

Nature-Based Bank Protection in Practice: Experiences from German Estuarine Waterways

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Summary

The banks of tidally influenced federal waterways are subject to competing land- and water-based uses. Consequently, banks are often reinforced with riprap revetments to protect them and adjacent tidal marshes from ship-induced erosion, which results in the loss and fragmentation of marsh habitats. Nature-based solutions for bank protection (NbS-BP) have the potential to combine the technical stabilization requirements with ecological functions. This article presents application-oriented recommendations for the most commonly implemented measure types, derived from case study evaluations and established theoretical understanding.

Results demonstrate that NbS-BP – ranging from living and dead wood measures to the structural improvement of riprap revetments – are already being implemented along estuarine waterways in Germany. However, under substantial ship-induced bank stresses, measures involving dead wood or vegetation require specialized expertise, practical know-how, and conceptual innovation to ensure reliable performance. In such contexts, technical interventions may be necessary to modify prevailing boundary conditions in a space-efficient manner, enabling ecological stabilization functions and ensuring sustainable erosion protection. At highly exposed sites, a complete replacement of conventional revetments is often not feasible due to high maintenance requirements or unacceptable risks. In these cases, existing riprap structures can be enhanced with structural modifications that create small ecological stepping stones by providing microhabitats for site-native plants and animals. While these are low-maintenance options, the ecological value generally remains lower than that of living or dead wood NbS-BP measures. Overall, the results highlight that NbS-BP can be applied across a wide range of estuarine settings, yet their development and performance remain inherently site-specific and associated with higher uncertainty than conventional armouring. Therefore, measure types must be selected and adapted to prevailing local conditions to minimize uncertainties related to material durability and long-term functionality, particularly amid resource constraints under current shortages of specialized expertise.

Keywords

nature-based solutions, bank protection, waterways, estuary, case studies, erosion control, ecological engineering



Zusammenfassung

Die Ufer der gezeitenbeeinflussten Bundeswasserstraßen sind unterschiedlichen land- und wasserseitigen Nutzungen ausgesetzt. Infolgedessen werden die Ufer häufig mit Schüttsteindeckwerken gesichert, um Ufer und Vorländer vor der schiffabtragsinduzierten Erosion zu schützen. Dies führt zum Verlust und zur Einschränkung der ästuartypischen Uferhabitate. Naturbasierte Lösungen zur Ufersicherung (NbS-BP) haben das Potenzial, die technischen Anforderungen der Ufersicherung mit ökologischen Funktionen zu verbinden. Dieser Artikel präsentiert anwendungsorientierte Empfehlungen für die am häufigsten umgesetzten Maßnahmentypen, die aus der Auswertung von Fallstudien sowie aus etabliertem theoretischem Wissen abgeleitet wurden.

Maßnahmen, die bereits an den gezeitenbeeinflussten Wasserstraßen in Deutschland angewendet werden, umfassen dabei Totholz- und Lebendbaummaßnahmen sowie Potenziale für die Schaffung ökologischer Trittsteine in und hinter Schüttsteindeckwerken. Aufgrund der oft hohen schiffsinduzierten Uferbelastungen erfordern Maßnahmen mit Totholz oder Pflanzen spezifische Fachkompetenz, praktische Erfahrung und konzeptionellen Einfallsreichtum. Ziel ist es, durch platzsparend eingesetzte technische Maßnahmen die vorherrschenden Randbedingungen so zu verändern, dass auch ökologische Regulierungsfunktionen wirken können und somit das Ufer nachhaltig vor Erosion schützen. An stark exponierten Standorten ist ein vollständiger Ersatz konventioneller Deckwerke durch NbS-BP aufgrund von hohen Unterhaltungskosten oder nicht vertretbarer Risiken häufig nicht realisierbar. In diesen Fällen können bestehende Steinschüttungen mit dem Potenzial kleiner ökologischer Trittsteine ausgestattet werden, um Mikrohabitate für standortheimische Pflanzen und Tiere zu schaffen. Obwohl es sich hierbei um unterhaltungsarme Optionen handelt, bleibt ihr ökologischer Wert in der Regel geringer als der von Lebendbau- oder Totholzmaßnahmen. Insgesamt zeigen die Ergebnisse, dass NbS-BP in einem breiten Spektrum ästuariner Randbedingungen angewendet werden können; ihre Entwicklung und Leistungsfähigkeit bleiben jedoch standortspezifisch und sind mit höheren Unsicherheiten verbunden als konventionelle Ufersicherungen. Daher müssen Maßnahmentypen sorgfältig ausgewählt und an die jeweiligen lokalen Bedingungen angepasst werden, um die Unsicherheiten hinsichtlich Materialbeständigkeit und langfristiger Leistungsfähigkeit in Zeiten des Fachkräftemangels zu minimieren.

Schlagwörter

Naturbasierte Lösungen, Ufersicherung, Wasserstraßen, Ästuar, Fallbeispiele, Erosionsschutz, Ingenieurbiologie

1 Introduction

As major ways of transportation, estuarine waterways in Germany are subject to high utilisation pressure (Federal Ministry of Transport 2016, Schuchardt et al. 1999, Steege et al. 2022). To allow the navigation of large container vessels, the inner estuaries have been deepened and widened, altering the hydrodynamic characteristics of the estuaries (Schuchardt et al. 1999, Schuchardt et al. 2007). In addition, the construction of dikes has cut off foreland areas from the waterbody to allow agricultural, urban or industrial use of the areas (Schmidt-Wygash and Heuner 2018; Schuchardt et al. 1999). This limits the available space for the ecologically valuable riparian ecosystems (Attrill et al. 1999, Schmidt-Wygash and Heuner 2018, Schuchardt et al. 1999, Schuchardt et al. 2007). The banks of the estuarine waterways are caught between these competing uses from the land- and waterward side.

Regular tidal fluctuations in water level and tidal currents have naturally always shaped estuarine river banks. Due to the man-made alteration in hydrodynamic characteristics and in combination with waves and currents generated by large seagoing vessels, the associated loads increased the hydrodynamic stress on these banks (Dempwolff et al. 2022, Duró et al. 2020, Melling et al. 2021, Muscalus and Haas 2022, Seemann and Goseberg 2025). Consequently, the banks of estuarine waterways are often reinforced with riprap revetments to protect banks against erosion (Dugan et al. 2017, Schmetterling et al. 2001). While these shoreline armouring methods provide reliable protection, they also lead to a loss of typical estuarine riparian habitats (Schuchardt et al. 1999) by lowering biodiversity and degrading habitat functions (Gittman et al. 2016b, Kornis et al. 2017) as well as disrupting the connection between terrestrial and aquatic habitats (Morley et al. 2012). From an ecological point of view, banks that are allowed to develop freely permitting natural processes such as erosion and succession are preferable (Bouma et al. 2014). Nature-based solutions for bank protection (NbS-BP) offer the key benefit of integrating the technical requirements of bank protection with ecological functions through the use of plants or natural materials, such as dead wood (Dunlop et al. 2023, Hacker and Johannsen 2012, Moraes et al. 2022). Although these solutions cannot fully substitute for the ecological benefits of natural development of river banks – including erosion – (Bouma et al. 2014, Florsheim et al. 2008, Janssen et al. 2019, Morris et al. 2019), NbS-BP are alternatives to hard engineered protection measures when bank protection is unavoidable (DWA-M 519). Unlike riprap or other hard bank protection measures, NbS-BP can enhance the provision of ecosystem services (Janssen et al. 2019, Symmank et al. 2020). The need to take environmental concerns into account when maintaining riverbanks is supported by national and EU-legislation such as the EU Water Framework Directive, which has been transposed into national law in Germany. The German Waterways and Shipping Administration must therefore support the objectives of the Water Framework Directive in maintenance and expansion of waterways (§8 (1) Federal Waterways Act (Bundeswasserstraßengesetz)). One element to support the implementation of the Water Framework Directive is the use of NbS-BP. This paper provides guidance on the successful design and implementation for NbS-BP in tidal waterways; it focusses on nature-based solutions for banks that need to be protected against erosion under the boundary conditions present in estuarine waterways. Drawing on practical experience from implemented projects, this paper bridges practice and science by translating observed real-world performance into best-practice recommendations informed by established theory.

In the tidal environment, many studies on nature-based solutions focus on the creation or restoration of natural habitats for coastal protection, such as salt marshes, mangroves or shellfish reefs (Baptist et al. 2021, Borsje et al. 2017, Cheong et al. 2013, Jordan and Fröhle 2022, Morris et al. 2018, Morris et al. 2019, Paxton et al. 2023, Smith et al. 2020, van Coppenolle et al. 2018, van der Meulen et al. 2022). These habitats are typical for open coasts, tropical or subtropical zones or wide intertidal zones and therefore not readily transferable to estuarine waterways in Germany. The hydrodynamic loads acting on riverbanks in heavily modified and trafficked waterways differ fundamentally from those on open coasts. While coastlines are typically influenced by occasional extreme storm-driven waves, banks along estuarine waterways are subject to continuous, and often strong, tide-induced changes in water level and currents in combination with frequent, ship-induced waves and currents. This results in ship-induced loads being a highly relevant load bank protection

measures have to withstand (Dempwolff et al. 2022, Herbert et al. 2018, Mao and Chen 2020, Melling et al. 2021, Melling et al. 2025, Safak et al. 2020). Studies on specific nature-based solutions for the protection of banks under the demanding conditions of confined estuarine waterways are limited (Everett et al. 2022, Safak et al. 2020). Regarding ship-induced loads, many studies on NbS-BP showed their efficiency to reduce short-period waves such as secondary ship waves or wakes from smaller boats or even just wind waves (Almström et al. 2022, Bilkovic et al. 2017, Ellis et al. 2002, Herbert et al. 2018, Manis et al. 2015, Safak et al. 2020). Studies often do not specifically differentiate between the primary and secondary ship wave system or do not discuss the high energy long period ship waves within the context of nature-based solutions in waterways. This may be due to the fact that NbS are preferably constructed in sheltered areas without high ship wave impact. Some nature-based bank protection designs, for example single row pile walls, have demonstrated limited effectiveness in attenuating primary ship waves (De Roo and Troch 2010). However, other NbS-BP were able to withstand also higher energy waves produced by large vessels, shown in field studies with willow mattresses (Fleischer and Soyeaux 2014).

While many case studies exist nationally and internationally, the widespread and regular use of NbS-BP remains challenging. A lack of technical guidance on implementation and dimensioning for the estuarine waterway environment is hampering more widespread adoption (Fleischer et al. 2006, O'Donnell 2017, Smith et al. 2020, Twomey et al. 2025). Existing guidelines on nature-based solutions, and similarly termed concepts, often remain largely conceptual and provide qualitative design principles to consider when planning nature-based solutions (Bridges et al. 2021, World Bank 2017). Guidelines that exist in Germany are valid for inland waterways but do not fully address the specifics of the tidal environment (DWA-M 519). Information provided is not always directly applicable to the estuarine setting; e. g. boundary conditions for willow growth differ between inland areas and tidal zones influenced by salinity and water level fluctuations. Additionally, uncertainties regarding the longevity and effectiveness under the given boundary conditions of NbS-BP as well as their cost-efficiency especially with regard to potentially higher maintenance costs exist (Eltzsch et al. 2026). Experience with NbS-BP to date indicates that planning and dimensioning are unlikely to achieve the same level of reliability as construction measures based on hard, technical materials. This results mainly from the heterogeneity of material properties, the greater number of influencing factors, and the dynamic evolution of riverbank protection, which can even be desirable.

2 Methods

This study applies a mixed-methods practice-based synthesis approach, integrating a collection of implemented NbS bank protection measures, practitioner-derived qualitative knowledge, targeted site monitoring and literature review.

Evaluation of implemented NbS-BP

To document effective NbS-BP types for estuarine waterways, the Federal Institute of Waterways Engineering and Research (BAW) and the Federal Institute of Hydrology (BfG) have compiled a collection of over 70 existing measures along the major estuaries in Northern Germany – Elbe, Weser, and Ems – as well as their tributaries (BAW and BfG 2026b). Measures were selected if they (i) occurred in tidal waterways, (ii) targeted bank erosion

control, (iii) featured nature-based or hybrid design elements, and (iv) provided adequate documentation of design and performance. The data collected for each measure included the location, year of implementation, contact person, materials, description of the construction and development of the measure and an approximation of the local boundary conditions, for example, to characterize the nature of the water body by specifying the tidal range or number of annual ship passages.

Practical know-how

Since 2019, practitioner expertise has been gathered through NbS-BP workshops with representatives from the Waterway and Shipping Administration's regional offices on the Weser, Elbe, Ems and Eider alongside site visits and technical discussions with design, construction, and maintenance specialists. Data from questionnaires, workshop notes and field exchanges were analysed to distil common themes in implementation, performance, maintenance needs and operational hurdles.

Targeted monitoring of selected case studies

To complement practitioner-derived insights with quantitative data, standardized monitoring has been conducted by BAW at several newly constructed NbS-BP sites. Monitoring consists of annual site visits documenting material condition, structural integrity and overall development of the protection measure and the surrounding area. Additionally, hydrodynamic loads have been measured at one existing NbS-BP in the Weser estuary by the BAW, with further measurements currently ongoing at another site at the Elbe to quantify hydrodynamic forcing acting on NbS-BP measures. Drone-derived aerial photos and digital surface models from the BfG and BAW enable the detection of changes in morphodynamics and vegetation dynamics before and after the implementation of indirect bank measures.

Translation into practical guidelines

The above-mentioned data were consolidated into standardized fact sheets to support the practical planning, design and implementation of NbS-BP. The fact sheets summarize e. g. suitable areas of application, ecological benefits, materials and their specifications and dimensions, construction and maintenance guidance and installation steps. Existing NbS-BP measures were used to distil recurring structure types and practical design considerations. Fact sheets were developed initially for the most commonly implemented dead wood measures, including brushwood boxes for direct and indirect bank protection (BAW and BfG 2025b, 2025d) as well as brushwood mattresses (BAW and BfG 2025c) and willow mattresses for direct bank protection (BAW and BfG 2026a). Fact sheets for additional NbS types are planned for future work. Additionally, a decision support tool especially targeted towards new and inexperienced practitioners in the field of NbS-BP was developed aiming to facilitate decision-making for bank protection and highlight ways in which NbS-BP can be used in a variety of ways under a wide range of boundary conditions (BAW and BfG 2025a).

All information derived from these sources was synthesised to identify the most commonly applied types of NbS-BP in estuarine waterways. The resulting typology is presented in the following section, providing a detailed overview that integrates insights from literature, practitioner knowledge, available site monitoring data and implemented case studies. Beyond supporting the typology, this synthesis also provided the evidence base for the

development of practitioner-oriented fact sheets and a decision-support tool by BAW and BfG, translating recurring design principles and implementation experience into actionable best-practice guidance for the planning, design and implementation of NbS bank protection measures in estuarine contexts.

3 Types of nature-based solutions for bank protection in German estuaries

Despite the challenging boundary conditions, bank protections using natural materials or plants have been implemented along German waterways for centuries (Klein 1965) and several types of these approaches have a proven track record in estuarine waterways (BAW and BfG 2026b). The collection of existing NbS-BP in German estuarine waterways shows a variety of different measures, that are divided into dead wood measures, living measures and measures for the structural improvement of revetments (Figure 1). Dead wood and living measures can provide bank protection either directly or indirectly. Direct bank protection is constructed at the erosion scarp or placed continuously over larger areas on the embankment. It provides immediate resistance to hydrodynamic loads and therefore serves as both direct erosion protection and structural support by stabilizing the bank edge and preventing collapse. When applied extensively over larger areas, it also protects the embankment against surface erosion. In estuarine waterways, direct bank protection is required wherever a shoreline migration cannot be permitted, for example due to adjacent infrastructure or insufficient distance to a dike. Wherever space is available, indirect solutions are generally preferred. Their benefit is the integration of ecological functions for sustainable bank protection. Indirect solutions are placed some distance in front of the shoreline (off-bank) to reduce incident loading while allowing dynamic development of the river bank to a limited extent. These off-bank structures promote sediment deposition behind the structure which serves to reduce erosion (BAW and BfG 2025d). Sheltered conditions allow the establishment and growth of plant species that would otherwise be unable to persist under the site's naturally higher exposure conditions (Schoutens et al. 2020). These plants act as key ecosystem engineers in vegetation stands, effectively reducing currents, damping waves, and thereby trapping sediment among other ecological functions (Heuner 2016). The following section lists various structural dead wood and living measures, that can contribute both directly and indirectly to bank protection. Additionally, implemented measures featuring structural improvements of revetments are described for areas where dead wood and living constructions are not feasible.

			
Estuary	Dead wood measure	Living measure	Structural improvement
Elbe	15	3	11
Weser	37	3	2
Ems	1	-	-
% of total existing measures	74 %	8 %	18 %

Figure 1: Type and number of nature-based solutions for bank protection along the Elbe, Weser and Ems estuaries according to BAW and BfG (2022).

3.1 Dead wood measures

Along German estuarine waterways, the majority of NbS-BP (74 %, see Figure 1) are composed of dead wood elements, such as brushwood bundles (fascines) and wooden piles, which are implemented in different structural configurations to stabilise riverbanks (BAW and BfG 2026b). These construction methods, being mainly brushwood boxes (Figure 2) and brushwood mattresses (Figure 3), are already widely applied in practice along German estuaries, resulting in substantial operational experience that has been condensed in fact sheets for brushwood boxes and brushwood mattresses (BAW and BfG 2025b, 2025c). Dead wood measures can be applied as indirect, off-bank structures or as direct bank protection at erosive banks along estuarine waterways, they are also used to initiate small-scale morphodynamic development for erosion prevention e. g. in damping tidal creeks (BAW and BfG 2026b). As indirect bank protection structures, they are placed around mean low water level or higher, reducing current and wave impact on the bank and promoting sedimentation and establishment of vegetation behind the dead wood structure (BAW and BfG 2025d). This configuration requires space between the bank and the navigation channel and is therefore generally only feasible along gently sloping banks with a wider, intertidal marsh. As direct protection, dead wood structures are placed at the bank edge to provide immediate stabilisation. In this context, brushwood boxes stabilise the bank edge and prevent collapse, whereas brushwood mattresses offer extensive and immediate protection against surface erosion. Where boundary conditions and bank protection requirements permit, indirect bank protection is preferred to maximize ecological benefits (BAW and BfG 2025d). Brushwood boxes usually consist of double pile rows filled with hardwood fascines that are compressed and secured through wire (Figure 2). Where boundary conditions necessitate more extensive areal protection, brushwood mattresses present an appropriate construction technique, where the fascines are laid flat on the substrate and secured in place using wooden piles and wire (Figure 3).

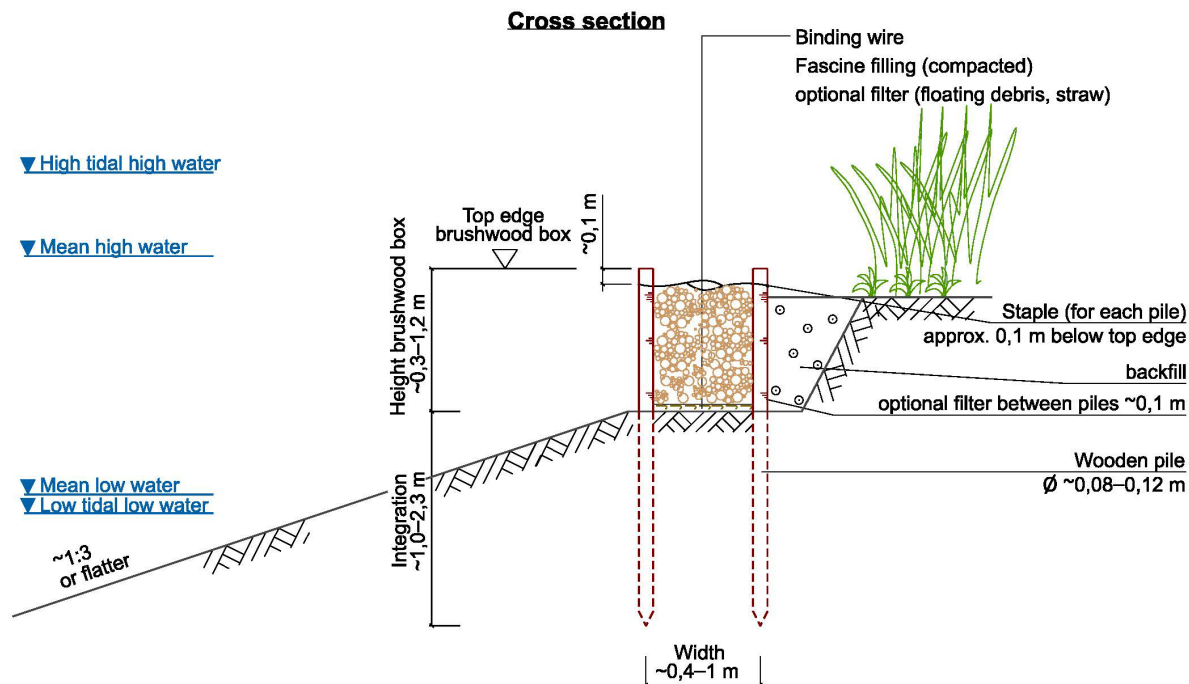


Figure 2: Technical drawing of a typical brushwood box for direct bank protection (BAW and BfG 2025b). When constructed as an indirect bank protection it would be located further off-bank.

Brushwood boxes have been used for land reclamation in the Wadden Sea for centuries and have been the focus of numerous studies within this setting (Borsje et al. 2017, Erchinger 1971, Pfeiffer 1938, Thorenz 2014). In the coastal context, brushwood boxes support salt marsh establishment, contribute to mudflat accretion and enable continued vegetation colonisation in coastal areas even under sea-level rise (Siegersma et al. 2023). The hydrodynamic effectiveness of brushwood boxes and similar dead wood structures has been investigated in several studies (De Roo and Troch 2010, Ellis et al. 2002, Mai et al. 1999, Safak et al. 2020). Measurements showed that brushwood structures were able to reduce short-period wave energy by 10 up to 80 % (De Roo and Troch 2010, Ellis et al. 2002, Everett et al. 2022). The wave-attenuating capacity depends on the relative freeboard of the structure and thus on water depth, decreasing when the water level exceeds the crest height (Mai et al. 1999). Accordingly, it is recommended that the top edge of the brushwood box should be at the level of the mean high water level for indirect bank protection structures; for higher loads, the structure can also be built higher (BAW and BfG 2025b). Wave attenuation further increases with increasing structure width (Liebermann et al. 1999, Spröer et al. 2025). Within the estuarine context brushwood boxes with widths of 0.4 m to 1 m have proven to be suitable (BAW and BfG 2025b).

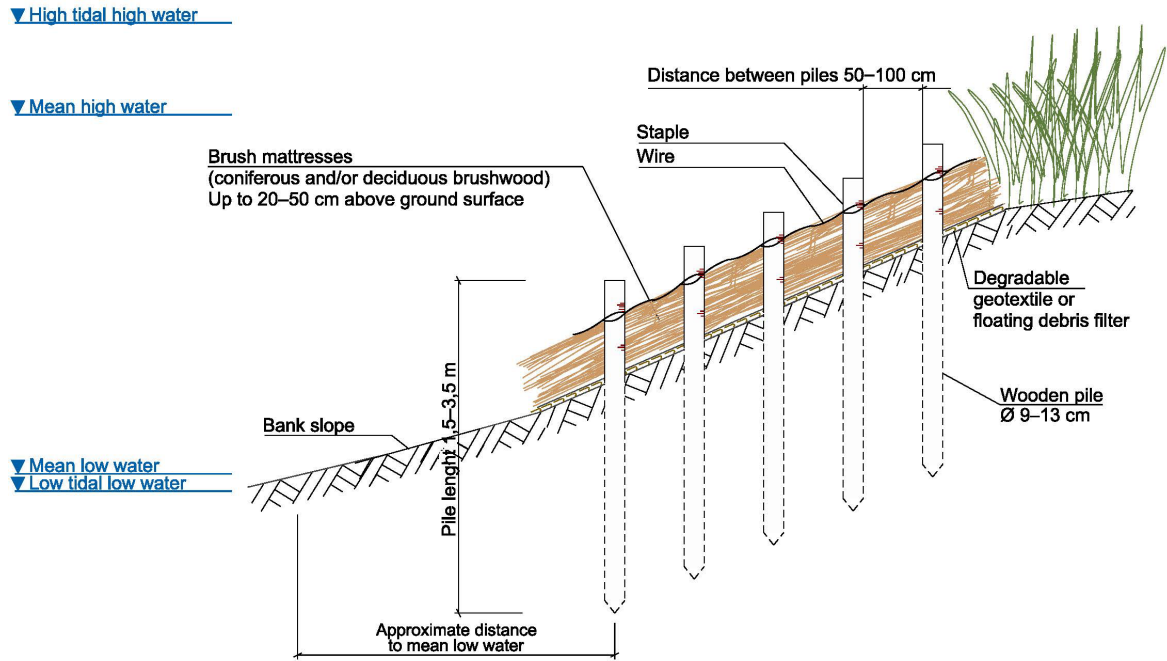


Figure 3: Technical drawing of a brushwood mattress for direct bank protection (BAW and BfG 2025c).

In contrast to rock, wood piles and brushwood are natural structural elements of the estuarine landscape and can contribute positively to landscape aesthetics (Hacker and Johannsen 2012). Dead wood is often locally available, typically sourced through regular vegetation management, which lowers material costs of protection measures, making it particularly attractive for application in waterways. The dead wood material can be installed using lighter (handheld) machinery without the need for heavy equipment. However, as organic material, it decomposes over time – a process accelerated by higher hydrodynamic loads (Hacker and Johannsen 2012) – which limits the durability of the bank protection structure, particularly when compared to rock structures. Yearly visual inspections are recommended to assess the structure's condition and replace the fascine material if required. Practitioners in German waterways report lifespans of dead wood structures as low as a few years necessitating regular maintenance. For brushwood boxes, regular maintenance at intervals of approximately three to five years is generally required to ensure sufficient protective performance. Brushwood mattresses are reported by practitioners to have lifespans of six to ten years, and under favourable conditions even longer. Short maintenance intervals lead to higher costs (Eltzsch et al. 2026); however, intervals depend strongly on the local boundary conditions and material quality that affect the biological and mechanical deterioration of the wood. The rate of biological wood decomposition depends on the local environmental factors and the associated colonisation by wood-dwelling organisms, such as fungi and insects (Hacker and Johannsen 2012). Wood exposed to strong sunlight and dry conditions, as well as permanently submerged wood under anaerobic conditions, decomposes more slowly. In addition, practitioners report mechanical weathering processes due to, e. g. hydrodynamic loads, ice and storms that also affect the wood degradation and lead to shorter maintenance intervals. Relevant material properties of brushwood and wood used in hydraulic engineering are specified in DIN 19657 and are further incorporated into

the fact sheets on brushwood boxes and brushwood mattresses (BAW and BfG 2025b, 2025c). In some cases, it is possible to use brushwood structures as an initial protection for the establishment of vegetation; if successful, the vegetation itself may provide sufficient bank protection, eliminating the need for continued reliance on engineered support structure. Under these conditions, maintenance requirements diminish, and the dead wood elements can be allowed to fully decompose naturally (Klein 1965).

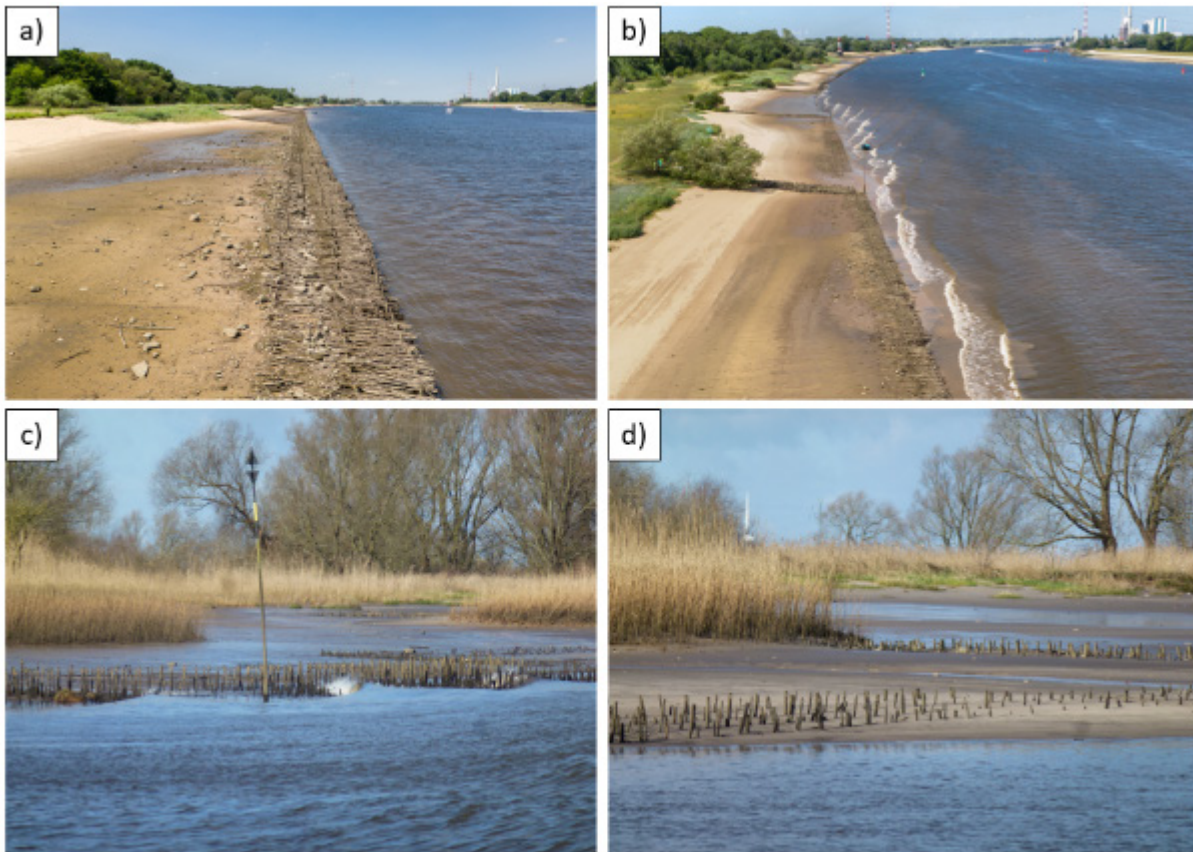


Figure 4: a)-b): Brushwood training walls and brushwood groynes along the Lower Weser. c)-d): Example of unmaintained brushwood structures at the Lower Weser. The bank is stable and maintenance no longer necessary (picture source: BAW).

Case study 1: Brushwood training walls and groynes on the Lower Weser

Along the Lower Weser, a heavily trafficked waterway with a tidal range of approximately 4 m, long stretches of banks are protected by brushwood training walls and brushwood groynes used for beach protection and for stabilising sand nourishments (Figure 4). These brushwood structures have been applied successfully over multiple decades (BAW and BfG 2026b). The brushwood training walls at the Lower Weser are constructed similarly to brushwood mattresses, with the fascines being placed perpendicular to the direction of flow and secured by wire and multiple rows of wooden piles (Figure 4 a, b). However, practitioners report that they will increasingly adopt the brushwood box configuration in future applications, which requires less material while providing adequate protection in this setting. Positioning the structure at mean low water provides a short window for maintenance work. For the example shown in Figure 4 a) and b), the most recent maintenance was conducted in 2020 and maintenance is expected within the next year. Figure 4 c) and d) show another site along the Lower Weser where maintenance of the brushwood training wall has been discontinued already approximately over 10 years ago since the bank is stable

and no further structural protection measure is needed. This example also underlines the longer durability of wood piles in contrast to the brushwood fascine material.

Case study 2: Brushwood boxes and brushwood mattresses on the Wümme

On the Wümme, a tidal tributary of the Lower Weser with recreational boating, brushwood boxes as well as brushwood mattresses were tested along three pilot sites with erosive banks (Figure 5). The brushwood material proved to be durable, as it became naturally covered by sediment over time, resulting in maintenance only after five to six years in this case (BfG, WSA Weser-Jade-Nordsee, WWK 2019). Based on the results of these pilot sites, a combination of brushwood mattress and brushwood boxes proved to be the preferred option for this application. Measurements conducted by BAW at these locations showed that tidal currents of up to 0.9 m/s affect the structures while recreational boat traffic does not pose a significant load due to secondary waves or ship-generated currents (Schreiber et al. 2023). Under these boundary conditions, brushwood boxes and brushwood mattresses therefore provide a suitable solution for tidal tributaries.

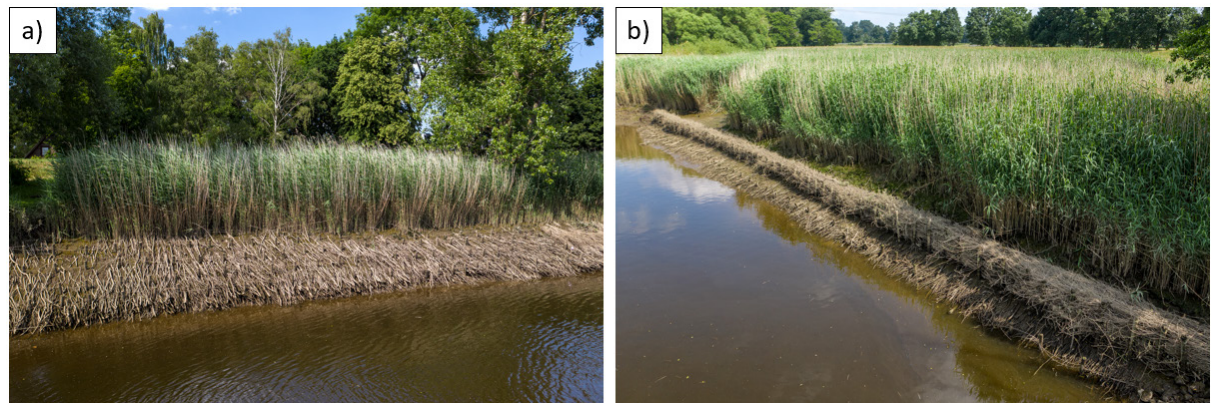


Figure 5: Pilot sites for alternative bank protections at the Wümme using a) a brushwood mattress and b) a combination of brushwood boxes and mattress (picture source: BAW).

Case study 3: Brushwood mattress on the Pinnau

Brushwood mattresses have also been successfully applied to protect an erosive dike toe along the Pinnau, a tidal tributary of the Elbe with a mean tidal range of little over 2 m and recreational boating. Immediately after implementation vegetation started to regrow (Figure 6 a)). Dense vegetation covers the upper half of the brushwood mattress while the lower part is covered with sediment (Figure 6 b, c)). The brushwood mattress is stable and no maintenance has been necessary to date.

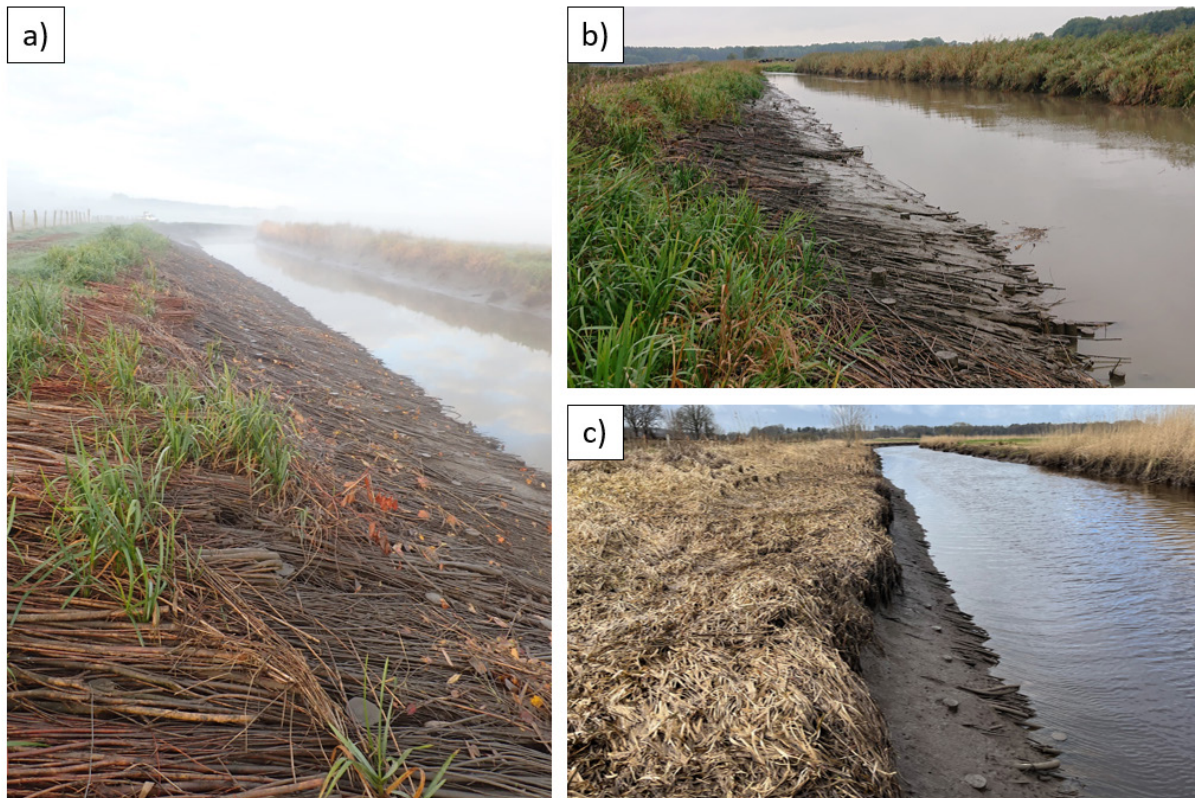


Figure 6: Brushwood mattress at the Pinnau a) four weeks after construction in August 2018 (picture source: WSA Elbe-Nordsee), b) two years later in October 2020 and c) in March 2026 (picture source: BAW).

Case study 4: Brushwood boxes for bank protection within groyne fields at the Oste Mouth

On the Outer Elbe estuary, at the mouth of the Oste, brushwood boxes are being used to protect the bank within groyne fields. Due to the poor accessibility of the area, dead wood construction methods that can be installed and maintained without heavy equipment are suitable here. The structures were initially built in 2011 and 2013 and last maintained in 2025. Practitioners reported annual losses of brushwood filling due to storm surges and ice drifts in some parts. Despite regular maintenance requirements, the site is reported to be successful in terms of sedimentation and vegetation development within the groyne field.



Figure 7: Brushwood boxes for bank protection within a groyne field on the Oste near its entrance into the Elbe. (picture source: WSA Elbe-Nordsee).

Case study 5: Double pile row with gabion filling as indirect bank protection on the Elbe

In the Outer Elbe estuary, under heavy wind-wave loading, double pile rows with gabion infill have proven a suitable, low-maintenance solution (Figure 8). Although the use of rock-filled gabions represents a non-native element in the estuarine environment and is therefore generally less favourable from an ecological perspective than pure dead wood structures, this hybrid design offers a robust, low-maintenance alternative under high hydrodynamic loading and is therefore included here as a relevant reference case. The measure was constructed in 2014 and vegetation established in front of the formerly erosive bank within just a few years. Gabion filling has a longer service life, especially when compared to brushwood boxes in the surrounding area, where practitioners report that the brushwood material sometimes needs to be replaced annually (see Case study 4). The design included 10 m wide openings at 30 m intervals to enable an improved ecological connectivity between the estuary and the bank, to allow animal passage and to prevent the structures from acting as a fish trap. This design is supported by international experience (Hardaway et al. 2017) and is included in design guidelines for indirect bank protection developed specifically for German estuarine waterways (BAW and BfG 2025d).



Figure 8: Example of an indirect bank protection with regular openings in the Elbe estuary consisting of two double pile rows with gabion filling and regular openings (picture source: BAW).

3.2 Living measures

A typical nature-based solution involves vegetation, which provides substantial long-term erosion control once dense plant cover develops (Europäische Föderation für Ingenieurbiologie 2015). Vegetation-based measures are generally regarded as the most ecologically favourable approach for bank protection. However, the effectiveness of its erosion control function depends significantly on site or habitat suitability for the selected plants (Hacker and Johannsen 2012). Self-colonization by plants indicates optimal habitat conditions, ensuring natural adaptation to local stresses. In estuarine waterways, tidal changes in water level, currents and salinity have a particularly strong influence on the flora and its estuarine typical zonation (Klein 1965). The tidal flats of Northwestern European estuaries are typically dominated by emergent macrophytes such as *Bolboschoenus maritimus* or *Schoenoplectus* spp. (Struyf et al. 2009). Willows (*Salix* spp.) typically establish above mean high water, where soil salinity limits their distribution and growth (Markus-Michalczyk and Hanelt 2019). Willow species native to German estuaries include particularly *Salix alba*, *Salix rubens*, *Salix fragilis*, *Salix triandra*, *Salix viminalis* and *Salix purpurea* (Struyf et al. 2009). Estuarine

vegetation such as reed species (e. g., *Bolboschoenus maritimus* (Carus et al. 2016, Schoutens et al. 2019) and willows (Borsje et al. 2017, Eisenmann 2015) act as a buffer against hydrodynamic loads, add to bank protection and enhance sedimentation processes. Even narrow strips of vegetation have a reducing effect, as the process of flow reduction mainly takes place within the first few meters of vegetation (Schoutens et al. 2019). Willows possess properties that make them particularly suitable for bioengineered bank protection; this includes their ability for vegetative resprouting, fast growth, high bending capacity and high breaking resistance (Markus-Michalczyk et al. 2019). Living measures make up only 8 % of documented NbS-BP (Figure 1) and experience along the estuarine waterways is scarce, including only a few examples of willow mattresses and initial plantings (BAW and BfG 2026b).

Willow mattresses consist of living willow rods which are laid flat on the embankment and secured with stakes and wire. Like brushwood mattresses, willow mattresses provide immediate protection against surface erosion. Additionally, once willows sprout, their root system reinforces this protection, while above-ground vegetation reduces hydrodynamic stress on the bank and the adjacent marshes (BAW and BfG 2026a). In contrast to brushwood mattresses, which can be implemented down to mean low water, willow mattresses are limited around mean high water, where willows are able to sprout and root (Markus-Michalczyk and Hanelt 2019). The combination of different willow species within a willow mattress promotes diversity and secures longevity of the bank protection; rods from *Salix viminalis*, for example, become rigid and inflexible over time and should therefore be combined with other willow species for long-term use as bank protection (BAW and BfG 2026a). Practitioners report that regular pruning of willow mattresses at intervals of approximately three to five years is necessary to keep willow shoots dense and flexible and to ensure bank protection. Ecological diversity can be enhanced by leaving selected areas uncut, extending maintenance intervals, or using targeted pruning instead of uniform large-scale cutting (BAW and BfG 2026a).

Initial plantings represent another living measure that supports and accelerates the establishment of vegetation. They can be easily combined with other structural bank protections. Natural vegetation development should be monitored first before adding initial plantings (BAW and BfG 2025d); Gittman et al. (2016a) recommend initial plantings if no natural vegetation develops after three years. In coastal areas, reeds should be planted only as bales or sods, as single stem cuttings cannot withstand wave attack (BfG, WSA Weser-Jade-Nordsee, WWK 2019, Klein 1965). This approach complemented the brushwood box presented in case study 2 on the Wümme (chapter 3.1) to initiate vegetation behind the structure.

While structural measures provide immediate bank protection upon installation, living measures require a critical establishment phase until roots form or plants sprout. Protecting young plants from livestock grazing and trampling is recommended during this period (Klein 1965). Initial plantings often require a structural protection to reduce the hydrodynamic loads on developing vegetation during the first few years (Almström et al. 2022, Klein 1965, Manis et al. 2015). As described in chapter 3.1, dead wood or stone structures in front of the estuarine vegetation reduce hydrodynamic loads, promote sediment accumulation and create suitable conditions for plant growth. This is particularly crucial in winter, when pioneer tidal marsh vegetation loses above-ground biomass, severely limiting wave attenuation capacity during peak storm conditions (Schoutens et al. 2019).

Case study: Willow mattresses on the Elbe Island Hanskalbsand

Above mean high water, living willow mattresses are used on the Elbe to provide bank protection and stabilize sediment on both sides of the island of Hanskalbsand (see Figure 9). Long-term monitoring by the Federal Waterways and Shipping Administration (WSV) reveals that willow mattresses only sprout and establish permanent stands from approximately 1 m above mean high water at this site; no permanent growth occurs below this elevation (Gätje et al. 2018). Practical experience from this pilot section informed the planning guidance for willow mattresses in tidal areas (BAW and BfG 2026a).



Figure 9: Living willow mattress for beach protection at the river island Hanskalbsand at the Elbe (picture source: BAW).

3.3 Structural improvement of technical measures

Dead wood or living measures are not feasible for all locations. Many banks along estuarine waterways must remain protected by hard engineering structures, such as riprap revetments, to safeguard hinterland infrastructure. In addition, riprap revetments often are still in good structural condition, making their complete removal and replacement by nature-based bank protection measures potentially economically unjustified despite their ecological benefits. However, where existing riprap revetments require maintenance or renewal, integrating nature-based solutions should be considered to enhance ecological functioning while maintaining engineering performance. International interest in enhancing hard protection structures is also growing (Browne and Chapman 2014, Firth et al. 2013, Firth et al. 2014, Morris et al. 2019).

Along German estuarine waterways, methods to add ecological value to existing bank protection – such as partial lowering of revetments as well as the integration of vegetation boxes, vegetation mats or tide pools– account for 18 % of the reported NbS-BP implementations (BAW and BfG 2026b). Although their ecological effect is limited compared to natural, undisturbed habitat, strategically placed structures offer potential as stepping stones for flora and fauna.

Partially lowering the crest of revetments facilitates tidal exchange between the estuary and the adjacent hinterland, thereby reactivating tidal marsh habitats. When designing such a partial lowerings, an appropriate balance must be achieved between promoting dynamic hinterland development and maintaining structural stability. Detailed topographic

information of the hinterland is essential to determine the suitable lowering depth. This depth is highly site-specific and varies between 0.6 m and 1.5 m at existing sites (BAW and BfG 2026b).

Integrating vegetation into riprap bank protection can enhance the ecological value of revetments and should be placed according to the species' suitable habitat (Hacker and Johannsen 2012, Scheres and Schüttrumpf 2019). Although existing guidelines on the integration of vegetation into riprap were originally developed for the use in inland waterways, their general design and construction principles can provide valuable insights and guidance for applications in estuarine environments (BAW and BfG 2018a, 2018b).

Integrating artificial structures, such as tide pools into the existing revetments has proven to be a cost-effective approach for enhancing their ecological value (Browne and Chapman 2014, Firth et al. 2014). Although artificial rock features provide important habitats for marine species, they are usually less diverse than natural habitats and lack environmental heterogeneity (Firth et al. 2013). Studies evaluating the ecological value of artificial rock formations are generally based on comparisons with natural rocky coasts used as reference sites (Evans et al. 2015, Firth et al. 2013). However, rocky shores, are not characteristic of German estuaries, where coastlines are predominantly sandy, clayey and silty (Schmidt-Wygasch and Heuner 2018). When stone protection structures replace soft sediments, this usually leads to changes in local biodiversity, as the sedimentary habitat is substituted by hard substrate (Browne and Chapman 2014). While hard substrates become rapidly colonized by various species (Evans et al. 2015), these are generally different from those typical of soft estuarine environments (Browne and Chapman 2014). Such ecological shifts need to be carefully considered when implementing artificial rocky features in estuaries.



Figure 10: Examples of a lowered revetment on the River Elbe, allowing for vegetation development (left) and increased tidal exchange (right) (picture source: BAW).

Case study 1: Lowering of revetment crests along the Elbe

Along the Elbe, revetments have been partially lowered at the crest, typically over 10 m sections, at several sites (Figure 10, BAW and BfG 2026b). The lowered sections were stabilized using gabion baskets. As a result of the reduced crest height, tidal creeks have developed, pioneer vegetation and algae have established and new habitat for microorganisms has been created (BAW and BfG 2026b, Gätje and Cordes 2013). To date, all implemented revetment crest lowerings have remained stable and have not required maintenance.

Case study 2: Vegetation boxes within a revetment along the Lower Weser

Examples of vegetation integrated into riprap structures can be found along the tidally influenced Lower Weser. In these cases, 4 m x 5 m sections were stabilized using gabion baskets filled with rocks, while the remaining approximately 30 % void space was filled with soil-bentonite mixture and vegetation bales (Figure 11). The vegetated patches are situated around and above mean high water, with only their lower parts exposed to high water levels and ship-induced waves. Since their implementation in 2014 and 2016, no maintenance has been required other than the removal of invasive species. Although various plant species have established within the patches, no conclusions regarding their ecological value can be drawn, as no dedicated ecological monitoring or assessment has yet been conducted.



Figure 11: Integration of vegetation into existing riprap revetments along the Lower Weser (picture source: BAW).

Case study 3: Vegetation mats along the Elbe

Figure 12 shows a pilot site featuring pre-vegetated mats installed along a riprap revetment on the tidal Elbe within the Hamburg Port area (Hamburg Port Authority 2025). The vegetated mats were attached to mattresses made of robust plastic mesh filled with rocks. Different types of pre-vegetated mats were used, containing either (1) *Carex acuta* and *Carex acutiformis*, *Phragmites australis*, *Typha*, (2) *Typha angustifolia* and *Typha latifolia*, *Schoenoplectus lacustris* and *Bolboschoenus maritimus* or (3) grasses and herbaceous plants such as *Iris pseudacorus*, *Lythrum salicaria* and *Caltha palustris*. The mats were placed at different altitudes along the revetment, ranging from –1 m to 5.3 m above mean sea level. The experiment demonstrated that vegetation establishment was most successful in the middle section of the embankment between 0.5 m to 2.0 m above mean water (type (1) vegetation mats), while the lower section below 0.5 m above mean water remained largely unvegetated throughout the four years of monitoring due to frequent tidal flooding (Hamburg Port Authority 2025). For a more successful vegetation establishment in the upper part of the revetment, more drought-tolerant species appear to be better suited due to the limited water availability in this part of the pilot site (Hamburg Port Authority 2025). In this context, the authors of this paper recommend paying attention to variation in plant community composition along the elevational gradient from low to high freshwater marsh zones. Issues observed include the gradual loosening of plant mats over time and the washing out of introduced substrate.

No new substrate accumulation was detected, likely due to strong tidal forces and the steep slope angle, which resulted in vegetation roots developing exclusively within the riprap. Therefore, it is essential to ensure that the plant mats remain permanently fixed and secured in place. To reduce the use of plastic material, anchoring the mats with wooden stakes may serve as a viable alternative (Hamburg Port Authority 2025); however, according to practical experience reported by practitioners involved in the study (personal communication), it is unclear whether piles will sufficiently secure the mats under the given boundary conditions.



Figure 12: Vegetated riprap using pre-vegetated mats at the Elbe (picture source: BAW).

Case study 4: Tide pools on the Elbe

In the Port of Hamburg area, artificial concrete-based tidal pools were integrated into the existing revetment in 2019 (Figure 13). These pools retain water during low tide and aim to improve the structure of riparian areas and underwater habitats (Hamburg Port Authority 2024). Monitoring showed, that the communities in the pools are more diverse than those in the reference areas. However, the communities found in the pools represent only part of the species spectrum of the Elbe and its harbor basins. No specialists and virtually no key species were detected, indicating that the observed ecological improvement is limited to a comparison with the revetment in this area and does not constitute an improvement relative to the natural aquatic habitat of the Elbe (Hamburg Port Authority 2024).



Figure 13: Tide pools in the Port of Hamburg area at the Elbe (picture source: BAW).

4 Discussion

4.1 Applicability and performance of NbS-BP in estuarine waterways

This study presents an implementation-focused typology of NbS-BP for estuarine waterways in Germany, synthesizing practitioner experience, monitoring data and literature into practice-oriented guidance. The compilation of implemented measures demonstrates that NbS-BP can be applied across a wide range of estuarine settings, from small tidal creeks to shoreline sections extending several hundreds of meters, such as the brushwood training walls along the Lower Weser (BAW and BfG 2026b). Moreover, the implemented measures operate under diverse boundary conditions, ranging from sheltered side arms and tidal tributaries influenced mainly by recreational boating to sites exposed to ship-induced loads from large seagoing container vessels.

Despite this broad applicability, the findings confirm that the design and performance of NbS-BP remain highly site-specific. In contrast to hard, abiotic engineering structures, NbS-BP depend on heterogeneous materials, biological processes and dynamic system evolution. Consequently, planning and dimensioning cannot achieve the same level of predictability and long-term reliability as conventional bank protection measures. This uncertainty should not be viewed as a limitation, but an inherent characteristic of nature-based approaches. It should therefore be explicitly recognized and accommodated within planning and approval processes. Practitioner experience further suggests that the applicability and durability of NbS-BP becomes increasingly constrained at sites exposed to persistent hydrodynamic stress, such as high-energy ship-induced waves, where hybrid solutions or conventional hard protections may be required to ensure bank stability.

4.2 Material-specific insights and trade-offs

The frequent implementation of dead wood measures across German estuaries underscores their suitability for achieving effective bank protection while simultaneously enhancing structural diversity. Practitioner experience and case studies indicate, however, that brushwood structures typically require maintenance after approximately five years or earlier, depending on site-specific conditions. However, as the case studies 1 and 3 in section 3.1 show, under suitable conditions the durability of dead wood measures can be longer or maintenance can be discontinued. Decomposition rates are influenced by factors such as hydrodynamic forcing, UV exposure, and material quality, which in turn may be affected by aspects such as the storage duration between harvest and installation. These factors constrain the predictability of both performance and lifespan.

At the same time, the natural decomposition of dead wood can be advantageous if vegetation establishes successfully on the landward side of the structure and provides sufficient long-term stabilization. Under such conditions, maintenance requirements decrease, and the dead wood elements can be left to decompose naturally; a design principle already recommended by Klein (1965). From an ecological perspective, this may offer advantages over rock-based solutions, which, although they are more durable and effective under higher hydrodynamic loads, remain non-native and can harm benthic habitats (Hardaway et al. 2017). Where boundary conditions permit, dead wood measures are therefore preferable to stone-based alternatives. Other degradable materials such as coconut fibre and coir logs,

are widely used internationally for NbS-BP but exhibit low longevity and decompose rapidly under tidal waterway conditions (Almström et al. 2022, Baldauf 2021, BAW and BfG 2026b), indicating that alternative materials are required for long-term structures.

Indirect solutions are preferred over direct bank protection measures across all materials, as they promote estuarine vegetation succession in sheltered zones while integrating ecological functions into bank protection (BAW and BfG 2025d).

4.3 Performance of living measures

Experience with living measures in estuarine waterways remains limited. Nevertheless, the presented case study indicates that living willow mattresses can provide effective bank protection at elevations approximately 1 m above mean high water, while requiring relatively low maintenance. Vegetation often establishes naturally once hydrodynamic loads decrease and sedimentation raises elevations to suitable levels for plant growth. This reduces the need for initial plantings, as shown in Elbe case studies on indirect bank protection (see section 3.1). These observations align with literature highlighting the role of vegetation in enhancing adaptive capacity and resilience of estuarine ecosystems under climate change (Cornacchia et al. 2024). However, more applications and monitoring are needed to define suitability and establishment requirements for living measures in estuaries.

4.4 Monitoring needs and remaining evidence gaps

Implemented NbS-BP exhibit a wide range of lifespans and maintenance intervals, particularly for dead wood applications. A better understanding of the factors controlling durability is essential to establish dead wood-based NbS-BP as a reliable alternative to riprap. In practice, high maintenance demands and local boundary conditions have prompted practitioners at some sites, as shown in Elbe case studies, to adopt hybrid solutions e. g. using gabions filled with stones rather than brushwood.

Although studies have investigated the effectiveness of dead wood structures in wave reduction (De Roo and Troch 2010, Ellis et al. 2002, Mai et al. 1999, Safak et al. 2020), they do not fully address the specific conditions of tidal waterways, including hydrodynamic loads from ship passages, wind and tides. Monitoring of newly constructed and existing NbS-BP sites in estuarine waterways is therefore essential. BAW and BfG are currently conducting intensive monitoring alongside a construction project, that secures an erosive bank using an indirect protection structure with gabion filling. These measurements yield quantitative data on hydrodynamic loads, wave damping, morphodynamic responses, vegetation establishment, and structural durability. Ideally, comparable monitoring at sites with different materials (e. g. brushwood filling), would enable direct performance comparisons and strengthen the evidence base for material selection and design.

From a practitioner and planning perspective, future monitoring should focus on tracking hydrodynamic loads, sediment changes, vegetation growth and material breakdown over time. This will help define realistic performance and maintenance needs.

4.5 Implementation challenges and enabling conditions

Although detailed technical guidance exists for planning and implementing direct and indirect NbS-BP in estuarine waterways, the inherent uncertainty of dead wood and living measures remains a major challenge. These approaches often demand intensive monitoring and adaptive maintenance, straining human resources. While German practitioners generally support environmentally friendly solutions, budget constraints and staff reductions increasingly limit the feasibility of labor-intensive NbS-BP. This represents a critical barrier to large-scale implementation, even where technical guidelines are available. Improved methods for quantifying and monetizing the ecological benefits of NbS-BP relative to conventional riprap revetments are therefore essential to support feasibility assessments and justify their typically higher costs (Eltzsch et al. 2026). In the context of the European Water Framework Directive and climate adaptation requirements, such considerations are becoming increasingly vital for future waterway management strategies.

Despite the demonstrated potential of nature-based bank protection measures, many estuarine waterway banks must continue to rely on robust engineering structures, such as riprap revetments to ensure stability for critical infrastructure, industrial activities, and residential areas. Additionally, numerous existing revetments remain in good structural condition, making their complete removal and replacement by NbS-BP economically infeasible despite the ecological benefits. Enhancing existing hard structures with e. g. tide pools, vegetation boxes, or locally lowered revetment crests offers a pragmatic compromise. It preserves engineering performance while improving structures and habitat potentials. The presented case studies all featured low maintenance needs post-implementation (see section 3.3.). Once established, these measures largely depend on natural hydrodynamic and ecological processes, requiring only occasional inspection rather than regular structural maintenance. While the ecological benefits of enhancing hard protection structures are limited compared to natural, undisturbed habitats, such measures can still improve ecological connectivity when implemented systematically. Enhanced riprap revetments can serve as stepping stones for flora and fauna along heavily engineered estuarine shorelines, especially when applied at regular spatial intervals. From a system-scale perspective, this incremental improvement may provide meaningful support for biodiversity in highly modified estuarine environments.

5 Conclusion

This study presents a practice-based typology of implemented nature-based bank protection measures for estuarine waterways in Germany, integrating practitioner experience, monitoring data and literature. The results show that NbS-BP are applicable across a wide range of estuarine settings and boundary conditions providing effective bank protection while ideally integrating ecological functions for sustainability. However, under high hydrodynamic loads the application of NbS-BP can be infeasible due to higher maintenance costs or unacceptable risks. NbS-BP exhibit higher uncertainty and lower predictability than conventional hard engineering solutions. Accepting this uncertainty and integrating adaptive management into planning and approval processes is essential for their successful application. Continued monitoring, better understanding of material durability, and improved valuation of ecological benefits will be key for broader NbS-BP implementation in estuarine

waterways amid future environmental and climate pressures. At the same time, the typology and synthesis presented here translate existing implementation experience into practical guidance through standardised fact sheets and a decision-support tool developed by BAW and BfG. These resources provide practitioners with structured recommendations on the selection, design and implementation of NbS-BP measures reducing barriers for the wider adoption of NbS-BP and supporting more consistent and informed implementation in future projects.

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