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Sustainable Asset Valuation (SAVi) of Nature-Based Coastal Protection in the Netherlands:

An economic valuation of the contribution of the Hondsbossche Dunes sand nourishment to climate adaptation and local development

NBI REPORT

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How Can Investment in Nature Close the Infrastructure Gap?

December 2021

Written by Ronja Bechauf, Emma Cutler, Matthew Gouett, and Marco Guzzetti

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Executive Summary

The Hondsbossche Dunes are a nature-based coastal protection solution in the Netherlands. Before the construction of the dunes, the section of the sea dike at that location no longer met Dutch flood safety standards. Instead of raising the dike, an artificial beach and dune landscape was built on the seaside of the existing seawall. It stretches along 7 kilometres of the Dutch North Sea coast between the villages of Petten and Camperduin.

The Netherlands is a low-lying country prone to inland and sea flooding. Sea level rise and increasing flood risks require constant upgrading of flood protection infrastructure. In parallel to (or in place of) conventional reinforcements, stakeholders can choose to implement nature-based infrastructure (NBI) solutions. For example, they can create salt marshes, widen floodplains, and use large-scale sand nourishments such as the Hondsbossche Dunes.

The Hondsbossche Dunes are designed to withstand 1-in-10,000-year storm surge conditions and to resist sea level rise for 50 years. While not having exact data on the area that would be flooded in case of storm surge, our assessment assumed that the dunes protect more than 900 hectares of land, of which more than 60% is used for agriculture. As the beach resort town of Petten is the community most likely to be significantly impacted were there to be a flood, the construction of the dune had a significant impact on the lives of 3,000 Dutch citizens, not to mention the impacts on other nearby communities and rural areas. The dunes provide another example of nature-based coastal protection and its implications for economic and nature development and serve to inform Dutch policy-makers.

The Hondsbossche Dunes also offer valuable space for nature and recreation. The project includes facilities for tourism and recreation close to the beach communities of Petten and Camperduin. Between the villages, the beach and dune landscape provides diverse habitats for plants and animals and has other biodiversity impacts. With bike paths, foot trails, and recreational facilities, the new area is a magnet for locals and tourists alike.

About This Valuation

This report was prepared with the assistance of the International Association of Dredging Companies (IADC). IADC is the global umbrella organization for contractors in the dredging industry. The dredging companies Van Oord and Boskalis constructed and maintain the Hondsbossche Dunes, where they dredged 30 million cubic metres of sand from the North Sea to create the new landscape. The integrated assessment of the Hondsbossche Dunes helps the dredging sector demonstrate the net positive value of NBI projects. This can support the planning of similar projects and the scaling up of NBI for coastal flood protection.

In this report we present the results of the Sustainable Asset Valuation (SAVi) assessment for the Hondsbossche Dunes project. The assessment quantifies the ecosystem services and economic impacts of the new dune landscape under several flood scenarios and compares this NBI solution to a conventional dike reinforcement. The valuation focuses on estimated benefits accrued due to increases in tourism when compared to the previous flood protection, which did not conform to Dutch flood safety standards. This type of valuation can inform the budgeting process as well as decisions on infrastructure investments, providing complementary information to analyses based on probabilistic flood risk assessments.

The analysis shows that for both infrastructure alternatives—the sheet pile wall (grey alternative) and the sand dunes (NBI alternative)—tourism is estimated to increase because both alternatives offer enhanced amenities to visitors. These projected amenities include a beach pavilion, foot and cycling paths, a viewpoint, tourist stores, restaurants, the expansion of parking space for cars and cyclists, and information boards. The sand dunes' benefits for nature make the area more attractive for visitors, and the valuation captures this benefit through the increased tourism potential.

The valuation also considered the marginal increase in the protection offered by both alternatives when compared to the previous coastal protection infrastructure. The avoided costs capture avoided flood damage to agricultural crops and livestock as well as avoided damage to property and infrastructure. These avoided costs are likely underestimated because personal safety, which would be at risk in case of a flood, was not included in the valuation.

Flood protection functions as a form of insurance that provides value (in the form of avoided costs) only when floods occur. This implies that costs avoided due to the flood protection investment should be counted only for years of potential flooding. Therefore, we calculate the value of the two investment alternatives based on numerous flood scenarios over a 50-year period. Given the difficulty in predicting when a flood would occur, we analyze how the value of each investment alternative changes based on the number of potential floods it avoids.

Key Messages and Caveats

- The sand dunes do more for less. They outperform traditional infrastructure due to lower construction costs and higher tourism revenue.
    - The sand dunes increase the present value of tourism revenue by almost EUR 203 million over 50 years, while the grey alternative would have increased it by only EUR 103 million.
    - Even though the sand dunes require more maintenance, their lower construction costs and positive effect on tourism make them the better investment.
    - The sand dunes offer future policy-makers significant flexibility to respond to dramatic changes in climate and sea level because they will be able to strengthen the flood protection without the type of reconstruction that would be necessary for traditional infrastructure.
- The sand dunes offer cost-effective flood protection. Over a 50-year horizon, the sustainable net present value (S-NPV)[1] of the NBI is positive even when there is no flood (see Table 3) and reaches EUR 98.27 million when assuming that the dunes prevent one flooding event.
    - Conversely, the grey alternative would need to prevent two floods to have a positive S-NPV. This is because the dunes are cheaper to build and provide more benefits besides flood protection.

The benefits calculated in the valuation are likely an underestimate because not all possible effects of the coastal protection investments were considered. As mentioned above, the sand dunes are a far more flexible solution to adapt to future climate scenarios than the grey alternative. As well, the valuation did not quantify possible auxiliary impacts aside from increased tourism that may be associated with changes in biodiversity or health benefits associated with increased tourist usage. Moreover, the shorter construction time of the sand dunes was also not captured in the analysis.

Our high-level results are presented in Table ES1.

[1] S-NPV is the difference between the present value of benefits and avoided costs net of financing costs and the present value of cash outflows. Sustainable internal rate of return (S-IRR) is an indicator of the net benefit prospects of a potential investment. The S-IRR is the discount rate that makes the NPV of benefits from a particular project equal to zero.

Table ES1. S-NPV and S-IRR under all flood scenarios accounting for all added benefits, added avoided costs, and investment and maintenance costs. All values are in 2015 EUR thousands.

	50-year lifetime (2015–2064)			
	Sheet pile wall (grey alternative)		Sand dunes (NBI alternative)	
	One flood avoided	Two floods avoided	One flood avoided	Two floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	103,074	103,074	202,702	202,702
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	51,010	102,021	51,010	102,021
Avoided loss of agriculture productivity	30,698	61,396	30,698	61,396
Avoided loss of agricultural wages	1,187	2,375	1,187	2,375
Avoided nitrogen pollution	136	271	136	271
Avoided phosphorus pollution	14	29	14	29
Carbon storage benefit	1,457	1,457	1,457	1,457
Residual value of flood protection infrastructure	30,133	30,133	25,537	25,537
Total avoided costs	**114,636**	**197,682**	**110,040**	**193,085**
Total added benefits and avoided costs	**217,710**	**300,756**	**312,741**	**395,787**
PRESENT VALUE of COSTS				
Capital cost – construction	224,197	224,97	190,000	190,000
Carbon cost of construction	4,863	4,863	3,866	3,866
Annual maintenance costs	6,762	6,762	19,141	19,141
Carbon cost of annual maintenance	-	-	1,466	1,466
Total costs	**235,822**	**235,822**	**214,474**	**214,474**
S-NPV	**-18,112**	**64,934**	**98,268**	**181,313**
S-IRR	4.2%	5.4%	5.9 %	6.9 %

Table ES2. How stakeholders and decision-makers can use the results

Stakeholder	Role in the project	How can the stakeholder use the results of the assessment?
Public authorities	Design, implementation, and finance of NBI projects	Public authorities can use the results to justify investments in nature-based flood protection. For example, the dune landscape has a sustainable NPV of EUR 98 million and a sustainable IRR of almost 6% when assuming it prevents one flooding event (see Table ES1). The valuation also highlights that the dune landscape can be considered a no-regret climate adaptation investment, as it has a positive NPV of more than EUR 13 million even without preventing a flood (see Table 3). Public authorities can use the report to appreciate the project's value for tourism and local development. The report can help them develop more integrated, area-based NBI projects that deliver additional benefits to people and to the planet. For example, the dunes are projected to boost tourism revenues by more than EUR 202 million over 50 years. The sand dunes offer future policy-makers significant flexibility to respond to dramatic changes in climate and sea level as they will be able to strengthen the flood protection without the type of reconstruction that would be necessary for traditional infrastructure. Policy-makers can also draw on the valuation to make decisions on biodiversity, nature conservation, and environmental policy. For example, the dunes provide valuable wildlife habitats and support biodiversity.
Planning, engineering, and construction sector	Preparation, construction, and maintenance of NBI projects	Private companies can use the results to make the business case for NBI. For example, the dunes are projected to boost tourism by more than EUR 200 million, and the sustainable IRR on the investment is nearly 6% assuming the dunes prevent one flood (see Table ES1). The report can also help the sector demonstrate the social and ecological advantages of NBI. For example, the sand dunes were strongly preferred by local communities and provide greater benefits for biodiversity.

Stakeholder	Role in the project	How can the stakeholder use the results of the assessment?
Civil society organizations, farmers, and the tourism sector	Consultation with government agencies on NBI projects Beneficiaries of NBI projects	Civil society organizations can use the valuation to advocate for NBI that brings additional benefits to nature and local communities. For example, the dunes landscape delivers about EUR 116 million more value than the conventional dike reinforcement (see Table ES1). The new dunes are also valuable habitats for plants and animals, creating a synergy with the Natura 2000 reserve nearby. Civil society organizations can use the results to promote climate adaptation and mitigation. For example, the dunes have an S-NPV of more than EUR 98 million when they prevent one flood, and more than EUR 181 million assuming they prevent two floods (see Table ES1).

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Glossary

Deep uncertainty: "A situation in which analysts do not know or cannot agree on (1) models that relate key forces that shape the future, (2) probability distributions of key variables and parameters in these models, and/or (3) the value of alternative outcomes" (Hallegatte et al., 2012).

Discounting: A finance process to determine the present value of a future cash value.

Indicator: Parameters of interest to one or several stakeholders that provide information about the development of key variables in the system over time and trends that unfold under specific conditions (United Nations Environment Program [UNEP], 2014).

Internal rate of return (IRR): An indicator of the profitability prospects of a potential investment. The IRR is the discount rate that makes the net present value of all cash flows from a particular project equal to zero. Cash flows net of financing give us the equity IRR.

Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST): "A suite of models used to map and value the goods and services from nature that sustain and fulfill human life. It helps explore how changes in ecosystems can lead to changes in the flows of many different benefits to people" (Natural Capital Project, 2019).

Methodology: The theoretical approach(es) used for the development of different types of analysis tools and simulation models. This body of knowledge describes both the underlying assumptions used as well as qualitative and quantitative instruments for data collection and parameter estimation (UNEP, 2014).

Model transparency: The degree to which model structure and equations are accessible and make it possible to directly relate model behaviour (i.e., numerical results) to specific structural components of the model (UNEP, 2014).

Model validation: The process of assessing the degree to which model behaviour (i.e., numerical results) is consistent with behaviour observed in reality (i.e., national statistics, established databases) and the evaluation of whether the developed model structure (i.e., equations) is acceptable for capturing the mechanisms underlying the system under study (UNEP, 2014).

Net benefits: The cumulative amount of monetary benefits accrued across all sectors and actors over the lifetime of investments compared to the baseline, reported by the intervention scenario.

Net present value (NPV): The difference between the present value of cash inflows net of financing costs and the present value of cash outflows. It is used to analyze the profitability of a projected investment or project.

Optimization: A stream of modelling that aims to identify the policy or set of policies that deliver the best possible outcome from a set of alternatives, given a set of criteria (i.e., parameters to optimize) and/or constraints (i.e., available budget) (UNEP, 2014).

Robust decision: A decision that produces favourable outcomes under a range of possible scenarios (Hallegatte et al., 2012).

Scenarios: Expectations about possible future events used to analyze potential responses to these new and upcoming developments. Consequently, scenario analysis is a speculative exercise in which several future development alternatives are identified, explained, and analyzed for discussion on what may cause them and the consequences these future paths may have on our system (e.g., a country or a business).

Simulation model: Models can be regarded as systemic maps in that they are simplifications of reality that help to reduce complexity and describe, at their core, how the system works. Simulation models are quantitative by nature and can be built using one or several methodologies (UNEP, 2014).

Sustainable internal rate of return (S-IRR): An indicator of the net benefit prospects of a potential investment. The S-IRR is the discount rate that makes the net present value of benefits from a particular project equal to zero.

Sustainable net present value (S-NPV): The difference between the present value of benefits and avoided costs net of financing costs and the present value of cash outflows. It is used to analyze the net value of a projected investment or project.

1.0 Introduction: The Hondsbossche Dunes as a nature-based coastal protection measure

1.1 Project Description

The Hondsbossche Dunes are a coastal protection project in the Northern Netherlands. Before implementation, the Hondsbossche and Pettemer sea dike between the villages of Petten and Camperduin no longer met Dutch flood safety standards. Instead of raising the dike, policy-makers opted for nature-based infrastructure (NBI). On the seaside of the dike, an artificial beach and dune landscape was built using 30 million cubic metres of sand. The project, called Hondsbossche Dunes, stretches along 7 kilometres of the North Sea coast[2] and cost EUR 190 million for design and construction, and an additional EUR 15.8 million for maintenance in the 20 years following construction.

Since the completion of construction in 2015, the Hondsbossche Dunes have protected the region from floods and offered space for nature and recreation. The project includes areas for tourism and recreation close to the villages of Petten and Camperduin. The space between the villages is designated for nature development, including a wet dune valley and large habitats for birds and plants. With bike paths, foot trails and recreational facilities, the new area attracts locals and tourists alike.

The design of the Hondsbossche Dunes had to meet many requirements for flood safety and spatial quality. The dunes are able to withstand 1-in-10,000-year storm conditions and are designed to resist sea level rise for 50 years. In addition, the NBI design is easy to adapt for future climate changes, has minor impacts on the environment compared to raising the sea dike, and had a shorter construction time than its alternatives.

Constructing the artificial dune landscape also enjoyed broad support from local stakeholders. The villages of Petten and Camperduin are two of the many beach resorts on the Dutch coast. They are particularly popular for camping vacations and known for their picturesque tulip fields. In the face of stagnating economic development, the communities strive to further develop their tourism sector and attract more visitors. Local and regional policy-makers therefore advocated using the flood protection investments as a catalyst for tourism and nature. In the Netherlands, infrastructure projects are increasingly created with such an integrated approach that combine multiple objectives and stakeholders.

[2] The stretch of previous flood protection infrastructure that needed reinforcement was approximately 7 kilometres. The sand for the dunes was placed along 8 kilometres of the North Sea coast (in order to connect the new dunes with the old ones).

The Hondsbossche Dunes reinforced a former weak link in Dutch coastal defences. Our analysis assumed that the dunes protect an area of at least 912 hectares from flooding. This area includes villages, agricultural land, and protected natural areas. As the beach resort of Petten and its surrounding area is the community most likely to be impacted in the case of a flood, the construction of the dune had a significant impact on the lives of 3,000 Dutch citizens, not to mention the impacts on other nearby communities and rural areas. The dunes provide an example of large-scale nature-based coastal protection and its implications for economic and nature development. They also serve to inform Dutch policy-makers.

1.2 Stakeholder Involvement

The Hondsbossche Dunes project was developed within the framework of the Flood Protection Program (HWBP in Dutch). The Flood Protection Program aims to make sure that all primary flood defences meet high protection standards by 2050 and forms part of the Dutch Delta Plan on Flood Risk Management.

The leading stakeholder for the Hondsbossche Dunes was the regional water board (Hoogheemraadschap Hollands Noorderkwartier), which is responsible for inland flood safety. As the responsibility for coastal protection lies with the Dutch Ministry of Infrastructure and Water Management, its executive agency, Rijkswaterstaat, was also closely involved.

Starting from the design stage of the project, the water board organized frequent opportunities for stakeholder participation. For example, there were several workshops and information meetings. In addition, an advisory group consisting of representatives of local residents, entrepreneurs, and nature and environmental organizations advised the project steering group.

The interests of different stakeholders were weighed as part of the project plan, and the design was adapted to local needs where possible. For instance, some residents were worried that the new dunes would lead to more sand transport to areas behind the dike. In response to these concerns, the design of the dune landscape was modified to minimize unwanted sand transport. All the land required for building the Hondsbossche Dunes was owned by public authorities, so no private land had to be bought.

In order to use the project as a catalyst for regional development, the Province of Noord-Holland, the two coastal municipalities of Bergen and Schagen, and nature organizations with interests in this area signed a cooperation agreement. In line with the new dune landscape, the partners implemented projects such as viewpoints, foot paths, and visitor guidance as part of the Spatial Quality program.

1.3 Context for This Valuation

Before implementation, the Hondsbossche Dunes and several grey-built alternatives were assessed in a societal cost-benefit analysis (Arcadis, 2010). Our report builds upon this initial work by adding indicators that were not considered in the previous report. For example, our valuation considers delays in improving the tourism infrastructure due to legal proceedings and accounts for the construction being completed in 2015. By complementing the previous work and utilizing newer information, we provide a more comprehensive assessment of the societal value of the NBI in comparison to the built infrastructure alternative.

Our report estimates the ecosystem services and economic impacts of the new dune landscape under several deterministic scenarios and compares this NBI solution to a conventional dike reinforcement. The analysis, using deterministic scenarios, is unique in that it exposes information that may not be revealed when using traditional, probabilistic methodologies. This approach is better aligned with the budgeting process of the government for infrastructure investment, which considers material impacts and resulting consequences for cash flow, both revenues and expenditures. In this regard, in the context of budgetary planning, it is critical to consider when an extreme event may take place (possibly with irregular frequency, affecting costs) and compare it with the emergence of co-benefits and side effects (e.g., tourism revenues that occur every year). The analysis can inform the budgeting process, as well as decisions on the infrastructure investments, providing complementary information to probabilistic assessments.

We conducted the valuation with the assistance of the International Association of Dredging Companies (IADC). IADC is the global umbrella organization for contractors in the private dredging industry. The dredging companies Van Oord and Boskalis constructed and maintain the Hondsbossche Dunes, where they dredged 30 million cubic metres of sand from the North Sea to create the new landscape. The integrated assessment of the Hondsbossche Dunes helps the dredging sector to demonstrate the societal value of NBI projects. This can support the planning of similar projects and the upscaling of NBI for coastal flood protection.

2.0 Methodology

2.1 Overview

We customized this assessment to the specific characteristics of the project and the local context. It is based on spatial analysis and financial modelling. The spatially explicit analysis quantifies biophysical indicators and allows us to estimate their monetary value. We used financial modelling to understand the financial performance of two coastal protection alternatives (conventional reinforcement and a nature-based reinforcement). In the financial modelling, we adjusted the benefits and costs to the time value of money and inflation over 50 years.

2.2 Causal Loop Diagram

A causal loop diagram (CLD) is an analytical tool that portrays the dynamics of a system. Creating a CLD is the first step in customizing a SAVi assessment to the local context. It shows the interconnectedness of key socio-economic and environmental indicators and exposes potential impacts of the coastal protection project.

The CLD in Figure 1 shows relationships among coastal defence strategies and biophysical and socio-economic systems. These relationships result in possible feedback loops that may help justify continued investment in dikes and/or dunes. We note that the Hondsbossche Dunes must be maintained to a specified safety standard, regardless of financial performance (EcoShape, 2021). We can, however, use the diagram to understand how the dunes and a dike would differentially affect the system.

Not all variables included in Figure 1 are applicable in the case of the Hondsbossche Dunes. We also note that, due to data limitations, we were unable to quantify all relevant indicators.

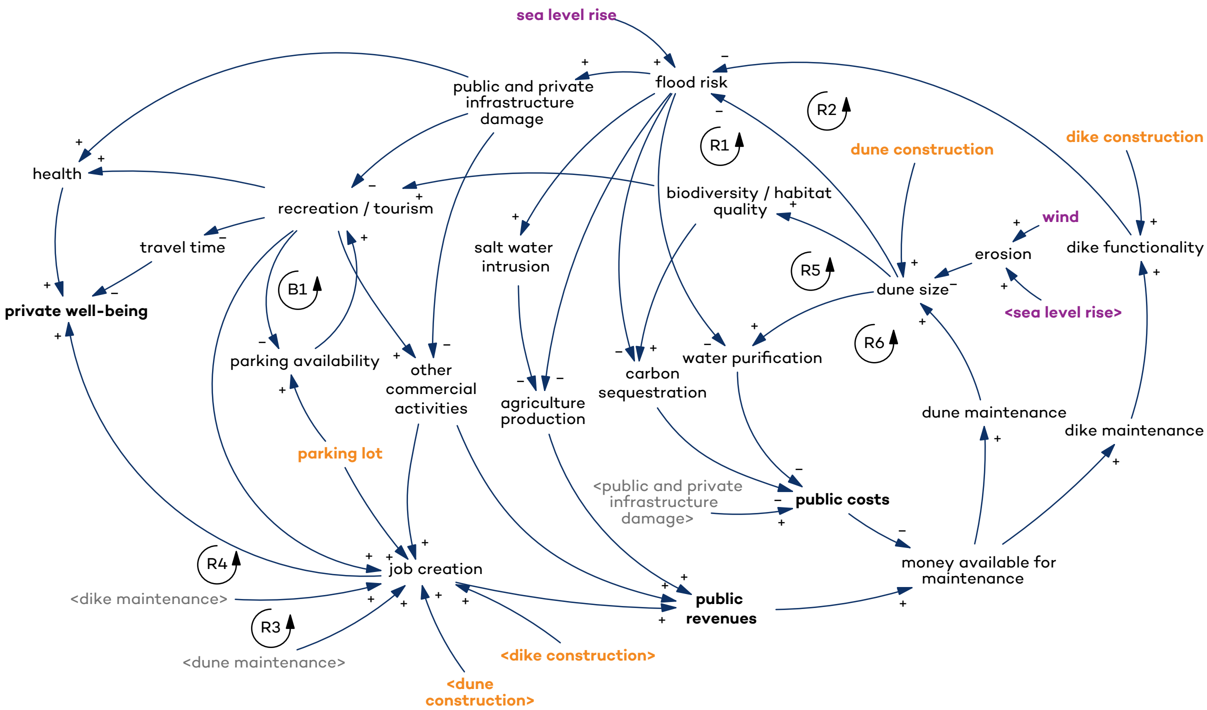
The CLD displays multiple reinforcing feedback loops between coastal defence infrastructure and money available for maintenance. We have grouped these into six categories, labelled R1–R6 in Figure 1:

- R1 – Dunes reduce flood risk, which becomes more important as sea level rises. Flooding causes infrastructure damage, which hurts tourism and other commercial activities and incurs public costs. Floods also destroy natural landscapes. This kills vegetation, which releases carbon into the atmosphere. Carbon emissions may need to be offset in other sectors, representing another cost. Flooding also causes nitrogen and phosphorus to enter nearby water bodies, potentially increasing costs for water treatment. Lowering flood risk avoids saltwater intrusion and other damage to agriculture, which is a source of public revenue. More revenue and lower costs may make dune maintenance more desirable.

- R2 – The dike reduces flood risk. If the dike provides the same flood protection as the dunes, then all the impacts of flood protection described in R1 also hold for R2. In this case, the increase in available money may motivate further dike maintenance.
- R3 – Dune maintenance creates jobs. These jobs result in tax revenue, which provides justification for continued maintenance. We note that dune construction also creates jobs, but this is a one-time impact, whereas maintenance must happen throughout the lifetime of the dunes.
- R4 – Dike maintenance creates jobs. Thus, by the same mechanism as dune maintenance, this enables additional maintenance. As with the dunes, construction creates temporary jobs.
- R5 – Dunes support habitat and generally improve the quality of the area. This makes the area more attractive to tourists (EcoShape, 2021). Tourism creates jobs and stimulates economic activity, which contributes to public revenues. This ultimately may motivate continued dune maintenance. Furthermore, vegetated dune habitats store carbon. We do not include this carbon stock in our analysis, but instead include only the carbon stored in the land behind the dunes. The dashed arrow from dune size to biodiversity/habitat quality indicates that this relationship is not a simple positive or negative causation. Although the positive feedback loop, R5, exists for the sandy habitat created, the dunes also had a negative impact on habitat for some birds, which relied on the rocky landscape of the existing flood wall.
- R6 – One source of drinking water in the Netherlands is surface water filtered through dunes (Remme et al., 2018). Thus, dunes can directly increase freshwater availability, which reduces public costs for water treatment. Lower public costs allow more money to be invested in dune maintenance. Note that we have not quantified this water filtration benefit, but instead include only the impact on water quality of the land behind the dunes.

We also note that constructing and maintaining flood defence structures emits carbon dioxide. In this assessment, we quantify the cost of carbon associated with materials used for flood protection. That is, we use the social cost of carbon to value the carbon footprint of sand used to build and maintain the dunes and the sand, soil, and concrete that would have been used to build a sheet pile wall. We do not quantify carbon emissions for maintaining the sheet pile wall, as there were no available estimates for how much and what type of material would be required.

Figure 1. CLD for coastal protection infrastructure. Orange variables are possible policy interventions. Pink variables are climate inputs. Arrows show causality, with plus and minus signs identifying positive and negative correlations, respectively. Feedback loops are labelled as either reinforcing (R) or balancing (B). Public costs avoided and revenues created motivate maintenance in coastal protection.



Source: Authors' diagram.

From the relationships in Figure 1, we see that dunes provide a wider variety of benefits than a dike. This highlights how investing in dune construction has different systemic impacts than choosing a conventional dike reinforcement. However, the CLD also shows potential climate vulnerabilities, as sea level rise and wind can erode dunes.

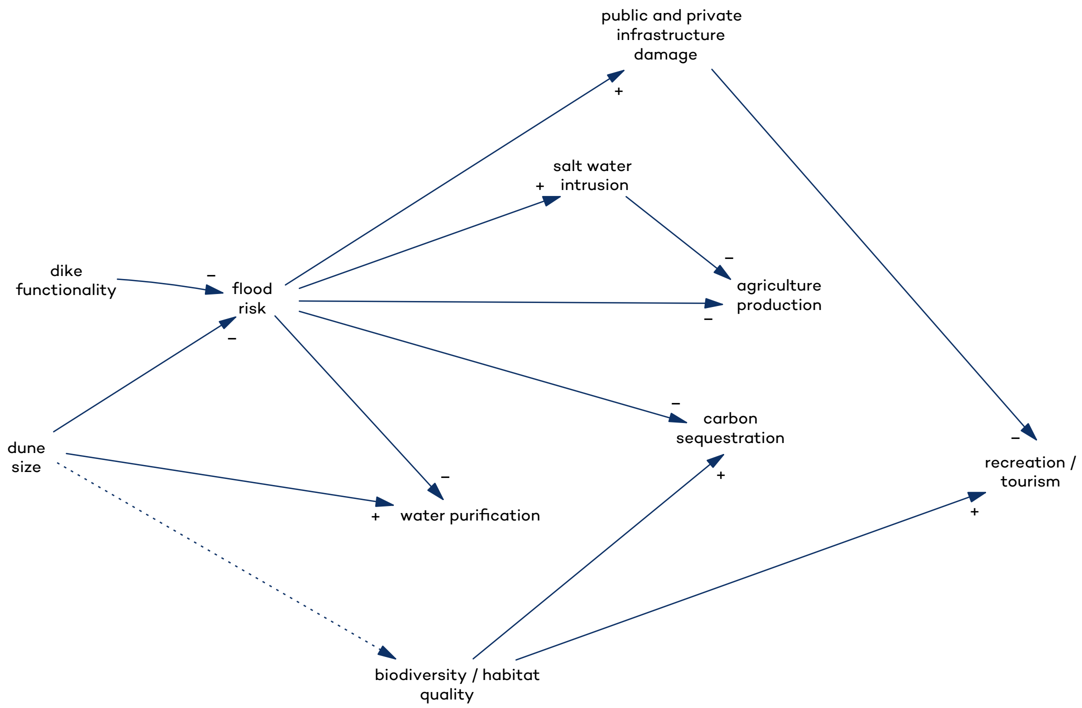
We have included variables in the CLD that directly contribute to private well-being, but we did not attempt to quantify these benefits. For example, recreation activities such as cycling and walking improve health. However, we note that given the high levels of cycling regardless of the dunes, this benefit is negligible for this assessment. Supporting recreation locally means that people may not need to travel as far for some activities. Jobs supported by coastal protection also contribute to private well-being, and flooding has negative impacts on health.

Finally, we note that parking availability can support recreation activities. This creates a balancing loop, whereby parking increases recreation/tourism, but as more people come to the area, parking availability decreases. Constructing a parking lot can thus promote tourism, while also creating construction jobs. As local stakeholders judged that there are sufficient parking places in the area, we did not include the parking dynamic in our valuation.

Figure 2 highlights the differences between the dunes and the dike. Instead of showing feedback loops, this "causal tree" includes only the effects of coastal protection. It does not display variables that may influence the defence structures or the carbon footprint of construction and maintenance.

As Figure 2 shows, both the dunes and the dike reduce flood risk. They are both, therefore, able to prevent infrastructure damage and saltwater intrusion. Thus, both types of coastal defence enable agricultural activity, carbon sequestration, and water purification. Minimizing flood damage allows for tourism and recreation. However, the dunes also have a direct impact on water purification and biodiversity/habitat quality. Although the impact on the latter is ambiguous, the sandy landscape was deemed to be more desirable for tourism and may store carbon in vegetation, despite possible harm to bird habitat. Thus, the dunes provide all the same benefits as the dike and more.

Figure 2. Causal tree highlighting the differences between the dunes and the dikes. Arrows represent causality. Dunes provide more services than a dike.



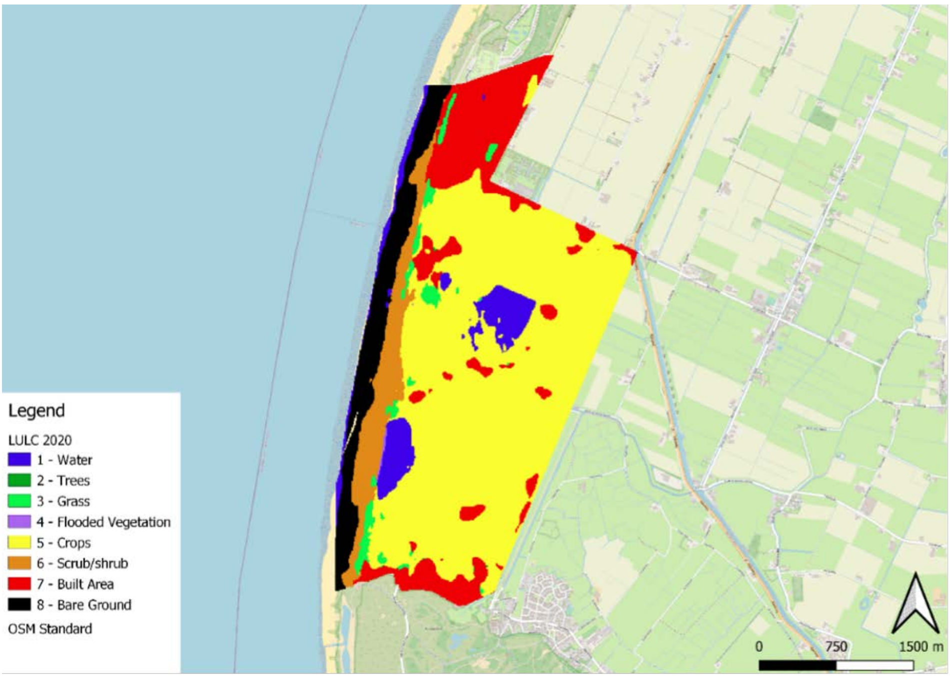
Source: Authors' diagram.

2.3 Spatial Analysis

Before undertaking any sort of financial analysis, it was crucial to determine the area most vulnerable to flooding. While we received anecdotal commentary that the entire Noord-Holland province would be flooded were there a dike breach, we relied upon previous work from the engineering firm Arcadis (2010) to define the boundaries of the study area for this assessment. Specifically, Arcadis' report considered two flood-damage scenarios involving the village of Petten and a cultivated area south of Petten. Our analysis also included the whole "Abtskolk & De Putten" reserve, which is a Natura 2000 site protected by the Bird Directive of the European Union. This reserve covers about 500 hectares between Petten and Camperduin. For details about the study area, please see Appendix A.

The Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) is a set of spatially explicit models from the Stanford Natural Capital Project that quantify ecosystem services (Natural Capital Project, 2019). We used InVEST to map carbon storage and nutrient delivery in the study area. Input for this analysis included a 2020 land cover map derived from European Space Agency (ESA) Sentinel-2 imagery at 10m resolution (Karra, et al., 2020).

Figure 3. Land-use map of the study area



Source: Authors' diagram based on Karra, et al. (2020) using QGIS software.

The study area is predominantly agricultural—60% (551.5 hectares) of the total 911.8 hectares is cropland. The built areas (15%, or 138.7 hectares) are primarily in the villages of Petten to the north and Camperduin to the south. Other land classes include bare ground, shrubs, and water, each of which accounts for less than 10% of the total area.

Below, we provide a brief overview of the spatially explicit indicators that were included in the financial analysis. For a more thorough discussion of the spatial analysis methods and results please see Appendix A.

2.3.1 Carbon Storage

Carbon storage in the study area amounts to approximately 45,000 tonnes. Figure 4 illustrates how this storage is distributed across the area; darker regions store less carbon than lighter ones. Comparing Figure 3 and Figure 4, we see that bodies of water, built areas, and bare ground store little to no carbon. Agricultural land and grass store moderate amounts of carbon per unit area, while scrubland and shrubs have the highest carbon density.

Figure 4. Carbon storage in the study area in tonnes

Source: Authors' diagram based on Karra et al. (2020) using QGIS software.

Many crops grown in North Holland have a low tolerance for salt water, and the area depends heavily on fresh surface water for agriculture. Thus, an increase in salinity due to sea level rise and/or land subsidence has a high potential for damaging the crops in this region (Bresser et al., 2005). Thus, we assume that without a sufficient coastal defence system, the crops in this area would be destroyed and the agricultural land would be converted to bare land or water. As a result, the carbon stored in crops would be released into the atmosphere as carbon dioxide.

Similarly, coastal vegetation is vulnerable to saltwater intrusion and flooding (Herbert et al., 2015; Middleton, 2016; Taillie et al., 2019; Tully et al., 2019). Although specific impacts depend on local species and vegetation (Tully et al., 2019), we assume that without either raising the dike or constructing protective dunes, all the carbon in the landscape of the study area would be emitted.

2.3.2 Nutrient Delivery

For this assessment, we quantified nitrogen and phosphorus stored in the ecosystem. Nutrients loads are defined as the total amount of nutrient (nitrogen or phosphorus) that enters the system, while the nutrients that leave are called the export. We subtract the export from the load to calculate the mass retained each year.

The total nitrogen export and load are approximately 14,000 and 46,000 kg/year, respectively. Thus, about 32,000 kg of nitrogen is retained every year. For phosphorus, we calculate that export is around 750 kg and the load is about 2,800 kg/year, leading to 2,100 kg/year retained.

As with carbon, we assume that without upgrading the coastal defence system, the stored nutrients would be released. In this case, they would enter nearby waterbodies, where elevated nitrogen and phosphorus increase algae growth. As the algae grow and eventually die, decomposition consumes dissolved oxygen in the water. This can harm fish and other aquatic species. Furthermore, some algal blooms are toxic and lead to adverse health impacts, such as damage to the liver, nervous system, and skin (Sanseverino et al., 2016; US EPA, 2021).

Economic impacts of harmful algal blooms that result from high nutrient concentrations include increased health care costs, a decline in fishery production, and impacts on tourism and recreation (Sanseverino et al., 2016). Although algal blooms can affect any body of water, the cost of environmental impacts has been shown to be larger in rivers and wetlands than in the ocean (Hernández-Sancho et al., 2009).

Box 1. High nitrogen loadings as a societal challenge in the Netherlands

Many ecosystems in the Netherlands are burdened with high nitrogen loadings. In more than 70% of the Dutch area, the levels of nitrogen deposition exceed critical loads. Too much nitrogen in the soil is a major reason for the loss of rare species, and is particularly problematic in forest, open dune, and heath ecosystems.

Among other processes, the high nitrogen availability in the Netherlands is caused by the atmospheric deposition of nitrogen. The major sources of the nitrogen deposited in the soil are ammonia and nitrogen oxides from intensive agriculture, industry, and transportation.

In recent years, the high nitrogen loadings have caused severe legal, political, and societal issues in the Netherlands. For example, the highest administrative court ruled in May 2019 that certain government rules could no longer be used for the permission of activities that cause nitrogen emissions in and around vulnerable Natura 2000 areas. As a result, up to 18,000 infrastructure and construction projects were stopped temporarily.

Sources: Schaart, 2019; Environmental Data Compendium, 2018, Adviescollege Stikstofproblematiek, 2019.

2.4 Financial Analysis

When considering the financial viability of an infrastructure project, it is important to consider direct and indirect benefits alongside the direct costs of the project. For example, the direct benefit of constructing the sheet pile wall or the sand dunes is better flood protection. However, for both investment alternatives, there is also the indirect benefit of increased tourism associated with the new construction. It is also important to capture how prices change over time, the time value of money, and the opportunity cost of the investment. To account for these issues, our financial analysis assumes an inflation rate of 1.79% for all modelled benefits and costs[3] and uses a discount rate of 4.5% per annum to determine the present value of costs and benefits at time of intervention. We calculate the NPV of the intervention and the internal rate of return (IRR) assuming a 50-year lifetime, but also assume that the projects would have a residual value of 50% of the original investment cost in Year 50. Also, we assumed that benefits and maintenance costs would continue in perpetuity.

To present a more nuanced picture of the value of the projects, we have also included a scenario that considers the opportunity investment cost. With any investment, there is a cost associated with choosing one alternative over another. By choosing to address the weak point in its coastal protection system, the Dutch government entities spent money that could have been allocated to other infrastructure, other programs, or left in the pockets of its citizens. This foregone spending would have generated other benefits for the Dutch economy. To estimate these benefits, we accessed the literature on fiscal multipliers and found that each EUR of government spending by a developed country generates an additional EUR 0.80 in GDP (Ilzetski et al., 2013). We deem this missed opportunity of EUR 0.80 of benefit per EUR of investment the opportunity cost of fixing the weak point in coastal protection. Following the literature, this opportunity cost is spread over the first 5 years of the financial analysis.

[3] We used a higher inflation rate of 3% per year to calculate the value of the carbon storage benefit, as we expect the value of carbon storage to increase more rapidly. This estimation is more conservative than the estimation made by Gollier (2021) that has carbon prices growing at 4% plus inflation.

3.0 Data and Assumptions

3.1 Investment Alternatives

We modelled two distinct flood protection investment alternatives: A grey-built dike reinforcement and the implemented dune landscape.

1. In the grey infrastructure scenario, the sea dike is reinforced to meet Dutch safety requirements. This infrastructure option entails raising the dike from 5 to 7 metres using a sheet pile wall and reinforcing the dike with asphalt. In the planning process for improving the flood safety in the study region, this option was closely considered but dismissed. We use it to compare the costs and benefits of grey infrastructure and NBI.
2. The NBI scenario covers the dune landscape that was constructed (see Figure 6). For this soft barrier, 30 million cubic metres of sand was dredged from the North Sea to create a beach and dune landscape. This sand nourishment meets the safety standards.

Figure 5. The newly created dune landscape on the seaward side of the existing dike and dunes

Source: Photo courtesy of Van Oord and Boskalis.

3.2 Flood Scenarios as a Basis for This Valuation

For this project, the main benefit is flood protection. As flood protection functions as a form of insurance that is only required at specific times, the costs that would be incurred in case of a flood do not occur every year. Instead, the costs that are avoided due to the flood protection investment should only be counted for years of potential flooding.

For the two investment alternatives, we calculate their value based on flood scenarios. Given the difficulty of predicting when a flood would occur, we analyze how the value of each investment alternative changes based on the number of potential floods it avoids.

Without knowing if or when the flood would occur, we alter the financial analysis so that the avoided costs are counted annually and scaled based on the number of floods avoided over a 50-year period. For example, if we run a scenario under which we expect one flood during the 50-year period, we would count 2% (1/50) of the estimated avoided cost every year during the 50-year project horizon. Further discussion on how this method differs from others can be found in Box 2.

Box 2. Differing approaches to analyzing the Hondsbossche Dunes

Many other assessments of flood protection in the Netherlands use a probabilistic approach to calculate expected NPVs. Unlike those studies, we report results for several deterministic scenarios. We believe that this analysis exposes information that may not be revealed when using only expected values.

This approach is also better aligned with government budgeting processes for infrastructure investment, which consider material impacts and cash flow. For budgetary planning, it is critical to consider when an extreme event may take place (possibly with irregular frequency, affecting costs) and compare it with the emergence of co-benefits and side effects (e.g., tourism revenues that occur every year). This analysis can inform budgeting and infrastructure investment decisions by complementing probabilistic assessments.

To illustrate the difference between the probabilistic approach and the scenario approach, consider the Hondsbossche Dunes, which replaced the existing, inadequate flood protection structure. Using probabilities, the analysis would focus on the annual expected flood damage. These annual expected damages would be discounted back to present value to calculate the expected value of flood protection over the asset lifetime. This relies on a continuous probability distribution function for damages in each year, which requires extensive meteorological, hydrological, and economic data. Calculating the value of upgrading flood protection would require this data-intensive analysis for both the old dike and the dunes.

In the deterministic scenario approach, we do not consider the probability of flooding but instead ask the question, “What happens if there is one flood event against which the existing structure would not protect but that the upgraded dunes would?” Instead of assuming when this event occurs, we smooth the avoided flood damages over the lifetime of the investment and discount back to present value. We make no claim regarding the probability that such an event would occur. We simply state that it is possible and examine its consequences. We can do the same analysis for a scenario in which two (or more) of these events occur.

The expected NPV calculated under the probabilistic approach is important in some decision-making contexts, but the deterministic approach also provides value. Specifically, deterministic scenarios:

1. **Accommodate deep uncertainty:** The future of water management in the Netherlands is uncertain due to changing environmental trends, shifts in human response and values, and technological uncertainties (Haasnoot & Middelkoop, 2012). When considering climate change, the probability of a particular event often cannot be quantified, a situation that is sometimes termed "deep uncertainty" (Hallegatte et al., 2012; Maier et al., 2016). Deterministic scenarios avoid this challenge by framing the problem as a series of "What if…?" questions without quantifying probabilities.
2. **Include low-probability, high-consequence events:** Assessing scenarios that include unlikely but highly damaging events shows outcomes under a range of futures, instead of only a single, most likely trajectory. This helps ensure "robustness," that is, the ability for a policy to perform well regardless of future conditions (Maier et al., 2016).
3. **Better communicate risk:** Scenarios are more closely aligned than probability distributions with how laypeople interpret risk. Compared to a single best guess or expected value, scenarios that present a range of plausible outcomes have been shown to better convey climate risk and uncertainty to the non-technical public. This enables better decision making in some contexts (Lawrence et al., 2013; Shepherd et al., 2018). It is critical to emphasize that scenarios are plausible, but not necessarily probable, descriptions of the future. When this is clarified, deterministic scenarios are a useful communication device.

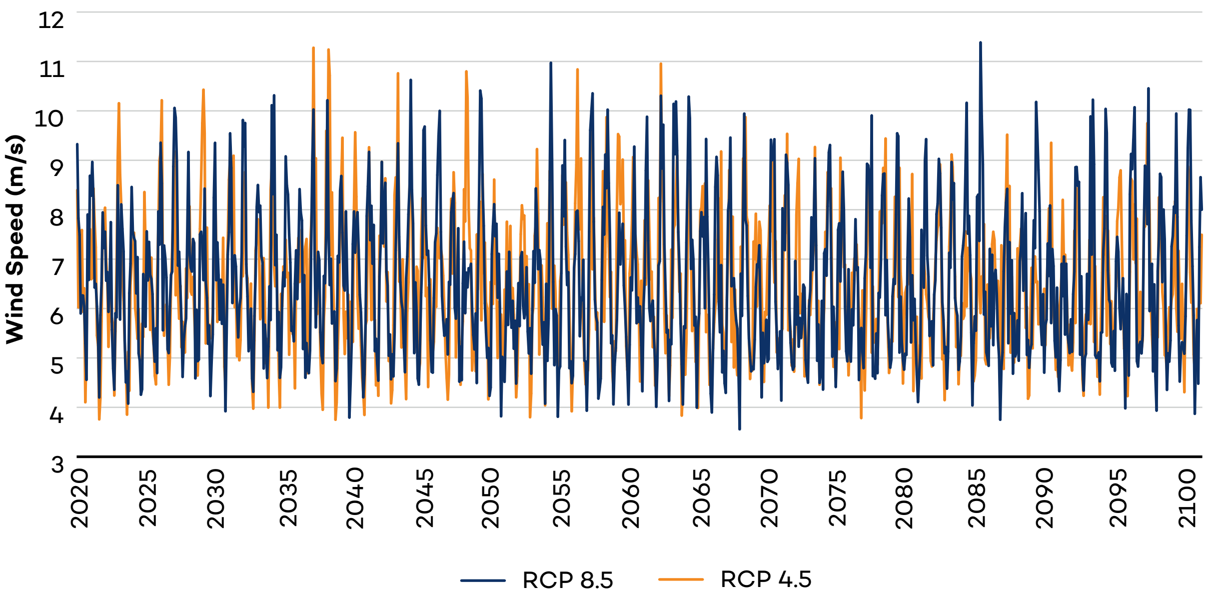
Thus, rather than calculating the expected NPV of the Hondsbossche Dunes, we assessed the value of the investment under several futures. These results communicate impacts that the expected value may obscure. Our assessment does not replace other flood studies but rather provides complementary information that promotes a holistic understanding of the coastal system in a changing climate.

3.2.1 Coastal Flooding Over the Next 50 Years

The Hondsbossche Dunes and the alternative grey dike reinforcement are designed to withstand a 1-in-10,000-year storm. Thus, there is a 0.0001 probability every year that such an event will occur. Before the dunes were constructed, the existing dike offered protection from a 1-in-500-year flood event, equivalent to an annual occurrence probability of 0.002. Thus, the dunes reduce the annual flood probability substantially. As explained below, this added flood protection can become more important with the impacts of climate change.

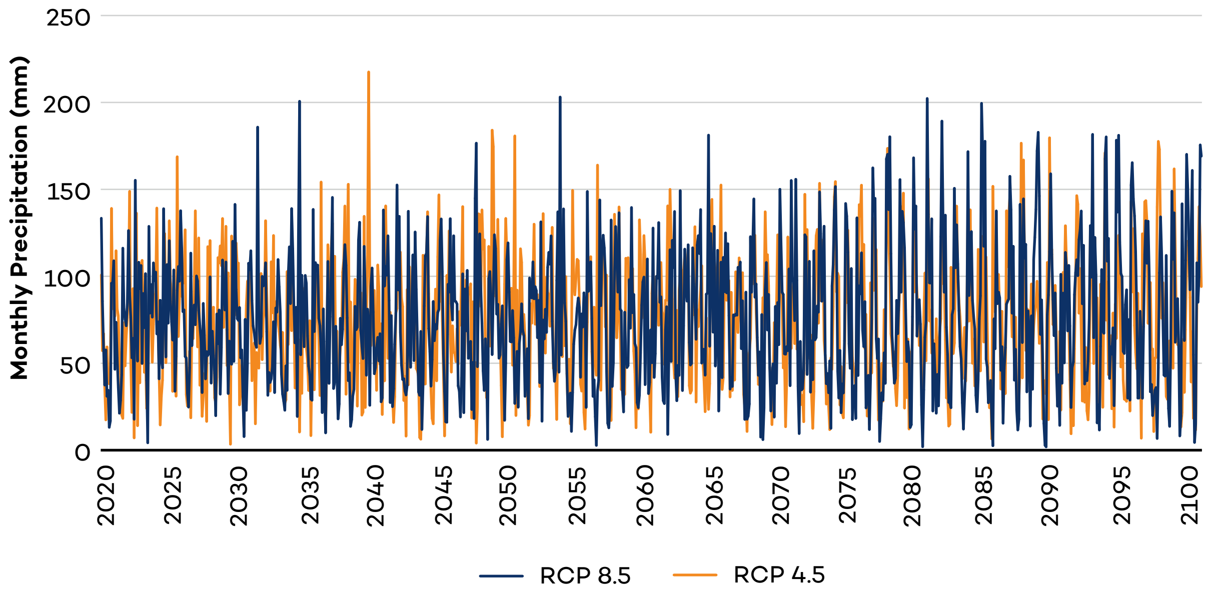
In Figure 6 and Figure 7, we display rainfall and wind speed from two climate projections for Petten. One of these scenarios (Representative Concentration Pathway [RCP] 8.5) assumes that greenhouse gas emissions continue to rise throughout the century, while the other (RCP 4.5) assumes that greenhouse gas emissions peak in 2040 and then decline (Intergovernmental Panel on Climate Change, 2013). It is important to note that these are outputs from only one model and do not necessarily represent the most likely wind and rain patterns for Petten under each emissions scenario. However, the projections can visualize possible future precipitation and wind. Under the scenario with stronger climate change (RCP 8.5), the figures indicate greater rainfall variability. The wind speed patterns are similar under the two projections.

Figure 6. Monthly average 10-metre winds speed for two possible scenarios



Source: Authors' diagram based on data from Copernicus Climate Change Service, 2018.

Figure 7. Monthly precipitation for two possible scenarios



Source: Authors' diagram based on data from Copernicus Climate Change Service, 2018.

Studies have shown that there will be little to no change in wind, wave height, and storm surges along the coast of the Netherlands over the 21st century. This includes no statistical difference in the wave height of 1-in-10,000-year events (de Winter et al., 2012; Sterl et al., 2009).

However, the impacts of precipitation on flooding may be significant. For example, Bevacqua et al. (2019) define compound flood events as the co-occurrence of high precipitation and extreme sea levels (due to tides and storm surges, excluding sea level rise). They found that along the Dutch coast, the probability of such events in 2070–2099 may be 40%–60 % larger than in 1970–2004. The study showed that the impact of changes in precipitation on this increase is larger than the impact of changes in storm surge and tides (Bevacqua et al., 2019).

Furthermore, when including the impact of sea level rise, the flood hazard increases further (Bevacqua et al., 2019). With sea level rise of 15 cm–45 cm in the Netherlands, a 1-in-10,000-year flood may become a 1-in-5,000 or even a 1-in-3,000-year event. That is, the probability that water would overtop a defence structure such as the Hondsbossche Dunes would increase by a factor of 2–3 (Klijn et al., 2012).

Not only does sea level rise increase the probability of flooding, it also exacerbates the consequences. For example, consider two scenarios, one representing the current state of the Netherlands and one with the same socio-economic conditions, but sea level is 1.3 metres higher than at present. A modelling study showed that under the second scenario, an equivalent flood event could cause 2.2–3.7 times more damage, and fatalities would increase by a factor of 3.1–4.7 compared to the scenario with no sea level rise. All of this suggests that flood protection must be continually upgraded to maintain the desired safety level (Klijn et al., 2012; Kwadijk et al., 2010).

3.3 Analysis Indicators and Assumptions

For the financial analysis, we used data from multiple project-specific and international sources. Table 1 outlines the key data and assumptions we made to assess the value of the different investment scenarios.

All monetary data values have been adjusted to be reported in 2015 EUR by inflating the data in its base currency to 2015 values and then converting to EUR based on the 2015 average annual exchange rates.

Before policy-makers decided to construct the dune landscape (the NBI scenario), they considered a range of alternatives. A societal cost-benefit analysis conducted by the engineering firm Arcadis (Arcadis, 2010) formed the basis for their considerations. Our analysis builds upon Arcadis's work by adjusting their 2010 figures to 2015, the year in which construction was completed, and adds details on agricultural impacts, nitrogen and phosphorus pollution, and carbon storage. It also adjusts the tourism benefits to reflect that they have not met expectations yet due to an ongoing legal proceeding.

Table 1. Indicators, assumptions, and data sources used for the financial analyses

Indicator	Assumptions
Investment costs	
Construction	• Sheet pile wall and asphalt reinforcement ∘ EUR 224,197,000 based upon estimated investment cost of EUR 210,200,000 in 2010 Arcadis report. • Artificial dune landscape ∘ EUR 190,000,000 as confirmed by the project developer.
Maintenance costs	
Annual maintenance	• Sheet pile wall and asphalt reinforcement ∘ EUR 181,320 based upon estimated annual maintenance cost of EUR 170,000 (Arcadis, 2010). • Artificial dune landscape ∘ EUR 1,055,000 per year for the first 10 years of project, then EUR 527,000 per year afterward, as confirmed by the project developer. ∘ These amounts were included in the original contract and are not adjusted for inflation until Year 21 (once the maintenance contract ends).
Other costs	
Embodied carbon (more details in Box 3)	• Sheet pile wall and asphalt reinforcement ∘ Construction phase - EUR 4,863,000 - Assumes that 7 km of dike will be raised and reinforced with a concrete sheet pile wall. - We estimate that the sheet pile wall has a cross-sectional area of 69 m^2 (23 m x 3 m) and that the sand/soil to raise the dike crest has a cross-sectional area of 438 m^2 (EcoShape, 2021). - We assume an embodied carbon content of 308 kg CO_2 per m^3 of concrete (Fantilli et al., 2019) and 3.63 kg CO_2 per m^3 of sand/soil (see below). - We use USD 31.21/t CO_2 for the social cost of carbon as the basis of our conversion to 2015 EUR (Nordhaus, 2017). ∘ Operational phase - We assume that no additional materials are required for annual maintenance and so include only the cost of carbon for construction.

Indicator	Assumptions

Embodied carbon (continued) (more details in Box 3)	• Artificial dune landscape
	  ◦ Construction phase
	    - EUR 3,865,880
	    - The embodied carbon content of sand used for construction was 127,000 t CO_2 (E. van Eekelen, personal communication, October 18, 2021). Construction required 35 million m^3 of sand (EcoShape, 2021), leading to a carbon intensity of 3.63 kg CO_2 per m^3 of sand.
	  ◦ Operational phase
	    - Annual maintenance carbon cost of EUR 28,000
	    - It was estimated that 5 million m^3 of sand would be needed for maintenance during the first 20 years of the project. This is an annual average of 250,000 m^3.
	    - We assume the annual average will be constant for 50 years, implying 12.5 million m^3 is needed over 50 years.

Investment opportunity cost	• The opportunity cost of funders investing in this project instead of other projects is based on a total fiscal multiplier of 0.8 (Ilzetski et al., 2013) (see Section 2.4). This multiplier is the cumulative multiplier to a "pure" public investment shock in developed countries. • This opportunity cost is evenly distributed across the first 5 years of the project.
Added benefits	

Additional tourism revenue	• Sheet pile wall and asphalt reinforcement
	  ◦ EUR 3,200,000 annually based upon estimated additional revenue of EUR 3,000,000 (Arcadis, 2010). Estimate is based on a 12.5% increase in tourism due to enhanced amenities.
	• Artificial dune landscape
	  ◦ EUR 6,293,000 annually based upon estimated additional revenue of EUR 5,900,000 (Arcadis, 2010). Estimate is based on a 24.5% increase in tourism due to enhanced amenities.
	• Tourism amenities listed in the Arcadis report included a beach pavilion, foot and cycling paths, a viewpoint, tourist stores and restaurants, expansion of parking space for cars and cyclists, information boards, connections to routes in the area, and enhanced biodiversity to which tourists are drawn.
	• Additional tourism revenue was modelled to increase by 5% per year from 2015 until 2021 as there are current legal proceedings that have impacted expansion plans of local touristic operations.
	  ◦ Proceedings are expected to end in 2021, so the full estimated additional tourism revenue is counted from 2022 onward.

Indicator	Assumptions
Avoided costs	
Avoided estimated flood damage (excluding agriculture)	• In Arcadis's 2010 report, it was estimated that the flood damage in the impacted area would cost EUR 104,200,000. Taking into consideration inflation, the value was estimated to be EUR 111,139,000. This estimation was inclusive of agriculture damage, property damage, infrastructure damage, and business interruptions. • Given that we have calculated the amount of lost agriculture productivity and income associated with agriculture employment in the impacted area, we deducted these figures from the total flood damage.
Avoided loss of agriculture productivity	• Agriculture production in all of the Netherlands based on an average of 2014 and 2016 figures is EUR 746.32 per are annually (CBS, 2021a, 2021d) • Agriculture area protected from flooding in potentially impacted areas is 55,149 are based on our spatial analysis.
Avoided loss of agriculture wages	• Number of people in the Noord-Holland province working in agriculture based on an average of 2014 and 2016 figures is 0.0013 persons per are (CBS, 2021b). • Average of 2014 and 2016 figures for yearly wage in agriculture, forestry, and fishing in the Netherlands is EUR 22,205 (CBS, 2021c). • Agriculture area protected from flooding in potentially impacted area is 55,149 are based on our spatial analysis.
Avoided nitrogen pollution	• The nitrogen retained in the potential impact area is 32.1 tonnes (see Section 2.3.2). • The value of avoiding nitrogen pollution is EUR 5,663 per tonne of nitrogen based upon 2004 estimates of 4,612 per tonne (Hernández-Sancho et al., 2010).
Avoided phosphorus pollution	• The phosphorous retained in the potential impact area is 2.1 tonnes (see Section 2.3.2). • The value of avoiding phosphorus pollution is EUR 9,249 per tonne of phosphorus based upon 2004 estimates of 7,533 per tonne (Hernández-Sancho et al., 2010).
Carbon storage	• The carbon dioxide stored in the potential impact area is 45,086 tonnes (see Section 2.3.1). • The social cost of carbon is EUR 30.44 per tonne of carbon dioxide (Nordhaus, 2017). • The total value is distributed evenly across years 1–50 of the project (2015–2065).

<table>
<tr><th>Indicator</th><th>Assumptions</th></tr>
<tr><td colspan="2">Other relevant information</td></tr>
<tr><td>Inflation rate</td><td>All values that were not in 2015 Euros were inflated or deflated in their base currency to 2015 values and then converted to EUR based on the 2015 average annual exchange rate. Inflation rates used for this process were sourced from the World Bank (n.d.).
Future inflation of the Netherlands-based figures is 1.79% per annum based on the 20-year average of Dutch inflation from 1996 to 2015.
Carbon storage benefit is adjusted by 3% per annum to acknowledge the higher value it will hold in the future.</td></tr>
<tr><td>Discount rate</td><td>A discount rate of 4.5% was the recommended rate for public physical investments/infrastructure in 2015 (Werkgroep discontovoet, 2015).</td></tr>
<tr><td>Residual values of alternatives</td><td>As sheet pile walls, asphalt, and sand dunes will all have value beyond the 50-year period, we estimated their value at the end of the 50-year forecast period to be half of the initial investment cost.
Sheet pile wall and asphalt reinforcement
Half of investment cost (EUR 112,098,500), adjusted for inflation.
Artificial dune landscape
Half of investment cost (EUR 95,000,000), adjusted for inflation.</td></tr>
<tr><td>Benefits and costs beyond time horizon</td><td>We assume that maintenance costs, tourism benefits, and avoided costs will continue beyond the 50-year time horizon of the financial analysis.
Terminal values (the value of flows beyond the forecast) are calculated using the same discount rate and adjusted using the same inflation rate in perpetuity.</td></tr>
</table>

During consultations with stakeholders, the issue of accounting for embodied carbon during the construction and maintenance was raised. To respond to this issue, we have estimated the cost of this embodied carbon for the period forecasted and included it in our calculations. These costs are inflated at the same inflation rate as the carbon storage benefit (3%) and discounted by the same discount rate as other flows. Details of the calculation can be seen in Box 3.

Box 3. Embodied carbon calculations: Dunes vs. grey alternative

The CO_2 footprint of dune construction was 127,000 t CO_2 (E. van Eekelen, personal communication, October 18, 2021). Assuming 35 million m^3 of sand for construction (EcoShape, 2021), this corresponds to a CO_2 intensity of **3.63 kg CO_2 per m^3 of sand**. It was estimated that for the contracted maintenance period of 20 years, 5 million m^3 of sand would be required for maintenance (Y. Daniel, personal communication, October 21, 2021). This corresponds to an average of 250,000 m^3 per year. We assume that annual average sand requirements will be constant for 50 years. Thus, over the project lifetime, **12.5 million m^3 of sand are required for maintenance**.

With 12.5 million m^3 of sand for maintenance and 3.63 kg CO_2 per m^3 of sand, we conclude that the carbon footprint for 50 years of dune maintenance is 45,357 t CO_2. Adding this to the 127,000 t CO_2 for construction, we get a total footprint of **172,357 t CO_2 for the dunes**. Using USD 31.21 per t CO_2 for the social cost of carbon (Nordhaus, 2017), the total carbon cost for the dunes is **USD 5.4 million** (undiscounted and uninflated).

Ecoshape's (2021) project website shows the design plan for the grey infrastructure alternative (crest raising with a sheet pile wall). From this design plan (the first one presented), we estimate that the cross-sectional area of sand/soil used to raise the crest of the dike is 438 m^2 and that the cross-sectional area of the sheet pile wall (assumed to be concrete) is 69 m^2. We assume that this would be constructed along 7 km, resulting in **3.066 million m^3 of sand/soil** and **483,000 m^3 of concrete**.

We assume the CO_2 intensity of sand/soil is 3.63 kg CO_2 per m^3. For concrete, we use a CO_2 intensity of **308 kg CO_2 per m^3 of concrete** (Fantilli et al., 2019). Therefore, we estimate **159,768 t CO_2 emitted for construction** of the grey alternative.

Although dike maintenance would also emit CO_2, we assume that no additional material is required. Thus, for the grey infrastructure alternative, considering embodied carbon for materials, we account for CO_2 emissions from construction only. Using the same social cost of carbon as before, we get a cost of **USD 5 million** for carbon emissions associated with the grey alternative.

4.0 Results

In this assessment, we compare two coastal protection scenarios: The dune landscape that was built and an alternative conventional dike reinforcement using a sheet pile wall. We modelled their benefits and costs using a 50-year time horizon and calculated how these values change depending on the number of avoided floods. The following section presents the results of the assessment and discusses how to interpret the results based on the limitations of this valuation.

4.1 Highlights

Key results from this analysis are as follows:

- Under all scenarios, the investment in the artificial sand dunes offers greater net benefits than the grey alternative of building a sheet pile wall.
- Net benefits and rates of return for the dune investment are positive under most scenarios. The NPV of the sand dune investment is only slightly negative (EUR -6.64 million) when only the additional tourism benefits are offset against the upfront investment and annual maintenance costs. This means that even without including their main purpose of flood protection, the dunes nearly break even, underlining their importance for the local economy.
- When the opportunity cost of investment is taken into consideration, the NBI alternative returns a positive net benefit if the dunes prevent more than one flood. For the grey alternative, the sheet pile wall investment would need to prevent more than three floods to offer positive net benefits.
- There are flexibility, biodiversity, and health benefits of the NBI investment that are not explicitly monetized in this valuation, as some of the value is captured in the increased tourism. In particular, the dune landscape is a valuable wildlife habitat and can contribute to people's health by encouraging physical activity.

4.2 Financial Analysis Under Different Scenarios

The main purpose of the financial analysis is to assess the financial performance of a project when the environmental, social, and economic benefits are counted. It allows decision-makers to take a more holistic approach when assessing whether the project would deliver value for money to society over its life cycle.

Flood protection projects, whether grey infrastructure or NBI, do not generate direct revenues. However, as seen in the previous section, they provide a range of benefits and avoided costs. The SAVi financial analysis treats those avoided costs as revenues and uses them to calculate the NPV and IRR of investments. This allows us to evaluate the investment worthiness of the flood protection projects. When the NPV and IRR calculations integrate avoided costs, we refer to them to as S-NPV and S-IRR.

The following sections present the results of the financial analysis by counting different benefits and costs (for in-depth analyses, see Appendix B and, for a sensitivity analysis, see Appendix C). Given the insurance-like nature of flood protection, each sub-analysis is presented by showing the S-NPV and S-IRR of the different investment alternatives based upon the number of potential floods avoided over 50 years. This helps clarify the rising value of these investments under increasing flood risks from climate change and sea level rise.

Table 2 is an illustrative example of how the S-NPV and S-IRR change depending on which costs and benefits are taken into account. All values in the table are for scenarios where the sand dunes prevent one flood event.

- Scenario 1 – All added benefits, avoided costs, investment costs, and maintenance costs (see Section 4.2.1).
- Scenario 2 – Scenario 1 + investment opportunity cost (see Section 4.2.2).
- Scenario 3 – Scenario 1 - avoided costs and other benefits (see Section 4.2.3).
- Scenario 4 – Only investment and maintenance costs (see Section 4.2.4).

Table 2. S-NPV and S-IRR under the same flood scenario accounting for different benefits and costs. All values are in 2015 EUR thousands.

	50-year lifetime (2015–2064)			
	Scenario 1 (Section 4.2.1)	**Scenario 2** (Section 4.2.2)	**Scenario 3** (Section 4.2.3)	**Scenario 4** (Section 4.2.4)
	Sand dunes	**Sand dunes**	**Sand dunes**	**Sand dunes**
	One flood avoided	One flood avoided	One flood avoided	One flood avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	202,702	202,702	202,702	-
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	51,010	51,010	-	-
Avoided loss of agriculture productivity	30,698	30,698	-	-
Avoided loss of agricultural wages	1,187	1,187	-	-
Avoided nitrogen pollution	136	136	-	-
Avoided phosphorus pollution	14	14	-	-
Carbon storage benefit	1,457	1,457	-	-

	50-year lifetime (2015–2064)			
	Scenario 1 (Section 4.2.1)	**Scenario 2** (Section 4.2.2)	**Scenario 3** (Section 4.2.3)	**Scenario 4** (Section 4.2.4)
	Sand dunes	**Sand dunes**	**Sand dunes**	**Sand dunes**
	One flood avoided	One flood avoided	One flood avoided	One flood avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
Residual value of flood protection infrastructure	25,537	25,537	-	-
Total avoided costs	**110,040**	**110,040**	**-**	**-**
Total added benefits and avoided costs	**312,741**	**312,741**	**202,702**	**-**
PRESENT VALUE of COSTS				
Capital cost – construction	190,000	190,000	190,000	190,000
Carbon cost of construction	3,866	3,866	-	-
Annual maintenance costs	19,141	19,141	19,141	19,141
Carbon cost of annual maintenance	1,466	1,466	-	-
Investment opportunity cost	-	140,576	-	-
Total costs	**214,473**	**355,049**	**209,141**	**209,141**
S-NPV	**98,268**	**-42,308**	**-6,440**	**-209,141**
S-IRR	5.9 %	4.1 %	4.4 %	N/A

From the illustrative example above, we see that even under the same investment and flooding prevention scenario, the S-NPV and S-IRR calculations are sensitive to inputs included. Scenarios 3 and 4 are particularly instructive, as they point to how the projects may be valued if only the monetary flows of tourism and costs (Scenario 3) are captured or when only the costs are counted (Scenario 4).

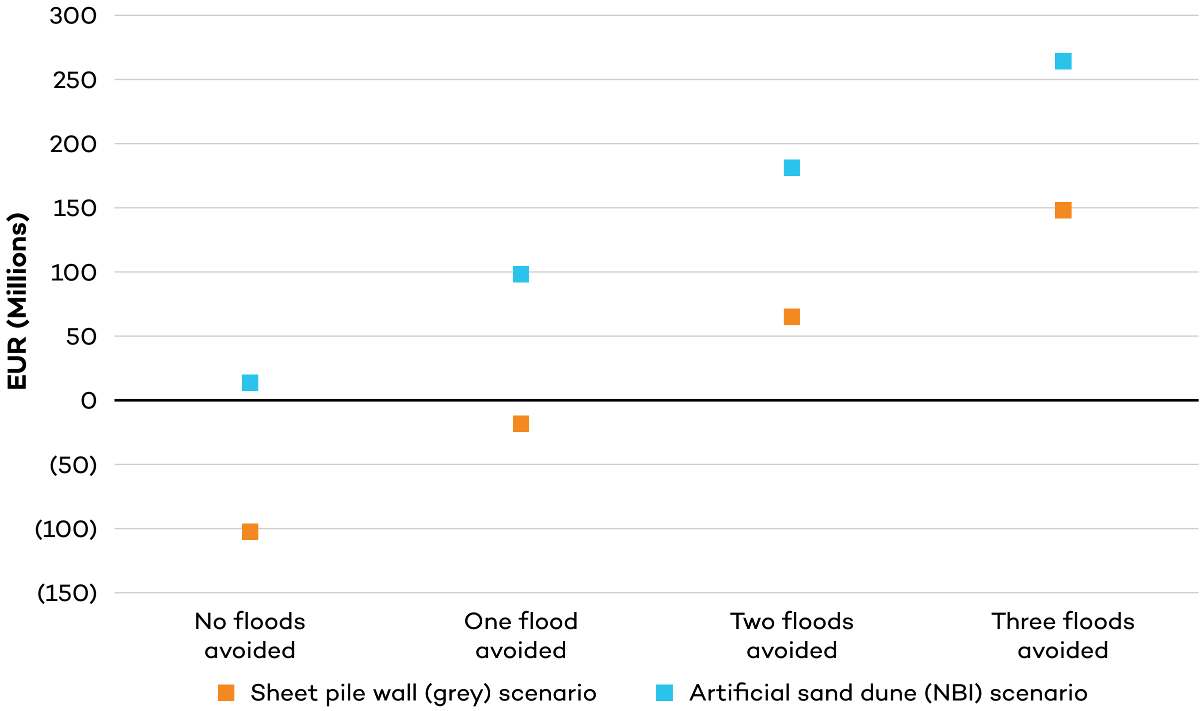
4.2.1 Financial Analysis Considering All Benefits, Avoided Costs, and Investment and Maintenance Costs

The results of the financial analysis, when accounting for inflation and applying a discount rate of 4.5%, underline that the S-NPV and estimated returns of the artificial dune landscape are positive even if there was no threat of flood over the next 50 years. With an estimated S-NPV of EUR 13.8 million and compounded average annual net benefit (S-IRR) of 4.7%, the dune investment performs much better than the sheet pile (grey) alternative. These positive outcomes are due to the estimated additional tourism in the artificial dunes to camp, bike, bird watch, and take in the other benefits that the area has to offer. As estimates of additional tourism associated with the grey alternative are approximately half of estimates for the NBI alternative, the grey alternative delivers EUR 116 million less in 2015 value than the NBI alternative. It also delivers between 1.5% and 1.8% less in compounded average annual net benefit (S-IRR) over the 50-year period.

Table 3. S-NPV and S-IRR under all flood scenarios accounting for all added benefits, added avoided costs, and investment and maintenance costs. All values are in 2015 million EUR.

		Floods avoided over 50-year forecast (2015–2064)			
Investment scenario		**No floods**	**One flood**	**Two floods**	**Three floods**
Sheet pile wall and asphalt reinforcement (grey alternative)	S-NPV	-102.62	-18.11	64.93	147.98
	S-IRR	2.9%	4.2%	5.4%	6.4%
Artificial dune landscape (NBI alternative)	S-NPV	13.77	92.27	181.31	264.36
	S-IRR	4.7%	5.9%	6.9%	7.9%

Figure 8. Chart of S-NPVs under different flood scenarios for each investment alternative



Source: Authors' diagram.

4.2.2 Financial Analysis Considering Investment Opportunity Cost

As mentioned in Section 2.4, we also modelled a scenario that considers the opportunity investment cost. As with any investment, there is a cost associated with choosing one alternative over another. For example, public authorities could have decided not to invest in the coastal protection but in other infrastructure.

We used a multiplier for fiscal spending by governments to estimate the opportunity cost of money being spent toward this project as opposed to other projects. The multiplier used in calculating the opportunity cost would change depending on the sectors of the alternative investment, but the government multiplier provides an adequate estimate.

When these costs are taken into consideration, Table 4 shows that among the grey and NBI alternatives, the NBI alternative still delivers superior value. The S-NPV for the NBI alternative (EUR -126.8 million under a no-flood-avoided scenario) is almost EUR 142 million higher across all flood scenarios than the grey alternative. Put differently, the NBI has a positive S-NPV if it protects Petten and surrounding areas from more than one potential flood; the grey alternative needs to protect the area from more than three potential floods to claim a similar positive S-NPV.

Table 4. S-NPV and S-IRR under all flood scenarios accounting for added benefits, avoided costs, investment and maintenance, and opportunity costs. All values are in 2015 million EUR.

Investment scenario		Floods avoided over 50-year forecast (2015–2064) No floods	One flood	Two floods	Three floods
Sheet pile wall and asphalt reinforcement (grey alternative)	S-NPV	-268.49	-183.99	-100.94	-17.90
	S-IRR	1.4%	2.6%	3.5%	4.3%
Artificial dune landscape (NBI alternative)	S-NPV	-126.81	-42.31	40.74	123.78
	S-IRR	3.1%	4.1%	4.9%	5.7%

4.2.3 Financial Analysis Only Considering Added Benefits and Investment and Maintenance Costs

As NPV and IRR are traditionally associated with cash flows, we thought it important to analyze the projects when only the added benefits of tourism and investment and maintenance costs are considered. As can be seen in Table 5, the NBI alternative only has a negative NPV of EUR 6.4 million despite costing EUR 190 million at the outset of the project, demonstrating the importance of the increased tourism.

Table 5. NPV and IRR under all flood scenarios accounting for added benefits and investment and maintenance costs. All values are in 2015 million EUR.

Investment scenario		Floods avoided over 50-year forecast (2015–2064) All flood scenarios
Sheet pile wall and asphalt reinforcement (grey alternative)	NPV	-127.89
	IRR	2.0%
Artificial dune landscape (NBI alternative)	NPV	-6.44
	IRR	4.4%

Further demonstrating the importance of the additional tourism benefits is the NPV difference between the grey and NBI alternatives. As can be seen in Table 5, the NPV of the NBI alternative (EUR -6.4 million) is more than EUR 120 million higher than the grey alternative (-127.9 million) if the tourism benefit estimates materialize as predicted. This finding reinforces the point that under all scenarios, the artificial dunes deliver superior value when compared to the sheet pile wall alternative.

4.2.4 Financial Analysis Considering Only Investment and Maintenance Costs

We also analyzed the infrastructure alternatives based solely on their investment and maintenance costs. This is useful because the added benefit of increased tourism is an estimate and because the avoided costs do not generate monetary flows. Table 6 shows the NPVs of both investments based solely on their investment costs and maintenance costs over the 50-year time horizon. The NBI alternative is still worth more, less negative in this case, than the grey alternative. This is because the dunes have a lower upfront cost than the sheet pile wall even though the dunes have higher annual maintenance costs.

Table 6. NPV and IRR under all flood scenarios only accounting for investment and maintenance costs. All values are in 2015 million EUR.

		Floods avoided over 50-year forecast (2015–2064)
Investment scenario		**All flood scenarios**
Sheet pile wall and asphalt reinforcement (grey alternative)	NPV	-230.96
	IRR	N/A
Artificial dune landscape (NBI alternative)	NPV	-209.14
	IRR	N/A

4.3 Interpreting Results in Light of Limitations for This Study

To interpret our results, it is important to understand the limitations of this study. The financial analysis includes impacts on society at large without differentiating who pays and who benefits. Similarly, we have not quantified all benefits from the investments, such as increased fitness levels due to greater recreational alternatives offered by the dunes (see Box 4) or the psychological benefits of better flood protection. By psychological benefits we are referring to how the citizens of Petten and Camperduin feel safer under the grey and NBI alternatives knowing that they would no longer be living near a weak spot in the Dutch flood defence system.

Box 4. Considering the health benefits from increased bicycle use

The Netherlands is well known for its high levels of bicycle use: On average, each person cycles about 1,000 kilometres per year, and cycling accounts for more than one quarter of all trips (Harms & Kansen, 2015). Creating attractive outdoor spaces can encourage more walking and cycling among residents and visitors. Such increased levels of physical activities can improve health and well-being. For example, cycling helps to reduce the risks of illnesses such as diabetes, cardiovascular diseases, and depression (Harms & Kansen, 2015).

Creating the Hondsbossche dunes, with their cycling paths and amenities, may have made cycling more appealing in the area. However, the levels of cycling in the municipality of Schagen are already among the highest in the country—people choose to cycle for nearly half of trips shorter than 7.5 kilometres (Harms & Kansen, 2015). It is therefore unlikely that the NBI project has increased the levels of active mobility even further. In coordination with local stakeholders, we have thus decided not to consider the health benefits of physical activity in the SAVi valuation.

Our assessment also does not assign a specific monetary value to the biodiversity effects of the different alternatives. The NBI includes elements such as wet dune valleys, beach areas, and different types of dunes. In a densely populated country like the Netherlands, these are valuable habitats for plants and animals. However, it is important to remember that biodiversity was lost as the area was converted from one that had a hard substrate to the dune solution. The impacts on biodiversity were such a concern that the regional water board (Hoogheemraadschap Hollands Noorderkwartier) included it as part of its assessments of proposals. Stakeholders indicated that there was neither a net loss nor a net gain of biodiversity due to the dune landscape, but that biodiversity with the dune area may gradually increase over time.

In the longer term, all these possible benefits of the infrastructure investment could contribute to higher property values in the area and an increased willingness to invest in local infrastructure.

Compared to the grey alternatives, the sand dunes are a more flexible flood protection. If increased flood risks require safety upgrades, the dunes could be easily strengthened by adding more sand, while reinforcing a sea wall would require larger construction works. This adaptability of the NBI can reduce investment needs in the long run and fits the Dutch approach of adaptive flood risk management.

Overall, the limitations of this analysis imply that the net benefits of the infrastructure investments may be larger than our estimate, but we do not know how these benefits are distributed or how they compare to other investment options.

5.0 Conclusions

To provide a comprehensive assessment of the Hondsbossche Dunes and a grey-built alternative, we modelled the added benefits, avoided costs, and costs of these two coastal protection options. The analysis focuses on how these investment alternatives lead to additional tourism revenues. It also sheds light on the cost savings associated with avoided flood damages and estimates the carbon storage benefits and avoided nutrient pollution related to the projects.

The results show that the sand dune investment was the superior choice under all conditions. Under all scenarios, it has higher NPVs and rates of return than traditional infrastructure. We estimate that the NBI boosts tourism revenues by EUR 202 million over 50 years. In contrast, the grey alternative could have only increased tourism by EUR 103 million. Even though the sand dunes require more maintenance, their lower construction costs and positive effect on tourism make them the better investment.

Our analysis confirms that the sand dunes provide cost-effective flood protection. Over a 50-year horizon, the S-NPV of the dunes is positive even when there is no flood. The value reaches almost EUR 98 million when assuming that the dunes avoid one flood. Conversely, the grey alternative would need to prevent two floods to have a positive NPV.

This report is intended to inform various stakeholders. Planning and engineering firms can use the results to make the business case for nature-based coastal protection. Civil society organizations can use the report to advocate for NBI that advances climate adaptation while delivering diverse benefits to biodiversity and local communities. Public authorities can use the report to understand the value of NBI like the Hondsbossche Dunes for tourism and local development. Assessments like this can help develop more integrated, area-based NBI projects that deliver additional benefits to people and the planet. The results can also help promote NBI as a cost-effective solution for climate adaptation.

On a final note, much is made of the inability to scale adaptation projects and the difficulties of attracting investors to NBI projects. Although the Hondsbossche Dunes is a public good funded by public capital, it is also a large-scale investment. In another context, the benefits for tourism could serve as a revenue stream for investors who want to consider NBI but need to offset construction costs. This dune project signals that investing in NBI does not need to be solely publicly funded if the monetary benefits can be properly internalized by other, private, investors.

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Appendix A. Assessing Ecosystem Services Supply in the Netherlands With InVEST

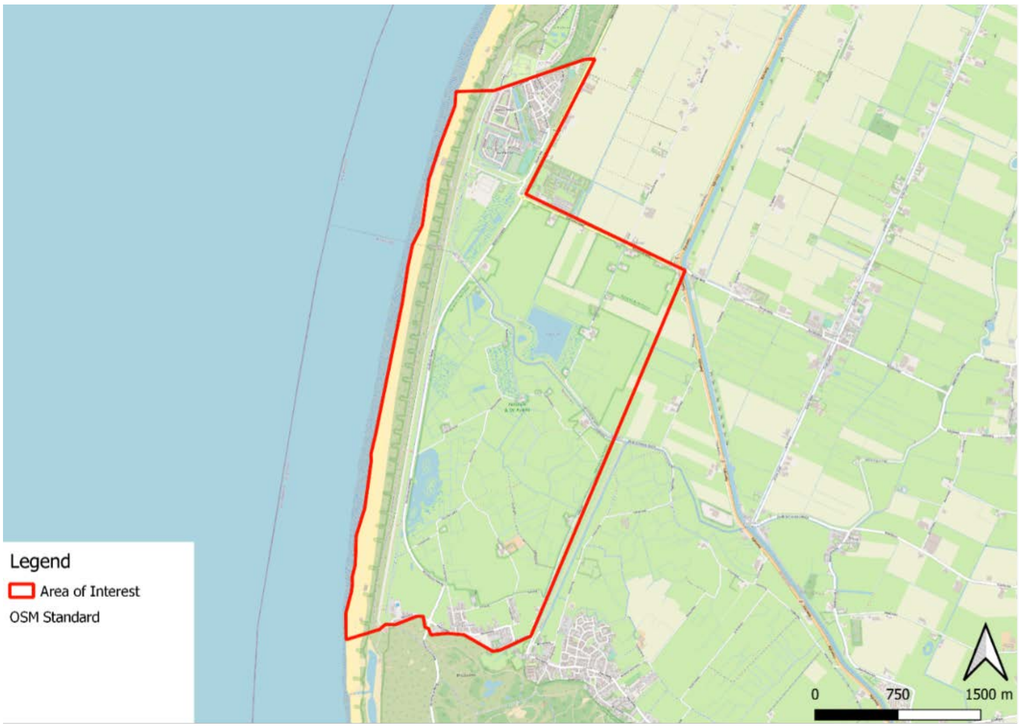
Appendix A presents details about the spatial analysis. We used an open-source suite of software models developed by Stanford University—InVEST. The maps produced by InVEST show us where ecosystem services are provided and how they change under different scenarios. The following sections contain information about the model setup as well as carbon storage and the nutrient delivery ratio in the study area.

1.0 Model Setup

1.1 Study Area

Starting from a societal cost-benefit analysis report produced by the engineering company Arcadis (2010), we were able to define the boundaries of the study area considered in this assessment. Specifically, that report considered two flood-damage scenarios involving the city of Petten and a cultivated area to the south. We also considered the whole reserve "Abtskolk & De Putten,"[4] which is a Natura 2000 site protected by the Bird Directive of the European Union. The study area considered in this assessment is represented in Figure A1.

Figure A1. Study area



Source: Authors' diagram using QGIS software.

[4] https://www.natura2000.nl/gebieden/noord-holland/abtskolk-de-putten/abtskolk-de-putten-kaart

1.2 Coordination System

The spatial assessment results are based on the world project coordinate system called "V WGS 84 / Pseudo-Mercator – Spherical Mercator – ESPG: 3857." Details on the coordinate system are provided in Figure A2.

Figure A2. Details on the coordinate system used for the spatial assessment

```
PROJCS["WGS 84 / Pseudo-Mercator",
  GEOGCS["WGS 84",
    DATUM["WGS_1984",
      SPHEROID["WGS 84",6378137,298.257223563,
        AUTHORITY["EPSG","7030"]],
      AUTHORITY["EPSG","6326"]],
    PRIMEM["Greenwich",0,
      AUTHORITY["EPSG","8901"]],
    UNIT["degree",0.0174532925199433,
      AUTHORITY["EPSG","9122"]],
    AUTHORITY["EPSG","4326"]],
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  PARAMETER["central_meridian",0],
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  PARAMETER["false_easting",0],
  PARAMETER["false_northing",0],
  UNIT["metre",1,
    AUTHORITY["EPSG","9001"]],
  AXIS["X",EAST],
  AXIS["Y",NORTH],
  EXTENSION["PROJ4","+proj=merc +a=6378137 +b=6378137 +lat_ts=0.0 +lon_0=0.0 +x_0=0.0 +y_0=0 +k=1.0 +units=m
+nadgrids=@null +wktext +no_defs"],
  AUTHORITY["EPSG","3857"]]
```
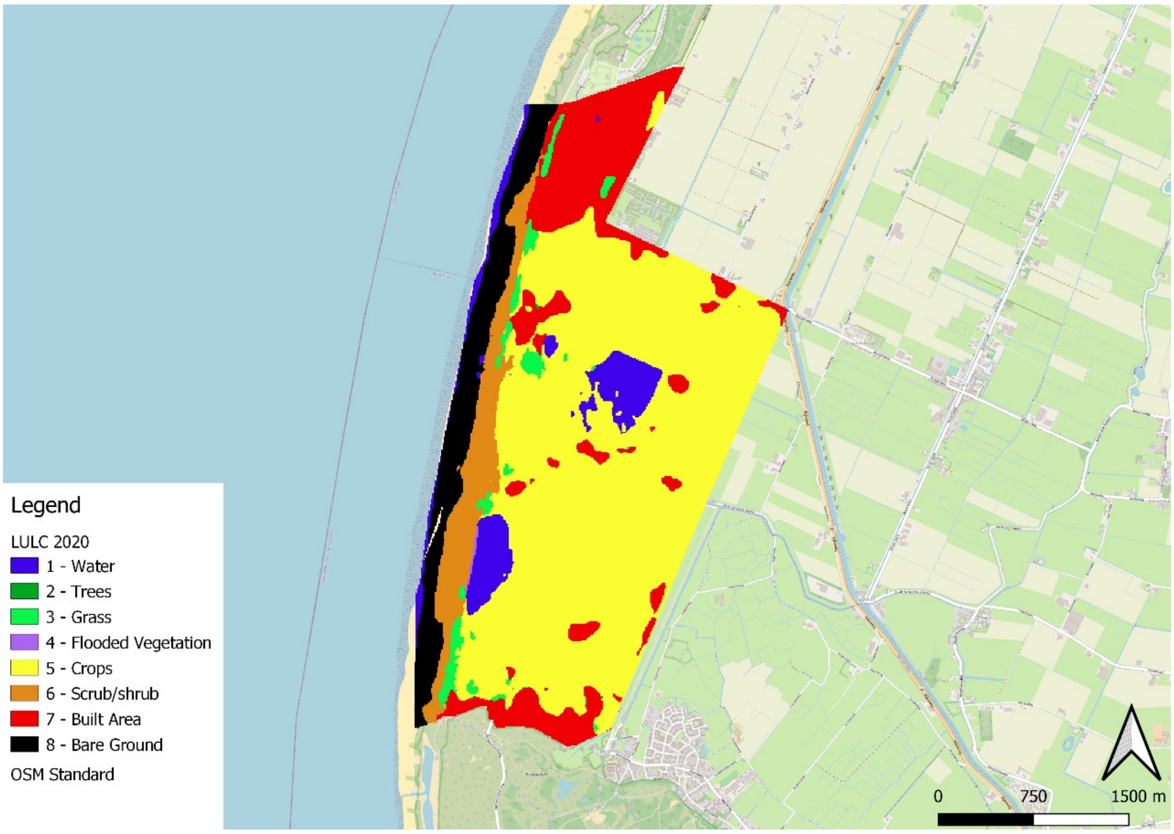

1.3 Maps Used

We used a global map of land-use/land cover (LULC), derived from ESA Sentinel-2 imagery at 10 m resolution. It is a composite of LULC predictions for 10 classes throughout the year to generate a representative snapshot of 2020 (Karra et al., 2020). Training data for that project makes use of the National Geographic Society Dynamic World training dataset, produced for the Dynamic World Project by the National Geographic Society in partnership with Google and the World Resources Institute.

Figure A3 shows the LULC map of the study area, including the values assigned for each land class (e.g., 1 – water, 5 – crops). Table A1 shows the breakdown of the different land classes, as well as the area covered by each of them.

Figure A3. Land-use map of the study area.



Source: Authors' diagram based on Karra et al. (2020) using QGIS software.

Table A1. Area covered by different land classes in the study area

LULC 2020

Land classes	Reference value	Area (m²)	Area (ha)
Water	1	534,300	53.43
Trees	2	1,900	0.19
Grass	3	204,800	20.48
Flooded vegetation	4	9,000	0.9
Crops	5	5,514,900	551.49
Scrub/shrub	6	664,800	66.48
Built area	7	1,387,100	138.71
Bare ground	8	801,500	80.15

1.4 Software and Simulation

The ecosystem services map simulation has been performed using InVEST software V.3.9.0 (https://naturalcapitalproject.stanford.edu/invest/). The inputs spatial data for the InVEST model have been prepared by utilizing QGIS-OSGeoW-3.4.2-1 (qgis.org/downloads/). The tabulated data was managed and prepared in Microsoft Excel V. 2016.

2.0 Carbon Storage

2.1 Input Data Preparation and Processing

1. Current LULCs: Spatial resolution – 10 m.
2. Carbon pools: Table of LULC classes, containing data on carbon stored in each of the four fundamental pools for each LULC class.
    - Carbon above ground: The values of carbon density in aboveground mass (mg/ha or tonnes/ha) of each land-use type are shown in Table A2.
    - Carbon below ground: The values of carbon density in belowground mass (mg/ha or tonnes/ha) of each land-use type are shown in Table A2.
    - Carbon stored in the organic matter: The values of carbon density in dead mass (mg/ha or tonnes/ha) of each land-use type are shown in Table A2.
    - Carbon stored in soil: The values of carbon density in dead mass (mg/ha or tonnes/ha) of each land-use type are shown in Table A2.

The unit of measurement for these coefficients is mg/ha or tonnes/ha. Average carbon coefficients values have been found in the *2006 IPCC Guidelines for National Greenhouse Gas Inventories* report, chapter 4 "Agriculture, Forestry and Other Land Use" (IPCC, 2006).

Table A2. Carbon pools

lucode	LULC_Name	C_above	C_below	C_soil	C_dead
1	lc_1	0	0	0	0
2	lc_2	88.1	22.9	76	0
3	lc_3	1	3.7	83	0
4	lc_4	14.1	54.05	49.5	0
5	lc_5	1	3.99	56	0
6	lc_6	56.4	3.7	83	0
7	lc_7	0	0	0	0
8	lc_8	0	0	0	0

Source: Authors' calculation based on Intergovernmental Panel on Climate Change (2006) inputs.

2.2 Results

Figure A4 shows the amount of carbon stored in tonnes in each pixel. They are a sum of all the carbon pools provided by the biophysical table. As Table A3 shows, the total carbon stored in the study area amounts to more than 45,000 tonnes.

Figure A4. Carbon storage in the study area in tonnes

Source: Authors' diagram based on Karra et al. (2020) using InVEST and QGIS software.

Table A3. Carbon pools statistics

LULC scenario	Total carbon stored (tonnes)
LULC 2020	45,086.17

Source: Data retrieved using QGIS software.

3.0 Nutrient Delivery Ratio

3.1 Input Data Preparation and Processing

1. **DEM Raster**: A GIS raster dataset with an elevation value for each cell. Spatial resolution: approximately 20 m. It was downloaded from the Copernicus website (https://land.copernicus.eu/imagery-in-situ/eu-dem)
2. **Land-use/land cover maps**: Spatial resolution: 10 m
3. **Nutrient Runoff Proxy Raster (Precipitation)**: A GIS raster dataset with a non-zero value for average annual precipitation for each cell. Its value is expressed in millimetres. The average annual precipitation (in mm) from 1970 to 2000 was downloaded from WorldClim version 2 (www.worldclim.com) was used for this study. The dataset was released on June 1, 2016. The original spatial resolution of the data is 30 seconds x 30 seconds (which is approximately 1 km^2). The spatial resolution was reclassified to 10 m.
4. **Watershed Polygons**: This is the polygon shapefile representing the watersheds.
5. **Biophysical Table**: A table of LULC classes, containing data on water-quality coefficients used in this tool (Table A4). Note: These data are attributes of each LULC class rather than attributes of individual cells in the raster map. The table has the following fields:

   5.1 Lucode: Unique identifier for each LULC class.

   5.2 LULC_desc: Nominal name for each LULC class.

   5.3 *load_nlload_p*: The nutrient loading for each land use. If nitrogen is being evaluated, supply values in load_n: for phosphorus, supply values in load_p. The potential for terrestrial loading of water-quality impairing constituents is based on nutrient export coefficients. The nutrient loading values are given as integer values and have units of kg. ha^{-1} yr^{-1}. The values of the nutrient load were assumed.

   5.4 *eff_nleff_p*: The vegetation filtering value per pixel size for each LULC class, as an integer percent between zero and 1. If nitrogen is being evaluated, supply values in eff_n: for phosphorus, supply values in eff_p. This field identifies the capacity of vegetation to retain nutrients, as a percentage of the amount of nutrients flowing into a cell from upslope. For example, if the user has data describing that a wetland of 5,000 m^2 retains 82% of nitrogen, then the retention efficiency that should be entered into this field for eff_n is equal to (82/5,000 * (cell size)^2). In the simplest case, when data for each LULC type are not available, high values (60 to 80) may be assigned to all-natural vegetation types (such as forests, natural pastures, wetlands, or prairie), indicating that 60%–80% of nutrients are retained. An intermediary value also may be assigned to features such as contour buffers. All LULC classes that have no filtering capacity, such as pavement, can be assigned a value of zero. The values of the capacity of vegetation to retain nutrients by LULC were assumed.

5.5 ***crit_len_n (and/or crit_len_p)*** (at least one is required): The distance after which it is assumed that a patch of a particular LULC type retains nutrient at its maximum capacity, given in metres. If nutrients travel a distance smaller than the retention length, the retention efficiency will be less than the maximum value eff_x, following an exponential decay. This value represents the typical distance necessary to reach the maximum retention efficiency. It was introduced in the model to remove any sensitivity to the resolution of the LULC raster. In the absence of local data for land uses that are not forest or grass, it is possible to simply set the retention length to constant, equal to the pixel size: this will result in the maximum retention efficiency being reached within a distance of one pixel only. Therefore, the value of 100 m was used for these parameters. It is the value of cell size used for model simulation.

5.6 ***proportion_subsurface_n or p (optional)*:** The proportion of dissolved nutrients over the total amount of nutrients, expressed as a floating point value (ratio) between 0 and 1. By default, this value should be set to 0, indicating that all nutrients are delivered via surface flow.

Table A4. Biophysical table – annual nutrient delivery ratio

lucode	LULC_ desc	load_n	load_p	eff_n	eff_p	crit_ len_n	crit_ len_p	proportion_ subsurface_n	proportion_ subsurface_p
0	lc_0	0	0	0	0	0	0	0	0
1	lc_1	2.2	0.1	0.1	0.69	200	200	0	0
2	lc_2	17.4	0.162	0.7	0.7	200	200	0	0
3	lc_3	24.1	1.5	0.54	0.7	200	200	0	0
4	lc_4	3.9	0.25	0.72	0.35	200	200	0	0
5	lc_5	67.2	4.46	0.15	0.15	200	200	0	0
6	lc_6	20.8	0.84	0.6	0.6	200	200	0	0
7	lc_7	57.8	2.55	0.2	0.24	200	200	0	0
8	lc_8	66	2.55	0.3	0.24	200	200	0	0
9	lc_9	0	0	0	0	0	0	0	0
0	lc_0	0	0	0	0	0	0	0	0
1	lc_1	2.2	0.1	0.1	0.69	200	200	0	0
2	lc_2	17.4	0.162	0.7	0.7	200	200	0	0
3	lc_3	24.1	1.5	0.54	0.7	200	200	0	0

Source: Data retrieved using InVEST software.

6. **Threshold flow accumulation value**: Integer value defining the number of upstream pixels that must flow into a pixel before it is considered part of a stream. This is used to generate a stream layer from the DEM. This threshold expresses where hydrologic routing is discontinued, i.e., where retention stops and the remaining pollutant will be exported to the stream. If the user has a map of streamlines in the watershed of interest, the threshold value should be "calibrated" by comparing the map with the stream.tif map output by the model. The default value of 1,000 was used in this simulation
7. **Subsurface maximum retention efficiency (nitrogen or phosphorus)**: The maximum nutrient retention efficiency that can be reached through subsurface flow, a value between 0 and 1. This field characterizes the retention due to biochemical degradation in soils. The default value of 0.8 was used for this study.
8. **Subsurface_crit_len (nitrogen or phosphorus) (in metres)**: The distance (travelled subsurface and downslope) after which is assumed that soil retains nutrients at its maximum capacity. If dissolved nutrients travel a distance smaller than subsubsurface_crit_len, the retention efficiency is lower than the maximum value defined above. Setting this value to a distance smaller than the pixel size will result in the maximum retention efficiency being reached within one pixel only. The default value of 150 was used in this simulation.
9. **Borselli k parameter**: Calibration parameter that determines the shape of the relationship between hydrologic connectivity (the degree of connection from patches of land to the stream) and the sediment delivery ratio (percentage of soil loss that reaches the stream). The default value is 2.

3.2 Results

The main outputs of this model are shapefiles containing biophysical output values per watershed, with the following attributes:

- N_export_tot (kg/year): Total nitrogen export from the watershed [units kg/year]
- surf_N_ld: Total nitrogen loads (sources) in the watershed, i.e., the sum of the nutrient contribution from all surface LULC without filtering by the landscape [units kg/year]
- P_export_tot: Total phosphorus export from the watershed [units kg/year]
- surf_P_ld: Total phosphorus loads (sources) in the watershed, i.e., the sum of the nutrient contribution from all surface LULC without filtering by the landscape [units kg/year]

Table A5. Annual nutrient export statistics

Total nitrogen export (kg/year)	13,890.21
Total nitrogen load (kg/year)	45,989.85
Total nitrogen retention (kg/year)	32,099.64
Total phosphorus export (kg/year)	742.02
Total phosphorus load (kg/year)	2,837.19
Total phosphorus retention (kg/year)	2,095.18

Source: Data retrieved using QGIS software.

Table A5 shows the annual nitrogen and phosphorus export and load in the study area in 2020. By calculating the difference between load and export, we calculated the total annual nutrient retention in the study area, which is more than 32,000 kg/year for nitrogen and almost 2,100 kg/year for phosphorus.

Appendix B Financial Results Tables

Appendix B presents detailed results from our financial analysis. For each of the two infrastructure investment scenarios, we calculated the financial performance under different flood scenarios.

1.0 Sand Dunes (NBI Scenario)

Table B1. S-NPV and S-IRR of the sand dunes (NBI) under all flood scenarios accounting for all added benefits, avoided costs, and investment and maintenance costs. All values in 2015 thousand EUR.

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	202,702	202,702	202,702	202,702
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	51,010	102,021	153,031
Avoided loss of agriculture productivity	-	30,698	61,396	92,094
Avoided loss of agricultural wages	-	1,187	2,375	3,562
Avoided nitrogen pollution	-	136	271	407
Avoided phosphorus pollution	-	14	29	43
Carbon storage benefit	-	1,457	1,457	1,457
Residual value of flood protection infrastructure	25,537	25,537	25,537	25,537
Total avoided costs	**25,537**	**110,040**	**193,085**	**276,131**
Total added benefits and avoided costs	**228,239**	**312,741**	**395,787**	**478,833**

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of COSTS				
Capital cost – dune construction	190,000	190,000	190,000	190,000
Carbon cost of dune construction	3,866	3,866	3,866	3,866
Annual maintenance costs	19,141	19,141	19,141	19,141
Carbon cost of annual maintenance	1,466	1,466	1,466	1,466
Investment opportunity cost	-	-	-	-
Total costs	**214,474**	**214,474**	**214,474**	**214,474**
S-NPV	**13,765**	**98,268**	**181,313**	**264,359**
S-IRR	4.7 %	5.9 %	6.9 %	7.9 %

Table B2. S-NPV and S-IRR of the sand dunes (NBI) under all flood scenarios accounting for all added benefits, avoided costs, and investment, maintenance, and investment opportunity costs. All values are in 2015 thousands EUR.

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	202,702	202,702	202,702	202,702
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	51,010	102,021	153,031
Avoided loss of agriculture productivity	-	30,698	61,396	92,094
Avoided loss of agricultural wages	-	1,187	2,375	3,562
Avoided nitrogen pollution	-	136	271	407

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
Avoided phosphorus pollution	-	14	29	43
Carbon storage benefit	-	1,457	1,457	1,457
Residual value of flood protection infrastructure	25,537	25,537	25,537	25,537
Total avoided costs	**25,537**	**110,040**	**193,085**	**276,131**
Total added benefits and avoided costs	**228,239**	**312,741**	**395,787**	**478,833**
PRESENT VALUE of COSTS				
Capital cost – dune construction	190,000	190,000	190,000	190,000
Carbon cost of dune construction	3,866	3,866	3,866	3,866
Annual maintenance costs	19,141	19,141	19,141	19,141
Carbon cost of annual maintenance	1,466	1,466	1,466	1,466
Investment opportunity cost	140,576	140,576	140,576	140,576
Total costs	**349,717**	**349,717**	**349,717**	**349,717**
S-NPV	**-126,811**	**-42,308**	**40,738**	**123,784**
S-IRR	3.1 %	4.1 %	4.9 %	5.7 %

Table B3. NPV and IRR of the sand dunes (NBI) under all flood scenarios accounting for added benefits, avoided costs, and investment and maintenance costs. All values are in 2015 thousand EUR.

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	202,702	202,702	202,702	202,702
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	-	-	-
Avoided loss of agriculture productivity	-	-	-	-
Avoided loss of agricultural wages	-	-	-	-
Avoided nitrogen pollution	-	-	-	-
Avoided phosphorus pollution	-	-	-	-
Carbon storage benefit	-	-	-	-
Residual value of flood protection infrastructure	-	-	-	-
Total avoided costs	**-**	**-**	**-**	**-**
Total added benefits and avoided costs	**202,702**	**202,702**	**202,702**	**202,702**
PRESENT VALUE of COSTS				
Capital cost – dune construction	190,000	190,000	190,000	190,000
Carbon cost of dune construction	-	-	-	-
Annual maintenance costs	19,141	19,141	19,141	19,141
Carbon cost of annual maintenance	-	-	-	-
Investment opportunity cost	-	-	-	-
Total costs	**209,141**	**209,141**	**209,141**	**209,141**
NPV	**-6,440**	**-6,440**	**-6,440**	**-6,440**
IRR	4.4 %	4.4 %	4.4 %	4.4 %

2.0 Sheet Pile Wall and Asphalt Dike Reinforcement (Grey Infrastructure Scenario)

Table B4. S-NPV and S-IRR of the sheet pile wall (grey) alternative under all flood scenarios accounting for all added benefits, avoided costs, and investment and maintenance costs. All values are in 2015 thousand EUR.

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	103,074	103,074	103,074	103,074
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	51,010	102,021	153,031
Avoided loss of agriculture productivity	-	30,698	61,396	92,094
Avoided loss of agricultural wages	-	1,187	2,375	3,562
Avoided nitrogen pollution	-	136	271	407
Avoided phosphorus pollution	-	14	29	43
Carbon storage benefit	-	1,457	1,457	1,457
Residual value of flood protection infrastructure	30,133	30,133	30,133	30,133
Total avoided costs	**30,133**	**114,636**	**197,682**	**280,727**
Total added benefits and avoided costs	**133,207**	**217,710**	**300,756**	**383,802**
PRESENT VALUE of COSTS				
Capital cost – sheet pile construction	224,197	224,197	224,197	224,197
Carbon cost of sheet pile construction	4,863	4,863	4,863	4,863
Annual maintenance costs	6,762	6,762	6,762	6,762
Carbon cost of annual maintenance	-	-	-	-
Investment opportunity cost	-	-	-	-

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
Total costs	**235,822**	**235,822**	**235,822**	**235,822**
S-NPV	**-102,615**	**-18,112**	**64,934**	**147,979**
S-IRR	2.9 %	4.2 %	5.4 %	6.4 %

Table B5. S-NPV and S-IRR of the sheet pile wall (grey) alternative under all flood scenarios accounting for all added benefits, avoided costs, and investment, maintenance, and investment opportunity costs. All values are in 2015 thousands EUR.

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	103,074	103,074	103,074	103,074
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	51,010	102,021	153,031
Avoided loss of agriculture productivity	-	30,698	61,396	92,094
Avoided loss of agricultural wages	-	1,187	2,375	3,562
Avoided nitrogen pollution	-	136	271	407
Avoided phosphorus pollution	-	14	29	43
Carbon storage benefit	-	1,457	1,457	1,457
Residual value of flood protection infrastructure	30,133	30,133	30,133	30,133
Total avoided costs	**30,133**	**114,636**	**197,682**	**280,727**
Total added benefits and avoided costs	**133,207**	**217,710**	**300,756**	**383,802**

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of COSTS				
Capital cost – sheet pile construction	224,197	224,197	224,197	224,197
Carbon cost of sheet pile construction	4,863	4,863	4,863	4,863
Annual maintenance costs	6,762	6,762	6,762	6,762
Carbon cost of annual maintenance	-	-	-	-
Investment opportunity cost	165,877	165,877	165,877	165,877
Total costs	**401,699**	**401,699**	**401,699**	**401,699**
S-NPV	**-268,492**	**-183,989**	**-100,943**	**-17,898**
S-IRR	1.4 %	2.6 %	3.5 %	4.3 %

Table B6. NPV and IRR of the sheet pile wall (grey) alternative under all flood scenarios accounting for added benefits and investment and maintenance costs. All values are in 2015 thousands EUR.

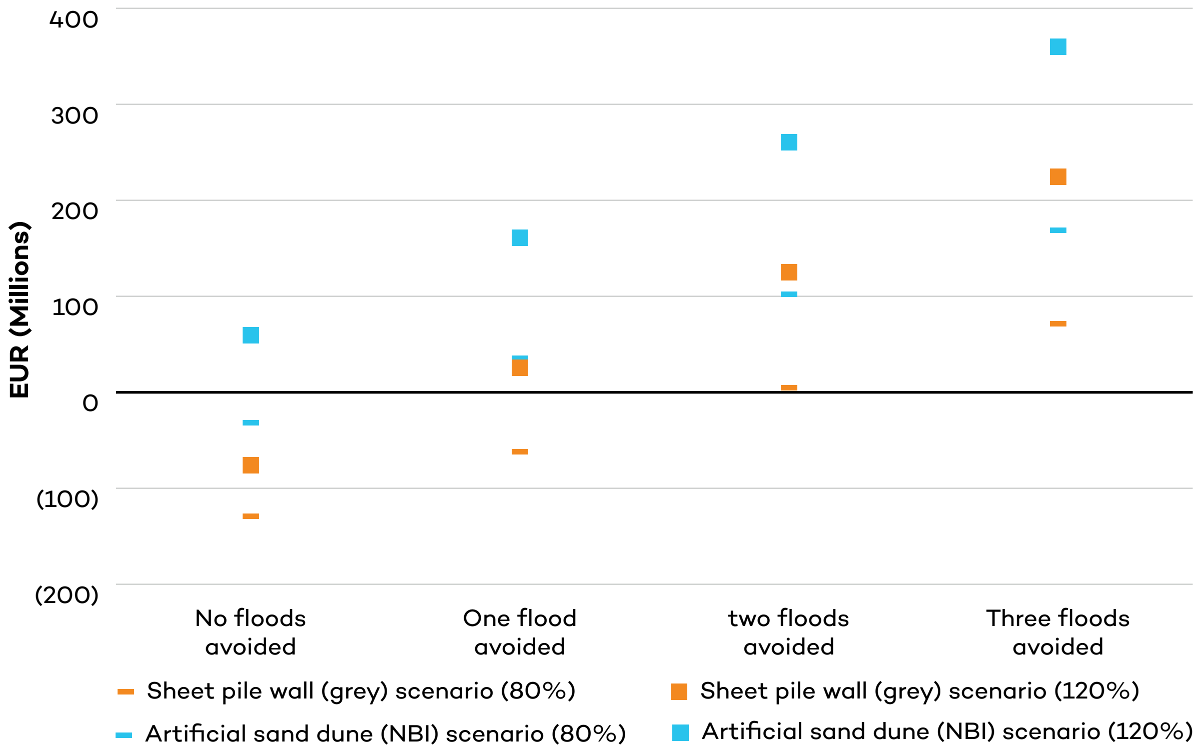
	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
PRESENT VALUE of ADDED BENEFITS and AVOIDED COSTS				
Added benefits				
Increased tourism revenue	103,074	103,074	103,074	103,074
Avoided costs and other benefits				
Avoided flood damages exclusive of agriculture	-	-	-	-
Avoided loss of agriculture productivity	-	-	-	-
Avoided loss of agricultural wages	-	-	-	-
Avoided nitrogen pollution	-	-	-	-

	50-year lifetime (2015–2064)			
	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
	EUR '000s	EUR '000s	EUR '000s	EUR '000s
Avoided phosphorus pollution	-	-	-	-
Carbon storage benefit	-	-	-	-
Residual value of flood protection infrastructure	-	-	-	-
Total avoided costs	**-**	**-**	**-**	**-**
Total added benefits and avoided costs	**103,074**	**103,074**	**103,074**	**103,074**
PRESENT VALUE of COSTS				
Capital cost – sheet pile construction	224,197	224,197	224,197	224,197
Carbon cost of sheet pile construction	-	-	-	-
Annual maintenance costs	6,762	6,762	6,762	6,762
Carbon cost of annual maintenance	-	-	-	-
Investment opportunity cost	-	-	-	-
Total costs	**230,959**	**230,959**	**230,959**	**230,959**
NPV	**-127,885**	**-127,885**	**-127,885**	**-127,885**
IRR	2.0 %	2.0 %	2.0 %	2.0 %

Appendix C Sensitivity Analysis Considering Annual Flows

The figures presented in the report and in Appendix B offer our best efforts to estimate the likely impacts of the different investment alternatives in flood protection. However, we recognize that forecasts are sensitive to assumptions and changing conditions over the life of an investment. For this reason, we have also calculated below a range of outcomes if the annual flows that follow post construction are different than projected. In Figure C1, we present how the S-NPV differs under the two investment scenarios (sheet pile wall and sand dunes) accounting for the number of floods avoided. Figure C1 goes further and presents how these calculations change if only 80% of the projected annual benefits and costs are realized and also presents the calculation if our estimates are too low and benefits and costs are 120% of current estimates.

Figure C1. Chart of S-NPVs under different flood scenarios for each investment alternative and different benefit/cost scenarios



Source: Authors' diagram.

The data supporting Figure C1 are presented with more depth in Table C1.

What is particularly striking—and unsurprising—is that when the prevention of more floods is considered, the range of S-NPV estimates widens. The difference between realizing 80% and 120% of the benefits and costs when no floods are prevented is much smaller than if three floods are prevented over the 50-year projection period because benefits increase with the number of floods avoided. It is also interesting that while the S-NPV of the dunes is less than zero if no floods are avoided and less than 100% of the tourism benefits are realized, the S-NPV of the dunes is positive if one flood is avoided and only 80% (or more) of the tourism benefits are realized.

Table C1. S-NPV of the sheet pile wall (grey) and sand dune alternatives under all flood scenarios accounting for different added

Investment alternative	Percent of annual costs and benefits	No floods avoided	One flood avoided	Two floods avoided	Three floods avoided
Sheet pile wall (grey) scenario	80%	(129.3)	(61.7)	4.8	71.2
	90%	(115.9)	(39.9)	34.9	109.6
	100%	(102.6)	(18.1)	64.9	148.0
	110%	(89.3)	3.7	95.0	186.4
	120%	(76.0)	25.4	125.1	224.7
Artificial sand dune (NBI) scenario	80%	(31.9)	35.7	102.2	168.6
	90%	(9.1)	67.0	141.7	216.5
	100%	13.8	98.3	181.3	264.4
	110%	36.6	129.5	220.9	312.2
	120%	59.4	160.8	260.5	360.1

Both the chart and the figure capture a common understanding that we recognize across all of our SAVi assessments: forecasting over longer time horizons increases uncertainty. However, our understanding and accounting for uncertainty are heightened as we take into consideration the environmental benefits and costs of an investments. Given the built-in uncertainty associated with time, the additional environmental uncertainty and volatility due to climate change requires that all estimates be considered carefully.

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