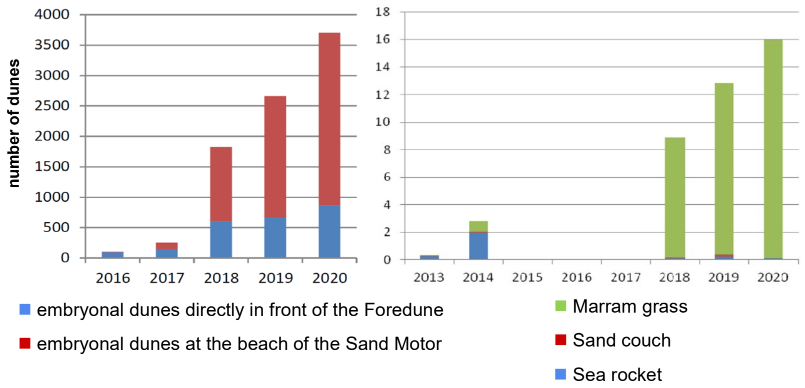


Figure 4.12 Number of dune complexes of embryonal dunes since 2016 (left) and vegetation abundance on the Sand Motor (right) (Arens, 2021).

New dunes developed especially at the southern side of the Sand Motor (Figure 4.12). In the first 5 years, the dune growth predominantly took place in the foredune (i.e. the dune reinforcement that was placed in 2010). From 2016 onwards the dune growth shifted more to new embryonal dunes on the beach of the Sand Motor. These new dunes are especially located at the connection of the peninsula with the coast and around the dune lake. Many individual dunes have grown and became interconnected forming larger complexes of low dunes, which can be classified as 'White dunes' (H2120 of the Natura-2000 classification). These white dunes host various plants, such as the perennial sowthistle (*Sonchus arvensis*), sea holly (*Eryngium maritimum*), sea spurge (*Euphorbia paralias*) and in some cases also nordic marram grass (*Ammophila baltica*).

The zone with new dunes is a couple of hundreds of meters wide (parallel to the foredune). Merged dune complexes with widths of some tens of meters are located within this zone. The height of these dunes reaches up to 2.5 meter above the adjacent beach in 2021. The most seaward located dunes are located about 350 m seaward of the dunefoot around the dune lake. The new formed dunes are very dynamic and create a very natural landscape at the Sand Motor.

Far less dunes developed in the middle and northern section of the Sand Motor. The dune lake and the lagoon capture most of the wind-blown sediments, thus reducing the supply of sand. In combination with the large number of shells in the sediment, this did create a very unnatural surface texture of the dry beach of the peninsula, where the necessary dynamics for reworking and sorting of sediment are absent (Arens, 2021). Some of the dunes that developed at the seaward side of the peninsula in 2013 have already disappeared as a result of the ongoing erosion of the peninsula by the sea. The cliffs at the peninsula also block the local aeolian sediment transport from the intertidal beach (see paragraph 3.2.6). For this reason, hardly any dunes developed at the seaward side of the peninsula.

Dune formation also took place on the narrow middle section of the Sand Motor, between the dune lake and the lagoon. And small-scale dunes have been developing at the coast landward of the lagoon, which is a region with very limited supply of aeolian sand. The current design of the Sand Motor limits the growth of the existing and embryonal dunes, as the lagoon and the dune lake catch a large proportion of the sand. Consequently, the vegetation (marram grass and sand couch) is often quite sparse and sometimes not so vital at the middle and northern sections of the beach, although this may as well relate to the dry growing seasons of 2019 and 2020.

The dune complexes at the Sand Motor are delineated by the tracks of cars. Especially in the first years they had a large influence on the settling of vegetation. Consequently, the new dunes developed as rather elongated dune stretches parallel to the foredune (see also paragraph 5.3.2 about recreation management). It is estimated that about 3 to 5 hectares of potential dune vegetation was not developed as a result of driving routes of cars and walking routes by visitors (and on horses). The vegetation did, however, grow gradually and has become dominant in certain regions, such as around the dune lake and at the southern end of the Sand Motor. The increase in the size (spatially and in height) of the dune complexes makes them less vulnerable now than in the preceding years. Instead, the dunes are now posing the limits to the walking and driving routes, although the delineation is often still rather straight or parallel to the dunes.

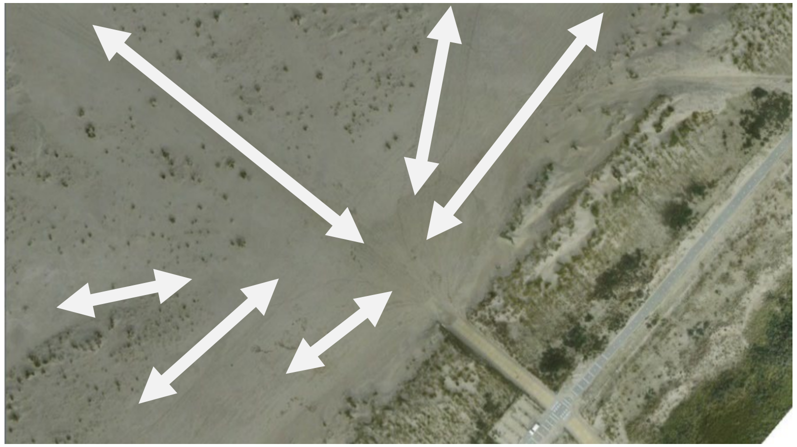


Figure 4.13 Driving tracks at the beach entrance of the Schelpenpad.

An impact of the cars and walking routes can still be seen after 10 years at the beach entrance of the Schelpenpad (Figure 4.13). Lots of narrow paths and unvegetated sections can be distinguished in radial directions from the entrance, even though the Schelpenpad entrance is not as much used as other beach entrances (e.g. the Molenpad and the beach entrances at the northern side of the Sand Motor; see paragraph 5.3.2). Furthermore, it is noted that two zones with dunes have developed on the beach of the Sand Motor as a result of the driving routes. The first zone is located directly in front of the foredune and the second group of dunes is separated by the main alongshore driving corridor. A single dune would have developed if no traffic would have been present. Another influence on vegetation growth came from the beach cleaning of the municipality of the Hague. This is typically done with tractors that plow the beach, which have a great impact on the growth of new vegetation.

Some zones with vegetation growth were demarcated in later years with small fences to keep the public from entering these zones (zonation). The effect of these measures was, however, very limited, because only regions were selected where the first more difficult steps in the development of vegetation and dune growth were already completed. In order to stimulate dune growth, it would have been better to demarcate the regions with very small dunes and young vegetation. Closing parts of the Sand Motor for 4WD's can have a substantial impact on the vegetation and dune growth.

In summary, it is clear that the Sand Motor has transformed towards a very natural and dynamic region. Both the dunes and the beach have become more diverse as a result of the growth of the embryonal dunes. The vegetation and dune growth have been slowed down by the recreational users and traffic on the beach, but eventually the vegetation is still transforming the beach.

Development of the dune reinforcement

The first dune row, which was constructed as part of the 'Zwakke schakels' dune reinforcement in 2010, changed considerably in the first years after construction which was the result of the natural aeolian sand supply and vegetation growth (Arens, 2021; Vertegaal, 2021). Marram grass tussocks were planted on a relatively smooth dune profile, which led to a rapid growth of the vegetation. Wind supplied sand was captured in the first dune row, which resulted in a considerable growth of the height and a progression of the dune foot in seaward direction. The foredune height now varies substantially for the vegetated and unvegetated sections, which makes the dunes more natural (Figure 4.14). Especially the dunes on the southern connection of the Sand Motor with the coast have been growing strongly. The most vital marram grass is also found here. The average volume growth of the foredunes (in m^3/m) was rather similar to the growth of the primary dunes on the adjacent Delfland coast (Huisman et al., 2021). Part of the aeolian transport at the northern and central section of the Sand Motor was captured by the lagoon and the dune lake, which therefore have been growing at a smaller pace. A vegetation succession has taken place at the foredunes. White dunes (H2120) are mainly found at the foredune sections North and South of the Sand Motor, while the central section of the foredune is currently characterized by sea-buckthorn (*Hippophae rhamnoides*; habitat type H2160). The rapid succession from pioneer plants to more developed vegetation at the central dune section is expected to be related to the sheltering from the sea that the Sand Motor provides. The foredunes at the center of the Sand Motor receive a smaller amount of sand and salt spray than the northern and southern coastal sections of the dune reinforcement.

Figure 4.14 Change in naturalness of the foredune at the southern side of the Sand Motor. Left : after construction; Right: after 8 years. Photo's : Bas Arens.

Solleveld is a protected Natura-2000 inner dune region, which is located just landward of the Sand Motor and dune reinforcement (or foredune). The dynamics and quality of this dune area need to be preserved. A point of attention here is that an increase in the area with sea-buckthorn is not desirable. If sea-buckthorn (*Hippophae rhamnoides*) habitats would grow in the dunes of Solleveld, then this development is corrected with management to prevent further growth. Prior to construction of the Sand Motor, it was expected that the amount of sand spray would increase in the dunes, while salt spray would decrease. The impact on the nature of Solleveld is therefore expected to be related to the sand and salt spray.

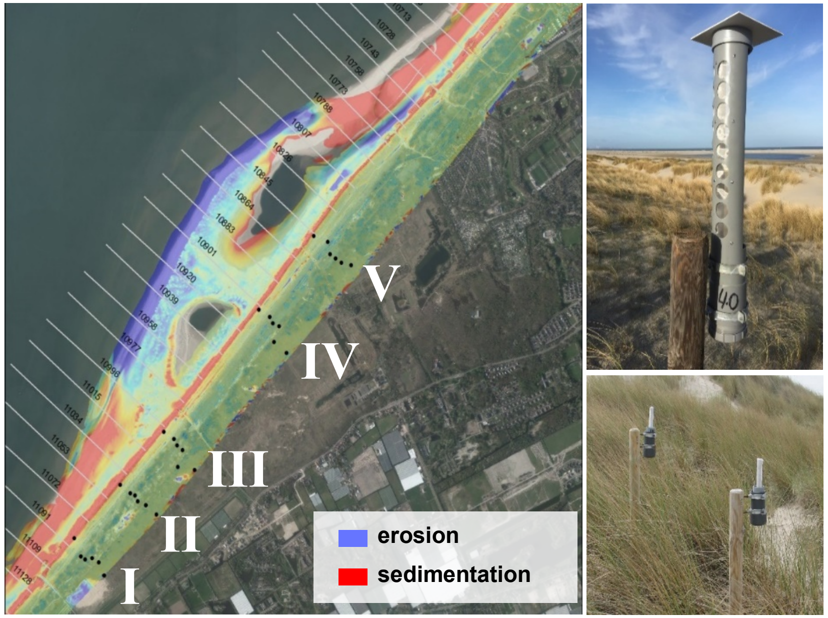


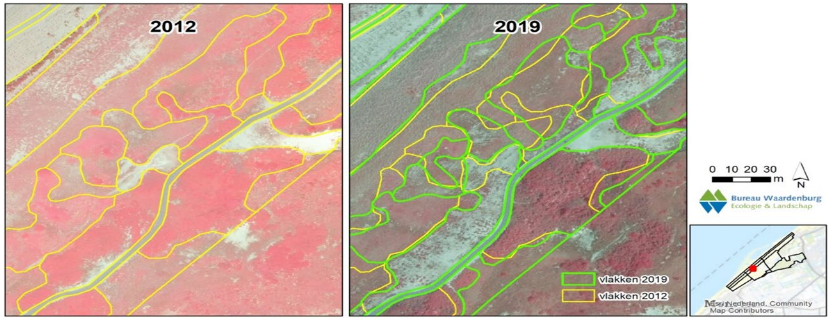
Figure 4.15 Sampling locations for sand spray (upper right) and salt spray (lower right) on the transects I t/m V in combination with an overview of the erosion and sedimentation rates (left). Photo's: Bas Arens. (Arens, 2021)

Small bins were placed at five cross-shore transects in the dunes to collect the sand and salt spray over the dunes (Arens, 2021). A first aim is to determine whether the physical conditions have changed as a result of the Sand Motor. It is noted that the first measurement station is located in the first dune row (or dune reinforcement 2010), which is therefore not a part of the dunes of Solleveld. The measurements show that the sand and salt spray in the dune reinforcement (first sampling location) are much higher than for the dunes that are located further landward in Solleveld. So, the dune reinforcement catches a large proportion of the sand and salt that is transported to the dunes. Consequently, the sand and salt spray are very small in the dunes of Solleveld, but they are still measurable. Typically, the sand and salt spray are slightly larger for the southern transects at the connection of the Sand Motor with the existing coast (transect I t/m III) than for the central and northern part. The degree of sand and salt spray was especially low at the northern side of the Sand Motor (i.e. landward of the lagoon; transect V). The limited sand spray in the central section is mainly related to the lagoon and the dune lake, and to a lesser degree also to the catchment of sand by the embryonal dune vegetation at the beach.

Incidentally, there can be very considerable sand and salt spray in the dunes after storm events (Arens, 2021). An example is the January 2018 storm, which transported a considerable volume of sand to the dunes of Solleveld. Aeolian sediment transport to the dune reinforcement (first dune row) typically took place during intermediate weather conditions (wind force 5 to 7), while the sand and salt spray to the existing dunes were determined by the extreme conditions. A single storm can contribute the majority of all the sand spray in a period of a few years. The incidental large transports of sand and salt are very relevant for the ecology of the existing dunes.

Both field measurements and aerial photos were used to assess the changes in the vegetation at the Sand Motor (Loermans et al., 2020; Vertegaal, 2021). The aerial photos are used to delineate areas with similar vegetation, which are then investigated in the field to determine the local plant species. This results in a map of the dune habitats (Figure 4.16). The resulting maps show that no net changes have taken place in the dune habitats (e.g. white dunes, grey dunes and sea-buckthorn). Sand and salt spray and vegetation were therefore not correlated for the dunes of Solleveld. Important here are the many dune-vegetation management measures that were taken to prevent the growth of brushwood. For example, the clearing of sea-buckthorn and grazing by cattle. It can be concluded that it is possible to preserve nature values in the dunes of Solleveld with active vegetation-management.

The Hoogheemraadschap Delfland has also created artificial blowout holes in the dunes North of the Sand Motor up till Kijkduin, which have an impact on the sediment dynamics in the dunes. The first blowout holes were, however, too small to have a relevant effect on the dune habitats. Larger artificial blowout holes were therefore constructed in 2020, which will likely have a significant impact on the dune dynamics, but it is still too early to analyze the effects of this measure.



4.6 Birds, fish and sea mammals

The Sand Motor creates a large new land area that can be used by foraging birds, resting sea mammals and fish in their juvenile stages. This has, however, not been an explicit aim of the Sand Motor. The relatively long distance from the beach entrances to the waterline of the peninsula does, however, result in a smaller number of visitors because of which also the disturbance of the birds and sea mammals is reduced. Another design-element was the lagoon, which is intended to create a new environment with quite conditions for juvenile fish.

Birds

More coastal birds have been spotted in the intertidal area and the shallow coastal zone of the Sand Motor in the first years after construction of the Sand Motor (in the years 2013 and 2014 in Figure 4.17; Vertegaal, 2021), although it concerns only a relatively moderate change in absolute numbers. Most birds were observed at the lagoon of the Sand Motor. The number of birds on the high beach was relatively limited.

The Sand Motor is of importance for sea birds, especially the *herring gull* which is rather common (Figure 4.18). From 2017 onwards the number of birds (especially the gull species) has decreased considerably, with the *black-headed gull* as the most strongly decreasing species. Also, the *cormorant* was observed far less often. The number of *terns* (*common tern* and *large tern*) and *oystercatchers* remained approximately the same. Noticeable is that the number of *three-toed sandpipers* has increased in recent years.

The bird population at the Sand Motor is very different from the beach of Noordwijk (Figure 4.18), but the total number of counted birds was comparable. The *black-headed gulls*, *cormorants*, *common tern* and *large terns* were especially present at the Sand Motor, while the *three-toed sandpiper* and *herring gull* were far less often observed than at Noordwijk. The relative quiet beach of the Sand Motor peninsula (compared to Noordwijk) makes it more suitable for *cormorants* than the other beaches, which is an added value for the nature values of the Sand Motor.

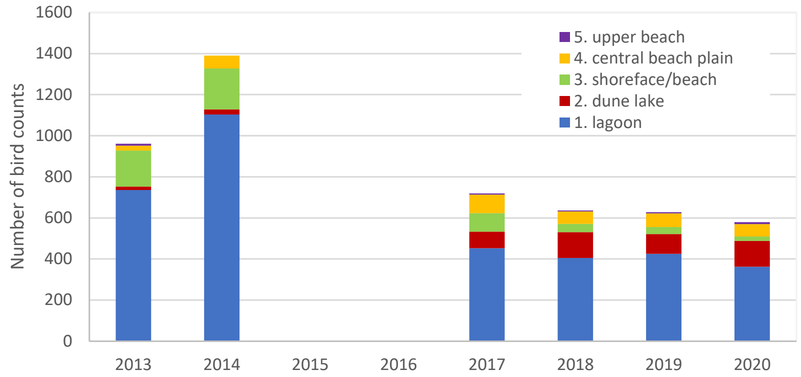


Figure 4.17 Overview of number of observed non-breeding birds.

The smaller number of *three-toed sandpipers* is expected to be related to the relatively new sand that was used for the construction of the Sand Motor, wherein the benthic community was far less developed than for the beaches at Noordwijk. These foraging species do, however, increase over time at the Sand Motor, which likely relates to the development of food availability on the beach of the Sand Motor.

Breeding birds hardly make use of the Sand Motor as a place for nesting and raising their offspring. Only in 2017 the first breeding bird was observed (the *ringed plover*) at the Sand Motor. In later years multiple pairs of breeding *ringed plovers* were observed which also brought up some young birds. The marram grass vegetation that developed in recent years has been essential as shelter for these birds, meaning also that the Sand Motor is becoming more and more suitable for breeding birds. However, as soon as the dunes get larger and too vegetated, the Sand Motor will also get less attractive for beach-breeding birds such as the *ringed plover*. Outer dune species, such as the *meadow pipit*, will then settle in the new dunes, of which the first species were observed in 2019.

Species		Noordwijk (pole 71-81)			Sand Motor		
		1998-2007	2007-2011	1998-2011	2013-2014	2017-2020	2013-2020
cormorant	Phalacrocoracidae	?	?	?	40.6	4.9	22.8
ringed plover	Charadrius hiaticula	0.09	0.07	0.08	0.3	0.6	0.4
pied sandpiper	Calidris alpina	0.06	0.06	0.06	0.7	0.5	0.6
three-toed sandpiper	Calidris alba	20.1	12.2	16.2	3	6	4.5
grebe	Podiceps cristatus	?	?	?	1.8	2	1.9
great black-backed gull	Larus marinus	3.4	5.2	4.3	7.4	5.4	6.4
large tern	Thalasseus sandvicensis	0.9	1.1	1	5.8	6.2	6
jackdaw	Corvus monedula	0.3	0.3	0.3	0.3	0.4	0.3
lesser black-backed gull	Larus fuscus	18.5	18.1	18.3	16.1	22.4	19.3
black-headed gull	Chroicocephalus	19.6	9.7	14.6	108.7	9.7	59.2
oystercatchers	Haematopus ostralegus	1.8	2.8	2.3	4.4	3.3	3.9
ruddy turnstone	Arenaria interpres	0.5	0.11	0.31	0	0	0
common gull	Larus canus	15.9	17.2	16.6	15.1	14.2	14.6
common tern	Sterna hirundo	2.3	1.6	2	14	7.8	10.9
herring gull	Larus argentatus	136.8	113.6	125.2	33.8	27.5	30.6
carrion crow	Corvus corone	2.3	2.6	2.5	2.9	3.8	3.4
total		**223**	**185**	**204**	**262.2**	**117.6**	**189.9**

Figure 4.18 Comparison of the number of observed non-breeding birds per kilometer beach length on the Sand Motor with the observations at the beach of Noordwijk (Vertegaal, 2021).

The main reasons for the decline of the number of (non-breeding) birds cannot be determined with certainty. The decreasing number of birds that were spotted around the lagoon is very relevant, which may have to do with the change of the lagoon morphology over time. It is expected that the disturbance by visitors (with dogs) has also contributed to the decline of the number of observed birds. Data on recreation shows that an increase of the number of visitors took place of 15 to 20% throughout the years. This, in combination with a decreasing land area of the peninsula, results in a higher visitor density at the Sand Motor.

Fish

The development of the fish population in the shoreface of the Sand Motor and in the lagoon has been monitored only in the first years after construction, with the aim to determine whether the lagoon would act as a nursery for juvenile fish (Wijsman et al., 2015). However, the variation in the catch of fish was very large, which makes it very difficult to draw firm conclusions. The fish monitoring program was therefore discontinued in 2015. Consequently, a direct judgement of the impact of the Sand Motor on juvenile fish cannot be given in this chapter. The increase in the number of and biomass of benthic animals is, however, a positive indicator for the presence of juvenile fish.

Sea mammals

Observations of sea mammals, such as seals, were made in the first years after construction of the Sand Motor (Wijsman et al., 2015). The number of seals was, however, very limited. Meaning that the Sand Motor is not going to be very important for this species group. Effectively the Sand Motor is not very different from the other beaches along the Holland coast when the impact on sea mammals is considered. Essential is that the Sand Motor provides a quiet environment, but still the number of recreational guests will be too large to make it a safe habitat for sea mammals.

4.7 Evaluation of nature development

The evaluation question with respect to the added value of the Sand Motor for nature development is separately assessed for 1) benthic animals in the shoreface (e.g. the one-off placement), 2) vegetation and dune growth on the beach and 3) benthic animals and birds around the lagoon and dune lake. It is noted that a, sometimes shortened, answer to the (sub)evaluation questions can be found in Appendix A.

Benthic animals on the shoreface

The influence of the one-off placement of a large quantity of sand, as done for the Sand Motor, on the diversity of the benthic communities in the shoreface is considered here.

- *EQ2-2b: Does the one-off placement of a large volume of sand result in a more natural benthic community composition in the shallow coastal zone? How does it compare to regular nourishments schemes? Is a one-off placement beneficial for longer living species?*
  More benthic species and biomass were found in the shoreface of the Sand Motor in comparison to the pre-construction situation. The changes in the environmental conditions (waves, currents, bed level change and sediment) led to more diverse habitats. Especially the milder conditions in the region just North of the Sand Motor created a specific habitat with a large number of benthic species, which is evidence of an impact from the Sand Motor that is not present at regular nourishments.

  The burial of benthos with nourishment sand occurs with lower frequency at a large-scale nourishment such as the Sand Motor than for regular nourishments. It was, however, not possible to differentiate the effects of this aspect from the influence of other changes in the environmental conditions, such as the wave forcing, tidal currents and bed sediment composition. Possibly, this effect of the one-off placement is rather small as the shallow nearshore zone is home to benthic species that are adapted to a high degree of sediment mobility. These benthic species can quickly recolonize the nourished shoreface. It is expected that the situation for the benthos will eventually return to the pre-construction situation over time, when the Sand Motor sediment is spread fully over the coast.

Vegetation and dune growth on the Sand Motor
The way in which new dunes develop at the Sand Motor is another point of attention. It is not only relevant how nature (vegetation and habitat types) will develop at the beach, but also to what extent the dynamics of the Sand Motor beach and shoreface (with a continuously changing landscape) will lead to a higher nature quality. And to what extent the recreation management affects the nature development.

- *EQ3-1a: Does the Sand Motor add attractive natural area on the beach and in the young foredunes seaward of the existing dunes?*
  The growth of vegetation and embryonal dunes at the beach of the Sand Motor has created a landscape with a large degree of naturalness, which is not found at other places along the Holland coast. A large area of embryonal dunes has developed at the beach (H2110). Smaller dune patches merged in some places into dune complexes of white dunes (H2120). A rare plant species found at the Sand Motor was the sea holly, which is a red list (endangered) plant species.

  The dynamics of the Sand Motor landscape have transformed the beaches of especially the southern end of the Sand Motor at the connection with the coast. The ongoing accretion of the coastal zone here has led to enhanced aeolian transports and subsequent growth of the new dunes at the beach. The vegetation development did, however, only kick off substantially after 2016, which was much later than expected. A very quick growth of the vegetation and dunes did, however, take place from 2016 till 2021.

  The dune lake and the lagoon reduced the potential vegetation and dune growth at the central and northern beach sections of the Sand Motor, because sand transport was captured by these water bodies. Also the supply of sand from the peninsula was more limited than expected, as a layer of coarse sand and shells developed here which armored the bed. The height of the dry beach of the peninsula was effectively too high to allow reworking of the bed. No wave stirring or wave run-up could take place on the dry beach of the peninsula even during storms with very high water levels. So, the coarse sediment and shell layer could not be cleared by natural forces. A design with a lower crest would have resulted in more sediment dynamics at the beach of the peninsula.

  Traffic and beach cleaning made it difficult for new young vegetation to survive in the first years after construction. The driving routes can still be distinguished in 2021 in the spatial distribution of the embryonal dunes (e.g. at the beach entrance of the Schelpenpad and at the division between foredunes and new dune complexes at the beach). Recreation management, with the aim of promoting vegetation- and dune growth, was hardly applied. The expectation is that a larger area of young dunes would have had developed if access restrictions would have been in place for visitors, such as the limitation of the driving routes of cars (with fences and/or signs) or when hikers would take predefined routes from the entrances to the beach (e.g. at the Schelpenpad beach entrance).

Development of the nature of lagoon and dune lake
The development of the sediment composition and ecology (e.g. benthic species and vegetation) was evaluated for the dune lake and lagoon. The relevance of these regions for birds, fish and sea mammals has been discussed.

- *EQ 3-1b: How does the temporary new nature develop in the intertidal area of the lagoon?*
  The construction of the Sand Motor, and subsequent changes of the nearshore waves, currents and bed sediment composition, have led to an increase in the diversity of habitats in the shoreface and for the lagoon. The relatively sheltered lagoon is filled in from the western side with aeolian sediment, while fines/silt and organic matter are accumulating on the bed. The sediment in the entrance channel is relatively coarse due to the strong local currents.

  Shells were collected at the edges of the lagoon, which indicated an increase in the number of benthic species in the lagoon over time. The number of species increased from one to a maximum of seven species. Shells were found that are uncommon on the beaches of the Holland coast. Besides this also the larvae of mosquitoes and small worms were found in the lagoon. The total number of species decreased since 2020, which can be explained from the diminishing flushing of the lagoon with water from the sea. This low influx of water in the lagoon is a point of attention, because it has led to deteriorating water quality in recent years (de-oxygenated conditions). Underwater vegetation developed (*snavelruppia*) in the dune lake. On the long-term the lagoon and the dune lake can change into ecologically highly valued wet beach plains. This may still take quite some time, as the lagoon and the dune lake are quite deep, thus requiring a lot of aeolian sediment supply to fill up.

A larger number of non-breeding birds was observed at the Sand Motor in comparison to the pre-construction situation. This holds especially for the herring and black-headed gull which were observed in large numbers. The presence of the cormorant, the large tern, the common tern (Sterna Hirundo) and the large black-backed gull were of particular added value, because these birds are not often seen at the Holland coast. More birds were observed in 2013 and 2014 than in later years. The smaller number of birds in recent years relates to the decrease of the area of the peninsula as a result of erosion, which reduced the available quiet places at the Sand Motor (i.e. which cannot easily be reached by visitors). Stilt walkers are less often seen at the Sand Motor than at other beaches, although the number of stilt walkers is still increasing over time at the Sand Motor, which most likely is the consequence of an increase in benthic life in the intertidal area. Also, for breeding birds the added value of the Sand Motor is quite limited, because it concerns only a small number of birds. Coastal breeding birds such as the beach- and ringed plover, the little tern and the oystercatcher are at present hardly breeding at the Sand Motor, because these species are quite sensitive to disturbance from visitors (and dogs).

An impact of the Sand Motor could not be shown for juvenile fish and sea mammals, as this was complicated by the large variation in fish catchment per survey and limited number of sea mammal observations. Despite the relative quietness of the beaches of the Sand Motor, there still is too much disturbance to create a safe environment for sea mammals.

5 Experience, appreciation, beach management and environment

5.1 Expectations and aims

The Sand Motor was designed to serve not only the purpose of a coastal maintenance measure, but also contribute to nature development and recreation. For an evaluation of the functional aims, it is therefore relevant to assess the experiences of beach users at the Sand Motor. Questions focus on the contribution of the Sand Motor to the experience and appreciation of the Holland coast and Scheveningen (evaluation question EQ3-2), lessons for swimmer safety (EQ2-1b) and societal added value of the Sand Motor (for arts, culture and archaeology/palaeontology). The societal function is of relevance for an overview of the appreciation of the area (EQ2-1c).

Management objectives for the beaches and dunes of the Sand Motor were defined by the Province of Zuid-Holland and Rijkswaterstaat at the start of the Sand Motor project. In general, the preferred approach is that not too much is organized by the managers, unless that it is a requirement for safety, nature preservation of the dunes or groundwater quality. The Province of Zuid-Holland and Rijkswaterstaat discussed the management in half-yearly meetings, wherein potential unexpected developments could be discussed. The management objectives focused on:

I. recreational safety (EQ4-1)
II. influence of recreation on nature development (EQ4-2)
III. ground water levels in the dunes of Solleveld (EQ4-3)
IV. impacts on sand and salt spray in Solleveld (EQ4-4)
V. impacts on wet infrastructure (e.g. navigation channels) (EQ4-5)

Prior to the construction of the Sand Motor it was expected that the increase of the land area on the Sand Motor would create opportunities for recreation, which are evaluated in this chapter. It was expected that hikers, horse-riders, fishermen and sun-bathers would benefit. Some worries were present, for example, about the safety of beach users. This mainly related to the risks of rip currents (seaward directed currents) and quicksand. Early on attention was paid to these subjects by the Province of Zuid-Holland and the lifeguards. It was furthermore expected that recreation would impact nature development (e.g. vegetation growth and new dunes) at the beach.

Further impacts were expected on groundwater, existing dunes and infrastructure. As a consequence of the construction of the Sand Motor, the groundwater in the dune area was expected to rise. Possibly, the infiltrated rainwater in the outer dunes could bring contaminations from rubble dumps in the dunes to the wells of the dune-water companies.

Also impacts were expected on the environment, such as a possible change in the vegetation type of the existing dunes of Solleveld. The influx of salt from sea was expected to diminish, while an increase was expected of the sand spray. It was not known a-priori, what would be the impacts on the vegetation of the Natura-2000 area of the dunes of Solleveld. The management of the existing dunes was therefore also included in the Sand Motor permit. An important question here was the potential impact a Sand Motor has on vegetation growth, and whether it can be mitigated with dune vegetation management measures.

Potential impacts of the Sand Motor sediment on the navigation channels of Rotterdam and Scheveningen were a separate management aspect to be investigated. Also, the coastline changes at the water pumping station of the Hoogheemraadschap of Delfland were a point of attention. A large volume of sand was nourished here, and it is very relevant to know the destination of the sediment.

This chapter discusses first the experience and appreciation of the Sand Motor for the recreational and societal functions (paragraph 5.2).

Then the management questions are discussed in paragraph 5.3. And finally, paragraph 5.4 provides answers to the evaluation questions.

5.2 Experience and appreciation of the Sand Motor

5.2.1 Recreation

The Sand Motor has become an attractive area for hikers, bathers and kite-surfers. Especially the residents from nearby villages in Delfland use the beaches of the Sand Motor for recreation, but there have also been guests from other places in the Netherlands, from Belgium and Germany (Figure 5.1). Visitors have a high appreciation of the Sand Motor (on average an 8; WUR, 2020). Visitors appreciated the clean beaches, the relative calm of the region, the open space for recreation, the kite-surf spot on the lagoon, the natural landscape, the nature and the services of beach pavilions.

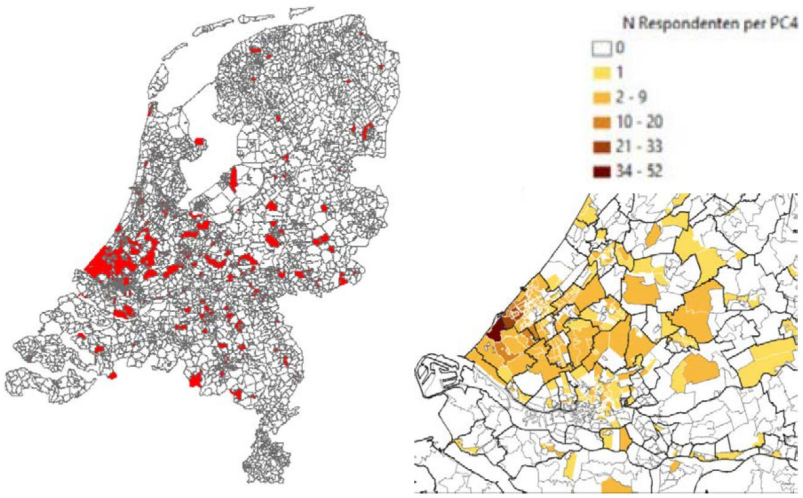


Figure 5.1 Map of the home addresses of visitors of the Sand Motor in the recreation survey (WUR, 2020).

Visitors gave the Sand Motor a better mark than the adjacent beach of Kijkduin, which shows that the Sand Motor brings something extra to the Delfland coast.

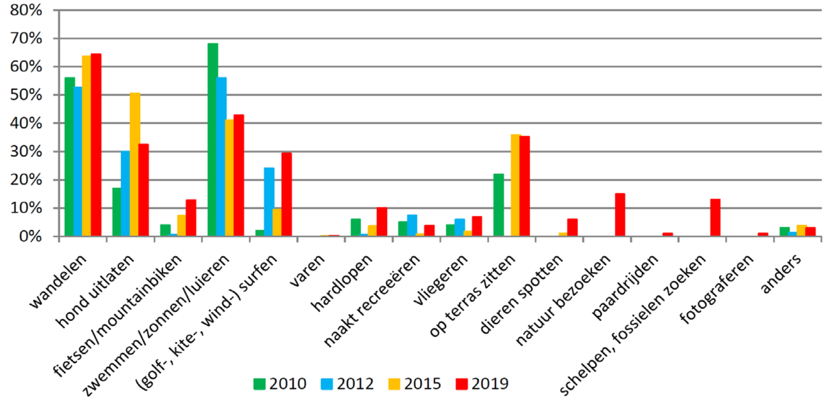


Figure 5.2 Activities undertaken by visitors of the Sand Motor, in Dutch (WUR, 2020).

Most visitors of the Sand Motor come to the Sand Motor to hike or for running, sometimes with a dog, or to visit a terrace of the beach pavilions (Figure 5.2). A lot of visitors indicate that they come to swim or for sun-bathing. The number of swimmers is, however, smaller than for other beaches, most likely because it is quite a long walk from the parking spots to the beach. The most catching use of the Sand Motor is kitesurfing. The Sand Motor has developed into a unique hotspot for kite-surfers. It is the only suitable kitesurfing spot on the Delfland coast. This is mainly due to the presence of the lagoon, where the wind can act freely while it still has relatively small waves, which makes it also a suitable for beginners. It is noted that the lagoon has been ideal for the kite-surfers in the last 10 years until 2021, but is now decreasing in size due to siltation, which will reduce the attractiveness for kite-surfers.

Other types of recreation are also taking place at the Sand Motor, such as enjoying nature (bird spotting), horseback riding and fishing. These activities benefit from the space that the Sand Motor offers. Also, the landscape and nature are appreciated by visitors and do improve the attractiveness of The Hague and Westland regions. The growth of natural dunes and vegetation has enhanced the nature value of the region substantially. Design aspects of the Sand Motor, such as the lagoon and freely developing dunes, have had an important impact on the recreational use (e.g. for kite-surfers and hikers). Different groups of beach users may be served depending on these design choices.

The Sand Motor facilitates recreation and tourism on the Delfland coast, but this has not led to a measurable increase in the number of visitors at this part of the coast, as this depends on many more aspects. The quantifiable added value of the Sand Motor from the perspective of recreation is limited. Only kitesurfing can be attributed directly (and solely) to the Sand Motor. Visitors from abroad are coming to kitesurf at the Sand Motor. Uncertain is how long the kitesurfing can be sustained at the Sand Motor, as the lagoon is gradually filling up with sand. The Sand Motor does not provide a measurable contribution to the work- and entrepreneurial conditions in The Hague region that has led to the attraction of new entrepreneurs and expats. For people looking for a place to live, the Sand Motor has not been a deciding factor. At least not more than the general preferences for a location close to the coast.

5.2.2 Art, Culture and Archaeology

In the design phase of the Sand Motor it has, on purpose, not been detailed out which activities should precisely take place on the extra space that became available at the Sand Motor and for the coast of Zuid-Holland. Consequently, the use of the Sand Motor has been led open to public initiatives, which has resulted in rather surprising uses of the Sand Motor (Vreugdenhil et al., 2021). Effectively, a variety of spontaneous cultural activities started, which effectively is the opposite of predefinition of use-functions. A network has developed of artist, amateur archaeologists and palaeontologists.

The Sand Motor offers not only space for recreation and nature, but is also used as a canvas by artist. For example, the artist Nico Laan creates exceptionally large sand drawings that can only be seen completely from the air. The works of art he makes are abstract, but also seamlessly fit into the natural scenery (Figure 5.3). The artist community 'The Satellietgroep' is also very active at the Sand Motor. They organize live performances at the Sand Motor for the cultural engaged public with the aim of providing an experience of the dynamics of the coast (Figure 5.4).

Figure 5.3 Art gallery on the beach of the Sand Motor (Laan, 2019 and 2020)

Figure 5.4 Cultural activities at the Sand Motor (Satellietgroep, 2015a/b).

Various discoveries were also made at the Sand Motor by amateur archaeologists and paleontologists (Niekus et al., 2019). The borrow area of the sediment at sea has been a settlement in prehistoric times as part of the delta area of the Rhine and Meuse (the ‘Eurogeul’ region). The rivers have transported and buried a large amount of materials from human settlers and remains of animals under thick layers of sand and clay. Various use-objects of earlier residents of this area and prehistoric animals were found, which give us a better insight in the past civilizations and nature of this delta. A special finding was a 50,000 year old flintstone which was covered with birch tar and made by Neanderthals (Figure 5.5).

Figure 5.5 Flintstone with birch tar (National museum of archelogy / Luc Armkreutz)

Steering of societal processes
Noticeable is that most societal developments took place spontaneously. It did not require specific organization by the government to startup these societal actions. Cultural organization and civilians have a lot of energy to organize activities. This holds especially for densely populated well accessible areas in the main Dutch metropolitan area (the ‘Randstad’) where various ‘institutional networks’ (e.g. museums) are capable of assisting amateur researchers.

A scientific analysis of policy management models for new coastal developments teaches us that the manager can make a deliberate choice to steer the societal development to higher or lesser degree at the start of the project. Strong steering or a relative open policy will not give the same results, but can both lead to added value. Obtaining societal added value depends on both physical and non-physical factors, which can be steered in the planning, design and management phases. It is of importance to develop a strategy in advance, which can be followed when the project is in place. It is relevant to be informed on the societal context, such as the stakeholders and the institutional setting (e.g. networks and subsidies). Decisions and agreements need to be clear for the different stakeholder groups to make sure they understand their roles, which creates a shared and sustainable ownership and responsibility.

5.3 Management and environmental impacts

5.3.1 Recreational safety

Agreements were made between the Province of Zuid-Holland, the Safety-region Haaglanden, municipality Westland, municipality of The Hague and the voluntary lifeguards of 's-Gravenzande, Monster and The Hague. These agreements were settled in the cooperation agreement ‘Beach- and swimmer safety pilot Sand Motor’. One can think of beach guarding (including prohibition of swimmers or other beach users). Closure of specific areas was an option if safety would require this. Special mitigation measures could be taken to mitigate risks. For example, the development of steep cliffs or quicksand.

Swimmer safety
Three natural processes are of relevance for the swimmer safety at the Sand Motor, which are 1) large-scale flow patterns (e.g. acceleration of the tidal currents and circulations; see Paragraph 3.2.3), 2) the emptying and filling of the lagoon (Paragraph 3.2.5); and 3) rip currents as a result of water-level setup (Paragraph 3.2.4). The potential impact of these processes on swimmer safety is then discussed.

The acceleration of the tidal currents at the Sand Motor and the large-scale circulations (‘gyre’) can cause rather complex current conditions seaward of the peninsula of the Sand Motor (Shore, 2019). These currents (and circulations) can move swimmers in seaward direction at moments of maximum tidal flow. In practice, the effects on swimmer safety were rather limited, since the tip of the peninsula is located at a large distance from the coast, where the number of swimmers is quite low. The effects of the Sand Motor on the tidal current acceleration also decreased over time due to the flattening of the coastal disturbance of the Sand Motor by natural sediment redistribution processes.

Relatively high flow velocities occurred in the entrance channel of the lagoon especially in the first two years after construction. Some bathers, who crossed the entrance channel during flood to the spit, considered themselves cutoff from the coast at rising tide, even though a connection of the spit to the peninsula was present. These tidal currents were, however, directed towards the lagoon, which meant that the actual safety risks were still rather limited. Over time, the flow velocities decreased in the entrance channel as a result of siltation of the lagoon and the lengthening of the channels. The actual location of the entrance channel could not be controlled, since it is a natural development, which needs attention in the design of future large-scale nourishments. The risk would only completely be mitigated when a design is made without a lagoon.

The swimmer safety risks due to seaward directed currents (also referred to as ‘rip currents’) were rather limited at the Sand Motor, as these currents were less often seen than for the adjacent coast, where they can especially be found near the groynes (Shore, 2019). These rip currents at the Sand Motor were typically present during bad weather conditions, which is a moment when hardly any beach users will be presents (Radermacher et al., 2018).

Swimmer safety risk is limited at the Sand Motor, because the more dangerous locations on the peninsula are not often used by beach users. Moreover, many risks related to swimmer safety (e.g. rip currents, acceleration of the tide and circulation flows) coincide with extreme conditions, which are moments in time with rather low numbers of beach users (Figure 5.6). The large walking distance to the peninsula in the current design has positively contributed to the swimmer safety.

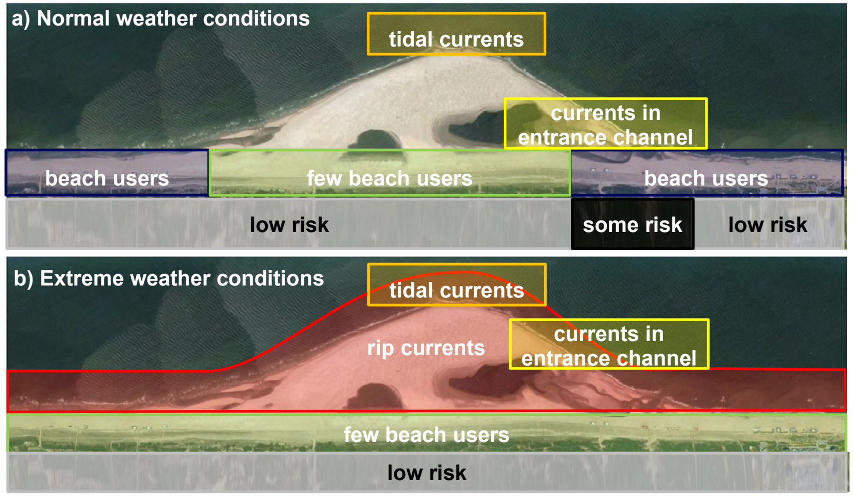


Figure 5.6 Overview of the location of dangerous currents, beach users and associated risks for normal and extreme weather conditions (modified version of Radermacher,et al., 2018)

Predictive numerical models have been set up for the identification of rip currents at the Sand Motor. A mobile phone app informs the lifeguards on the actual flow conditions at the Sand Motor, which helps them to anticipate more quickly in dangerous situations.

Quicksand

No serious issues with quicksand were reported at the Sand Motor. A few observations of quicksand were made by horse riders near the lagoon and the dune lake. This happened just after a storm, which deposited a lot of wind-blown sediment at the western sides of the lagoon and dune lake. The way in which the Sand Motor was constructed did not lead to dangerous situations with quicksand, but it is not clear why it has been relatively safe. Possibly, the quicksand did not develop as a result of the method of construction by the dredger or due to the type of sediment that was applied.

Cliffs

The cliffs that developed at the Sand Motor had heights of some decimeters to meters and can potentially be dangerous to beach users. Especially when motorized traffic is driving over the beach. However, in practice there are no cases known of accidents due to cliffs. It is expected that the rather shore-parallel position of the cliffs, and the remote location at the peninsula, were of relevance. As there are relatively little visitors here. In addition, there are considerable periods wherein no or only small cliffs are present.

5.3.2 Influence of recreation on nature

The management of the Sand Motor was intended to not steer the precise use of (sections of) the Sand Motor by beach users. No areas were demarcated (i.e. not accessible) for visitors and terraces/restaurants were located at the beach entrances. As a result, the whole area was used for recreation. The impact of the recreation on nature development is therefore a relevant aspect to consider, which consisted of the already earlier mentioned driving on the beach, beach-cleaning and hiking pathways of visitors (see paragraph 4.4).

The most prominent impact is made by the cars driving on the beach and the beach-cleaning, which affect the development of embryonal dunes. The development of wider more natural dunes is frustrated especially at the landward side of the Sand Motor, where various wide tracks are present which are intensively used by cars. These tracks are mostly created as a result of the “competent authorities” such as the beach guards and police. The impact of the traffic on the Sand Motor did, however, decrease over time as the areas with substantial dune formation became in-accessible for cars. The traffic is getting confined in a smaller number of tracks. The impact that hikers have on the formation of embryonal dunes also seems to decrease over time, as the dunes have reached a critical size that allows them to grow sustainably regardless of the walking tracks. Nevertheless, a clear impact is noticeable of the walking routes of beach users near the entrance of the Schelpenpad (Figure 4.13), even though this route is less often used than the other beach entrances of the Sand Motor (Figure 5.7; WUR, 2020).

Figure 5.7 Beach entrances providing access to the Sand Motor (WUR, 2020).

The disturbance of breeding birds is quite considerable at the Sand Motor as visitors (with dogs) can use all of the beach throughout the whole year. No breeding birds were observed in the first years and some in later years. The environment for breeding has improved since 2015 as a result of vegetation growth. The Sand Motor, with its relatively difficult to reach beaches of the peninsula, is a quite favorable spot for resting birds, which are present in large numbers.

It is concluded that cars and hikers have a substantial impact on the development of nature values of the beach and dunes (especially for breeding birds). It would therefore have been desirable to make agreements on (and prohibitions of) the use cars and other vehicles on the Sand Motor. If hosting breeding birds is also an aim of a measure, then it would be beneficial to close-off parts of the Sand Motor for visitors in the breeding season.

5.3.3 Groundwater quality in the dunes

The Province of Zuid-Holland and Dunea have signed a covenant wherein they make an agreement on the mitigation measures in case adverse impacts are found on the nature and drinking water in the dunes of Solleveld.

The construction of the Sand Motor was expected to have some impact on the groundwater, because the infiltrated groundwater in the existing dunes will less easily flow towards the sea (Huizer et al., 2016; Pantelli, 2017). The groundwater in the dunes may rise due to the blockage of the seaward directed ground water flow by the Sand Motor, which is considered undesirable for the drinking water extraction in this area. Ground water may flow through potentially contaminated rubble in the more seaward dunes, which may (or may not) have been placed there in the beginning of the 20th century. This groundwater may then affect quality of the water in the inner dunes at the extraction wells, as it cannot flow as easily towards the sea. A function of the dune lake was to drain water from the beach, preventing too high groundwater levels in the dunes. The intention was to first monitor the changes in groundwater levels after construction of the Sand Motor and takes measures if needed, but very shortly after construction it was already decided to take extra measures to lower the groundwater. Extra drainage pipes were placed on the beach directly seaward of the first dune row, which managed to lower groundwater levels in the dunes. Effectively no change in groundwater levels was observed in the dunes. Eventually, the groundwater that infiltrates in the dunes with rubble will flow towards the sea.

It is noted that the dune lake, and its function to lower groundwater levels, is very specific for the Sand Motor. A rise in the groundwater levels may be considered very positive for many other locations. It may be beneficial for the dune nature if the dunes become more wet. Furthermore, it will also be useful in many regions to increase groundwater storage.

5.3.4 Nature management of the dunes of Solleveld

The environmental impact assessment (EIA) posed the question whether there can be adverse impacts of the Sand Motor on the nature of the dunes of Solleveld. And in addition to this also whether these impacts can be prevented with management. Prior to construction of the Sand Motor, it was expected that the volume of aeolian sand influx in the dunes of Solleveld would increase, while the salt spray would decrease. As a consequence, an accelerated succession could take place with enhanced growth of sea buckthorn, which is considered undesirable. Removal of sea buckthorn brushwood and other management measures were, however, already in place to prevent further succession and preserve the current white and grey dunes. The main question here is whether the current measures are sufficient to prevent any adverse impacts of the Sand Motor on the dunes.

Monitoring in the dunes of Solleveld shows, as a result of the vegetation management, no significant change in the areas of the dune habitats of Solleveld (e.g. sea buckthorn, white and grey dunes; Paragraph 4.4). Active management, such as the removal of sea buckthorn, grazing and construction of blowouts by the Hoogheemraadschap of Delfland has been sufficient in preventing impact of the Sand Motor on the succession in the dunes of Solleveld.

5.3.5 Impacts on natte infrastructure

Prior to construction of the Sand Motor it was not known if the Sand Motor sand would have an impact on the navigation channels of the ports of Rotterdam and Scheveningen. And whether the water outfall pumping station of Delfland would be affected (the so-called ‘J.J.J.M. Van den Burg gemaal’; see Figure 5.8).

Figure 5.8 Location of the 'J.J.J.M. Van den Burg gemaal' with respect to the Sand Motor.

An impact of the Sand Motor on the siltation of the harbour channel of Rotterdam is very unlikely, as the channel is well protected by the very long Noorderdam breakwater. Furthermore, the transport is predominantly in northern direction (Leijnse & Huisman, 2019).

The impact of the Sand Motor on the area of Scheveningen has been estimated with numerical models. These computations show a small impact on the siltation of the navigation channel. This effect is much smaller than the effect of the dune reinforcement of Delfland which was constructed in 2010 (the so-called 'Zwakke-schakels'; Leijnse & Huisman, 2019). The yearly variability of the wave conditions turned out to have the largest impact on the siltation. The siltation can be considerably larger for years with relatively dominant wind and wave forcing conditions from the West and South-West.

The outfall of the 'J.J.J.M. Van der Burg gemaal' is hardly affected by the Sand Motor (Leijnse & Huisman, 2019). The coast has accreted here, but this is mainly due to the dune reinforcement of Delfland and the 2013 shoreface nourishment at Hoek van Holland and 's Gravenzande. A substantial future impact of the Sand Motor is not expected here, but there may be an effect of future sand nourishments at 's Gravenzande and Ter Heijde.

5.4 Evaluation of experience, appreciation, management and environmental impacts

This chapter evaluates the experience, appreciation, recreation in relation to nature management and environmental impacts of the Sand Motor. It is noted that a, sometimes shortened, answer to the (sub)evaluation questions can be found in Appendix A.

Experience and appreciation
The evaluation of the experience and appreciation of the Sand Motor focuses on the recreational use and societal functions such as art, culture and archeology.

- *EQ3-2: How did the appreciation of the coast between Hoek van Holland and Scheveningen change as a result of the Sand Motor?* The Sand Motor is attractive for hikers, bathers and kitesurfers and the visitors have a positive experience. The number of bathers is, however, smaller than for nearby beaches, which is related to the relatively large distance from the beach entrances to the coastline of the peninsula. Kitesurfing is the most distinguishing use of the Sand Motor compared to other beaches. The design of the Sand Motor with a lagoon is essential for kitesurfing and makes it unique, but the dynamic character of the Sand Motor also implies that the possibilities for kitesurfing will decrease over time as a result of expected future siltation of the lagoon. The nature experience will further improve over time as a result of the natural growth of the dunes. A contribution to the work- and entrepreneurial conditions in the region (i.e. more appeal for enterprises and expats) could not be shown though. Also, real estate value cannot be linked to the Sand Motor, as the Sand Motor is not providing additional residential appeal.

- *EQ2-1b: Which lessons can be learned on the planning and design of (mega) nourishments following from the morphological development of the Sand Motor, such that it is beneficial for swimmer safety at nourishments?*

The design of the Sand Motor has led (especially in the first two years) to a slightly enhanced risk related to large flow velocities in the entrance channel of the lagoon during the flood phase. There have been unsafe situations for bathers that decided to cross the channel, which were in some occasions taken into the lagoon with the flood current. Other risk factors were present at the peninsula, such as strong currents (e.g. due to gyres and rip currents), but these have not led to problems since few people were present at the beach when they occurred. The design lesson is that the coincidence of risky situations (such as rip currents, strong currents due to a 'gyre' or tidal current in the entrance channel) and the number of expected beach users should be investigated in the design phase of a large-scale nourishment.

- *EQ2-1c: Which lessons were learned on the planning and design of (mega)nourishments following from insights on the added value of the Sand Motor for other functions (amongst which aspects like cultural heritage, spatial planning and economy).*
  The location and design of the Sand Motor have a substantial impact on the effective use of the area. The dynamic character of the region is attractive for artists. Also, the relatively free way in which the beach is managed has been of relevance for cultural activities. A lesson is that the desired degree of steering can be defined in a strategy per use-function depending on the presence of institutional parties in the region.

Management of the Sand Motor
Impacts are managed for swimmer safety, recreational use, groundwater quality, nature in the dunes of Solleveld and wet infrastructure, such as nearby navigation channels. Here the evaluations are given of the management on these five aspects:

- *EQ4-1: Are there adverse impacts of the Sand Motor for recreational safety? Can these effects be mitigated with management measures? Was the management protocol sufficient?*
  Swimmer safety at the Sand Motor was manageable. Rip currents and acceleration of the tide at the peninsula have not led to incidents. The rip currents are also less often seen at the Sand Motor than for the adjacent beaches. However, a number of beach users got trapped at the spit during high water. They crossed the entrance channel of the lagoon during low tide, but were surprised by the high current velocities during flood, which makes it difficult to cross the entrance channel to the beach. Some cliffs developed at the seaward side of the peninsula of the Sand Motor, but in practice this risk was very low as only a few people visit this area. Quicksand has been seen locally in the first years, but caused no problems. The water quality of the lagoon deteriorated over time as a result of the diminishing exchange with the sea via the channel. This did, however, not create any health issues.

- *EQ4-2: To what degree can recreation and nature development goals be united on and around the Sand Motor?*
  Both recreation and nature values are of relevance for the Sand Motor. Recreation does, however, have some impact on nature development. Traffic, beach-cleaning and hiking by visitors also have a clear impact on the dune development. This holds especially for the cars, which created a series of unvegetated tracks parallel to the dunefoot and radial driving patterns at the beach entrances. The recreational use of the Sand Motor has slowed down the development of the embryonal dunes. Recreational zonation and management have not been investigated at the Sand Motor, but it is likely that more disturbance-sensitive breeding birds would have been present without the recreational use.

- *EQ4-3: Is it possible to prevent adverse impacts of the Sand Motor on the groundwater?*
  The drainage tubes that were installed just seaward of the foredune have effectively lowered the groundwater levels in the existing dunes. Any potential contaminations and/or salt in the groundwater could not have spread towards the landward water

extraction areas. The groundwater at the Sand Motor has become fresh in recent years.

- *EQ4-4: Are there adverse impacts on the natural values of the existing dunes? Can they be prevented? How can they be mitigated?*
  The sand dynamics in the dunes of Solleveld were found to be relatively low and also the influx of salt is small. The dense plant cover at the dune reinforcement catches most of the wind-blown sand from the Sand Motor, thus bypassing only a small fraction of sand to the inner dunes. Sand is only blown to the inner dunes of Solleveld during storm conditions. Additional effort needs to be spent on the removal of sea buckthorn and marram grass as well as on the construction of blowouts. The artificial construction of small blowouts in Solleveld has increased the dynamics of the dunes for a few months. The impact of the Sand Motor on the sand and salt spray into the dunes has not led to a measurable effect on the vegetation of the dunes of Solleveld though. The management measures have compensated for any effects.

  The Sand Motor does, however, have a noticeable impact on the first dune row (the 'dune reinforcement'). More growth of brushwood was observed in the section of the dune reinforcement that is located directly landward of the Sand Motor, which is a result of the reduction of the sand and salt spray here. Considerably less vegetation succession was observed just North and South of the Sand Motor. The changes in salt and sand spray were not substantial enough to lead to a shift in the vegetation of the dunes of Solleveld.

- *EQ4-5: What adverse effects of the Sand Motor can be present for the wet infrastructure, such as navigation channels and outfalls? Can these effects be mitigated?*
  Accretion in the navigation channel of Rotterdam has not changed as a result of the Sand Motor, while only a very limited impact is expected for the navigation channel of Scheveningen. The dune reinforcement of Delfland had a much more considerable impact on the siltation. Year on year variation in the siltation is, however, very strong for Scheveningen and depends on the occurrence of wind and wave conditions (storms) from the West and South-West. The Sand Motor has hardly any impact on the outfall of the 'Van der Burg gemaal'. The accretion here was related to the dune reinforcement of 2010.

6 Knowledge development

6.1 Expectations and aims

Already for centuries the coastal research has been of relevance for the Netherlands. A good understanding of the forces of nature is required to effectively manage coastal defences. Knowledge of historic storm events has proven to be essential for accurate predictions of required sand volumes and potential storm erosion in the dunes, and because of this knowledge we can efficiently distribute the sediment. However, new questions are popping up, in particular on the impact of accelerated sea level rise and the naturalness of large-scale nourishments. Knowledge of the coastal processes is required in order to be able to anticipate future challenges. The application of the Sand Motor is effectively a new knowledge chapter.

Various knowledge development projects have been started in the Netherlands, which kickstarted new ideas and further knowledge development. One can think of the project ‘Kustgenese’ in the 80’s, which formed the basis for the decision to maintain the 1990 coastline position. These projects had an impact on the currently common methods of the hydraulic engineering sector in the Netherlands, and provided an indirect contribution to the economy. The Sand Motor can also be seen as a 'laboratory’ for coastal maintenance. And a relevant question is what kind of spin-off for knowledge and innovation was generated by the Sand Motor (EQ2-3).

Prior to the construction of the Sand Motor it was the expectation that widely applicable knowledge would be created in this project (EQ2-3a), that this would lead to innovations for national and international use (EQ2-3b) and that knowledge dissemination would take place, effectively securing the findings (EQ2-3c).

6.2 Generic knowledge

Research on the Sand Motor was aimed especially on the morphological and ecological development of the dunes, beach and surfzone. The redistribution of sand at the Sand Motor was investigated both below and above the water surface, recreational safety for visitors was essential, while also the ecological impacts and governance aspects were investigated. Generic knowledge was created in the field of hydrodynamics, morphology, geology, ecology, groundwater quality, dune formation and decision-making.

The knowledge and models that were developed for the Sand Motor can also be applied at other types of sand nourishments and other coasts (Huizer et al., 2016; Stronkhorst et al., 2017). General predictions of the lifespan of mega-nourishments could, for example, be made on the basis of observed coastline changes at the Sand Motor (Tonnon et al., 2018). The generic wind transport model Aeolis can be used for complex coasts with dunes and beaches (Hoonhout & De Vries, 2016). Sediment sorting models have been used for the evaluation of bed sediment changes at shoreface nourishments (Huisman et al., 2018). Innovative measurement techniques were also introduced and proven useful for coastal monitoring. Video cameras gave us a measurement toolbox for sub-tidal bar behavior (e.g. Rutten et al., 2018), while drones can now be used to measure small dunes at the beach and classify vegetation (Shore, 2020; Figure 6.1). The sampling of benthic life in the sea can now be performed more efficiently (Wijsman et al., 2021). The monitoring of the macrobenthos in the shoreface has also resulted in a unique dataset of benthic animals in sandy substrate (Herman et al., 2021). The shallow coastal zone has never been monitored so intensively and multi-disciplinary over a period of 10 year. Luijendijk and of Oudenhoven (2019) provide a detailed description of scientific research programs Nature-Coast and NEMO, which both had a focus on the Sand Motor. Not too much research was, however, carried out on the added value, appreciation, and governance aspects of the Sand Motor, resulting in a relatively small number of publications on these topics.

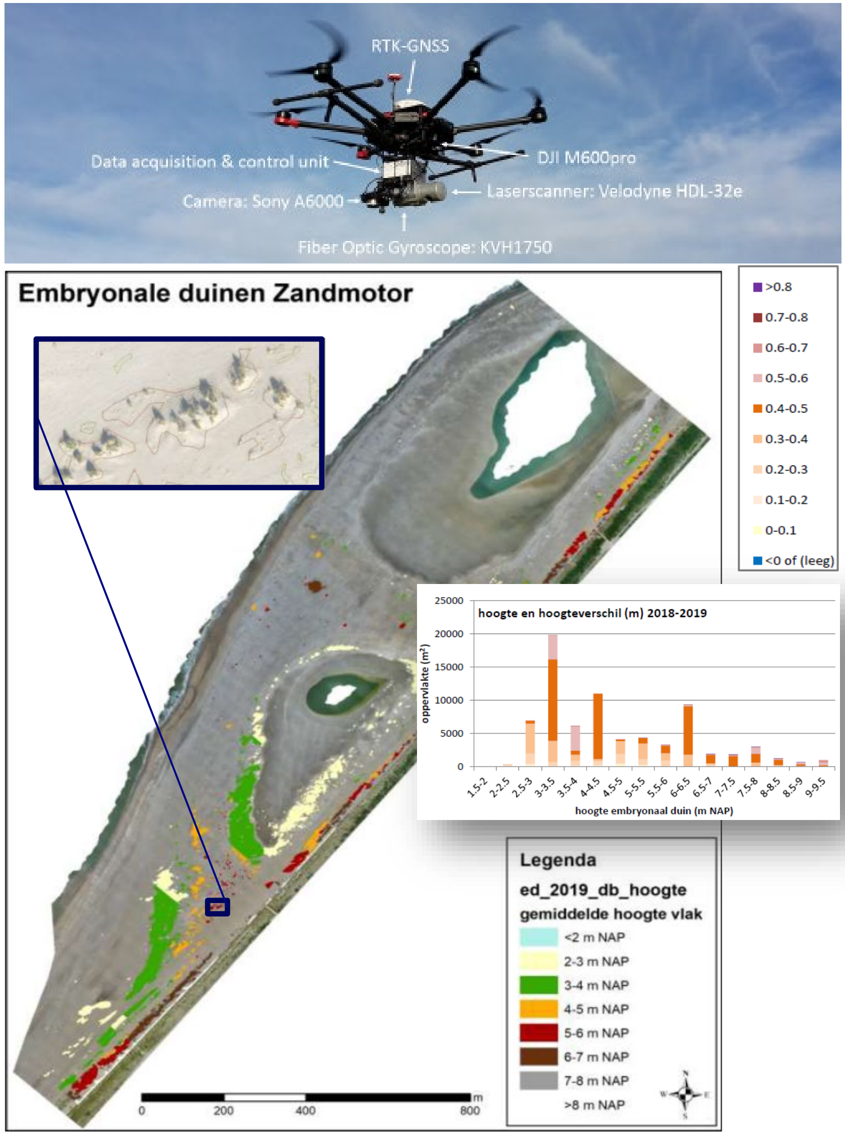


Figure 6.1 Monitoring of the height of embryonal dunes with a drone (Upper: Shore, 2020; Lower: Arens, 2021; Huisman & the Vet, 2021)

6.3 Knowledge application

The pilot Sand Motor offers coastal engineering companies a unique opportunity to gain knowledge about innovative coastal maintenance projects. The combination of coastal maintenance with other coastal functions (such as nature and recreation) becomes clear at the Sand Motor. The Sand Motor is an international icon of the water sector which illustrates the joint realization of functions such as coastal safety, ecology and recreation. The 'building with nature' concept has become a trademark of Ecoshape, which is a cooperation between businesses, knowledge institutes, universities and the Dutch government. A lot of international attention is also focused on the Sand Motor. Sandy coastal measures were developed for Negril beach (Jamaica) and Bacton (United Kingdom). The morphological models which were developed at the Sand Motor could be used to assess the lifespan of these measures and give insight in the redistribution of sand. The Sand Motor was also an example for an even larger scale sand nourishment at the Hondsbossche Dunes in the Netherlands, where an even larger more elongated nourishment was realized. The actual application of the 'building with nature' concept is, however, very much tailored to the specific conditions and requirements of other locations. The local safety and maintenance requirements play a role as well as the need for natural and recreational areas.

Attention is also given to the Sand Motor in various educational programs. For example, the knowledge about coastal maintenance with natural materials was part of courses at secondary schools and universities. The materials used in these courses may have been distributed better, as more schools would then have added this case study to their curriculum. Facilitating education was, however, not a primary aim of the Sand Motor.

6.4 Research programs and networks

Research programs with a focus on the Sand Motor were initiated at the universities and knowledge institutes. These knowledge networks have been growing over time. Not only the national universities and knowledge institutes, but also international partners joined the research programs at the Sand Motor (Vreugdenhil et al., 2021). Basically, two separate knowledge networks developed, namely the scientific network and the monitoring network (Figure 6.2).

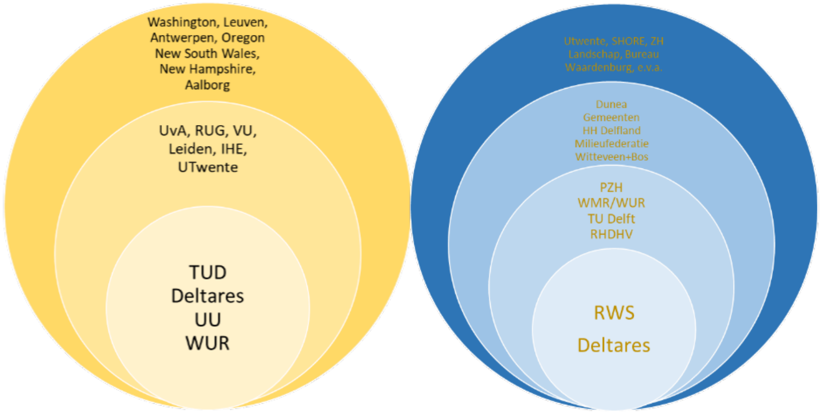


Figure 6.2 Overview of the scientific (left) and monitoring network (right) with the most involved partners in the center (Vreugdenhil et al., 2021)

Scientific network

Scientific research was carried out at the universities in the research programs NatureCoast and NEMO (Figure 6.3). A total of 15 PhD's and 6 PostDoc's have been working on interdisciplinary research. The researchers were located at a large number of Dutch universities which worked together on coastal research for this project (e.g. Technical University Delft, Utrecht University, University of Twente and Wageningen University). Collaboration between the universities was intensified and the network was growing over time. Each of the research groups had their own field of expertise focusing on hydraulic engineering, geology, ecology or governance. Dutch universities were also able to use the Sand Motor research as an opportunity to strengthen their relationship with international universities (e.g. Oregon, Aalborg, Mexico, Bordeaux, Antwerpen and Leuven). The knowledge network at the Sand Motor had an international appeal. Currently, still some new research proposals are made (e.g. at universities in Delft, Utrecht, Wageningen, Groningen and Leiden) wherein knowledge and experience from the Sand Motor has a central place.

Monitoring network

The monitoring network was initiated by Rijkswaterstaat, the Province of Zuid-Holland and Dunea. They have set up a cooperation agreement to address questions from the Environmental Impact Assessment (EIA), permits of the Sand Motor and general coastal management of the Sand Motor. In addition, the research is meant as a means of getting insight in the actual application of large-scale future measures, and as such to prepare for the future. The monitoring of the physical environment was set up and financed by RWS in close cooperation with Deltares and Wageningen Marine Research (WMR). The Province of Zuid Holland coordinates the monitoring of recreation and added value for the regional economy. A large number of consultancy firms were involved in the monitoring, and (semi)public organizations took care of specific measurements (e.g. the local municipalities, Water board of Delfland and Zuid Hollands Landschap). Cross-links were made with the scientific network which contributed to the collection of field data from the Sand Motor (e.g. the MegaPEX field experiment), but with a focus on the scientific questions rather than the coastal management.

Most scientific and monitoring programs are organized jointly by the Dutch ministries and universities, which is indicative for the relevance of the pilot Sand Motor for the future of large-scale nourishment projects in the Netherlands. The consensus here was that a better understanding needed to be obtained from the Sand Motor pilot with coastal research. More spontaneous knowledge development also took place, especially in the field of archeology and paleontology, as the Sand Motor is an ideal site for finding historic objects. The existing network of amateur researchers and museums (e.g. Naturalis, the National Museum of Antiquities and the Museum of Natural History in Rotterdam) have been essential for this development.

Figure 6.3 NatureCoast congress (source: tweet of Oudenhoven, 2017)

6.5 Evaluation of knowledge development

The degree in which spin-off from the Sand Motor research took place can be concretized through an evaluation of the wider applicable knowledge. The degree to which an application has been made in national and international coastal projects is of relevance, as well as the knowledge dissemination in scientific publications. An answer to the sub-questions can be found in Appendix A.

Generic knowledge development
The first question focuses on the availability of generic knowledge on the coastal system, efficiency of coastal maintenance, ability to combine coastal functions and available methods (e.g. numerical models) that can be used in other studies in the future.

- *EQ2-3a: To what extent do the developed knowledge and methods have a wider applicability for the development of sandy strategies and innovations?*
  Generic knowledge was developed in a large number of research studies focusing on the Sand Motor, generating new insights and methods in the field of hydrodynamics, morphology, sediment, ecology, groundwater and dune formation. The intensive sampling of the bathymetry, bed sediment composition and benthic communities of the shallow shoreface is unique for the Sand Motor. Research on governance of the project provided new insights with respect to the steering of the use-functions of a large-scale nourishment. Numerical models and expertise from the Sand Motor studies is much wider applicable for other types of nourishments and other coasts. The obtained knowledge and models allow for more accurate predictions of the lifespan of large-scale sand nourishments, understanding of sediment sorting on the shoreface and accretion of navigation channels. The Sand Motor has also been indispensable for the development of a wind transport model (Aeolis), which can be used to investigate dune development at a wide variety of coastal situations. Innovations in the computation and visualization of currents in shallow water (with a mobile phone-app) assist the lifeguards with the detection of rip currents. Innovative measurement techniques could also be used and developed at the Sand Motor. For example, making it possible to monitor embryonal dune growth in great detail with a drone.

Applicability
The use of Sand Motor knowledge in other projects is a good indicator for the applicability of the concept of large-scale nourishments that contribute to natural and recreational functions.

- *EQ2-3b: To what extent has the developed knowledge been used in innovative national and international projects?*
  The developed knowledge at the Sand Motor has been used at research of alternative coastal management in Jamaica and the United Kingdom. Furthermore, the Sand Motor is often used as an example of innovative coastal management for international delegations. The Dutch council of entrepreneurs (RVO), the Netherlands Water Partnership (NWP), Ecoshape and Deltares are actively using the Sand Motor as an illustration of the Building with Nature philosophy. The Sand Motor has an iconic status in the hydraulic engineering community. The Sand Motor has also been the inspiration for the large-scale sandy dune reinforcement at the Hondsbossche Dunes and for the recent coastal nourishment at Ameland in the framework of the Kustgenese-2 project (Rijkswaterstaat, 2020). In the coming years we will have to see how the knowledge development of the Sand Motor will be extended in coastal engineering research.

Knowledge dissemination
Dissemination of knowledge through scientific publications and publicity in news channels are very important for the preservation of Sand Motor knowledge on the long-term.

- *EQ2-3c: To what extent has knowledge been disseminated, both nationally and internationally?*
  Sand Motor knowledge has been disseminated broadly either through formal or informal communication. Multiple groups were addressed (from scientists to the broad public) and at different communication levels (ranging from scientific journals to local newspapers). The Sand Motor research had a positive impact on the relations and collaboration in scientific networks, amongst which the Dutch Center of the Coast (NCK). Knowledge dissemination to the general public took place via an information center at the Sand Motor and news feeds. Many other informative events were organized for the broad public, such as excursions from cultural groups, expositions, workshops at museums, television programs and educational programs. The knowledge dissemination at the Sand Motor was co-organized with universities and research institutes, which eagerly took up this opportunity. The degree of steering on knowledge dissemination is a choice that can be made at the start of projects.

7 Conclusions

7.1 Findings

The monitoring and evaluation program of the Sand Motor (MEP), over the period 2011 to 2021, has resulted in many new insights into the effectiveness of large-scale sand nourishments that also aim at realizing co-benefits for natural and recreational functions. The experiences obtained from the Sand Motor can be used for effective future coastal measures that not only protect the coast, but also serve other functions. The following conclusions can be drawn from the MEP:

Dune growth and coastal development

- The dune growth in the dune reinforcement just landward of the Sand Motor was 14 m^3/m/year which was not very different from the dune growth on the adjacent Delfland coast.
- The dune growth is limited by the catchment of wind-blown sand in the lagoon and the dune lake. The expected dune growth would have been ~27 m^3/m/year without these landscape features. In the design-phase a choice has to be made for either dune growth or the alternative recreational and natural functions that are offered by a lagoon and/or dune lake.
- Dune growth mainly took place in the first dune row. Additional measures, such as artificial blowouts, are needed to allow aeolian sand transport to the inner dunes.
- Sediment from the Sand Motor is distributed by the waves in alongshore direction to the beaches of Kijkduin and Ter Heijde, where coastal accretion takes place.
- Sand Motor sediment is preserved within the active nearshore zone of the coast (referred to as the 'coastal foundation' which extends from 20 meter water-depth to the dunes). The Sand Motor supplies sediment to the Delfland coast, and therefore contributes to the long-term protection of this coastal section. A small proportion of the sediment will be transported to Rijnland by natural wave forces, where it also maintains the coast.
- The spit at the northern side of the Sand Motor has closed off the lagoon in the first year after realization. After the closure, the filling and emptying of the lagoon took place via an entrance channel. The location of the entrance channel changes over time. During storms a new entrance channel can develop.
- Cliffs can develop at the Sand Motor during storm events that coincide with low water. A design with a lower beach height of the peninsula will probably prevent the occurrence of cliffs.

Nature development

- The benthic population has increased substantially after realization of the Sand Motor (i.e., in biomass as well as density and number of species).
- No measurable impact was found of the one-off nourishing of the beach with a large volume of sand compared to regular more frequent beach or shoreface nourishments.
- The underwater nature became more diverse after realization of the Sand Motor. Also, a larger number of benthic communities was found. This is a consequence of the impact of the Sand Motor on waves, currents and bed sediment. A more seaward extending nourishment, such as the Sand Motor, has a larger effect on the bed sediment composition than regular nourishments.
- Shellfish are found at the perimeter of the lagoon that are not common for the adjacent beaches of Delfland. Since 2018 the water quality of the lagoon deteriorated strongly as a result of the limited remaining exchange of water with the sea, which resulted in a decrease of the number of shells that were found at the lagoon.
- The catchment of sand in the lagoon and the dune lake can create a shallow wet beach plain (with green beach) on the long-term.
- A layer of coarse sand and shells developed at the dry beach of the peninsula which is very unnatural. This is the consequence of fine sand grains being picked up by the wind. The crest height of

the peninsula is too high to allow reworking of the bed by waves and currents.

- Embryonal dunes developed mainly at the southern side of the Sand Motor, which in some places already merge into complexes of white dunes. However, the dune development took longer than expected. Vegetation growth can, if desired, be stimulated by planting marram grass.
- Marram grass was responsible for most of the initial dune formation, which differs from the classic theory wherein 'sand couch' acts as the primary dune-forming species.
- A large number of birds was observed in 2013 and 2014, but their numbers decreased substantially in later years. The number of birds was, however, not larger than for the nearby beach of Noordwijk. The presence of cormorants on the Sand Motor in the first years after construction is an added value of the Sand Motor, because these birds are less often seen at nearby beaches. The three-toed sandpipers (and other foraging birds) were not seen more often than at other beaches, but the population is still increasing. The benthic community at the inter-tidal beach needs years to develop, meaning that the food availability for the three-toed sandpipers is also only gradually increasing over time.
- An impact on sea mammals and fish could not be found.

Recreational and societal use, beach management and environmental impacts

- Recreation at the Sand Motor has benefited from the calm environment and naturalness of the landscape (with high appreciation by the users). Kitesurfing in the lagoon is an added value to this section of the coast, as the tranquil conditions that are suitable for beginners, which is not the case elsewhere along the Holland coast.
- Societal functions developed spontaneously at the Sand Motor (e.g. art, culture and archeology). It can be decided prior to the construction to what degree each of the user functions needs to be steered by the government (e.g. societal use or knowledge development). This depends on the context (i.e. location of the measure and institutional setting in the area). Added value may develop also without steering of specific user functions.
- Recreational safety was manageable at the Sand Motor. Prevention of dangerous situations was an aim prior to construction. In practice the situation was not worse than for other beaches. Rip-currents were observed more often at the adjacent beaches than at the Sand Motor. Very important was that the potentially unsafe conditions at the Sand Motor did not coincide with the presence of visitors, which limited the risk.
- Vegetation growth on the Sand Motor was hindered by driving, beach-cleaning and hiking by visitors. No recreation management was applied (e.g. demarcation of nature areas) as the Sand Motor was meant for multiple user functions. A trade-off needs to be made in the design phase between recreation and nature development.
- Groundwater was not affected by the Sand Motor, because of the placement of drainage pipes in front of the foredunes. A rise in the groundwater levels would, however, have taken place without these drainage pipes, which can be beneficial at other sites.
- Only a small volume of sand and salt is transported to the dunes of Solleveld, which stimulated the growth of brushwood in the foredune area. Removal of vegetation was required in the dunes of Solleveld to mitigate succession of dune vegetation. Sand and salt were transported to the inner dunes during storm events, which is still quite important for the ecology of the dunes.
- No significant impact was found on the nearby navigation channels and outfall of the Delfland pumping station.

Spin-off for knowledge development

- The monitoring program of the Sand Motor has created a unique dataset with highly detailed records of the development of the bathymetry, sediment and ecology (benthic animals, birds and vegetation), while at the same time the hydrodynamics, groundwater and recreational use were extensively measured. These data can still be used for many years to strengthen the knowledge base of our coastal system, and they provide us the opportunity to prepare for the upcoming challenges associated with climate change.

- A successful cooperation was developed between the Dutch government (at the national and province level), knowledge institutes and universities, which made it possible to acquire additional scientific research funding.
- The group of knowledge partners working at the Sand Motor was very large, well beyond the critical mass needed to attract other (international) knowledge institutes and universities. This network effect could be created because of the Sand Motor.
- Generic knowledge was developed on the physical coastal system (hydrodynamics, morphology, ecology, groundwater), innovative field measurements, numerical models and the efficient design of large-scale nourishments with an added value for natural and recreational use.
- Application of Sand Motor knowledge in national and international projects confirms the relevance (or 'icon function') of the Sand Motor for the coastal engineering sector.

7.2 Recommendations

The experience with the Sand Motor as a multifunctional nourishment has led to recommendations for future nourishments. These recommendations were defined for the fields of monitoring, knowledge development, prioritization of coastal functions (following from design-decisions), steering of the user functions and management decisions to limit environmental impacts.

Monitoring

The 10-year long intensive (and multidisciplinary) monitoring at the Sand Motor created a very comprehensive data set, which is unique in coastal engineering worldwide. It is recommended to continue the monitoring of the Sand Motor in the coming 10 years, with the aim of capturing the long-term development. In this way the second part of the a-priori envisioned 20-year lifespan of the Sand Motor is also monitored. A re-analysis needs to be done of the development of the Sand Motor in 2026 and 2031 (after 15 and 20 years) to obtain a complete picture of the development.

It is recommended to aim the monitoring at the continuation of the most relevant measurement series: morphology, vegetation development, dune formation, benthic animals and birds. Especially the long-term monitoring is valuable to obtain insights for practical coastal engineering and science.

- Measuring the bed level of the coastal zone and dunes is essential for obtaining insight into the redistribution of sediment along the coast. It is recommended to pay attention to the (predominantly northward) sediment transport and the aeolian transport to the dunes. Specific attention is required for the development of the lagoon. The expectation is that the lagoon shape will change considerably in the coming years as a result of a foreseen breach of the hook of the peninsula and subsequent strong import of sediment through the breach into the lagoon.
- A second priority is the vegetation on the Sand Motor and growth of the embryonal dunes. The vegetation and dunes have been growing substantially in recent years. Monitoring of the bed level and vegetation will be essential for gaining insights into the growth of the dunes, the succession of vegetation and the ecological value of the new dune nature.
- Long-term measurements of benthic animals in the shoreface (and sediment composition) are necessary to find out whether the benthic communities will eventually develop back to a similar situation as was the case before the realization of the Sand Motor. Furthermore, these data are the only source of information on benthic animals in the shallow coastal zone. The data can be used as a reference for other coastal projects. The year-to-year variations in benthic species will also be understood better. The data can be used as a basis for the derivation of relations between abiotic conditions and the presence of benthic animals, allowing

better future estimates of the impact of measures on benthic animals.

- Monitoring birds is important for the understanding of the long-term impacts of the Sand Motor on natural quality. A relevant question is whether the number of stilt-walkers on the beach will further increase over time (as is expected). Furthermore, the bird counts are used to estimate the natural value of the new dunes.

The frequency of the measurements can be lower than for the preceding ten years, which is possible because the changes are not as rapid anymore. Bathymetric measurements (e.g. in the dunes and underwater on the shoreface) are needed at least 2 times per year. Possibly, an extra bathymetric measurement will be needed for the analysis of the morphological development of the lagoon. If desired, a measurement campaign can be executed just before summer, which can be used in the app for the lifeguards to support recreational safety. Vegetation and benthic animals can be monitored every 2 to 5 years. Birds need to be counted monthly, but this can be done every 2 to 3 years.

Knowledge development
A lot of new knowledge development is still taking place based on the datasets of the Sand Motor. The current analyses focus predominantly on the description of the observed developments, while it would be beneficial if new analyses gain more insight into the underlying physical processes. It is advised to investigate the development of sand bars, bed sediment composition, vegetation/dunes, bird populations and benthic animals. These are the fields of science with large knowledge gaps and where adequate numerical models are still lacking. Dutch science organizations are encouraged to stimulate the fundamental and applied research of the Sand Motor. For practical engineering, the Sand Motor is also instrumental as a validation case for the coastal management toolboxes.

Design-decisions in relation to anticipated user functions
Insights in the priorities are very relevant in the design phase of large-scale sand nourishments that aim to support additional coastal functions (e.g. recreation, nature and coastal maintenance). The following design considerations are especially relevant for future applications:

- The choice for an elongated coastal nourishment (typically below the water at the shoreface) which is effective for coastal maintenance versus the use of an alternative more seaward extending beach nourishment that is more dynamic and also includes options for recreation and nature development (e.g. lagoon, dry beach and dune formation).
- The choice for a dune lake or lagoon to be included in the design depends on the aims for the recreational use, natural values and the desired rate of dune growth. A lagoon (or dune lake) enhances the natural value and options for recreation temporarily, but the dune growth will be less substantial.
- The accessibility of a coastal project for recreation has an impact on the development of vulnerable nature (e.g. embryonal dune vegetation and shelter for breeding birds). Especially the traffic with cars in the region may impact nature development and needs to be considered in advance.
- A large-scale nourishment with a freely developing sand spit results in a very dynamic coastal landscape. The naturalness of the region is enhanced. The coastal development is, however, also less predictable for (non-informed) beach users, which implies that extra effort needs to be spend on informing beach users on risks, and possibly will also require more frequent interventions by the lifeguards.

Recreational safety
Recreational safety needs to be considered for all new large-scale nourishments. The main point of attention is the anticipation of potentially unsafe situations, and it is relevant to investigate whether these conditions coincide with the presence of bathers. The swimmer

safety app was very valuable at the Sand Motor, improving the capabilities of the lifeguards to anticipate unsafe situations. Specific monitoring and dedicated knowledge development are, however, needed for coastal sections with a different environment or other types of nourishments and also have other safety challenges.

Impacts on existing nature and drinking water

A coastal extension with a large nourishment leads to a decrease of the salt spray in the dunes. This can result in the enhancement of the growth of brushwood. It is therefore recommended to account for a (limited) increase of the management of the dune vegetation nearby a large-scale nourishment. This applies especially to the more landward located dunes that are designated as Natura-2000 areas. New nature is, however, also created at the Sand Motor, such as new embryonal dunes. It is recommended to investigate how the (temporary) new nature is valued in government policies.

Drainage pipes were placed in front of the foredune to ascertain that potentially contaminated groundwater cannot flow towards the drinking water extraction areas. Such a drainage would, however, not be required in many other places along the Dutch coast. Instead, elevated groundwater levels would be very valuable for dune nature. A wetter environment of the existing dunes can be a goal of a future large-scale nourishment.

Degree of steering of user functions and knowledge development

Already in the design phase it is recommended to think about the extent of steering of various societal and cultural user functions and knowledge development. The institutional and social context of the region where the nourishment is placed determine the actual development of the user functions (e.g. the presence of nearby universities) or social initiatives. Steering of the processes is very relevant for regions with an underdeveloped institutional context, where a clear demand is present for an actor that initiates and organizes the use of the region.

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A Answering the evaluation questions

The evaluation questions for the Sand Motor are aimed at answering the questions from the Environmental Impact Assessment (EIA) and to gain information that is relevant for the management of the beach and dunes. These questions are described in the 'implementation program' of the Sand Motor monitoring (Tonnon et al, 2011) and were slightly modified after the evaluation in 2016 to adapt them to the actual observed issues at the Sand Motor (Taal et al., 2017; Huisman, 2018).

The questions are grouped as follows:

- EIA 1: stimulate natural dune growth,
- EIA 2: physical and ecological knowledge development focused on innovation,
- EIA 3: creation of high-quality natural and recreational areas
- Management and mitigation of adverse impacts related to (1) recreational safety, (2) recreational use in relation to nature value, (3) groundwater quality, (4) vegetation in the dunes of Solleveld and (5) potential siltation at navigation channels and outfall.

A.1 EIA I : stimulate natural dune growth

EQ1-1: Does the Sand Motor contribute to long-term preservation of the coastal foundation and basis-coastline between Hoek van Holland and Scheveningen? To what degree will this lead to natural dune growth?

- **EQ1-1a: How large is the increase of the sand volume in the central zone of the primary water defenses (in space and time) since the realization of the Sand Motor?**
  Sediment accumulation has taken place in the dunes landward of the Sand Motor with a rate of 14 m^3/m/year between 2011 and 2021. This sand mostly ended up in the first dune row. The dune growth at the Sand Motor is slightly larger than the average dune growth of the Delfland coast (13 m^3/m/yr). Even though much more sand was available for aeolian transport at the Sand Motor, a large part of it was captured by the lagoon and the dune lake. If this accretion in the dune lake and the lagoon is taken into account, the wind transport at the Sand Motor would have been considerably larger (~27 m^3/m/yr).

- **EQ1-1b: Which part of the added sediment via the Sand Motor is still present in the area and contributes to the preservation of the basis-coastline?**
  In 2011 is 21.5 million m^3 of sediment was added to the coast between Ter Heijde and Kijkduin over a length of about 2.5 km. Over a period of ten years the sediment in the Sand Motor construction area has decreased by 5 million m^3. About 3 million m^3 of sediment is found in the close vicinity directly North and South of the Sand Motor (i.e. stretches with a length of about 1 km). The remaining 2 million m^3 contributes to the maintenance of the adjacent coastline and dunes of Delfland (e.g. at Ter Heijde, Kijkduin and Scheveningen). The Sand Motor sediment is expected to feed the Delfland coast and dunes for many years to come.

- **EQ1-1c: Which part of the added sand via the Sand Motor is still present in the coastal foundation and how is the distributed spatially?**
  Almost all of the nourished sediment of the Sand Motor is still available within the coastal foundation. Some redistribution did, however, take place within the coastal foundation from the coastal cell of Delfland to Rijnland. Approximately 200,000 m^3/yr of sediment was transported to the dunes of the Delfland between 2011 and 2021 (not only from the Sand Motor) and 150,000 m^3/yr northward towards Rijnland.

A.2 EIA II : Knowledge development and Innovation

EQ2-1: Does the Sand Motor create new physical system knowledge on the realization of coastal maintenance with an added value for recreation and nature?

- **EQ2-1a: Which lessons were learned about planning and design of (mega)nourishments from the morphological development of the Sand Motor, in particular for the nourishments that also aim at an added value for nature and recreation?**
  The reshaping at the Sand Motor is different from the behavior of regular (shoreface) nourishments. Shoreface nourishments deform predominantly in the cross-shore direction, whereby the crest gradually moves onshore. While redistribution at the Sand Motor takes place especially in alongshore direction as a result of the wave-driven transport. This provided insight in the lifespan of the Sand Motor. The dynamics of the sand bars were enhanced as a result of the addition of sediment to the coastal system. Tidal current velocities have increased seaward of the peninsula as a result of the Sand Motor, and in addition also a recirculation of the currents takes place at the flanks. For this reason, erosion takes place at the lower shoreface seaward of the Sand Motor affecting bed sediment and the habitat for benthic life. The dunes were strengthened by a rather continuous supply of sand from the Sand Motor, which originated mostly from the intertidal area. Catchment of sand took place in the dune lake and the lagoon which resulted in a decrease of the supply to the more landward located dunes. In addition, the development of vegetation and new dunes on the beach can also result in a decrease of the sediment supply to the existing dunes. Only a small amount of sediment becomes available for wind transport at the higher sections of the dry beach, because a protective armor layer of coarser sand and shells is developing through selective transport of the finer sand. The peninsula is effectively too high for the waves (and wave runup) to rework this layer.

- **EQ2-1b: Which lessons can be learned on the planning and design of (mega) nourishments following from the morphological development of the Sand Motor, such that it is beneficial for swimmer safety at nourishments?**
  The design of the Sand Motor has led (especially in the first two years) to a slightly enhanced risk related to large flow velocities in the entrance channel of the lagoon during the flood phase. This was an unsafe situation for bathers that decided to cross the channel, which were in some occasions taken into the lagoon with the flood current. Other risk factors were present at the peninsula, such as strong currents (e.g. due to gyres and rip currents), but these have not lead to problems since few people were present at the beach when they occurred. The design lesson is that the coincidence of risky situations (such as rip currents, strong currents due to a ‘gyre’ or tidal current in the entrance channel) and the number of expected beach users should be investigated in the design phase of a large-scale nourishment.

- **EQ2-1c: Which lessons were learned on the planning and design of (mega)nourishments following from insights on the added value of the Sand Motor for other functions (amongst which aspects like cultural heritage, spatial planning and economy)?**
  The location and design of the Sand Motor have a substantial impact on the effective use of the area. The dynamic character of the region has been attractive for artists. Also, the relatively free way in which the beach is managed has been of relevance for cultural activities. A lesson is that the desired degree of steering can be defined in a strategy per use-function depending on the presence of institutional parties in the region.

EQ2-2: What is the added value of a mega-nourishment, such as the Sand Motor, for nature when compared to regular nourishments? And which aspects are creating this added value?

- **EQ2-2a: Which mechanisms may cause changes in the sediment composition of the Sand Motor (i.e. grain size distributions and organic content) on the wet beach and the lower shoreface?**
  Large-scale nourishments, such as the Sand Motor, influence both the waves and the tidal currents. The wave forcing and resulting wave-driven currents create a strong erosion in the surfzone of the peninsula, because of which the bed sediment composition will get slightly coarser. The biggest impact on the bed sediment composition is, however, found on the lower shoreface (>6m water depth), where the Sand Motor creates an enhancement of the tidal currents. Areas with a finer bed sediment composition developed at the adjacent coastal sections (at the lower shoreface) just North and South of the Sand Motor. The impacts on the bed sediment composition extend further than the initial construction area of the Sand Motor (up to 3 km from the coast). The seaward extent of a nourishment determines the impact on the tidal currents, and consequently also the changes in bed sediment composition

- **EQ2-2b: Does the one-off placement of a large volume of sand result in a more natural benthic community composition in the shallow coastal zone? How does it compare to regular nourishments schemes? Is a one-off placement beneficial for longer living species?**
  More benthic species and biomass were found in the shoreface of the Sand Motor in comparison to the pre-construction situation. The changes in the environmental conditions (waves, currents, bed level change and sediment) led to more diverse habitats. Especially the milder conditions in the region just North of the Sand Motor created a specific habitat with a large number of benthic species, which is evidence of an impact from the Sand Motor that is not present at regular nourishments.

  The burial of benthos with nourishment sand occurs less frequently at a large-scale nourishment such as the Sand Motor. It was, however, not possible to differentiate the effects of this aspect from the influence of other changes in the environmental conditions, such as the wave forcing, tidal currents and bed sediment composition. Possibly, this effect of the one-off placement is rather small as the shallow nearshore zone is home to benthic species that are adapted to a high degree of sediment mobility. These benthic species can quickly recolonize the nourished shoreface. It is expected that the situation for the benthos will eventually return to the pre-construction situation over time, when the Sand Motor sediment is spread fully over the coast.

EQ2-3 : What spin-off is created for knowledge and innovation?

- **EQ2-3a: To what extent do the developed knowledge and methods have a wider applicability for the development of sandy strategies and innovations?**
  Generic knowledge was developed in a large number of research studies focusing on the Sand Motor, generating new insights and methods in the field of hydrodynamics, morphology, sediment, ecology, groundwater and dune formation. Research on governance of the project provided new insights with respect to the steering of the use-functions of the large-scale nourishment. Numerical models and expertise from the Sand Motor studies is much wider applicable for other types of nourishments and other coasts. The obtained knowledge and models allow for more accurate predictions of the lifespan of large-scale sand nourishments, understanding of sediment sorting on the shoreface and accretion of navigation channels. The Sand Motor has also been indispensable for the development of a wind transport model (Aeolis), which can be used to investigate dune development at a

wide variety of coastal situations. Innovations in the computation and visualization of currents in shallow water (with a mobile phone-app) assist the lifeguards with the detection of rip currents. Innovative measurement techniques could also be used and developed at the Sand Motor. For example, making it possible to monitor embryonal dune growth in great detail with a drone.

- **EQ2-3b To what extent has the developed knowledge been used in innovative national and international projects?**
  The developed knowledge at the Sand Motor has been used at research of alternative coastal management in Jamaica and the United Kingdom. Furthermore, the Sand Motor is often used as an example of innovative coastal management for international delegations. The Sand Motor has also been the inspiration for the large-scale sandy dune reinforcement at the Hondsbossche Dunes and for the recent coastal nourishment at Ameland in the framework of the Kustgenese-2 project. In the coming years we will have to see how the knowledge development of the Sand Motor will be extended in coastal engineering research.

  EQ2-3c To what extent has knowledge been disseminated, both nationally and internationally?
  Sand Motor knowledge has been disseminated broadly either through formal or informal communication. Multiple groups were addressed (from scientists to the broad public) and at different communication levels (ranging from scientific journals to local newspapers). The Sand Motor research had a positive impact on the relations and collaboration in scientific networks, amongst which the Dutch Center of the Coast (NCK).

A.3 EIA III : Nature

EQ3-1a: Does the Sand Motor add attractive natural area on the beach and in the young foredunes seaward of the existing dunes?

- **EQ3-1a1: To what extent will wider, more natural and dynamic dunes develop?**
  The growth of vegetation and embryonal dunes at the beach of the Sand Motor has created a landscape with a large degree of naturalness, which is not found at other places along the Holland coast. It is expected that this development will continue and that the dunes will eventually merge with the foredune and first dunes of Solleveld. So, wider and more robust complexes of outer dunes are developing. Over time the dune reinforcement got a more natural character with more spatial variation in the bed level and vegetation.

- **EQ3-1a2: What is the impact of the landscape dynamics following from the method of realization and management on the quality?**
  The dynamics of the Sand Motor landscape have transformed the beaches of especially the southern end of the Sand Motor at the connection with the coast. A large area of embryonal dunes has developed at the beach (H2110). Smaller dune patches merged in some places into dune complexes of white dunes (H2120). The vegetation development did, however, only kick off substantially after 2016, which was much later than expected. A very quick growth of the vegetation and dunes did, however, take place from 2016 till 2021. The dune lake and the lagoon reduced the potential vegetation and dune growth at the central and northern beach sections of the Sand Motor, because sand was captured in by these water bodies. The height of the dry beach of the peninsula was effectively too high to allow reworking of the bed by waves and currents. Consequently, an area with rather coarse sand and shells developed, which lacks the necessary dynamics to mix and sort the sand.

- **EQ3-1a3: Wat is the impact of recreation management (‘flexible demarcation of zones’)?**
  Recreation management, with the aim of promoting vegetation- and dune growth, was hardly applied. As a result, the dunes at the Sand Motor were hindered in their development. Traffic and beach

cleaning made it difficult for new young vegetation to survive in the first years after construction. Especially the driving routes can still be distinguished in 2021 in the spatial distribution of the embryonal dunes (e.g. at the beach entrance of the Schelpenpad and at the division between foredunes and new dune complexes at the beach). The expectation is that a larger area of young dunes would have had developed if access restrictions would have been in place for visitors, such as the limitation of the driving routes of cars (with fences and/or signs) or when hikers would take predefined routes from the entrances to the beach (e.g. at the Schelpenpad beach entrance).

EQ3-1b: How does the temporary new nature develop in the intertidal area and the lagoon of the Sand Motor?

- **EQ3-1b1: How did the diversity in sediment composition develop in the lagoon and in the shoreface?**
  The realization of the Sand Motor, and subsequent changes of the nearshore waves, currents and bed sediment composition, have led to an increase in the diversity of habitats in the shoreface and for the lagoon. Bed sediment at the shoreface seaward of the Sand Motor has become coarser, while finer sediment is found just North and South of this area. The relatively sheltered lagoon is filled in from the western side with aeolian sediment, while fines/silt and organic matter are accumulating on the bed. The sediment in the entrance channel is relatively coarse due to the strong local currents. Over time the Sand Motor will gradually disappear implying that also the grain size distribution will go back to the situation before construction with a fining of sediment in seaward direction. This may, however, take tens of years.

- **EQ3-1b2: Has the Sand Motor created new habitats/ecotopes and more variation in habitats/ecotopes? Do these new areas lead to higher nature values in the intertidal areas and shallow coastal zone? Can this be quantified for benthic animals, fish, birds and sea mammals?**
  The realization of the Sand Motor has led to an increase in the diversity of habitats on the land and in the shallow coastal zone. Both the biodiversity and naturalness have increased. The lagoon is now a unique brackish habitat for this part of the Dutch coast, even though the lagoon has become cut-off from the sea by the spit, which limits the exchange of sea water. On the long-term the lagoon and the dune lake can change into ecologically highly valued wet beach plains. This may still take quite some time, as the lagoon and the dune lake are quite deep, thus requiring a lot of aeolian sediment supply to fill up. The habitat “dune lake” is a new habitat, with rare, characteristic plants. Underwater vegetation developed (*snavelruppia*) in the dune lake.

  On the beach of the Sand Motor the dune development has accelerated substantially since 2016. A large area of embryonal dunes has developed at the beach (H2110). Smaller dune patches merged in some places into dune complexes of white dunes (H2120). This dynamic dune formation is not seen elsewhere on the Holland coast. Also, the benthic animals in the shoreface of the coast increased in diversity and biomass, which relates to a change in the habitat of the lower shoreface. Birds increased in number, but still a large difference in the total number of birds was not seen compared to Noordwijk. Relevant was, however, that new species were observed at the Sand Motor (e.g. more cormorants and black-headed gulls), which likely is due to the lagoon habitat and relative quietness of the beach at the peninsula. It could not be shown whether the Sand Motor provides a better habitat for fish and sea mammals.

- **EQ3-1b3: How did the benthic community develop in the lagoon and the shoreface?**
  Shells were collected at the edges of the lagoon, which indicated an increase in the number of benthic species in the lagoon over time. The number of species increased from one to a maximum of

seven species. Shells were found that are uncommon on the beaches of the Holland coast. Besides this also the larvae of mosquitoes and small worms were found in the deeper bed area of the lagoon. The total number of species seemed to get lower since 2020, which can be explained from the diminishing flushing of the lagoon with water from the sea.

- **EQ3-1b4: Has the nursery function for juvenile fish developed in this area?**
  An impact of the Sand Motor could not be shown for juvenile fish, as this was complicated by the large variation in fish catchment per survey. The increase in the number of and biomass of benthic animals should, however, be seen as a positive indicator for the presence of (juvenile) fish.

- **EQ3-1b5a: What kind of developments were taking place for breeding birds in the area?**
  For breeding birds, the added value of the Sand Motor is quite limited, because it concerns only a small number of birds. Coastal breeding birds such as the beach- and ringed plover, the little tern and the oystercatcher are very sensitive to disturbance from visitors (and dogs). Still a few birds were spotted in recent years, while at most a single bird pair was spotted up till 2016.

- **EQ3-1b5b: How did stilt-walkers and seabirds develop in this area?**
  A larger number of non-breeding birds was observed at the Sand Motor in comparison to the pre-construction situation. More birds were observed in 2013 and 2014 than in later years. The smaller number of birds in recent years relates to the decrease of the area of the peninsula as a result of erosion, which reduced the available tranquil Sand Motor area (i.e. which cannot easily be reached by visitors). Stilt walkers are less often seen at the Sand Motor than at other beaches, although the number of stilt walkers is still increasing over time at the Sand Motor, which most likely is the consequence of an increase in benthic life in the intertidal area.

- **EQ3-1b6: Does the Sand Motor create a foraging and resting area for sea mammals?**
  The habitat suitability at the Sand Motor is for sea mammals hardly different from the other beaches at the Holland coast. Despite the relative quietness of the beaches of the Sand Motor, there still is too much disturbance to create a safe environment for sea mammals

EQ3-2: How did the appreciation of the coast between Hoek van Holland and Scheveningen change as a result of the Sand Motor?

- **EQ3-2a: How does the Sand Motor contribute to a more attractive place for residents and visitors in the region of The Hague and Westland?**
  The Sand Motor is attractive for hikers, bathers and kitesurfers and the visitors have a positive experience. The quietness and naturalness of the area are important. Also, the residents of the Westland and The Hague use the Sand Motor for recreation.

- **EQ3-2b: How does the Sand Motor contribute to the welfare of the region between Scheveningen and Hoek van Holland? (economical development, better business climate)**
  The Sand Motor has not led to an increase in the number of visitors on this part of the coast. A contribution to the work- and entrepreneurial conditions in the region (i.e. more appeal for enterprises and expats) could not be shown. Also, real estate value cannot be linked to the Sand Motor, as the Sand Motor is not providing additional residential appeal

- **EQ3-2c: How does the Sand Motor contribute to the recreational use of the coast between Hoek van Holland and Scheveningen?**
  The Sand Motor offers ample extra space for visitors. The number of bathers is, however, smaller than for nearby beaches, which is related to the relatively large distance from the beach entrances to the coastline of the peninsula. Kitesurfing is the most distinguishing

use of the Sand Motor compared to other beaches. The design of the Sand Motor with a lagoon is essential for kitesurfing and makes it unique, but the dynamic character of the Sand Motor also implies that the possibilities for kitesurfing will decrease over time as a result of expected future siltation of the lagoon. The nature experience will further improve over time as a result of the natural growth of the dunes.

A.4 Management

EQ4-1: Are there adverse impacts of the Sand Motor for recreational safety? Can these effects be mitigated with management measures? Was the management protocol sufficient?

- **EQ4-1a: Has the swimmer safety at the Sand Motor been manageable?**
  Swimmer safety at the Sand Motor was manageable. Rip currents and acceleration of the tide at the peninsula have not led to incidents. The rip currents are also less often seen at the Sand Motor than for the adjacent beaches. However, a number of beach users got trapped at the spit during high water in the first years after realization. They crossed the entrance channel of the lagoon during low tide, but were surprised by the high current velocities during flood, which makes it difficult to cross the entrance channel to the beach.

- **EQ4-1b: Were the health risks as a result of deteriorating water quality in the lagoon and/or dune lake manageable?**
  The water quality of the lagoon deteriorated over time as a result of the diminishing exchange with the sea via the channel. This did, however, not create any health issues.

- **EQ4-1c: Has recreational safety with regard to quicksand been manageable?**
  Quicksand has been seen locally in the first years, but caused no problems.

- **EQ4-1d: Was the recreational safety with regard to cliffs manageable?**
  Some cliffs developed at the seaward side of the peninsula of the Sand Motor, but in practice this risk was very low as only a few people visit this area.

- **EQ4-1e: Has there been a negative impact on the attractiveness for beach users following from the siltation of the lagoon and the subsequent development of a green beach?**
  A green beach has not yet developed at the Sand Motor.

EQ4-2: To what degree can recreation and nature development goals be united on and around the Sand Motor?

- **EQ4-2a: What has been the impact of recreation management via demarcation of nature on the Sand Motor?**
  Recreational zonation and management have not been investigated at the Sand Motor, but it is likely that more disturbance-sensitive breeding birds would have been present without the recreational use.

- **EQ4-2b: What has been the impact of extra visitors in the dunes of Solleveld on the natural quality?**
  There are no data on the impact of extra visitors in the dunes of Solleveld. There were also no extra permits granted for visitors to this area by Dunea.

- **EQ4-2c: What is the impact of hiking and driving at the Sand Motor on the nature of the beach and dunes?**
  Traffic, beach-cleaning and hiking by visitors have a clear impact on the dune development. And to a lesser degree also an effect can

be seen of hiking by visitors. Cars created a series of unvegetated tracks parallel to the dunefoot and driving patterns at the beach entrances. The vegetation maps show that the dune vegetation at the southern side of the Sand Motor is radially shaped as a consequence of hiking pathways of visitors (and possibly also cars). Some narrow paths can be observed in the embryonal dunes. The recreational use of the Sand Motor has most likely hindered the vegetation growth and development of embryonal dunes.

- **EQ4-2d: To what degree is the ecology of the dune lake influenced by recreation?**
  The dune lake is hardly visited by beach users. The embryonal dunes around the dune lake develop very steadily, which is an indication that local disturbance by visitors is limited.

EQ4-3: Is it possible to prevent adverse impacts of the Sand Motor on the groundwater?

- **EQ4-3a: Is permanent drainage effective as a preventive measure against salinization and contamination in subregion 1 of the drinkingwater extraction site of Solleveld (compartment 16)?**
  The drainage tubes that were installed just seaward of the foredune have effectively lowered the groundwater levels in the existing dunes, preventing an impact of the Sand Motor on the groundwater levels. Any potential contaminations could not have redistributed towards compartment 16. There are no data available about salinization and contaminations of groundwater in the drinkingwater extraction area.

- **EQ4-3b: Is permanent drainage effective as a preventive measure against the spreading of contaminations to dune compartment 17? (in the direction of Kijkduinpark)**
  The drainage tubes that were installed just seaward of the foredune have effectively lowered the groundwater levels in the existing dunes, preventing an impact of the Sand Motor on the groundwater levels. Any potential contaminations could not have redistributed towards compartment 17. There are no data available about salinization and contaminations of groundwater in the drinkingwater extraction area.

- **EQ4-3c: Is temporary drainage required and sufficient to prevent salt from the newly nourished sediment to reach the extraction wells in subregion 2 of the drinkingwater extraction site of Solleveld (compartment 14/15)?**
  The drainage tubes that were installed just seaward of the foredune have effectively prevented salt groundwater from the Sand Motor to flow in the direction of the extraction wells of Dunea. The groundwater at the Sand Motor has become fresh after a few years.

- **EQ4-3d: Is temporary drainage required and sufficient to prevent 'old salt' (above the clay layer at NAP -16m) from entering subregion 2 and affecting the 'raw water' quality negatively (compartments 14/15)?**
  There are no clues that older salt water has had a negative impact of the raw water quality in subregion 2.

- **EQ4-3e: Can there be a long-term risk of groundwater disturbance along the inner edge of the dunes? (subregion 3, compartment 13)**
  The drainage tubes that were installed just seaward of the foredune have effectively lowered the groundwater levels in the existing dunes, preventing an impact of the Sand Motor on the groundwater levels.

- **EQ4-3f: What is the impact of changes in groundwater levels in dunes of Dunea landward of the third dune row?**
  The drainage tubes that were installed just seaward of the foredune have effectively lowered the groundwater levels in the existing dunes, preventing an impact of the Sand Motor on the groundwater levels.

EQ4-4: Are there adverse impacts on the natural values of the existing dunes? Can they be prevented? How can they be mitigated?

- **EQ4-4a: What were the impacts of changes in sandspray in the existing dunes?**
  The sand dynamics in the dunes of Solleveld were found to be relatively low for all measurement locations. The dense plant cover at the dune reinforcement catches most of the wind-blown sand from the Sand Motor, thus bypassing only a small fraction of sand to the inner dunes. Sand is only blown to the inner dunes of Solleveld during storm conditions. Additional effort needs to be spent on the removal of sea buckthorn and marram grass as well as on the construction of blowouts. These mitigation measures will enhance the dynamics of the dunes for a period of a few months.

- **EQ4-4b: What were the impacts of changes in salt spray in the existing dunes? What is the impact of vegetation management? (grazing, mowing, removal of brushwood)**
  An impact of the Sand Motor on the sand and salt spray into the dunes cannot be seen in the vegetation of the dunes of Solleveld, because mitigation measures have been taken which compensate any changes. The salt spray in the inner dunes has already changed as a result of the construction of the dune reinforcement of Delfland in 2010. The Sand Motor does, however, have a noticeable impact on the first dune row (the 'dune reinforcement'). More growth of brushwood was observed in the section of the dune reinforcement that is located directly landward of the Sand Motor, which is a result of the reduction of the sand and salt spray here. Considerably less vegetation succession was observed just North and South of the Sand Motor.

- **EQ4-4c: What is the impact of changes in sand and salt spray in the dune area of Dunea landward of the current third dune row?**
  Less sand and salt are transported to the dunes that are located landward of widest section of the Sand Motor, but the changes in salt and sand spray were not substantial enough to lead to a shift in the vegetation of the dunes landward of the third dune row.

EQ4-5: What adverse effects of the Sand Motor can be present for the wet infrastructure, such as navigation channels and outfalls? Can these effects be mitigated?

- **EQ4-5a: Has there been extra accretion in the navigation channels of the ports of Rotterdam and Scheveningen which can be attributed to the Sand Motor attributed?**
  Accretion in the navigation channel of Rotterdam has not changed as a result of the Sand Motor, while only a very limited impact is expected for the navigation channel of Scheveningen. The impact of the dune reinforcement Delfland was larger than the impact of the Sand Motor. Natural accretion at Scheveningen is strongest for years with relatively large occurrence of wind and storms from the West and South-West.

- **EQ4-5b: Is there siltation of the outfall of the 'J.J.J.M. Van den Burg' pump station that can be attributed to the Sand Motor?**
  The Sand Motor has hardly any impact on the outfall of the 'Van der Burg gemaal'. The accretion here was related to the dune reinforcement of 2010.

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