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Monitoring Nature-Based Solutions: Insights from the Dutch Sand Motor

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Summary

Nature-based Solutions (NbS) are increasingly being implemented globally in coastal zone management to sustainably maintain coastal functions and preserve natural characteristics. Sand nourishments have proven to be an effective way to protect sandy coastlines. Upscaling these nourishments to allow for more natural coastal processes, as exemplified by the Sand Motor at the Delfland coast, is gaining worldwide attention. These measures enhance the potential to combine coastal safety with nature and recreational opportunities in the area.

The evaluation of large-scale NbS, such as the Sand Motor, requires effective monitoring of performance and impacts, underscoring the need for clear guidelines. Insights from setting up the monitoring campaign for the Sand Motor, as well as its evaluation every five years, provided valuable insights. These are important building blocks for developing such guidelines.

This document summarizes key lessons learned at the Sand Motor, offering guidance and best practices for setting up monitoring and management for future large-scale sandy NbS. Depending on the readers' interest, they can inform themselves on experiences with monitoring at the Sand Motor (Chapter 2) or the more generalized guidelines for large-scale sandy NbS (Chapter 3).

It is crucial to follow a structured approach for effective monitoring and management. The scope of the monitoring program will depend on the level of innovation involved. This level is higher for a pilot compared to the implementation of an already established concept. Furthermore, it is essential to explicitly define the objectives of the large-scale NbS at hand, as these objectives will guide the need for monitoring data, which should always be tailored to the specific context. The type and frequency of the monitoring could then be linked to the specific features of the NbS design. Finally, it is assessed whether management measures can further contribute to achieving the objectives.

Drafting these guidelines was initiated as part of the MANABAS coast project, which contributes to the goal of Interreg North Sea to support the implementation of sandy NbS in the North Sea area. Deltares, commissioned by Rijkswaterstaat (the coastal authority of the Dutch Ministry of Infrastructure and Water Management), conducted this study, leveraging its extensive experience from ongoing field monitoring activities and analyses at the Sand Motor.

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1 Introduction

Nature-Based Solutions (NbS) are increasingly being implemented worldwide to sustainably maintain coastal functions and natural characteristics amidst changing climate conditions. Sand nourishments have proven to be effective in protecting sandy coastlines. A notable NbS option is the multi-functional large-scale sand nourishment, exemplified by the Sand Motor at the Delfland coast in the Netherlands. Such measures not only ensure coastal safety and preserve the coastline but also offer additional benefits. They create additional space for leisure activities, and promote the development of natural habitats and biodiversity. They leverage the dynamic processes of the natural system for spreading sand alongshore and to the dunes. The strength of these NbS is that they use the natural processes, but their impacts and benefits may also vary over time.

To mainstream these measures, effective monitoring of sandy NbS is essential to ensure their objectives are achieved. Clear guidelines for monitoring their performance and impacts are therefore needed. Currently, such guidelines are lacking, as this is not the standard method for coastal maintenance. A study, wherein general guidelines are created for optimized monitoring and management of future large-scale sandy NbS, is therefore very much needed. This study was initiated as part of the MANABAS coast project, which contributes to the goal of Interreg North Sea to support the implementation of sandy NbS in the North Sea area. Deltares has been commissioned by Rijkswaterstaat (i.e. the coastal authority of the Dutch Ministry of Public Works) to conduct this study, as Deltares can bring in valuable experience from the ongoing field monitoring activities and analyses at the Sand Motor.

This overview of experiences with the Sand Motor, and more general guidelines for setting up monitoring, are developed for the preliminary and pre-feasibility phases wherein large-scale sandy NbS are considered, and to a lesser extent for Environmental Impact Studies. For the more detailed design phases this guideline provides just a rough outline of what can be done, as it is assumed that much more will then be known of the local context and precise specifications of the NbS which cannot be accounted for in a general guideline. Typical users of the guideline will be coastal managers and specialists in ecology and engineering who want guidance on the process of setting up monitoring requirements of large-scale sandy NbS.

Chapter 2 summarizes the experiences gained from monitoring the Sand Motor. The main source of information for setting up the guidelines in this report is the experience that was gained at the large-scale Sand Motor nourishment. A general overview of the Sand Motor is provided to give the reader understanding of the project. The type of monitoring activities at the Sand Motor are described in relation to its objectives and design. The experiences are the basis of an evaluation of the effectiveness of these monitoring activities in relation to the objectives of the monitoring campaign.

Chapter 3 is the translation to general guidelines for future large-scale sandy NbS, especially for North Sea beaches. The regional context is also discussed (e.g. environmental conditions, nature protection areas and socio-economic activities). For those seeking information specifically on setting up monitoring for a large-scale NbS, this chapter can be directly consulted.

2 Monitoring of the Sand Motor

2.1 Background of the Sand Motor

In 2011, the Sand Motor was implemented at the Delfland coast (Figure 1). This large-scale nourishment was designed for three objectives: (i) Stimulating natural dune growth in the coastal area between Hoek van Holland and Scheveningen. This dune growth serves multiple functions, namely safety, nature, and recreation; (ii) Generating knowledge development and innovation to answer the question of to what extent coastal maintenance and added value for recreation and nature can be jointly realized; (iii) Adding an attractive (temporary) recreation and nature area to the Delfland coast.

The hook-shaped peninsula of the Sand Motor was created with approximately 21.5 million cubic metres of sand that was sourced from offshore borrow areas. A lagoon is located on the northern side of the Sand Motor, just inland from the hook-shaped peninsula. This lagoon is protected from waves and currents, creating an additional type of ecological habitat close to the exposed coast. The Sand Motor initially had a seaward extent of about 1,000 metres and spanned an alongshore length of about two kilometres between Ter Heijde and Kijkduin. Over time, natural processes such as waves and currents have distributed the sand from the Sand Motor along the coast, enhancing both the adjacent coastline and the dunes.

Figure 1. Sand Motor after realisation in 2011 (Rijkswaterstaat / J. van Houdt).

The Environmental Impact Assessment (DHV, 2010a) outlined the following objectives for the Sand Motor project:

1. **Coastal preservation**: Stimulate natural dune growth in the coastal area between Hoek van Holland and Scheveningen, enhancing safety, natural, and recreational functions.
2. **Knowledge & Innovation**: Foster knowledge and innovation to determine the added value of coastal maintenance for recreational and natural functions and assess the feasibility of achieving these together.
3. **Recreation & Nature**: Create an attractive (temporary) recreational and natural area along the Delfland coast.
4. **Managing the coast**: Evaluate the management of the Sand Motor and its surroundings. This includes ensuring recreational safety (e.g., swimmer safety, cliffs, and quicksand), integrating recreational and natural objectives, and preventing

negative impacts on groundwater, the natural values of the existing dunes of Solleveld, and port entrances. This was not one of the objectives of the Sand Motor, but it was a prerequisite for the project.

2.2 Monitoring of the Sand Motor

2.2.1 Objectives

A monitoring and evaluation program has been in place since 2011 to assess whether the Sand Motor meets the predetermined objectives. For this purpose, evaluation questions have been formulated. These questions arise from the Environmental Impact Assessment (EIA) and permit requirements (management questions). A monitoring and evaluation study is available for the 5-year and 10-year assessments (Taal et al., 2016 & Huisman et al., 2021).

The ***Environmental Impact Assessment (EIA)*** related questions are focusing on:
- the contribution of the Sand Motor to coastal maintenance and natural dune growth
- physical knowledge about coastal maintenance in relation to recreation and nature
- added value of the Sand Motor for nature
- spin-off of the Sand Motor for knowledge and innovation
- development of the added dune and intertidal areas
- perception and appreciation of the Sand Motor

The ***Management questions*** of the Sand Motor focus on:
- effects on recreational safety and possible management measures
- compatibility of nature and recreation objectives
- effects on groundwater
- sand and salt drift to the existing dunes
- potential effects on the harbour channels of Scheveningen and Rotterdam
- data management and the lessons learned about managing large data files

Each of the above objectives were redefined into evaluation questions and further substantiated with practical sub-questions. These questions were then used as a basis for the ‘monitoring and evaluation programme’ of the Sand Motor. This approach ensured that 1) the initial monitoring was designed to collect information specific to the EIA and Management questions, and 2) the evaluation of the Sand Motor’s development was conducted based on these questions. Every five years, an answer was formulated for each of these (sub)questions during the performance evaluation, including addressing the more challenging questions.

2.2.2 Subsequent monitoring programs

A 5-year cycle was established for evaluating the performance of the Sand Motor. During each cycle, monitoring information was analysed to answer the evaluation questions. The efficacy of the monitoring conducted in the previous cycle was assessed, and new monitoring requirements were defined for the upcoming period. Rijkswaterstaat and Deltares found that these cycles worked very well, providing a sufficiently long period to collect information while allowing for program adjustments based on evaluation findings. Four distinct periods have been identified so far: the pre-construction period (before 2011), the period directly after construction (2011-2016), the second program after construction (2017-2021), and the current program (2022-2027). A general overview of these monitoring/evaluation phases is provided here.

A baseline report (Tonnon & Baptist, 2011) was created in the pre-construction phase to describe the initial situation before the construction of the Sand Motor. Indicators were derived to assess the evaluation questions, which each were tied to required monitoring.

This report, based on data available in March 2011, not only describes the T0 situation but also the expected impacts of the Sand Motor. A key contribution of the study is the identification of various relevant data sources. It found that hydrodynamic data (e.g. for waves, wind, water levels, rip currents, and precipitation) and annual beach and nearshore profile measurements (JARKUS – Jaarlijkse Kustmetingen) were available, while other data were unavailable or scarce. Consequently, new data were collected on sediment composition and benthic fauna (Medusa, 2010; Wijsman & Verduin, 2010 & 2011). Bird populations, vegetation/plants, fish larvae, and juvenile fish could be inventoried based on various literature data sources, but marine mammal data were too limited for the studies. As a result, a reference situation could be well established for some system properties, while other characteristics of the (natural) system were not extensively investigated before construction.

The first monitoring phase after construction took place from 2011 to 2016. The monitoring coordination and execution of the first round were managed by Deltares, Wageningen Marine Research (WMR), and the foundation 'Zuid-Hollands Landschap'. Additionally, several other bureaus contributed to the monitoring and analyses, including SHORE monitoring, Arens Bureau for Beach and Dune Research, Vertegaal Ecological Advice and Research, Bureau Waardenburg, and Ecoresult. At the end of the first monitoring period, the results of the evaluation were published in Taal et al. (2016). This first phase was characterized by a very intensive monitoring of a large number of different (mainly physical) characteristics of the Sand Motor and its impacts. Especially the coastal morphology and ecology were measured in much higher frequency and detail. This phase of the project has provided us with a lot of insight in the monitoring of ecology for such a relatively small coastal section.

The second monitoring phase commenced in 2017 and was completed in 2021. The coordination and execution of the monitoring were primarily carried out by Deltares (in collaboration with SHORE monitoring, Arens Bureau for Beach and Dune Research, and Vertegaal Ecological Advice and Research), Wageningen Marine Research (WMR), and the Zuid-Hollands Landscape Foundation (in collaboration with Bureau Waardenburg and Ecoresult). At the end of the second monitoring period, the results of the evaluation were published in Huisman et al. (2021). In this phase the number of monitored parameters was reduced considerably focusing more on the required aspects from the EIA and permits, and in addition to a small set of morphological/ecological parameters that could provide a real benefit to the understanding of the functioning of a Sand Motor NbS at a decadal time scale.

The third monitoring phase began in 2022 and will continue until 2026. The coordination and execution of the monitoring are carried out by Deltares (in collaboration with SHORE monitoring and Arens Bureau for Beach and Dune Research) and Wageningen Marine Research (WMR). Measurements are further brought back to the fields wherein impacts are still expected after 10 years. This program not only includes the required monitoring but also focuses primarily on the predominant evolution of beach and dune morphology, as well as the ecology of benthic species in the shoreface of the Sand Motor.

2.2.3 Monitoring overview

The above-described phases of the monitoring program contained many monitoring techniques, which would be too extensive to fully describe here. The different monitoring items can best be grouped in the following themes:

- **Meteo and hydrodynamics**
  This concerns local point-measurements of waves and currents at the shoreface of the Sand Motor. Also drifter buoys have been employed at the Sand Motor at two campaigns at the beaches and in the (entrance of) the lagoon. Radar and ARGUS camera observations have also been used. These measurements were intended to collect data

for numerical studies of hydrodynamics/morphology and to support swimming safety assessments.

- **Morphology of shoreface and beach**
  Measurements of the bathymetry of the shoreface form the backbone for our understanding of the efficacy of the Sand Motor in distributing sediment to adjacent beaches and to the dunes. Furthermore, sediment composition has been investigated with the aim of making accurate morphological computations and to describe the ecological ecotopes/habitats. Also remote sensing has been used to assess coastal position from ARGUS cameras.
- **Ecology of shoreface and intertidal beach**
  The composition of the bed sediment and local hydrodynamics have been used to interpret the ecotopes in the shoreface and lagoon (Van Donk & Wijsman, 2020). Local surveys collected benthic species (or shellfish) to characterize the development of the numbers and biomass of benthic macrofauna species (Wijsman et al., 2020). During the first monitoring period, the fish in the shoreface and lagoon, as well as beach mammals, were also monitored, although the fish monitoring was unsuccessful.
- **Nature of the Sand Motor and dunes**
  The dry beach and dunes of the Sand Motor dynamically change over time from a sandy flat area to a diverse environment. The sand dynamics/geomorphology and sand/salt spray to existing dunes were therefore key parameters that were monitored. The influences on the local vegetation/habitats and (breeding/foraging) birds have been monitored as well as the rare plant species.
- **Socio-economic value**
  The Province of South Holland has commissioned four (2010, 2012, 2015, and 2019) recreational surveys on the experience and use of the Sand Motor (Goossen et al., 2020). An assessment of other socio-economic benefits of the Sand Motor has also been done in the second monitoring phase (Wienhoven et al., 2020), but monitoring on added value hasn’t been a key part as it turned out difficult to establish a good approach.
- **Groundwater**
  Influence of the Sand Motor on ground water was to be avoided, as it may have impacted the drinking water extraction from the dunes ground water reserves by Dunea (drinking water company), and therefore a relevant part of the monitoring. The installation of additional groundwater extraction tubes, which dewatered the dunes just seaward of the first dune, effectively made this aspect non-crucial at this site.

Figure 2 displays each of the monitoring items categorized accordingly. Note that each item has a distinctive code for easy classification of these datasets.

Figure 2. Overview of the monitoring activities.

The monitoring activities in the three phases of the monitoring can be summarized in a table. For this purpose, the monitoring is categorized in the themes for the first five years, the first ten years and the ongoing fifteen-year period (see Table 1).

Table 1. Overview of the monitoring of the Sand Motor. The table presents the monitoring activities for the baseline, first five years, the first ten years, and the ongoing fifteen-year period in separate columns. White cells indicate that the monitoring activity was neither planned nor executed. Gray cells represent monitoring activities that were conceived but not carried out (this does not apply to the ongoing campaign).

Monitoring activities	before 2011	2011 - 2016	2017 - 2021	2022 - 2026
Meteo & hydrodynamics (S&V H)				
Wind (ND6)	• Regular wind speed measurements by the KNMI station Vlugtenburg	• Regular wind speed measurements by the KNMI station Vlugtenburg	• Regular wind speed measurements by the KNMI station Vlugtenburg	• Regular wind speed measurements by the KNMI station Vlugtenburg
Water levels (ND7)	• Regular water level measurements by Rijkswaterstaat	• Regular water level measurements by Rijkswaterstaat	• Regular water level measurements by Rijkswaterstaat	
Wave height (S&V H1)	• Based on a specific transformation matrix	• Temporary wave buoy • Based on data collected with an ARGUS video monitoring system		
Current velocities		• Based on data collected with an ARGUS video monitoring system		

Drifter measurements		• Drifter measurements at two locations *1x in 2012*	• Drifter measurements at two locations *1x in 2019*	
Groundwater		• Groundwater level tubes at the permanent quadrants (pq's)		
Morphology of the shoreface and beach (S&V M)				
Elevation of the hinterland (S&V M1)	• Digital Elevation Model of the Nederlands (AHN)	• Digital Elevation Model of the Nederlands (AHN)	• Digital Elevation Model of the Nederlands (AHN)	• Digital Elevation Model of the Nederlands (AHN)
Bathymetry of the beach (S&V M2 & M3)	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually* • Regular coastal profiles (JARKUS) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually* • Regular coastal profiles (JARKUS) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually* • Regular coastal profiles (JARKUS) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually* • Regular coastal profiles (JARKUS) by Rijkswaterstaat *annually*
Nourishment characteristics (S&V M4)	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data
Dredging and dumping data (S&V M5)	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data	• Rijkswaterstaat's *annual* reports and data
Sediment mapping (S&V M6)	• Medusa measurements *2010*			
Wave and breaker bar data (S&V M7)		• ARGUS video-based monitoring *continuously*	• ARGUS video-based monitoring *Intermittent periods*	
Bathymetry of the shoreface (S&V M8)		• Jet ski/quad monitoring 6x in first year after placement (aug 2011 till 2012) *5x in 2011, 11x in 2012, 6x in 2013, 5x in 2014, 6x in 2015, 5x in 2016, 2x in 2017*	• Jet ski/quad monitoring *3x in 2018, 2x in 2019 and 2x in 2020* • Seaward extended jet ski monitoring (-14 m NAP) *annually (2018, 2019, 2020 en 2021)* • Pre and post-storm jet ski/quad monitoring *1x in 2019*	• Jet ski/quad monitoring *biannual (2023, 2024, 2025)* • Seaward extended jet ski monitoring (-14 m NAP) *biennially (2023 & 2025)*
X-band radar (S&V M9)		• X-band radar at Kijkduin at Regional water authority of Delfland		
Sediment composition (S&V M10)		• Van Veen grab • Sediment sampling *simultaneously with benthos sampling*	• Sediment sampling *1x in 2019*	• Sediment sampling *1x in 2024*
Ecology of the shoreface and beach (S&V E)				
Benthos in the shoreface (S&V E1)	• Benthic dredge *1x in 2010*	• Benthic dredge *annually*	• Benthic dredge *biennially (2017, 2019)*	• Benthic dredge *1x in 2024*
Shellfish in the lagoon (S&V E1b/E5)			• Collect molluscs along the lagoon edge *monthly*	• Collect molluscs along the lagoon edge *monthly*
Benthos at the beach and intertidal area (S&V E2)		• Monitoring macrobenthos *2012, 2014, 2015, 2017, 2020*		
Juvenile fish and epibenthos (S&V E3)	• Historical data were digitized	• beam trawl survey *biannually (2012, 2013, 2015)*	beam trawl survey *biannually (2017, 2020)*	
Non-breeding seabirds at the beach (S&V E4)	• Bird populations were described using various existing data sources	• Three daily counts by bird groups *annually*	• Bird survey *monthly (2017-2020)*	

Marine mammals (S&V E5)		• Three daily counts by bird groups *annually* • Counting seals using ARGUS imagery *annually*		
Ecotope map (S&V E6)		• Production of ecotope map		
Nature / dunes (ND)				
Sand dynamics (ND1)		• Analyses of Aerial photos *annually*	• Analyses of Aerial photos *annually*	• Analyses of Aerial photos *annually*
Dynamics of the dunes (ND2)		• Analyses of Aerial photos *annually*	• Analyses of Aerial photos *annually*	• Analyses of Aerial photos *annually*
Height of the dunes (embryonal, foredunes and Solleveld) (ND3)	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually*	• Regular Laser altimetry (LiDAR) by Rijkswaterstaat *annually*
Sand spray into the dunes of Solleveld (ND4)		• Sand traps *continuously, emptied weekly*	• Sand traps *continuously, emptied biweekly (2017-2019)*	• Sand traps *continuously, emptied biweekly (2022, 2023, 2024)*
Salt spray into the dunes of Solleveld (ND5)		• Salt traps *continuously, emptied weekly*	• Salt traps *continuously, emptied biweekly (2017-2019)*	• Salt traps *continuously, emptied biweekly (2022, 2023, 2024)*
Vegetation / habitats in the dunes of Solleveld (ND8)		• Aerial photos *comparison 2015 with 2009*	• Habitat mapping *1x in 2019*	• Analysis of regular habitat mapping
Vegetation/habitats in wet-sensitive areas (ND9)		• Detailed description in permanent test plots (permanent quadrants, pq's) *1x in 2012, 1x in 2015*		
Detailed sampling of dune vegetation (ND10)		• Vegetation sampling at sand traps *annually*	• Vegetation sampling at sand traps *biennially (2018 & 2020)*	
Higher plants in the dunes Solleveld (ND11)		• Species inventory in early and late summer *biannually (2012, 2014, 2015)*	• Species inventory *biannually (2018 & 2020)*	
Butterflies (ND12)				
Sand lizard (ND13)				
Breeding birds in the dunes of Solleveld (ND14)		• Inventory of breeding birds by volunteers of the Vogelwerkgroep Solleveld *annually*		
Development of embryonal dunes (ND15)		• GPS measurements *Sand Motor (2013, 2014), large test areas (2014, 2015), small test areas (2015)*	• Drone LiDAR *1x in 2019, 1x in 2020* • Drone orthophoto *1x in 2019, 1x in 2020*	• Drone LiDAR *annually (2023-2026)* • Drone orthophoto *annually (2023-2026)*
Flora and vegetation at the beach (ND16)		• Mapping combined with analysis of aerial photos *annually (2013-2016)*		
Breeding birds at the beach (ND17)		• Survey of breeding birds (simultaneously with non-breeding birds) *monthly (2013-2016)*	• Survey of breeding birds (simultaneously with non-breeding birds) *monthly (2017-2020)*	

Appreciation and added value				
Recreational use	On-site usage and perception survey *(2010)*	On-site usage and perception survey *(2012 & 2015)*	• Counts using infrared sensors *(July 2019 – February 2020)* • On-site usage and perception survey *(2019)* • Online user and perception survey *(2019)* • Social media analysis • Interviews with stakeholders *(2019)*	
Economic value			• Interviews	
Societal functions			• Literature reviews • Interviews • Database research	

2.2.4 Data management

The monitoring program of the Sand Motor has created a unique dataset with highly detailed records of the hydrodynamics, bathymetry, sediment, and ecology (including benthic animals, birds, and vegetation). Data management was essential to store these measurements clearly and consistently, ensuring accessibility for both the project consortium and external users.

The adopted approach involves distinguishing between two stages of data: raw data and base data. Raw data are the actual measured parameters, with no quality control requirements. Base data, on the other hand, come with a quality mark indicating the quality checks performed. Additionally, metadata has been added to the base data.

A repository serves as the primary storage and exchange platform for raw and base data. It facilitates the exchange of raw data among the various partners within the consortium. The repository contains base data in the format in which it is provided, which can vary from Excel files to relational databases and CSV files. While these formats are generally suitable for exchange between partners and parcels within the project, there is often a need for data to be visualized, searched, and/or selected geographically or otherwise using various criteria. To facilitate this, a uniform storage system for the base data has been setup (i.e. THREDDS server at https://zandmotordata.nl/).

2.2.5 Lessons learned

The monitoring campaign conducted at the Sand Motor has provided invaluable insights into the dynamics of the area. Through meticulous data collection and analysis, we have been able to observe and document various environmental and ecological changes over the course of the project. This section aims to encapsulate the key lessons learned from the monitoring efforts, highlighting both the successes and challenges encountered.

In certain instances, baseline measurements for monitoring aspects were unavailable. Consequently, time and were allocated to conduct thorough baseline assessments. However, establishing accurate baseline measurements prior to construction can be challenging under time constraints, potentially compromising their quality. Additionally, without extended series of baseline measurements, long-term trends prior to construction cannot be identified. Ensuring comprehensive baseline data is crucial for the accuracy and reliability of subsequent monitoring activities and should ideally commence well in advance of any measures.

The overview in Table 1 shows a reduction of the monitoring over time from phase 1 to 3. The reasons for the change in the monitoring were related to three aspects:

- A focusing of the activities that are relevant for the long-term
- Monitoring that already achieved sufficient insights in the first phase(s)
- Monitoring which did not achieve useable results
- Gaps in socio-economic impact of the measure

The monitoring has focused on key aspects relevant for advocating future Sand Motor-type Nature-based Solutions, as well as meeting EIA and beach management requirements. This is illustrated by the bathymetric surveys, which have proven valuable both for knowledge acquisition and for addressing broad questions about the efficacy and impacts of the Sand Motor. Over time, the frequency of underwater surveys decreased as changes slowed, but the measurement area was extended seaward, and more detailed drone-based surveys were introduced to monitor the morphological changes of the (embryonal) dunes at the Sand Motor as they became more complex. Another continuous element in the monitoring-program was ecotope/habitat-based monitoring and analysis. Benthic surveys were continued as they were considered the best way to gain insights into the ecological development of the shoreface. In later years, additional orthophoto drone surveys were conducted to understand the ecological and morphological interactions at the dry beach of the Sand Motor.

Sufficient insights were gathered from various monitoring items. For example, wave and current measurements showed that numerical models could be trained with the data to provide adequate predictions for most applications, eliminating the need for extended measurement periods. Groundwater monitoring revealed that the extraction tubes at the beach effectively mitigate the full impact of the Sand Motor, removing the need for further investigation. Additionally, monitoring the impact of the Sand Motor on sand and salt spray in the existing dunes, and the subsequent effects on vegetation and succession, indicated that hardly any sand and salt end up in the dunes except during extreme weather events or storms. The effects on vegetation were not noticeable compared to natural development, which is already characterized by significant undesired succession of dune habitats. This reduced the incentive to further investigate the impacts on existing dunes in the third phase of the monitoring program. Drifter measurements also showed that the situation at the Sand Motor after the first 10 years is not significantly more dangerous than at adjacent beaches. Moreover, future morphological changes of the Sand Motor are expected to make it even more similar to the adjacent/reference section of the coast.

Monitoring that did not achieve the envisioned result was often still a valid method that had been used elsewhere but could not yield results in this context. This was especially true for ecological studies, which are often harder to carry out effectively. The following reasons can be provided:

1. Some monitoring could not obtain sufficient samples to provide explanatory power. This was the case for fish and mammal monitoring, where the number of species caught was too small, especially given the diversity of species that could have been present, and further detailed insight into their diets was needed.
2. The measurement area of the Sand Motor was relatively small for some parameters to be assessed. This was particularly true for monitoring mammals, (juvenile) fish, breeding birds, and rare plant species. Due to their low numbers in this area, it was challenging to find statistically reliable results. While measurements are still useful, they are more effective as part of larger projects that monitor broader sections of coast than just the NbS. Therefore, the focus shifted to ecotopes/habitats throughout the project phases.
3. Research was conducted on potential ecological impacts for which the baseline was not known for the considered region. This was particularly true for juvenile fish, which are not yet well understood for the Dutch coast, making it difficult. Similarly, bird counting could not be well compared to the baseline, so comparisons were made to other beaches instead.

4. Unexplainable temporal variability between years can be very significant for some ecological parameters. This applies not only to fish but also to benthic species in the lagoon and vegetation development on land. However, it has still been possible to use these data in relation to developments at other sites along the Holland coast.
5. The complexities of data analysis and large data streams make some monitoring difficult to handle. This is especially true for Radar data and ARGUS camera streams, which produce large amounts of data that need to be stored and can clog servers and connections. Additionally, skilled scientific personnel are needed to transform these data sources into valuable resources for understanding physical changes in bars, beach lines, wave conditions, and currents.
6. Given the substantial volume of data, it was occasionally infeasible to ascertain the origin, timestamp, geographical location, and the status of the data (raw or processed). Consequently, a comprehensive data management system has been implemented. This system incorporates a detailed management report, also known as a “metadata record,” for each dataset.
7. Errors in measurements due to inconsistencies in surveys or analyses. This was likely the case for early measurements of sediment composition, which yielded scattered results, while later measurements showed smoother patterns of changes in bed composition, indicating a learning curve throughout the monitoring program. Additionally, measurements by Medusa were not suitable for this environment, where relatively small changes between sandy sediments are to be found, as the methodology focuses on distinguishing between more diverse fine-grained material (silt/fines) and medium to coarse sandy sediments.
8. Equipment breakdowns, especially with the ARGUS cameras, which turned out to be very sensitive to the environment. The glass was blocked by debris or fog, cameras broke down, servers had issues, and internet connections were interrupted. Although these issues could be fixed, they impacted the availability of data, which is crucial as these were meant to be continuous data sources.

Conducting socio-economic studies on societal benefits and added values, such as those related to recreation, is very valuable. However, these studies were prioritized only after it became clear that there was a gap in addressing the research questions. The main reason for the lower priority of socio-economic studies is that the stakeholders for whom these studies are most relevant were less engaged with the Sand Motor project. The primary stakeholder (and funder) for coastal NbS is the Dutch Ministry of Public Works, which is primarily responsible for the morphological and ecological impacts. Therefore, these aspects need to be thoroughly understood before engaging in similar future sandy NbS projects along the Dutch coast.

In conclusion, the monitoring was technically appropriate, but local characteristics (such as size, species, and sediment) and practical issues made some of the monitoring less effective. This demonstrates that while some techniques are likely to work in any environment, others depend heavily on the specific system or context in which they are applied. Reliable techniques in any environment include bathymetric measurements (using boats, jetskis, quads, or drones), aerial/orthophotos, wave measurements, drifter measurements, physical sediment sample collection, benthic surveys, habitat mapping, foraging bird counts, and the collection of sand and salt in dunes. Socio-economic studies are also very relevant, but they require the involvement of the right stakeholders (e.g., municipalities and the Province) throughout the entire project duration.

2.3 Generalization of the Sand Motor experiences

The Sand Motor is an innovative coastal defence project specifically designed for the unique conditions of the Dutch coastline. Experiences with the Sand Motor have already been used to strengthen other large-scale NbS. An example is the design of the 'Hondsbossche Dunes' (Kroon et al., 2022), which is a large-scale sandy NbS of 30 million m^3 in the Netherlands with a double dune-row and beach in front of the existing sea dike. The Hondsbossche Duinen are, however, a managed NbS which requires ongoing sand nourishments to preserve its function for long-term coastal protection, while the Sand Motor was an experimental concept which that could freely deform after initially placing a large quantity of sand. In both cases the natural forces distribute the sediment along the coast over time, but frequent management of the NbS is only needed at the Hondsbossche Duinen. Even for very similar areas, the objectives and requirements can be different. Therefore, the Sand Motor concept and the monitoring cannot simply be copied and pasted to another location without thorough adaptation and consideration of local needs and conditions. Here are some key reasons why customization is crucial:

1. **Local Environmental Conditions**: Each coastal area has unique environmental factors such as tides, currents, sediment dynamics, and ecological systems. The monitoring methods that work for the Sand Motor in the Netherlands may not be suitable for another location without considering these specific conditions.
2. **Project Objectives**: The objectives of the Sand Motor project, such as coastal protection, recreation, and nature development, are tailored to the Dutch coastline. Other locations might have different priorities, requiring a customized monitoring approach to accurately assess and achieve those objectives.
3. **Community Needs and Expectations**: The success of monitoring efforts depends heavily on the involvement and support of the local community. Different communities have varying needs and expectations, which must be integrated into the monitoring design to ensure its relevance and effectiveness.
4. **Technical Requirements**: The technical aspects of monitoring, including the types of data collected, the frequency of measurements, and the tools used, need to be adapted to the specific conditions of each location. This requires detailed planning and possibly different methodologies to ensure accurate and meaningful data collection.

The next chapter will translate these findings into general guidelines for future sandy Nature-based Solutions (NbS).

3 Guidelines for monitoring

3.1 How to approach monitoring

Monitoring plans are relevant (and often mandatory) for large-scale multi-purpose sandy Nature-based Solutions, such as the Sand Motor. This is due to the nature of sandy NbS, as their performance depends on natural forces (e.g. wind, waves, and currents) that redistribute sand along the coast. The monitoring is aimed at providing information that is beneficial for achieving its objectives.

Building on the experiences gained from monitoring the Sand Motor, this chapter outlines an informed approach to creating a monitoring plan for general large-scale sandy Nature-based Solutions (NbS) for open wave-dominated coasts. The following steps are proposed for the setup of the monitoring plan:

- Deriving monitoring questions based on the objectives of the Nature-based Solution for supporting coastal functions (Section 3.2)
- Adjusting the monitoring needs based on contextual elements (Section 3.3)
- Inventorying potentially relevant monitoring activities based on the geomorphological features of the Nature-based Solution design (Section 3.4)

Section 3.5 provides a summarizing guideline for the monitoring plan development.

3.2 Objectives of the NbS steer the monitoring program

The objectives of the NbS in supporting coastal functions (e.g. safety, coastline preservation, recreation, dune nature, etc.) are the starting point for assessing the required monitoring parameters. The monitoring should demonstrate how effectively each aspect contributes to specific functions. A distinction is made between the following functions: Safety / Coastal Management, EIA / Nature Management, Recreation Management, Socioeconomics, and Research. In Table 2, the parameters are evaluated based on the functions they support.

Safety / Coastal preservation
The sandy NbS most-often aims to provide safety against flooding and prevent regional erosion by leveraging natural conditions to spread sediment along the coast. However, this reliance on natural conditions introduces variability in sediment supply over time, making the monitoring of sediment dynamics crucial. Key aspects to monitor include tracking the movement of sediment from the initial area to the adjacent coast and measuring how much sediment the adjacent coast receives. Additionally, identifying sediment supply to the dunes is important, as local dune growth impacts coastal safety. Detecting potential negative impacts on the adjacent coastline, such as local erosion or excessive accretion near infrastructure, is also necessary. Monitoring sediment movement towards channels or offshore is typically considered a negative impact, as it depletes the coastal system. Maintenance can be planned based on the evaluation of sediment dynamics in these areas.

Nature
The goal of the sandy NbS is to create diverse and dynamic (non-permanent) habitats that support various plant and animal species. Different regions impacted by the sandy NbS can experience positive or negative effects on nature values. For example, distinctions can be made between underwater shoreface ecology, beach/lagoon ecology and dune ecology. Both the ecotopes/habitats in these regions and the number of (rare) species encountered are relevant for assessing nature values, and this will vary by region. Additionally, a formal distinction should be made between nature properties that need to be monitored according to

EIA assessment requirements (which must be followed strictly) and the specific nature objectives set for the project.

Recreation
The sandy NbS can provide new areas for recreational activities such as walking, swimming, and water sports. This may require some monitoring and recreation management. Recreational activities should focus on ensuring swimmer safety, making sure that recreational activities are not interfering with other functions such as nature development. In some cases, it may be necessary to supervise the recreational activities by designating restricted areas.

Socio-economic
In this context, socioeconomic functions refer to the roles and activities that influence and are influenced by the economic and social aspects of a sandy NbS. For example, beach width serves a significant socioeconomic function. The new land created by the Sand Motor has been utilized for recreational activities, expanding the usable beach area and boosting local tourism, thereby generating economic benefits for nearby communities. Another example is the water table in the existing dunes, which directly influences groundwater levels and plays several critical socioeconomic functions.

Knowledge & Innovation
NbS, such as the Sand Motor at Delfland, can serve as living laboratories. These NbS provide scientists and engineers with opportunities to study coastal dynamics and develop sustainable coastal management techniques. While all monitoring parameters are relevant for research, Table 2 includes only those primarily serving a research function. It is noted that the innovative character of an NbS will be strongest when applied in a new coastal settings or when it has very different characteristics from earlier applied NbS.

Table 2. Parameters to monitor and their functions. Less useful parameters are highlighted in lighter green.

	Functions → Parameters↓	Safety / Coastal preservation	Nature	Recreation	Socio-economic	Knowledge & Innovation
SHOREFACE	Bathymetry					
	Waves					
	Currents / Drifters					
	Sediment composition					
	Benthos					
	Fish					
	Ecotope characterization					
(INTERTIDAL) BEACH	Elevation / width					
	Breaker bars / rips					
	Sediment composition					
	Marine mammals					
	Foraging birds					
	Benthos					
	Beach users					
EMBRYONAL DUNES	Morphology					
	Precipitation					
	Wind					
	(breeding) birds					
	Endangered species					
	Vegetation / habitat					
	Disturbances / hikers					
LAGOON	Water level					
	Water quality					
	Morphological changes					
	(migratory) birds					
	Benthos					
	Fish					
	Recreational users					
EXISTING DUNES	Morphology					
	Sand and salt spray					
	Vegetation / habitat					
	Endangered species					
	Water table					
	(breeding) birds					
WET DUNE VALLEY	Groundwater table					
	Vegetation / habitat					
	Soil and sediment					
	Morphological changes					
	Environmental conditions					
	Disturbances (management)					

3.3 Accounting for contextual elements

Monitoring should not only consider the intended objectives, but also be evaluated within the context of the area. This context includes various socio-economic and legislative factors relevant to the region:

- Presence of critical coastal protection infrastructure
- Nature protection status of the area
- Current recreational use of the coast
- Innovative character of the proposed Nature-based Solution

The presence of critical (hard) coastal protection infrastructure necessitates more intensive monitoring of bathymetric responses and hydraulic conditions to ensure safety is appropriately evaluated. This may involve additional surveys of local bathymetry to assess scour or measurements of wave and current conditions near the infrastructure. These measurements can be used to evaluate the impacts of Nature-based Solutions (NbS) on the safety of coastal protection. In some cases, the structure is part of the NbS (e.g., dyke-in-dune), which requires thorough monitoring to ensure minimal sediment coverage at the NbS.

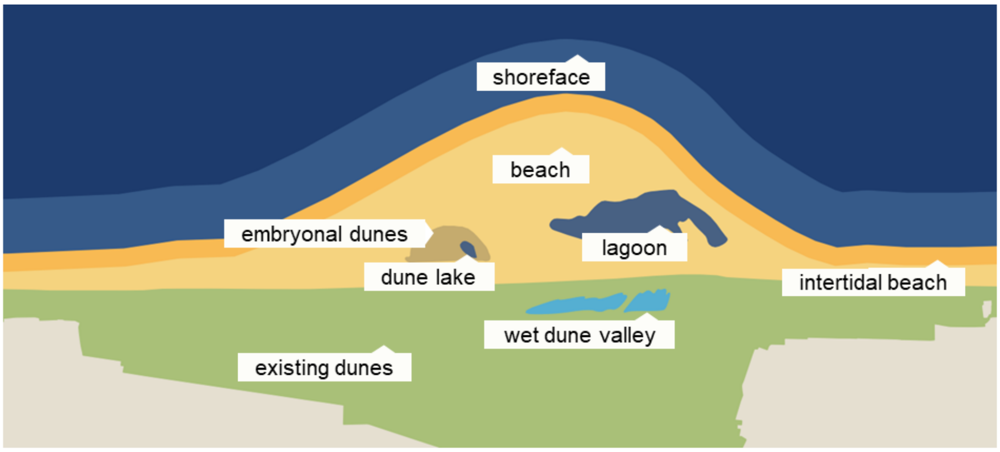
The status of the area where the Nature-based Solution is planned is highly relevant. A Natura-2000 protected area will require considerably more substantial monitoring as the habitats should be preserved. For large-scale sandy NbS projects, there will be strict objectives for the developed natural area of the ecotopes at the NbS and for its surroundings. In such cases, it is recommended to prioritize monitoring of benthic species, dune/beach vegetation, and the ecotope/habitat mapping. Additionally, foraging birds can be counted at regular (e.g. monthly to quarterly) intervals. If needed, additional surveys can be conducted to inventory the presence of rare plant species, breeding birds, mammals or fish, provided there is an indication that sufficient numbers of these species can be found.

The coast is typically used for various activities, mainly recreational. The intensity of beach use is crucial, as it determines whether swimmer safety protocols and monitoring should be implemented. The presence of dangerous currents can be identified through surveys with drifters at the NbS and a reference area during favourable weather conditions. Additionally, delineating nature and recreational areas is more relevant for more heavily used beaches, as they impact each other. Beach use and/or access to protected areas may need to be monitored. Other beach uses, such as outfalls from industry or fisheries, should also be considered.

The innovative nature of the proposed Nature-based Solution is highly relevant for monitoring. More extensive monitoring is required if: 1) the NbS is a new type with geomorphological features not yet implemented elsewhere, or 2) the area has different environmental characteristics from previously explored areas. Monitoring will naturally focus on the newer, innovative elements. For well-known measures in similar coastal environments, it may be possible to reduce monitoring and assess impacts upfront during the design phase or Environmental Impact Assessment (EIA). Detailed monitoring with more complex instruments, such as measurement devices on submerged rigs (ADCP, ADV, sediment sensors, ripple scanners) and camera/radar-based surveillance streams, may be considered and analysed by skilled analysts.

3.4 Monitoring in relation to sub-regions of the NbS

The objectives of the sandy NbS will determine its actual design, with geomorphological features being a crucial component. This section provides an overview of the monitoring that can be conducted to assess the efficacy of these physical attributes. The monitoring options presented here are for a conceptualized design of a sandy NbS for open, wave-dominated coasts, using a modified version of the Sand Motor design. Whether specific components of this concept are needed for a project will depend on the objectives that are to be achieved and characteristics of the area in question. The implementation of a Sand Motor like NbS can result in various subsystems, which depending on their characteristics need specific monitoring which is visualized in Figure 3.



SHOREFACE

PARAMETER	ACTIVITY
bathymetry	JARKUS, jet ski
waves	buoy
currents	ARGUS, drifters
sediment composition	Van Veen grab
benthos	benthic dredge
fish	beam trawl survey
ecotopes	ecotope map

(INTERTIDAL) BEACH

PARAMETER	ACTIVITY
elevation / width	JARKUS, LiDAR
breaker bars / rips	ARGUS
sediment composition	Medusa
grain size	sediment surveys
marine mammals	surveys
foraging birds	surveys
benthos	surveys
beach users	counts, surveys, cameras, social media posts

EMBRYONAL DUNES

PARAMETER	ACTIVITY
morphology	topographic surveys (GPS), LiDAR, photogrammetry, fixed-point photography
precipitation	rain gauges
wind	anemometers
(breeding) birds	surveys, aerial photos
endangered species	surveys
vegetation / habitat	surveys
disturbances / hikers	surveys, visitor counts, trail monitoring

LAGOON

PARAMETER	ACTIVITY
water level	sensors, tide gauges, imagery
water quality	water samples
morphological changes	aerial photos
(migratory) birds	surveys
benthos	Van Veen grab
fish	beam trawl survey
recreational users	counts, surveys, cameras, social media posts

EXISTING DUNES

PARAMETER	ACTIVITY
morphology	JARKUS, LiDAR, drones
sand- and salt spray	sand- and salt traps
vegetation / habitat	surveys
endangered species	surveys
water table	wells, piezometers, imagery, geophysical methods
breeding birds	counts

WET DUNE VALLEY

PARAMETER	ACTIVITY
water table	wells, piezometers, imagery, geophysical methods
vegetation / habitat	field surveys
soil and sediment	sediment sampling
morphological changes	aerial photos
environmental conditions	rainfall, temperature, wind, water quality
disturbances	surveys, imagery, trail cameras

Figure 3. Overview of potential monitoring activities for large-scale nourishments creating new habitats.

It is noted that not all subsystems that are presented in Figure 3 have to be present at each NbS. For instance, the Sand Motor between Kijkduin and Monster lacks a wet dune valley, but it has been added for completeness as it is an important part of for example the Hondsbossche Dunes. With the overview the monitoring can be tailored such that it contains the relevant monitoring related to the actual physical features of the envisioned NbS.

The following subsections describe the potential monitoring for each subsystem. In addition to the activities mentioned below, it is recommended to keep track of human interventions, such as sand nourishments, dredging and dumping, in the area. This does not necessitate setting up a monitoring campaign, which is why ‘human interventions’ are not included in the overview below. Another consideration that should be kept in mind is that local laws and regulations, such as the Environmental Impact Assessment, may mandate certain monitoring activities.

3.4.1 Shoreface

The underwater topography (bathymetry) can be mapped using jet skis equipped with echosounders, but also using the yearly Dutch bathymetric surveys (JARKUS).

Wave buoys are designed to monitoring the wave conditions, such as wave height, period and direction. By analysing ARGUS images, the temporal development of currents can be obtained. Drifters can be used for real time tracking of ocean surface currents.

To sample sediment in water environments the Van Veen grab sampler can be used. This instrument collects sediment samples from the seabed for analysis of grain size, organic content, and chemical composition.

Benthos on the shoreface can be monitored using a benthic dredge. This process involves lowering the dredge to the seabed, dragging it to collect sediment and benthic organisms, retrieving it, and then sorting and analysing the collected material. This method helps study the composition and abundance of benthic communities in the shoreface area. Similarly, fish on the shoreface can be monitored using a beam trawl survey. This involves lowering a beam trawl to the seabed, towing it to capture fish, retrieving the trawl, and then sorting and identifying the catch. This process helps assess fish populations and their distribution in the shoreface area.

Lastly an ecotope map helps to identify and monitor different habitats in the shoreface, assess biodiversity, plan conservation efforts, and evaluate environmental impacts.

3.4.2 (Intertidal) beach

JARKUS and LiDAR can be used to monitor the elevation and width of the (intertidal) beach. JARKUS data help track changes in beach elevation and shape. LiDAR (Light Detection and Ranging) is a remote sensing technique that involves emitting laser pulses from an aircraft to measure distances to the ground. This creates high-resolution topographic maps. JARKUS and LiDAR data can be combined for a comprehensive view of beach elevation changes. Moreover, the temporal changes in bed elevation of the intertidal beach can be continuously monitored through the analysis of ARGUS images. ARGUS images can also be used to monitor aeolian transport, as aeolian transport can be seen on camera as streamers and sand strips.

Medusa is a gamma-ray spectrometry system designed for non-invasive, real-time monitoring and mapping of sediment composition over large areas. However, experience has shown that this technique is not suitable for the Sand Motor. Measurements taken at Vlugtenburg revealed significant deviations in data for grain size, silt content, and seabed roughness when

compared to conventional methods, such as the Halpern Coulter Counter for grain size distribution. Therefore, it is advised not to use Medusa for monitoring the Sand Motor.
On the (intertidal) beach sediment surveys (i.e. collect samples) can be used to analyse grain size, helping monitor changes in sand, silt, and clay distribution over time.

Information on the presence of seals can be collected through surveys. Surveys can also be used to obtain information about the presence of foraging birds and beach benthos.

To monitor recreational use of the Sand Motor, the number of visitors can be tracked using automated counters or manual counts. Moreover, surveys can be conducted to gather information on visitor activities, preferences, and satisfaction. Using cameras or direct observations activities such as swimming and kite surfing can be monitored. Lastly, social media posts and geotagged photos can be analysed to understand popular activities and visitor experiences. Experience shows, however, that the monitoring of visitor activities on the Sand Motor is challenging due to privacy concerns. Strict privacy laws, the public nature of the area, and technological limitations make it difficult to track activities without infringing on individuals' privacy. Additionally, visitors' awareness of their privacy rights adds to the complexity.

3.4.3 Embryonal dunes

The height and shape (morphology) of embryonal dunes can be monitored using topographic surveys (using GPS), LiDAR (high-resolution laser mapping), photogrammetry (aerial or drone photography), and fixed-point photography (repeated photos from the same spot).

Monitoring wind and precipitation is crucial for understanding embryonal dune dynamics. Wind can be monitored using anemometers and wind vanes to measure wind speed and direction. Precipitation can be monitored using rain gauges and weather stations to track rainfall.

Breeding birds in embryonal dunes can be monitored through field surveys and remote sensing. Field surveys involve regular visits to identify and count bird species, nests, and chicks. Remote sensing uses imagery to locate nests and monitor bird populations without causing disturbance. Both methods are also effective for monitoring vegetation in these areas.

Lastly, surveys can effectively monitor human impact in embryonal dunes. Visitor counts can be conducted to track the number of visitors. Trail monitoring involves mapping and observing footpaths.

3.4.4 Lagoon

To monitor the water level in the lagoon, water level sensors can be installed to continuously measure the water level. Tide gauges are another option to track changes due to tidal influences. Additionally, satellite or drone imagery can be used to observe and measure water levels over time.

The water quality in the lagoon can be monitored by regularly collecting water samples to test for parameters such as pH, salinity, turbidity, and nutrient levels in a laboratory.

Aerial photos are a valuable tool for monitoring morphological changes in the lagoon over time.

The sediment in the lagoon can be monitored using the Van Veen grab sampler. This instrument collects sediment samples from the seabed for analysis of grain size, organic content, and chemical composition.

(Migratory) birds at the lagoon can be monitored through regular field surveys to count and identify species. Fish in the lagoon can be monitored using a beam trawl survey. This involves lowering a beam trawl to the bed, towing it to capture fish, retrieving the trawl, and then sorting and identifying the catch. This process helps assess fish populations and their distribution in the lagoon.

To monitor recreational use of the lagoon, the number of visitors can be tracked using automated counters or manual counts. Moreover, surveys can be conducted to gather information on visitor activities, preferences, and satisfaction. Using cameras or direct observations activities such as swimming and kite surfing can be monitored. Lastly, social media posts and geotagged photos can be analysed to understand popular activities and visitor experiences. Experience shows, however, that the monitoring of visitor activities on the Sand Motor is challenging due to privacy concerns. Strict privacy laws, the public nature of the area, and technological limitations make it difficult to track activities without infringing on individuals' privacy. Additionally, visitors' awareness of their privacy rights adds to the complexity.

3.4.5 Wet dune valley

Monitoring the water table in wet dune valleys involves several methods. Observation wells can be installed to measure groundwater levels directly. Piezometers can be used to measure the pressure of groundwater at specific depths. Remote sensing techniques, such as satellite or aerial imagery, help assess changes in vegetation and surface moisture, indicating water table levels. Geophysical methods, like electrical resistivity, map subsurface water distribution.

Vegetation can be effectively monitored using field surveys. This method involves researchers visiting specific sites to collect data on plant species, density, and health. By conducting regular surveys, changes in vegetation over time can be tracked, providing valuable insights into ecosystem health and the impacts of environmental changes.

Sediment sampling is used to monitor soil and sediment in wet dune valleys by analysing collected samples for composition and organic content. This helps track erosion, nutrient levels, and ecosystem health over time.

Aerial photos help detect morphological changes in wet dune valleys by comparing images over time, revealing shifts in vegetation, water levels, and landscape features.

Rainfall, temperature, and wind can be monitored to assess environmental conditions in wet dune valleys. The amount of rainfall over a specific period can be measured using rain gauges. Thermometers track temperature changes. Anemometers are used to measure wind speed and direction. The water quality can be monitored by regularly collecting water samples to test for parameters such as pH, salinity, turbidity, and nutrient levels in a laboratory.

There are several approaches to monitor human impact in wet dune valleys. Field surveys allow researchers to observe and record human activities and their effects on the environment. Remote sensing, using satellite and aerial imagery, helps detect changes in land use and vegetation. Trail cameras capture images of visitor activities and wildlife disturbances.

Environmental sensors measure changes in soil, water, and air quality due to human presence. Experience shows, however, that the monitoring of visitor activities on the Sand Motor is challenging due to privacy concerns. Strict privacy laws, the public nature of the area, and technological limitations make it difficult to track activities without infringing on individuals' privacy. Additionally, visitors' awareness of their privacy rights adds to the complexity.

3.4.6 Existing dunes

JARKUS, LiDAR, and drones are effective tools for monitoring the height and shape (morphology) of dunes at the Sand Motor. JARKUS provides detailed coastal profile data, while LiDAR uses laser scanning to create precise 3D models of the terrain. Drones offer high-resolution aerial imagery, allowing for frequent and flexible monitoring. Together, these technologies give a comprehensive view of dune dynamics and changes over time.

The effect of a sand motor on the influx of sand and salt into the existing dunes can be measured using sand- and salt traps. By analysing the amount and composition of sand and salt spray, dune succession is monitored and changes in dune formation and vegetation patterns are tracked.

Species surveys monitor vegetation in dunes by recording plant types and abundance. This helps track changes, identify invasive species, and assess ecosystem health.

Coastal expansion can lead to changes in the groundwater level of the existing dunes. Monitoring the water table in the dunes involves several methods. Observation wells can be installed to measure groundwater levels directly. Piezometers can be used to measure the pressure of groundwater at specific depths. Remote sensing techniques, such as satellite or aerial imagery, help assess changes in vegetation and surface moisture, indicating water table levels. Geophysical methods, like electrical resistivity, map subsurface water distribution.

Breeding birds in the dunes are monitored by conducting counts. This involves systematically surveying the area to record the number and species of birds nesting there. Regular counts help track population trends, breeding success, and the overall health of bird communities in the dunes.

3.5 Guideline for setting up the monitoring

In this section, a process guideline for setting up monitoring of sandy multi-purpose Nature-based Solutions (NbS) is provided. This will be achieved through four key questions that significantly influence the direction and content of the monitoring.

1. Is the Nature-based Solution a pilot concept or one that has already been applied before?

The innovative character of the NbS measures determines the intensity of monitoring required. Pilots featuring new types or implemented in new areas therefore need a more comprehensive package of monitoring activities. This not only includes the measurements focused on impact after construction, but also requires a good understanding of the natural system in the T0 situation. These T0 data will make it easier to detect any NbS induced changes in coastal trends. In contrast, the well-established concepts of NbS require fewer monitoring efforts, as they can rely on previous experience and understanding of their impacts. These already practically tested NbS will therefore primarily need assessments focused on their effects on the surrounding coast (i.e. mainly morphology and ecology).

PILOT NATURE-BASED SOLUTION	Requires more comprehensive monitoring to validate and refine the concept
ESTABLISHED NATURE-BASED SOLUTION	Requires less frequent and less detailed monitoring due to its proven track record

2. Which socio-economic and/or legislative factors apply to the Nature-based Solution?

The specific context plays a crucial role in determining the appropriate monitoring program. Factors such as the environment and the objectives of the monitoring influence the design and implementation of the monitoring plan. When (NbS are essential for safety, different aspects are prioritized compared to when NbS are implemented in nature protection areas or regions heavily used for recreation. For example, on the Holland Coast, the focus might be on recreation, whereas on the tail of a Wadden Island, nature could be more important. In this case, monitoring beach users is more relevant on the Holland Coast than on the tail of the island. Furthermore, the monitoring of Nature-based Solutions is highly dependent on the project's level of ambition. Higher ambition levels typically require more extensive and detailed monitoring. Additionally, it is important to be aware of legal monitoring requirements. If a certain activity is mandated by law, it must be included in the monitoring plan.

CRITICAL LINK FOR SAFETY	When the NbS is a critical link for safety, monitoring becomes more intensive and focused on ensuring its structural integrity and effectiveness. Key aspects: 1. Enhanced bathymetric surveys 2. Hydraulic condition monitoring 3. Safety evaluations
NATURE PROTECTION STATUS	If the NbS is implemented in a nature protection status region, it requires more detailed monitoring to preserve habitats and comply with environmental regulations. Key aspects: 1. Habitat preservation 2. Species monitoring 3. Environmental impact 4. Compliance with regulations
INTENSIVE RECREATIONAL USE	If the beach is heavily used for recreational activities, it is important to *monitor safety* by using *drifters* to identify dangerous currents
OTHER FUNCTIONS	..

3. Which of the following features are part of you Nature-based Solution design?
The performance and impacts of the physical features of the NbS that have changed compared to the natural situation require dedicated monitoring. An overview is provided below. The ambition level (I to III) for understanding the performance of each geomorphological component should form the basis for selecting the monitoring activities.

SHOREFACE	Monitoring the shoreface involves the following key activities: 1. Bathymetric change (single or multibeam) 2. Sediment composition 3. Benthic species 4. Wave/Current measurements	*Priority I to III* I II II III
(INTERTIDAL) BEACH	Monitoring of the intertidal beach primarily focuses on the morphology/hydrodynamics: 1. Bathymetric surveys 2. Monitor beach scarps 3. Evaluate beach safety with drifters (for rip-currents) 4. Activity of beach users	*Priority I to III* I III I II
EMBRYONAL DUNES	Monitoring embryonal dunes involves several key components: 1. Drone-Lidar surveys 2. Vegetation surveys / Aerial photography 3. (breeding) bird counts 4. Activity of beach users	*Priority I to III* I I III II
LAGOON	Monitoring a lagoon involves various aspects: 1. Bathymetric surveying 2. Measuring water quality 3. Bird counting 4. Benthic surveys 5. Monitoring entrance channel	*Priority I to III* I III II III II
(EXISTING) DUNES	Monitoring dunes involves several key aspects: 1. Bathymetry monitoring (LiDAR) 2. Sand and salt spray 3. Vegetation surveys / habitat mapping 4. Water table levels	*Priority I to III* I II II III
WET DUNE VALLEY	Monitoring wet dune valleys involves several key components: 1. Water table levels 2. Vegetation surveys / habitat mapping 3. Plant species identification 4. Infill with sediments / bathymetry 5. Bird counts	*Priority I to III* I I II III III
OTHER FEATURES	..	

4. What management measures can be implemented to support the objectives of the Nature-based Solution?
In some cases, management measures can support the objectives aimed to be achieved with a Nature-based Solution (NbS). For example, if certain trends or issues are identified during monitoring, informed management decisions can be made to address them. To effectively manage a Nature-based Solution, start by setting clear objectives. Conduct monitoring to gather data on the progress towards these objectives. Analyse the collected data to determine if the objectives are being achieved. Based on this evaluation, decide if any adjustments are needed. Implement these decisions through specific management actions. Finally, use the results of these actions to refine the objectives and monitoring strategies, ensuring a continuous improvement cycle (Figure 4).

Here are a few examples of management measures:
- If an NbS is designed to encourage (breeding) birds, fencing off the area might be considered. Additionally, the use of vehicles in the area should be prohibited, as they will deter the breeding birds. Dogs should be prohibited in the area, as they scare away birds

and sea mammals. Areas that cannot be reached by cats and other predators are also useful for beach breeding birds.

- If promoting recreation is the goal, cleaning the beach could be an effective management measure. Great care should, however, be taken when planning beach pavilions (and other structures at the beach). These pavilions require rather static coastal conditions (i.e. not too much erosion or accretion), while NbS are typically areas characterized by large shoreline dynamics, as these dynamics are beneficial for sediment redistribution and coastal nature development.
- When the ecology of the shoreface is considered, measures in relation to offshore activities (i.e. nourishing or fishery) may be implemented.
- If swimmer safety is a top priority, installing warning signs for unsafe swimming conditions would be appropriate. A water safety app could also be considered.
- If the aim is to promote the growth of the dunes at the NbS (e.g. for coastal safety), caution should be exercised with permit applications for beach pavilions, as the beach pavilions may block wind transport towards the dunes and the installation and local reshaping of the beaches may adversely affect local dune foot stability.

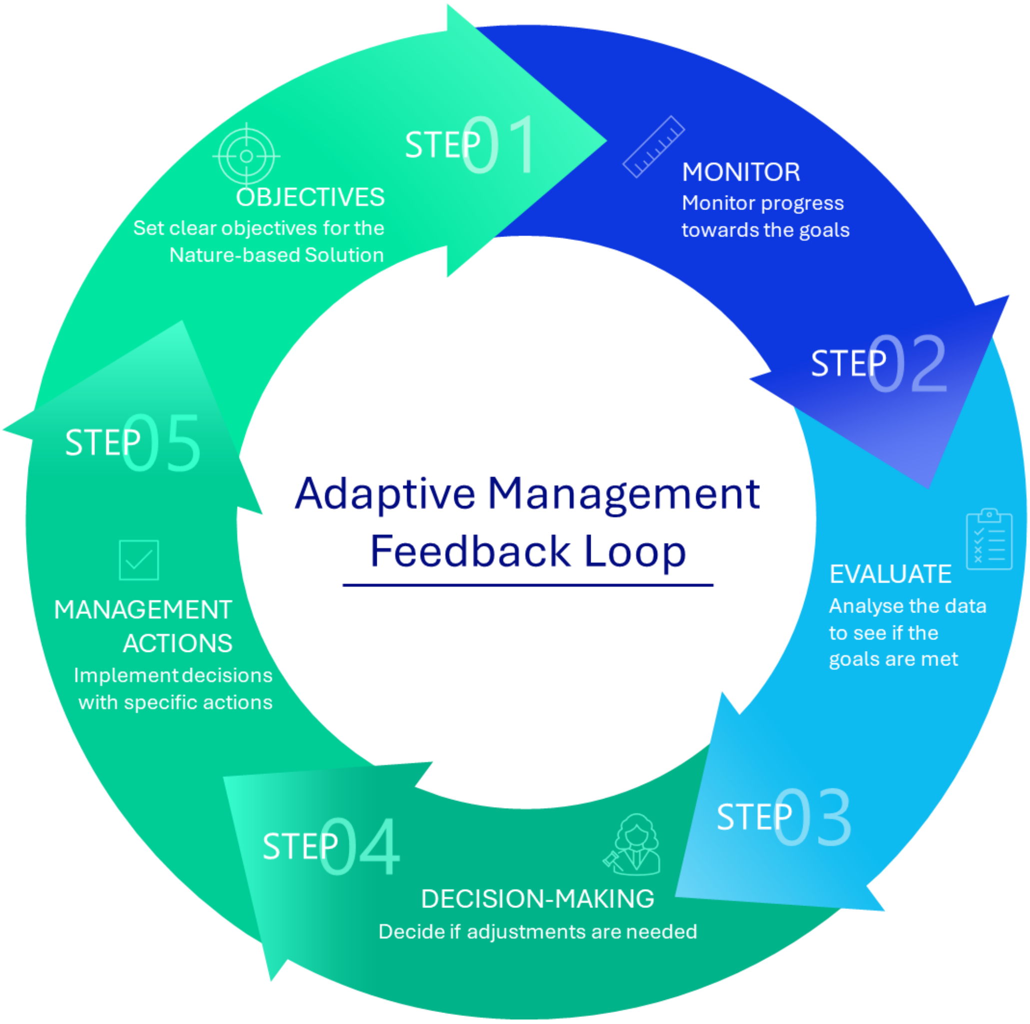


Figure 4. Adaptive management feedback loop for Nature-Based Solutions.

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