Urban dunes
Towards BwN design principles for dune formation along urbanized shores

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Abstract

Sandy shores worldwide suffer from coastal erosion due to a lack of sediment input and sea-level rise. In response, coastal sand nourishments are executed using 'Building with Nature' techniques (BwN), in which the sand balance is amplified and natural dynamics are instrumental in the redistribution of sand, cross- and alongshore. These nourishments contribute to the growth of beaches and dunes, serving various design objectives (such as flood safety, nature, and recreation). Nevertheless, human interference (such as buildings and traffic) along urbanized sandy shores may have significant, yet poorly understood, effects on beach and dune development. Better insight is required into the interplay of morphological, ecological and urban processes to support Aeolian BwN processes for dune formation and contribute to the sustainable design of urbanized coastal zones. This paper aims to bridge the gap between coastal engineering and urban design by formulating design principles for BwN along urbanized sandy shores, combining nourishments, natural dune formation and urban development on a local scale to strengthen the coastal buffer. The first part of the paper analyses sedimentation processes in the (built) sea-land interface and identifies spatial mechanisms that relate coastal occupation to dune formation. Hence a preliminary set of design principles is derived by manipulating wind-driven sediment transport for BwN dune formation after nourishment. In the second part of the paper, these principles are applied and contextualized in two case-studies to compare their capability for BwN in different coastal profiles: the vast, rural, geomorphologically high dynamic profile of a mega-nourishment (Sand Motor); versus the compact, highly urbanized, profile(s) of a coastal resort (Noordwijk). Conclusions reflect on the applicability of BwN design principles within different coastal settings (dynamics, urbanity) and spatial arrangements facilitating BwN dune formation.

KEYWORDS

Building with Nature, nourishment, dune formation, urban coast, design principles

1. Introduction

Sandy shores offer a multitude of ecosystem services; regulation- (e.g. flood protection), production- (e.g. drinking water, tourism) and cultural services (e.g. recreation), all depending on the quality of supporting services (e.g. natural balances of water, nutrients and sediment). For *sandy* shores especially, the long-term physical existence is dependent on the sediment balance in response to sea-level rise. Therefore, sediment balances and dynamics are conditional to any spatial design of sustainable urbanized sandy shores.

Examples of such a design are sand nourishments where, in accordance with 'Building with Nature' techniques (BwN), the sand balance of the system is amplified and natural dynamics are instrumental in the redistribution of sand cross- and alongshore. The Netherlands have been employing sand nourishments for coastal management since 1990, with an average yearly nourishment volume of 12 million m^3 of sand since 2001, serving different design objectives (flood protection, nature, urban and/or economic activities). Typical magnitudes of individual nourishments vary between 0.5 and 2 million m^3 (Mulder et al., 2011); whilst the Sand Motor is an experimental mega nourishment of 20 million m^3. Results are positive, featuring seaward trends for shoreline development and improved safety levels (Giardino et al., 2012, 2013, 2014).

After nourishment, the sediment is transported by natural processes (waves, tide, wind, etc.) to become part of the beach and dune system. These dunes depend on wind-driven sand transport to recover from storm erosion and to counterbalance for sea-level rise and higher storm impacts due to climate change (Morton et al., 1994; Carter, 1991; Keijsers, 2015; De Winter & Ruessink, 2017). This makes the supply and free movement of sediment essential for dune formation as part of the coastal buffer.

A main concern is that coastal zones are becoming increasingly urbanized, not only in the Netherlands, but also globally (Hoonhout & Waagmeester, 2014; Hall, 2001; Schlacher et al., 2008; Malavasi et al., 2013). This includes recreation, traffic, beach housing, and waterfront development. Stabilization of the Dutch coastline through nourishments has attracted more economic development and led to a twentyfold increase of beach housing in the last decade (Armstrong et al, 2016; Broer et al., 2011; Panteia, 2012; Buth, 2016).

These forms of urban occupation may have significant, yet poorly understood, effects on beach and dune development, affecting the sediment transport to the dunes (Nordstrom and Jackson, 2013). Better insight is required into the interplay of morphological, ecological and urban processes to support BwN for the consolidation of urban coastal zones. A complicating factor is that urban and nourishment strategies are often developed and modelled in isolation. Synergizing these systems not only creates chances to improve dune formation after nourishment, but also gives way for a nature-based reinforcement of the coastal profile in response to sea-level rise, whilst maintaining its function as a vital recreational landscape.

This paper fuses insights from coastal engineering and spatial design to formulate BwN design principles that combine nourishment strategies and urban development to strengthen the coastal buffer. They employ wind-driven (aeolian) processes and spatial interventions for sediment allocation, promoting dune formation. Such an approach depends on the sediment supply from nourishment strategies – in terms of amount, frequency and location (along the coast, on the shore face or beach) – on the regional scale (Mulder et al., 2011) and (adaptive) urban typologies for waterfront development. They set the preconditions for combined morphological and urban development on the local scale, as first outlined by Van Bergen and Nijhuis (2020).

The first part of the paper employs typological research (de Jong & van der Voordt, 2002) to analyse sedimentation processes in the (built) sea-land interface and identifies local spatial mechanisms that relate coastal occupation to dune formation, based on literature-review, GIS-analysis and field experiments (par. 2). Hence a first set of Aeolian design principles is derived to stimulate positive interaction between wind-driven sediment transport and urban construction for dune formation (par. 3).

The second part of the paper discusses two design studies (de Jong & van der Voordt, 2002) that apply and contextualizes the design principles in two coastal settings with contrasting profiles, nourishment regime, and urbanity:

- The vast profile of a mega-nourishment (Sand Motor), featuring a 'low frequent, high volume' nourishment strategy (20Mm^3/25 years) with dominant geomorphological dynamics in a rural setting.
- The compact profile of a coastal resort (Noordwijk), featuring a 'high frequent, low volume' nourishment strategy (5Mm^3/5 years) in an urbanized setting.

Both case-studies explore how the BwN design principles can be employed to compose spatial arrangements accommodating nature-based dune formation (par. 4). This requires an interplay of nourishment, the desired coastal buffer profile and directed sediment transport in the beach-dune interface. Conclusions reflect on the applicability of the BwN design principles within different coastal settings and spatial arrangements to facilitate BwN dune formation (par. 5).

2. Conditions for dune formation

Dunes are a natural coastal phenomenon that can take on many forms and expressions (Van Dieren, 1934). The development of dunes is dependent on geomorphological and ecological mechanisms that operate differently and according to the conditions as put forward by their spatial and geographical context. Alterations in geomorphological parameters and human intervention with wind-driven sediment transport lead to different types of dune formation. In general, there are three main factors that affect dune formation.

The supply of sediment

Sediment is transported ashore by natural processes (waves, tide, wind etc) contributing to beach and dune development. Coastal nourishments mined in the North Sea and transported by ships, bring more sediment into the nearshore, thereby increasing the available sediment budget to land ashore. Up to 25% of the nourished volume can become available for transport to the dunes (Van der Wal, 1999). Sustainable dune formation occurs when the supply of sediment exceeds coastal erosion.

Wind-driven (aeolian) transport is essential for dune formation and recovery after storms. Mega-nourishments can also offer temporary wider and gradually sloping beaches, a positive condition for dune formation (Puijenbroek, 2019). Wider beaches not only provide accommodation space for dunes to form (Galiforni-Silva et al., 2019), but also enlarge the so-called fetch-length: the length of (dry) beach where wind can blow and pick up sediment (Delgado-Fernandez, 2010). The fetch length is related to the wind direction: at more oblique directions (SW and NW in Holland), wind covers a larger stretch of beach before reaching the dunes. The wind driven sediment transport is also dependent on the erodibility of the beach surface, which is related to the ground water levels, and affects the dune topography evolving (Galiforni-Silva et al, 2018) Furthermore, nourished sediment may be coarser and contain more shells, preventing the wind from picking up sediment (Hoonhout, 2019). Thus, sediment availability, fetch-length and ground level height are determining factors for the stimulation of dune formation.

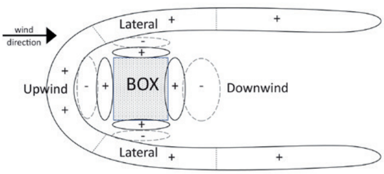
Aeolian sediment transport

Wind has three mechanisms for sediment transport: creep, saltation and suspension. Creep (sediment rolling over the beach) generally starts at wind force Beaufort 4. Saltation occurs when grains are picked up from the bed and make short jumps before hitting the bed again and expelling new grains. Around wind force Beaufort 5-6 sediment transport becomes more substantial and so-called ‘streamers’ occur (Williams, 2019): episodic clouds of repeatedly bouncing particles moving close to the beach. Smaller particles can even become suspended and are carried by the wind over long distances.

Once transported, the sediment is deposited when wind speeds decrease and is trapped at the lee side of objects, the (vegetated) dune foot or the winter flood mark where seaweed and driftwood are deposited. Seeds from pioneering vegetation as Sand Couch and Marram Grass germinate here in spring, stimulating and growing along with sand deposition. If no large storms occur, the first embryonic dunes will form.

Interaction between sediment transport and built objects

Beach buildings alter the wind field and therefore affect sediment transport in their vicinity. The diversion of airflow around a building can decelerate the wind, causing sedimentation (e.g. in front or at the lee side of buildings) and results in a horseshoe deposition pattern (figure 1). Conversely, it can also lead to an acceleration of wind, promoting scour and an increase of sediment transport such as below beach housing on poles (Peterka et al., 1985; Nordstrom, 2000; Jackson & Nordstrom, 2011; Smith et al., 2017). An elementary study on flow dynamics in a CFD computer model (Van Onselen, 2018) has indicated that buildings on low poles (< 0,5m) still stagnate wind flow below and directly behind the building, whilst buildings on higher poles (1 –2m) accelerate the wind compared to non-built situations (figure 2). However, the relationship between sedimentation and pole height needs further investigation.



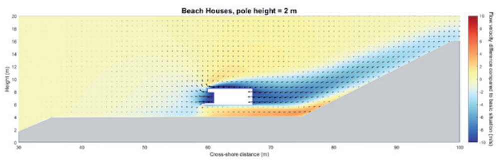


Figure 1 (left). Horseshoe pattern of sediment deposition around a built object (source: D. Poppema, 2019).

Figure 2 (right). Increased flow velocity (orange) below beach housing on 2m high poles (source: Van Onselen, 2018).

Field experiment spring 2019

Effects of elevated beach housing on sediment transport have been investigated in the ShoreScape project during a field experiment in spring 2019. 1:5 scale models with increasing pole heights (in steps of 25 cm) were placed on an wide beach at the Sand Motor (figure 4) for 6 weeks. In weeks 1, 3 and 6 morphological changes around the boxes were measured by Terrestrial laser scanning. From the laser data, sections, difference maps and volume calculations were derived.

Analysis of the elevation difference through maps and sections show that the lower the poles, the more local deposition (and erosion) of sediment, probably due to the larger disturbance of wind speed at ground level. The overall calculated volume change is positive (+7m^3 per box in 6 weeks). This makes non-elevated objects suitable for the local 'harvesting' of sediment (see figures 3, 4, 7a and 7b).

The sedimentation pattern around the elevated boxes is more dispersed. The deposition tail is located at a larger distance from the object, keeping the deposited sediment available for further wind transport

(i.e. the tail is less sheltered by the building). This makes elevated buildings suitable for transitional sediment transport. (see figures 4, 6a and 6b).

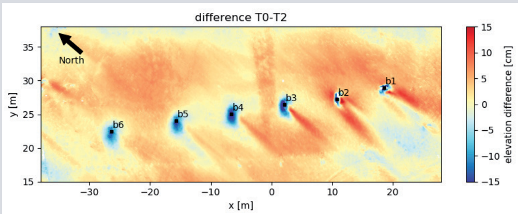


Figure 3 (left) and 4 (right). Final photo and elevation difference map of the beach group - in red the concentrated local deposition (up- and downwind) around the non-elevated boxes (B1, B2); versus local erosion (in blue) and dispersed tails around the boxes with increasing pole-height (B3 (+25cm) - B6 (+1m)

3. BwN design principles for dune formation

The optimization of BwN for dune development along urbanized coasts clearly asks for an integrated spatial design that – besides the chosen nourishment strategy on a regional scale –, is based on design principles at a local scale, taking account of all factors influencing aeolian sand transport in the beach dune interface. Design principles are spatial concepts used to organize or arrange structural elements of the design, in this case, the aeolian sedimentation process. In the previous paragraph the geomorphological and urban mechanisms that influence aeolian sediment transport for dune formation are described. Their spatial parameters can be employed as design principles for sediment allocation at the sea-land interface. A first attempt to define such principles is presented below (figure 5), derived from three determining mechanisms of aeolian sediment transport: A) mobilization, B) acceleration and C) deceleration. For each of them, specific spatial interventions and sediment patterns apply, leading to a preliminary set of six BwN design principles, listed below.

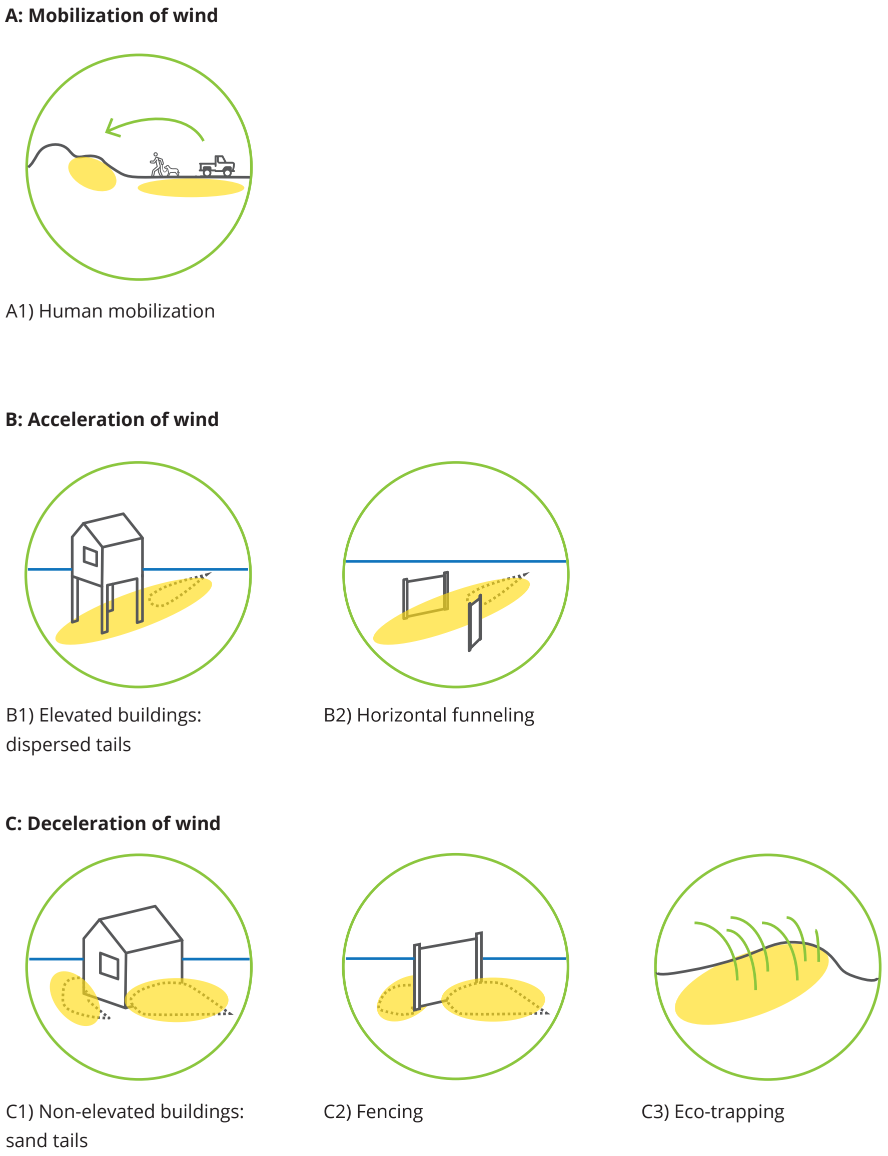


Figure 5. Overview of the six Aeolian design principles

A: Mobilization of wind

Nourished sediment is brought ashore by tidal and wave-driven currents, mobilised by waves and then blown from the beach to the dunes by the wind. Here, spatial interventions can be made to increase inland sediment transport.

Design principle A1): Human mobilization

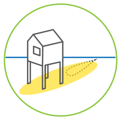
Recreation and urbanization in coastal zones can lead to an increase in sediment mobility, due to grouting by traffic (visitors, cars), beach maintenance and sand removal.

Human mobilization of sediment may have both positive and negative effects on the build-up of the dunes. Intense tramping leads to a decrease of vegetation and erosion, bringing embryonic dune growth to a halt (figure 6). But grouting of the beach by traffic can also improve the availability of fine sediment for wind transport to the dunes. This *mobilization* effect can be applied for BwN design.

Figure 6. Example of urban mobilization at beach access points (white circles) intervening with embryonal dune growth (green). Aerial photo: PDOK.nl

B: Acceleration of wind

Acceleration of wind speed causes erosion and increased sediment transport. This can be induced by funnel-effects through the vertical or horizontal convergence of the wind flow.



B1) Elevated buildings: dispersed tails

Diversion of wind around built objects on poles (> 0,5m) causes an acceleration of wind flow below and behind the building (Van Onselen, 2018), leading to a local increase of sediment transport. This sediment is transported downwind and deposited in the vicinity of the building (figures 4 and 7). These *dispersed tails* collect sediment but also keep it exposed for transitional sediment transport, from the beach to the fore,- and the back dunes, for example.

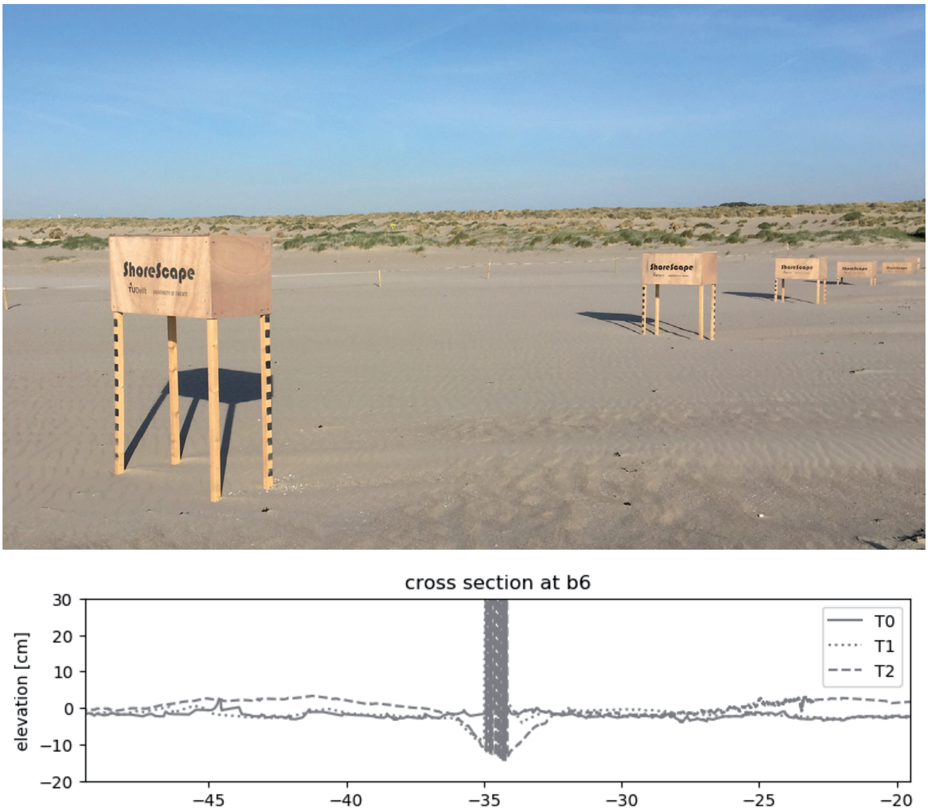
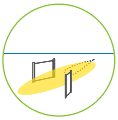


Figure 7 a,b. Photo and section of scale model (100 cm elevated) showing the scour below the model and dispersed deposition after six weeks of exposure at the Sand Motor.

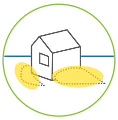


B2) Horizontal funneling

Wind directed into a V-shape (or funnel) is locally accelerated, causing erosion. Behind the funnel, this sand is deposited by the subsequent deceleration of the wind. Examples are (narrow) beach access points, where sediment is blown in, accelerated and transported upward, to be deposited at the top. A similar setup could be used for urban configurations. Furthermore, by placing built objects in a V-shape, the incoming sediment flow becomes less fragmented compared to row housing. *Funneling* is applicable to accelerate sediment transport inland.

C: Deceleration of wind

Obstacles create diversion of wind flow, leading to a local increase of erosion and of deposition. The reduction of windspeed by a lay-out of half-open obstacles, such as fences and vegetation, promotes deposition, to widen the dunes, for instance.



C1) Non-elevated buildings: sand tails

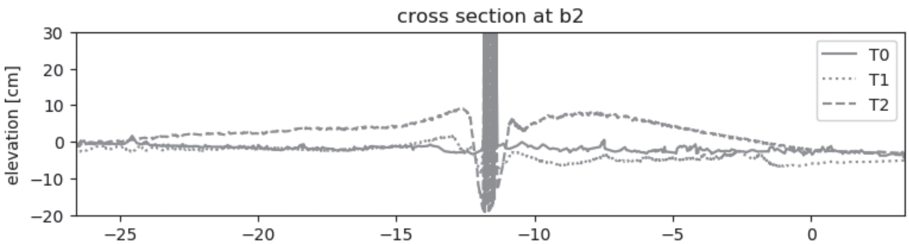
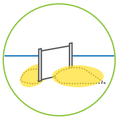


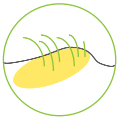
Figure 8 a,b. Final photo and section of scale model (0 cm elevated) showing the concentrated deposition (Sand tail) and horseshoe shaped erosion.

Diversion of wind around beach buildings causes wind to accelerate (picking up sediment) and decelerate, leading to local deposition of sediment on the lee sides, or the formation of '*Sand tails*'. The deposition starts in horse-shoe patterns (Poppema, 2019), but can accumulate in combined tails at the back of the building under changing wind conditions as illustrated by GIS-analysis (Van Bergen, 2020) and fieldwork (figure 8). The surplus in deposition can be used for the local harvesting of sediment (e.g. seaward extension of the foredunes).



C2) Fencing

This principle is based on increased sediment deposition around semi-transparent fences on the beach (Goldsmith, 1985). Due to its half-open structure, the wind is mainly decelerated, instead of being diverted, leading to a local deposition of sediment. The local deposition can be used to build up (fore)dunes, for example in non-vegetated places.



C3) Eco-trapping

The foliage of plants decreases wind speeds and traps sediment to support the build-up of the dunes in width and height (Van Dieren, 1934). Furthermore, vegetation is very effective in stabilizing sediment due to its extensive root system. Species like Marram Grass can even grow along with the process of deposition. However, due to these mechanisms beach vegetation can also block sediment transport to the (fore)dunes. Vegetation plays a role in '*Eco-trapping*' both passively, through natural succession, and actively by planting. At the beach and in the foredunes this relates mainly to Beach Couch and Marram Grass and in the mature back dunes to scrubs and forest which prevent sediment from blowing inland.

4. Application of BwN design principles in two case studies

The BwN design principles are tested in two different coastal settings to explore spatial arrangements that support dune formation. This is done by a design study for two cases (figure 9), each with a contrasting profile, nourishment regime and level of urbanity:

- The extensive profile of a mega-nourishment (Sand Motor), featuring a 'low frequent, high volume' nourishment strategy (20Mm³/25 years) with dominant geomorphological dynamics in a rural setting.
- The compact profile of a coastal resort (Noordwijk), featuring a 'high frequent, low volume' nourishment strategy (5Mm³/5 years) in an urbanized setting.

Figure 9. Map of the Netherlands and the two case-study locations.

First, the spatial conditions of the cases and their corresponding coastal profiles are discussed. Depending on the design objectives and desired profile, BwN design principles can be applied to support the sediment transport to the dunes. This leads to a (dynamic) spatial arrangement illustrating if and how multiple use of the coastal profile can be made compatible with BwN dune formation processes.

Case-study Sand Motor: application of BwN design principles in a mega-nourishment context

The Sand Motor (South Holland) is an example of a 'high volume, low frequent' BwN nourishment strategy (20Mm³/25 years) in a rural setting. The hook-shaped peninsula of 128 ha was constructed in 2011 and designed to slowly erode, thereby feeding the adjacent shore with sediment. This promotes dune growth for coastal safety, whilst expanding natural areas and space for leisure activities (Taal et al., 2016). This case study analyses the resulting dune formation at the mega-nourishment so far and explores, via design study, how BwN design principles might contribute to *accelerated* fore dune formation as aspired buffer.

Figure 10. Aerial photo of mega-nourishment Sand Motor just after construction in 2012, showing accretion at the south side (source: RWS).

Dune formation processes after mega-nourishment

The Sand Motor landscape (2011-2019) features extensive beaches, increased recreation (e.g. beach pavilions) and a highly dynamic geomorphology. Erosion of the peninsula and the continuous dispersion of sediment along the coast have induced an accreting shore on the south side in the first years (figure 10 and 11a). This was followed by a retreating shoreline and embryonic dune growth on the beach from 2016 onwards (figure 11b). These embryonic dunes catch and stabilize sediment, but block sediment transport to the foredunes.

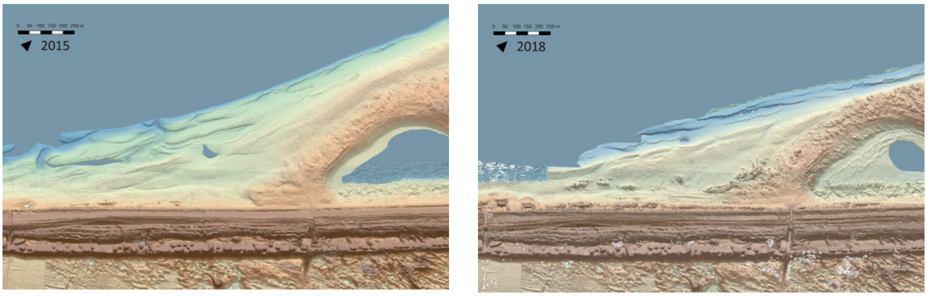


Figure 11 Elevation maps of the south side of the Sand Motor. Figure 11a (left) shows the accreted shoreline (2011-2015); figure 11b (right) shows the eroding shoreline and embryonic dune growth (2016-2018).

Vegetated foredunes are a desirable state for sediment to accrete in a sustainable way (van Vliet et.al., 2017) offering maximum resistance during storms (coastal buffer). Assuming that a quarter of the nourished sediment

(20Mm³) becomes available for aeolian dune formation (after Van der Wal, 1999), this volume (5 Mm³) would correspond with an additional foredune, for instance, of +100m wide, 3m high and 15 km long; and an estimated BwN construction time of 21 years. This calculation shows the potential for BwN foredune formation as a coastal buffer following mega-nourishment. However, this process is now delayed by the embryonic dunes at the beach, blocking sediment transport to the foredunes.

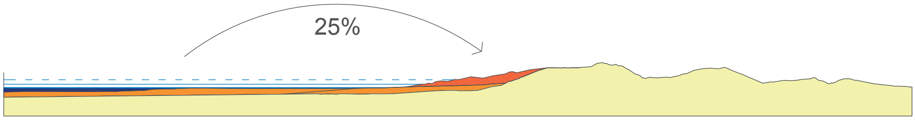


Figure 12. Section of the Sand Motor, its initial volume and aspired buffer (in red, ≈ 25% of nourished volume).

Spatial arrangement to accelerate BwN Dune Formation

Given the observed land-shaping processes, BwN principles were applied to study how *direct* sediment flow to the foredunes could be improved to accelerate the BwN build-up of the coastal buffer.

Firstly, the principle of '*Human mobilization*' applies to limit the growth of (vegetated) embryonic dunes and mobilize sediment for aeolian transport inland. This could be organized by relocating the existing recreational program (beach pavilions and -housing) to the south wing, intensifying pedestrian traffic (figure 13).

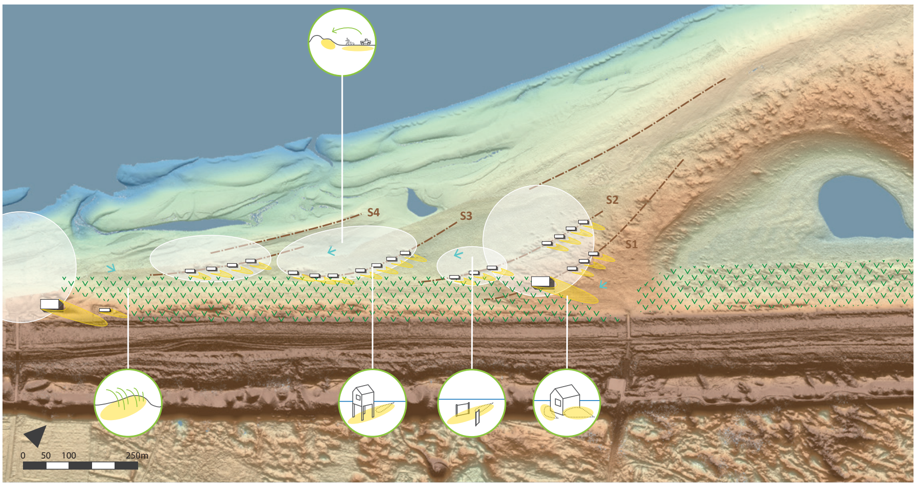


Figure 13. BwN ensemble of beach houses situated on beach ridges of the south Sand Motor to keep sediment mobile (white circles) and harvest sediment (yellow) for landward foredune formation (green).

At the same time, these seasonal beach buildings on poles offer chances to collect and direct sediment transport to the back for further transport inland. This sediment can be collected during a sequence of summers (S1, 2, 3, 4) in a dynamic urban set up (*Horizontal Funnelling*), that moves along with the shifting shore and transport zone. The resulting '*Dispersed tail*' patterns then act as local aeolian sand sources during winter to feed the foredune zone. Once transported to the dune foot, the '*Sand tails*' of the remaining buildings and (planted) Marram Grass offer opportunities for accretion and stabilization of sediment ('*Eco-trapping*'); an old Dutch coastal tradition of BwN.

Case-study Noordwijk: Application of BwN design principles in an urbanized waterfront

Noordwijk aan Zee is a seaside resort along the coast of South Holland, featuring an urbanized waterfront maintained by a regular 'high frequent-low volume' nourishment strategy (2Mm^3/4 years since 1998).

In the past, Noordwijk has faced several urban transformations. It began as a fishing village but developed into (luxury) seaside resort around 1900, turning the front dunes into a coastal strip of hotels along a boulevard. In World War II, this strip was partly torn down for military defence purposes, but was reconstructed afterward and densified. The resort now hosts 1,1 million day-visits and 0,5 million overnight stays a year, including conferences, upmarket lodging and beach development (de Witte-Romme et al., 2018). In 2003, Noordwijk was appointed as a weak link in the coastal defence line and transformed once more with a 'Dike-in-Dune' reinforcement in 2008 (figure 15a), anticipating future climate changes and sea-level rise. Although close access to the beach and sea view was maintained, the northern boulevard lost its direct contact with the beach (figure 14).

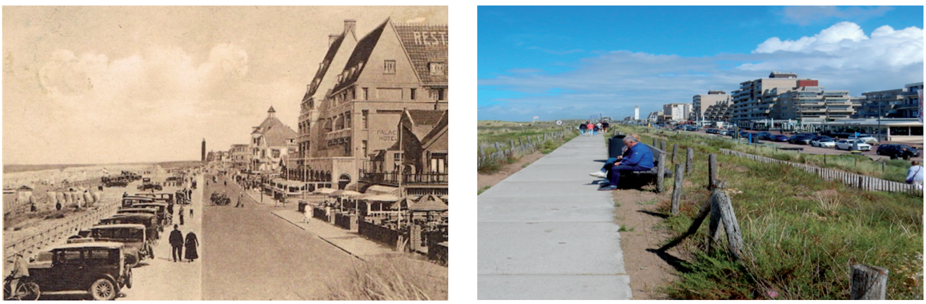


Figure 14. Photos of boulevard Noordwijk in 1920 (left, source: deoudedorpskernnoordwijk.nl) and after reinforcement in 2020 (right, photo J. van Bergen).

Future flood safety reinforcement models for Noordwijk

The present flood safety level of the Noordwijk Dike-in-dune accounts for a sea-level rise of 30 cm in 2050 (60 cm in 2100). To withstand higher sea level rise scenario's, future reinforcements of Noordwijk will be inevitable. To investigate the feasibility of BwN solutions to provide a necessary reinforcement after 2060, Mulder et al. (2013) took a two-step approach. First, using a dune erosion model DUROS+ (Vellinga, 1986) a number of potential sandy reinforced profiles were calculated (Boers and Mulder, 2014), able to withstand storm conditions after a sea-level rise to 85 cm in 2100 (figure 15b, 'Dike in dune plus' and figure 15c, 'Sand Buffer'). Next, a nourishment evaluation tool ('Ntool'; Huisman et al., 2013; Giardino et al., 2013-A) was applied to confirm that a regular, high frequent sand nourishment strategy (increased SLR, four year intervals), would be able to deliver (most of) the required seaward extensions of both profiles in 2060. However, these calculations are based on the free natural transport of sediments and is crucial for its success. The current high occupancy rate (70%) of the beach by pavilions can affect this process.

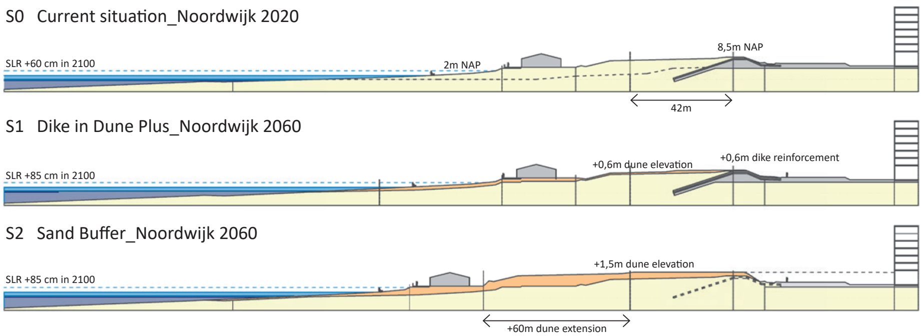
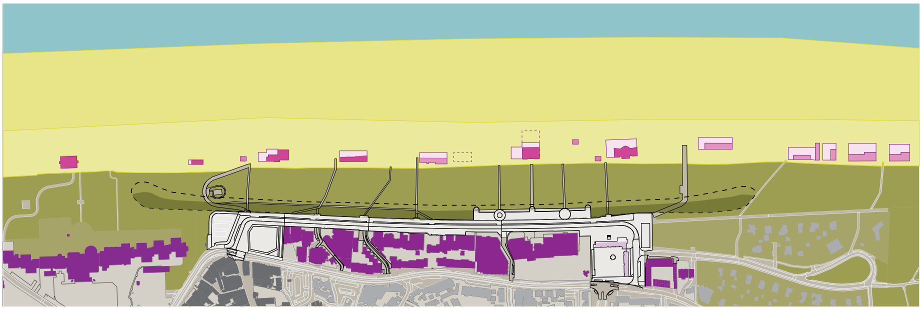


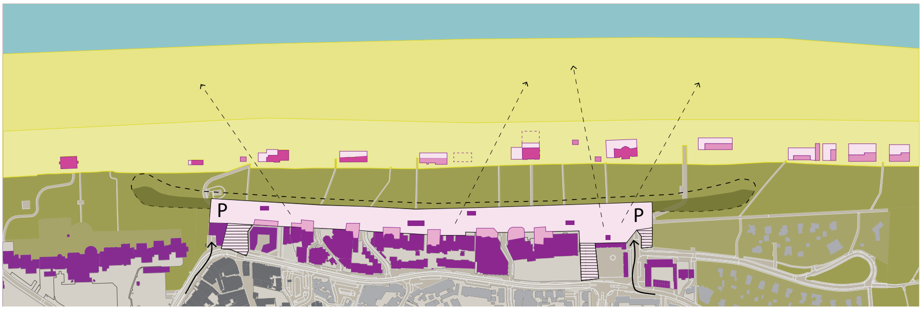
Fig 15 a,b,c. Cross-sections of Noordwijk boulevard. S0 – Current situation 2020 with 'Dike-in-dune' reinforcement implemented in 2008; S1 – potential reinforcement model to counteract effects of a sea-level rise increase to 85 cm in 2100, by a slight heightening of the existing dike (+60 cm) and dunes (+60 cm); S2 – id. by a Sand Buffer only, avoiding a costly dike reinforcement (Image by author, after Mulder et al., 2013).

Urban models for future waterfront development of Noordwijk

The future reinforcement of Noordwijk, as discussed in the previous section, illustrates that more room is needed within the existing coastal profile to adapt to sea level rise. The expected dune reinforcement pressures the existing values of the current waterfront, such as the sea view and beach vicinity; and makes a reassessment necessary. In this design study, four future urban models were composed to facilitate future urban coastal occupation. These urban models are based on two main choices that (re)define the urban coastal profile (fig 16).

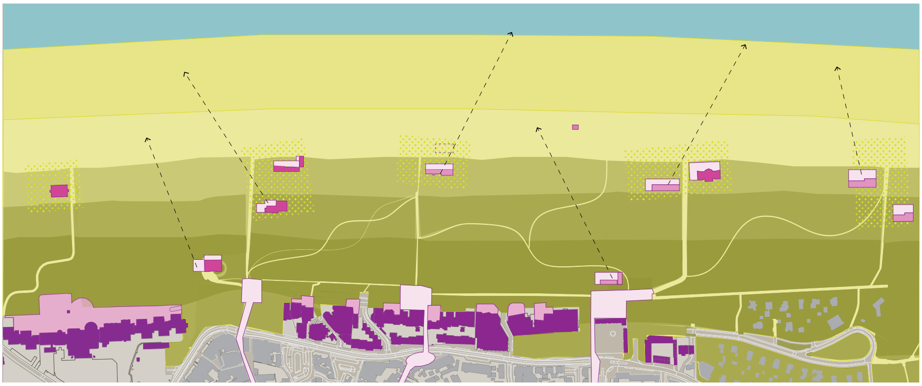


U1. Traditional boulevard



U2. Elevated boulevard, with parking below

U3: corridor model, with compact beach housing



U4: Terraces model, with beach pavilions distributed within the beach-dune landscape

Figure 16. Overview of four urban models for the future waterfront development of Noordwijk; based on parallel versus perpendicular access and varying beach layout. Images by the author.

1. **Reassessment of the waterfront layout.** The current boulevard typology (U1) acts as a distributor for beach access, parallel to the shore whilst offering sea view, public facilities and close beach access. These qualities are facilitated best by compact (but costly) reinforcements, such as Dike-in-dune. The boulevard can be elevated (U2, with parking below) to provide extra room for reinforcement in height. An alternative is the corridor typology (U3, U4), that gives direct perpendicular beach access, reorganising the urban program along public routes from the town to the sea. This offers opportunities for dune extension in between the corridors.These dunes would marginalize a boulevard but could offer a more exclusive landscape setting for the hotels and room for urban dune development instead, creating alternating spheres of urbanity along the coast.
2. **(Re)arrangement of the urban beach layout**, such as beach pavilions and -houses: The current beach layout is linear (U1, 2), featuring a strip of 16 beach pavilions & terraces (50% year-round) with equal spatial layout. They now cover around 70% of the foredunes, obstructing sediment transport to the dunes. An alternative could be to cluster pavilions around the main beach corridors (U3) or to distribute them within the dune landscape (U4, Terraces model) to differentiate spatial quality and urban use along the beach and in the dunes. The more open dune foot allows for natural dune growth.

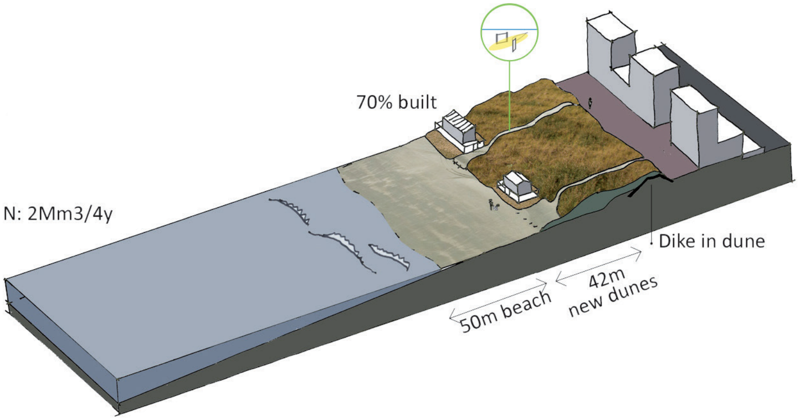
Matching models for future flood safety reinforcement and urban development

The combination of the two potential reinforcement models (S1 Dike-in-dune and S2 Sand Buffer, Fig. 14b and 14c) and urban models (U1-4, figure 16) lead to two feasible future coastal profiles for Noordwijk, each with its own distinct features. Test profile 1 'Dike-in-dune plus' (S1+U1 = T1, figure 17b) stays close to the traditional boulevard typology as an urban balcony at the sea with the most compact Dike-in-dune reinforcement. Test profile 2 'Sand Buffer (S2+U3 = T2, Fig. 16c) rearranges and concentrates the urban program onto two main routes to the beach, allowing for more free sediment flow to widen the dunes.

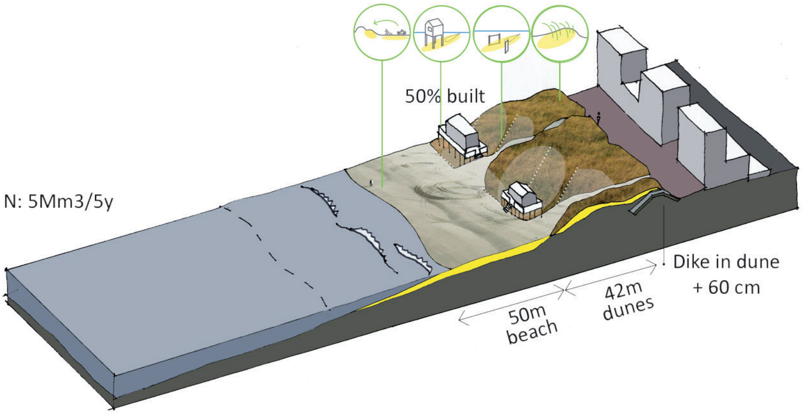
Application of Aeolian design principles to stimulate BwN dune formation

The success of BwN dune formation not only depends on the nourishment strategy but also on the spatial layout of the sea-land interface, affecting wind-driven sand transport. The urbanized context and the current compact profile of Noordwijk (figure 17a) make it a major challenge to allow for free sediment flow and accommodate dune formation. Within this context aeolian design principles (see par 8.3; marked *italic* in text) can be applied to stimulate the gradual build-up of the aspired test profiles (Figures 17 b and c):

Current profile: Dike in Dune 2020



Testprofile 1: Dike in Dune Plus 2060



Testprofile 2: Sand Buffer 2060

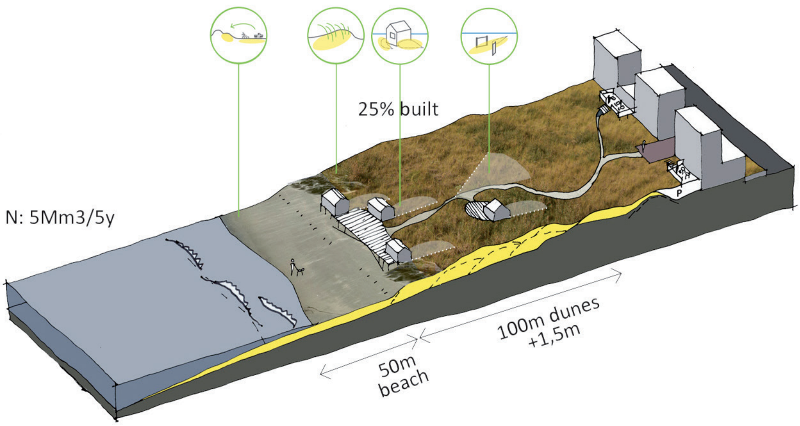


Figure 17 a. The current profile of Noordwijk has a 6,5m high Dike-in-dune construction, with 42m wide dunes. The beach is relatively narrow (50m) limiting the fetch and space for dune formation. Beach buildings block a large part (70%) of the dune front, limiting sediment flow. Although this profile design has not intentionally incorporated BwN-processes, the numerous beach accesses help to transport sediment deeper into the dunes (corresponding with the design principle of *Horizontal Funneling*).

Figure 17 b. The Dike-in-dune Plus profile of Noordwijk 2060 requires a 60 cm elevation of the existing dike and dunes. To this end, a regular nourishment strategy is implied to compensate an increase in SLR to +85 cm in 2100. The current boulevard typology is maintained. To stimulate dune growth, the principle of '*Human mobilization*' of the beach and foredune zone helps to keep sediment mobile for inland transport. A nature-based (BwN) elevation of the dunes (+60cm) is stimulated by an open dune-foot (reduced occupation rate) alternated by pavilions on poles (*Dispersed tales*) and beach access (*Horizontal Funneling*) to facilitate sediment transport inland (+60 cm). '*Eco-trapping*' stabilizes sediment in the back dunes and prevents it from reaching the boulevard.

Figure 17 c. The 2060 Sand Buffer profile of Noordwijk consists of a dune that, due to successive nourishments starting in 2020 (compensating an increase in SLR to +85 cm in 2100), gradually grows in height (+1,5m) and width (+60m). The former boulevard has been transformed and provides a new landscape setting for the hotels with parking below. A central beach access ends in a boardwalk with clustered beach houses, leaving 75% of the dune foot open for BwN dune formation. In the first stage, elevated pavilions (*Dispersed tails*), beach access points and blow-outs (*Horizontal Funnelling*) facilitate sediment transport for dune-elevation (similar to profile 1, but with a more open dune foot). In the second phase (figure 16c) '*Eco trapping*' and the '*Sand tails*' of the concentrated (seasonal) pavilions facilitate extension of the dunes. A wide beach (fetch) could further enhance this process.

5. Conclusion: comparing BwN design principles in diverse coastal settings

There are several aspects that contribute to a successful BwN build-up of a coastal buffer. The objective of this paper is to fuse insights from coastal engineering and spatial design to formulate BwN design principles that combine nourishment strategies, wind-driven sediment flows and urban settlement for BwN dune formation.

First sedimentation processes in the (built) sea-land interface were analyzed to identify spatial mechanisms that relate coastal occupation to dune formation. Hence, a preliminary set of aeolian design principles was derived, employing urban and ecological interventions to stimulate BwN dune formation after nourishment. These principles mediate between two drivers: the nourishments, that provide sediment for dune formation and the urban beach development, that affects sediment transport.

To contribute to the gradual build-up of the coastal buffer, the design principles employ manipulated wind flow for sediment allocation. These types of sediment transport are generic but dependent on the requested type of dune formation (e.g. widening or heightening the dunes). Each transition requires a specific set of principles, clustered in different zones and sequences within the coastal profile:

- Heightening the dunes, for example, is a slow sedimentation process, and the sediment needs to be tilted to the back dunes. This is promoted by a mobilized, dynamic dune foot zone, a gradual slope of foredunes and accelerated wind flow stimulated by *Elevated buildings* and *Horizontal Funnelling*.
- Widening the dunes benefits from a wide beach as a long wind fetch and space to accommodate dune growth; next to stable, vegetated foredunes to collect and fixate the sediment. This is matched by design principles as *Sand tails* behind buildings, *Fencing* and *Eco-trapping*.

Secondly, the developed aeolian design principles were applied in two case-studies to compare their functionality for BwN in different coastal settings. The nourishment strategies in both cases provide enough sediment to build up the coastal profile, but generate different conditions for BwN to take place, altering the role of the BwN arrangement:

The Sand Motor case study shows that the design principles are applicable in a mega-nourishment situation - featuring an extensive, dynamic profile - and can help to stimulate sediment transport from the beach to the foredunes. '*Human mobilization*' helps to source sediment and stops vegetation, whilst beach housing on poles (*Dispersed tails*) collects sediment for inland transport. '*Eco trapping*' finally stabilizes sediment in the foredunes to extend the coastal buffer. Here, the BwN arrangement acts as a form of *responsive* spatial design: following morphological development and transforming in time, as illustrated in figure 18.

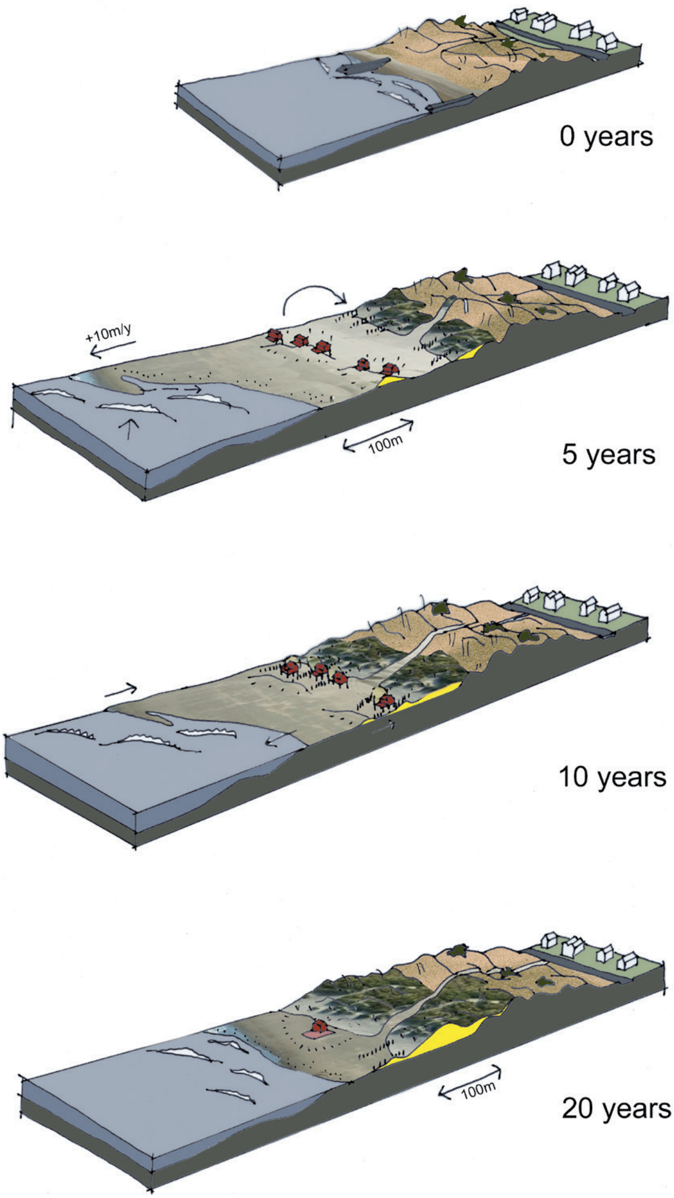


Figure 18. Design sequence of BwN foredune formation following mega-nourishment. 0y: the coastal profile before nourishment; 5y: the coastal profile after mega-nourishment, with extensive beaches; 10y: the coastal profile in 5-10y with an eroding shoreline; and 20y: the concluding profile, with a narrow beach and consolidation of the dunes.

The Noordwijk case features two relatively compact profiles for future reinforcement, dependent on small, high frequent nourishments. Without a vast beach as a resource, the design principles play a more important role in the harvesting and steering of sediment to the designated places: dune morphology now follows the urban layout and urban arrangements facilitate dune growth, as a form of *directive* spatial design.

Furthermore, in Noordwijk urban parameters, such as sea view, beach access, and beach housing have a defining role in the coastal profile design, balanced with the (future) requirements for coastal safety. Optimization of these profiles for BwN could eventually lead to alteration of the waterfront layout, such as the transformation of the Noordwijk boulevard; or nourishment strategy, creating more room for future reinforcements and BwN.

Both design studies illustrate how coastal nourishment and urban development can be intertwined to support the BwN build-up of the coastal buffer. Synergizing these developments not only creates chances to improve dune formation after nourishment, but also gives way for a BwN-based reinforcement of the coastal profile in response to sea-level rise, whilst maintaining its function as vital recreational landscape. The case studies illustrate that the developed aeolian design principles are applicable in diverse settings, but their position and sequence vary depending on the aspired coastal profile. This makes the coastal profile, integrating morphological, urban and ecological programs, an important design tool and spatial framework for the allocation of aeolian design principles.

Research by design can assess each profile and identify the various zones needed for the BwN process. Further research is needed to categorize, extend and cluster the design principles to spatial arrangements fitted for each zone within a specific coastal profile. This includes the assessment of the related boundary conditions such as nourishment type and urban demands. To quantify the morphological effects of the design principles, an additional dedicated field test is foreseen, as well as computer model tests, see also the chapter by Wijnberg et al. (2021, p. 244). These give way for a BwN design approach in the sea-land interface, as a new symbiosis of coastal occupation and dune formation.

Acknowledgements

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