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Research paper

Sustainable hydraulic engineering through building with nature

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Abstract

Hydraulic engineering infrastructures are of concern to many people and are likely to interfere with the environment. Moreover, they are supposed to keep on functioning for many years. In times of rapid societal and environmental change this implies that sustainability and adaptability are important attributes. These are central to Building with Nature (BwN), an innovative approach to hydraulic engineering infrastructure development and operation. Starting from the natural system and making use of nature's ecosystem services, BwN attempts to meet society's needs for infrastructural functionality, and to create room for nature development at the same time. By including natural components in infrastructure designs, flexibility, adaptability to changing environmental conditions and extra functionalities and ecosystem services can be achieved, often at lower costs on a life-cycle basis than 'traditional' engineering solutions. The paper shows by a number of examples that this requires a different way of thinking, acting and interacting.

Keywords: Building with nature; Sustainability; Infrastructure; Hydraulic engineering; Ecosystem services; Design

1. Introduction

Present-day trends in society (urbanization of delta areas, growing global trade and energy demand, stakeholder-emancipation, etc.) and in the environment (reducing biodiversity, climate change, accelerated relative sea level rise, etc.) put ever higher demands on engineering infrastructures. Mono-functional solutions designed without due consideration of the surrounding system are no longer accepted. Sustainability, multi-functionality and stakeholder involvement are required instead. This trend equally applies to hydraulic engineering works and the associated water system management.

The design of hydraulic engineering projects is no longer the exclusive domain of hydraulic engineers. Collaboration with other disciplines, such as ecology, economy, social sciences and administrative sciences is crucial to come to acceptable solutions. The specialists involved in such design projects must learn how to put forward their expertise in much more complex decision making processes than before: being right according to the laws of physics no longer guarantees being heard in such processes. If this reality is ignored, it may

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lead to long and costly delays of projects, as stakeholders and other interested parties are becoming ever more proficient in using the legal opportunities to oppose developments and have decisions postponed. In the Netherlands the court-cases that delayed the realisation of the extension of the Rotterdam harbour taught an expensive lesson, keeping the investments in the initiation, planning and design phases of the project without any return for a long time.

This and other experiences triggered the awareness that projects should be developed differently, with nature and stakeholder interests incorporated right from the start. In other words: from a reactive approach, minimizing and mitigating the impacts of a set design, to a pro-active one, optimizing on all functions and ecosystem services. Although in principle the concept of Building with Nature (BwN) is broader than hydraulic engineering, we will focus here on water-related projects. This paper, which is an extension of De Vriend (2013), discusses the project development steps as they have been suggested by the BwN innovation programme and illustrates their use by describing a number of hydraulic engineering projects in which the concept has been tested and some other examples where successful application is to be expected.

2. The building with nature (BwN) concept

2.1. General principles

Building with Nature (BwN) is about meeting society's infrastructural demands by starting from the functioning of the natural and societal systems in which this infrastructure is to be realized. The aim is not only to comply with these systems, but also to make optimum use of them and at the same time create new opportunities for them. This approach is in line with the need to find different ways of operation and it requires a different way of thinking, acting and interacting (De Vriend and Van Koningsveld, 2012; De Vriend et al., 2014).

2.1.1. Thinking

Thinking does not start from a certain design concept focussing on the primary function, but rather from the natural system, its dynamics, functions and services, and from the vested interests of stakeholders. Within this context, one seeks optimal solutions for the desired infrastructural functionality.

2.1.2. Acting

The project development process requires different acting, because it is more collaborative and extends beyond the delivery of the engineering object. The natural components embedded in the project will take time to develop afterwards, and one has to make sure they function as expected. Post-delivery monitoring and projections into the future are an integral part of the project. This also creates opportunities to learn a lot more from these projects than from traditional ones (see also Garel et al., 2014).

2.1.3. Interacting

BwN project development is a matter of co-creation between experts from different disciplines, problem owners and stakeholders (e.g., Temmerman et al., 2013). This requires a different attitude of all parties involved and different ways of interaction, in interdisciplinary collaborative settings rather than each actor taking away his task and executing it in relative isolation.

2.2. Design steps

Project development, albeit iteratively, generally goes through a number of consecutive phases. The BwN innovation programme distinguished 'initiation', 'planning and design', 'construction' and 'operation and maintenance'. BwN solutions may be introduced in each project phase in the form of ecologically preferable and more sustainable approaches. Although there is room for improvement in any phase, the earlier the approach is embraced in the project development process, the greater is its potential impact.

An important starting point for any development should be the environment at hand. A key characteristic that distinguishes a BwN design from other integrated approaches is the proactive utilization and/or provision of ecosystem services as part of the engineering solution. The following design steps were developed, tested and supported by scientific knowledge in the BwN innovation programme (De Vriend and Van Koningsveld, 2012; EcoShape, 2012):

- Step 1: Understand the system (including ecosystem services, values and interests).
  - The system to be considered depends on the project objectives. The project objectives are influenced by the system (problems, opportunities)
  - Information about the system at hand can/should be derived from various sources (historic, academic, local etc.)
  - Look for user functions and eco-system services beyond those relevant for the primary objective
- Step 2: Identify realistic alternatives that use and/or provide ecosystem services.
  - Take an inverted perspective and turn traditional reactive perspectives into proactive ones utilizing and/or providing ecosystem services
  - Involve academic experts, field practitioners, community members, business owners, decision makers and other stakeholders in the formulation of alternatives
- Step 3: Evaluate the qualities of each alternative and preselect an integral solution.
  - More value does not necessarily imply higher construction cost
  - Dare to embrace innovative ideas, test them and show how they work out in practical examples
  - Perform a cost-benefit analysis including valuation of natural benefits
  - Involve stakeholders in the valuation and selection process

- Step 4: Fine-tune the selected solution (practical restrictions and the governance context).
  - Consider the conditions/restrictions provided by the project (negotiable/non-negotiable)
  - Implementation of solutions requires involvement of a network of actors and stakeholders
- Step 5: Prepare the solution for implementation in the next project phase.
  - Make essential elements of the solution explicit to facilitate uptake in the next phase (appropriate level of detail varies per phase)
  - Prepare an appropriate request for proposals, terms of reference or contract (permitting)
  - Organise required funding (multi-source)
  - Prepare risk analysis and contingency plans

Fundamental to the above design steps is a thorough knowledge of how the natural system functions and a correct interpretation of the signals to be read from its behaviour. The latter may indicate in what direction the system is evolving, how best to integrate the desired infrastructure into it and how to make use of the ecosystem services available. They may also provide an early warning of adverse developments, or indicate an increased sensitivity to natural hazards. Investing in increased understanding of the natural system and its inherent variability does not only pay off to the realisation of the project at hand, but also to the system's overall management.

2.3. Spectrum of applicability

What kind of BwN solution may be applied in a given situation, be it coastal or riverine, sandy or muddy or dominated by living components, is governed by the ambient physical system. Practical experience has shown that four parameters span up a range of potential applications (see Fig. 1): bed slope, hydrodynamic energy, salinity and geo-climatic region (e.g., temperate or tropical).

2.3.1. Flat slopes

In low-slope environments generic BwN solutions can be completely sediment-based. This is true for both saline and fresh water systems. Differentiating is possible according to energy levels. High-energy tidal environments favour designs that are wide and contain a large volume of sediment (kilometres scale) in order to produce equilibrium shorelines and slopes, and enough bulk volume to withstand extreme conditions (for example parts of the Dutch coastline with beaches and dunes). Where these highly energy-exposed systems are typically low in biomass, the low-energy sheltered environments, saline or fresh, allow soft solutions with high biomass, lower width (hundreds of metres) and with tendencies to accrete cohesive sediment. This often results in a mix of sand and mud, stabilized by (root systems of) vegetation cover.

2.3.2. Moderate slopes

As the bed slope increases, the width available for a soft foreshore in the wave impact zone is reduced. To maintain safety against flooding, for example, hybrid solutions are required, such as a ‘stable sediment foreshore with hard dike’ combination. Wave reduction on the foreshore enables dikes to be lower and softer (e.g., grass-clay cover) than traditional engineering designs. The foreshores in these solutions can typically be stabilized through vegetation and/or reef-structures (e.g., a ‘sediment nourishment-wave-reducing

Fig. 1. Range of potential BwN applications along the main axes of given bed slope and hydrodynamic energy. Of course factors like salinity and geo-climatic region also determine potential solutions.

floodplain forest-dike' combination in fresh water, or a sediment nourishment-stabilizing and wave reducing oyster reef-mangrove-saltmarsh-dike systems in saline water). The selection of the living components of the application is obviously dependent on the prevailing geo-climatic system relevant for the case.

2.3.3. Steep slopes

As the bed slope increases further, hard solutions may eventually prevail as most suitable solution. It is possible, however, to introduce ecological enhancements on hard solutions, in order to increase habitat diversity, biodiversity or productivity of the structures. This could result in interesting combinations of safety, economic and natural win–win solutions.

The following sections describe examples for a number of distinct environments. We will indicate what role Design Step 1, reading (or not reading) the natural system, has played. For each environment a distinct example is described, followed by a brief analysis of the potential for more general application.

3. BwN in riverine environments

3.1. Example: room for the river

Floodplains of lowland rivers are very attractive areas for development. This explains why in the past centuries, man has encroached on these rivers and deprived them from large parts of their floodplains (Fig. 2). As a consequence of the reduced storage capacity, flood waves in these rivers become higher and proceed faster (Fig. 3, showing the same floodwave in the Upper Rhine with an old and a recent river geometry), thus increasing the hydrodynamic load on the flood defences and reducing the lead time for precautionary measures such as evacuation.

The traditional response to these trends is to raise and strengthen the embankments. This is basically a reactive approach, as it does not remove the cause of the problem, viz. the lack of storage capacity.

In recent years, governments and managers of various rivers around the world have recognized this and have started proactive floodplain restoration projects, sometimes primarily driven by the need for flood alleviation, in other cases by the wish to restore nature or both (for instance, see Room for the River (2012) for the Dutch Rhine branches, or Mississippi (2013), or Schneider (2007) for the Danube).

In case of the Rhine and Meuse rivers in the Netherlands, extensive schemes have been developed to reconnect removed floodplain area to the river, thus restoring storage capacity. Part of the returned floodplain area was made available to nature development, provided that this did not unacceptably reduce the river's flood conveyance capacity. The strategy of cyclic floodplain rejuvenation was developed to solve the dilemma between flood protection and nature rehabilitation (Baptist et al., 2004).

Clearly, the signals of nature (like in Fig. 3) have been read and understood in this case. It is also an example of thinking,

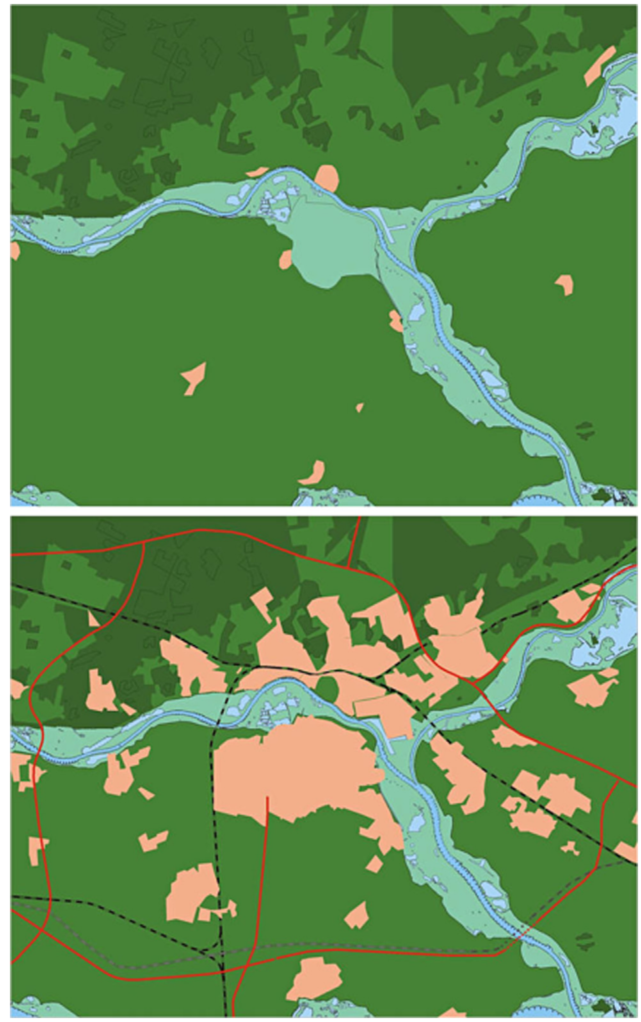

Fig. 2. Urban encroachment on the Rhine branches near the city of Arnhem, NL, between 1830 (top) and 2000 (bottom) (from: Silva et al., 2001). The pink colour indicates urban area, light green the flood plain and blue the main channel. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

acting and interacting differently. Thinking differently, because this goes against the traditional reactive approach (acting after a problem has become manifest). Acting differently, because different measures are taken, such as floodplain lowering, side channel excavation and dike displacement. And interacting differently, because other parties (e.g., Non Governmental Organisations (NGOs), terrain managers, recreation organisations, inhabitants) are actively involved in decision making on these projects.

3.2. More general applicability

Flood alleviation and nature restoration are not the only river issues. Dam building, excessive water offtake, sand mining and normalisation are activities that profoundly influence river behaviour and invoke a variety of problems. Immediate effects concern the flow regime and the sediment transport capacity, but in the longer run the large-scale morphology is affected. Especially changes of the

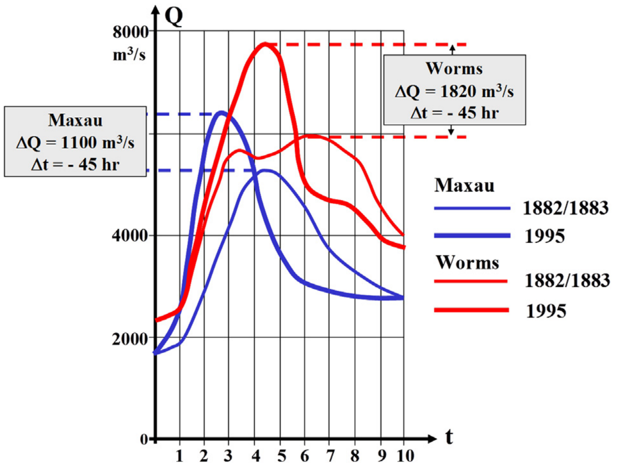

Fig. 3. Computed flood wave in the Upper Rhine, Germany, with the river geometry of 1882/1883 and 1995 respectively (adapted from: ICHR, 1993). The horizontal axis indicates time in days.

longitudinal slope can have severe consequences. The river may incise, which leads to erosion and groundwater level drawdown, e.g., downstream of dams. In other cases, the river bed builds up far above the surrounding area, leading to an increased flood risk, as has become manifest during the 2010 Indus flood (Fig. 4).

Also, the cross-sectional area and the flood conveyance capacity can be severely reduced, which further enhances the flood risk. An example of the latter is the Lower Yellow River near Huayankou, China (Fig. 5), where a peak discharge of 7.860 m^3/s in 1996 gave about the same peak water level as a peak discharge of 22.300 m^3/s in 1958.

In order to deal with these problems, the river has to be read in terms of flow discharge, sediment transport and (large-scale) morphological behaviour. Water management has to be attended with corresponding sediment management in order to avoid problems as described above. Being part and parcel of the river bed, the floodplains also need to be managed carefully, as they will play an important role in storing and conveying flood waters, whereas in the meantime they may support a valuable ecosystem and/or important economic activities such as agriculture.

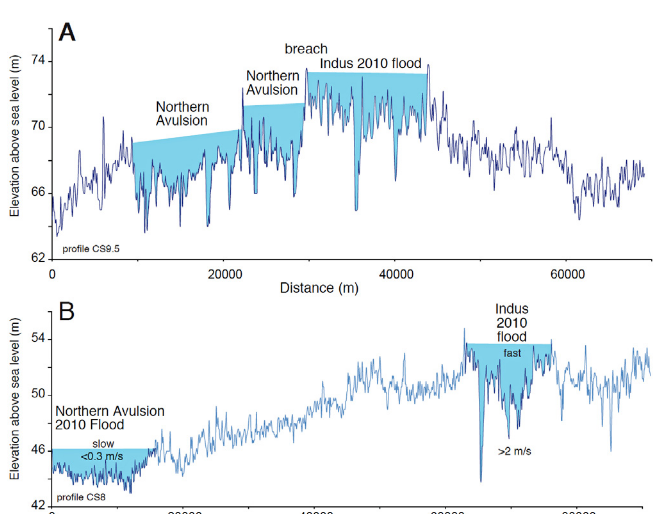

Fig. 4. Landscape profiles across the Indus, Pakistan, and the avulsions during the 2010 flood (from: Syvitski and Brakenridge, 2013).

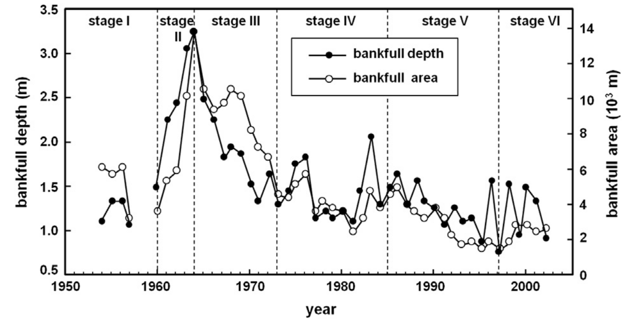

Fig. 5. Evolution of depth and cross-sectional area of the Lower Yellow River at Huayankou Station, China; the stages refer to different regimes of dam operation (derived from: Ma et al., 2012).

The managers of the Yellow River have understood this, in that they noted that heavily sediment-laden floods tend to scour the river bed (Fig. 6). After the construction of the Xiaolangdi Dam, they flush the river from time to time by creating so-called man-made floods. Through joint operation of three consecutive reservoirs, they create a flood wave and at the same time release large amounts of sediment from the reservoirs (Fig. 7). The resulting highly concentrated flow scours the river bed over a large distance, thus restoring the river's conveyance capacity for natural floods.

4. BwN in sandy shore environments

4.1. Example: the Delfland Sand Engine

Since the 1990s, the Holland coast, an exposed sandy dune coast bordering the North Sea, is maintained by nourishing it with sand taken from offshore. In principle, this is a nature-friendly and sustainable way of coastal maintenance, even in times of sea level rise. Yet, present-day practice is

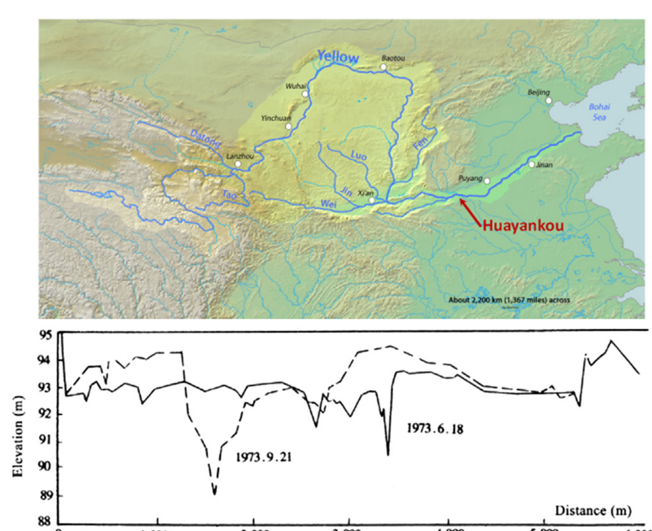

Fig. 6. Cross-section of the Lower Yellow River at Huayankou, China, before and after the 1973 flood (from: IRTCES, 2005).

Fig. 7. Man-made flood generation in the Yellow River at Xiaolangdi, China. The highly sediment-laden flow scours the river channel over a long distance downstream.

reactive: whenever the coastline threatens to withdraw behind a given reference line, a relatively small amount of sand (up to a few million m^3) is placed on the beach or the upper shoreface. A typical return period of these nourishments is some five years. This practice has a few disadvantages. Every nourishment buries part of the marine ecosystem, the recovery of which takes several years. As a consequence, five-yearly nourishments tend to bring the ecosystem into a more or less permanent state of disturbance (Baptist et al., 2008). Moreover, nourishing only the upper part of the shoreface tends to lead to over-steepening of the coastal profile, hence to more offshore-directed sediment transport and, in the long run, the necessity to nourish ever more frequently. Or, otherwise, this over-steepening leads to an increased susceptibility to coastal erosion when the nourishments stop (Stive et al., 1991).

In 2011, the Province of Zuid-Holland and Rijkswaterstaat started an experiment to find out whether nourishing a large amount at once is a better solution. Between February and July 2011, 21.5 million m^3 of sand was deposited on the shoreface in front of the Delfland coast, between The Hague and Rotterdam (Fig. 8). The idea of this mega-nourishment is that in the coming decades the sand will be distributed by waves, currents and wind over this 18 *km* long coastal reach, thus feeding the lower shoreface, as well as the subaqueous and subaerial beach and the dune area. Once the nourishment has been placed, the ecosystem is expected to suffer less than in the case of repeated small nourishments. The experiment should provide an answer to the question to what extent the disadvantage of the earlier investment (the costs of the nourishment) will be outweighed by additional benefits, such as less harm done to or even new opportunities for the ecosystem, recreational opportunities (for instance, the Sand Engine has soon become a favourite site for kite surfers, which brings profit to the local economy), a wider dune area (i.e. also a larger freshwater reserve) and a better adaptation of the coastal defence system to sea level rise.

Fig. 8. Upper panel: The Delfland Sand Engine shortly after placement (July 2011). Lower panel: The Sand Engine has evolved into an almost symmetrical salient (October 2013). source: https://beeldbank.rws.nl, Rijkswaterstaat/Joop van Houdt.

A recent morphological survey showed that in the two years since construction about 2 million m^3 of sand (i.e. some 10% of the total volume) have moved, of which 0.6 million m^3 have stayed on the Sand Engine, 0.9 million m^3 in its immediate vicinity and 0.5 million m^3 have been transported outside the survey area, i.e. to the dune area or to deeper water, which agrees well with earlier model predictions (e.g., Stive et al., 2013a, b). As coastline processes tend to slow down as they approach the equilibrium state (in this case a straight coastline), these results suggest that a lifetime estimate of 20 years is probably conservative.

Ecologically speaking, the Sand Engine exhibits interesting developments (Linnartz, 2013), e.g., juvenile dune formation and establishment of pilot vegetation, including rare species. It also turns out to be a favourite resting area for birds and seals, and the lagoon is full of juvenile fish. Whether the Sand Engine approach is economically attractive remains to be seen. First calculations (Stive, 2013, private communication) suggest that, even if only the costs of sand reaching the shore are considered, the economy of scale and the presence of heavy equipment in the vicinity (building Maasvlakte II, a seaward extension of Rotterdam harbour) outweigh the effect of discounting the early investment.

4.2. More general applicability

The concept and the way of thinking underlying the Sand Engine are generic for eroding sandy coasts, but its design cannot simply be copied to other locations. The design should rather comply with the local situation and the local dynamics. Moreover, not only sea level rise may be the cause of coastal erosion, but also a lack of sediment supply, e.g., due to damming or sand mining in rivers feeding the coast, or interruption of the longshore drift by engineering structures, or removal of stabilizing vegetation (mangrove). This may lead to different designs and different ways of construction and operation.

Stable sandy coasts usually exist thanks to a sediment source, often a river or an eroding cliff. If this source is reduced, for instance by damming upstream, or by fixation of the cliff, the coast will tend to erode. One example is the Yellow River Delta, where the sediment source was first fixed in place by embanking the river, and subsequently reduced by a dam-induced change of the discharge regime (Fig. 9), followed by a coarsening of the bed, both of which bring down the river sediment transport capacity. As a consequence, the past rapid build-out of the delta first concentrated around one location (the fixed river mouth) and later dropped dramatically, came to a standstill and even turned into erosion (e.g., NASA, 2013). Other parts of the delta coast were cut off from their sediment source and eroded rapidly, in some places over a large distance (kilometres). Coastal nourishment and fixation by vegetation may be an option here, but this requires thorough reading of the system, i.e. consideration of the local situation, with very fine and easily erodible sediment and a high groundwater salinity.

Other examples of dramatic coastal erosion can be found on tropical mud coasts where the natural mangrove protection has been removed, for instance in order to build fish ponds in the coastal zone. Fig. 10 shows an example of the north coast of Java near Demak, Indonesia, where heavy erosion started after the fish ponds, which covered the entire coastal zone, had been abandoned. Given the many ecosystem services provided by mangrove forests, their restoration seems attractive here. Many failures of mangrove replantation schemes (e.g., Primavera and Esteban (2008); Lewis III (2009)), however, have shown that this is nowhere near a trivial task. For the replanted system to survive it is crucial to have the right combination of coastal morphology (with a concave downward profile), wave conditions, tidal motion, fresh groundwater availability, sediment supply and plant species (Winterwerp et al., 2013). This is another example of the necessity to read the local natural system, as it is now and as it has been in the past, and to adapt the design accordingly.

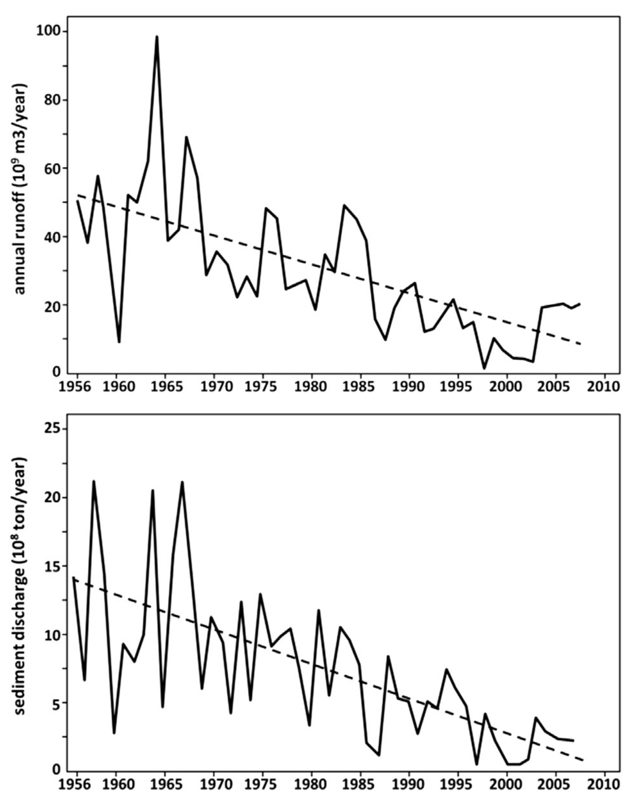

Fig. 9. Evolution of the annual runoff (upper panel: after Grafton et al., 2013) and sediment discharge (lower panel: after Wang et al., 2011) at Lijin Hydrological Station, Lower Yellow River, China. The dashed lines represent the linear trend through the available data points.

5. BwN in lake shore environments

5.1. Example: Lake IJssel Shore nourishment

In 2008, a State Committee advised the Netherlands government on flood safety and freshwater availability under a

Fig. 10. Coastal degradation between 2003 and 2013 near Demak, Indonesia (courtesy: J.C. Winterwerp).

scenario of accelerated sea level rise (Delta Committee, 2008). Part of this advice concerned the Lake IJssel, the inland freshwater lake that was created by closing off the Zuiderzee in 1932. The Committee advised to gradually raise the lake level along with the rising sea level, so that one could keep on discharging surplus water by free outflow. Although in the meantime this idea has been abandoned in favour of increased pumping capacity, the suggestion has raised the awareness of terrain managers of the former coastal saltmarshes, now valuable freshwater wetlands that protect the dikes behind them against wave attack. They realized that these wetlands require maintenance, in order to be ready for stronger variations of the lake level, to combat ongoing subsidence and to enable the vegetation to rejuvenate.

Although southwesterly winds have a considerable fetch here and local waves and water level set-up can be significant, the lake shores can be categorized as low-dynamic. This means that nourishing these shores would lead to a slow supply of sediment to the coastline, exactly what is needed to maintain these wetlands without destroying their vegetation.

In 2011, and 2012, respectively, small-scale shoreface nourishments were performed at two locations (Workumerwaard and Oudemirdumerklif) on the northwesterly shore of the lake. Figs. 11 and 12 show the development of the Workumerwaard nourishment, which involved some 30.000 m^3 of sand. Although after the first year the nourished sand has hardly reached the shoreline, morphodynamic activity is clearly present, as the original hump has dispersed into a number of sand waves which are in line with the natural bed topography. Recent visual observations suggest that the sand is moving northward, along with the net longshore drift, and is trapped in the lee of the pole screen.

At this location, reading nature boiled down to (1) realizing that the wetlands had to remain in open connection with the lake in order to keep their unique character, (2) concluding that the wetland vegetation had reached a climax stage and would need rejuvenation in order to restore diversity and vitality, (3) interpreting the natural sand waves on the subaqueous shore as a signal of morphodynamic activity that might bring nourished sediment onshore, and (4) realizing that the prevailing longshore drift will tend to carry the sand further north, so that a sediment retaining structure is needed.

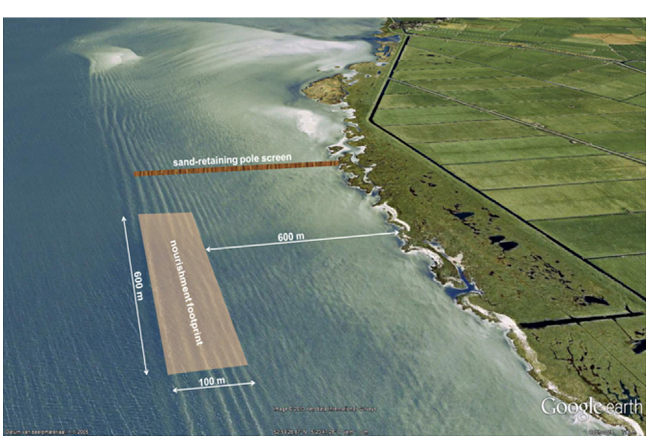

Fig. 11. Design of the Workumerwaard nourishment experiment (grey rectangle: nourishment footprint; brown line: sand retaining pole screen); the primary flood defence, a dike, lies outside the photo to the right.

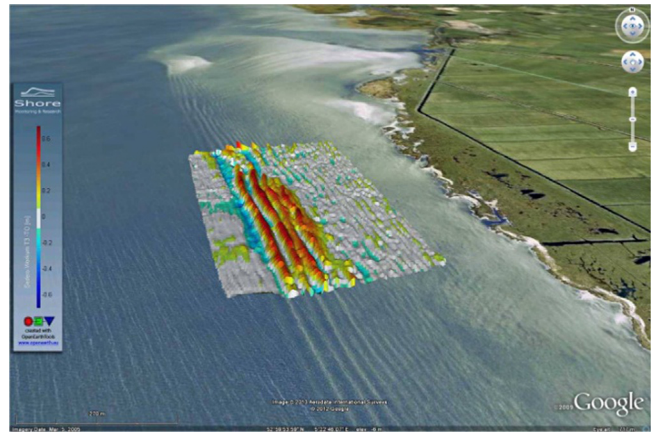

Fig. 12. Bed topography after 1 year; warmer colours represent higher bed levels (courtesy: A. Wiersma); note the pole screen screen is not shown in this picture. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Thinking differently means here the recognition that the wetlands are not only valuable from an ecological and recreational point of view, but also have the capability -when properly managed-to keep the dikes behind them from being strengthened. People acted differently here because they decided not to strengthen the dike (and probably let the wetlands get drowned) or build a protection levee along the shore (and probably destroy the wetlands' character), but to opt for slow sand nourishment. And they interacted differently because this project was developed by experts from various disciplines, together with a variety of stakeholders and the local administration. At another location, Hindeloopen, this stakeholder involvement even led to a drastic change of plans, to the effect that for the time being no nourishment will be made, at all.

5.2. More general applicability

The example above concerns an existing, more or less natural foreshore. Such features are not always available in lakes. Lakes in soft sediment environments like deltas tend to expand in the direction of the prevailing winds. As this process continues, they become more susceptible to wind-induced water level variations, especially at the eroding end. Also, floods in adjacent rivers may cause flood problems. Tai Lake, near Shanghai in China, for instance, lies close to the Yangtze River and well below typical flood levels in that river (Gong and Lin, 2009).

This shows that flood protection is an issue for the riparian areas of such delta lakes. If the water from the lake has to be kept out, dike building is an obvious way to achieve this. If the subsoil is soft, however, like in the case of a dike built on peat, the soil's carrying capacity may limit the dike height. Also, subsoils with sandy streaks, e.g., remainders of old streams and creeks, may give rise to piping, i.e. the formation of sediment conveying seepage channels which undermine the dike (e.g., De Vries et al., 2010).

The height of a traditional dike is determined to a significant extent by wave overtopping restrictions, the width by geomechanical stability requirements and the need to extend the seepage length in order to prevent piping. As an alternative to dike raising, one may consider designs that reduce the wave attack and increase the stability and the seepage length in another way. Depending on the local situation, a shallow vegetated foreshore may be such an alternative (Fig. 13).

Both the shallowness of the foreshore and the vegetation on top of it attenuate incoming waves before they reach the dike. A clayey substrate hampers seepage, hence increases the effective seepage length. Such foreshores can carry valuable ecosystems that provide a large number of additional services, such as water purification (e.g., helophyte filters), breeding, feeding and resting grounds for a variety of species (among which migratory birds), carbon sequestration and biomass production. It forms an alongshore connection between ecosystems that were separated before and it provides space for a variety of recreation activities.

This, too, is not a panacea. If excessive rainfall is the main cause of flooding, for instance, effective drainage is more important than keeping the water out. And if severe algal blooms occur (see Fig. 14) it is better to eliminate the sources of eutrophication than to try and remove the nutrients once they are in the system. This illustrates, once again, the importance of reading and understanding the local environment.

6. BwN in estuarine environments

6.1. Example: Eastern Scheldt oyster reefs

Bio-architects or ecosystem engineers are species that modify their habitat, to their own benefit and that of other species (e.g., Bouma et al., 2009). Oysters and coral are examples, they build reefs that provide habitat to a wide range of others species. Apart from this effect on their own habitat and that of other species, the activities of bio-architects may have other positive effects, such as sediment trapping and coastal protection. This makes these species interesting from a BwN point of view. In temperate climate zones, oyster reefs may be used to prevent erosion and saltmarshes to trap sediment and attenuate waves. In a tropical climate, mangrove forests, seagrass meadows and coral reefs, often in combination, may help stabilizing and protecting coasts.

A set of experiments with oyster reefs for the protection of eroding intertidal shoals was performed in the Eastern Scheldt, the Netherlands. These shoals are consistently losing sediment to the gullies after the construction of a storm surge barrier in the mouth of the estuary and a number of auxiliary works have reduced the tidal amplitude by about 20% and the tidal prism in the mouth by some 25% (e.g., Eelkema, 2013). This loss of intertidal area, together with the flattening of the shoals by wave action, is detrimental to the populations of residential and migratory shorebirds or waders, which use this area for feeding and resting.

One way to interrupt the sediment transport from the shoals into the gullies would be to create oyster reefs on the shoal edges. This raises the question how to establish live oyster reefs at the right locations. Since oyster shells are the perfect substrate to settle on for juvenile oysters (spat), gabions (iron wire cages) filled with oyster shells (Fig. 15) were placed on the shoal edges at various locations, first in small patches, later on in larger strips (typically 10 m wide and a few hundreds of metres long). After a few years (Fig. 16) we can conclude that this approach can work, provided that the locations of the gabions be carefully selected (Ysebaert et al., 2012).

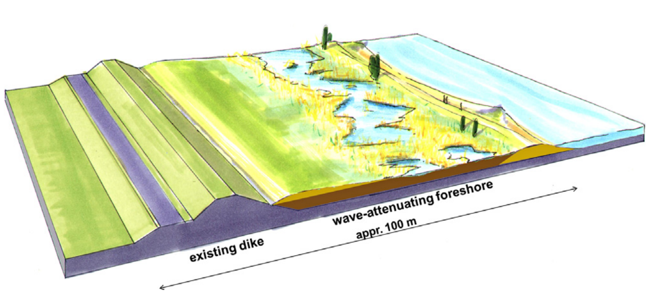

Fig. 13. Artist impression of a lacustrine shallow foreshore in front of a traditional dike; the dark brown material is clayey, in order to prevent seepage; the light brown material is sandy, as a buffer against erosion (courtesy: Bureau Stroming).

Fig. 14. Some lakes have severe water quality problems, such as algal blooms (photo from Tai Lake, China).

Fig. 15. Placement of gabions with oyster shells (courtesy: T. Ysebaert).

In this case, the natural processes were carefully analysed and interpreted. The reduction of the tidal motion has weakened the hydrodynamic forces building up the shoals and has given room to the erosive action of locally generated waves. This explains why the shoals tend to be 'shaved' off almost horizontally. The sediment eroded from the tops of the flats ends up in the nearest deeper water, so on the subtidal banks of the gullies. This means that there are no mechanisms to carry this sediment further away, and that if one would manage to keep the sediment on top of the shoals it would probably stay there. This explains why oyster reefs on the shoal edges may help. The ecosystem was also read carefully: oyster spat settling preferentially on oyster shells, oyster reefs being more resistant than mussel banks, for instance, because oysters glue their shells together and mussels use byssus threads to connect to each other. Environmental conditions necessary for a live oyster reef to establish and survive (wave exposure, nutrient flows, risk of sand burial, risk of macroalgae preventing spat settlement, ect.) were also carefully considered.

Here, too, thinking, acting and interacting were unusual. Even though blocking shoal erosion may be considered as an end-of-pipe measure (the real causes of the erosion are not removed), using biological elements to achieve an engineering goal, viz. erosion prevention, is a change in thinking. Moreover, if the reefs are viable in the long run, they will also be able to adapt themselves to a changing sea level. This is a capability beyond what traditional engineering structures can deliver. The design constitutes a different way of acting. The placement of the gabions is hardly intrusive (no digging, mostly indigenous components). The ironwire gabions will corrode quickly in this aggressive environment, so after some time the system relies on the ability of the oyster reef to sustain and rejuvenate itself. This is different from traditional engineering, with its focus on durable structures.

Finally, different experts (apart from technicians also physicists, ecologists and social scientists) and different stakeholders (apart from Rijkswaterstaat also NGOs, fishermen, etc.) were involved in the decision making process. Moreover, coastal defence experts keenly followed the experiments, because of the potential positive effects on the wave-attenuating and dike-stabilizing function of shallow shore-connected shoals.

6.2. More general applicability

Intertidal areas are found in estuaries around the world and usually they are of great value, environmentally, but also from an economic point of view (flood protection, land reclamation, aquaculture, etc.). Many of these estuaries, however, suffer from a reduced sediment supply, due to river damming, sand mining and excessive water offtake from the river that debouches through the estuary. The Yangtze River, with its many thousands of dams (Yang et al., 2011), is just one example, but there are many others. Many estuaries also have been deprived from their inter- and supra-tidal storage area, with severe consequences, not only for extreme surge levels and flood risks (Temmerman et al., 2013), but also for suspended sediment import and environmental quality (Winterwerp et al., 2013). Before the sediment supply to the Yangtze Estuary was drastically reduced, the islands and shoals in the Yangtze Estuary would build out rapidly, enabling consecutive reclamations of large pieces of land to meet the urgent need for space in this part of China (Fig. 17).

At present, the shoals in the estuary tend to erode. An early indicator of this tendency is the cross-shore profile, which has

Fig. 16. Successful oyster reef after one year (courtesy: T. Ysebaert).

Fig. 17. Consecutive reclamations of accreted marsh on East Chongming Island, Yangtze Estuary, China.

turned in recent years from concave upward to convex upward (Yang et al., 2011); also see Fig. 18. A dense and vital vegetation canope (in this case a combination of endemic *Scirpus* and imported *Spartina*) can slow down this process (Yang et al., 2008), but cannot remove the principal cause, viz. the lack of sediment supply from upstream. Whether ecosystem-engineers like oysters or mussels can provide a solution here remains to be seen, given the intense fisheries activity in this area. Moreover, the need for space creates pressure from society to reclaim more land, be it not at East Chongming Island, then in other parts of the estuary, and be it not above Mean Sea Level (MSL), then below it (cf. Chen et al., 2008). The latter requires dike construction below MSL, which is bound to aggravate erosion in front of the dike. Clearly, not only the natural system needs to be read to find an adequate solution, but also the socio-economic system.

7. Dredging-induced turbidity

Dredging, instrumental to many hydraulic engineering works, often leads to environmental concerns because of the turbidity it induces. This may harm valuable ecosystems, such as coral reefs in tropical areas, or shellfish reefs in moderate climate zones. So far, regulations used to focus on the sediment flux released from the dredging equipment, rather than on the actual impact on the ecosystem. BwN proposes to reverse the order, starting from the ecosystem's vulnerability and working one's way back to the dredger. This enables optimization of the dredging operation.

A useful tool to assess ecosystem vulnerability are species response trajectories for the key species (Fig. 19), describing the abundance of a species as a function of stress level and exposure duration. Given a certain ecosystem and the hydrodynamic and sedimentologic conditions in its surroundings,

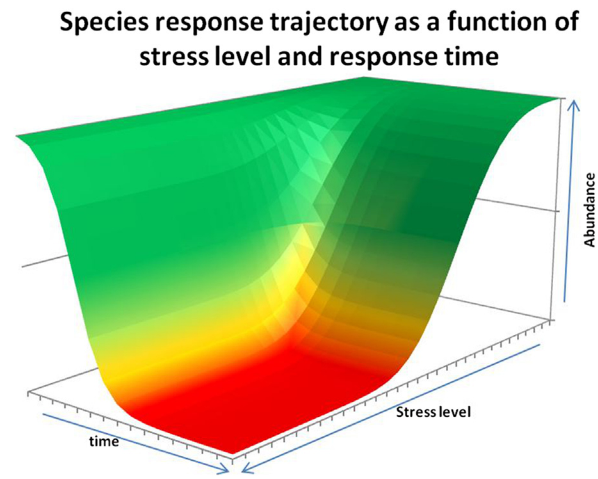

Fig. 19. Species response trajectory for tropical seagrass (source: EcoShape, 2012).

one can work out the maximum allowable sediment release at every location and every point in time using a sediment dispersion model. Fig. 20 shows a screen shot of a dredging support tool in which this has been implemented. The green dots indicate locations where exposure to turbidity is predicted to remain below predefined threshold levels. The tools supports planning the dredging operation such that this is secured.

8. Discussion

8.1. Translation to practice

The above examples are just a selection of applications and application potential of the BwN-principles and design steps. Together they cover the range of applications outlined in Section 2. Many more examples are described by Waterman (2008), on the EcoShape website http://www.ecoshape.nl, in the BwN-booklet (De Vriend and Van Koningsveld, 2012) and in the BwN-design guideline (EcoShape, 2012). For new insights acquired from experiments and pilot projects to be used

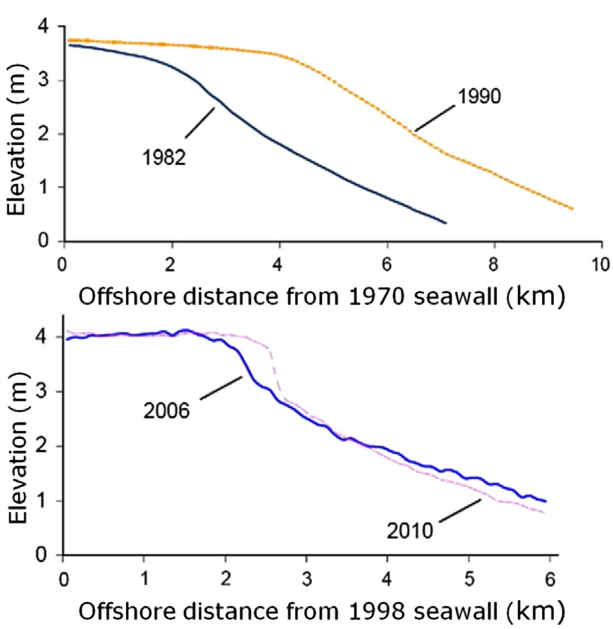

Fig. 18. Cross-shore profile evolution at East Chongming Island, China (from: Yang et al., 2011).

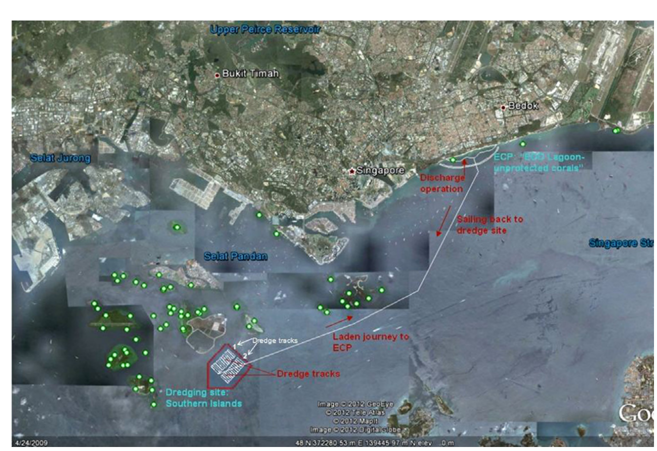

Fig. 20. Screenshot of a dredging support system applied to a dredging operation near Singapore.

in practice, translation to practical usability is crucial. This goes far beyond writing papers in scientific or professional journals or presenting material at conferences and workshops. It requires a complete reworking of the material into guidelines for practical use, user-friendly tools, tutorials, low-threshold access to data and models, examples of earlier projects, ready-to-use building blocks, etc.

In the Dutch BwN innovation program (2008–2012) a significant part of the effort was spent to this reworking activity. It has led to a wiki-like environment, accessible via the EcoShape-website mentioned above, which includes all these elements and contains a wealth of information. Based on feedback from users and continued input from ongoing and new projects and experiments, this wiki is to be improved further.

8.2. Dissemination and outreach

The concept underlying BwN has been taken up by various other organisations. In the United Kingdom (UK), managed realignment, i.e. realignment of flood defences in such a way that there is more room for flood water storage and at the same time for nature, is basically a form of building with nature (e.g., Garbutt et al., 2006). The World Association for Waterborne Transport Infrastructure (PIANC) supports a similar movement named 'Working with Nature' (see PIANC, 2013). The US Army Corps of Engineers (USACE) promotes the use of dredged material to create room for nature areas in the coastal zone: 'Engineering with Nature' (Bridges et al., 2008). Also in Belgium, there are plans for extensive multi-functional 'soft engineering' in front of the North Sea coast of Flanders (see Vlaamse Baaien, 2013). Finally, the European Commission (EC) has included the concept in its Green Infrastructure Strategy (see European Commission, 2013).

Yet, mainstreaming the approach in practical hydraulic engineering projects still meets several obstacles. Some of these have to do with conservatism and risk-aversion, but others are associated with the economic point of view and the prevailing legislation. When considering only the short-term economics of adding sand to the backbeach and the dune area, the Delfland Sand Engine may be economically suboptimal, as nourishing small amounts whenever necessary may well be cheaper. But from a longer-term and multi-functional perspective, mega-nourishments may just as well be economically attractive. Moreover, BwN requires investing time and money into knowing how the natural system -including the ecosystem- functions, an investment that pays off later, but possibly not as directly as a traditional hard engineering solution.

If, like in the European Union (EU), legislation forces all government-funded infrastructural projects to be internationally tendered, innovative pre-competitive experiments and pilot projects tend to be out-competed by traditional approaches of which the uncertainties are perceived to be less. Another example of the effect of prevailing rules concerns the assessment of the flood defence systems in the Netherlands, which excludes shallow foreshores. This renders shallow-foreshore solutions for flood defences useless.

9. Conclusions

The existing experiments, pilot projects and showcases show that the BwN approach works, provided that one thinks, acts and interacts accordingly. Knowing the natural biotic and abiotic environment in which an infrastructural functionality is to be realized, as well as knowing how the relevant social system functions, is a necessity for this approach to be successful. This applies in Europe, as well as in other countries around the world, as shown by the examples in Asia and the United States of America (USA). Initiatives in different countries and international organisations are merging into an international movement, but mainstreaming the approach in hydraulic engineering practice still meets a number of obstacles. They need to be overcome in the next few years in order to have this approach broadly implemented.

Acknowledgements

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Acronyms

BwN: Building with Nature;
EC: European Commission;
EU: European Union;
MSL: Mean Sea Level;
NGOs: Non Governmental Organisations;
PIANC: World Association for Waterborne Transport Infrastructure;
UK: United Kingdom;
USA: United States of America;
USACE: US Army Corps of Engineers.