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CONCEPTUAL NOTE TO THE EDITOR

Building with Nature: in search of resilient storm surge protection strategies

E. van Slobbe · H. J. de Vriend · S. Aarninkhof · K. Lulofs ·
M. de Vries · P. Dircke

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Abstract Low-lying, densely populated coastal areas worldwide are under threat, requiring coastal managers to develop new strategies to cope with land subsidence, sea-level rise and the increasing risk of storm-surge-induced floods. Traditional engineering approaches optimizing for safety are often suboptimal with respect to other functions and are neither resilient nor sustainable. Densely populated deltas in particular need more resilient solutions that are robust, sustainable, adaptable, multifunctional and yet economically feasible. Innovative concepts such as 'Building with Nature' provide a basis for coastal protection strategies that are able to follow gradual changes in climate and other environmental conditions, while maintaining flood safety, ecological values and socio-economic functions. This paper presents a conceptual framework for Building with Nature

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E. van Slobbe (✉)
Alterra, Wageningen University and Research Centre, PO Box 47, 6700 AA Wageningen,
The Netherlands
e-mail: erik.vanslobbe@wur.nl

H. J. de Vriend
EcoShape Foundation/Deltares/Delft University of Technology, Burgemeester de Raadtsingel 69,
3311 JG Dordrecht,
The Netherlands

S. Aarninkhof
EcoShape Foundation/Royal Boskalis, Burgemeester de Raadtsingel 69, 3311 JG Dordrecht,
The Netherlands

K. Lulofs
School of Management and Governance, University of Twente, PO Box 217, 7500 AE Enschede,
The Netherlands

M. de Vries
Deltares/University of Applied Sciences, Hogeschool Zeeland, PO Box 177, 2600 MH Delft,
The Netherlands

P. Dircke
ARCADIS Nederland/Rotterdam University of Applied Sciences, PO Box 4205,
3006 AE 'Rotterdam, The Netherlands

that is used to evaluate coastal protection strategies, based on a case study of the Holland coast in the Netherlands. The added value and the limitations of these strategies are discussed.

Keywords Storm surge protection · Coastal maintenance · Building with Nature · Ecosystem services · Adaptive management · Sea-level rise

1 Introduction

1.1 Engineering our own vulnerability

In natural environments, flood-induced inundations may be regular and beneficial phenomena that bring new sediment and nutrients onto the land, thus offsetting subsidence or sea-level rise. In densely populated parts of the world, however, flooding is perceived as an undesirable event against which defences are needed. In this ‘fight against water’, dikes, barriers and other hard structures have become common instruments, focusing primarily on the area to be protected rather than on the water system.

Once flood defence technology had become sufficiently reliable, demographic and economic drivers led people to settle in and extend the protected areas, thus enhancing the potential risk of casualties and damages if the defences are broken, reducing the room available to the water system and disrupting natural sediment flows (Smits et al. 2006; Van Koningsveld et al. 2008). In a study of 33 deltas worldwide, Syvitski et al. (2009) considered not only the effects of flood defences but also other human-induced changes, including ‘sediment compaction from the removal of oil, gas and water from the delta’s underlying sediments, the trapping of sediment in reservoirs upstream and floodplain engineering in combination with rising global sea level’ (p. 681). They warned of the increasing risk of ‘sinking of modern deltas’ due to disturbed sediment balances.

One example of a deteriorating coastal wetland area is the Mississippi delta in the United States. Farber (1987) and Costanza et al. (2006) point to a number of human interventions that have contributed to the growing vulnerability of the Louisiana coast. These include urban and agricultural drainage, the construction of levees for flood protection and navigation, and cutting of channels through the marshlands and wetlands of the Mississippi delta and along the Louisiana coast by the oil and gas industry.

Another example, at a smaller scale, is the Rhine–Meuse–Scheldt delta in Belgium and the Netherlands, where a 3-km-long movable storm surge protection barrier has been constructed in the Eastern Scheldt estuary. The barrier was multifunctional by design: It was intended to protect the area behind it from storm surges, while at the same time maintaining the tidal motion in the basin in order to preserve the unique tidal environment (Bijker 2002). The barrier, considered a triumph of engineering skill, has functioned as foreseen, but with some unforeseen environmental effects (De Vriend 2004). One of these is that the barrier blocks all sediment transport, in or out, thus morphologically separating the estuary from the sea. This will inevitably have undesirable long-term effects. For instance, the outer delta will tend to rise with the rising sea level, but the bed in the basin behind the barrier will not because of the lack of sediment transport. This sediment deficit will mean that it will be virtually impossible to remove the barrier at the end of its life cycle.

For modern societies in river deltas, in estuaries and along low-lying coastal areas, protection infrastructures are essential elements of flood safety systems. The need for such infrastructures is growing, as societies continue to develop, and as coastal areas become more vulnerable to sea-level rise, ongoing land subsidence and more frequent extreme weather events (IPCC 2012). But 'hard' engineering approaches like dams, storm surge barriers and defensive coastal maintenance strategies may well, in the long run, increase rather than reduce the vulnerability of the societies they are supposed to protect. There is a need to develop more sustainable coastal protection infrastructures.

1.2 Emerging approaches

Although in most parts of the world the process of building defences against the sea has not yet exhausted the technological means available, the 'hard' engineering approach is increasingly being challenged (Adger et al. 2005; Kamphuis 2006; De Bruijn 2005; Kabat et al. 2009). Farber et al. (2006, p. 117), for example, noted that 'the tragic consequences of Hurricane Katrina on the Gulf Coast, and in New Orleans in particular, have highlighted the importance of addressing ecosystem services—such as the storm surge protection that wetlands provide—in management decisions involving coastal settlement and infrastructure policies' (see also Costanza et al. 2006).

New approaches are emerging, motivated by the lack of sustainability of the 'hard' engineering approach, as well as by concerns for the environment (Airoldi et al. 2005). Around the world, innovations and scientific discussions are focusing on ways to integrate coastal protection strategies with the use of natural, socio-economic and governance processes (see McHarg 1995; Mitsch and Jørgensen 2004; Farber et al. 2006; Waterman 2008; Misdorp 2011). Shi et al. (2001), for example, describe an integrated coastal zone management framework developed for the Shanghai coast in the People's Republic of China. Controlled inundation of land by setting back sea defences is increasingly being used for coastal protection and in anticipation of climate change. In the United Kingdom, this so-called managed realignment is regarded as a cost-effective and sustainable response to the loss of coastal biodiversity and sea-level rise (Turner et al. 2007; French 2006). Vandenbruwaene et al. (2011) describe managed realignment experiences in the Scheldt river basin in Belgium. New approaches have been institutionalized in Dutch flood defence policies (Van der Brugge et al. 2005) with campaigns such as 'living with water' and 'increasing the resilience of our flood defences' (Kabat et al. 2009).

The European Environment Agency uses ecosystem services and resilience assessments for the development of European coastal protection policies (European Environment Agency 2006). The engineering sector is also searching for new strategies. The World Association for Waterborne Transport Infrastructure (PIANC), for example, recently issued a position paper on its 'Working with Nature' approach, which is described as 'an integrated process which identifies and exploits win–win solutions with respect to nature, which are acceptable to both project proponents and environmental stakeholders' (PIANC 2011, p. 1).

1.3 Outline of this paper

One approach that focuses on resilience and ecosystem services is 'Building with Nature' (Kamphuis 2006; Kabat et al. 2009; Waterman 2008; Aarninkhof et al. 2010; Van Slobbe and Lulofs 2011). The approach is in line with several other initiatives, such as PIANC's Working with Nature and the 'Engineering with Nature' movement within the US Army Corps of Engineers (Bridges and Walker 2011).

This paper presents this approach in the context of coastal protection strategies. It assesses the possible added value of the approach and its limitations for storm surge protection based on a case study of the Netherlands in which three coastal management strategies, applied at the same location on the North Sea coast, are compared and evaluated. First, however, we present our understanding of Building with Nature in a conceptual framework that is used for the evaluation of the three management strategies.

Costanza et al. (2008) pointed out the lack of experimental studies and model results in relation to the effects of coastal marshes on storm surges. The present case study may help to fill that gap. The research is based on the work done within Building with Nature, a national transdisciplinary research and innovation programme in the Netherlands. The information presented here has been drawn from research reports, both published and unpublished, on physical and ecological aspects of coastal management and governance processes, as well as from an environmental impact assessment of a major experiment called the Delfland Sand Engine (Fiselier 2010).

2 Building with Nature: a conceptual framework

The various approaches mentioned above have emerged from scientific discourses that aim to reframe the relationship between human societies and their natural environment. In the second half of the twentieth century, the Enlightenment ideal of subduing nature for the benefit of mankind was rejected in recognition of the need to mitigate the negative impacts of human interventions on the environment. Both of these positions, however, assume a boundary between mankind and nature as if they are two separate entities. The new discourses start from the premise that humans are part of the natural system (Walker et al. 2004). The Millennium Ecosystem Assessment (2005, p. VII), for example, assumed that people are ‘integral parts of ecosystems and a dynamic interaction exists between them and other parts of ecosystems, with the changing human condition driving, both directly and indirectly, changes in ecosystems and thereby causing changes in human well-being’.

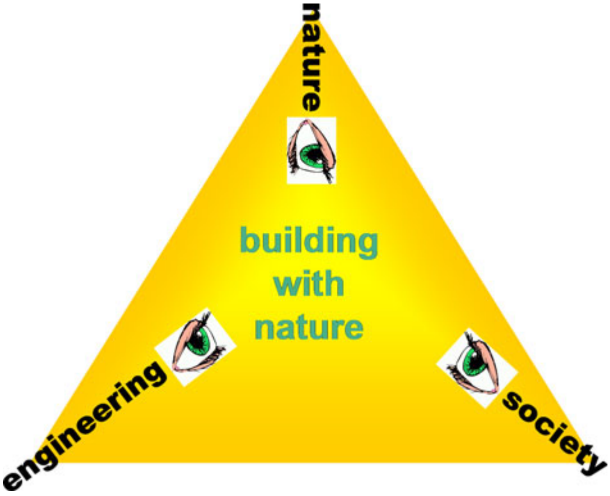

Fig. 1 The three perspectives of the Building with Nature programme

The Building with Nature innovation programme uses a triangle to depict the relationship between the three subsystems that are relevant in coastal protection: the biotic and abiotic environment, man-made infrastructures and the governance of society (Fig. 1).

The natural system encompasses hydro-morphological processes (sedimentation and erosion, water- and wind-induced sediment transport) and ecological processes (food webs, the influence of bioengineering) in the coastal zone. The engineering system represents all human interventions that aim to influence the natural system (dams, dikes, groins, harbours, shipping lanes, reclamation projects, etc.). The societal system represents the institutional side, both formal (laws, regulations, standards, decision-making structures and stakeholder involvement) and informal (political power, networks, agreements and established practices). The state of a coastal protection scheme is the result of interactions between these three subsystems (Van Koningsveld et al. 2008).

For the analysis of the interactions between humans and nature, Berkes and Folke (1998) introduced the concept of socio-ecological systems. Studies of these systems have revealed their nonlinear development over time and patterns of crisis and renewal due to interactions between ecosystem behaviour and human exploitation. Human management strategies in many such systems tend to focus on rapidly changing variables. If system variables or environmental conditions that induce slow system changes (drift) are overlooked, the system may undergo crises (Holling 1998) or critical transitions (Scheffer 2009).

Analysis of coastal protection systems must start by 'reading' such systems in terms of dynamic interactions and possible drift phenomena. In this conceptual framework, we use three elements of socio-ecological systems: resilience, social learning and the use of ecosystem services (see Berkes and Folke 1998; Gunderson and Holling 2001; Holling 1998; Adger et al. 2005).

2.1 Resilience in complex systems

The first element of our conceptual framework is resilience, defined as the capacity of a dynamic system to absorb shocks while maintaining its structure and functioning (which is different from the capacity of a system to return to a certain steady equilibrium state following a disturbance). This definition focuses on 'persistence, adaptivity, variability, and unpredictability' and is 'measured by the magnitude of disturbance that can be absorbed before the system changes its structure by changing the variables and processes that control behaviour' (Gunderson and Holling 2001, p. 28). A resilient infrastructure is able to adapt to changing conditions that influence safety thresholds or standards in the long run. In contrast, traditional engineering works (dams, dikes, etc.) are usually designed to withstand events with a given probability of occurrence at the time of their construction and accept failure under more severe conditions.

2.2 Social learning

The second element is the role of learning to cope with uncertainties. The uncertainties related to climate change, and especially to extreme weather events, are increasing (IPCC 2012), as are the ambiguities and the range of political issues arising from the increased involvement of stakeholders and the growing complexity of coastal zone governance. In view of these uncertainties, straightforward expert-dominated management of coastal protection systems is no longer feasible, and coastal protection issues are becoming unstructured problems (Funtowicz et al. 1998). The research and management challenge is to learn how to make sense of past events, such as the impacts of extreme weather or changes in societal preferences, and to learn from experiments, monitoring and the divergent views of stakeholders (Wals 2007; Blackmore et al. 2007; Pahl-Wostl 2002; Aerts et al. 2011).

2.3 Ecosystem services

The third element of our conceptual framework is the capability to produce robust ecosystem goods and services, which 'represent the benefits human populations derive, directly or indirectly, from ecosystem functions' (Costanza et al. 1997). Various recent studies have paid explicit attention to the value of ecosystems in coastal protection. The Millennium Ecosystem Assessment, for example, analysed the functions of mangroves, coastal wetlands, dunes and wide beaches as protective measures against cyclones and coastal flooding in countries such as India, Bangladesh and New Zealand (Millennium Ecosystem Assessment 2005, part 3, p. 345). Costanza et al. (2008) and Farber (1987) assessed the value of wetlands in protecting the coast of Louisiana in the United States. Granek et al. (2009) proposed that ecosystem services be used as a common language in coastal ecosystem-based management. Moberg and Rönnbäck (2003) and Gedan et al. (2011) examined the role (and the limitations) of ecosystems as protective measures and the importance of ecosystem restoration. Borsje et al. (2011) describe the successful use of bioengineering and ecosystem engineering to create ecosystem services in coastal protection schemes.

3 Case study: from reactive to proactive coastal protection

The provinces of North and South Holland on the North Sea coast of the Netherlands are protected by a 120-km-long sandy shore, the Holland coast. Before 1990, the coastal protection was managed with a 'hard' engineering strategy (dams, reinforcements and acceptance of beach erosion). After 1990, the policy changed and nowadays the coast is maintained by nourishing it with sand mined offshore. At present, these nourishments each involve a limited volume of sand (typically 1 million m^3) and are applied whenever the coastline appears to be retreating beyond a predefined setback line. As part of the search for strategies to cope with an accelerating rise of the sea level (Kabat et al. 2009; Vellinga et al. 2009), an experimental mega-nourishment (20 million m^3) was implemented recently. This experiment is called the Delfland Sand Engine. The aims of this experiment were to test whether the benefits of such a concentrated mega-nourishment would outweigh the extra costs and to determine to what extent this method can be used as a way to maintain this and other sandy coasts.

In this chapter, we present a case study of these three coastal protection strategies. We describe the Holland coast as a socio-ecological system, with the human and natural systems (on the right side of Fig. 2, see also Table 1) as subsystems in interaction with three engineering strategies: 'hard' engineering (dams, reinforcements and acceptance of beach erosion); dynamic preservation (maintenance of the 1990 coastline with small-scale nourishments); and Sand Engine (coastal maintenance by mega-nourishments).

In Sect. 3.4 we use the conceptual framework to compare the three strategies.

The Delfland Sand Engine was completed mid-2011, so it is too early to present a final assessment, but it has been possible to draw lessons from the initiation, design and construction phases. For the later phases, we use *ex ante* evaluation data from an extensive

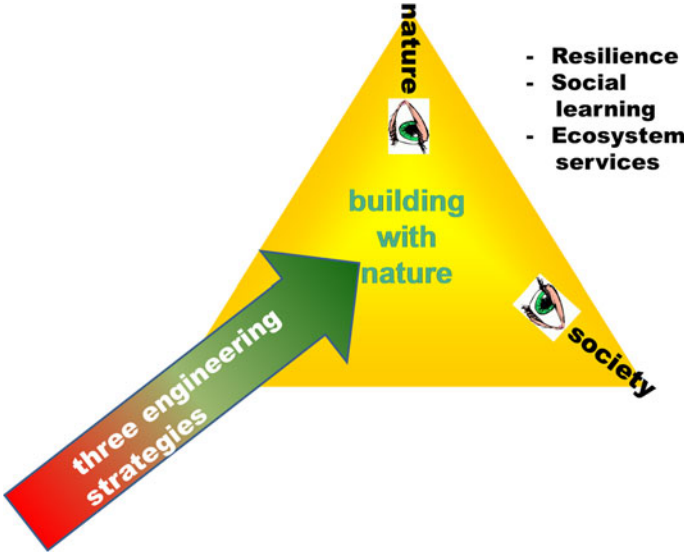

Fig. 2 Conceptual framework for evaluating three coastal protection strategies

environmental impact assessment (Fiselier 2010). On the basis of this information, we compare the potential of the Building with Nature strategy with other coastal protection methods.

3.1 The Holland coast

The Holland coast lies on the Southern Bight of the North Sea (see Fig. 3), which funnels northwesterly storm surges that may reach up to 4 m above mean sea level (Sterl et al. 2009). The coast as it is today is the product of a dynamic history of geological, climatic and morphological processes (Beets et al. 1992; De Ruig 1998; Van Koningsveld et al. 2008). Throughout the Holocene, that is, since approximately 10,000 years BP, the coast has been subject to relative sea-level rise. Within the last century, the sea level in this region has risen by about 20 cm, but some areas of land have subsided by even more than that. Inland lakes, wetlands and floodplains have been reclaimed by constructing dikes, dams and drainage canals. Such activities have not only prevented further accretion by sedimentation, but also promoted peat oxidation and compaction. Some areas in the west of the country have subsided by up to 4 m due to peat compaction over the last millennium. Today, the urbanized economic heart of the country, with a population of 8 million, is situated in flood-prone areas, much of it below mean sea level (Van Koningsveld et al. 2008).

The Holland coast's sandy beaches are backed by an area of dunes that varies in width from less than 100 m up to several kilometres (De Ronde et al. 2003). The coast is interrupted by the entrances to three harbours—Rotterdam, Scheveningen and IJmuiden—and by the former mouth of the River Rhine near Katwijk.

Apart from a number of villages and tourist resorts, the beaches and dunes are mostly free of housing and rural functions. Although heavily modified by human interventions and management, most of the landscape is valued as natural, and important areas are part of the Natura 2000 conservation regime (European Commission 1992), which aims to protect

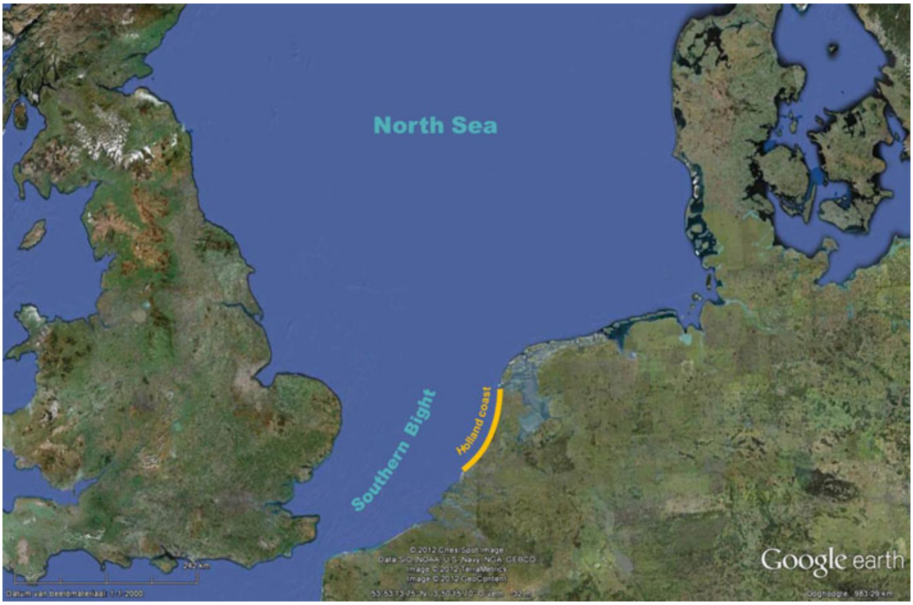

Fig. 3 The Southern Bight of the North Sea and the Holland coast

specific species and habitats. The dunes and beaches provide for a number of services apart from flood protection: as areas for recreation and leisure, the locations of valuable terrestrial and marine ecosystems and sources of clean drinking water.[1] These services are particularly important as they are located near the most densely populated part of the country.

Relative sea-level rise, in combination with a gradually increasing northbound residual sediment transport along the shore, is causing coastal retreat, amounting to 5 km in four centuries (De Ronde et al. 2003). This explains why remnants of ancient coastal villages are found on the seabed just off the present coast.

3.2 A brief history of Dutch coastal protection management

A defining event in the recent history of Dutch coastal protection was the 1953 storm surge, which resulted in over 1,800 casualties and caused significant economic damage. The disaster motivated politicians to modernize the coastal protection system (Kabat et al. 2009) and to design flood protection infrastructures to resist a load (water level, wave height and period) with a given probability of exceedance. The Holland coast, which protects 8 million people, a GDP of about €400 billion per year and capital investments amounting to some €1,800 billion, is maintained at a probability standard of 10^{-4} per year (Kabat et al. 2009). Lower levels of probability are applied in other parts of the country.

Most of the Holland coast, except for a number of so-called weak links, has a flood protection capacity well above the design standard. Therefore, its maintenance used to be limited to small-scale measures, such as planting marram grass in the dunes to prevent wind erosion. At the weak links, special structures, mainly groins, were built to reduce coastal erosion.

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[1] The dunes—with fresh groundwater lenses in a salt groundwater environment—are used to filter and purify fresh river water and store it for use as drinking water.

Ongoing erosion, driven by sea-level rise and the lack of sediment supply from the rivers, led to growing concerns, not only because of security issues but also because of its detrimental effects on the use of the beaches and dunes for recreation, nature conservation and drinking water supply. The further loss of beaches and dunes was considered undesirable, and in 1990 the Dutch government adopted the national policy of 'dynamic preservation' (De Ruig 1998; Van Koningsveld et al. 2008). Acknowledging sand as 'the carrier of all functions', the principal intervention procedure today is to compensate for the erosion and to maintain the coastline at its 1990 position. This is done by nourishing the beaches and foreshore with sand and allowing the wind, tides and waves to distribute the sand over the beaches and dunes, thus making use of natural processes and leaving room for natural dynamics (hence the term *dynamic* preservation).

This 'soft engineering' approach to coastal maintenance is not unique to the Netherlands and has been adopted for other sandy coasts, such as along the east coast of the United States (National Research Council 1995) and the Australian Gold Coast (Strauss et al. 2009).

In 2000, after measurements showed a steepening of the lower shoreface (6–8 m below mean sea level), it was decided to extend the sand nourishment strategy to deeper water. The new maintenance zone, called the 'coastal foundation', extends down to the −20-m-deep contour. Since 2000, the average volume of sand used to nourish the entire Dutch coast has amounted to 12 million m^3 per year (Rijkswaterstaat 2011).

This volume of sand can be brought onshore via the regular small-scale nourishments, a process that has its advantages (e.g. immediate return on investment), but also some drawbacks. In the long run, it will lead to an over-steepening of the coastal profile (Stive and De Vriend 1995; Walstra et al. 2006). Moreover, the beach and foreshore ecosystems are significantly affected, initially by the burial of biota and by the loss of habitats, such as in the troughs between the nearshore sandbars (Janssen et al. 2008). After some time the system is likely to recover (Mulder et al. 2005), but the continuing tendency of the coast to retreat and the over-steepened coastal profile necessitate repeated nourishments, and hence repeated disturbances of the ecosystem. The use of this practice of small-scale nourishments means that the system is in a more or less permanent state of perturbation.

3.3 The Sand Engine experiment

The expected need for larger nourishment volumes and the mounting evidence of the adverse environmental effects of current practices led to the idea of conducting an experiment with a mega-nourishment concentrated in space and time. This mega-nourishment was expected to reduce construction costs, create a more natural coastal profile in the long run and provide a number of ecological and recreational benefits. The planning for a pilot experiment on the Delfland coast (the southern part of the Holland coast, see Fig. 4) started in 2006.

Initiating the pilot involved a complex political and policy-making process. The experiment's political 'champions' framed it as an important initiative that would help to maintain and enhance the image of Dutch water management around the world. They drew parallels with the Palm Island land reclamation in Dubai and other major coastal engineering feats. This 'political' image was a crucial driver of the project. At the same time, however, local stakeholders raised concerns about the potential impact of such a large and new infrastructure project just off 'their' coast. Inevitably, these concerns were taken up by politicians with agendas opposing 'green investments' (Van Slobbe and Lulofs 2011).

A number of alternative designs for the Delfland Sand Engine were investigated in an environmental impact assessment (Fiselier 2010). On the basis of this study, a preferred alternative was identified, and in 2010 a coalition of public and (one) private partners, led

Fig. 4 The Delfland Sand Engine. The *red lines* indicate 'weak links' in the coastal protection system; the *yellow areas* represent dunes. The location of the Sand Engine (*Zandmotor* in Dutch) was chosen near one of the weak links in the 15 km stretch of coast between the entrances to the harbours of Rotterdam and Scheveningen

by the province of South Holland,[2] decided to go ahead. Under the direction of Rijkswaterstaat (the state water management agency), work on the Delfland Sand Engine began, and construction was completed in the summer of 2011.

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[2] The coalition members included the province of South Holland, the Ministry of Infrastructure and Environment, Rijkswaterstaat (the state water management agency), the municipalities of The Hague, Westland and Rotterdam, the Delfland water board and the Milieufederatie Zuid-Holland (an environmental NGO).

3.3.1 Definition and objectives of the pilot

The environmental impact assessment (Fiselier 2010) described the pilot project as follows: ‘A sand engine is a large sand nourishment just off the coast. The sand is distributed by waves, currents and wind in such a way that the coast continues to grow naturally. This creates a buffer of sand on the coastal foundation against sea level rise, thus guaranteeing the safety of the coast in the longer term. It also creates extra space for nature and recreation. The scale of the sand engine is larger than ever seen before. That is why the construction of the sand engine off the Delfland coast has the character of a pilot, meant to gather knowledge on how to build with nature for climate adaptation’ (p. 46; authors’ translation).

The objectives of the Delfland Sand Engine were defined as:

1. Encouraging natural dune growth, primarily in width, in the coastal cell between Rotterdam and Scheveningen. This creates not only a larger sand buffer to cope with rising sea level, but also more space for nature and recreation and a larger freshwater lens under the dunes.
2. Generating knowledge and innovations related to:
   - Sustainable coastal development in low-lying areas.
   - The transition from reactive coastal maintenance strategies based on regular small-scale nourishments to more proactive strategies based on concentrated mega-nourishments.
   - The governance (collaboration among actors, new forms of contracting, new financial arrangements and monitoring) of integrated multifunctional and multistakeholder coastal protection schemes.
   - The potential and limitations of mega-nourishments in terms of location, design, ecology, dynamics and acceptance among the public.
3. Adding an attractive dune and beach area for leisure and nature reserves to the Delfland coast.

3.3.2 Design and functions

The Sand Engine is meant to be sacrificial and will not be maintained, and its shape will change over time. Morphological model projections indicate that the sand will be gradually redistributed over the beaches, dunes and foreshore over several decades (Fig. 5), at a rate of some hundreds of metres per year.

The nourishment involved a total of 20 million m^3 of sand, which took the form of a large hook extending northwards. Immediately after completion, the area of sand above mean sea level was 128 hectares, and the alongshore extent at the water line was 2 km. The maximum seaward extent of the hook was 1 km and its maximum height 7 m above mean sea level. At the root of the hook, a small beach lagoon was created to trap fine sediment and provide a temporary habitat for species that are not usually found on sandy beaches.

Over time, wind-blown sand transport is likely to mould the higher parts to form juvenile dunes. The lake is expected to fill up gradually to form a wet dune valley, and the same may occur in due course for the lagoon at the north side. Pioneer vegetation will develop, trapping sand and further influencing the morphological evolution. The extent to

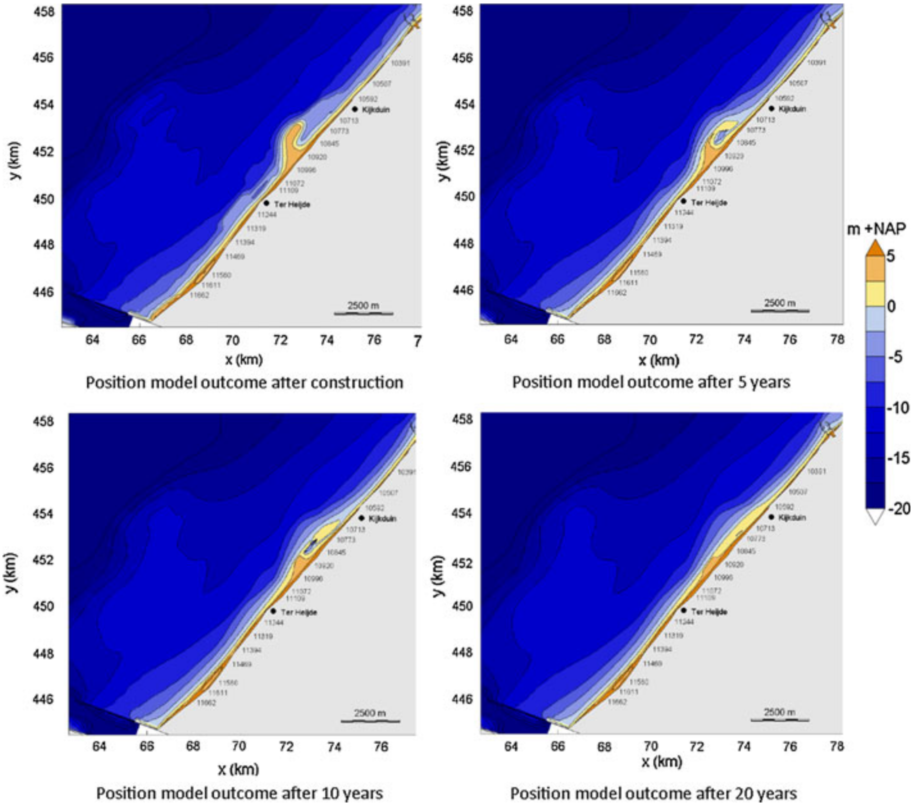

Fig. 5 Morphological model projections after 0, 5, 10 and 20 years with surface heights in relation to mean sea level (NAP is the Dutch standard). A process-based numerical model, Delft3D, was used in combination with a wave simulation model, SWAN (Tonnon et al. 2009)

which this will happen will depend on the dynamics of the wind-blown sand bodies. As the sand is nutrient-rich and brought onshore by natural processes, dune vegetation will develop more easily than in the case of a man-made environment (Denys 2003). Whether the vegetation will allow enough wind action to raise the primary dune ridge remains an open question.

In the long run, the body of sand will be redistributed over shoreface, beach and dunes, thus enriching the entire coastal cell between Rotterdam and Scheveningen.[3] The Sand Engine will change the alignment of the coast, however, giving rise to concerns about the possibility of the generation of dangerous currents and unstable erosion fronts, which may constitute a danger to swimmers. Another concern is the possible impact of the project on the quality of fresh groundwater stored in the dunes.

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[3] Assuming that the 20 million m^3 of sand will stay within the coastal cell and will be evenly distributed over the entire coastal profile, the Sand Engine will ultimately yield some 50 m of coastal progradation in the cell.

3.3.3 Costs and benefits

The design of the Sand Engine is the result of complex negotiations regarding the objectives, contributions and expected effectiveness of the project. Its benefits—financial (lower cost of sand per m^3 because of the concentrated dredging effort), economic (extra recreation, more fresh groundwater) and ecological—are sometimes difficult to evaluate. Preliminary calculations show that, if one compares the experiment with the traditional nourishment strategy, the reduced cost of sand does not outweigh the loss of interest on capital during the time it will take for the sand to come onshore.[4] If the Sand Engine strategy is deployed over the entire coast, however, as part of a new coastal management regime involving the same total amount of sand as the old one, then the loss of interest on capital no longer counts and the overall cost effectiveness may well exceed that of regular small-scale nourishments.

The higher costs of the isolated Delfland Sand Engine experiment will have to be compensated by other benefits, such as enhanced ecosystem services, a larger stock of freshwater under the dunes and increased opportunities for recreation. It is too early to make reliable estimates of these benefits; monitoring over the 20-year life cycle will be necessary.

3.3.4 Observations and initial findings

The construction of the Sand Engine was completed in the summer of 2011 (see Fig. 6). Immediately after the completion, the northern bay area was invaded by kite surfers who welcomed the new environment.

First observations show signs of interesting ecological developments. Basking seals have been spotted (unusual on this coast), and pioneer vegetation, birds and fish have found new habitats on and around the Sand Engine, especially around the lakes and new dunes. One very rare plant (*Atriplex laciniata*) has settled on a newly formed small dune ridge.

In the first winter (2011/2012), an unusual series of northwesterly storms changed the Sand Engine's morphology significantly. The tip of the hook bent over the beach, almost closing off the bay used by the kite surfers. Only a small tidal channel remained, connecting the newly formed lagoon with the sea (see Fig. 7).[5] The planform evolution of the mega-nourishment is in line with the model projections, although it seems to have occurred more rapidly than foreseen (compare the aerial view in Fig. 7 with the projections in Fig. 5).

Morphological monitoring of the Sand Engine commenced during implementation of the mega-nourishment in 2011. These measurements will be continued on a monthly basis during the first few years after construction, as part of an extensive research and monitoring programme that also includes hydrodynamic measurements, ecological and hydrological (groundwater) investigations, analyses of dune evolution and assessments of the safety of swimmers and recreational users. Both remote sensing techniques (automated video and radar stations, airborne laser altimetry) and in situ measurements are being deployed for data collection. It will take a decade or more, however, before the long-term effects on the coastal system can be fully assessed.

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[4] This observation is based on a cost of sand of €2.5/m^3 in 2011 for the Sand Engine (compared with €6/m^3 for regular nourishments) using a discount rate of 5.5 %.

[5] In the meantime, the channel has been closed artificially and replaced with another one further from the beach. It was considered to constitute an unacceptable danger to people using the beach.

Fig. 6 Aerial view of the Delfland Sand Engine from the north, immediately after completion in July 2011 (photograph: Rijkswaterstaat/Joop van Houdt)

Fig. 7 Aerial view of the Delfland Sand Engine from the northeast, March 2012 (photograph: Rijkswaterstaat/Joop van Houdt)

3.4 Analysis

The Holland coast is the result of dynamic interactions between natural processes and human interventions. The management of this system has evolved over centuries. From a storm surge protection perspective, three different strategies have been used (see Table 1).

The first strategy was resistance, that is, to defend weak spots with engineering works (dams, groins) and to accept the erosion of beaches and dunes. This strategy was abandoned in 1990, as the further loss of sandy beaches and dunes was considered unacceptable. Today, with the 1990 coastline position as a reference, sand nourishments are applied

Table 1 Comparison of three storm surge protection management strategies using elements of the conceptual framework

	'Hard' engineering. Dams, reinforcements and acceptance of beach erosion	Dynamic preservation. Maintenance of 1990 coastline with small-scale nourishments	Sand engine. Coastal maintenance by mega-nourishments
System orientation	Focus on defence, no explicit relationship with other functions of the water system	Recognizes connections between protection, recreation and nature conservation functions	Recognizes connections between all relevant coastal functions and multistakeholder involvement
Resilience	Resistance approach, the structure is fixed in place	Adaptable to changing conditions, requires repeated interventions	Naturally adapts to changing conditions within its lifetime (approximately 20 years)
Social learning	Long-standing coastal engineering practice, with a well-established knowledge base and experience in the coastal engineering community	Observe-and-respond approach with a well-established knowledge and experience base in the coastal engineering community	Multi- and interdisciplinary learning by experimentation and monitoring (coastal engineering, geomorphology, public administration, ecology, governance, communication)
Use of ecosystem services	Use of existing beaches and dunes, no attempt to exploit their potential. Loss of beach and dunes seawards of hard structures	Use of wave and wind dynamics to bring sand onshore and into the dunes; use of the dune area as a protective sand buffer. Repeated disturbance of offshore and terrestrial ecosystems	Use of currents, waves and wind for natural sediment distribution; creation of new habitats in the coastal zone. One-time disturbance of the coastal ecosystem
Costs and benefits	Depending on the structure, low maintenance costs of the structure as is, but high adaptation costs. Loss of beach and dune areas may be a cost item	€60 m per year (2011) for the entire Dutch coast. Costs are expected to increase due to the increasing demand for sand. Benefits restricted to maintenance of coastline and preservation of beaches and dunes	€70 m over 20 years for one experimental location. More expensive as an isolated experiment but probably cheaper once upgraded to regular practice. Benefits for coastal protection, nature, recreation and freshwater extraction

wherever the coastline appears to be retreating further landwards. This second strategy is based on annual monitoring of the coast and uses distributed small-scale nourishments.

The third strategy, the application of concentrated mega-nourishments, anticipates a growing demand for sand in order to cope with the effects of climate change and to create extra areas for recreation and nature. Table 1 compares the management strategies on the basis of the orientation to a system approach and the three elements of socio-ecological systems, the conceptual framework described in Sect. 2. Because sooner or later discussions will focus on the potential costs and benefits of the strategies, these have been included as a separate evaluation criterion.

The table shows the fundamental differences between the three approaches. The traditional resistance strategy with ‘hard engineering’ makes little use of the natural environment and partly destroys it. The two other strategies, based on ‘soft engineering’, do make use of the natural system to achieve their goals and are therefore more resilient, flexible and adaptable. Small-scale nourishment as practised in the Netherlands is reactive, whereas the mega-nourishment strategy is proactive. Mega-nourishments, with a cycle of 20 years or more, may be better able to adapt to slow and persistent changes (like sea-level rise), but may be vulnerable to the impacts of extreme events (such as heavy storm surges causing massive dune erosion), unless it is possible to redistribute the sand after the event.

A fundamental difference between these two nourishment strategies is the involvement of stakeholders. Annual nourishment is a technical affair, and learning takes place within the boundaries of the epistemic community of coastal engineers, while the design of the Sand Engine integrates ecology, recreation, land use and other aspects of coastal management. Its size, its visibility and its many stakeholders make it an issue of public, and thus political, debate. Decision-making is no longer a matter of coastal engineering, but one of integrated governance. A potential advantage is that public involvement raises awareness—stakeholders can see and visit the Sand Engine and are able to learn about the importance of sound coastal flood protection.

4 Discussion and conclusions

This paper has explored the added value and the limitations of Building with Nature strategies for coastal maintenance and protection. In the light of sea-level rise and the increasing probability of severe storms in many parts of the world, as well as the growing vulnerability of rapidly urbanizing delta areas, more sustainable coastal protection strategies are needed.

We have developed a conceptual framework for evaluating coastal protection strategies based on socio-ecological systems. The starting point is that humans and their natural environment are seen as interacting parts of one dynamic system. The consequence of this position is that old paradigms in which the sea is regarded as a separate system, such as ‘water is an enemy to be fought’, or ‘resisting the sea with all the power we can mobilize’, are no longer valid. We have identified resilience, social learning and the use of ecosystem services as three elements of such socio-ecological systems and have used this framework to ‘read’ three coastal protection strategies. This approach may also be useful in other applications, but the crucial step concerns the selection of appropriate elements. Although the framework can be used to analyse and compare different strategies in a qualitative way, for more detailed and quantitative analyses, sharper definitions of concepts (system boundaries and interaction processes, levels of resilience, etc.) are required.

The potential of this approach is illustrated using a case study of the Holland coast, where a resistance strategy based on ‘hard engineering’ was replaced by a resilience strategy based on ‘soft engineering’ via regularly distributed small-scale shore nourishments and an experiment with a concentrated mega-nourishment with 20 million m^3 of sand. The reason for this transformation was that the loss of beaches and dunes due to hard structures was considered unacceptable and unsustainable in the light of climate change. The present coastal maintenance practice of small-scale nourishments is climate-robust for existing beaches and dunes, as it is flexible and adaptable. Mega-nourishments are expected to mitigate some of the negative impacts of small-scale nourishments and create additional wildlife habitats and opportunities for recreation and economic activities.

The Delfland Sand Engine experiment, if properly monitored and analysed, will generate important new knowledge and expertise regarding the behaviour and the effects of such coastal maintenance strategies. The multidisciplinary design approach also involves public administrators, stakeholders and the public. It does so by considering people as integral parts of the ecosystem, interacting with other parts of the system and influencing its services to society. It is early days, however, to draw definitive conclusions on the effectiveness of the mega-nourishment approach.

The Delfland Sand Engine has attracted international interest and has been discussed at international platforms such as the World Water Forum in Marseille, France, in March 2012. The design, scale and setting of the Delfland experiment, however, are site-specific and cannot simply be replicated elsewhere without taking due account of each local situation. The mega-nourishment experiment is a logical next step in the existing coastal maintenance strategy with shore nourishment in the Netherlands. The technical and institutional requirements for such nourishments are in place, and they are accepted by politicians and the public.

In order to answer the question of how effective Building with Nature approaches will be in sustainably maintaining soft-sediment coasts, more research and innovation is needed. Developing the necessary knowledge, tools and expertise remains a challenge. There are several important lines of research, including ecosystem restoration (Mitsch and Jørgensen 2004), the use of bioengineering (Borsje et al. 2011) and the valuation of ecosystem services (Costanza et al. 2008). In an analysis of the role of vegetation in coastal wetland protection, Gedan et al. (2011) caution against overenthusiasm about the use of eco-engineering. They believe that such projects need to be carefully implemented, based on deep knowledge of the local situation, implying that generic knowledge will be of limited value if it is not carefully translated to suit local conditions. Adger et al. (2005) stress the urgency of enhancing the resilience of coastal systems, but point out that a project or engineering approach alone will not be sufficient if the underlying causes of the declining resilience (human pressure and climate change) are not addressed.

Because we cannot wait until these larger challenges are met, it is essential that we improve the knowledge, tools and expertise needed to develop new, sustainable ways to protect our coasts. We have to learn to avoid engineering that aggravates the decline of coastal resilience while maintaining societally acceptable levels of flood safety. Real-life experiments have a crucial role to play in this process.

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