ShoreScape: Nature-Based Design for Urban Coastal Zones

van Bergen, J.; Nijhuis, S.

Publication date
2020

Document Version
Final published version

Published in
Coastal Management 2019

Citation (APA)
van Bergen, J., & Nijhuis, S. (2020). ShoreScape: Nature-Based Design for Urban Coastal Zones. In N. Hardiman (Ed.), *Coastal Management 2019: Joining forces to shape our future coasts* (pp. 319-332). ICE Publishing. https://www.icevirtuallibrary.com/doi/full/10.1680/cm.65147.319

ICE Publishing

Nick Hardiman and the Institution of Civil Engineers
ISBN 978-0-7277-6514-7
https://doi.org/10.1680/cm.65147.319

ShoreScape: Nature-Based Design for Urban Coastal Zones

Janneke van Bergen, Delft University of Technology - Faculty of Architecture & The Built Environment, Delft, The Netherlands
Steffen Nijhuis, Delft University of Technology - Faculty of Architecture & The Built Environment, Delft, The Netherlands

Abstract

Since the 1990's the Netherlands has changed its coastal defence system from hard to sediment-based measures, compensating coastal erosion by adding sediment to its sandy shores. In order to keep pace with sea level rise, more nourishments will be needed in the future, including the 'Building with Nature' (BwN) technique: large scale nourishments to feed the coastal system for a longer period of time and using natural forces to bring sediment ashore. However, these dynamic nourishments are still in development and put new demands on spatial coastal planning to support dune formation and increase the coastal buffer zone.

The objective of this paper is twofold: (1) to discuss how the interactions between the land-shaping processes induced by the nourishments and other coastal functions can be improved as stepping-stones to new design principles for integrated coastal planning enhancing BWN processes, and (2) to provide an overview of initial design principles. Two Dutch cases serve to illustrate the land-shaping processes and the involved design principles.

The Walcheren case shows a regional design study for the positioning of BwN (mega) nourishments. This mega-nourishment feeds the narrow dune system as an alternative to the current (more frequent) ways of local beach nourishment. By zoning and staging the nourishment and land use, not only coastal safety, but also other coastal functions, such as recreation, waterfronts and ecology can be improved.

The Sand Motor is a prime BwN experiment of mega nourishments in the south of Holland. It is now seven years in progress, featuring an accreting shore, new embryonic dune formation and increased beach recreation. The study shows on a local scale how morphological processes and urban use have evolved and how these processes could be altered and integrated in order to enhance BwN fore dune formation to enlarge the coastal buffer against erosion.

The case studies show that the regional design and spatial zoning of nourishment dynamics can help to fine-tune BwN with other coastal functions, such as waterfronts and nature reserves. On the local level dune formation can be improved by adjusting the initial nourishment design, urban and ecological layout to the desired sand transport, using natural landscaping mechanisms as design principle. These will be investigated further in the ShoreScape project.

Introduction

Due to climate change and sea level rise, urban coastal areas around the world face increased risks of coastal flooding and erosion; leading to loss of land, lives and settlement. To avoid losses in the present and future, we must rethink and redesign coastal zones in a more integrated way. Since the 1990s, the Netherlands has changed its coastal defence strategy from hard to sediment-based defence measures: compensating coastal erosion by adding sediment (nourishments) to its sandy shores. The government is now nourishing around 12 million m^3 of sand per year, but this amount may triple or more towards 2100 to keep pace with an increasing rate of sea level rise. To investigate the efficiency of such large scale nourishments, 'Building with Nature' (BwN) pilots are now executed: large scale nourishments to feed the coastal system for a longer duration of time and using natural forces to transport the sediment to the coast.

However, these dynamic nourishment techniques are still in development and put new demands on spatial coastal planning. More knowledge is needed on the resulting dune formation and urban use. The question is how to position and tune these dynamic nourishments; not only to optimize them for coastal safety, but also sync them with the coastal urban and ecological functions. Therefore, new design principles are needed for both land shaping processes and adaptive urban and ecological configurations to deal with coastal dynamics such as erosion, nourishments and accretion in order to increase the buffer capacity of coastal zones.

The ShoreScape project (2017-2022), an interdisciplinary collaboration of the University of Twente and Delft University of Technology, focuses on coastal urban configurations that integrate pro-active sediment management using the 'Building-with-Nature' (BwN) technique (Wijnberg et al. 2016). The sandy, dune-aligned west coast of the Netherlands is currently employed as a 'Living Lab' to study the interaction of Aeolian sediment flows and building-configurations in the beach-dune environment. This is done through research by design, field experiments and computer modelling.

The objective of this paper is twofold: (1) to discuss how the interactions between the land-shaping processes induced by the nourishments and other coastal functions can be improved as stepping-stones to new design principles for integrated coastal planning enhancing BWN processes, and (2) to provide an overview of initial design principles. Two Dutch case studies, Walcheren and the Sand Motor, are used to illustrate these processes and identify design principles.

The paper is structured in three parts: The first part addresses the set up and methodology of the ShoreScape project. The second part addresses two Dutch cases: Walcheren and the Sand motor. The last part reflects on the two Dutch cases and gives an overview of the lessons learned for the spatial integrated planning of BwN to support coastal buffer zones.

Building with Nature Redefining Coastal Planning

Sandy shores worldwide face sea level rise due to climate change, leading to an increased risk of coastal flooding and the loss of land, lives and settlement. To anticipate these coastal processes now and in the future, we have to rethink and redesign coastal zones in a more integrated way. As an urbanized delta, the Netherlands is obliged to renew its water strategy continuously. The Dutch coasts' sandy shores currently protect two-thirds of the country against the sea. The fore-dunes provide a storm buffer and are maintained by coastal 'nourishments' adding sediment to the system. Sea level rise makes it necessary to expand and innovate this strategy, not only to make coastal protection more sustainable, but also to integrate it with the other coastal functions.

Since the 1990s, the Netherlands has changed its coastal defence strategy from hard to sediment-based coastal defence measures. Sandy nourishments are more effective, are more compatible with the natural coastal morphology and offer higher resistance during storms compared to hard structures such as seawalls. Currently, the Dutch coast is nourished with about 12 million m^3 of sediment per year. This volume may triple or more (Delta programme Coast, 2013; Haasnoot et al., 2018) by 2100, in order to keep the sand volume of the coastal system in equilibrium with an increasing rate of sea level rise. To investigate the efficiency of large-scale nourishments, Dutch test pilots such as the Sand Motor (2011-2031) (Mulder and Tonnon, 2010) are being executed in South Holland (figure 1). The central notion to the experiments is the BwN technique (De Vriend et al., 2015), where sediment is added to the fore shore and natural forces from tides, waves and wind are used to transport it to the shore in order to strengthen the dunes for coastal safety. The Sand Motor project is now used as an example for other Dutch mega-nourishment projects, such as the coastal reinforcement of the Hondsbossche Zeewering.

Figure 1: Sand Motor in progress (RWS)

These dynamic nourishment techniques are still in development and put new demands on spatial coastal planning. Solutions for coastal erosion are often sectoral and tend to be only made from an engineering perspective. Effects of these solutions on other functions are often neglected, for example 'Safety zones' restricting urban use. Also, other coastal functions have negative impacts as well; for example, recreation can affect the vegetation that is vital for stabilizing the dunes. Current urban typologies, such as boulevards or beach row housing, are not equipped to anticipate to dynamic land-shaping processes and obstruct the sediment transport to the dunes. In addition, the Natura 2000 values do not always correspond with a nourished shoreline. These examples show that interactions between coastal functions do not always run smoothly and limit the build-up of a more resilient coastal defence zone. Therefore, a more integrated approach is necessary, connecting different coastal functions to enhance a more sustainable adaptation to sea level rise.

ShoreScape: an Integral Approach for Coastal Zones

How to engineer and design dynamic nourishments; not only to optimize them for coastal safety, but also sync them with the coastal urban and ecological functions? The ShoreScape project addresses this issue and aims to develop design principles for integrated coastal landscaping connecting adaptive urban and ecological design with morphological processes (Wijnberg et al., 2016). These principles deal with coastal dynamics such as erosion, nourishments and accretion and employ BwN mechanisms to increase the buffer capacity of coastal zones. In this project, the disciplines of civil engineering, urban and landscape design and computer science are combined to investigate, model and test the interaction of dune formation and BwN based urban planning as a means to construct sustainable coastal buffer zones.

ShoreScape focuses on Aeolian (wind driven) Building with Nature processes to stimulate dune growth in combination with adaptive urban and ecological design. New coastal configurations are explored that integrate pro-active BwN-based sediment management and urban program into a multi-functional adaptive coastal landscape. Better understanding and integration of natural dune formation, urban and ecological processes is needed to set new conditions for sediment dynamics and settlement. They should lead up to the planning of more sustainable coastal ‘buffer’ zones that combine flood defence, urban- and ecological development and improve the spatial quality of the coastal landscape.

In the research approach, the coastal zone is regarded as the interplay of three systems: the morphological system, the urban and the ecological system (figure 2). Each system interacts and creates conditions for other systems in the coastal zone. Current interactions (such as erosion, urban development and loss of stabilizing vegetation) show that interdependencies between the systems do not always run smoothly. However, analysis of the overlapping mechanisms also offers a key to improve collaboration between the systems, creating a positive feedback. The question is; how can integral spatial design rearrange morphological, ecological and urban development to create more synergy and enhance BwN-based dune formation for coastal protection?

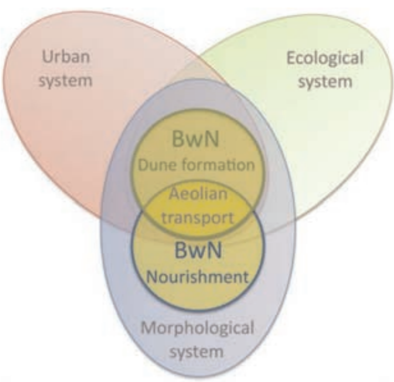

Figure 2: Interplay of the 3 coastal systems, with Building with Nature as main strategy

The sandy, dune-aligned west coast of the Netherlands is employed as a Living Lab to study the interaction of Aeolian sediment flows and building-configurations in the beach-dune environment. In the first phase of the project, initial spatial design principles are composed based on systems analysis and development through field observations and GIS-analysis. In the second phase these initial designs will be tested in peer-reviewed case studies, field-experiments and computer modelling. The central notion is to support BwN dune formation and to increase coastal resilience by re-designing the interaction between the coastal systems. Walcheren and the Sand Motor serve as cases to elaborate on the involved processes and showcase initial design principles.

Case study Walcheren: Optimizing BwN for Spatial Functions

The Walcheren case study shows a regional design study on the positioning of BwN (mega) nourishments aimed to feed the narrow dune system and complement the urban program in a collaborative way. The case study investigates how zoning and staging of the nourishments and urban use combines into a dynamic multifunctional coastal program supporting the morphological, urban and ecological system.

Figure 3: Map of west-Walcheren (www.opentopo.nl) and photo of the 'Manteling' (right) with forestry as former BwN method against erosive, mobile dunes

The Isle of Walcheren is situated in the Dutch South West Delta. It started off as a dune ridged sand bank in the delta and was then reclaimed centuries later. Through time the dunes of Walcheren became erosive and moved landward. Severe erosion of the west cape around 1500 even forced the village of Westkapelle to retreat and turn the dunes into a double seawall. The mobile northern dunes were finally stopped by foresting, an old BwN method. The resulting forest is still visible today (the so called 'Manteling', figure 3) and now hosts a beautiful landscape of dunes, forest and countryseats.

Coastal Safety Walcheren

The dynamic coastal system of Walcheren presents a number of challenges, including the consolidation of advancing tidal channels off Noord-Beveland and Westkapelle. Without corrective actions, these channels threaten the coastal safety and stability of the shore. Locally, erosion along the north coast of Walcheren has narrowed the beaches to the extent that they are no longer suitable for recreation. Since the 1990's, the littoral strip has been nourished to prevent further erosion and this has held the shoreline in place. At the moment, one-eighth of the Dutch national nourishment programme is nourished here, making Walcheren an intensive zone of nourishment. Most of the nourishments are beach nourishments in smaller volumes recurring every 4 years (figure 4). They maintain the coastline, but do not anticipate to the need of increased dune formation for coastal safety on the long term.

Figure 4: Recent beach nourishment programme west-Walcheren (Prov. of Zeeland)

An Alternative BwN Scenario for Walcheren

In 2013, the long-term vision for the Dutch coast (Delta programme Coast, 2013) was explored, including regional workshops with stakeholders (Hoekstra, Van Bergen et al. (2013). It focussed on a nourishment strategy till 2100 with optimization for social-economic and ecological functions. The study resulted in a regional seaward design for Walcheren, including the application of a BwN-based mega nourishment, fine-tuned for functions along its route. The central notion in this proposed strategy is to project a mega-nourishment on the cape, the weakest point in the coastal defence by using the natural dynamics of sand waves in this area moving from west to east (figure 6). This creates a temporary beach that could give an incentive to establish recreation in this western (seawall) area, with a flexible recreational programme to fit its high dynamic development. This mega-nourishment could then gradually feed the eastward beaches of Domburg, a historical seaside resort with a close connection to the sea. The gradual annual flow of sediment might offer a more stable beach and swimming environment suited for this historical seaside resort.

Figure 5: The historical seaside resort of Domburg (RWS beeldbank)

More to the east, the dunes of the Manteling are known for its calcium deficient grey dune habitats. These habitats profit from erosive dune cliffs, allowing sediment to blow deeper into the dunes. Beach nourishment stimulates new fore dune growth, obstructing the sediment transport to the inner dunes. This increases succession. Therefore, in the regional design nourishments in the eastern area are reduced in favour of the grey dune habitats and gradients perpendicular to the coast (figure 6). The dune ridge here is wide enough to allow for natural coastal erosion within the contours of coastal safety. Nature values are increased further by zoning recreation into central places, north of Domburg and along Veerse Dam.

Figure 6: Mega-nourishment design for west-Walcheren feeding the waterfront of Domburg, with dynamic dunes for the ecology of the Manteling (Studio Coastal Quality, TUD)

Findings Walcheren: Integrated Design Optimizing BwN Nourishment for Coastal Functions

The regional design for Walcheren shows how BwN-design might offer opportunities for more efficient ways of coastal nourishment by making maximum use of natural dynamics. Furthermore it shows how the different stages of development of the nourishment can be fine-tuned with other coastal programs (urban, ecological) to reach an optimum in functional use. The fine-tuning is based on the desired coastal profile, the amount of dynamics and trajectory development in time and is planned in three optimized zones: a high dynamic extended zone at the heart of the nourishment; a gradually fed mid-section supporting the waterfront functions; and an erosive part where nourishment is limited for ecology. Its sequential design is an example of a regional design principle for the planning of BwN mega-nourishments in urbanized coastal zones. It allows for more dynamics (seaward/landward) in rural or ecological areas, whilst offering more stable beach conditions in urban areas. This integrated design study, where the sum of the joint planning is more than its separate components, has proven its value during the later re-assessment of the nourishment plan for the isles of Zeeland. It resulted for example in the transfer of a planned beach nourishment at the cape of Schouwen (2015, north of Walcheren) to Brouwersdam in favour of the dynamic grey dune ecology and landscape.

Sand Motor: From Sand Nourishment to Dune Formation

The Delfland Coast Sand Motor is a prime BwN experiment for mega-nourishment in the south of Holland. The hook-shaped peninsula of about 20 million m^3 of sand (128 ha) was constructed in 2011 and was designed to erode and feed the shore with sediment for 20-50 years. Presently, the project has been ongoing for seven years and has continued to slowly erode and spread sediment along the coast (Taal et al, 2016). On the south side, this has led to an accreting shoreline and a new embryonic dune formation. The northward directed peninsula has attracted extra beach recreation. This study analyzes how the initial nourishment design has affected the dune formation pattern and explores how spatial design integrating morphological, urban and ecological configuration might contribute to the aspired BwN-based fore dune formation. The study was based on field observations (September 2018) and GIS-analyses of the coastal profile development.

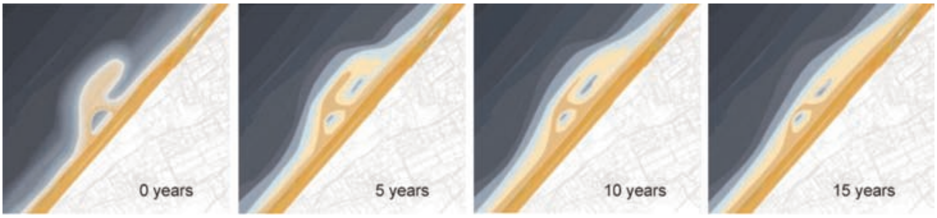

Figure 7: Predicted progress of the Sand Motor (www.zandmotor.nl)

Building Towards a Coastal Buffer

The main goal of the Sand Motor is "the encouragement of natural dune growth on the Delfland Coast between Hook of Holland and Scheveningen. This dune growth is not only to improve coastal safety, but also nature and leisure activities" (Taal et al., 2016). The initial volume of the Sand Motor corresponds with the volume needed for 50 years of the coastal maintenance between Hook of Holland and Scheveningen (Taal et al., 2016). Vegetated fore dunes is a desirable final state for the sediment to accrete in a sustainable way (Vliet, et al, 2017) offering maximum resistance during storms. Assuming that a quarter of the nourished sediment of the Sand Motor becomes available for dune formation (after Van der Wal, 1999), this volume (5 Mm^3) would correspond with an additional fore dune of ca +100m wide and 3m height and an estimated construction time of 21 years.

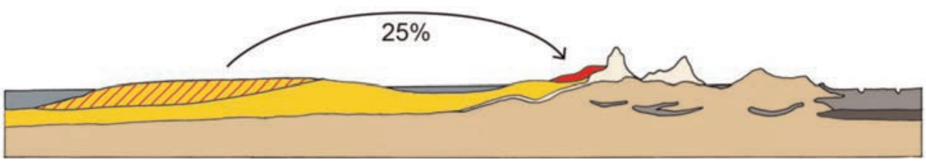

Figure 8: Section of the Sand Motor with initial volume and aspired buffer

Key Mechanisms for Dune Formation

The study investigated how integral coastal design can contribute to the improvement of the BwN process design of the Sand Motor, and direct more sediment to the fore dunes. The evaluation report of the Sand Motor (Taal et al., 2016) showed that fore dune formation has been affected by two main factors: design and use of the Sand Motor. Design features such as the central lake, the lagoon and the high barrier have obstructed fine sediment transport and delayed the embryonic (vegetated) dune growth for 5 years. The first vegetated embryonic dunes for example only occurred in 2016 (figure 9).

At the same time, urban use has also affected the natural growth of dunes. Around beach accesses and beach pavilions embryonic dune growth is interrupted due to loss of vegetation by recreational use and coastal maintenance (e.g. the removal of the winter flood mark). Vehicle transport lines also affect fore dune formation. Beach pavilions on stilts show increased lateral horseshoe deposition or 'Sand tails' behind the building caused by turbulence: accelerated and decelerated airflow resulting in the pickup and accretion of sediment (See section below (11)).

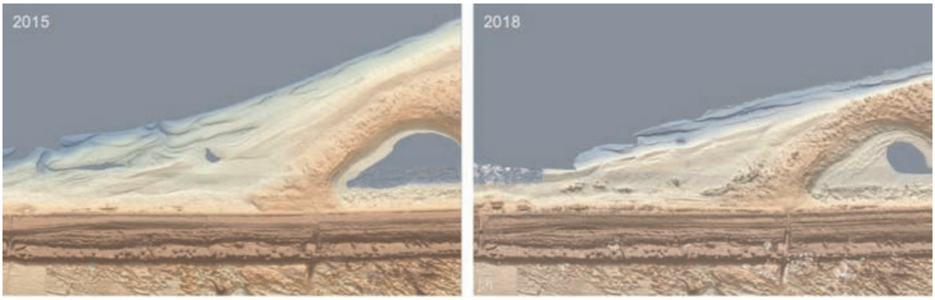

Figure 9: Dune formation on the Sand Motor: accreting shoreline (left) and embryonic dune growth (right)

Both insights offer opportunities to improve the BwN design for dune formation. Another opportunity is derived from the insights into the long shore development of the Sand Motor over time. The Sand Motor progressing along the coast will induce an accreting shoreline followed by the formation of new embryonic dunes. On one hand, these embryonic dunes catch and stabilize sediments from the high dynamic transport zone near the berm through pioneering vegetation such as Marram grass. It results in a series of beach ridges following the accreting shoreline (see figure 9). On the other hand, these new vegetated beach ridges; formed seawards of the existing dune front within 1-3 years; block a large part of the landward sand transport. They prevent the inland fore dunes to receive fresh sand supplies which are essential for bio builders like Marram grass. This delays the process of direct fore dune formation.

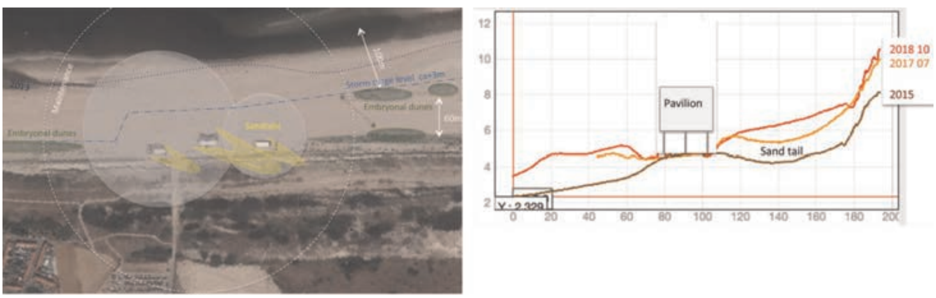

Figure 10: Left: urban use limiting embryonal dune growth (Aerial photo: PDOK.nl) Right: shadow dune formation behind beach buildings

Spatial Design supporting BwN Dune Formation

Improvements in dune formation start off with the initial nourishment design. As the evaluation report of the Sand Motor shows, the optimization of the coastal nourishment profile (elimination of the lake and barrier, adding gentle slopes) might help to improve the landward transport of fine sediment.

A closer look at the observed land shaping processes and their interaction with urban use offers other opportunities for the enhancement of the desired landward sediment transport. By rearranging the local effects of urban use and morphological build up, integral spatial design can help to improve the sediment flow to the fore dunes. One option is to move the urban program (beach access and buildings) to the south accretion zone of the Sand Motor. This limits the growth of (vegetated) beach ridges, keeping sediment mobile for transport inland. At the same time, the 'Sand tail' pattern of seasonal beach buildings offers chances to catch additional sediment, that supports the main goal to broaden the existing fore dunes as a coastal buffer. This sediment can be collected during a sequence of summers (S1, 2, 3, 4) in a dynamic urban set up that moves along with the shifting shore and transport zone. The resulting 'sand tail' patterns then act as local Aeolian sand sources during the winter season to feed the fore dunes inland. Corridors between the beach buildings can offer high-speed inland transport during storms (figure 11).

Once transported inland, ecological interventions can be used for accretion and stabilization of sediment in a desired fore dune locations. In fact, the Netherlands has a very long tradition in sediment catchment by nature, such as: the planting of Marram grass in fore dune areas, the placing of brushwood wind fences or foresting of erosive dunes. These BwN methods could be introduced in the Sand Motor area to speed up fore-dune formation. Planting Marram Grass for example is very effective due to its extensive root system and ability to build up the fore dunes in height. Literature also shows that dynamic fencing could increase accretion (Goldsmith, 1985) and reduce the construction time of fore dunes substantially. The ways of accelerating (fore) dune formation will become more valid in the future, when the lifespan of nourishments will be reduced due to increasing sea level rise.

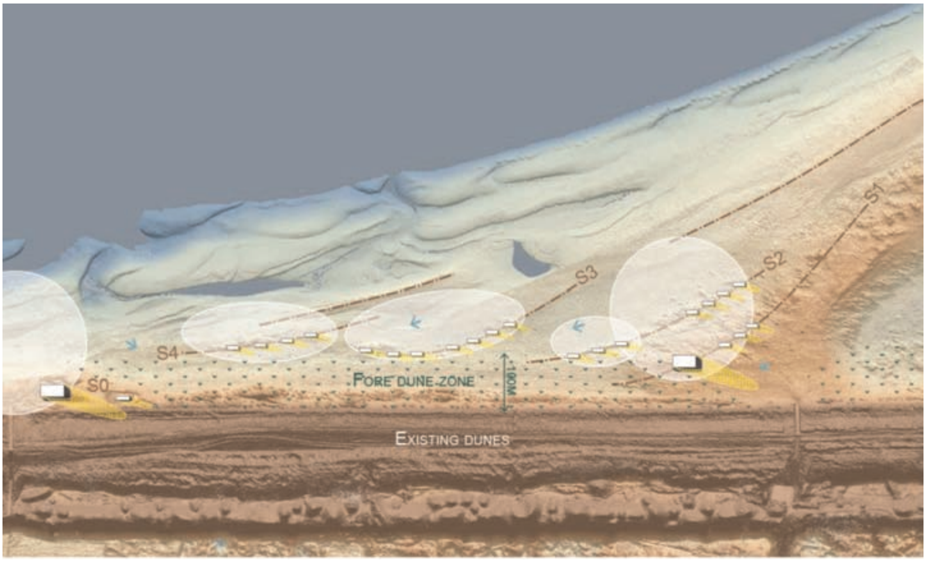

Figure 11: BwN ensemble of beach houses situated on beach ridges to keep sediment mobile for landward fore dune formation (green)

Findings Sand Motor: Spatial Design Integrating Morphological, Urban and Ecological Layout to Support BwN Dune Formation

The Sand Motor design study is an example of the optimization of sediment flow, urban and ecological design in order to induce and accelerate BwN dune formation, needed for the formation of a sustainable coastal buffer zone for the protection of South Holland. By redirecting morphological development, urban and ecological programmes through design intervention, not only the efficiency of the BwN nourishment can be improved, but also the functional use of the coastal zone. Once the final goal of the Aeolian sediment flow is set (in this case reinforcing the fore dunes), key spatial features, such as urban use preventing the growth of beach ridges, or the accretion via the 'Sand tails' behind beach buildings can help to collect and keep sediment mobile for inland transport. Zoning and vegetation planting in the fore dune zone can help to accrete and stabilize sediment in order to extend the coastal buffer (figure 12). These are examples of local design principles for the layout of mega-nourishments, steering and stabilizing sediment to the right places, supporting BwN dune formation, whilst giving room for urban and ecological use. These design principles will be explored further in ShoreScape in order to compose a palette of integral BwN design principles for coastal buffer zones.

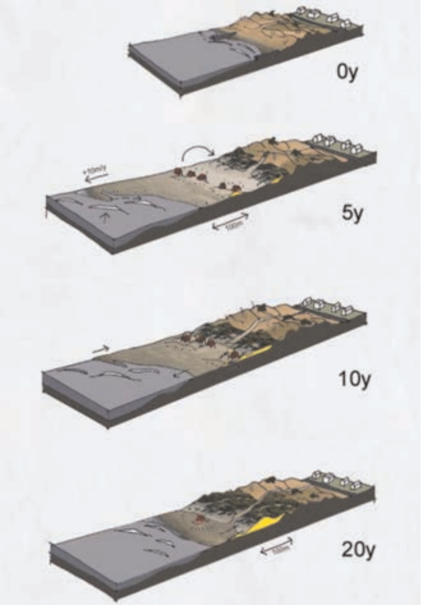

Figure 12: Design sequence of BwN fore dune formation following mega-nourishment

Conclusion: Integral Design Principles for BwN based Dune Formation

To compensate coastal erosion and sea level rise in the future, suited for the natural dynamic character of sedimentary coasts, mega-nourishments along urbanized sandy shores will play a role of increasing importance. To increase the efficiency of these BwN based nourishments, more integrated design is needed on the resulting dune formation process:

- Design of the evolution of the nourishment in space and time in correspondence with dune formation processes in order to increase the coastal buffer and dynamics for coastal functions
- Optimization of the urban and ecological functions enhancing BwN dune formation and vice versa.

The regional case study of Walcheren shows that larger scale BwN nourishments might offer an interesting alternative to the current, more frequent, smaller scale nourishments. Regional design and spatial zoning of the nourishment dynamics (high/low, expanding/eroding) can help to fine tune BwN nourishment with other coastal functions. This could not only result in more effective ways of nourishment, but also in a more dynamic and varied coastal landscape.

The local case study of the Sand Motor shows that optimisation in the nourishment design and process can help to speed up fore-dune formation. This process can be backed up by spatial design that integrates urban and ecological interventions to support the BwN-processes, whilst maintaining multi-functional use in this dynamic engineering context.

When zooming into land shaping coastal processes, there are three main spatial factors: the initial nourishment, urban use and ecological succession. Each factor has key spatial features to influence the dune formation process. Regarding the nourishment, the design of the coastal profile over time is a key to improve the landward transport of sediment, for example by limiting steep obstacles or water bodies. In urban and ecological design, the acceleration or deceleration of wind transport plays a key role in order to steer sediment to the correct locations. Vertical buildings for example cause turbulence and acceleration of sediment transport, whilst vegetation can slow winds down, resulting in accretion and stabilization of sediment.

In the Sand Motor study, several spatial mechanisms were identified that can be used for intervention. Urban use for example can be used to keep sediment mobile in the foreshore. Urban structures, such as pavilions on stilts, create ‘Sand tails’ that can be used to harvest sediment for dune formation. They are examples of ‘Urban Harvesting’: increasing landward sediment transport through urban intervention. Ecologically there are also ways to direct sediment, for example through the planting of Marram grass or eco-fences. These interventions support accretion, as examples of ‘Dune Farming’ (figure 13). These spatial mechanisms provide the basis for design principles supporting BwN dune formation processes and make the connection between the morphological, urban and ecological system. Integrating them by spatial design will not only improve spatial synergy between the coastal systems but will also contribute to the establishment of sustainable coastal buffer zones powered by BwN-based dune formation.

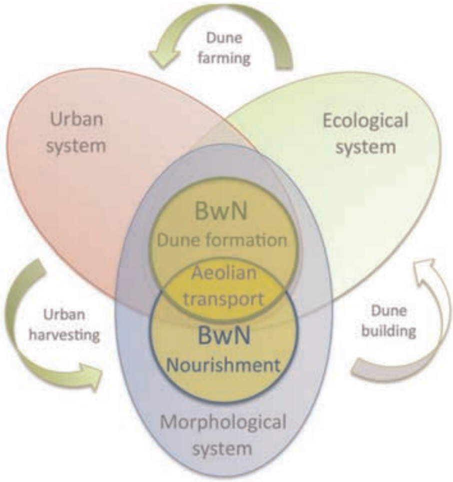

Figure 13: Joining principles for BwN dune formation

Future research is needed to validate and test the design principles of urban harvesting and dune farming. In the second phase of the ShoreScape project (2019-2021), the initial integral design principles will be elaborated further and tested in (peer reviewed) case studies, field experiments and computer modelling.

Acknowledgements

Shorescape is funded by NWO, the Netherlands Organisation for Scientific Research (Top Sector Water grant ALWTW.2016.038) and consortium partners HHNK, RWS, HNS, Witteveen + Bos, Deltares, Imares-WUR.

We like to thank Dr Jan Mulder for his proofreading and invaluable advice and Prof Kathelijne Wijnberg from the University of Twente for providing data and feedback.

References

Delta programme Coast (2013) *National Coastal Strategy*, pp 37, Ministry of Infrastructure & Environment. This vision predicts volumes between 30 till 66 million m3/year or more based on the sea level prognosis of the Delta Programme (2013), referring to the report *Zandsuppleties in de 21ste eeuw, onderzoek naar alternatieve lange termijn suppleties t.b.v. Deltaprogramma Kust*, final rapport, Deltares, 2012.

Goldsmith, Victor (1985) Coastal Dunes, *Coastal Sedimentary Environments*, second Revised, Expanded Edition, by R.A. Davis, Springer-Verlag New York, p303-370.

Haasnoot et al (2018) *Mogelijke gevolgen van versnelde zeespiegelstijging voor het Deltaprogramma, een verkenning* (Possible effects of accelerated sea level rise for the Deltaprogramme) p11, Deltares. The estimated nourishment volume of 120 million M3/year (median K5) is based on the IPCC RCP 4.5 sea level rise scenario, and corresponds with 2 degrees Celsius temperature rise in 2100 (policy target Paris Convention on Climate change).

Mulder, J.P.M, Tonnon, P.K. (2010) *“Sand Engine”: Background and design of a mega-nourishment pilot in the Netherlands*, Coastal Engineering Proceedings, no 32.

Hoekstra, J.D.; Bergen, van, J. *et al.* (2013) *Ontwerpen aan de Zandige kust*, TU Delft.

Taal, M.D. et al *Development of the Sand Motor* (2016), Deltares. Erosion of the Cape in the period 2011-2016 was ca 250m, spreading along the coast was +2,2km.

Vliet, X.X. et al (2011/2017) Reserveringszone, Stowa/Foundation For Applied Water Research.

Van der Wal, D. (1999) Aeolian transport of nourishment sand in beach-dune environments, p129, UvA.

Wijnberg, K., Nijhuis, S. & Hulscher, S. (2016) *SHORESCAPE: Sustainable co-evolution of the natural and built environment along sandy shores*. University of Twente, Faculty of Engineering Technology, Dept. Water Engineering & Management & Delft University of Technology, Faculty of Architecture and The Built Environment. NWO Top Sector Water grant ALWTW.2016.038.