AN ECOSYSTEM SERVICES ASSESSMENT OF THE PRINS HENDRIK ZANDDIJK

This study examines which and, if possible, how much more ecosystem services are provided by the most recent nature inspired coastal protection project Prins Hendrik Zanddijk.

The second coastal safety assay in The Netherlands, reported in 2006, showed that more than 70% of the 24-kilometre-long Wadden Sea dyke on the island of Texel failed to meet safety standards. A refurbishment was executed on 14 kilometres of the dyke, increasing its width and height, and adding a cover layer of grass and asphalt. Along the remaining 3.2-kilometre long section in front of the Prins Hendrik Polder (Section 9), a soft coastal protection design called the Prins Hendrik Zanddijk (PHZD) was realised. A dune and beach sandbody was reclaimed seaward of the dyke, upgrading some 200 hectares of the Wadden Sea area.

FIGURE 1

Location of Section 9 Wadden Sea Dyke (source: HHNK).

During the last decade, reclamation of a sandbody as a coastal protection measure has evolved into a viable and attractive alternative to handbook-engineering using concrete and asphalt. The latter, considered traditional coastal protection methods, offers the reassurance of multiple generations of engineering experience and reliability. Nature based solutions (NBS) are defined as 'solutions that are inspired and supported by nature, which are cost-effective, simultaneously providing environmental, social and economic benefits and help build resilience' (European Commission 2019). NBS such as sandbody designs must cope with dynamic behaviour and variability of the building material as well as with uncertainty of maintenance costs. The quantification of the cost-effective part of this definition remains however a difficult task.

Nevertheless, notable examples of nature-inspired sandbody designs have been constructed in The Netherlands, such as Zandmotor Ter Heijde, Kustwerk Katwijk and Zwakke Schakels Noord-Holland (Hondsbossche-Pettemer Zeewering).

The main argument for choosing the soft alternative was the assumed benefit over the traditional design for society both locally (habitants, farmers and visitors) and for society in general (air and water quality, creation of scarce habitats). Although the approval of these projects shows that these arguments can be decisive, the question remains whether it is worth to pay more for these NBS and take the associated risks, and if so by how much. The tool to quantify these benefits for society is called Ecosystem Services (ES).

This study examines which and, if possible, how much more ecosystem services are provided by the most recent nature inspired coastal protection project Prins Hendrik Zanddijk, in comparison with a traditional concrete and asphalt construction.

The choice between the hard solution (the refurbishment) and the soft alternative (sandbody) was not an obvious one. In fact, both scenarios have been developed in parallel in pre-tender phase. Partly to better understand the pros and cons of each solution, partly to mitigate the risk of a hick-up during the permitting process.

In this article, three different scenarios are compared:

I. **Dyke restoration:** refurbishment of the existing dyke consisting of a crest height increase and inland landfill to improve stability
II. **Tender design:** sandbody design used as the basis for the permitting process and provided to all tenderers.
III. **Final design**: realised sandbody design including extras proposed in the awarded offer.

The approach for the quantification of the benefits for society is based on the assessment framework developed to evaluate ecosystem services of marine infrastructure projects (Boerema et al., 2016). First, the type and size of habitats are identified for each scenario, and the services that each habitat delivers are subsequently identified. This step is mostly based on the results of five case studies (Boerema et al., 2016). For those habitats or services that are not covered, additional literature is searched to identify potential ecosystem services, including documentation directly linked to the project (EIA, Project Plan). Finally, the relevance of each ecosystem service is described and quantified based on the work done in Van der Biest et al. (2019). This ecosystem services quantification is complementary to the Social Cost Benefit Analysis (Hoogheemraadschap Hollands Noorderkwartier and Witteveen+Bos, 2013), performed during project permitting phase, where the focus was societal losses, whereas in this approach nature benefits are the central focus.

Habitat identification

Ten different habitats are identified within the footprint of the three different scenarios, and ordered below from land to sea.

I. Cropland: loss of cropland is inevitable for the dyke restauration scenario due to landfill required to stabilise the landside of the dyke. Cropland is also affected by salt water intrusion through aquifers under the dyke. Artesia estimated an average seepage flow of 1 m^3/m/day or about 1 mln m^3/year for the entire section (Caljé 2017). Loss of crop yield due to salt intrusion in dry periods of 17 to 89% was reported (Van Tol 2018).
II. Grassland on the dyke inland slope and crest is grazed by sheep. The sandbody designs include a bicycle path on part of the dyke crest, thereby reducing the grassland area by 0.3 ha.
III. Asphalt: the seaward slope of the dyke is covered with an impermeable asphalt layer, which is nearly completely covered in the sandbody designs. Knowledge on long term effects such as heat absorption and leaching is lacking and is therefore neglected in this study.
IV. Landward dune valley (NATURA2000 habitat type H2160): sheltered habitat between dyke and dune
V. Dune crest and seaward slope above NAP+3m, covered by planted marram grass (NATURA2000 habitat type H2130A).
VI. Shifting dunes (NATURA2000 habitat type H2120) on the seaward slope and foot of the dune.
VII. Tidal flat (NATURA2000 habitat type H1140A) unsheltered sandbars and tidal beach.

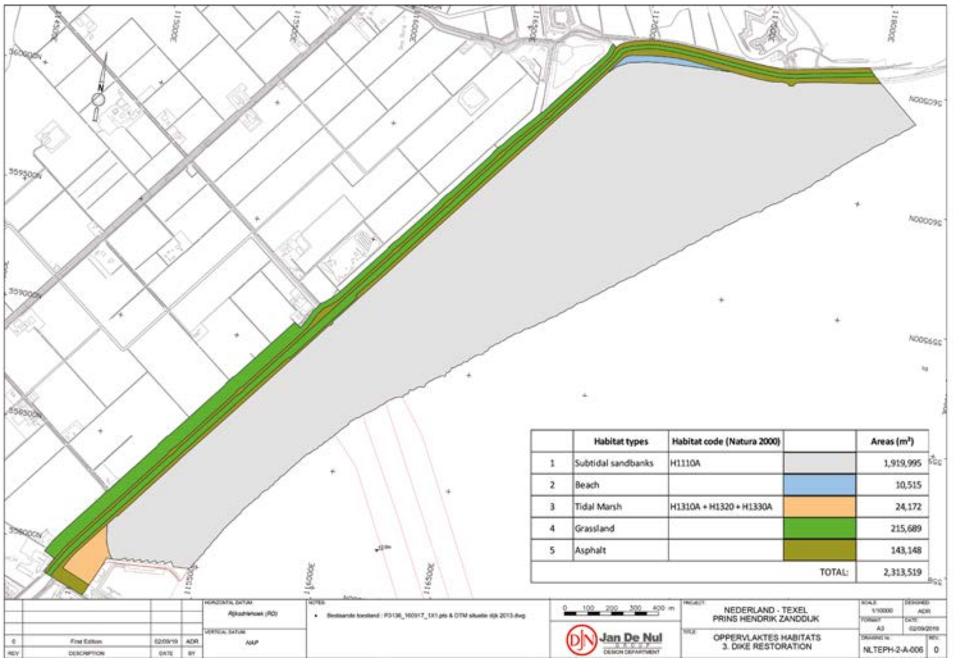


FIGURE 2

Total surface area covered by each habitat – dyke restoration scenario.

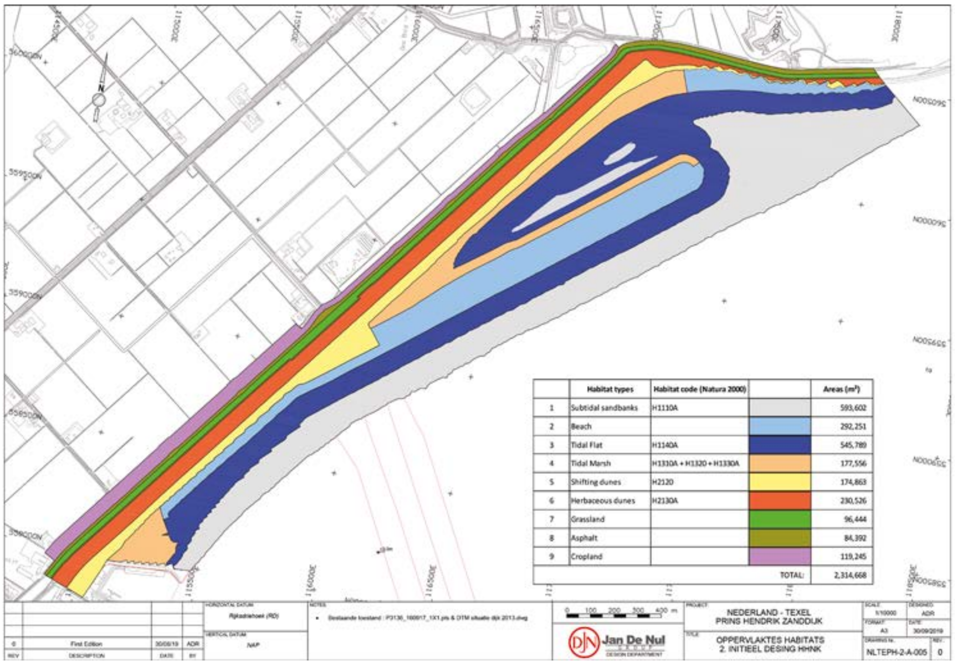


FIGURE 3

Total surface area covered by each habitat – tender design scenario.

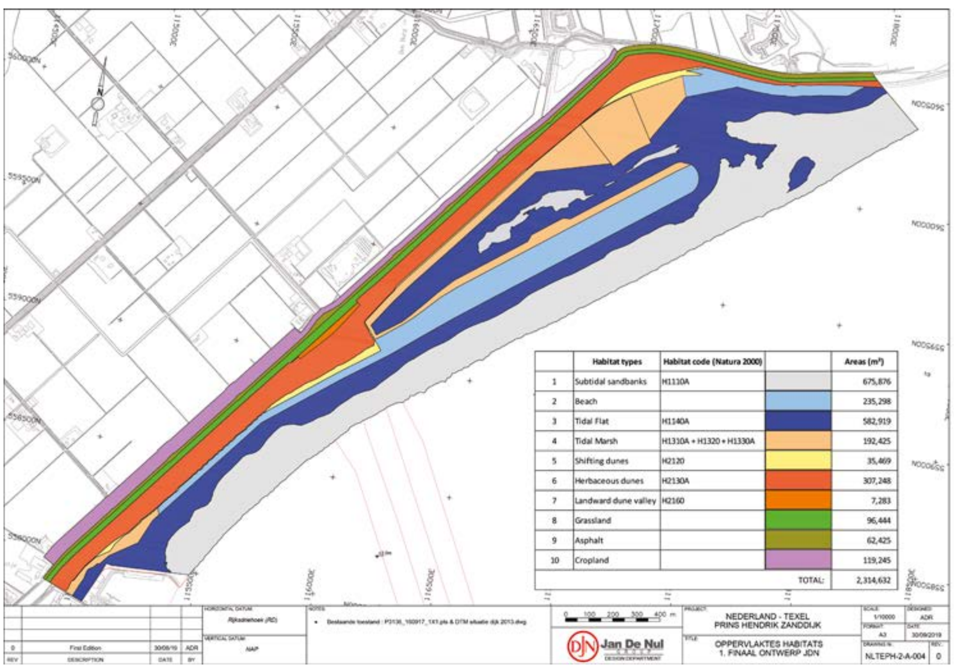


FIGURE 4

Total surface area covered by each habitat – final design scenario.

VIII. Tidal marsh (NATURA2000 habitat types H1310A + H1320 + H1330A): tidal areas sheltered by the NIOZ breakwater in the south and the sandspit in the northern part of the project area.
IX. Supratidal beach and sandspit.
X. Subtidal beach (NATURA2000 habitat type H1110A).

In Figures 2-4, an overview of the total surface area of the fully developed habitat areas – one to three years after project execution – for each of the three project scenarios is given.

Ecosystem services

For this study, we have selected ten relevant ecosystem services.

1. Flood protection
   Flood protection is a service to the hinterland considered equally fulfilled by all scenarios and therefore not included in this study. The quantification of this service remains however a pertinent question.

2. Agricultural production
   The area directly behind the primary flood defence – The Prins Hendrik Polder – is used for cultivation of a.o. flower bulbs. The refurbishment of the dyke requires the expropriation of a narrow strip of agricultural land due to a landfill required to ensure the stability of the landward side of the dyke. The value for agricultural production used in Boerema et al. (2016b) is 2,250 €/(ha.y). This value is based on the productivity of intensive cropland in Flanders. Maximum flower bulb yield in The Netherlands is estimated at 21,447 €/(ha.y) (Van Tol 2018).

3. Fish production
   The Wadden Sea is an important nursery area for various commercial and non-commercial fish species (Tulp et al., 2008). For the study area, sampling of the H1110A habitat has shown that the habitat is an average quality nursery ground due to the low biomass (Hoogheemraadschap Hollands Noorderkwartier and Witteveen+Bos 2017).

   De Groot (1992) estimated the value of the Wadden Sea wetlands to support fisheries production to be 281 €/(ha.y). A comparable estimate of 227 €/(ha.y) (consumer price index 2006 and today's exchange rate; value based on estimates from different continents) was found by Brander et al. (2006) (in Folmer et al., 2010), who used a market price based direct use value of fish. We here take the average of both studies, which is 254 €/(ha.y) for the nursery function of tidal marshes.

Lower benthos biomass and absence of structural complexity lead to conclude that the foreshore sandbanks in the study area are less important for this ecosystem service.

4. Fresh water production
Water abstraction from Texel dunes for drinking water purposes has been abandoned since 1993 a.o. due to increasing tourism and water needs and for nature purposes (Duinen en Mensen 2013). The newly developed dunes are relatively small. Water abstraction from these dunes may affect other ecosystem services and salinity levels in the hinterland. It is therefore not desirable to make use of this function hence the ecosystem service is not further considered.

5. Climate regulation
The capacity of an ecosystem to regulate the climate is to a large extent determined by its capacity to store organic carbon. Based on Brion et al. (2004), Lancelot et al. (2005) and Thomas et al. (2005) we use a value for yearly carbon burial in sandbanks and foreshore without vegetation of 0.0012 to 0.0019 ton C/(ha.y).

In salt marshes values range between 0.55 and 2.46 ton C/(ha.y) (Middelburg et al., 1995, Böhnke-Henrichs and de Groot, 2010, Mcleod et al., 2011, Adams et al., 2012, Duarte et al., 2013, Tamis and Foekema, 2015), taking into account greenhouse gas emissions. For unvegetated mudflats, literature is scarce. Phang et al. (2015) found that unvegetated mudflats and sandbars in a habitat mosaic with mangrove forest and seagrass meadow have similar soil carbon stocks as seagrass meadow. We here apply the same values for the habitat tidal mudflats and sandbanks as for tidal marsh habitat.

Project Presentation

The Prins Hendrik Zanddijk project on the Dutch island of Texel is a multifunctional land reclamation project where flood defense is combined with nature development, public services and recreational appeal. Seaward of the existing dyke, a dune is landscaped to act as primary coastal protection. The existing dyke thereby loses its main function but remains in place as a scenic element.

Instead of using a classical engineering design approach with rule and compass, the inclusion and enhancement of public, recreational and ecosystem services are made the focal point of the design (Fordeyn et al. 2019). A unique and dynamic nature reserve with dunes, salt marsh and beach in front of the current dyke was designed, with the goal of upgrading some 200 hectares of the Wadden Sea area (UNESCO World Heritage Site). Central to the design are the interactions between ecology and sediment dynamics. In traditional hydraulic engineering, there is a trade-off between safety and ecological value, and between sediment stability and dynamics. Coarse sand resists erosion better, but provides a less suitable habitat for benthos, which makes the area less attractive to wading birds.

Therefore, the target species and habitats were analysed and sediment characteristics chosen accordingly. A specific strategy of including fine sands to stimulate benthos growth is applied. Other strategies for habitat creation include salt marsh recuperation and seashell patches. The design further deals with a trade-off between recreational opportunities and the natural habitat disturbance, and between the dynamics of soft coastal protection and the lifetime of public functions.

For the mudflat habitat in the lagoon, higher values for carbon storage may apply due to the high sedimentation rate: 2–5 cm/y (Hoogheemraadschap Hollands Kwartier and Witteveen+Bos Raadgevende Ingenieurs B.V. 2016).

On the beach, which is rich in shell fragments, strong oxygenation of the porous sediment in a highly dynamic environment causes rapid mineralisation of C and thus a release of C to the sea. Rauch and Denis (2008) calculated a release of 226 kg C/(ha.y) from the sandy beach to the sea based on measurements in the eastern English Channel. Charbonnier et al. (2013) found a value of 1041 kg C/(ha.y) along the coast of Aquitaine. The values for carbon sequestration in the different dune habitats are derived from

In traditional hydraulic engineering, there is a trade-off between safety and ecological value, and between sediment stability and dynamics.

literature references used in Van der Biest et al. (2017b).

The value for carbon sequestration in the polder area is derived from Boerema et al. (2016a) and is 0.95 ton C/(ha.y). This value is derived from a statistical model applied to Flemish polders using the ECOPLAN-SE toolbox for quantifying ecosystem services (Vrebos et al., 2017).

The economic value of climate regulation is calculated as the avoided reduction cost, i.e. the costs for emission reduction measures that can be avoided in other areas to reach the environmental targets (related to the worldwide maximum 2°C temperature increase relative to the pre-industrial level of 1780). Data is based on a meta-analysis of several climate model studies (Kuik et al., 2009). A monetary value of 220 €/ton C was used to calculate the economic value of carbon sequestration (Mint and Rebel, 2013).

6. Water quality regulation
Water quality regulation refers to the removal of excessive nutrients (nitrate and phosphate) from water (soil pore water, groundwater, surface water and sea). With the presence of an important agricultural area in the polder behind the Prins Hendrik sand dyke, the ecosystem service provided by the newly created tidal marshes in the lagoon in front of the dune can be of importance. These marshes are capable of storing nutrients that are discharged to the sea from the polders and by atmospheric deposition. The dunes can remove nutrients that are volatised during fertiliser application in the polder and from atmospheric deposition. Atmospheric deposition of nitrogen within the study area varies between 14–21 kg N/(ha.y) (RIVM 2017).

The values for denitrification, N retention and P retention in sediments in subtidal and intertidal habitats are based on Boerema et al. (2016b). For dunes, removal of N is estimated based on the N input through atmospheric deposition and N leaching to groundwater, where the amount of N that is not leached is the result of retention, mineralisation and denitrification processes. For dunes with herbaceous vegetation (grass and moss), N-leaching prevention is calculated based on leaching experiments in dunes near The Hague (70% leaching in calcium rich dunes (ten Harkel et al., 1998), and today's input through atmospheric deposition (RIVM 2017), resulting in a reduction of 4.2–6.3 kg N/(ha.y). The value for N-leaching in dune shrub with *Hippophae rhamnoides* (H2160) is derived from Stuyfzand 1984, who found that symbiotic N-fixing bacteria nearly triple the amount of leaching to groundwater compared to atmospheric deposition (-63– -42 kg N/ha.y). Similar results were obtained by Gerlach et al. (1994) on the Wadden island Spiekeroog. On the beach rich in shell fragments, denitrification is assumed to be negligible due to oxygenation of the porous sediment in a highly dynamic environment (Cockcroft en McLachlan, 1993, Charbonnier et al., 2013). The strong oxygenation of the beach on the other hand causes high rates of mineralisation of N, thus a release of N to the sea. For the coast of North France, Rauch and Denis (2008) found that N mineralisation in the beach sediments released on average 44.24 kg N/(ha.y) to the eastern English channel. Higher values were found along a beach in North Carolina (257.67 kg/(ha.y) (Avery et al., 2008) and for the coast of Aquitaine in France (181 kg N/(ha.y) by Charbonnier et al. (2013) and 191.68 kg N/(ha.y) by Anschutz et al. (2009). We here use the value of Rauch and Denis (2008) because of its proximity to the study area in comparison with the other studies. Like N, P is also quickly mineralised in highly dynamic intertidal areas. The sand used for the Prins Hendrik Zand dijk is dredged from two areas close to Texel (<15km). Due to the poor capacity of the

Ecological Pilots

Five ecological pilots were designed by Altenburg & Wymenga and included in the final design to kick start colonisation of fauna and flora (van der Zee, 2018).

- **Salt marsh transplantation:** 5,000 m² of existing salt marsh vegetation adjacent to the NIOZ port was relocated before construction of the sand dune and irrigated until it was transplanted in the sheltered zone at the corresponding isoline and slope.
- **Benthosplots:** fine sand including associated microfauna from the NIOZ salt marsh is deposited in 2,000 m² plots on the coarse-sand beach to form a biotope for macrofauna.
- **Seagrass:** The PHZD design provides promising conditions for reintroduction of seagrasses in the Waddenzee. A pilot experiment will be conducted at a suitable location when the morphology has stabilised.
- **Embryonic dunes, resting areas and nesting sites:** Both beach and sand spit are resculpted to create suitable habitats for dune vegetation, seals and birds.
- **Rock & Shell island:** Hard substrate is created near the outfall of the Prins Hendrik pumping station to split the outfall flow into meanders while creating a habitat for bivalves and shellfish.

soil to bind P in Fe- and $CaCO_3$-poor soils, it is more likely that P will be mineralised and the beach becomes a source of P to the open sea (Anschutz et al., 2009). Based on the consistent Redfield nutrient ratio of marine phytoplankton (ratio C:N:P = 106:16:1) and the value of N mineralisation on the beach (44.24 kg N(ha.y)), we assume a release of 2.77 kg P/(ha.y) from the sandy beach to the sea. Because atmospheric deposition of P is negligible (RIVM 2012) and because it is assumed that most of the P that comes in with sea water is mineralised on the beach (Anschutz et al., 2009), P retention in the dune is expected to be negligible and most of the available P is consumed by the vegetation. This is also confirmed by Kooijman et al. (2009).

Values for water quality regulation in cropland are derived from Boerema et al. (2016b). N and P storage in cropland is negligible (high consumption of N and P by crops). Denitrification is negative due to the usage of fertilizer and the leakage of N to the groundwater (-50 kg N/(ha.y)).

For the economic valuation, the shadow price for nitrogen removal (€/kg N) is used which is the cost for an equal removal of nitrogen using (other) technical investments (e.g. to reduce nutrient loads from the streams draining the agricultural area behind the dune). A monetary value of 40 €/kg(N) was used, this is the average from the range found in literature (5–74 €/kg(N) (Liekens et al., 2012). An important note has to be made on the value of P retention in coastal sediments. Due to the strong dominance of N over P in coastal waters in the North Sea, it has been suggested that further lowering the P content in the water should not be strived for until the N content diminishes, as this may induce changes nutritional quality of phytoplankton and disturbing Phaeocystis blooms in spring (Rousseau et al., 2002). In other words, P retention can only be considered for as a potential benefit for human well-being. The actual benefit can be accounted for under conditions of high P-loads or reduced N-load. With the proximity of an intensive agricultural area it can be assumed that there is a significant P-input to the coastal water in the project area, allowing to take into account the benefit. The economic value of P retention is based on the shadow price for P removal, which is 55 €/kg P (average of range found in literature: 8-103 €/kg P (Liekens et al., 2012).

7. Air quality regulation

Air quality regulation is the capacity of vegetation to remove fine dust particles (a.o. PM10) from the atmosphere by precipitation of the particles on the leaves, stems and branches and subsequent accumulation in the soil after rainfall events. Fine dust particles mostly come from emissions from cars, industry and households. In the study area, air quality may also be influenced by aeolian transport of very fine sand when spring tide low water and strong easterly and southerly winds co-occur. However, this phenomenon is expected to become negligible when the vegetation is full-grown and is capable of trapping the sand.

The benefit of fine dust removal by vegetation is reflected in reduced costs for health care. In the study area, fine dust concentrations are very low (< 15 µg pm10/m³), or of temporary nature. Air quality regulation is therefore not further considered.

8. Recreation

The design of the safety dune aimed to offer an appealing landscape to the visitor without disturbing the natural habitat. The safety dune is therefore overlain with an undulating layer that replicates the character of natural dunes. The dune reaches its maximum level near the southern and northern end both to increase the visual appeal to hikers and cyclists and to create a physical barrier between recreation on the dune and nature on the beach and in the tidal marsh.

The sandbody design increases the diversity of the landscape due to the creation of several habitats, both in the intertidal (beach, tidal flats and tidal marshes) and in the supratidal zone (dunes with *H. rahmnoides*, dunes with herbaceous vegetation and dunes with *A. arenaria*). Literature points out that structural complexity of landscapes is positively correlated with landscape aesthetics and number of visits (Harrison et al., 2014; De Nocker et al., 2015). Yet, it is a challenge to express in monetary terms its exact contribution in attracting people (Van der Biest et al., 2017).

The development of the project is expected to have positive impacts on recreation as a result of maintaining bicycle access, creation of an accessible beach, increased diversity of the landscape (different habitats) and increased opportunities for bird watching and seal spotting. Some of these elements were added to the final design as extras to the tender design (viewpoints and walking trail). Although the qualitative analysis provides arguments of added value for recreation, this is hard to substantiate in numbers. A comparison of numbers of visitors to the area before and after implementation of the project would allow for a quantification of the added recreational value.

9. Heritage

There are no objects of historical or archaeological value present in the project area.

10. Cognitive development

The economic benefits of cognitive development are created through application and export of knowledge and expertise by the companies and institutions involved in the project design and evaluation. The PHZD project design and evaluation (through model studies and monitoring) add to the know-how on the development of ecosystem- and nature-based solutions for coastal protection and the creation of additional benefits in terms of ecosystem services. However, these cognitive benefits are difficult to quantify and literature on this matter is nearly inexistent. The importance of the project for cognitive development can therefore only be qualitatively described.

The latter three services are categorised as cultural ecosystem services.

Biodiversity is not included in this study as an ecosystem service as such. However, benefits of biodiversity are taken into account through the creation of added value for several other ecosystem services (e.g. fish production, recreation). Detailed information on the impacts of the Prins

The ecosystem services provided by the sandbody alternatives are quantified to be at least triple of the benefits of the hard solution and at most seven times larger.

Hendrik Zanddijk on specific biodiversity aspects can be found in a.o. van der Zee et al. (2018) and Witteveen+Bos (2016).

Qualitative, quantitative and monetary assessment

The quantification of ecosystem services in this study is based on values of healthy and fully developed ecosystems. It is noted that in the first years after the construction of the project the habitats need to develop and that the realisation of the full potential of ecosystem services as presented below may require some years (Boerema et al., 2016a). Therefore, temporary effects associated with construction, both positive, e.g. the ecological pilots to accelerate the habitat development and negative, e.g. the extraction of sand from the North Sea, are not included in the final quantification of the ecosystem services given its longer-term outlook.

Temporary effects

The construction and maintenance of the PHZD require the extraction of a large amount of sand from the North Sea (5.5 mio m^3 for construction + 1 mio m^3 for maintenance). The extraction sites are located at about 10–15 km distance from the island of Texel. The extraction involves disruption of the soft sediment seabed and its habitats (NATURA2000 H1110 Sandbanks which are slightly covered by sea water all the time), and increased turbidity due to the overflow plume during dredging. However, the impact is temporary and benthic life restores after 1 to 4 years (Simonini et al., 2007; Essink, 2005). Especially in highly dynamic areas in the North Sea impacts are considered to be insignificant in comparison with the large natural dynamics of the system (Rozemeijer et al., 2013, Schellekens et al., 2014, Wijsman et al., 2014). The impact assessment of the sand extraction and transport (Kleijberg, 2016) also concludes

TABLE 1

Summary of potential effects of the 3 scenarios on the yearly provisioning of ecosystem services.

	Ecosystem Service	Indicator	Unit	Dyke restoration	Tender design	Final design
Provisioning	Agricultural production	expected agricultural production polders	k€/y	0	26.8	26.8
	Fish production	fish production supported by nursery function	k€/y	0.6	4.5	4.9
	Drinking water production	–	–	0	0	0
Regulating	Climate regulation	C sequestration/burial rate	k€/y	6–7	21.1–53	19.9–52.5
	Water quality regulation	N removal/retention/burial rate	k€/y	190.1–215.5	659.9–1255.8	743.2–1384.2
		P retention/burial rate	k€/y	0.3–5.9	7.5–154.8	9.2–167.2
	Salinisation prevention	–	–	0	0	0
	Air quality regulation	–	–	0	0	0
	Flood protection	avoided damage costs	mio €	60	60	60
		avoided casualties	# people	0–5	0–5	0–5
	Erosion prevention	reduced dyke maintenance costs by wave attenuation	k€/y	0	37.6	37.6
	Sedimentation regulation	–	–	0	0	0
Cultural	Recreation	landscape quality, infrastructure	score	+	++	+++
	Heritage	heritage values	score	+	–	–
	Cognitive development	expertise, know-how	score	0	+	+
	Sum Additional Monetary Benefits (excluding flood protection)		**mio €/y**	**0.2–0.23**	**0.75–1.53**	**0.84–1.67**

that the extraction has no significant effects on the habitat types and associated species.

The sandbody scenarios have a temporary effect on saltwater intrusion in the construction phase. Overpressure on the groundwater may cause instability of the dyke and the nearby buildings. In the polder, the saline seepage water may squeeze out the fresh rain water layer at the surface of the agricultural land, causing damage to growing crops. This phenomenon was observed in earlier projects such as Zandmotor and Zwakke Schakels Noord-Holland (Hondsbossche Pettemer Zeewering). At Prins Hendrik Zanddijk, these temporary effects are mitigated through an extensive real-time measurement system and extraction of seepage water by horizontal and vertical drainage.

Comparison of longer-term effects

The potential longer-term ecosystem services effects of the three scenarios (dyke restoration, tender design and final design) were compiled in monetary terms (see Table 1). This excludes the flood protection benefits. As was mentioned earlier, all three scenarios provide the same flood protection service. The effects of the three cultural ecosystem services can only be compared qualitatively.

The ecosystem services provided by the sandbody alternatives are quantified to be at least (minimum added value) triple of the benefits of the hard solution (dyke restoration) and at most (maximum calculated added value) seven times larger. Each year, the sandbody alternative creates an additional 0.55 to 1.47 million euro of ecosystem services benefits, mainly due to enhanced fish production, climate regulation, water quality regulation and erosion prevention.

The ecosystem service in this case study with the largest additional benefits is water quality regulation, which is explained by the high monetary value for nitrogen removal and the importance of the tidal flats and marshes for nutrient storage in sediments and denitrification. The creation of the sand dyke results in a loss of 132.5 ha (tender design) or 124.3 ha (final design) shallow sandbanks on the foreshore. The economic benefits in terms of ecosystem services of this habitat are however low in comparison with tidal flats

FIGURE 5

Overview of expected changes in habitats and ecosystem services within the boundaries of the Prins Hendrik Zanddijk (comparison of final sand dyke design with scenario restoration of asphalt dyke).

TABLE 2

Evaluation of the cost efficiency of the sand dyke

	Dyke restoration	Tender design	Final design
Construction cost	18.80 mio €	23.90 mio €	23.90 mio €
Management and maintenance costs per year	18.80 mio € x 0.2% per year = 0.04 mio €/y	20000 m³/y x 6 €/m³ = 0.12 mio €/y	20000 m³/y x 6 €/m³ = 0.12 mio €/y
Ecosystems services benefits per year (min–max estimate)	0.2–0.23 mio €/y	0.75–1.53 mio €/y	0.84–1.67 mio €/y
Total costs vs. benefits per year (min–max estimate)	***0.16–0.19 mio €/y***	***0.63–1.41 mio €/y***	***0.72–1.55 mio €/y***

FIGURE 6

The design of the PHZD focuses on nature development and recreational appeal in addition to its function as primary coastal protection. Planting of marram grass at the project site supports the NATURA2000 habitat type H2130A.

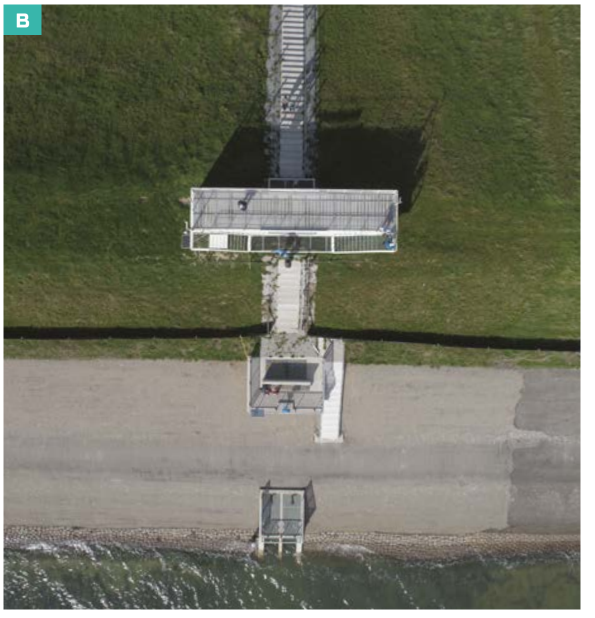
and dunes.

Some newly created habitats have negative impacts on ecosystem services, such as the emission of carbon and nutrients from the beach and leakage of nitrogen in shifting dunes with *Hippophea rahmnoides*. However, these losses are compensated for in other newly created habitats (e.g. tidal marshes). An important note is that the value of ecosystem services for the dyke restoration-scenario is actually not on account of the asphalted dyke itself, but results from the loss of foreshore habitat and associated ecosystem services due to the construction of the sand dyke.

Comparing the two sandbody alternatives, an added monetary benefit of 0.09–0.14 million euro/year is noted for the final design (PHZD). This is mainly attributed to the creation of a larger area of salt meadows (15 ha) and a smaller area of beach (5 ha). Again, the higher value is related to the importance of salt marshes for biochemical ecosystem services (C, N, P). Additionally, the reduction in beach area diminishes the emission of

A

B



C

D

FIGURE 7

During the works, an experience centre on top of the dyke near the Prince Hendrik pumping station informed residents and tourists about the project.

Comparison with Other Projects

In a dedicated publication about ecosystem services for IADC, Ecobe has analysed the socio-ecological benefits of five marine construction projects (Boerema, 2016b).

- **C-power wind farm:** six wind turbines on a surface of 1.5 ha create a ESS benefit of 14 k€/year, mainly attributed to the hard substrate of the scour protection.
- **Botany Bay container terminal:** 16 ha of new salt marsh is created with a ESS benefit of 5.5k€/yr to partly compensate for the 63 ha container terminal which has a negative ESS impact of 126 k€/yr, the saltmarch a positive ESS impact of 15 k€/yr.
- **Zandmotor:** NID of coastal protection in Ter Heijde 815 k€/yr.
- **Western Scheldt Container Terminal:** 166 ha compensation area (ESS 642 k€/yr) created for the development of 133 ha container terminal (ESS -821 k€/yr).
- **Polders of Kruibeke:** insufficient data to perform cost-benefit analysis.

Who's Involved in the PHZD Project

The Prins Hendrik Zanddijk is part of the 'Hoogwater Beschermingsgprogramma 2' the Dutch government programme to protect The Netherlands against floods from rivers, lakes and the sea. PHZD is one of 87 projects upgrading 362.4 km of dykes and 18 civil engineering works that are realised between 2015 and 2020. The programme is managed by an alliance of the responsible ministry (Ministerie van Infrastructuur en Waterstaat) and the waterboard (Hoogheemraadschap Hollands Noorderkwartier, HHNK). Lead Consultant to the HHNK is Witteveen+Bos Raadgevende Ingenieurs.

The tender was awarded in September 2017 to the Jan De Nul team: Altenburg & Wymenga was in charge of environmental management and came up with the ecological pilots, Feddes & Olthoff designed the cycling path and the dune landscape, John Körmeling designed the bird watchhouse, Waterproof B.V. ran hydrodynamic, morphological and aeolian models with the help of Leo Van Rijn Sediment, BT Geoconsult ensured integrity of the existing dyke and freshwater supplyline, Wiertsema & Partners analysed the geology and Artesia calculated the hydrological effect of the sand reclamation and drainage system.

The Ecosystem Management Research Group (ECOBE) at the University of Antwerp conducted the ecosystem assessment, Vito realised a remote sensing turbidity pilot, student D.D. Van Tol of Hogeschool Amsterdam investigated crop damage and students D. Clybouw and T. Vande Ryse of KULeuven campus Brugge measured and modelled aeolian transport.

nutrients and carbon to the sea. The total ecosystem services benefits of the final design are 9–12 % more than those of the tender design.

It is assumed that the results of the quantification of ecosystem services are representative for qualitative and fully developed habitats, which may not be the case in the first years after the construction. The usage of pilots in the final design, such as the transplantation of marsh vegetation, aims to accelerate the creation of additional benefits for nature and for ecosystem services. The final design will be faster in realising the full potential of ecosystem services in comparison with the tender design.

Taking into account the costs for construction and maintenance of the sand dyke and the restored dyke, a rough estimate can be made of the cost efficiency of the project (see Table 2).

A range of one to three years must be taken into account for the habitats to become sufficiently qualitative to provide the ecosystem services. Using the value for the maximum estimate of economic benefits (1.55 mio €/y – 0.19 mio €/y = MAX + 1.36 mio €/y total benefits), it requires five to seven years to entirely compensate the initially higher costs of the construction of the final design (23.9 mio € – 18.80 mio € = + 5.1 mio € investment costs) by the higher benefits it generates in terms of ecosystem services, in spite of the higher maintenance costs. Assuming that habitats are fully developed and qualitative only after three years and using the minimum estimate (0.72 mio €/y – 0.16 mio €/y = MIN + 0.56 mio €/y total benefits), the costs are compensated after maximum of nine years (5.1 / 0.56 mio €/y).

The final design will be faster in realising the full potential of ecosystem services in comparison with the tender design.

Conclusion

The creation of the PHZD generates both positive and negative effects on the ecosystem services. While replacing shallow sand bank area with beach increases emissions of carbon and nutrients and leakage of nitrogen, these negative effects are more than compensated by the creation of tidal marsh area and its associated beneficial ecosystem services, resulting in an overall positive result. It is estimated that the additional cost compared to the dyke refurbishment alternative is compensated within five to seven years.

The design of the PHZD focuses on nature development and recreational appeal in addition to its function as primary coastal protection. While the current ecosystem services methodology allows for a quantitative comparison of nature development, the differences in cultural ecosystem services between the designs (e.g. dune relief to create sea view from the bicycle path) could not be taken into account in the quantification. This leads to an underestimation of the benefits of the final design in comparison with the tender design and the dyke restoration alternative.

Summary

This article quantifies the benefits of the realised soft coastal protection design for the Prins Hendrik Zanddijk project (PHZD) and compares this result against the alternative of upgrading the existing dyke. The quantification in terms of ecosystem services is based on the assessment framework developed by Boerema et al. (2016). First, the type and size of habitats and associated ecosystem services are identified. and subsequently, the relevance of each ecosystem service is described and quantified.

The creation of the Prins Hendrik Zanddijk generates both positive and negative effects on the ecosystem services as the soft coastal protection project replaces shallow sand bank areas with both beach and tidal marsh area. The positive effects outweigh the negatives, with additional benefits created by the Prins Hendrik Zandijk quantified at 0.4 –1.07 million €/yr, mainly due to enhanced fish production, climate regulation, water quality regulation and erosion prevention.

The design of the PHZD focuses on nature development and recreational appeal in addition to its function as primary coastal protection.

Jan Fordeyn

Jan studied at the University of Ghent and graduated as a naval architect in 1994. Since 2007, he has helped develop projects around the world that fall outside the classic canon of marine construction and whose result relies on the symbiosis of different disciplines. As such he maintains close relations with experts, consultants, universities and manages several innovation projects. During the tender and realisation of the Prins Hendrik Zanddijk, he was technical manager and co-ordinated all design aspects.

Katrien Van der Biest

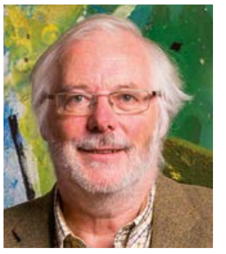
Katrien is a doctoral student at the Research Group Ecosystem Management of the University of Antwerp, Belgium. She obtained her Master's degree in Physical Geography at the University of Ghent and her Master's degree in Oceanography at the University of Liège, both in Belgium. Her current research focuses on quantifying and mapping ecosystem services as a supportive tool in environmental management, both in terrestrial and in marine ecosystems.

Emile Lemey

Emile works as Project Development Engineer at Jan de Nul Group. His background is in Bioengineering and Marine conservation. At Jan De Nul he has focused on nature based solutions projects in which ecological considerations are an essential part of the design phase. He worked as Environmental Engineer on the Prins Hendrik sand dyke project during the realisation phase.

Annelies Boerema

Annelies is a doctoral student in environmental science at the Research Group Ecosystem Management of the University of Antwerp, Belgium. Her research focuses on biophysical and economic evaluation of ecosystem services to assess the impact of ecosystem management, with an emphasis on estuaries. She obtained her Master's degree in commercial engineering and a Master's degree in environmental science at the University of Antwerp.



Patrick Meire

Patrick is professor in biology and head of the research group Ecosystem Management (ECOBE) at the University of Antwerp, Belgium. His research focuses on the environmental impact of human activities on aquatic and wetland systems and these insights are used to develop concepts for integrated water management and ecosystem management. He obtained his PhD in biology from the University of Ghent, Belgium.

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