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Usability of the climate-resilient nature-based sand motor pilot, The Netherlands

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Abstract Coastline maintenance in the Netherlands, formally in place since 1990, aims at a sustainable preservation of coastal flood protection. Over 25 years annual assessments, comparing the actual coastline positions with the 1990 reference position of the coastline, have governed the execution of sand nourishments following an adaptive management method. This method involves yearly assessment of the coastline based on measurements, design and adoption of nourishment strategies and measures and execution of the nourishments. This management approach has enabled learning and introduction of innovations in coastline maintenance. For instance, in comparison to the early nineties, nourishments are now placed more on the foreshore and the yearly nourishment budget has doubled. The most recent innovation in coastline maintenance is the 'Sand Motor', a nature-based nourishment approach, which concentrates the regular nourishments in space and time, given that natural processes should redistribute the sediment over the wider coastal system. In contrast to regular nourishments, the Sand Motor combines flood protection with nature and recreational objectives and is much larger in dimensions. Five years after the construction of the Sand Motor we investigate its usability in this article. We present the results of first Sand Motor evaluation and draw conclusion on the adoption and usefulness of it for coastline management from the perspective of the adaptive management method used in coastline maintenance. Recent evaluation of the monitoring data shows that the large amount of sand used for the Sand Motor has a positive impact on coastal protection. Bridging between the Sand Motor pilot and daily nourishement practice is however not yet achieved.

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Introduction

Climate and human-induced changes will pose a significant threat of extensive and/or frequent flooding in deltaic, estuarine, and other low-lying coastal regions such as the Netherlands in the twenty-first century and beyond (Nicholls et al. 2011). Accordingly a paradigm shift, from conventional hard approaches towards a nature-based response, has been advocated to mitigate the increased flood risk (Stive et al. 2013). Whereas the traditional approach is formulated as fighting the forces of nature, a more recent approach of water and coastal management recognizes the multiple ecological forces that have to be accommodated and can help the processes of coastal protection. Moreover, this so-called "Building with Nature" or nature-based approach (De Vriend and Van Koningsveld 2012) does not only imply the use of methods from natural sciences, but also involves a range of different disciplines (governance, economics, etc...). This implies that water and coastal management have become interdisciplinary as well as transdisciplinary (Waterman 2008).

This paradigm shift is very prominent in Dutch coastline management, and it is within this context that the so-called Sand Motor concept was developed. In 2008, the Second Delta Committee delivered far-reaching recommendations on how to keep the Netherlands flood proof over the next century in the light of possible climate and human-induced changes (Delta commissie 2008). These recommendations supported the implementation in July 2011 of an innovative soft engineering intervention, known as the Sand Motor pilot and consisting of an unprecedented 20.8 million m^3 sand nourishment. This mega-nourishment was expected to be more efficient, economical, and environmentally friendly in the long term than traditional beach and shoreface nourishments. It serves multiple functions: the sand that is needed for flood protection and compensation of coastal erosion in the coming decades is nourished beforehand, giving even extra safety and land in the coming decades; the creation of temporary land adds values for leisure and nature; moreover the extra available sand is expected to enhance the natural dune formation. The Sand Motor was designed as a pilot and is not yet part of the regular coastline management approach. As such what is needed is an assessment of the usability of the sand engine for regular coastline management. In this article we investigate the usability of the Sand Motor pilot for regular coastline management based on the results of the first evaluation of the project.

In the next section we introduce Dutch coastline management, which functions according to an adaptive management cycle. In section 3 the Sand Motor pilot project is presented. The results of the first Sand Motor evaluation are discussed in Section 4. Section 5 provides a discussion on the results and usability of the Sand Motor pilot. In the last section we conclude on Sand Motor usability for coastline management.

Coastline maintenance policy in The Netherlands

In the Netherlands, the objective of coastline maintenance is the sustainable preservation of coastal flood defense and values and functions in the dune area (Ministerie van V&W 1990). The Ministry of Infrastructure and Environment (hereafter called Ministry of I&M) has a central position being responsible to execute the coastline maintenance policy and being responsible for water policy.

Decisions on nourishments in coastline management are governed by the requirement of keeping the coastline at its 1990 position, defined as the Basal Coast Line (BKL). Since 1990, the locations that require sand nourishments for maintaining the coastline have been determined based on systematic annual monitoring using transects and a precise methodology for assessment, that was unique in the world at the time. Already in the 1990's foreshore nourishment experiments were carried out (Hoekstra et al. 1994), which led to the decision to use foreshore nourishments as much as possible (Fig. 1). At the end of that decade the first experiments were carried out with channel slope nourishments which were successful. Furthermore, the total nourishment volume in 2001 increased to 12 million m^3 of sand per annum. This amount corresponds with the sand requirement for 'growing with the historic sea-level rise' (18 cm/century) of the coastal foundation. Part of the success of the nourishment strategy was a decrease in the amount of stretches where a nourishment was needed per year. This made it possible to increase (experimentally) the sand volume of individual nourishments. Nourishments with a volume up to 5 million m^3 were added several times. The next step in innovation was a mega-nourishments like the Sand Motor, with a gross sand volume of 21.5 million m^3 (including two smaller additional foreshore nourishments). The way of working in coastline maintenance is generally regarded as a success (Mulder et al. 2011; Van Koningsveld and Mulder 2004) and is characterized by on-going innovation (Oost et al. 2016). Nevertheless challenges are also identified, such as achieving coherence among different parts of the coast and also sustaining other functions in the coastal zone (Mulder et al. 2011).

Coastline maintenance can be described using a stepwise adaptive implementation method, which is being used for the implementation and management of climate-resilient coastal

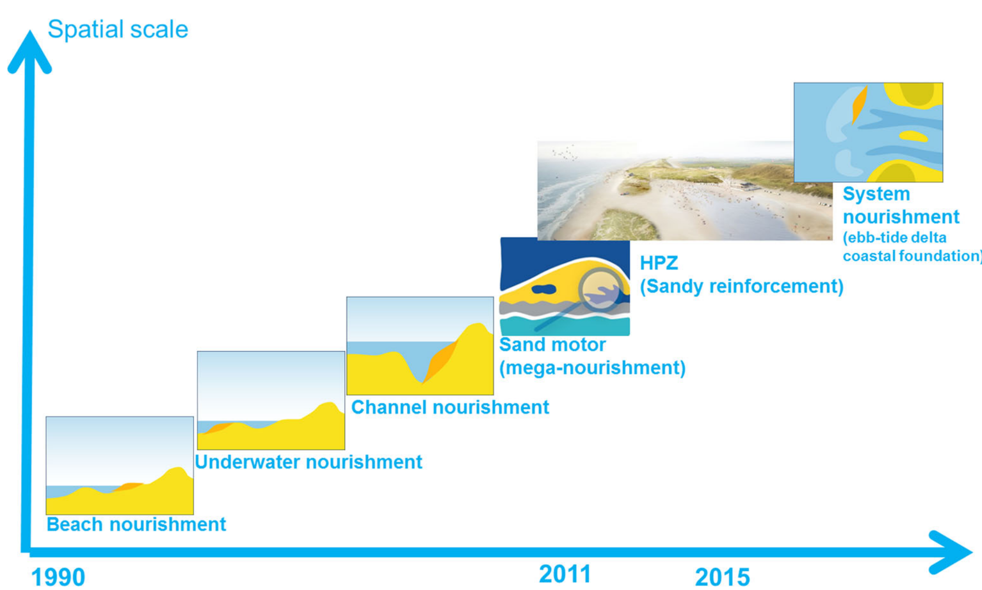

Fig. 1 On-going innovations in nourishment strategies in The Netherlands (Oost et al. 2016)

zone management plans (Fig. 2). The five steps that are used are: (i) issue identification (socio-economic and physical assessment, definition of strategic and operational objectives), (ii) strategic planning (identification of climate-resilient measures), (iii) formal adoption (mainstreaming), (iv) adaptation implementation (anticipation of new challenges and potential conflicts) and (v) adaptive management (monitoring, evaluation and possible adjustment of the strategy).

In this article we assess the usability of the Sand Motor for coastline maintenance. As argued before, learning plays a crucial role in the adaptive approach employed in coastline maintenance learning. New insights and techniques have led to adjustments of the coastline maintenance approach. The Sand Motor is organised as a pilot, which has two important consequences. First, the pilot is organised outside routine coastline management. Second, the pilot has been subject to intensive monitoring and research. Pilots are useful instruments for the exploration and evaluation of innovative measures, but at the same time the crucial challenge of pilot is the actual upscaling of the pilot into daily management routines (Vreugdenhil et al. 2010). Therefore usability is a critical feature of the Sand Motor pilot. In this article, we assess how the lessons learned are usable for coastline maintenance.

Sand motor pilot

In the process towards the Sand Motor realisation, the Ministry of I&M and the province of Zuid-Holland (PZH) joined forces. PZH was leading the planning phase, initiated design workshops and commissioned (research) reports to consultants. RWS, as part of the Ministry of I&M, was leading

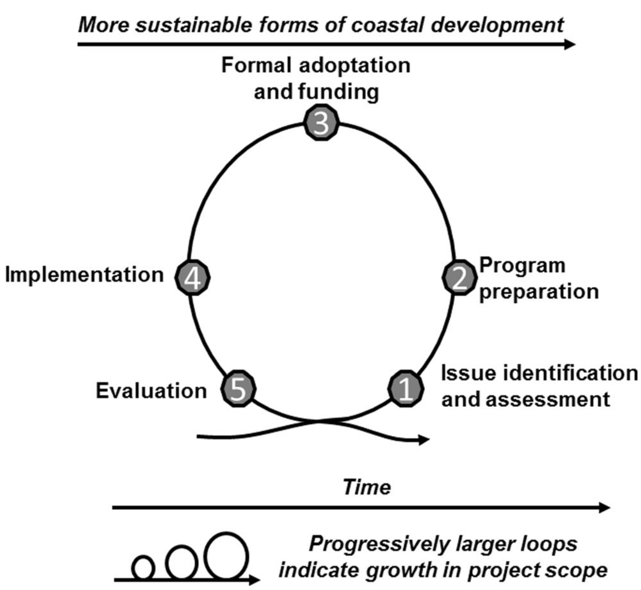

Fig. 2 Five-step methodology for adaptive implementation of climate-resilient integrated coastal zone management plans (adapted from USAID 2009)

during the project execution (2010–2011). In the organization of the project many different actors were involved, including the Ministries of I&M, Housing, Spatial Planning and the Environment (VROM) and Agriculture, Nature and Food Safety (LNV), PZH, three municipalities, the water board and an environmental NGO. In addition, knowledge parties were part of the organization: Delft University of Technology, Deltares, the innovation programme Ecoshape and consultancy companies. During the course of the project, some of the orginal actors left wheras new ones became involved. For instance, drinking water company DUNEA was included in the project team when effects of the Sand Motor on groundwater appeared important.

The decision-making process was guided by project objectives, legislation and policy objectives. The project objectives express the intention to combine flood protection, nature, recreation and innovation. Prevailing legislation and policy objectives for both flood protection and nature did not specify the design, but functioned as boundary conditions: coastline (BKL) erosion and negative impacts on the bordering Natura2000 areas were to be prevented. The environmental impact assessment (EIA) procedure formed the basis for acquiring the necessary permits.

Planning and design

An ambition agreement was signed by the main stakeholders and marked the start of the planning and design phase. For PZH, recreational green and visibility of the Sand Motor were key interests. The Ministry of I&M valued knowledge development for long-term coastline maintenance, being moreover the executor of the project and the manager of the coastline (Janssen et al. 2014).

Four different designs for the Sand Motor were developed: (1) an elongated underwater nourishment along the Delft coast, (2) a delta-shaped peninsula (hook-south), (3) a streamlined spit (hook-north) and (4) a small island (PZH 2010; see also Fig. 3). The main themes for the assessment were coastal safety, nature, recreation, other functions and innovations and feasibility. The dynamic character of the Sand Motor – the continuously changing form over the longer period – was one of the bigger challenges of the assessment, requiring a state-of-the-art morphodynamic modelling approach to be set-up.

More specifically, numerical modelling provided an optimum design for the Sand Motor given the functionality criteria. An important design criterium was life expectancy and the amount and duration of its contribution to coastal protection and filling the sand demand up to -20 m below MSL. One refers to Appendix for details on the morphodynamic modelling in support to the selection of the final design.

From the four designs, the hook-north was selected as the preferred option, but its seaward expansion was slightly decreased. The underwater nourishment was not a viable

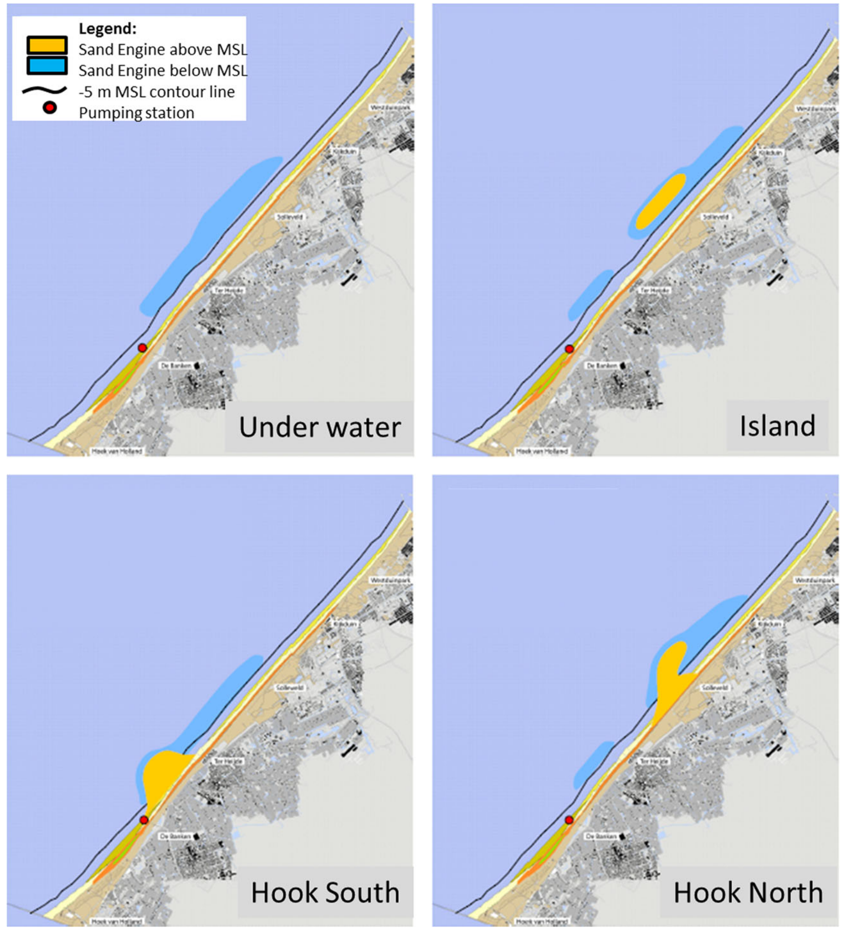

Fig. 3 Overview of four design alternatives. Clockwise, starting upper left corner: underwater, island, hook-south and hook-north (PZH 2010)

solution as it did not yield any recreational options (important criterium for PZH). The island was considered too risky for recreation. The hook-south could have negative impact on existing recreation and interfered with a local pumping station. The hook-north was the most desirable option as it would not disturb any on-going activities, yield to some recreational facilities and be both visible and accessible.

During the planning phase, there was discussion on the cost-effectiveness with regard to coastal protection. Calculations based on the expected maintenance volumes without a Sand Motor and the average nourishment price per m^3, showed that the Sand Motor was at that time a cost-efficient idea for coastal maintenance irrespective of other functions (Oost et al. 2016).

Implementation

The implementation process of the Sand Motor evolved smoothly: after signing the ambition agreement in April 2008, it took about 3.5 years, without any significant delays, until the Sand Motor was fully realized. The official construction of the the Sand Motor was on 17 January 2011 in Ter Heijde and the final batch of sediment for the Sand Motor was brought in on 29 June. At the north and south side one foreshore nourishment each was placed. The northern foreshore nourishment (the smaller of the two) was completed at almost the same time. The southern foreshore nourishment was completed in November 2011. Dredging vessels picked up the sand ten kilometres offshore and pumped it into the project area. The total net quantity was 18.7 million m^3. The quantities for the southern and northern foreshore nourishment operations were 1.7 and 0.4 million m^3 respectively. The initial nourishment spans the coastal system over a 2.4 km stretch and extends up to 1 km offshore. The large hook-shaped peninsula is attached to the shoreline by a base of ~1 km and includes a small (7.5 ha) lake (Fig. 4). The curved tip of the peninsula provides shelter from waves, and the shallow artificial lagoon formed behind the tip is expected to offer habitats for flatfish and other organisms. The bulk of sand is expected to disperse along the coastline and dunes in a natural manner and disappear over a period of about 20 years (Stive et al. 2013; Taal et al. 2016).

Results: after five years sand motor

A comprehensive Monitoring and Evaluation Plan (MEP) was drafted during the preparations for the Sand Motor (DHV

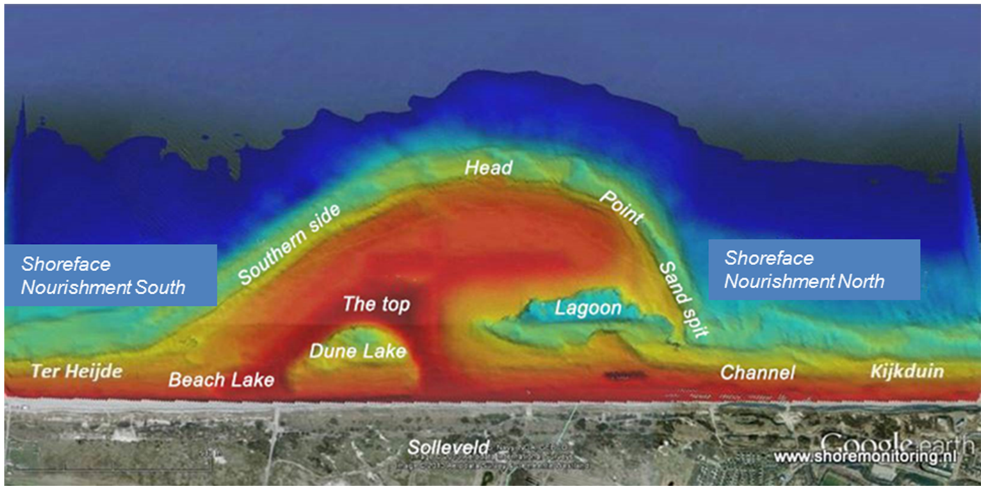

Fig. 4 The Sand Motor with names of the different parts (source: Shore Monitoring and Research 2013)

2010) and was further elaborated in 2011 to produce an implementation programme (Tonnon et al. 2011). The research program was extended by additional funding of several sources. The abstract objectives and management objectives were broken down in specific and concrete evaluation questions and hypotheses. Corresponding monitoring programmes were drawn up for weather, sea conditions and hydrodynamics, morphology of beach and nearshore, ecology of beach and nearshore, nature and dunes, leisure and groundwater. The main findings from the evaluation of the monitoring data collected from 2011 to 2016 have been reported in Taal et al. (2016), which is linked to the other reports about the Sand Motor that were produced in 2015 or in early 2016 (Oost et al. 2016; De Boer et al. 2015).

Evaluation of physical development

All results depend ultimately on the morphological development. Since the completion of the Sand Motor in summer 2011, the topographic and bathymetric evolution of the Sand Motor is monitored on a monthly basis via a purpose-built Jetski mounted with RTK-GPS and an echo sounder. This is in addition to the regular yearly bathymetric coastal profile measurements, which are intensified to four per year. Furthermore, two ARGUS stations have been installed overviewing the Sand Motor and its adjacent beaches (Santinelli et al. 2013), and regular aerial photographs are collected to visualize the development.

De Schipper et al. (2016) provides a detailed analysis of the evolution of the Sand Motor beach nourishment and of the effects of waves on its morphological evolution. The morphological developments were generally according to expectations, although they occurred in a greater pace then expected in the first years. Since the construction, sand has spread along the coast leading to accretion to the North and South of the Sand Motor (Fig. 5), as foreseen in the modelling stage. The shape has changed in the first two years after construction from curved peninsula into a more triangular shape with concave arch shapes in the coastline. After four years, the sand body protrudes 260 m less into the sea on average (with a maximum of approximately 350 m at the Head of the Sand Motor). At the same time, the stretch of coast that has been extended seaward has become 2.2 km longer. After four years, only 5% of the sand volume that was added for the Sand Motor pilot project has disappeared from the monitoring area. Based on this, the conclusion can be drawn that the lifespan of the Sand Motor is longer than the originally expected 20 years. The volume of sand used for constructing the Sand Motor is sufficient to nourish the coastal foundation for almost 20 years. Dune development occurred at a slower rate than expected.

Fig. 5 Left: aerial photo taken in July 2011; right: aerial photo from May 2015. Source: www.dezandmotor.nl

Evaluation of the ecological development

Taal et al. (2016) shows that the variety in environments and therefore the potential for ecological values by constructing the Sand Motor pilot has increased. The sand spit, the highly dynamic stretch of coast with shoals, the lagoon and dune lake are landscape elements that are not or are hardly ever present along the Holland coast. Due to the shape of the Sand Motor pilot, the variety of habitats for benthos, birds and fish has increased along the coast as a whole.

In particular, the sheltered, shallow part of the lagoon and the surrounding borders are attractive areas for benthos and birds. In 2015, the ecological values in the deep part of the lagoon were lower than previously as a result of the limited exchange of water with the North Sea and the reduced oxygen levels. This restricted the function for juvenile fish. With regard to benthos, in 2015, 4 years after the Sand Motor was constructed, there was no evident shift towards longer living benthos species compared with the regular sand nourishments. It remains to be seen whether longer living species can develop in the dynamic environment of the Delfland coast. The high sand transport rates and corresponding sorting of the sand possibly hinder the successful establishment of aging benthos species.

At less than 1 ha, the newly formed dune acreage is still modest. These dunes are mainly situated on the eastern edge of the Sand Motor pilot, against the foot of the early applied coastal reinforcement and to the southwest of the Sand Motor pilot. Most of the dune formation takes place on the outer slope of the coast reinforcement, whereby less ecologically valuable marram grass was replaced by the 'white dunes' habitat. The new dunes are highly dynamic and therefore scenically attractive.

The number of plant species and habitats has been increasing, but as a whole, the Sand Motor pilot was scarcely vegetated. This concerns typical sand couch grass and marram vegetation, habitat types that the Netherlands is under an international obligation to preserve. The Red Listed species *sea holly*, even grows in some areas. Between 2011 and 2015, 40 bird species were observed on and around the Sand Motor on a more than incidental basis. To date, no birds have been breeding on the Sand Motor.

Not much can be said of what the Sand Motor means for marine mammals like the seal due to the small number of official counts available. However, there is some evidence to suggest that attempts of birds to breed and establish seal resting spots have failed due to disturbances by man (Taal et al. 2016).

Evaluation of leisure activities

The Sand Motor pilot temporarily adds an extra area to the Holland coasts, offering possibilities for recreation that were previously unavailable. The developments that have taken place show that the current design of the Sand Motor pilot has resulted in a landscape that is otherwise absent along the Holland coast and offers space for extensive recreation. The visitors are becoming more familiar with the different aspects of the Sand Motor. During and immediately after the construction of the Sand Motor, various stakeholders examined the Sand Motor in a critical to moderately critical light (Berendsen et al. 2005). A still increasing bigger group is now positive about the Sand Motor and the project has gained wider support.

The initial recreational study following the construction of the Sand Motor shows that the four most important recreation groups are seaside visitors, dog walkers, walkers and (kite, wave and wind) surfers. Together with the various outdoor activities like horse-riding, mountain bike riding, fishing and jogging, this creates more forms of recreation on the beach between Ter Heijde and Kijkduin than was the case prior to the construction of the Sand Motor (Taal et al. 2016). However, the accessibility and connection to the Sand Motor pilot is mediocre. DHV and HNS landschapsarchitecten (2010) and De Boer et al. (2015) suggest that a better connection could possibly lead to more recreation.

Evaluation of contribution to knowledge and innovation

One of the three objectives of the Sand Motor was 'knowledge and innovation'. Both within the MEP as in academic setting interdisciplinary research questions and themes were used (e.g. nature-based design/ecosystem services/blue and green). Key research themes for the 15 PhD- and 3 postdoc-researchers are the development of the beach and surf zone morphology, the sand transport rate by wind, the ecology of the shallow sea and surf zone and the ecological impacts of mega-nourishments. The Sand Motor pilot has drawn a lot of international interest, being innovative and due to the extreme seaward extending shape and dynamic nature. The pilot offers the business community and knowledge institutions opportunities. The nature-based principle is a spearhead of the marine Dutch engineering business sector, together with the the knowledge sector and government. The Sand Motor allows all these sectors to demonstrate that marine engineering and ecology can go hand in hand. Already at several places in the world Sand Motor-type solutions are under investigation (Sweden, United Kingdom, Belgium, United States, Mexico).

Discussion on the usability of the sand motor

Lessons for usability looking at morphological development

The Sand Motor concept ties in logically with the nourishment strategy and the tradition of innovation and knowledge development that is characteristic of the Dutch coastal policy. It is a tool that can be deployed for coastal management. Naturally, the construction of a Sand Motor for coastal maintenance requires a great deal of sand, which may have consequences for the nourishment programme of 12 million m^3 sand annually. The option of using a Sand Motor within the regular nourishment programme therefore implies saving sand over a number of years, or use other sources of funding for sand.

The interim evaluation (Taal et al. 2016) shows that the Sand Motor pilot has made a positive initial contribution to the coastal protection by a seaward shift of the erosion point, thus attributing to coastal primary safety. The development in recent years shows that by dispersing sand parallel to the shore an increasingly greater part of the stretch of coast has a higher level of safety thanks to the seaward expansion. All in all, it can be established that the protection-level of the primary flood defence is heightened in the sphere of influence of the Sand Motor and the lifespan of the coastal reinforcement is extended. During construction, the coastline has shifted seaward at the site of the Sand Motor, while this also happened later on in the accretion areas. With the Sand Motor in Delfland, the expected positive effect on dune formation (and thus gaining extra safety from flooding) were not met up to 2015. This is partly due to the morphological adjustment of the coastal reinforcement constructed in 2010, causing the foot of the dunes to recede. Also, the chosen design with a lagoon and a dune lake which catch part of the sand blowing towards the dunes and beach cleaning activities hinder dune formation. On top of that new extensive dune formation occurs once in a few decennia along stretches of broad Dutch coastal plains (De Groot et al. 2015; Oost et al. 2016).

The usability study (Oost et al. 2016) gives as general learning points for new Sand Motor designs:

1) The actual design of the Sand Motor would have been very different if the objective would have been only 'increased safety'. In that case a more conventional and more streamlined shape would most likely have been sufficient, needing relatively the least amount of sand (Bruens 2007);
2) The costs effectiveness for coastal protection turned out to be lower then originally estimated, due to smaller sediment demands and new lower cost prices of sand. However, it is concluded that new Sand Motors can be built cost efficient when life expectancy is long enough and the sand price is low enough. Both can be calculated with morphodynamic, respectively economic models (Oost et al. 2016).
3) The creation of a lagoon has led to the growth of a sand spit and a meandering channel, as expected (Deltares 2009; DHV and HNS landschapsarchitecten 2010). Such a channel can have negative impact on the primary sea defence dunes like those caused by meandering channels on Ameland (Israel and Oost 2001). In Delfland, probably thanks to the presence of stone breakwaters, this was not the case.

Lessons for usability looking at ecology

Taal et al. (2016) shows that the variety in environments and therefore the potential for ecological values by constructing the Sand Motor pilot has increased.

Also for nature some general learning points can be formulated:

1) The development of the dunes, the dune lake and the lagoon greatly depends on variable and incidental factors, such as the weather. One example of this is the intermittent water exchange of the lagoon with the North Sea because of growth in the channel and the sudden recovery after a new channel has broken through.
2) Dunes develop successfully on beach plains, with a sufficient beach width of 200 m or more (DHV et al. 2007; Keijsers et al. 2014), a random process that occurs once in 1 to 2 decades (de Groot et al. 2015). It is quite possible that after years in which there has been little development, dunes will form rapidly and establish vegetation, due, for instance, to the beach becoming higher (Van Tooren and Krol 2005). It still remains to be seen whether this also will be the case with the Sand Motor. Whether a more conventional, streamlined mega-nourishment of 200 m or wider transverse to the coast would lead to new dune formation on the beach sooner will perhaps become clear as the Sand Motor 'spreads out' further along the Delfland coast.
3) It takes a long time before decisive statements can be made on the success of the Sand Motor pilot for nature development. Natural developments go slow and more time is needed for monitoring.
4) The management of the Sand Motor pilot is not primarily focused on the development of specific ecological values. For instance, cleaning the beach hinders dune formation. Also, the decision was made not to apply zoning by means of allocating resting, breeding and growing zones. The leisure activities disturb birds and sea mammals.

Lessons for usability looking at leisure

For recreation some general learning points can be abstracted:

1) The design of the current Sand Motor pilot appears to be less usable for locations where mass recreation is present or has to be developed, because the distance to the

waterline can be extremely far. The dynamic development is probably also too strong. If people do not want to change the character of a seaside resort but do want to apply the Sand Motor concept, a more elongated and restricted temporary expansion of the beach could be pursued.

2) A meandering channel has developed (as already anticipated; DHV and HNS landschapsarchitecten 2010) that connects the lagoon to the North Sea. Since the currents in such a channel can be strong, this poses a risk for recreational users, particularly when they become closed in at high tide and find themselves seaward from the channel. When the lagoon (for the most part) becomes cut off from the North Sea, water can no longer be refreshed and decay processes are likely to occur. On the other hand, a lagoon is very appealing to kite surfers. Risks have been kept under control in the case of the Sand Motor pilot. Whether a lagoon with tidal channel formation is desirable should be taken into consideration for a future Sand Motor.
3) Currents at the tip of the Sand Motor pilot flow very fast. This is a point that requires continuous attention. The far protruding tip has also resulted in an extremely wide sandy beach. Both developments diminish the usability for swimmers at the location.

Conclusions

New insights into the sediment balance of the Netherlands coastal system and recommendations in 2008 by the Second Delta Committee on climate change adaptation have recently led to the application of the nature-based philosophy to the Dutch coastal protection strategy. A mega scale nourishment of 21.5 million m^3 has been implemented at the Holland coast between Hook of Holland and The Hague in 2011. The idea is to concentrate regular coastline maintenance nourishments in space and time, given that natural processes will distribute the sediment over the wider coastal system utilizing ecosystem services.

In the design phase of the Sand Motor pilot, morphodynamic model calculations of various alternatives have contributed to decision making by estimating morphological effects and changes in important indicators, especially coastline maintenance and dune development. Considering the objectives of the Sand Motor to create long term safety conditions in combination with extra space for nature and recreation, the Environmental Impact Assessment (EIA) has decided on the hook-north design as the preferred alternative.

Regarding the effect of a Sand Motor on maintenance of the coastline, model estimates indicate that additional nourishments will be necessary adjacent to the Sand Motor. At the present rate of sea level rise, the coastal foundation of Delfland would require approximately 5.5 million m^3 per 5 years in order to grow with the sea level. A Sand Motor of about 20 million m^3 is therefore expected to contribute to the maintenance of the coastal foundation for a period of around 20 years.

The recent evaluation of the monitoring data collected from 2011 to 2016 (Taal et al. 2016) shows that the large amount of sand used for the Sand Motor has a positive impact on coastal protection, particularly in the vicinity of the Sand Motor. Although the contours of the Sand Motor have changed drastically since 2011, the observed developments have matched the expectations. Waves and currents transport sand from the Sand Motor to the north-east and south-west, where the beach has become much broader. Over a period of 4 years, the sand body became approximately 260 m narrower and 2.2 km longer. An amount of sand equal to 95% of the deposited sand is still present in the monitoring area after 4 years. The fact that the Sand Motor pilot generally functions as expected, while the lagoon and dune formation are functioning somewhat below expectations, implies that, on average, the innovation can already be deemed a success for coastal management innovation.

In addition, the Sand Motor has resulted in the creation of an extra area on the coast with opportunities for nature and leisure that were not available previously on the coast between Hook of Holland and Den Helder. The shape of the Sand Motor has led to an increase in the number of different habitats for benthos, birds and fish. In particular, the sheltered, shallow part of the lagoon and the edges around it are attractive areas for benthos and birds. It is not yet possible to make decisive statements on the ultimate success of the Sand Motor pilot for nature development. The Sand Motor has not been in place long enough for that (Taal et al. 2016). The Sand Motor pilot shows that it offers rest, space, nature and vastness and is particularly usable for extensive recreation.

The Sand Motor pilot has proven to be extremely usable from the point of view of knowledge development and innovation. Future Sand Motors are also expected to contribute to this and help further the Sand Motor concept internationally.

Acknowledgments The Building with Nature program 2008–2012 received funding from the Dutch Ministry of Transport, Public Works and Water Management, the municipality of Dordrecht, EFRO as well as the participants to the Foundation EcoShape. Field data was collected by the Dutch Ministry of Infrastructure and the Environment (Rijkswaterstaat) with the support of the Province of South-Holland, the European Fund for Regional Development EFRO and EcoShape Building with Nature.

Appendix: morphodynamic modelling in support to design

A depth-average morphodynamic Delft3D model (Lesser et al. 2004) of the South Holland coast has been set up for the evaluation of the morphological effects of the 4 designs, selected in the exploratory phase, on a time scale of 20–50 years. The morphodynamic approach comprises the use of the SWAN wave module (Holthuijsen et al. 1993) and of TRANSPOR2004 (Van Rijn 2007a, b, c) as sediment transport model; see Mulder and Tonnon (2010) for more details.

The flow domain is about 26 km long and 15 km wide, while the wave domain stretches further to the south and north to minimize boundary effects (see Fig. 6a). The maximum grid resolution in both domains in the area of interest is 80 m alongshore by 20 m cross-shore. The flow model applies Neumann boundary conditions (Roelvink and Walstra 2004) at both lateral boundaries, water levels at the north-western (sea) boundary and a discharge at the entrance of the Nieuwe Waterweg entrance channel to the Port of Rotterdam in the South West. Boundary conditions were derived from the validated large-scale ZUNO-FIJN North Sea model (Roelvink et al. 2001) and the ZEEDELTA v8 model (Zijlema 2003) (Fig. 6b). Offshore wave data from wave buoys Euro Platform and Meetpost Noordwijk was classified into 10 wave height bins between 0.25 m and 5.25 m and in 12 directional bins between 195 °N and 15 °N.

Tidal and wave boundary data have been schematized to enable the long-term net total transports. A so-called representative, morphological tide was derived using the method of Latteux (1995). A harmonic analysis using 16 components was performed over this period to result in a cyclic tidal signal. A representative morphological wave climate of 10 conditions was derived using the so-called "Opti" method, based on a statistical description of the performance of wave conditions with respect to the net and gross transport fields. The parallel-online approach developed by Roelvink (2006), has been used to simultaneously compute the weighted bed changes resulting from these 10 representative wave conditions. The uncalibrated net transport rates thus computed by the model, were found to be in the order of the net transport rates reported by Van Rijn (1997).

Estimates of dune development were required given that both long term safety and nature development are main objectives of the pilot Sand Motor. A dedicated dune module has been developed and implemented following De Vriend and Roelvink (1989) to account for intertidal, beach and Aeolian processes. An empirical relation, considering that the migration rate of the dune foot is function of the difference between the actual beach width and its equilibrium width (i.e. approximately 125 m based on historic data of the Dutch coast), was implemented in the dune module to simulate horizontal migration of the dune foot.

A schematized nourishment program was implemented in the model for investigating the effect of the Sand Motor on the regular maintenance effort of the adjacent BKL and the coastal foundation. The schematization consists of a nourishment of the erosive stretches with a frequency of 5 years. The shoreface nourishments were placed at a depth of −5 m, with a volume equal to twice the calculated loss in the MCL-zone (i.e. Momentary Coast Line zone between +3 and −4.4 m; see e.g. Van Koningsveld and Mulder 2004). Sea level rise was assumed to be constant and equal to the present rate of 2 mm/year. As a consequence, the total nourishment volume to maintain the coastal foundation of the coastal cell of Delfland (between Hook of Holland and The Hague), in the reference case without a Sand Motor, is 1.1 million m^3 per year. The implemented nourishment program was found to maintain the coastline at its position in the reference simulation with realistic nourishment volumes.

The different designs for the Sand Motor were evaluated based on computed wave fields, flow velocity fields, sediment

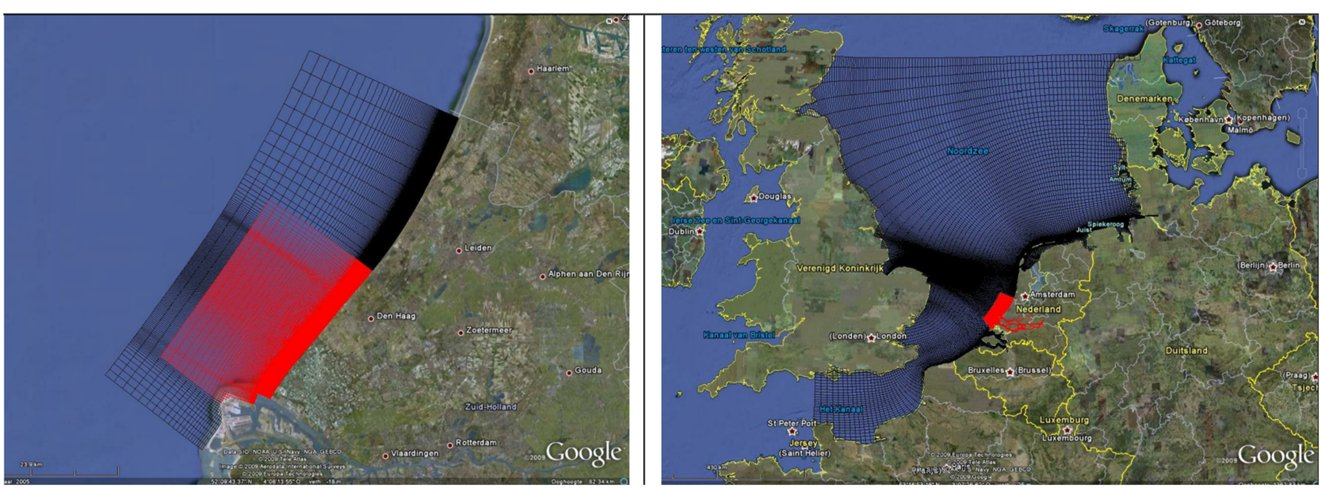

Fig. 6 Left: model domains for flow (red) and wave model (black). Right: ZUNO-FIJN domain (black) and ZEEDELTA v8 domain (red). (From Mulder and Tonnon 2010)

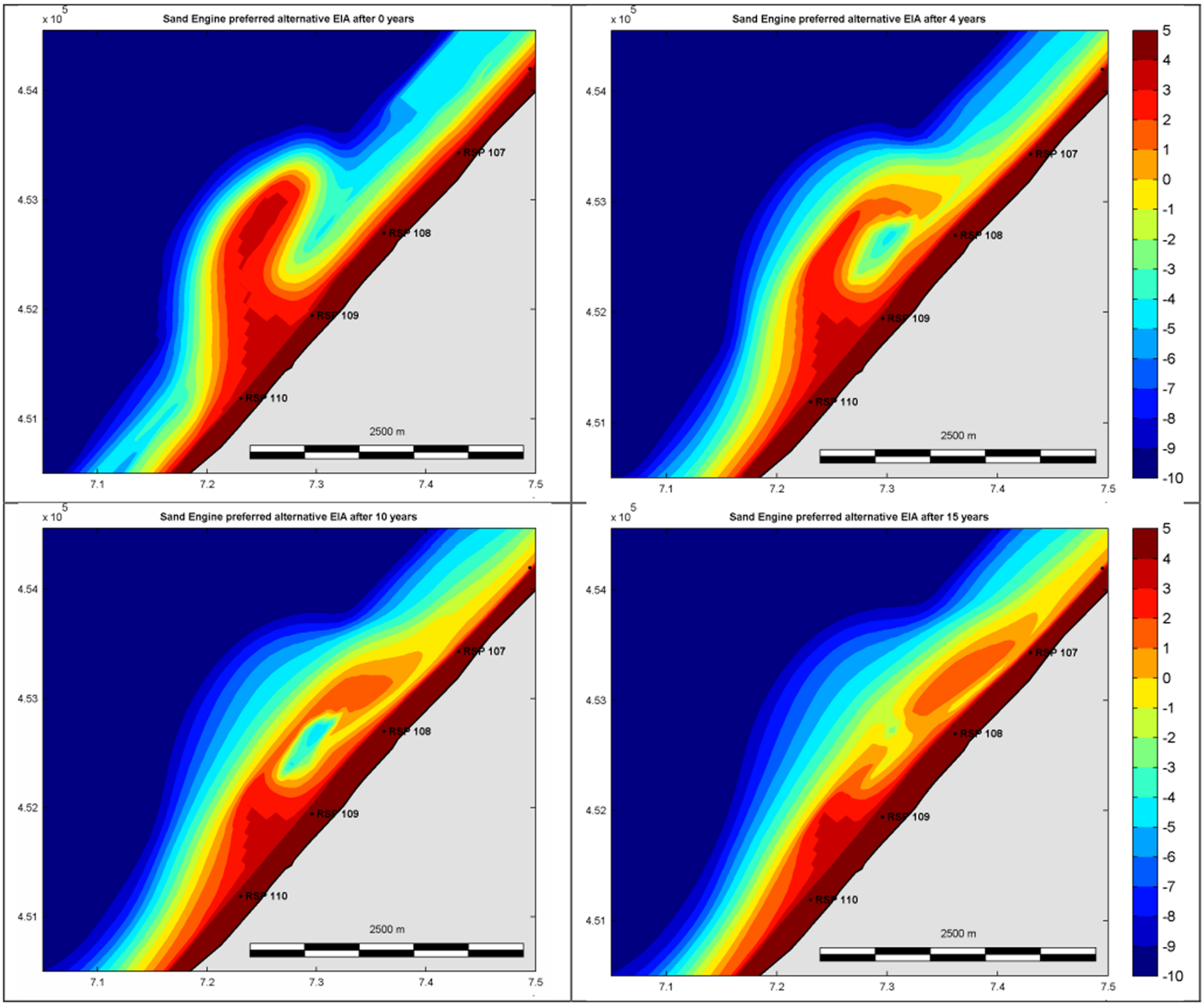

Fig. 7 Computed morphological development of hook-shaped design with the initial bathymetry in the upper left panel, the bathymetries after 5, 10 and 15 years in the upper right, lower left and lower right panel respectively. (From Mulder and Tonnon 2010)

transport fields, morphological evolution, sedimentation/ erosion patterns, erosion of adjacent coastlines, necessary nourishment volumes and evolution of dune area. Results were compared to the reference simulation without a Sand Motor (Mulder and Tonnon 2010).

Sensitivity computations were carried out in which forcing conditions, model parameters and numerical settings were varied. For instance, an uncertainty of about 30% in magnitude and time was estimated for the erosion volume of the MCL zone.

Figure 7 shows the computed morphological development of the hook-shaped alternative after 5, 10 and 15 years. The top of the hook is elongated in northern direction and pushed onshore, creating a shallow, sheltered area that is filled and emptied through a small channel. In time the elongated sand body is breached and a shallow plain is formed, ultimately

Table 1 Estimates of increase in dune area (ha)

Alternative	After 1 year	After 5 years	After 10 years	After 15 years	After 20 years
Reference	0.2	2.6	6.2	10.8	17.0
Hook-north	1.6	6.8	13.7	22.7	32.9
Hook-south	1.2	7.0	16.6	28.0	38.8
Shoreface	0.3	3.5	11.0	20.1	30.6

Table 2 Estimates of nourishment volumes to guarantee maintenance of the coastline and of the coastal foundation (millions m3)

Alternative	After 5 yrs	After 10 yrs	After 15 yrs	After 20 yrs.	Total maintenance	Sand Motor vol.
Reference	5.5	5.9	5.3	6	22.6	-
Hook-north	2.0	1.5	1.2	0.9	5.6	20
Hook-south	1.3	0.6	0.7	0.7	3.3	20
Shoreface	1.4	1.1	0.8	0.9	4.2	20

leading to wide beaches. Sand is spread in both northern and southern directions.

The horizontal migration of the dune foot has been estimated, resulting in estimates of the change in total dune area for the Delfland coast. The results for three different designs compared to a reference situation are shown in Table 1. All alternatives implied 5 yearly nourishments with as purpose the maintenance of the coastline in case of the different Sand Motor designs, and the maintenance of both the coastline and the coastal foundation in case of the reference situation. The nourishments were schematised according to the approach mentioned above.

The Sand Motor designs create approximately twice as much new dune area in comparison to the reference situation without a Sand Motor. The dune creation by the three designs hardly shows significant differences. As the dune growth contributes to a stronger dune, the model results suggest that a Sand Motor represents an effective method to enhance long term safety against flooding.

The effect of a Sand Motor on the nourishment effort is presented in Table 2. Firstly, for the reference situation, the schematized nourishment scheme implies a 5 yearly nourishment of an amount of 5.5 million m^3 equal to the volume enabling the coastal foundation to grow with the sea level (with rise of 2 mm/year). When considering the placement of the Sand Motor, the 5 yearly nourishment volumes range from 1.3–2.0 million m^3 after 5 years to 0.7–0.9 million m^3 after 20 years. After 20 years, the total sand input by each of the Sand Motor alternatives is still but slightly larger than in the reference case: 23.3–25.6 million m^3 compared to 22.6. In case of a Sand Motor design of 20 million m^3 and for a seal level rise of 2 mm/year, additional nourishments will be required to maintain the coastal foundation after a period of approximately 22–25 years.

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