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A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine

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ABSTRACT

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A boldly innovative soft engineering intervention, comprising an unprecedented 21.5 Mm^3 sand nourishment known as the Sand Engine, has recently been implemented in the Netherlands. The Sand Engine nourishment is a pilot project to test the efficacy of local mega-nourishments as a counter measure for the anticipated enhanced coastal recession in the 21st century. The proposed concept, a single mega-nourishment, is expected to be more efficient, economical, and environmentally friendly in the long term than traditional beach and shoreface nourishments presently being used to negate coastal recession. Preliminary numerical model results indicate that this local nourishment will result in the widening of the beach along a 10 to 20 km stretch of the coastline and a beach area gain of 200 ha over a 20-year period. First observations show indeed a redistribution of the sand feeding the adjacent coasts, roughly 40% toward the south and 60% toward the north. While the jury is still out on this globally unique intervention, if proven successful, it may well become a global generic solution for combating sea-level-rise driven coastal recession on open coasts.

ADDITIONAL INDEX WORDS: *Nourishment techniques, coastal erosion, coastal protection, concentrated feeder nourishment.*

INTRODUCTION

Climate-change-induced and human-induced changes in environmental forcing will pose a significant threat of extensive and/or frequent flooding in deltaic, estuarine, and other low-lying coastal regions in the 21st century and beyond (Gratiot *et al.*, 2008; Houghton *et al.*, 2010; Nicholls *et al.*, 2007; Nicholls *et al.*, 2011; Ranasinghe *et al.*, 2012). As these regions arguably host the world's most productive urban, industrial, and agricultural metropolises, a paradigm shift in thinking and concrete responses is required to effectively mitigate their increased flood risk. This is what we will address in this contribution, expecting a true debate on the merits of a paradigm shift as presented here.

A recent Dutch State Committee (also known as the New or 2nd Delta Committee, following the 1953 flooding induced 1st Delta Committee) delivered far-reaching recommendations on how to keep the Netherlands flood proof over the next century and even longer in the light of possible climate change and human-induced change leading to accelerated relative sea-level rise (SLR) and increasing river discharges.

In line with their recommendations, the Netherlands have recently adopted a boldly innovative intervention approach named "The Sand Engine" (*Zand Motor*, www.zandmotor.nl). The Sand Engine is a very large, locally concentrated sand nourishment of 21.5 Mm^3, aiming to provide safety against flooding in combination with new spatial values. Such an approach could provide useful elements for other low-lying

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Figure 1. Aerial photograph of the Sand Engine after completion (September 2011) looking southward. Picture courtesy of Rijkswaterstaat/Joop van Houdt.

areas around the globe. The Sand Engine nourishment initially spans the coastal system over a 2.4 km stretch and extends up to 1 km offshore following a specific shape (Figure 1). The main expectation is that the Sand Engine will stabilize the coastline at its present position and feed the adjacent coastal sections over an extended length of time (20 years) and space (order of 10 km). Here, for the first time, we describe the thinking behind this world-first climate-change adaptation strategy and present numerical model predictions of its long-term evolution along with the observed natural evolution of the Sand Engine during its first year of existence. Implementing far-reaching interventions like the Sand Engine in the modern reflective society, however, requires a paradigm shift, which is necessary to implement such interventions in light of possibly accelerated climate change.

PARADIGM SHIFT

The paradigm shift in the approach of water and coastal management that is observable during the last decades represents a major challenge for the coming century. Where in the past the challenge was formulated to "fight" the forces of nature, today's approach recognizes many issues other than protection against flooding, especially the multiple ecological forces that have to be accommodated and can help the processes of protection. While this issue has received attention in the western world for about two decades, it is increasingly also being recognized by the nonwestern world, notably the growth countries. This implies that water and coastal management have become interdisciplinary as well as transdisciplinary (Waterman, 2008). Some of the issues and dilemmas involved in this challenge are illustrated by the following examples.

In a critical evaluation of the morphological, ecological, and socio-economic effects of a large number of human interventions in the Dutch Delta project (following the 1953 flood disaster), Saeijs *et al*. (2004) advocate working with nature in any future flood protection project in estuarine and coastal environments. A number of their recommendations exemplify this: "(1) If there is still is a choice, leave untouched estuaries and deltas alone. (2) If there is already a history of human intervention, try to adopt the most flexible approaches to safety and development. (3) Reversible and local measures within the limits of the natural processes are preferable" (p.7).

The recommendations of Saeijs *et al*. (2004) regarding working with nature are in line with today's policy (*cf*. the coastal policy to maintain the coastline with soft solutions

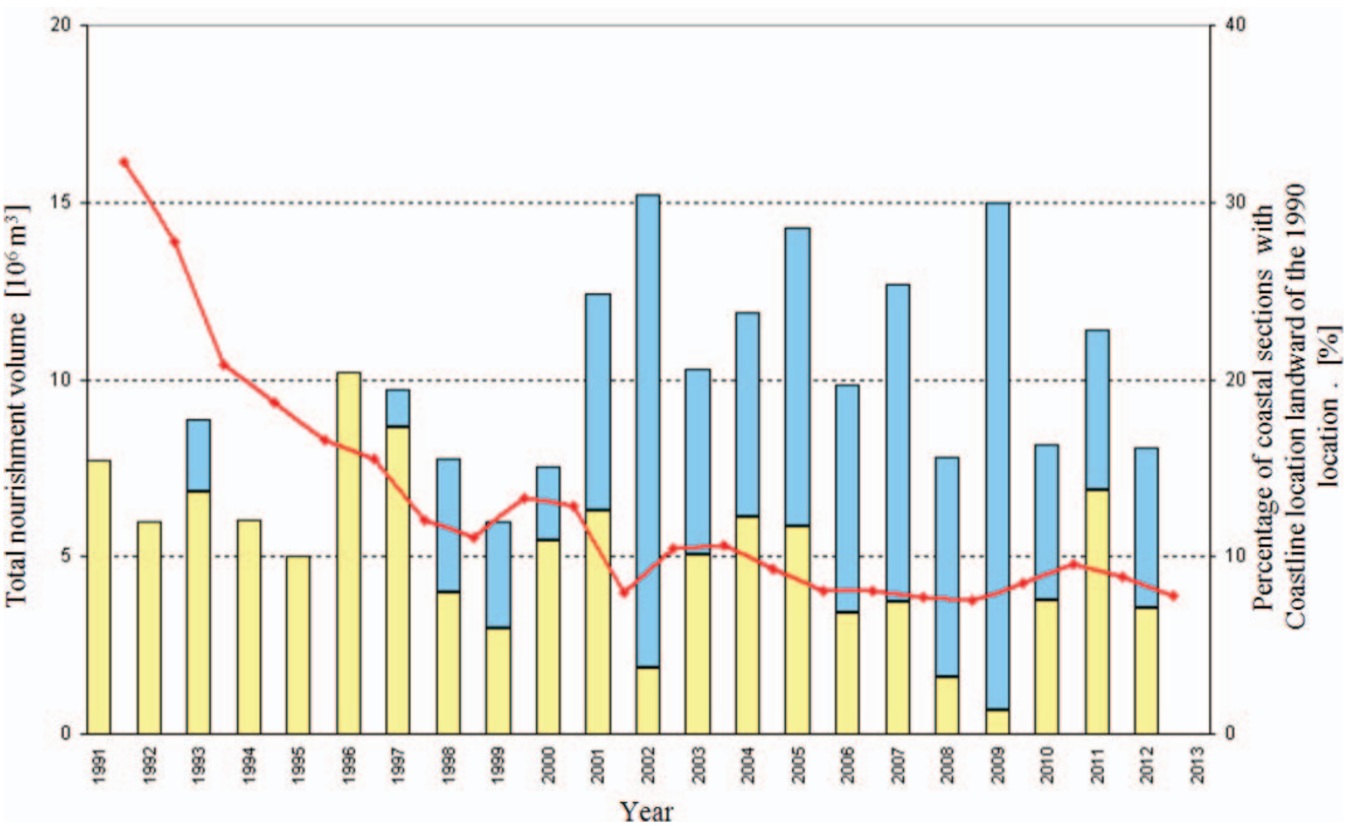

Figure 2. Annual nourishment volumes at the Dutch coast since 1990. Yellow bars indicate annual volume in beach and dune nourishments, blue bars indicate shoreface nourishments. Red line shows the percentage of coastal profiles where the coastline position was landward of the desired state of 1990. The 21.5 Mm^3 Sand Engine project in 2011 is not included in these statistics (Source: Rijkswaterstaat nourishment statistics dated from 2013).

rather than hard [concrete] barriers). Nevertheless, implementing the recommendations appears to be complex. For instance, sea revetments may hamper natural processes, but from an economic viewpoint, it is generally not justifiable to remove revetments, let alone from a socio-emotional perspective. The complexity may be further illustrated by the conclusions of Jonkman, Stive, and Vrijling (2005) drawing lessons for the Dutch from the New Orleans flood disaster of 2005. These authors observe a tendency in Dutch policy to head towards the U.S. model of mitigating the consequences instead of strengthening the flood defences, while prevention of floods is receiving gradually and relatively less attention. Then, arguing that (1) the protection standards are over 40 years old and have not evolved with the increase of economic value of the protected area over time, and that (2) the societal risks associated with flood defences on a national scale are larger than in other domains of the Dutch society (Ten Brinke and Bannink, 2004), these authors concluded that a fundamental debate on the required safety levels of Dutch flood defences is necessary. This will undoubtedly lead to the need for stronger flood defences, challenging the proponents of soft solutions to fulfil safety requirements as well as incorporating ecological and societal aspects in an evaluation of a design.

Coping with these dilemmas is an example of the major challenge for the near future. It illustrates that "building with nature" (De Vriend and Van Koningsveld, 2012) not only simply implies the use of methods from natural sciences but also involves a range of different disciplines and asks for a transdisciplinary approach. This paradigm shift is very prominent in Dutch coastal zone management, and it is within this context that the Sand Engine concept was developed.

THE DUTCH SITUATION

The Netherlands, where one-third of the land mass is below mean sea level (MSL), is one delta that is faced with potentially massive socio-economic consequences attributable to relative SLR (*i.e*. eustatic SLR and other regional and local effects). It is a densely populated country (494 people/km^2) with a 350 km long coastline, and, at present, nine million residents (out of a total of 16.7 million) live in the coastal areas, vast regions at an elevation below MSL. Roughly 65% of the country's gross national product—about €400 billion—is generated within this coastal region.

The Dutch coastal zone, similar to many other low-lying coasts, is, however, also vulnerable. These coasts have suffered from structural erosion over the last centuries because of the

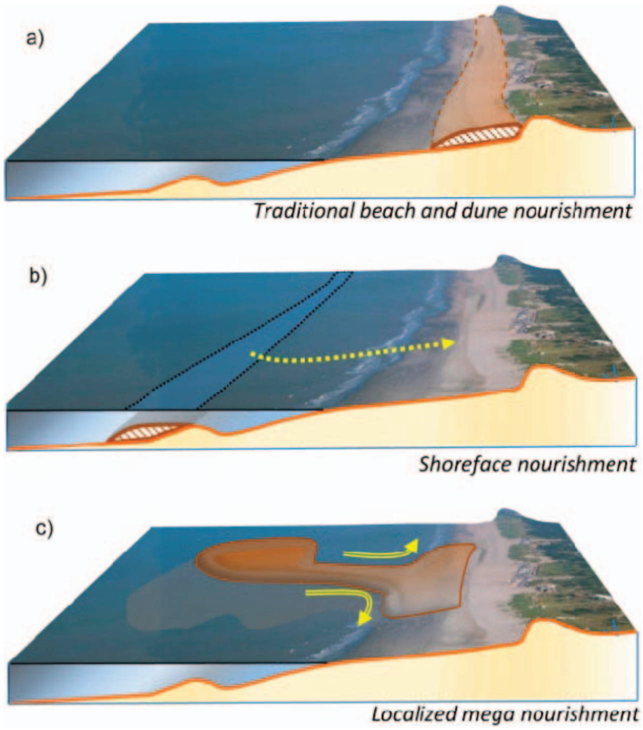

Figure 3. Conceptual diagram displaying different nourishment strategies. (a) Traditional beach and dune nourishments, used frequently from the 1970s onward, place sand directly on the beach and dunes. (b) Shoreface nourishments, initiated in the 1990s, make use of natural marine processes to redistribute the sand that is placed under water in the cross-shore direction and gradually create a wider coastal defense over time. (c) Concentrated mega-nourishments, as introduced here, exploit both marine and aeolian processes, to redistribute the sand both in cross and alongshore directions.

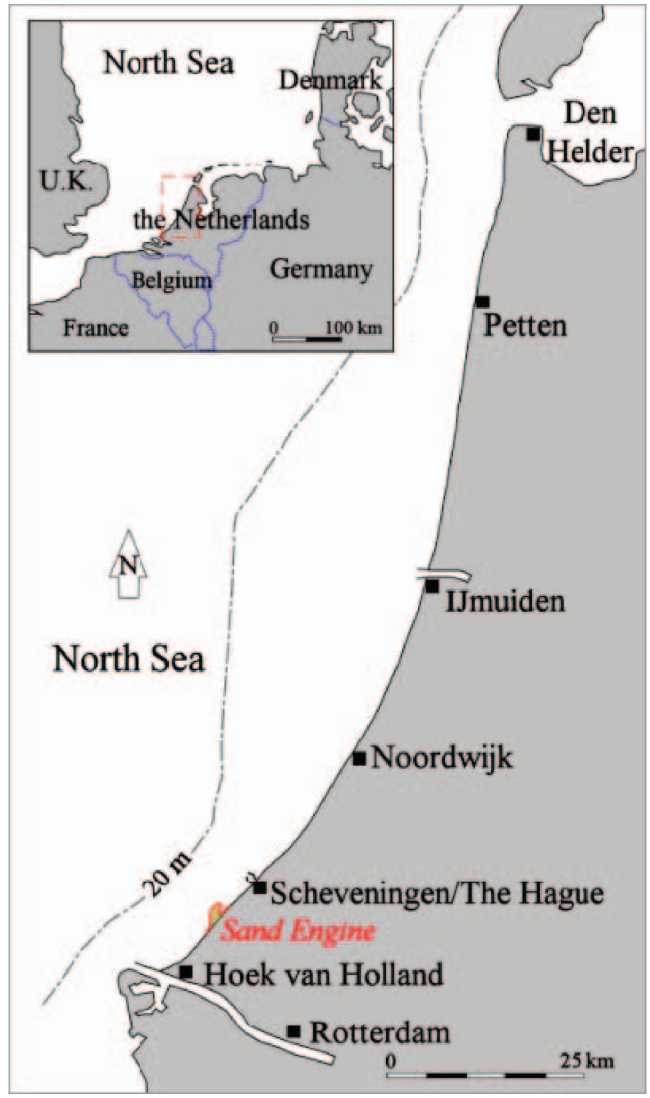

Figure 4. Location map of the Sand Engine project on the southern coast of the Netherlands.

combined effect of relative SLR on both uninterrupted (Bruun, 1996) and inlet-interrupted coasts (Van Goor *et al.*, 2003) and losses to the deeper shoreface. To mitigate the effects and reduce the risk of flooding, coastal structures were built from the 1700s onward, strengthening the coastline locally with seawalls, breakwaters, and wooden or rubble mount groynes. These, however, did not prove to be a sustainable solution, and coastal recession persisted. A new, more fruitful way of mitigating erosion was introduced in the more recent past (1950s) by using artificial sand nourishments. After successful initial projects, it became government policy to maintain the Dutch coastline at its 1990 position at all costs, with sand nourishments as primary mitigation intervention. Since then, sand nourishments have been used fruitfully in the Netherlands to mitigate coastal recession (Figure 2; Hanson et al., 2002; Rijkswaterstaat, 1990). Initially these nourishments were implemented as traditional beach and dune nourishments, *i.e.* sand directly placed on the sub-aerial beach and/or the dunes (Figure 3a). Based on theoretical and field-based findings (Bruun, 1996; Grunnet and Ruessink, 2005; Stive, Nicholls, and de Vriend, 1991; Van Koningsveld *et al.*, 2008), that placing the sand on the foreshore just outside or just inside of the outer breaker bar is not only as effective as the traditional beach/dune nourishment approaches but also cheaper, less intrusive on beach amenity, and much more acceptable to the public these shoreface nourishments have been widely used along the Dutch coast since the late 1990s (Figure 3b). Typically, a shoreface nourishment consists of about 1–2 Mm^3 of sand and has a lifetime of about 3–5 years (Hamm *et al.*, 2002). The main impact of a shoreface nourishment is to feed the shoreface with sediment, thus modifying surf-zone processes to ultimately result in a non-eroding or accretive beach (Grunnet and Ruessink, 2005; van Duin *et al.*, 2004). At present, the majority of the nourishments are implemented as shoreface nourishments rather than beach or dune nourishments (Figure 2).

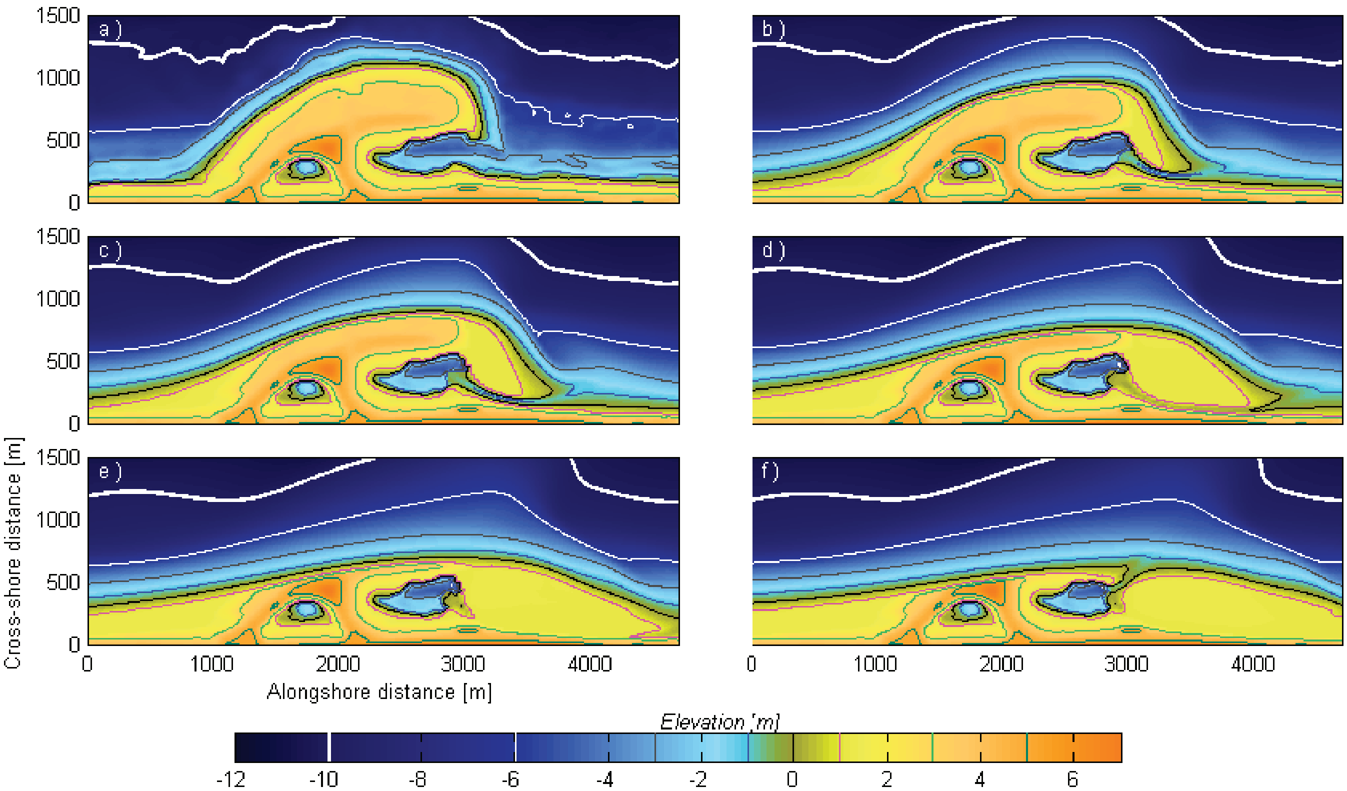

Figure 5. Long-term model prediction of the morphological development of the Sand Engine. (a) The initial model bathymetry; (b–f) the prediction 3, 5, 10, 15, and 20 years after construction. Blue colors indicate sub-aqueous zones; yellow-to-brown colors show the sub-aerial beach; and green colors indicate the intertidal area between high and low water. Depth values of the contour levels are indicated in the color bar.

The damage done by hurricane Katrina in 2005 was a wake-up call to many nations around the world on the potential consequences of coastal flooding. This disaster galvanized the Dutch government to implement a New Delta Committee in 2007 (after the first Delta Committee, which was implemented following the flooding of 1953), primarily to provide advice on the country's preparation for mitigating flood risk in the near and far future (up to 2200). In 2008, the New Delta Committee delivered 12 recommendations for coping with climate and other environmental changes (Kabat *et al.*, 2009). A firm recommendation of the New Delta committee regarding coastal defense options was to adopt a soft engineering strategy (*i.e.* sand nourishment of the coastal system) to mitigate long-term coastal recession. The New Delta Committee report also indicated that to negate the enhanced potential for coastal recession attributable to accelerated SLR in the 21st century, the yearly sand nourishment volume for the Dutch coast should be increased from a presently outdated volume of around 12 Mm^3/y (see Figure 2) to 80 Mm^3/y for a high end climate change scenario (Kabat *et al.*, 2009).

If this volume of sand were to be provided in the form of traditional shoreface nourishments to prevent SLR-driven coastal recession, these nourishments will need to be implemented along the entire coastline. This will result in a significant widening of the beach along the entire Dutch coastline. A very wide beach is, however, unattractive to the average beach user, primarily because the water becomes less accessible. It is within this backdrop that the bold, world-first concept of a localized mega-nourishment, or the Sand Engine, was conceived (Figure 3c).

The main advantages of the localized mega-nourishment concept are as follows. (1) A nourishment will only be required approximately every 10–20 years as opposed to the 2–5 year cycle of present day beach and shoreface nourishments. (2) The nourishment will slowly diffuse and advance the shoreline over a O (10 km) stretch of the coastline in a more natural fashion. (3) The large initial local perturbation will result in a short-to-medium term increase of locally available space for recreation and the environment. (4) The ecological stress, while considerable at the initial nourishment location, does not disturb adjacent areas, thereby containing it to a small ($\sim$2.5 km^2) area.

THE SAND ENGINE

The previous discussion and context calls for adaptation strategies that are unprecedented both in form and magnitude. Recognizing this need, policymakers in the Netherlands, in close collaboration with the scientific community, have recently adopted an innovative intervention approach named The Sand Engine (*Zand Motor*, www.zandmotor.nl) to address the

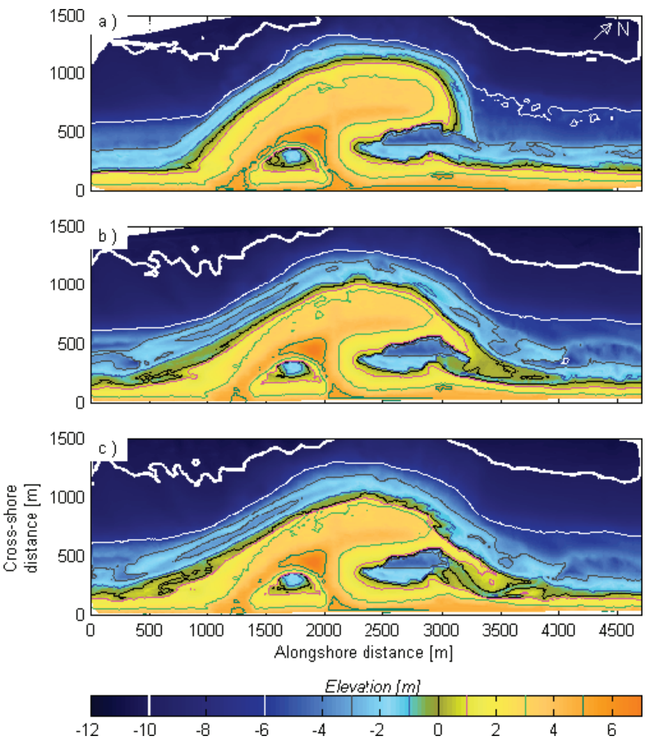

Figure 6. Topographic surveys of the Sand Engine bottom elevation (a) immediately after construction in August 2011, (b) 6 months (February 2012), and (c) 1 year after construction. Blue colors indicate sub-aqueous zones; yellow-to-brown colors show the sub-aerial beach; and green colors indicate the intertidal area between high and low water. Depth values of the contour levels are indicated in the color bar.

potentially massive threat of flooding in the low-lying coastal zone of the Netherlands from projected SLR. The Sand Engine is a very large sand nourishment of 21.5 Mm^3: a nourishment magnitude for defence against flooding that is unprecedented anywhere on the globe.

The initial nourishment spans the coastal system over a 2.4 km stretch and extends up to 1 km offshore following a specific shape (Figure 1). The shape of the nourishment was largely inspired by the potential to provide areas for nature and recreation. It consists of a large hook-shaped peninsula attached to the shoreline by a base of ~1 km and includes a small (7.5 ha) lake (Figure 1). 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 responsible decision makers found this solution attractive and approved the mega-nourishment of 21.5 Mm^3 at Ter Heijde coast in the province of South Holland (Figure 4). The Sand Engine was largely constructed between March and July 2011 using sand mined from approximately 10 km offshore, with some additional work in early 2012. It presents a world-first research site as well as a practical demonstration of a total coastal management system linking a coastal engineering construction with environmental, ecological, and social considerations. To date, the project has received a very positive response from the public, especially from recreational beach users, notably wave, wind, and kite surfers.

The main expectation is that the Sand Engine will perturb the coastal system such that the coastline will, as a minimum, be stabilized at its present position over an extended length of time (20 years) and space (10 km). An anticipated secondary benefit is the creation of environmentally and recreationally attractive space in this strongly urbanized coastal stretch.

PROJECTIONS AND FIRST OBSERVATIONS

The state-of-the-art coastal morphodynamic numerical model Delft3D (Lesser *et al.*, 2004) was used to obtain preliminary projections of the temporal and spatial evolution of the Sand Engine over its 20-year planning horizon. In this preliminary model application, a slightly schematized initial bathymetry, which closely followed the prototype, was adopted.

The initial and model-predicted morphology after 3, 5, 10, 15, and 20 years is shown in Figure 5. The results show that the nourishment will gradually diminish in its width (*i.e.* cross-shore direction) and extend alongshore by 8 km over a period of 20 years as desired (Figure 5a–f). The approximate beach area gained over the 8 km modified coastline is approximately 200 ha. In the model, the Sand Engine has an initial maximum cross-shore extent (maximum width) of 0.95 km and an alongshore extent (length) of 2.4 km. Within 3 years, the nourishment length increases by 1.1 km (0.7 and 0.4 km extensions to the south and north, respectively), while its maximum width decreases by 0.2 km (Figure 5b). The tip of the initially alongshore parallel spitlike feature recurves shoreward and develops into a transverse sand bar that is separated from the shoreline by a narrow channel (about 50 m wide), forming an artificial lagoon with a surface area of 17 ha (Figure 5b). From 3–10 years, the Sand Engine slowly diffuses such that its maximum width decreases from 0.8 km to 0.6 km while its length increases from 3.5 km to 5.3 km (extensions of 1.6 km [south] and 1.2 km [north]), relative to the initial configuration (Figure 5c, d). The lagoon area decreases to 14 ha, while the ocean-connecting shore parallel channel continues to prevail during this time. After 15 years (Figure 5e), the Sand Engine is 7 km long (extensions of 2.5 km [south] and 2.1 km [north]) with a maximum width of 0.5 km, while the shore parallel channel disappears. Between 15–20 years, a new, more hydraulically efficient channel develops on the northern side of the main part of the remaining nourishment to maintain connectivity with the ocean. The projections show that once the 20-year planning horizon is reached (Figure 5f), the maximum width of the nourishment is 0.45 km and its length is 8 km (extensions of 3 km south and 2.5 km north), while the artificial lagoon area decreases to 8 ha but remains open to the ocean via its north shore channel.

Since the completion of the project in summer 2011, the topographic and bathymetric evolution of the Sand Engine is monitored on a monthly basis via a purpose-built Jetski mounted with RTK-GPS and an echo sounder (accuracy ~10 cm; van Son *et al.*, 2010). This is in addition to the regular yearly bathymetric coastal profile measurements, which are intensified to four per year. Furthermore, two ARGUS stations

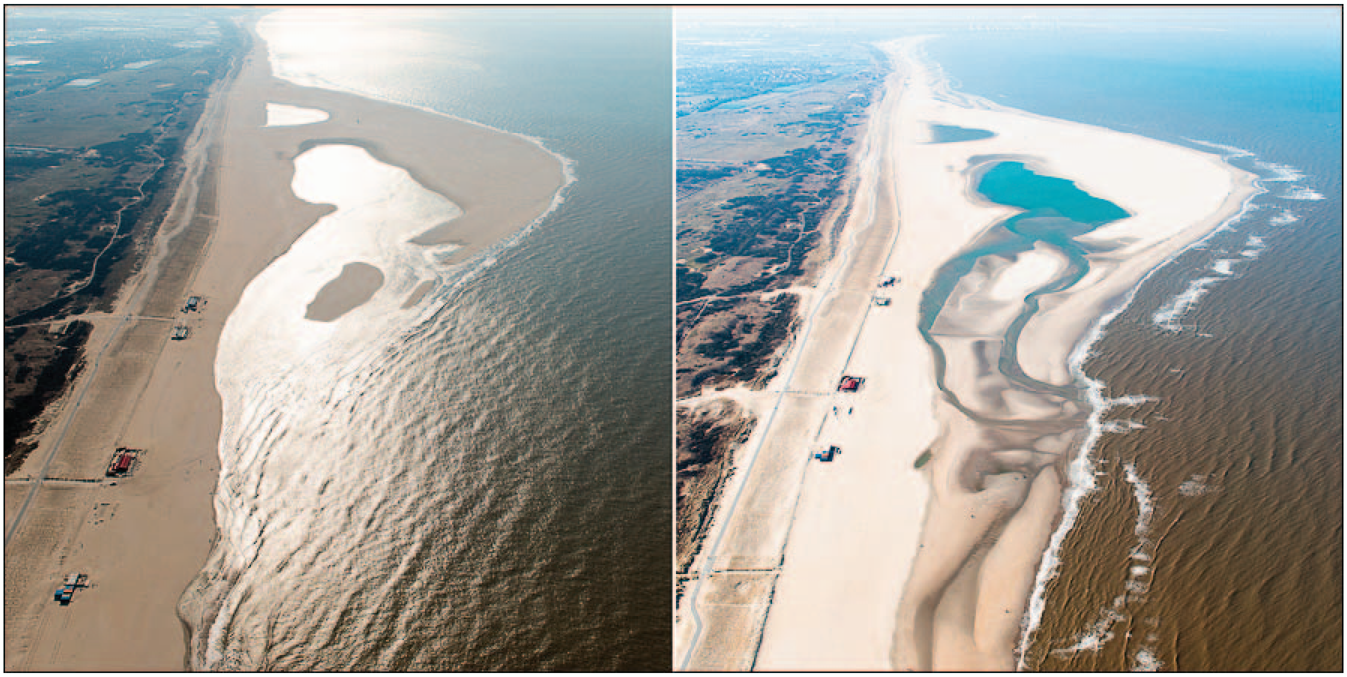

Figure 7. Southward looking aerial photograph of the Sand Engine at high water and at low water (spring 2013). Pictures courtesy of Rijkswaterstaat/Joop van Houdt.

have been installed overviewing the Sand Engine and its adjacent beaches, and regular aerial photographs are collected to visualize the development. During the first year of its existence, which included the stormy winter of 2011–12, the shape of the Sand Engine peninsula has changed considerably (Figure 6). The maximum width decreased from 0.96 km to 0.84 km, while its length increased from 2.4 km to 3.6 km ($\sim$0.6 km extensions to the south and north). The sediment volume at the location of the initial peninsula has decreased during this first year by about 1.4 Mm^3, while adjacent coastal sections have shown a total increase in sediment volume of 0.9 Mm^3, confirming the feeding aspect of the nourishment. The remaining 0.5 Mm^3 is expected to have settled beyond the coastal section around the Sand Engine measured in the monthly surveys (see Figure 6). This evolution is close to the numbers behind the original estimated lifetime of the Sand Engine. Given the order of magnitude of the gross alongshore-sediment transport of 0.8–1.0 Mm^3 (van Rijn *et al.*, 1995), the average yearly loss was estimated at 1 Mm^3; hence, the design volume was 20 Mm^3 to be diffused in 20 years.

Furthermore, the first year of observations reveals large changes in the morphology on the northern side of the Sand Engine where the tip of the initial spitlike feature has recurved shoreward and formed a transverse sand bar. The spit is separated from the shoreline by a $\sim$100-m-wide approximately shore-parallel channel, forming an artificial lagoon with a surface area of $\sim$20 ha.

Above observations of the large-scale behavior of nourishment are consistent with the envisioned behavior of the peninsula feeding the surrounding coast thus providing a reasonable level of confidence in the longer term model projections shown in Figure 5.

DISCUSSION ON PUBLIC SAFETY

While in general the political and public perception of the Sand Engine over the last 18 months is positive, there have been some incidents concerning public safety. Because regular visitors of the Holland coast and the Beach Lifeguard units had become familiar with a straight, nearly uniform beach, they are now confronted with a very dynamic and transient beach and lagoon system. Specifically, the large difference in the morphology at high water *vs*. low water (see Figure 7) leads to two safety issues. First, as the lagoon starts to fill and the water level rises, the inward flood-flow velocities in the channel(s) are rather high, comparable to a strong rip current. This has surprised some beach goers and lifeguards. Second, some parts that can be reached by foot during low water become isolated at high water (see Figure 7). This has surprised some beach visitors. Because of an increased effort of both lifeguards and beach police, most incidents concerning these issues have been avoided. Nevertheless, it remains important to inform both the lifeguards and the public on these safety issues.

CONCLUSIONS

A boldly innovative soft-engineering intervention comprising an unprecedented 21.5 Mm^3 sand nourishment known as the Sand Engine has been recently implemented in the Netherlands. The Sand Engine is a pilot project to test the efficacy of local mega-nourishments as a counter measure for the anticipated enhanced coastal recession attributable to accelerated SLR in the 21st century. This single mega-nourishment is expected to be more efficient and economical in the long term rather than traditional shoreface nourishments that are presently being used to negate coastal recession. Preliminary numerical model results indicate that this nourishment will result in the widening of the beach along an 8 km stretch of the coastline and a beach area gain of 200 ha over a 20-year period. Initial observations show indeed a redistribution of the sand feeding the adjacent coasts, roughly 40% toward the south and 60% toward the north. While the jury is still out on this globally unique intervention, if proven successful, it may well become a global generic solution for combating SLR-driven coastal recession on open coasts.

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