Cost analysis of nature-based solutions for bank protection compared to rock armour revetments under consideration of embodied CO_2 emissions

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Summary

Although numerous scientific studies claim ecological and functional advantages of near-natural shoreline or bank protection over hard bank protection, responsible authorities often still prefer hard construction methods, assuming them to be more cost-effective. While there is anecdotal support for this assumption, there has been no rigorous evaluation in terms of a comprehensive cost comparison based on real-world data. In this study a complete cost comparison between nature-based solutions for bank protection and hard bank protection is presented using cost data from bank protection measures carried out in German estuarine waterways with the aim of supporting evidence-based decision-making. A sensitivity analysis highlights the most important boundary conditions such as maintenance intervals influencing total costs. The study highlights different cost structures, maintenance intervals and total costs for the investigated measures. Embodied carbon emissions of rock armour revetments were calculated and amounts monetised to investigate influence on total costs. Results show that nature-based solutions for bank protection typically require lower initial investment but incur higher maintenance costs. Monetised values of embodied carbon emissions do not significantly influence the overall costs. Nevertheless, nature-based solutions are shown to be cost-competitive with hard-engineered structures if maintenance intervals are low.

Keywords

Nature-based solution, bank protection, technical-biological bank protection, cost analysis, cost comparison, brushwood box, live willow mat

Zusammenfassung

Obwohl zahlreiche wissenschaftliche Studien ökologische und funktionale Vorteile von naturnahen Ufer- oder Böschungsschutzmaßnahmen gegenüber harten Uferbefestigungen belegen, bevorzugen die zuständigen Behörden oft noch immer harte Bauweisen, da sie diese für kostengünstiger halten. Auch wenn es hierfür einige mündliche Aussagen gibt, existiert jedoch keine fundierte Bewertung in Form eines umfassenden Kostenvergleichs auf der Grundlage realer Daten. In dieser Studie wird ein vollständiger Kostenvergleich zwischen technisch-biologischer Ufersicherung und hartem Verbau anhand von Kostendaten aus Uferschutzmaßnahmen in deutschen Ästuaren vorgestellt, mit dem Ziel, eine evidenzbasierte Entscheidungsfindung zu

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unterstützen. Eine Sensitivitätsanalyse hebt die wichtigsten Randbedingungen hervor, wie z. B. Unterhaltungsintervalle, die die Gesamtkosten stark beeinflussen. Die Studie zeigt die unterschiedlichen Kostenstrukturen, Unterhaltungsintervalle und Gesamtkosten für die untersuchten Maßnahmen auf. Zudem wurden CO_2-Emissionen von Steinschüttungen berechnet und monetarisiert, um den Einfluss auf die Gesamtkosten zu untersuchen. Die Ergebnisse zeigen, dass naturbasierte Lösungen für den Uferschutz in der Regel geringere Anfangsinvestitionen erfordern, aber höhere Unterhaltungskosten verursachen. Die monetarisierten Werte der CO_2-Emissionen haben keinen wesentlichen Einfluss auf die Gesamtkosten. Dennoch erweisen sich naturbasierte Lösungen als kostengünstig bzw. zumindest gleich teuer im Vergleich zu technischen Strukturen, wenn die Unterhaltungsintervalle gering sind.

Schlagwörter

Naturbasierte Maßnahmen, Ufersicherung, technisch-biologische Ufersicherung, Kostenanalyse, Kostenvergleich, Buschkiste, Weidenspreitlage

1 Introduction

Status quo – Hard-engineered River banks

A significant proportion of estuarine river banks in Germany have been protected from erosion using hard-engineered bank protection, such as rock armour revetments (see Figure 1d) or sheet piling, leading to limited ecological value. The use of hard-engineered bank protection is often necessary due to a variety of loads on river banks, such as tidal currents, wind waves and currents originated from shipping traffic (Dempwolff et al. 2022, Melling et al. 2025). While hard-engineered bank protections are reliable and well-understood, their widespread use leads to monotonous river banks characterised by low land-water connectivity and structural diversity. Despite rock revetments providing some habitat value (Gittman et al. 2016), their widespread and uniform application in estuaries results in a dominant, homogenous habitat type that lack the structural diversity necessary to support a broader range of floral and faunal species (Torre and Targett 2016, Lawrence et al. 2021). Recent investigations have shown that the majority of water bodies in Germany and Europe do not reach good ecological status; one reason is the straightening and reinforcement of river banks leading to limited habitat availability (EEA 2024). The EU Water Framework Directive (EU 2000)) demands achieving good ecological status or good ecological potential for all water bodies in the EU. An alternative approach for estuarine river bank protection becomes necessary to reach ecological goals while ensuring bank stability and safety of navigation.

New approaches – large-scale nature-based solutions

Nature-based solutions (NbS) for coastal protection have experienced increased attention over the last years (Jordan and Fröhle 2022; Perricone et al. 2023) and can offer a solution to increase ecological status and reach ecological goals. Many NbS projects for coastal protection focus on large-scale systems, such as salt marshes (Baptist et al. 2021), mangroves (van Coppenolle et al. 2018), wetlands (Ferreira et al. 2023), seagrass meadows, beaches, dunes, and reef ecosystems (e.g., Jordan and Fröhle 2022, van der Meulen et al. 2023). Their ability to reduce flood risk and to provide erosion control while providing greater ecological benefits has been proven within these studies. Further, there are other NbS investigations that focus on riverbank stabilization, flood protection, and erosion control using living vegetation in natural rivers without tides (Moreau et al. 2022, Seele-Dilbat et al. 2022) showing an increase of ecosystem services (Symmank et al. 2020).

Small-scale nature-based solutions for bank protection

Besides large-scale NbS, there are also small-scale nature-based solutions. So-called living shorelines is a concept of using coastal habitats to stabilise shorelines and river banks (Morris et al. 2022). Roo and Troch (2015) used off-bank timber piling combined with live vegetation in a Belgian waterway, however the mitigation effect on erosion was limited. In the Furusund Fairway in Sweden, sills and planted vegetation were successfully used against erosion induced by hydrodynamic forces from large, ocean-going ferries and cruisers with a length of 150–300 m, a width of 30–40 m, and a draught of 6–9 m (Almström et al. 2022). Other examples of living shorelines exist in the United States, in Maryland and Virginia (Public Policy Institute of California 2008). Carus et al. (2025) investigated wave attenuation by tidal reeds in the Elbe Estuary and show that they play a key role in shore stabilization, even in winter during reduced plant biomass periods their root systems still provide protection (Carus et al. 2025). These examples illustrate the wide range of small-scale NbS approaches already applied internationally. Building on this broader context, various nature-based bank protection measures have been applied in German estuaries.

In Germany, nature-based solutions for bank protection (NbS-BP), such as brushwood boxes, live willow mats, and gabion boxes (Figure 1) have been used in a significant number of locations (Schreiber et al. 2026) and can be a solution to secure estuarine river banks while providing more ecological benefits. Brushwood boxes are double timber pile rows filled with deadwood fascines and generally have a width of about 0,8 m and a height of approximately 1 m (Figure 1a). Brushwood boxes run parallel to the riverbank and protect it by reducing wave and current loads (cf. Spröer et al. 2025). Similar structures filled with bamboo sticks have proven the ability to reduce wave impact on shorelines (Shu et al. 2023). Live willow mats are made from live willow branches that are ready to sprout. They are placed on the ground and fixed in position, where they grow into living trees. (Figure 1b). Width covered by willow mats is generally 9 m and these structures have a height of about 0,5 m. They protect against erosion in two ways: underground roots increase shear strength of the soil while above-ground leaves and branches reduce impact of waves and currents. Gabion boxes are similar to brushwood boxes in dimension, however the filling between the double-pile row consists of rock-filled gabions (Figure 1c). Brushwood boxes and gabion boxes are predominantly used as indirect bank protection, aiming to be used in load-reduced areas to enhance sedimentation and growth of reeds in front of the shoreline as natural shoreline protection.

Despite existing successful examples, widespread adoption of NbS-BP seems to be hindered by mainly two factors: firstly, a lack of best practice guidance (Eisenmann and Fleischer, Martin et al. 2025) even though some technical guidelines (BAW und BfG 2025) already exist and secondly the perception that NbS-BP incur higher resource expenditure over the structure lifetime. However, no detailed cost comparison between hard-engineered bank protection, such as rock armour revetments, and NbS-BP has been carried out so far.

Figure 1: Nature-based solutions for bank protection in German estuaries, brushwood box (a), live willow mat (b), gabion box (c), and in comparison, hard-engineered bank protection, rock armour revetment (d). Source: BAW.

Economic assessment of nature-based solutions

Some cost comparisons of nature-based solutions against engineering structures have been performed, however many focus only on coastal protection and large-scale systems such as coral reefs, mangroves, and salt marshes (e.g., Narayan et al. 2016, Resilient Islands 2019). NbS are, from an economic perspective, increasingly perceived as cost-efficient alternatives to hard-engineered infrastructure. Narayan et al. (2016) showed that coastal habitats have a high potential to reduce wave heights while often being two to five times less expensive compared to engineering alternatives. Similarly, Reguero et al. (2018) compared hard engineered structures with NbS in a case study in the Gulf of Mexico and found that NbS could be among the most cost-effective options. Other studies showed that NbS can be more effective or at least as effective for flood protection compared to hard-engineered structures (Turkelboom et al. 2021, Hynes et al. 2022, Vicarelli et al. 2024) while providing higher recreational value (Hynes et al. 2022), more ecosystem service benefits and higher biodiversity values (Turkelboom et al. 2021) and carbon sequestration. This notion is echoed by Hynes et al. (2022) who show that oyster reefs can outperform engineered structures in some scenarios, however uncertainty in the cost-benefit analysis is introduced by assumptions on cost estimates, lifespan of the structure, discount rate, maintenance intervals and uncertain outcomes; uncertainties for NbS are deemed higher than for grey infrastructure. For hard-engineered infrastructure, cost data are generally more readily available due to the large number of projects constructed over the last decades and the widespread availability of bidding documents. In contrast, NbS although not new and in some cases established for decades or even centuries, remain comparatively underexplored in terms of costs, largely because few bidding documents are available and the Water and Shipping Administration (WSV) constructs many of their NbS-BP in-house without documenting costs in a detailed way. Furthermore, there is a greater uncertainty regarding ecological development and success of NbS. Another approach for shoreline protection are hybrid measures. (Huynh et al. 2024) performed a meta-analysis comparing hard, hybrid, soft, and natural costal defence options based on risk reduction, climate change mitigation, and cost-effectiveness. They show that soft measures are the most cost-effective, followed by hybrid and hard measures while all measures have a similar risk reduction effect. They claim that most studies considered in their meta-analysis have not incorporated benefits such as cultural ecosystem services, which would lead to a higher Benefit-Cost-Ratio for soft measures. Narayan et al. (2016) mention that consistent and detailed cost reporting is still lacking.

Quantification of embodied carbon dioxide emissions

Economic comparison of investment alternatives traditionally does not include quantification of carbon dioxide emissions, or embodied carbon emissions, respectively. However, due to increasing attention to climate change, global warming potential plays an important role and should be included in investment decisions. Life cycle assessment (LCA) has become the most suitable tool to estimate the potential environmental impact of products throughout their lifecycle (ISO 14040) and may as well be used to evaluate NbS (Larrey-Lassalle et al. 2022). LCA of rock armour revetments are very limited. Bakker et al. (2024) compared rock armour revetments and XblocPlus structures with respect to their embodied carbon emissions. Broekens et al. (2011) have developed a tool to account for carbon emissions for coastal construction schemes and used breakwaters as an example but performed no comparison. Although, to the authors knowledge, no comparison of embodied carbon emissions of hard-engineered and NbS bank protection exist, it is reasonable to assume that NbS emit lower carbon emissions throughout their whole life cycle due to the use of natural materials such as wood and living plants, which not only uptake carbon dioxide from the atmosphere (Rytter et al. 2015) but furthermore can be harvested locally decreasing transport distances.

Research gap – goal of this paper

While some economic analysis has been conducted for NbS, to the authors knowledge, there is i) no openly available data for nature-based solutions for bank protection (NbS-BP) such as used in estuaries made from deadwood and living plants and ii) no cost comparison of NbS-BP against harder engineered alternatives. Addressing this knowledge gap, this study collates real-world cost data for a number of NbS-BP and presents a dynamic cost assessment and cost comparison for three NbS-BP (brushwood boxes, live willow mats, and gabion boxes) and a hard-engineered rock revetment. This study aims to conceptually identify the key factors influencing economic performance based on averaged real-world data. The overall goal is to explore the long-held perception of cost disadvantage and illustrate the hydrodynamic and maintenance boundary conditions under which NbS-BP can be cost-competitive.

2 Method and data

2.1 Cost calculation and comparison

To compare the costs associated with different bank protection measures, a dynamic cost comparison calculation using the discount method approach based on DWA (2012) is carried out. This proven method allows two or more investment alternatives to be compared under consideration of all types of cost (investment, reinvestment and maintenance) over the whole reference period. Furthermore, the dynamic cost comparison considers a changing monetary value over time, i.e. future investments and maintenance cost is valued less (discounted) in the future than today. This is explained by the assumption that money declines in value over time due to opportunity costs and inflation. As a result, all future costs, such as maintenance and reinvestment, are discounted to the present year in order to achieve comparability. This approach is essential as hydraulic engineering structures often have a comparably long life time of fifty years or more and hence changing monetary value over time plays a key role in comparison.

The dynamic cost comparison utilises real-world data of the four different structures and includes averaged initial investment costs (not discounted), costs for maintenance and reinvestment (discounted). Total costs (i.e., project net present value) are calculated by creating the sum of investment cost and all discounted cost over the reference period, regarding the following formula:

$$c_{tot} = c_{inv,0} + \sum_{t=1}^{N}(c_{main,t} * DF_t + c_{reinv,t} * DF_t) \quad (1)$$

with

- c_{tot} = total cost,
- $c_{inv,0}$ = investment cost in year 0,
- $c_{main,t}$ = maintenance cost in year t,
- DF_t = discount factor in year t,
- $c_{reinv,t}$ = reinvestment cost in year t, and
- N = number of years.

The discount factor assumed depends on the timing of the costs incurred and the interest rate used, which is usually 3 %. It follows the following formula:

$$DF_t = \frac{1}{(1+r)^t} \quad (2)$$

with

- DF_t = discount factor in year t,
- r = discount rate, and
- t = target year.

2.2 Calculation of embodied carbon emissions and monetization

Cost comparison is paired with a consideration of embodied carbon emissions. Embodied carbon emissions for the rock revetment are estimated for raw material production and transport. Construction, use, and end-of-life phase is not included, as no reliable data is available. An analysis of embodied carbon emissions associated with NbS-BP is not possible for the same reason.

First, processes taking place during raw material production and transport were being identified together with necessary materials used during these processes. Then, the amount of each material was multiplied with collected specific carbon factors for the used materials, resulting in carbon emissions for each process. The sum of all carbon emissions is the total carbon emissions calculated. Data for specific carbon factors was taken from Life-Cycle-Assessment databases, such as "OekobauDat" (OekobauDat 2025) and Environmental Product Declarations (International EPD System 2021). The estimated embodied carbon emissions from raw material production and transport are then monetised using the current carbon price in Germany for 2025, currently 55 Euro per ton (BEHG 2019). In a second scenario, another carbon price of 300 Euro per ton (Matthey et al. 2024) is used, which describes the overall internalised social costs of embodied carbon emissions. Monetised values of carbon emissions are compared to calculated total costs.

2.3 Comparability

This study compares different types of bank protection that vary in material, width, and height. Each type of bank protection has their specific area of application depending among others, on bank slope, available space and hydrodynamic loads. However, even though each construction type has their specific use case, there is some overlap where all types of bank protection presented here could be applied. Despite their structural differences, all protection types serve the same primary function of stabilizing the estuarine bank and preventing erosion. Although the individual designs do not provide identical hydraulic resistance, we assume they achieve the same protective outcome (i.e., embankment is stabilised). This justifies a comparison of these different type of structures on the basis of outcome equivalency. This study compares the different construction methods only at a conceptual level and shows the theoretical financial potential of each method. Assumptions made here may not always apply when planning and installing estuarine bank protection. In any case, a cost analysis must be carried out for each specific site and construction method, taking into account the prevailing boundary conditions. These can vary greatly from place to place.

In Germany´s estuarine waterways, applied bank protection measures include rock armour revetments (often in combination with groynes), sheet pile walls, and NbS, such as brushwood boxes, live willow mats and gabion boxes. Besides these bank protection measures, some bank sections do not require such measures and have a natural bank consisting of soil, sand, and vegetation. Most commonly, estuarine banks are secured using rock armour revetments, while some sections remain unsecured and natural. A few sections are secured using NbS-BP. The present study focuses on a selected subset of these measures in order to ensure comparability within the available dataset. This necessarily restricts the scope of the analysis but allows for a consistent conceptual comparison.

Further, it is implicitly assumed that all alternatives provide equal benefits since benefits are not considered here. To compare benefits of different construction types, a cost-benefit analysis (CBA) or a multi-criteria analysis (MCA) is needed.

2.4 Data

Investment costs are based on tender documents and contracts provided by the Federal Waterway and Shipping Authority (WSV) for construction projects in German estuarine waterways from the past ten years. Only cost data of executed projects were used. Two projects of rock armour revetments were provided with full cost data including division into material, labour and machine costs. For the brushwood boxes, in total five projects from different rivers were provided with detailed data. For live willow mats costs from five projects are available with no division into material, labour and machine cost. For gabion boxes, costs from two projects are available, however costs are only estimated. The used investment costs for each construction type are averaged values based on the provided real-world data, representing typical costs. The following table gives an overview of all projects of which data was used in this study.

In order to use realistic maintenance intervals and costs for maintenance, adequate values are based on several years of observation and documentation (BAW und BfG 2022) as well as on experience from the WSV. An average value of maintenance interval was derived from those observations and additionally a range of intervals was set to represent high and low maintenance in a sensitivity analysis. Values for structure lifetime were derived in the same way. For maintenance costs, it was chosen to represent them as a certain percentage of investment costs.

To discount future reinvestments and maintenance cost, a discount rate (%) needs to be chosen. Here, an average discount rate of 3 % per year was chosen, as suggested by DWA (2012). Additionally, a few other discount rates were tested to investigate influence of this parameter, namely 1, 4, and 5 %.

Table 1: Overview of all projects used in this study.

Bank protection type	Estuary	Type of waterway	Location coordinates (WGS 84)	Year of construction
Brushwood box	Elbe	Main river, large cargo-vessels, behind a training dam	53.5625, 9.6804	1995
Brushwood box	Stör (tributary of Elbe)	Tributary of Elbe, 20 m wide, recreational boat traffic	53.9397, 9.6706	2023
Brushwood box	Elbe	Main river, shipping traffic bulk carriers	53.4369, 10.1023	2025
Brushwood box	Weser	Main river, in a bay, shipping traffic	53.2174, 8.4990	2023
Brushwood box	Weser	Main river, in a bay, shipping traffic	53.2194, 8.4959	2025
Gabion box	Elbe	Main river, large cargo-vessels	53.8462, 9.0395	2015
Gabion box	Elbe	Main river, large cargo-vessels	53.8578, 9.2697	2025/2026
Live willow mats	Elbe	Side channel of main river	53.5582, 9.6749	2017
Live willow mats	Elbe	Main river, large-cargo vessels, behind a training dam	53.5621, 9.6821	2019
Live willow mats	Elbe	Main river, large-cargo vessels, behind a training dam	53.5622, 9.6807	2023
Live willow mats	Elbe	Main river, large-cargo vessels, behind a training dam	53.5621, 9.6831	2024
Rock armour revetment	Weser	Main river, shipping traffic	53.1578, 8.6284	2017
Rock armour revetment	Stör (tributary of Elbe)	Tributary of Elbe, 20 m wide, recreational boating traffic	53.9273, 9.6333	2024

2.5 Scenarios

In order to represent real-life conditions of the four compared bank protection types, basic scenarios for each of the four construction types are developed characterised by average investment costs, maintenance intervals and lifetimes. Based on these basic scenarios, the net present value (total cost) of these different construction types is calculated as described in chapter 2.1 and they were compared to each other over a chosen lifetime of 50 years. The structures are compared under the assumption of outcome equivalency, i.e. all structures are suitable for the stabilization of the shoreline under the predominant loading conditions. The underlying assumptions of the basic scenarios are summarised in Table 2.

Table 2: Overview of basic scenarios for dynamic cost comparison over reference period of 50 years.

Construction type	Maintenance interval [y]	Lifetime [y]	Interest rate [%]
Rock armour revetment	25	50	3
Brushwood box	5	10	3
Live willow mat	4	25	3
Gabion box	5	15	3

In order to check the significance of individual scenario assumptions, a sensitivity analysis using different sensitivity scenarios is carried out to determine the influence of changed maintenance intervals, structure lifetimes and applied interest rates (see Table 3). This process is especially valuable for NbS-BP as the lifetime and maintenance interval can be quite variable depending on location and loads to which they are exposed. Interest rate range is chosen based on DWA (2012). Values were selected based on prior experience, assuming conditions representative of real-world scenarios.

Table 3: Variation of values used in sensitivity analysis of cost comparison; bold numbers were varied in the scenarios.

Construction type	Maintenance interval [y]	Lifetime [y]	Interest rate [%]
Rock armour revetments	25	50	**1, 4, and 5**
Brushwood box	5	10	**1, 4, and 5**
	3	10	3
	5	**15**	3
	7	**15**	3
Live willow mat	4	25	**1, 4, and 5**
	2	25	3
	6	25	3
	4	**50**	3
Gabion box	5	15	**1, 4, and 5**
	5	**20**	3
	10	**20**	3

3 Results

3.1 Investment cost

Investment costs per meter of all construction types were calculated based on real-world cost data (cf. Section 2.2), the mean value is quoted here. The mean cost per meter of brushwood box is 910 €. For live willow mats cost per meter is 1170 € or 130 €/m² (price per area because it is an area-based structure). For gabion boxes, the average investment cost is 1000 € per meter. Compared to NbS-BP, rock armour revetments show higher initial investment costs: investment costs per meter are 2000–2500 €. In comparison, Aerts (2018) collected costs for rip-rap based on Public Policy Institute of California (2016) and estimated costs of $292–780 (330–870 €) per meter; these values are taken from 2016 and have increased since then. In the UK, rock armour revetments costs range from 650–2850 £

(470–2100 €) per meter according to the Environment Agency (Environment Agency UK 2015), while Gonyo et al. (2023) reported mean prices of $1400–4900 (1500–5200 €) per meter, making investment costs high.

3.2 Maintenance cost

Maintenance cost depends on level of degradation and resources required to repair a damaged structure. As brushwood boxes and live willow mats are almost completely made of natural materials, they naturally degrade and therefore need recurring replacement. For all construction types, maintenance intervals depend on exposure to loads from waves and currents, occurring storm events and quality and longevity of used material. Monitoring has shown that, on average, brushwood boxes need maintenance every three to seven years (on average every five years). The maintenance work for brushwood boxes includes restacking fascine material. Typical damages of brushwood boxes can be seen in Figure 2. Live willow mats need regular maintenance for vegetation management and to repair storm damages. On average, live willow mats need maintenance every four years. Some typical cutting works and replanting of willow stakes can be seen in Figure 3. Gabion boxes do not require such high maintenance intervals. The stone fill lasts for a long time, however wooden piles might need to be replaced (see Figure 4 for condition of gabion boxes). Therefore, maintenance interval for gabion boxes is five years but with comparably low costs. Rock armour revetments need very little maintenance. However, due to very high loads and storm surges, damages may appear, as seen in Figure 5. Therefore, a maintenance interval of 25 years is assumed for rock armour revetments.

As no data on maintenance costs is available, plausible assumptions are made. Based on the detailed construction cost for one brushwood box, including a breakdown of labour, material and equipment cost, specific values for the cost of maintenance for brushwood boxes can be derived. It is assumed that approximately half of the total labour time is spent on driving piles into the ground, while the remaining half is associated with adding the brushwood filling. As maintenance activities typically involve only the replacement of filling material and do not include pile installation, 50 % of the original labour costs are applied for maintenance. Similarly, for material costs, only the brushwood filling and wire components are considered, as the piles are generally expected to remain in good condition and do not require replacement. For brushwood boxes, typical maintenance work includes restacking of filling material. For the live willow mats, typical maintenance work includes cutting and potentially replanting willow stakes. Since no specific cost data for the maintenance of live willow mats is available, it is assumed that maintenance costs are 15 % of the investment costs. A similar approach is used for the gabion boxes, where maintenance costs is five percent of the initial investment costs. Maintenance costs for rock armour revetments are estimated at 15 %. Using a certain percentage of investment costs to calculate maintenance costs is common practice in early planning stages. Such procedure can be found in the Rock Manual (CIRIA et al. 2007), where maintenance cost is described as the multiplication of the cost of an item with the probability of occurrence for damage. Thereby, maintenance costs for specific items can be obtained.

The total cost calculation is carried out for a reference period of 50 years. However, some structures need to be replaced before the end of the reference period due to degradation processes. This is the case for all NbS-BP. It is assumed that brushwood boxes need to be replaced after a lifetime of 10 years, live willow mats after 25 years and gabion boxes after 15 years. Rock armour revetments have a lifetime of at least 50 years and need no replacement. The cost for building a completely new construction is calculated using the initial investment costs and called reinvestment costs.

Figure 2: Typical damages of brushwood boxes: Degradation of filling. Source: BAW.

Figure 3: Typical maintenance work for live willow mats. Left: Cutting of branches. Right: Planting of willow stakes after storm event. Source: WSV.

Figure 4: Condition of gabion boxes after ten years. Small damages to wooden piles. Source: BAW.

Figure 5: Damage to a rock armour revetment: Erosion of armour stones. Source: BAW.

3.3 Total cost over reference period

The total cost over the reference period of 50 years for each construction type origin from investment, maintenance and reinvestment costs. To calculate the total costs, investment, reinvestment and maintenance costs were summed up and discounted according to the described method. Total costs for each construction type are summarised in Table 4.

Table 4: Total costs of all construction types over the reference period of 50 years based on current year (numbers in brackets represent cost range based on scenarios).

Construction type	Maintenance interval [y]	Reinvestment interval [y]	Estimated total costs per meter [€]
Brushwood box	5	10	4000 (2900–5100)
Live willow mat	4	25	2800 (2300–3900)
Gabion box	5	15	2700 (1800–3800)
Rock armour revetment	25	50	2500 (2400–2600)

Table 4 shows the differences in maintenance interval, reinvestment interval and total costs for all construction types. Estimated total costs are represented for the basic scenario and the numbers in brackets describe range of total costs calculated on basis of the different scenarios included in the sensitivity analysis. While rock armour revetments showed the greatest investment costs, they do not have the highest total costs of all construction types. In fact, rock armour revetments are less expensive compared to the nature-based solutions presented here if all maintenance and reinvestment costs are included over a period of 50 years. Gabion boxes and live willow mats are 5–10 % more expensive; under certain conditions, for example if lower maintenance is required, nature-based solutions can hence become cost-competitive.

3.4 Estimated embodied carbon emissions or rock armour revetments

To estimate carbon dioxide emissions of rock armour revetments, two life cycle phases are considered: production of raw materials and transport of materials. For the life cycle phase production of raw materials, rock armour, sand and gravel as filter and geotextile are included. For 100 m of rock armour revetment with an embankment slope of 1:3, 600 tons of armour rocks, 710 tons of sand and gravel and 950 m² of geotextile is assumed. It is considered that armour rocks are produced in Norway. Sand and gravel are sourced in Northern Germany, as well as the geotextile. Life cycle phase transport includes transportation of rock armour via cargo ship from Norway (1200 km), inland ship (100 km) and truck to and from the ships (100 km). It is assumed that sand and gravel are being transported by inland ship (100 km). For 1 m of rock armour revetment, an estimated amount of around 300 kg per meter of carbon dioxide is released during raw material extraction and transportation.

This amount of embodied carbon emissions can be monetised using the current carbon price in Germany of 55 € per ton (cf. Section 2.1). By doing so, an additional amount of 16,5 € per meter is be added to the calculated total costs of a rock armour revetment (which is about 2500 € per meter, see Table 3). Using the higher carbon price of 300 € per ton (cf. Section 2.1), an additional cost of 90 € per meter would be added to the construction costs. In other words, using an additional carbon price of 55 € per ton would lead to an increase in total cost of about 0,7 % per meter, and using a carbon price of 300 € per ton would lead to an increase of 3,6 % per meter; both values are comparably low and the influence of embodied carbon on the total cost is insignificant. For the carbon price to have an impact, the total costs of the least expensive nature-based solution and rock revetments in addition with carbon price needs to be at least equal. By comparing the least expensive option (gabion box for 2700 €/m) with rock revetments, an additional cost of 200 € is necessary. This added amount would be achieved with a carbon price of at least 660 € per ton of carbon dioxide emissions, which is twelve times greater than the current carbon price.

The three life cycle phases construction, use phase and decommissioning are not included in this study, as they are expected to generate less carbon dioxide emissions compared to the other two phases. During use phase, only maintenance will create emissions, and during use and decommissioning phase, it is mostly the use of construction machinery that will determine carbon dioxide emissions. Also, carbon dioxide emissions for the NbS-BP could not be reliably estimated due to lack of data. However, due to the use of natural and local materials for NbS-BP, which are partly produced on self-owned sites adjacent to the river sections, low emissions from production and transportation are expected. During construction and decommissioning, less or at maximum the same amount of machine use would appear.

4 Discussion

Differences in cost structure between rock armour revetments and NbS-BP

NbS-BP and rock armour revetments generally show very different cost structures. While rock armour revetments are associated with high investment costs, they incur low maintenance costs throughout their lifetime. In turn, NbS-BP start with low investment costs but recurring maintenance costs, leading to higher or at least similar total costs over the whole reference period. Moreover, results show the high sensitivity of total costs towards maintenance intervals and life times. Therefore, these parameters offer optimization potential in order to improve total cost performance of NbS-BP. Most sensitive parameters are maintenance interval and chosen discount rate, which may increase cost by up to 23–46 % (cf. Section 3.3). Total costs of NbS-BP can differ substantially depending on lifetime and maintenance intervals which is a result of degradation due to loads from waves and currents. NbS-BP can be less expensive than hard-engineered constructions if maintenance intervals can be extended and lifetime is increased, as applicable e.g., when they are located in a sheltered area with low wave and current intensity. As such, there is a strong incentive to make NbS-BP more durable, leading to significant cost savings. Further research will be carried out in this area over the next years, including field trials.

Uncertainties relating to real-world performance and to data availability

In this study, NbS-BP and rock armour revetments were assigned a lifetime and maintenance interval for the basic scenario and the scenarios tested in the sensitivity analysis and it was assumed that these intervals remain constant throughout the reference period. However, in reality, lifetime and maintenance intervals can vary considerably depending on the location-specific setting. A set of maintenance intervals and lifetime was included in the sensitivity analysis but without varying these parameters within the reference period. Moreover, use cases for NbS-BP are wider in reality than shown in this comparison. For example, brushwood boxes can be used as indirect bank protection placed in the nearshore area some distance away from the embankment. With this setup, they attenuate waves, encourage sedimentation and may create a habitat suitable for reeds and other plants along the shoreline, serving as initial measure to create a natural shoreline protection. In the best-case scenario, NbS-BP requires no further maintenance or reinvestment, as bank protection is ensured by naturally developing vegetation following a single initial intervention.

As Aerts (2018) mentioned, information regarding the cost of measures is often hidden in non-peer-reviewed literature. Here, the cost data is derived from various construction projects over the past decade, it includes a degree of uncertainty due to price changes over time. In several cases, cost data documentation only allowed rough estimates. While some cost data provided is very detailed, including division into labour, material and machine costs, other data is only a combined value of investment costs. Although data was sourced from a total of 13 different projects, more and detailed data would have been advantageous for this study. Values presented here are representative, but may not apply to other construction projects due to local boundary conditions and uncertainties in cost estimations (Aerts 2018, Hynes et al. 2022). The projects listed here are subject to broadly similar boundary conditions with respect to wave and current exposure, tidal range, and salinity. The maximum wave height at all sites is below 1 m, while the maximum current velocity is less than 2 m/s. The tidal range varies between approximately 3.5 and 3.8 m across all locations. Salinity differs slightly depending on the position within the estuary and ranges between 1 and 25 PSU. However, salinity only affects the wire material used, and its service life can be extended through the use of corrosion-resistant wire. Temperature is not considered a relevant factor, as it is approximately the same at all sites.

NbS-BP and rock revetments were only compared at locations where both solutions could feasibly be constructed under the given boundary conditions. In general, each type of structure has its own specific field of application; for example, properly designed rock revetments can withstand very high hydraulic loads. Nevertheless, there is an overlap range in which both NbS-BP and light rock revetments can be applied. This overlap range is the focus of the present study. The sites listed in the Table 1 above indicate that NbS-BP structures are often implemented at moderately sheltered locations that are not exposed to extreme hydraulic loads. For the selection of a specific design solution, the local boundary conditions must always be considered, including factors such as shoreline geometry and the distance to the navigation channel.

Despite the mentioned uncertainties, the authors believe that the key trends and outcomes described in this study remain robust.

In order to include embodied carbon emissions across construction, use, and end-of-life phases, emissions associated with these stages should be systematically recorded in future projects. During the construction phase, all necessary materials and equipment should be documented. Most likely, the majority of carbon emissions during construction origin from fuel consumption by machinery, such as ships and excavators. Therefore, fuel use and operating hours should be recorded wherever possible. The use of standardised data collection templates could support consistent data acquisition. During the use phase, emissions may occur as a result of maintenance activities. Accordingly, the frequency of maintenance, as well as the type and quantity of materials and equipment used, should be tracked over time. The same systematic approach should be applied to the end-of-life phase, including demolition processes, material disposal, and potential recycling or reuse pathways. To improve data availability and comparability, future projects could adopt standardised reporting frameworks and require the documentation of carbon-relevant data within tendering and procurement processes. By using the collected data, material quantities and energy use can be combined with emission factors to estimate total carbon emissions.

Embodied carbon emissions and inclusion of ecosystem services

The method used focusses on costs only. In fact, this method implicitly assumes equal benefits across all alternatives which does not necessarily reflect reality. Hard structures generally withstand higher wave and current forces while NbS-BP provide more ecosystem services. However, here, in order to compare these different bank protection systems, the comparison is based on outcome equivalency, i.e., all approaches lead to a secured shoreline. Beyond that NbS-BP provide broader, though often less readily quantifiable, ecosystem benefits and services (e.g., Jordan and Fröhle 2022, Perricone et al. 2023). As a first step towards full cost-benefit comparison, which is necessary, embodied carbon emissions are included in this cost analysis. However, it was shown that monetised values of embodied carbon emissions are low compared to estimated total costs and do not influence the cost comparison significantly. Even using the higher carbon price of 300 €/ton, it did not significantly influence the main result.

The cost comparison serves as a basis to build upon and include other ecosystem services. Ecosystem services include regulating (e.g., climate regulation), provisioning (e.g., raw materials), cultural (e.g., recreation), and supporting (e.g., nutrient cycling) services (Millennium Ecosystem Assessment 2005). While methods to quantify ecosystem services exist, prevalence of methodological gaps, a lack of standardization of procedures and a methodological focus on large-scale areas (Grêt-Regamey et al. 2014, Grizzetti et al. 2019) makes applicability to individual bank protection challenging. However, knowledge on quantification of ecosystem services is growing, extended to coastal and marine habitats and applied at smaller scales (e.g., Schernewski et al. 2022), making it more applicable for the setting of NbS-BP. Several studies (Huynh et al. 2024, Turkelboom et al. 2021) comparing NbS and hard-engineered structures have mentioned that the inclusion of ecosystem services is necessary. NbS offer a far wider range of ecosystem services than hard-engineered structures – including enhanced biodiversity, habitat provision, water purification, and carbon sequestration. As a result, cost–benefit analyses are generally expected to favour NbS.

5 Conclusions

In this study, the costs of nature-based solutions for bank protection (NbS-BP) currently used in German estuaries are compared to hard-engineered rock armour revetments using a dynamic cost comparison based on real-world cost data. The assessment included different scenarios with varying lifetime, maintenance intervals, and interest rates over a reference period of fifty years. Results show that NbS-BP generally have lower investment costs compared to rock armour revetments but require higher maintenance which results in overall similar or higher costs. NbS-BP can be less expensive if maintenance intervals and/or structure lifetime is extended, underscoring the importance of resilient design. The addition of costs for embodied carbon emissions is negligible as these costs amount to less than five percent of total estimated costs of rock armour revetments using current the current carbon price in Germany. In the future, the cost data basis should be improved, regularly updated, and expanded to cover a wider range of structure types, e.g. via data from new construction projects. This involves conducting regular inquiries with local authorities regarding scheduled maintenance and performing site inspections of newly completed structures.

A further step toward a holistic cost-benefit analysis is the integration of ecosystem services, which are crucial for capturing the non-market benefits of nature-based embankment protection. This study establishes a foundation for such integration.

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