CHALLENGES IN DEVELOPING SUSTAINABLE SANDY STRATEGIES

Jaap van Thiel de Vries[1,2,3] Erik van Eekelen[1,4] Arjen Luijendijk[1,3,5], Sonja Ouwerkerk[1,6] and Henk Steetzel[1,7]

ABSTRACT

Sandy nourishments are worldwide applied along sandy shores as maintenance strategy and to enhance the values of coastal areas. In this context, there is a challenge in developing competitive sandy strategies that optimally suit local demands and needs. Within the Building with Nature innovation program three pilots projects based on sandy strategies are explored and discussed in this paper. The pilot projects are based on existing concepts reinvented for new environments in which the challenge is to better suit a local context with respect to conventional approaches. This obviously is a design challenge in which the capacity to 1) develop designs with controlled morphodynamics and 2) engineer with vegetation are both critical.

Keywords: Building with Nature, Sandy Strategies, Adaptive Management, Engineering with vegetation.

INTRODUCTION

A substantial part of the world's coastlines consists of sandy beaches and dunes that form a natural water defense protecting the hinterland from flooding while at the same time providing valuable space for recreational activities and nature development. Due to alongshore variation in hydraulic loads, sandy shorelines can experience structural sand losses which on the longer term results in a set back of the coastline, negatively influencing the functions and values of these areas. To mitigate these effects, coastal managers implement mitigating measures, which can either be hard constructions (i.e. sea wall or revetment) or soft (sandy) sediment strategies by periodically conducting sand nourishments. This contribution focusses on soft sandy strategies.

Sandy strategies are usually realized by means of sand nourishments of which design (shape, volume, frequency) typically depends on local demands on the one hand side and on the nearby availability of qualitatively good sand, (median grain diameter and sand color) and equipment on the other hand. Most nourishments are conducted as beach and dune nourishments, which means that sand is placed directly on the beach and dunes (panel a, Figure 1). In addition shoreface nourishments (panel b, Figure 1) are applied (on a large scale in the Netherlands). These nourishments typically are cheaper for the same volume (about 50% reduction in costs) and make use of natural marine processes that transport the sand towards the coast where the beach will widen over time. With the Sand Motor (Stive et al., 2013) the so called concentrated (mega) nourishments was introduced (panel c, Figure 1) in which both marine and aeolian processes are utilized to redistribute the sand both in cross and alongshore directions.

An important aspect of sandy shorelines and thus nourishments concerns their dynamics. Sandy shores constantly reshape their active profile to suit the actual hydraulic conditions and efficiently dissipate the incoming wave loads (Dean, 1977, 2002). In longshore direction a sandy coastline tends to rotate perpendicular towards the incoming wave angle, which over a longer period of time may result in structural sand losses from a coastal section. Sand nourishments are typically placed to replenish these structural losses, but don't take away the cause of erosion and as such will have a limited lifetime depending on volume and local erosion rate.

[1] EcoShape, Burgemeester de Raadtsingel 69, 3311 JG Dordrecht, The Netherlands

[2] Royal Boskalis Westminster N.V., PO Box 43, 3350 AA Papendrecht, The Netherlands

[3] Delft University of Technology, Faculty of Civil Engineering and Geosciences, PO Box 5048, 2600 GA Delft, The Netherlands

[4] Van Oord Dredging and Marine Contractors BV, PO Box 8574, 3009 AN Rotterdam, The Netherlands

[5] Deltares, PO Box 177, 2600 MH Delft, The Netherlands

[6] HKV Consultants, PO Box 2120, 8203 AC Lelystad, The Netherlands

[7] Arcadis Nederland BV, Postbus 33, 6800 LE Arnhem, The Netherlands

Despite the limited lifetime of nourishments, sandy strategies seem to gain popularity, which has two reasons. First nourishments allow for adaptive management, which introduces the flexibility to anticipate on changing conditions and unexpected circumstances. In line with this adaptive approach, costs for maintenance measures can typically be postponed w.r.t. hard alternatives, which can make sandy strategies more competitive. Secondly, there is an increasing demand for measures that can harmonize multiple functions (coastal safety, economy and nature) at once, which can eminently be realized with a smart sandy strategy.

Over the past decades environmental awareness has increased substantially and this has put new challenges in aligning nourishment schemes with natural values both at the nourishment location and at the sand mine area (De Jong et al. 2016). Also in line with above observations sand is becoming a more valuable resource with (usually) limited availability. Efficient use of sand (by smartly interfering with the natural system) and combining sand with alternative construction materials (as i.e Holocene clay) are therefore welcome opportunities to increase feasibility and application range of (sand) nourishments.

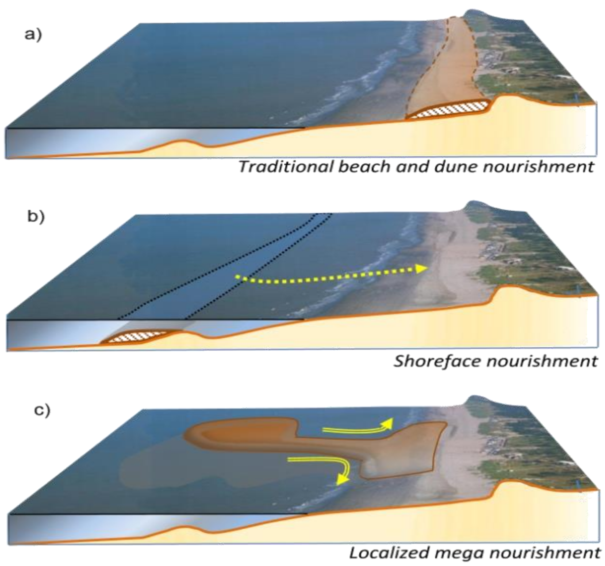

Figure 1. Alternative nourishment designs, (a) Traditional beach and dune nourishments, used frequently from the 1970s onward, place sand directly on the beach and dunes. (b) Shoreface nourishments, initiated in the 1990s, make use of natural marine processes to redistribute the sand that is placed under water in the cross-shore direction and gradually create a wider coastal defense over time. (c) Concentrated mega-nourishments, as introduced here, exploit both marine and aeolian processes, to redistribute the sand both in cross and alongshore directions.

Sandy strategies based on Building with Nature

People and economic activities keep on concentrating in deltaic areas and moreover society increasingly demands for safety, prosperity and sustainability (Vitousek et al., 1997; Ehrlich and Ehrlich, 1997). This demand puts new challenges to infrastructure developments and asks for innovative infrastructure solutions. Building with Nature aims to develop these solutions by taking the advantage of the opportunities offered by nature services (ecosystem services) and by stakeholder involvement from the early stages of project development (co-creation). This requires a change in thinking and a paradigm shift in all aspects of project development, which will result in a shift from minimizing negative environmental impacts, via neutrality by compensation, to optimizing on a positive balance for water infrastructure development.

Within the Building with Nature innovation program (www.ecoshape.nl) a learning by doing approach is adopted in which case studies and pilot projects are developed that connect with current infrastructure challenges in the Netherlands and abroad. Within each case, cross-disciplinary research teams develop new knowledge about how to

The Sand Motor

Location: Netherlands, Delfland Coast

Environnent: Marine sandy environment

What: Coastline maintenance with concentrated mega nourishment of ~ 20 Mm3 as an alternative for smaller volume beach and foreshore nourishments

Concept: Due to local perturbation of the coastline adjacent coastlines are naturally fed with sand without making dredging impacts here. At the nourishment location (temporarily) space for added values is realized.

Challenge: 1) Predictable sand supply to adjacent coastlines over time 2) insight in how nourishment design can influence landscape forming processes and thus the potential for additional values 3) insight in ecological performance w.r.t. conventional nourishment schemes.

The Hondsbossche and Pettemer Sea Defense (HPZ)

Location: Netherlands, North Holland Coast

Environment: Marine sandy environment

What: Sandy beach and dune system in front of sea dike protruding ~ xx m into the sea with respect to adjacent coast.

Concept: Coastal safety solution with added value for recreation and nature. The constructed beach dune system serves as a suspension point (including maintenance) from where sand distributes to the adjacent coasts North and South of it.

Challenge: Insight in 1) how nourishment design can influence landscape forming processes and thus the potential for additional values 2) perception about created solution.

The pilot sandy foreshore Houtribdijk

Location: Netherlands, Lake Marker

Environment: Sand poor, fresh water lake environment with controlled water level

What: Sandy foreshore as an alternative for a dike reinforcement.

Concept: sandy foreshore with vegetation dissipate and attenuate incoming wave loads and therewith reduce wave loads on the dike behind it.

Challenge: Minimize dynamics in sand volume in front of the dike by engineering smartly with vegetation;

Figure 2. Overview of ongoing Building with Nature pilots based on sandy strategies

smartly utilize the interaction between biotic and abiotic processes in efficient designs, which are realized within existing administrative and legal frameworks. Presently three pilots projects related to sandy strategies are ongoing, which concern an innovative maintenance strategy by a concentrated mega nourishment (Sand Motor, Stive et al, 2013) and two sandy dike reinforcement strategies, including a sandy beach and dune system in front of a sea dike (Hondsbossche and Pettemer Sea defense) and a sandy foreshore in a sand poor, fresh water lake environment (pilot Houtribdijk). The objectives of the piloted strategies, the natural environment in which they are realized and stakeholder dialogue are unique per case resulting in site specific challenges (see Figure 2).

This paper aims to identify some of the overarching themes and aspects in developing sandy strategies in line with the Building with Nature philosophy and using the pilot cases as the main source of inspiration. Based on these cases studies it is assessed to what extend piloted sandy strategies are really innovative and unique. Secondly conventional infrastructure solutions are discussed as being a critical benchmark in defining the potential for innovative sandy nourishment strategies. This potential depends on the ability of a sandy to suit the local context with respect to conventional approaches. This obviously is a design challenge of which two important aspects are discussed; the ability 1) to control the morphodynamics of a design and 2) to engineer with vegetation and realize specific landscape properties.

EXISTING CONCEPTS IN NEW ENVIRONMENTS

In developing sandy shoreline infrastructure solutions, managers and engineers usually simplify the complex world in order to isolate the essence of the challenges they are facing and to be capable to pick an efficient engineering solution of the shelf. This procedure is a prerequisite to make progress in each design processes and also applies to a Building with Nature approach. The difference for BwN is that these simplifications are realized in a cross-disciplinary context with understanding of the physical, biological and the societal context. But does this also lead to new, alternative sandy strategies that indeed create additional vales for nature and economy?

Starting with the Sand Motor (Mulder and Tonnon, 2010). The initial motivation for its development was that, based on sea level rise scenarios for the Netherlands, the sand nourishment volume needs to increase in the coming decades. However at the same time there was an ongoing debate about the environmental impacts of these nourishments (related to destroy and recovery of the benthos community, fish population, birds and dune ecosystems). This raised the challenge to explore strategies that allow to nourish more sand for coastal safety on the longer term, while at the same time reduce the environmental impact in respect to present day approaches. In finding this solution, the Bornrif beach area (engineered by nature; see Figure 3 upper right panel) along the barrier island Ameland (part of the Wadden Sea inlet system that is located in the Northern part of the Netherlands) revealed a nice source of inspiration. The Bornrif beach area developed from a sand bypass mechanism over the ebb-tidal delta in which sand migrates in large shoals from one island to its downstream neighbor, therewith morphologically connecting the barriers of the Wadden Sea inlet system. The Bornrif beach area acts as a large concentrated volume of sand that gradually feeds the downstream barrier coast with sufficient sediment to prevent structural losses.

The natural system dynamics along the Dutch Holland coast (most intensively nourished area in the Netherlands) do not allow for the natural development of a Bornrif beach area. However in respect to the challenge above a concentrated mega nourishment, inspired on the Bornrif, was expected to have multiple potential advantages for this densely populated coastal area. By nourishing a large concentrated volume, the coastline is locally distorted creating a natural mechanism to feed (maintain) adjacent coastlines without having (environmental) dredging impacts here. Also the local accumulation of sand may create interesting ecological intermediate stages (i.e lagoon area) and temporarily space for other functions as beach recreation activities. Finally, due to the large volume, the placed sand buffer is an order higher than for conventional nourishments, the frequency of nourishing can go down.

The sandy foreshore solution in the pilot Houtribdijk aims to (partly) dissipate the incoming waves during storms before these waves can reach the dike behind, therewith enhancing the safety against flooding. This concept has been applied at several marine sandy environments in The Netherlands (i.e. the Brouwersdam in South Western part of The Netherlands, see Figure 2, lower panel right side) and is a well-known measure to create coastal safety, however has not been considered as a solution for dikes along large fresh water lakes at this stage. In the Houtribdijk pilot, the challenge is to bring this concept from a sandy North Sea Marine environment towards a sand poor fresh water lake environment with controlled water level and in absence of a tide. Are sandy foreshores a feasible solution under these conditions and what are the critical success factors in this respect?

Sand Motor shortly after construction in 2011 (left) and the Bornrif at Ameland (right)

Pilot sandy foreshore Houtribdijke just after construction, fall 2014 (left) and the Brouwersdam with a andy foreshore in front (right)

Figure 3. On the left hand side the Ecoshape sandy pilots Sand Motor (upper) and Sandy foreshore Houtribdijk (lower) and on the right similar already existing solutions in other environments

Considering the present sandy cases in the Building with Nature innovation program, it is out of question that they all break with “conventional” solutions that have been applied in the past. However on the other hand the concepts underpinning the sandy strategies discussed are not unique and have been applied / observed in other environments as has been illustrated above. In this context the main challenge is much more in translating existing examples in generic concepts that can be made feasible again for new (challenging) environments.

CONVENTIONAL ALTERNATIVES AS A BENCHMARK

The feasibility of innovative sandy strategies typically depends on the extent to which these strategies can fulfill existing and new demands for a reasonable price. To evaluate this in a quantitative way it is useful to take the conventional (usually robust and proven) infrastructure solution as a reference and to assess whether an alternative sandy strategy provides either additional values (for which someone wants to pay) or is potentially cheaper.

The pilot Hourtibdijk is initiated together with the Dutch high water defense program, which has the assignment to reinforce the dikes around lake Marker in the coming years by means of cost efficient solutions. The conventional approach to realize this assignment concern dike reinforcements in which the strength of the dike armor layer is replaced / improved and in which higher parts of the dike are made overtopping resistant. A proven measure with several successful application in the past. The sandy foreshore solution as piloted along the Houtribdijk would introduce a new type of measure for dike reinforcement in the lake Marker environment, and the main reason why it is considered is that it potentially can be cheaper. Especially at dike locations where the water depth in front of the dike is relatively small, the foreshore solution tends to be a competitive alternative, since with a limited amount of sand an effective foreshore can be created. The question is whether this potential cost benefit is nulified by accounting for (un)certainties in morphodynamics, which may result in the need for extra measures as a sand buffer to deal with volume dynamics, groins to interfere with the littoral drift and a maintenance strategy to replenish structural losses form coastal sections. The challenge is to optimize the sandy foreshore concept for a sand poor environment using a thorough understanding of morphological processes and by smartly engineering with vegetation.

The Sand Motor and Hondsbossche and Pettemer Sea defense are both realized along the Dutch Holland coast in a marine environment. The main objective of these strategies is to provide a sustainable management strategy for long term coastal safety and to guarantee short term protection of the hinterland against flooding respectively. However the main reason why in these projects innovative sandy strategies where selected above conventional solutions (being beach and foreshore nourishments for the Sand Motor and a higher and wider seadike in case of the HPZ) is that these sandy strategies provided additional landscape values related to recreation and nature development. These additional values resulted in extra investments form new financers, but also created a broader commitment to implement the required measures. With respect to the Sand Motor, the Province of South Holland financed 20% of the construction costs because of the space (land) that was created could be used for amongst others recreational purposes. Regarding the HPZ, the province of North Holland co-invested and after realization of the project ~ 6 MEuro of additional investments were made to further develop the spatial quality of the area.

CONTROLLED MORPHODYNAMICS

Sandy strategies are inherently dynamic and are constantly changing their shape to fit the actual hydrodynamic conditions. These dynamics make sandy strategies adaptive solutions, efficient in attenuating a broad range of hydraulic loads (i.e. cross-shore profile reshapes during storm surge conditions to efficiently attenuate severe wave loads). Also the dynamics are considered of value (experience of a constantly changing natural landscape) or might create additional value (i.e. windblown sand feeding the dune system behind it with fine sand fractions). However on the other hands these dynamics also may introduce side effects and uncertainties influencing the feasibility of a sandy strategy. In coastal sections with structural losses sandy strategies will have limited life time and require a maintenance strategy on the longer term, which should be accounted for in evaluating its feasibility. Secondly variations in sediment volume (without structural losses) will introduce uncertainty in the beach width or sand volume at specific location and moment in time. To guarantee specific functions (i.e. coastal safety or beach recreation) may require an extra sand buffer, which also should accounted for in assessing feasibility. To properly evaluate the potential of sandy strategies requires therefore the ability to design for predictable morphodynamics and uncertainty therein.

The Sand Motor has been designed as a maintenance strategy that is constantly on the move. As a result of the concentrated mega nourishment the coastline is locally perturbed, which affects the littoral transport capacity and gradients therein. This creates a mechanism where the Sand Motor feeds the adjacent coastlines (North and South) with sand over time (decennia) and space (~ 17 kilometer coastal section). An important aspect is whether this natural (temporal and spatial varying) spreading capacity suits with the required volume for maintenance.

Considering the temporal spreading of sand; on the short term seasonal variations in hydraulic loads (i.e storms) are observed to influence the spreading capacity along the shore and the shoreline perturbation can be considered reasonably constant. On the longer time scale (of years) the original coastline perturbation will be smoothened (becoming less pronounced) by natural processes, reducing its spreading capacity. Even though the spreading capacity of the Sand Motor will decrease over time, its alongshore reach will increase. This means that the coastline perturbation will become less pronounced but covers a wider alongshore coastline section. Therefore over time, the Sand Motor will be able to feed coastal sections farther away from the original nourishment location. Figure 4 shows how the sand volume of the Sand Motor has decayed over the first years after construction. It shows that in the (stormy) winter seasons the erosion rate is highest, and that over time erosion rates decay. About 30% of the eroded sand is found back South and about 50% to the North of the nourishment location. About 20% of the Sand volume has not been found back in the presently available monitoring data and is deposited either already farther North and South alongshore or has been transported cross-shore towards deeper water or behind the first dune row. Finally it is remarked that the volumes considered are integrated over all depth contours whereas bed surveys reveal (in line with expectations) that sand in deeper water spreads relatively slow whereas in the surf the spreading is highest. This means that the smoothening of the depth contours is not uniform over time, which may create morphological feedback mechanisms that can affect the spreading capacity on the longer time. In the first two and half year about 2.5 Mm3 of sand was redistributed, which is in line with the anticipated maintenance strategy so far and no additional nourishments were required. Based on the data as presented in Figure 4 though, it is also seen that the spreading rate has decreased quite a bit already after the first half year. In the coming years the spreading capacity will continue to be monitored to assess whether the maintenance objectives are sufficiently realized.

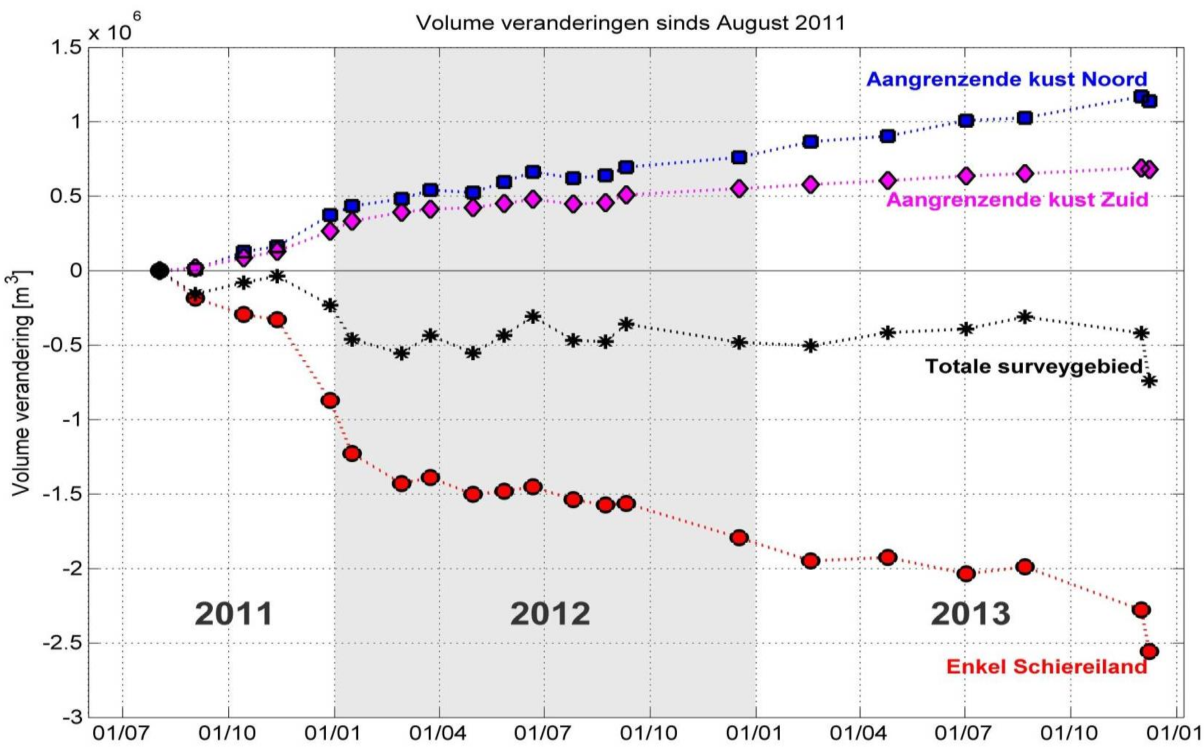

Figure 4. (From De Schipper et al., 2016), accepted for publication). Sand Volume decay of Sand Motor (red line) and volume increase at coastal sections North (blue line) and South (purple line) The black line indicates the sand volume that has disappeared out of the survey area (i.e deeper water)

The HPZ protrudes hundreds of meters into the sea and the sandy strategy contains concepts, which are comparable to the Sand Motor, meaning that the HPZ also locally perturbs the coastline. Main differences are that the perturbation is less pronounced and that the HPZ comes with a 20 year maintenance contract. As a result the sediment losses from the HPZ will be substantially smaller w.r.t. the Sand Motor but still will be substantial. The Sand that erodes a way will reach the adjacent coastal sections that used to be nourished regularly. Construction of the HPZ was just finished in 2015 and its morphological evolution will be monitored by the contractors responsible for the maintenance.

As stated in previous sections, the sandy foreshore in the Houtribdijk pilot is meant to be part of the water defense and starting point in its design was to make it as stable (static) as possible. This is also due to the fact that the foreshore solution is constructed in a sand poor environment in which any loss of sand form the foreshore section cannot be replenished form adjacent sections. The (cross-shore) foreshore design is based on the dynamic equilibrium profile concept (Dean 1977, 2002). Based on this approach the anticipated equilibrium foreshore slope was ~ 1:30 assuming a grain diameter of D50 = 250 μm. The foreshore was designed as a triangular beach (see figure 2, lower panel) where the initial coastline orientation was oriented perpendicular to the mean wave angle. Since the foreshore has been built in a freshwater environment the foreshore was designed to be planted with willows (higher parts) and reed (shoreline area). The foreshore construction was finalized mid-September 2014 (outside the growing season) and during the first winter the morphodynamics without effects of vegetation were monitored and analyzed.

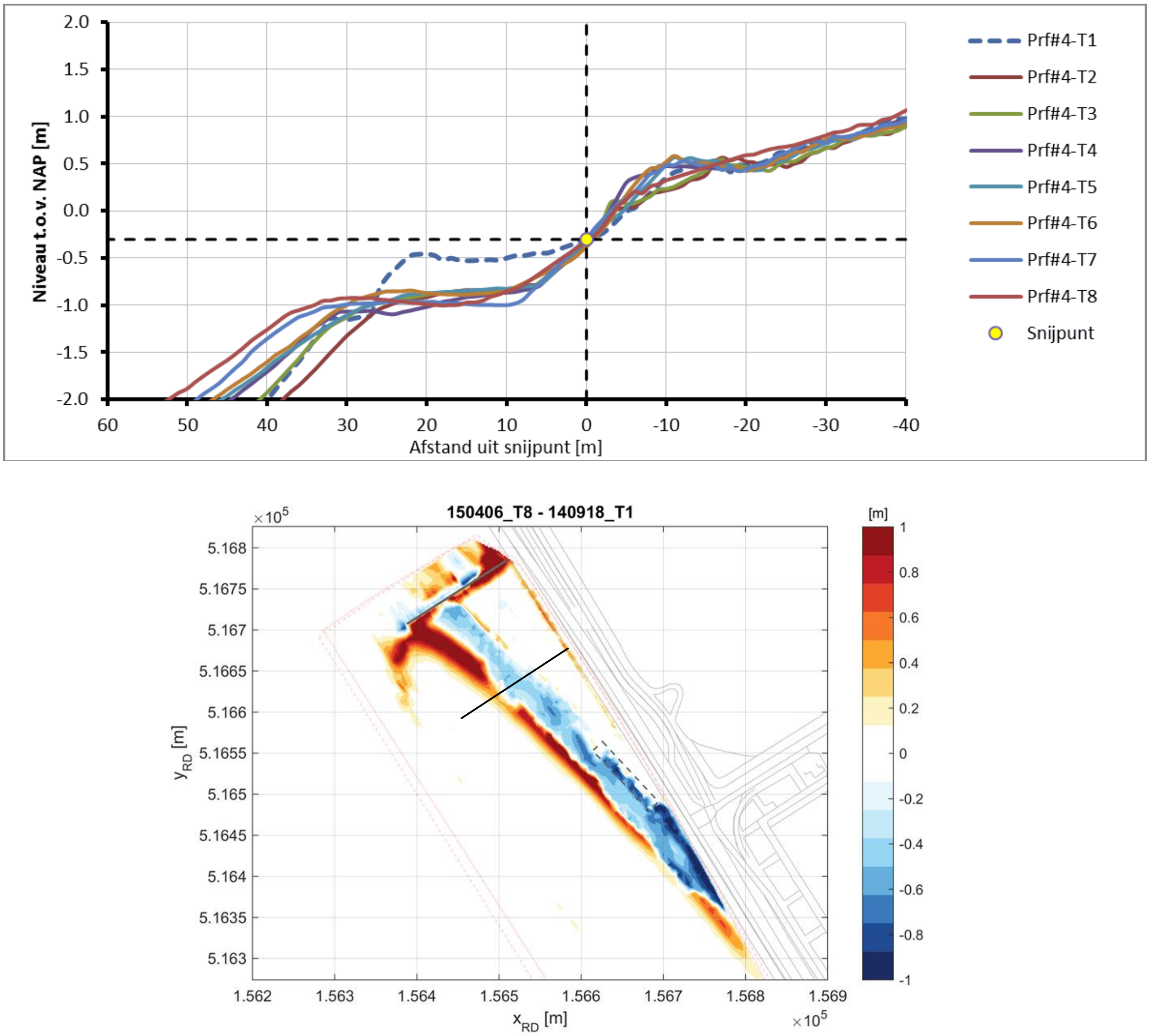

Figure 5. Upper: cross-shore profile evolution at transect 4, located in the middle of the pilot (see lower panel black line). The blue dashed line shows the initial profile just after construction (September 2014). T2-T8 show the successive monthly surveys from October 2014 till April 2015. Lower: total bed level changes, 8 months after construction. Blue areas indicate erosion, red sedimentation.

First the 1:30 design slope for the foreshore was not feasible to construct and was never realized (see Figure 5 below, blue dashed line). Also, after realization the cross-shore profile did not develop towards a dynamic equilibrium profile in line with Deans theory. Instead a step profile developed with a steep profile slope of 1:10 in the active zone and a profile step located roughly at one meter water depth (See Figure 5). This cross-shore profile shape developed in the first month after construction and remained stable afterwards. The step in the profile widened slightly by building out farther offshore. At this stage exploratory numerical simulations are performed to obtain a more generic understanding of this profile shape. It is hypothesized that the strong grading of the material (150-550 um) in combination with the absence of a tide (smoothing the hydraulic loads over the cross-shore profile) is the main reason for observed profile shape. With respect to profile step at one meter water depth, it is found that the width of this step varies along the shoreline and in time, with maximum width at the outer edges of the pilot. Though the initial coastline was oriented towards the main angle of wave incidence, instantly the wave angel will deviate from the mean, causing the coastline to rotate roughly around transect 4 (see Figure 5). These coastline rotations cause the development of (an extra) wide profile step at roughly one meter water depth at transects away from transect 4 (Figure 5, lower panel). First insights indicate that the morphodynamics at the pilot site are rather large, though no sand has disappeared form the monitoring area. Nevertheless the coastline rotations cause substantial variations in volume in front of the dike, which affects the safety level of the anticipated water defense. Therefore the next step is to plant vegetation to damp the morphodynamics.

ENGINEERING WITH VEGETATION

Engineering with vegetation is becoming a more important aspect in designing successful sandy strategies. The first reason is that vegetation can contribute to stabilizing a sand body at a specific location and second reason is that by planting vegetation the landscape evolution can be influenced (i.e. to stimulate dune formation) to which specific functions can be attributed. Below the role of engineering with vegetation in the Building with Nature pilots is discussed.

Figure 6. Upper Artist impressions with vegetated dunes for the Sand Motor (left) and the HPZ (right). Lower: Natural dune development at the Sand Motor (left) using the existing dune system as a basis versus artificial constructed and planted dunes at the HPZ (right).

In landscape impressions of the Sand Motor before construction (see Figure 6 upper right panel for example), the Sand Motor was usually pictured with vegetated dunes. These dunes were considered of additional value for landscape experience (related to nature and recreational functions). However as part of the Sand Motor pilot no planting activities were initiated and starting point was to allow for natural dune development. Observations of natural dune development on the Sand Motor reveal that new dunes mainly develop from the original dune system and from here built out seaward. These dunes are vegetated with marram grass mainly, which have rather heavy seeds that tend to establish in the neighborhood of the mother plant. In the summer months also temporal dunes develop form other vegetation species as sea rocket. These dunes develop randomly and their location seems not related to the original dune system. In the winter months these small dunes disappear since the specific vegetation does not survive the winter season.

Like for the Sand Motor in the HPZ project dunes are considered of additional value for landscape experience, However here a more pro-active approach is chosen in creating dunes. Instead of having natural dune development solely, artificial dunes were constructed and planted with marram grass as part of the nourishment activities. Grown-up marram plants were used for planting during spring. Also screens were positioned at the toe of these artificial dunes to stabilize dune foot position and prevent substantial dune migration.

As discussed in the previous section, the dynamics along the pilot Houtribdijk foreshore were found to be substantial during the first winter when it was not covered with vegetation. To reduce these dynamics, and increase the feasibility of the concept several approaches to stabilize the sandy foreshore with vegetation are assessed. To this end the foreshore was divided in sections with different approaches and conditions for vegetation development (see Figure 7). In two of the sections the sandy top layer of the foreshore was mixed with Holocene clay to improve the conditions for vegetation development. Vegetation was planted in a sandy section and a mixed sandy-clay section. In the other sections natural vegetation development was allowed. Planting took place during growing season at the end of March and April and concerned planting of four type of willows on the higher parts of the foreshore and reed near the waterline. A sprinkles installation was installed for the first two months to make sure the plants received sufficient water to survive the critical few months.

Figure 7. Left: section on foreshore pilot Houtribdijk with natural vegetation evolution. Right: planted section of the foreshore with four type of willows at the higher foreshore and reed. The photo also shows an exclosure in which the reed density is substantially higher due to the absence of grazing here.

The first results at the end of the summer season 2015 revealed that natural vegetation development was minimal. Locally some plants developed but the surface in these sections was mostly without vegetation (Figure 8, left panel). In the planted sections the willows established well, the reed tough had a much more difficult time due to grazing by geese an due to shoreline dynamics. The effect of the grazing was assessed in more detail by placing exclosure areas that could not be grazed by birds (see figure 8, right panel), here the reed density was substantially higher at the end of the summer season.

CONCLUSIONS

Within the Building with Nature innovation program three pilots projects with sandy strategies are ongoing. Inspired by these pilots some overarching themes and aspects were identified that more generally can apply to developing sandy strategies.

Presented sandy strategies all break with “conventional” solutions that have been applied in the past. However, the concepts underpinning the pilot cases are not unique and have been applied / observed in other environments. In this context the main challenge in developing sandy strategies is much more in translating existing examples in generic concepts that can be made feasible and applicable again in other (challenging) environments. In doing that the conventional (usually robust and proven) infrastructure solution should be considered as a reference to answer the questions whether a sandy strategy provides either additional values (for which someone wants to pay) or is potentially cheaper.

The feasibility of a sandy strategy is directly related to the quality of the design in which two aspects are found to be important. First is the ability to design for predictable morphodynamics and uncertainty therein and second is the ability to engineer with vegetation. The role of vegetation is becoming more important in the development of sandy strategies because vegetation can contribute to 1) stabilizing a sand body and 2) landscape evolution such that the surface can be shaped for specific functions.

REFERENCES

Hunt, J.B. (2011). *Environmental Dredging*. New York: Smith & Son, Inc.

Dean, R.G., 1977. Equilibrium beach profiles: U.S. Atlantic and Gulf coasts. Department of Civil Engineering, Ocean Engineering Report No. 12, University of Delaware, Newark, DE

Dean, R.G., Kriebel, D.L. and Walton, T.L., 2002. Cross-shore secdiment transport processes. Chapter 3 of Part III of the Coastal Engineering Manual, EM 1110-2-1100.

De Jong, Maarten F., Bas W. Borsje, Martin J. Baptist, Jan Tjalling van der Wal, Han J. Lindeboom, Piet Hoekstra, Ecosystem-based design rules for marine sand extraction sites, Ecological Engineering, Volume 87, February 2016, Pages 271-280, ISSN 0925-8574, http://dx.doi.org/10.1016/j.ecoleng.2015.11.053.

De Schipper M.A., de Vries, S., Ruessink G., de Zeeuw, R.C., Rutten J., Gelder-Maas, C. and Stive, M.J.F. (2016). Initial spreading of a mega feeder nourishment: observations of the Sand Engine pilot project. Journal of Coastal Engineering .

Ehrlich, P.R. and A.H. Ehrlich, 1997. The population explosion: why we should care and what we should do about it. Environmental Law, Winter, 1997.

Mulder, J.P.M. and Tonnon, P.K., 2010. “Sand engine“: Background and design of a mega-nourishment pilot in the netherlands. Proceedings of the 32nd International Conference on Coastal Engineering, Shanghai, China.

Stive, Marcel J.F., Matthieu A. de Schipper, Arjen P. Luijendijk, Stefan G.J. Aarninkhof, Carola van Gelder-Maas, Jaap S.M. van Thiel de Vries, Sierd de Vries, Martijn Henriquez, Sarah Marx, and Roshanka Ranasinghe. A New Alternative to Saving Our Beaches from Sea-Level Rise: The Sand Engine. Journal of Coastal Research: Volume 29, Issue 5: pp. 1001 – 1008. doi: http://dx.doi.org/10.2112/JCOASTRES-D-13-00070.1

ACKNOWLEDGEMENTS

Research related to the pilot Houtrbdijk and HPZ is funded by the Dutch Ministry of Infrastructure and Environment under the Innovation fund (theme Building with Nature) of the High Water Protection Program. Research related to the Sand Motor was a.o. funded through the European Fund for Regional Development EFRO. We thank the broader Building with Nature community for their effort and input to the results and context presented in this paper.