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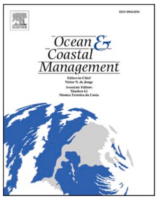

Review

From pilots to policy: upscaling sediment management strategies for climate resilience in a transboundary estuary

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ABSTRACT

The Ems Estuary faces existential challenges including flood risk, increasing turbidity, and biodiversity loss, all of which may intensify under future climate scenarios and require transboundary collaboration between the Netherlands and Germany. Addressing these challenges requires compliance with EU, national, and local regulations. Simultaneously each nation pursues socioeconomic benefits from the restoration through a holistic, system-based approach. This study synthesizes the key processes driving flood risk, hyper-turbidity, and salinization within the Ems Estuary. From this understanding the paper catalogues the planned and implemented pilot measures from both countries to advance their climate adaptation plans. Both nations share a common vision of leveraging the high turbidity of the estuary as an asset in climate adaption, e.g. for land raising, dyke reinforcement or habitat creation. Building on the pilot projects and shared visions, three transboundary upscaling strategies involving sediment management are proposed: (A) land elevation using dredged sediment; (B) multifunctional flood defences incorporating nature-based solutions; and (C) habitat creation and restoration to enhance ecological resilience. The Ems Estuary offers valuable insights for global transboundary estuarine management, illustrating how innovative sediment management and transboundary cooperation can be achieved to support climate adaptation and sustainable development. The study underscores the need for harmonized governance, standardized success metrics, and cross-border planning to enable effective upscaling.

1. Introduction

The transition between land and sea in tide-dominated coasts is among the most complex natural environments on Earth (Dalrymple and Choi, 2007) and one of the most populous; around 1 billion people live within 10 km of the coast (Cosby et al., 2024). Because of their strategic location over half of the world's estuaries have been altered in the past decades, particularly those with strong economic development (Jung et al., 2024). Additionally, estuaries are ecologically important due to the gradient from freshwater to saltwater and the gradual transition from marine to terrestrial ecosystems (Cardoso, 2020). Because estuaries are shaped by a complex interplay of geomorphological and ecological processes and human activities, managing them requires insight in natural processes and balancing competing interests. Balancing these interests becomes even more challenging when estuaries cross national boundaries and require coordinated adaptation strategies to address climate change.

There is a myriad of examples where differences between countries, whether politically, culturally, or in governance and management structures, hampered the development of effective transboundary

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policies for coastal and estuarine management (Ansong et al., 2023; Berzi and Ariza, 2018; Jones et al., 2021; Moodie and Sielker, 2022). Nevertheless, agreements on aspects for estuarine management can be in place based on global legal frameworks (e.g. through conventions like United Nations Convention on the Law of the Sea (UNCLOS)), regional frameworks (e.g., the EU Water Framework Directive, or the Nairobi convention for management Western Indian Ocean) (UNECE, 2025).

The Ems Estuary is an example of a transboundary system. It is shared by the Netherlands and Germany and is a part of the larger Wadden Sea. The Ems Estuary exemplifies an estuarine system that is ecologically stressed and politically complex. The estuary has undergone extensive human interventions, including land reclamation, channel deepening, and dredging, which have led to increasing turbidity (de Jonge et al., 2014; van Maren et al., 2015b, 2016). These changes have had cascading effects on the estuarine ecology, including reduced primary production, oxygen depletion, and habitat degradation (Brinkman and Jacobs, 2023; Colijn, 1982; Compton et al., 2017; Talke et al., 2009a). The complexity of processes (both natural and anthropogenic) controlling the sediment dynamics and the ecological development within the Ems Estuary limit our current understanding and our ability to predict to predict future morphological and ecological changes. This leads to compounding uncertainties in the understanding of how the estuary may evolve in response to the future changes such as sea-level rise and nature restoration. Such uncertainty underscores the necessity of adaptive, flexible management frameworks that can respond to both ecological dynamics and climate change pressures. In the Ems Estuary, such limitations pose a significant challenge for developing sustainable and adaptive management strategies.

The estuary's sediment dynamics span broad spatial and temporal scales, yet management responsibilities are divided between two nations, each operating under different legal and institutional frameworks. Both countries have initiated restoration programs, in Germany the "Masterplan Ems 2050"; The State of Lower Saxony (2015), and in the Netherlands the "Ems-Dollard 2050 Programme"; ED2050 (2017) and have been collaborating since 1982 through 'Joint Declaration on the Protection of the Wadden Sea'. However, existing environmental legislation such as the Water Framework Directive and Natura 2000 is often too rigid or sector-specific to support integrated or innovative

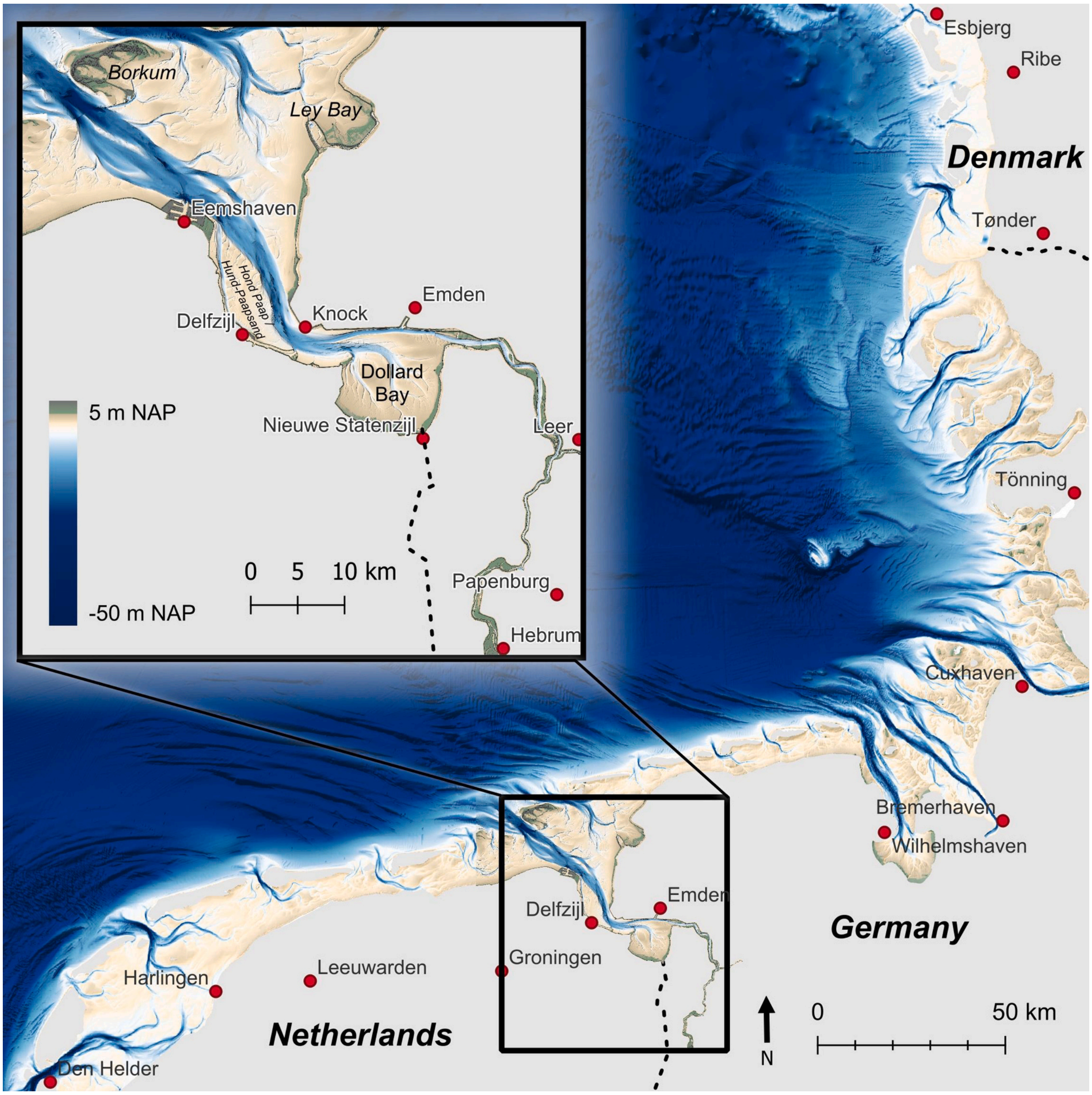

Fig. 1. The Wadden Sea with the Ems Estuary in the top left. Bathymetry composited from EMODnet (https://erddap.emodnet.eu/erddap/files/bathymetry_dtm_2024/), and public surveys by Rijkswaterstaat (https://maps.rijkswaterstaat.nl/dataregister/srv/api/records/a025743c-2db7-4537-a7eb-c8b2921a3d82) and WSV (https://www.kuestendaten.de/Tideems/DE/Service/Kartenthemen/Kartenthemen_node.html).

restoration measures (van der Werf et al., 2022). This institutional rigidity limits the ability to respond effectively to the estuary's evolving challenges.

To explore how a transboundary sediment strategy for the Ems Estuary might be developed, this paper begins by examining the biophysical challenges that sediment management strategies aim to address. It then reviews the historical policy context within which these strategies must operate. Building on this foundation, the paper discusses the various visions for the estuary's future and catalogs the restoration pilots implemented to date in pursuit of these goals. Finally, it presents three potential strategies for scaling up joint sediment management to meet the estuary's adaptation challenges. Through this case study of the Ems Estuary, the paper aims to present programmatic, transboundary approaches to managing complex estuarine systems under conditions of uncertainty.

2. Bio-physical system understanding and challenges

2.1. Wadden Sea and Ems Estuary

The Ems Estuary is part of the Wadden Sea (Fig. 1). The Wadden Sea forms the world's largest continuous expanse of tidal flats, covering approximately 4700 km^2, and stretches from the Netherlands to Denmark. Over the past 8000 years sediment deposition from marine sources has sufficiently counterbalanced a gradual rise in sea level, maintaining a coastal morphology characterized by a seaward sandy barrier, extensive intertidal flats, and intermittently inundated salt marshes. The Wadden Sea is of global ecological significance, serving as a critical stopover site for 10 to 12 million migratory birds annually along the East Atlantic Flyway. Biodiversity within the Wadden Sea is remarkably high, supporting an estimated 10,000 species of plants, fungi, and animals. Following historical periods of over-exploitation, conservation initiatives have led to notable recoveries in populations of breeding birds and marine mammals, particularly seals (Reise et al., 2010).

The Ems Estuary is located at the border between the Netherlands and Germany (Fig. 1). The upstream part of the estuary starts at the tidal weir at Herbrum and consists of a tidal river known as the lower Ems River up until Emden. The downstream boundary generally of the estuary is defined at the east Frisian island Borkum. The length of the Ems Estuary, including the tidal river, is approximately 110 km and the surface area is, excluding the ebb delta at the island of Borkum, approximately 460 km^2 (de Jonge et al., 2014). The tidal range in the Ems Estuary typically varies between 2.4 and 3.0 m at its entrance near the island of Borkum (Talke et al., 2009b). River discharge in the Ems fluctuates seasonally, ranging from approximately 20 to 400 m^3/s, with an average of around 80 m^3/s and occasional extreme peaks reaching up to 1200 m^3/s (NLWKN, 2018). Over time, the Ems Estuary, and the Lower Ems River in particular, has experienced increasing turbidity. Near-surface suspended particulate matter (SPM) concentrations now average up to 1 g/L along nearly its entire length (de Jonge et al., 2014). Today, the lower Ems River is marked by thick, highly mobile fluid mud layers with SPM concentrations as high as 200 g/L (Papenmeier et al., 2012; Winterwerp et al., 2017). These dynamics pose significant barriers to ecological restoration and water quality improvement.

The Ems Estuary is a funnel-shaped and partially mixed alluvial estuary. Alluvial estuaries have movable beds, consisting of sediments of both riverine and marine origin, which are primarily remobilised by tidal currents but are additionally transported by residual flows resulting from freshwater inflow. The water moving in the estuary can either erode the bed (leading to deepening or widening) or it can deposit sediments (making the estuary narrower or shallower). Hence, the shape of an alluvial estuary is directly related to the hydraulics of the estuary (Savenije, 2012). The Ems Estuary, however, has an atypical planform resulting from a number of storm surges in the 15th century and a major flooding in 1509 shaping the Dollard Bay and reshaping the Ems Estuary. Today, the system's sediment balance and morphology are dominated by these combined legacies and ongoing human interventions. About 20% of the Dollard's extent from the 16th century remains, with most of the former intertidal flats and salt marshes reclaimed as polders (Schrijvershof et al., 2024). This history and natural evolution continues to reshape sediment pathways and tidal dynamics today.

2.2. Rising turbidity and degrading biodiversity

Turbidity in the Ems Estuary has increased significantly since the 1990s, with concentrations in the Dollard Bay rising by approximately 2.5 mg/L per year (Smits and van Maren, 2021). This trend is the result of a complex interplay between estuarine dynamics and human interventions (see Fig. 2). The estuary imports about 1.5 million tons of fine sediment annually from the Wadden Sea (Colina Alonso et al., 2024). However, a vast quantity of the suspended sediment is recirculated from dredging and dumping in the estuary. Dredging in the Ems Estuary has surged since the 1960's and peaked between 1970 and 1980 at ∼18 million m^3/year (van Maren et al., 2015a). The average dredged volumes over the last decade (2014 to 2023) are ∼2.5 million m^3 on the Ems River and ∼5.5 million m^3 between Emden and Eemshaven (Wasserstraßen- und Schifffahrtsamt Ems-Nordsee, 2021; Zentrales Datenmanagement Küstendaten, 2025). Most sediment dredged from the fairway east of Emden up to Eemshaven is dispersed northeast of Hond Paap while sediment dredged from the Lower Ems River is brought on land. Dredging north from Eemshaven to the North Sea of predominantly sandy material has increased since 2017 from ∼0.5 million m^3/year to ∼3 million m^3/year after deepening of the fairway in 2017 (de Wit et al., 2024).

A key driver of the landward transport of sediment into the estuary is estuarine circulation (Flöser et al., 2011): denser saline water from the sea sinks and flows landward along the bottom, mixing gradually with lighter freshwater from the Ems River on top. This bottom flow transports sediment upstream as particles settle towards the bottom. Numerical modelling by Stanev et al. (2003) in analogous Wadden Sea inlets highlighted how flood-dominant tidal asymmetry enhances net upstream sediment flux, with relevance for managing estuarine sediment budgets in the Ems. Sediment settling in the harbours of Emden and Delfzijl is kept unconsolidated through water-injection, allowing tides to flush sediment out of the harbour and back into the estuary. The Dollard, which acted as a sediment sink in the past centuries, appears to be a sediment conduit nowadays, acting as a temporal storage for sediments exchanged between the Ems Estuary and lower Ems River. During calm summer conditions sediment entering the Dollard Bay tends to settle, but particularly during winter storms it is resuspended and net transport back into the Ems River over the Geisedam is enhanced (van Maren et al., 2021). The low net deposition within the Dollard Bay so far remains largely unexplained but could be the result of extensive historic land reclamation which degraded the natural coastal habitats. Local ecosystem disruption reduces biodiversity and diminishes the natural buffers that protect shorelines from erosion and flooding.

The upper reaches of the Ems Estuary (the lower Ems River) have shifted towards a hyper-turbid state by self-reinforcing feedback mechanisms triggered by channel deepening (Winterwerp et al., 2013). Deepening initially triggered tidal amplification, thereby strengthening up-estuary sediment transport and deposition. This resulted in development of fluid mud layers within the lower Ems River that suppress turbulence and reduce drag on tidal flows. In an already turbid environment, rising turbidity further enhances sediment-induced stratification, thus resulting in a positive feedback loop of increasing turbulence suppression and stratification (Bailey et al., 2024). This leads to further tidal amplification, which in turn strengthens the landward transport into and the lower Ems River increasing the turbidity further (van Maren et al., 2015b). As a result, turbidity reaches a maximum near the city of Weener, south of Leer, where levels can exceed 200 g/L (Borgsmüller

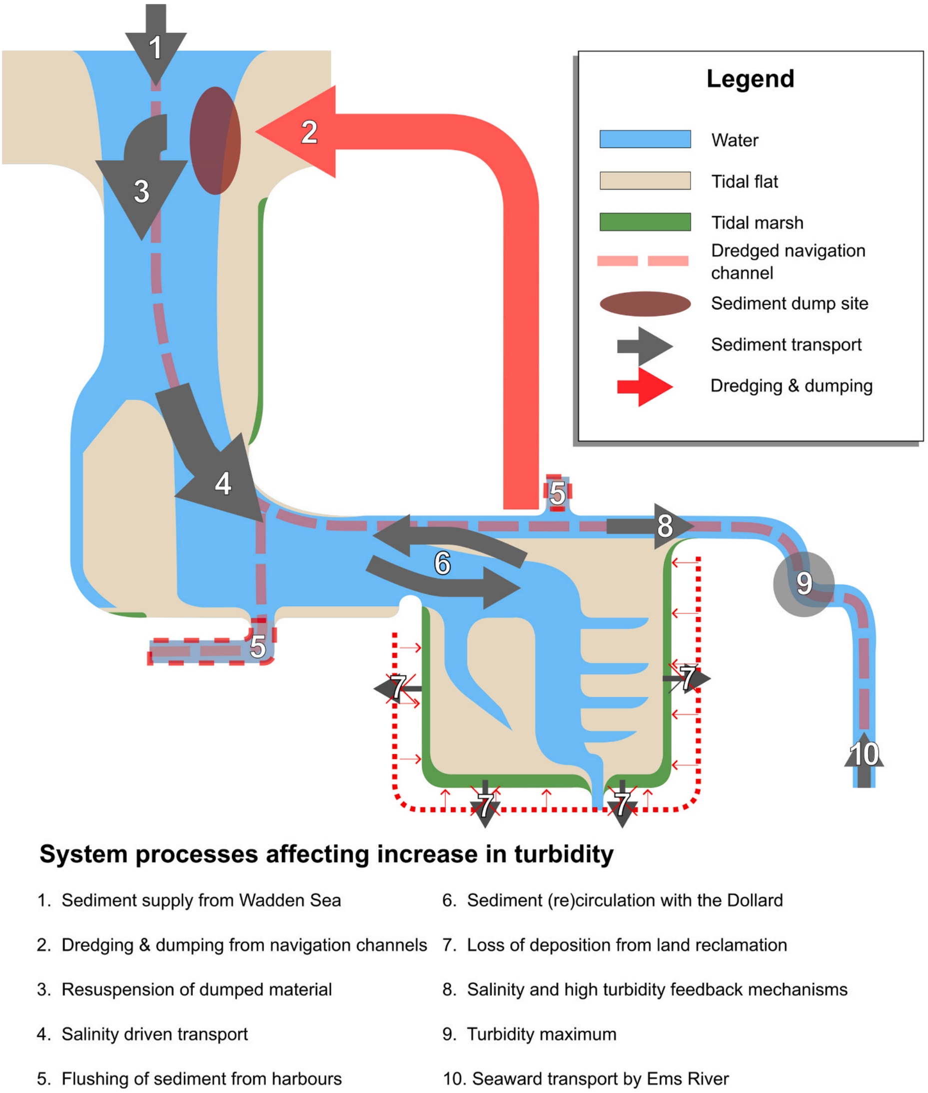

Fig. 2. Diagram depicting the current understanding of the mechanisms responsible for the rising turbidity.

et al., 2016; Papenmeier et al., 2012).

The increase in suspended sediment concentrations in the Ems River may have also influenced the turbidity in the outer estuary (de Jonge et al., 2014). Finally, the deepening of channels in the outer estuary has strengthened estuarine circulation and thereby estuarine turbidity; necessitating further maintenance dredging from the Emden fairway. The high turbidity has negative ecological consequences which are different for the lower Ems River and the outer estuary. In the lower Ems River, the breakdown of organic matter within fluid mud layers is the main driver of oxygen depletion even regularly leading to anoxic zones (<2 mg/L in summer) (Talke et al., 2009a). In the outer part of the Ems Estuary biomass has diminished severely as well from the increase in turbidity (de Jonge and Schückel, 2019).increase in turbidity has limited light penetration and thereby lowered primary production (Brinkman and Jacobs, 2023), but the increasing mud availability probably also led to shifting benthic communities (Compton et al., 2017). Although elevated turbidity levels may harm fish, no adverse effect of the higher silt levels to juvenile fish could be established (Tulp et al., 2022). Biological factors themselves, e.g. diatom blooms, can temporarily (de) stabilize sediment and seasonally affect turbidity levels (Kornman and Deckere, 1998), although it remains unclear if these affect long-term erosion or turbidity trends (van Duyl et al., 2000).

2.3. *Land subsidence, salinization and agriculture*

Its long geological history along the fringes of the Wadden Sea has shaped the Ems Estuary and its subsoil. This geology is largely reflected in the challenges of land subsidence and salinization today. The topsoil layers along the estuary consist primarily of former intertidal deposits of sandy and organic clay, with more sandy deposits close to former tidal channels (Vos and Knol, 2015). These layers in the topsoil reflect the landscape from before the land was reclaimed. Further inland, thick peat layers of several meters thick remain in places where during the Holocene inland peat bogs existed (Vos and Knol, 2015). Below the Holocene deposits the subsoil consists of compact fine sandy material accumulated during the Pleistocene with regionally strongly consolidated clay layers that act as non-erodible layers limiting the depth of tidal channels in the outer estuary (Pierik et al., 2023).

The geological setting plays a crucial role in the susceptibility to salt intrusion with sea-level rise. The hydraulic properties, particularly the transmissivity of the first aquifer (usually permeable Pleistocene sand deposits and Holocene tidal channel deposits) and the thickness and vertical hydraulic conductivity of the top confining layer (Holocene marine clay and peat deposits), are dominant factors (Oude Essink et al., 2010). Land subsidence and drainage further exacerbate salt intrusion by lowering the phreatic water level and hydraulic head in the aquifer, resulting in larger seepage fluxes (Oude Essink et al., 2010).

Anthropogenic activities have significantly impacted salinization. Land cultivation and peat degradation have contributed to 41% of the total inland salinity increase in Northwestern Germany, while the construction of drainage networks accounts for 34% (Seibert et al., 2023). The present-day salt distribution in the subsoil is not in equilibrium due to human interventions from the past (e.g. land reclamation and drainage in polders) and further autonomous salinization is expected to continue for centuries (Feseker, 2007; Pauw et al., 2012; Seibert et al., 2023). Along the Dutch side of the Ems Estuary salinization of agricultural land is projected at a few hotspots coinciding with the low-lying peatlands south of Delfzijl, as well as the reclaimed polders near Eemshaven (Delsman et al., 2022). Salinization threatens the crop production and has prompted the search for new agricultural practises to adapt to more saline conditions (van den Burg et al., 2024). Moreover, this reduction in crop production caused by the salinization of aquifers and agricultural fields threatens sustainable economic growth of the agricultural sector. Therefore, addressing salinization is crucial for maintaining long-term agricultural output and supporting sustainable economic growth in the Ems-Dollard region.

2.4. Flood protection infrastructure and sea-level rise

The land surrounding the Ems Estuary is highly vulnerable to flooding due to its low-lying topography, which ranges in elevation between ±2 m compared to mean sea level (MSL). While flood protection regulations and institutional framework differ between the Netherlands and Germany, the primary coastal dykes are similar in size along both sides of the estuary, roughly 6 to 8 m above MSL in height and over 100 m wide (AHN, 2023; LGLN, 2024). Traditionally dykes have been constructed with an outer layer of clay covered by a grass revetment, with stones and asphalt applied where hydraulic loads during design conditions are too great for grass and clay to withstand. Alternatively, dykes can be designed to cope with such loads by widening the dyke with a more gently sloping grass cover as a “wide green dyke” (van Loon-Steensma and Schelfhout, 2017). Another coastal structure is the Ems storm surge barrier (Emssperrwerk) located east of Pogum, approximately 4 km east of the Dollard. It is 476 m in length and designed to protect the hinterland of the Ems River from storm surges and will be closed at water levels higher than 3.7 m NHN (i.e., NHN is the standard German notation similar to MSL).

Along the Dutch section of Dollard, dykes are currently being reinforced for not meeting the Dutch safety standard due to the risk of erosion of the grass revetments by storm waves during design conditions as well instability of the dyke slope at the low-lying landward side (SWECO, 2022). The local water authority Hunze & Aa's responsible for these flood defence, recently presented a long-term vision that includes the need to start raising the land on the low-lying areas to secure the stability of the flood defences in the future (Hunze&Aa’s, 2025). By 2100, sea-level rise is expected to have risen between 0.43 m (median SSP1-1.9) and 0.81 m (median SSP5-8.5) at Borkum (Garner et al., 2021), the seaward edge of the estuary, with increasing loads from storm waves within the Dollard depending on the wind conditions (Niemeyer et al., 2014). This further increases the need for reinforcement in the near future.

More recently, the role of natural features like tidal flats and salt marshes have garnered attention for their ability to significantly attenuate wave energy (Möller et al., 2014) and reduce loads on flood defences (Vuik et al., 2016). An additional benefit is that marshes grow in elevation with rising sea-levels and can recover from storms, provided sea-level rise does not outpace sedimentation rates (Best et al., 2018; Pannozzo et al., 2021). Moreover, the maintenance and expansion of marshes provides valuable carbon sequestration services, capturing and storing carbon (Artigas et al., 2015; Mueller et al., 2019) and helping to mitigate climate change. Nevertheless, relying on nature-based elements like marshes for flood protection is contentious as such (marsh) ecosystems do not typically develop naturally along coastal stretches with high hydrodynamic loads where they would be most effective (Marin-Diaz et al., 2023).

3. Policies and governance context

3.1. Governance setting

The Ems Estuary is a transboundary water system shared by the Netherlands and Germany, and its governance is shaped by a long history of bilateral negotiation and cooperation. Nevertheless, part of the Ems Estuary is officially disputed territory. According to the Netherlands, the Dutch German border should be drawn at the thalweg of the Ems River, a customary rule for establishing a river border between two countries. According to Germany, the border lies at the western bank of the Ems River at the low tide mark. This is based on a bill from 1454 claiming the entire river (Tanja, 1987). This was later confirmed in 1558 by King Ferdinand and re-established in 1648 when the border between a sovereign Dutch republic and the German empire was drawn (Brunet-Jailly, 2015). The actual borderline has not been settled and instead it has been agreed to “disagree” on the boundary while practical arrangements on maritime affairs were made in the Ems-Dollard Treaty (Eems-Dollardverdrag, 1960). The rationale behind this pragmatic arrangement was to prevent political deadlock while ensuring coordinated navigation, environmental protection and flood safety in the estuary. As a result, a joint water commission (the G-Commission, G indicating the Ems-Dollard region among the 7 subcommittees) was established in 1963 focusing on the transboundary administration of water resources to provide joint guidelines for sustainable water management.

Water management and nature conservation are based on the Eems-Dollard Environmental Protocol (1996), which consists of the Water Framework Directive (WFD) and High-water Risk Management Directive (HWRM-RL). To operationalize these frameworks, specialized working groups (WG) such as Water Quality, Monitoring, and Hund-Paapsand are commissioned with experts from both countries to coordinate technical implementation.

A new border dispute arose when the 1982 UN Convention on the Law Of the Sea (UNCLOS) came into force extending territorial waters to 12 nautical miles offshore with the necessity to adjust national legislation. Since 1988, Germany and the Netherlands have been negotiating over the lateral delimitation of their territorial sea between 3 and 12 nautical mile (Brunet-Jailly, 2015) and in 2014 an agreement was signed stating that the border will remain ambiguous, and both nations will share responsibility for the area. This reflects a broader trend of shared sovereignty in transboundary estuaries, where ecological and economic interdependence make rigid demarcation impractical.

Flood protection around the Ems Estuary is organized separately by the Netherlands and Germany, each governed by distinct legal and institutional systems. In the Netherlands, flood safety is regulated by the Water Act (Waterwet), which mandates protection standards based on cost-benefit analyses and a minimum requirement for safety against flooding (Kok et al., 2017). Along the Ems Estuary, this translates to a design standard of a 1/3000 annual exceedance probability. Implementation and maintenance of flood defences are the responsibility of regional water boards with funding provided for 90% through the national High Water Protection Program (HWBP), 10% by the regional water authority and supplemented by regional contributions from the Province of Groningen or other funding programs to align with local spatial and ecological goals. On the German side, the estuary falls within the province of Lower Saxony, where flood protection is guided by the General Plan for Coastal Protection (Generalplan Küstenschutz) (NLWKN, 2007) and legally underpinned by the Lower Saxony Dyke Act (Niedersächsisches Deichgesetz: NDG). The NDG defines the planning, construction, maintenance, and legal responsibilities for dykes and other coastal protection structures and is complemented by additional legislation such as the Environmental Feasibility Act (NUVPG), the Nature

Conservation Act (NNatG), and the Spatial Planning Act (NROG). The region is protected by approximately 610 km of dykes maintained by 22 Dyke Organizations (Deichverbände: DVB). These DVBs are local dyke associations include representatives from local communities and the NLWKN. They are responsible for specific stretches of dyke and operate under NDG guidelines. According to the Highwater Risk Management Directive (Hochwasserrisikomanagement-Richtline: HWRM-RL) 2016-2021, the water depths due to the risk of inland flooding are estimated under three scenarios (high, medium and low probability of occurrence). The landward boundaries of DVBs are based on the most extreme of these potential flooding scenarios, hence they are responsible for a risk-based buffer zone along the Lower-Ems estuary rather than predefined regions. Funding is shared between the Lower Saxony state (30%) and the federal government (70%), with additional support from EU programs. In the Ems-Dollard region, six DVBs are active, including those from Heede-Aschendorf-Papenburg (1) to Krummhörn (6) (Fig. 3). The contrasting governance traditions are notable: Dutch management is centralized and technocratic, aiming for safety optimization, while German management is decentralized and participatory, reflecting federal administrative traditions.

3.2. Jurisdictional complexity

The governance of the Ems Estuary is shaped by a dense and often overlapping web of international, European, bilateral, national, and regional legal frameworks (see Table 1). At the European level, four key directives apply: the Water Framework Directive (WFD; 2000/60/EC), the Natura 2000 network consisting of the Habitats Directive (92/43/EEC), the Birds Directive (79/409/EEC), and the Marine Strategy Framework Directive (MSFD; 2008/56/EC). These directives aim to protect water quality, biodiversity, and marine ecosystems. The management of European Directives in the Ems Estuary is carried out jointly by the Netherlands and Germany but their implementation across the Dutch-German border is far from uniform, leading to a fragmented governance landscape. This creates asymmetrical environmental responsibilities and fragmented implementation across the border. For example, most salt marshes on the German coast (including Dollard) are designated as Natura 2000 sites, but not included as WFD water body, whereas on the Dutch side the Dollard salt marshes are part of both. And within the Ems-Dollard Treaty area there are two Natura 2000 sites that have overlapping authorities, these are the tidal flat Hond-Paap/Hund und Paapsand and the northern part of the Dollard named Ems Marsh extending from Pogum to Knock. Moreover, although Germany applies all eleven descriptors of the MSFD within the coastal water bodies of the Wadden Sea, based on Dutch legislation implementing UNCLOS, the waters of the Wadden Sea are internal waters and thus the MSFD does not apply. Consequently, within the Treaty Area, the overlapping WFD coastal water bodies Eems-Dollard coastal area and Polyhalines coastal area of the Ems Estuary form part of the MSFD for the German authorities, but not for the Dutch authorities. These examples illustrate the complex cross-boundary jurisdictional and policy implementations in the Ems Estuary.

Further jurisdictional complexity arises from conflicts with flood protection regulation. While this legal framework ensures high levels of flood safety by dykes, it also physically and administratively disconnects the estuary from its hinterland. This disconnection is recognized as a contributing factor to the estuary's degraded ecological state, particularly in relation to sediment dynamics and turbidity (van Maren et al., 2016). Programs on both sides of the border have acknowledged the need to reconnect the estuary with its adjacent low-lying coastal zones,

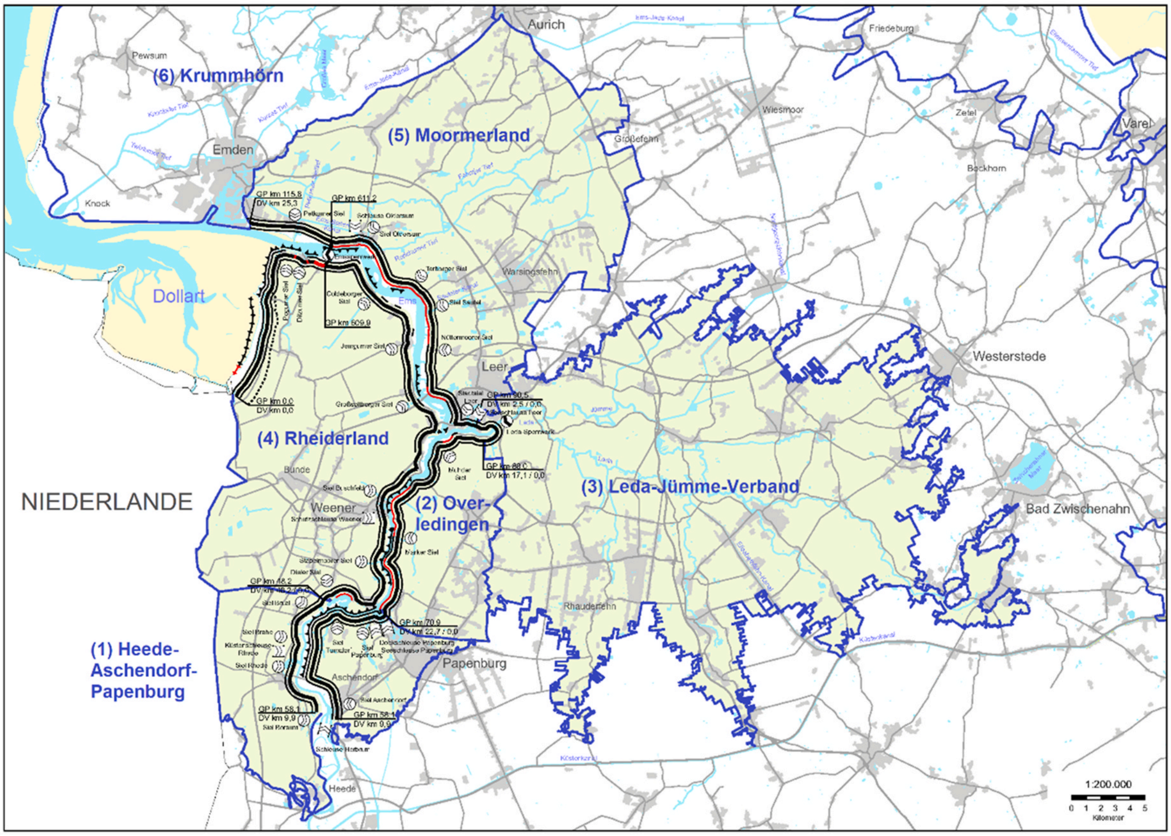

Fig. 3. Deichverband (DVB) along the Ems-Dollard estuary: Heede-Aschendorf-Papenburg (1), Overleding (2), Leda-Jümme-Verband (3), Rheide (4), Moormerländ (5) and Krummhörn (6) (green-line). Thick-black-line: Heightened Dyke, thick-red-line: under construction dyke, thin-black-line: available dyke protection roads, thin-red-line: required dyke protection road, black-saw-line: revetment area (NLWKN, 2007). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 1
Overview of legal instruments affecting policies in the Ems Estuary.

Jurisdiction	Legal Instrument	Institutional Lead in the Ems Estuary	Description
Netherlands (NL)	Water Act (Waterwet)	Rijkswaterstaat and Regional Water Boards	Governs water safety, quality, and spatial planning; sets flood protection standards.
	High Water Protection Program (HWBP)	HWBP Board (Rijkswaterstaat + Water Boards)	National program funding flood defence upgrades and maintenance.
Germany, Lower Saxony (GE)	Lower Saxony Dyke Act (NDG)	NLWKN and Deichverbände (Dyke Associations)	Legal basis for dyke planning, construction, and maintenance responsibilities.
	General Plan for Coastal Protection	NLWKN and Lower Saxony State Government	Strategic framework for coastal protection and dyke safety.
	Environmental Feasibility Act (NUVPG)	Lower Saxony State Government	Regulates environmental assessments for infrastructure and planning projects.
	Nature Conservation Act (NNatG)	Lower Saxony State Government	Provides legal protection for habitats and species.
	Spatial Planning Act (NROG)	Lower Saxony State Government	Governs land use, zoning, and spatial development.
European Union	Water Framework Directive (WFD)	National ministries and regional water authorities (NL & GE)	EU directive to achieve good ecological and chemical status of water bodies.
	Flood Risk Management Directive (HWRM-RL)	NL: Rijkswaterstaat and Regional Water Boards; GE: NLWKN and Deichverbände (Dyke Associations)	EU directive for assessing and managing flood risks.
	Habitats Directive (92/43/EEC) and Birds Directive (79/409/EEC)	NL: Ministry of Agriculture, Fisheries, Food Security and Nature + Rijkswaterstaat (maritime areas); GE: the Lower Saxony Ministry for the Environment, Energy, Building and Climate Protection + NLWKN	Protects natural habitats and (bird) species across EU member states.
	Marine Strategy Framework Directive (MSFD)	NL: Rijkswaterstaat (limited); GE: NLWKN and Federal Maritime Agencies	Ensures sustainable use of marine waters and protection of marine biodiversity.
Transboundary	Ems-Dollard Treaty (1960)	G-Commission	Treaty enabling cooperation on navigation, flood safety, and environmental protection.
	Ems-Dollard Environmental Protocol (1996)	G-Commission and Working Groups	Protocol operationalizing joint water management under WFD and HWRM-RL.
International	UN Convention on the Law of the Sea (UNCLOS)	Ministries of Foreign Affairs and Maritime Authorities (NL & GE)	Defines maritime boundaries and rights; influences MSFD applicability.

but no legally binding mechanism exists to facilitate systemic cross-border restoration, relying instead on cooperation between both nations. Renaturalization plans and projects for the Ems-Dollard require weighing the interests of the natural system and of society and economy, which has proven to be a sensitive matter. The present socio-economic use of the waterways such as navigation, harbours and shipyards, for which an increased channel depth is required, prevents hydromorphodynamics from returning to a natural balance (Van der Werf et al., 2022). Yet, given this unbalanced starting position, many initiatives are undertaken to improve the natural functioning of the water system, such as the "Ems-Dollard 2050 Programme" in the Netherlands and the "Masterplan Ems 2050" in Germany (further elaborated in Section 4.1).

4. Restoration plans

4.1. Transboundary plans and visions

The development history of the Wadden Sea coastal area has always been strongly influenced by climate change. For a long time, measures were focused on water safety (construction and reinforcement of dykes) and the agricultural use of the hinterland, anticipating the expected change in sea level rise and water management due to climate change. As raised in the previous sections, since the 1970s, also measures have been taken aimed at improving water quality and nature conservation and restoration. There has been a cooperation between Germany, the Netherlands and Denmark for almost 50 years aimed at protecting the Wadden Sea as an ecological entity. The cooperation is based on the 'Joint Declaration on the Protection of the Wadden Sea', and the guiding principle is "to achieve, as far as possible, a natural and sustainable ecosystem in which natural processes proceed in an undisturbed way".

In response to the increasing concern about the potential impact of climate change, in 2008 the Dutch Delta Committee developed a vision for the future that extends beyond 2100 and in which water safety plays an important role. This involves protection against both flooding due to a rising sea level and more extreme river discharges but also securing the freshwater supply. The recommendations of the committee emphasize the ability to adapt to climate change by 'building with nature', incorporating natural and ecological processes to adapt to the coast in the coming century (Delta Committee, 2008). Since 2011, various studies have been carried out by the Wadden Sea Deltaprogram to explore possible adaptation strategies, followed by the exploration of various pilot projects (see section 4.2). Sediment was recognized as an important adaptation asset for long term adaptation but requires measures that would need space both on sensitive N2000 areas (salt marshes) and inland. The province of Groningen started in 2015 and 2016 with reserving land in its spatial planning to implement pilots and explore such strategies. Pilot projects explore a long-term vision to transition from a linear coastal defence to a broader, multifunctional coastal zone.

Governmental, non-governmental, and commercial users have proposed a series of measures to restore the ecological quality of the Ems Estuary. In the Netherlands, the proposed measures target three key aspects: i) Hydromorphological integrity; ii) Estuarine connectivity; iii) Primary productivity (Lenselink et al., 2015). To coordinate and implement these efforts, the Dutch government launched the

"Ems-Dollard 2050 Programme" in 2016, bringing together several parties under a shared implementation framework. This program outlines several environmental objectives: i) To build new habitats along the coastline of the Dutch part of the Ems Estuary in combination with dyke reinforcements for flood safety; ii) To explore, develop and test methods to extract silt from the Ems Estuary and subsequently use this material in an economical viable way; iii) To develop more knowledge on the interplay between currents and sediments in order to influence these dynamics to reduce turbidity. In 2024, Dutch regional water authorities (Noorderzijlvest and Hunze & Aa's) and the province of Groningen jointly advanced a programmatic vision for coastal development, reaffirming and further elaborating the previous plans for raising agriculturally valuable areas and enhancing inland connectivity Delfzijl and Lauwersmeer. The concepts are depicted in Fig. 4.

In Germany, the "Masterplan Ems 2050" was developed in response to the European Commission's demands to enhance conservation efforts in the Natura 2000 sites along the Ems River. The "Masterplan Ems 2050" was signed in 2014 by the Lower Saxony Government, the Central Government, the local administration authorities (Emsland, Leer and Emden), Worldwide Fund for Nature in Germany (WWF), The Environmental agency from the central government, the nature conservation agency from the Lower Saxony government and the Meyer Dockyard company. The plan's main objectives are: i) improving water quality, with an emphasis on reducing turbidity; ii) enhancing riverine and estuarine habitats, particularly for bird species; and iii) supporting regional economic growth, particularly by maintaining navigation channels.

Jointly the province of Lower Saxony and the Netherlands have agreed to explore ecological sediment management strategies. The main objectives are to minimize the siltation in the estuary and to ensure further utilization of fine material considering the natural sediment dynamics and pathways. These strategies are operationalized through action plans designed to increase resilience to climate change and sea-level rise, under the coordination of the G-Commission. The first agreement between Lower Saxony and the Netherlands was signed on the April 5, 2019 with the objectives to decrease suspended sediment concentration, improve the quality of habitats and biodiversity, continuous growth of foreshores within the Wadden Sea areas with sea-level rise, and the use of fine material to adapt flood defences to sea-level rise. These action plans are implemented under the framework of the G-Commission. The Netherlands and Germany have recently (April 2025) reinforced their partnership by signing an updated "Ecological Strategy for Sediment Management", marking a further step towards long-term, joint ecological stewardship of the estuary. This initiative reaffirms joint strategies to tackle shared challenges of turbidity and sediment imbalance, so to enhance ecological quality, navigability, and liveability within the Ems Estuary.

4.2. *Catalogue of pilot measures in the Ems Estuary*

The restoration measures implemented in the Ems-Dollard region by both countries are listed and linked to the specific challenges from section 2 (Table 2). Two primary objectives have been defined to enhance ecosystem quality: reducing water turbidity, and expanding and strengthening native habitats. These environmental objectives must be pursued alongside ensuring flood safety and promoting sustainable agriculture, reflecting the shared ambition of both countries to achieve a restoration outcome with ecology and economy in balance.

Strategic dredging in Ems-Dollard aims to extract sufficient fine sediment from navigation channels and tidal basins to reduce turbidity levels in the water column, thereby improving water quality, while simultaneously preserving the geomorphological stability of sandbanks and mudflats (ED2050, 2017). The extracted sediment is not treated as waste but as a valuable resource, repurposed through deposition in sheltered zones or through its integration into clay ripening project (2). In this context, extensive pilot-scale clay ripening facilities have been established in the Ems-Dollard region, with test plots totalling approximately 24 ha in Delfzijl and along the Dollard dyke, and where multiple techniques were applied and monitored to accelerate the transformation of soft sediment into structurally stable clay (ED2050, 2023). Following the ripening of the sediment, in 2021, approximately 4 ha of low-lying agricultural land were elevated by 70 cm using the dredged material (3). As part of the ripening process, this sediment was desalinated and dewatered to promote its transformation into workable arable soil (Barciela-Rial and van der Star, 2024; ED2050, 2021). Continuous monitoring is necessary to assess key factors following the raising of the land (e.g., the subsidence behaviour, drainage characteristics) to ultimately evaluate its long-term suitability for agricultural use. Furthermore, clay derived from dredged sediment was successfully utilized in the construction of a 750-m test section of the Broad Green Dyke (4), after a 3-5 year sediment ripening period (Leod et al., 2025). The Broad Green Dyke is a multifunctional flood defence that integrates ecological

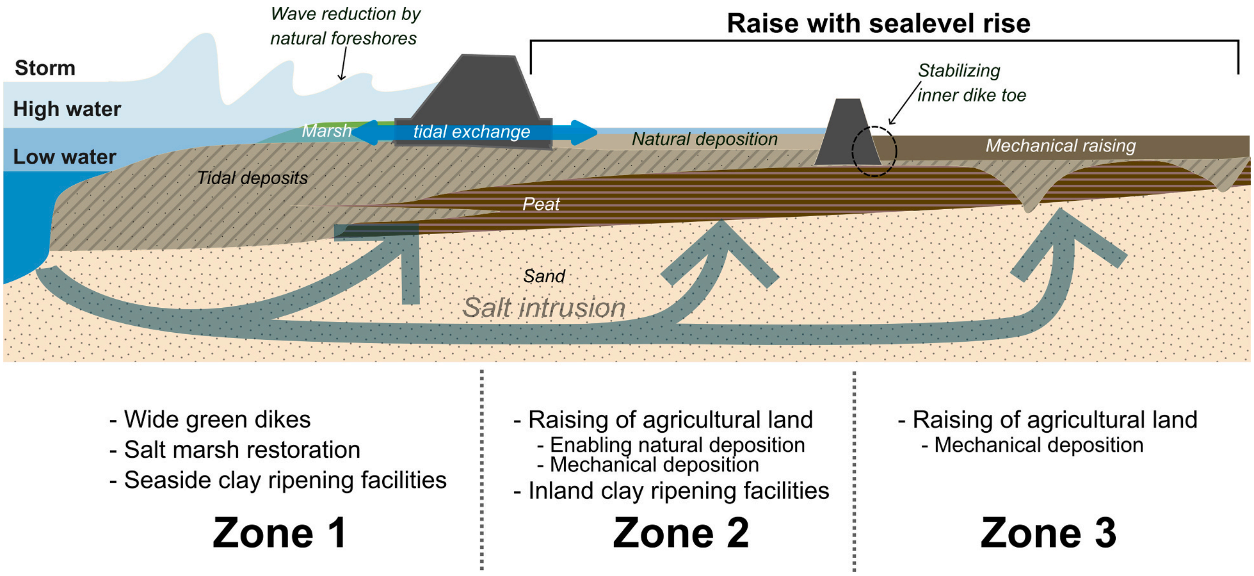

Fig. 4. Vision for the coastal zone along the Ems Estuary following the programmatic vision for coastal development by the Dutch regional water authorities and province of Groningen.

Table 2
Overview of restoration measures implemented or prepared by the Netherlands (NL) and Germany (GE) with the specific challenges they address. The numbers next to each measure correspond to references cited in the text. Measures indicated with a * are currently being considered for upscaling.

	Country	Challenges			
		Ecosystem health		Sustainable agriculture	Flood safety
		Reducing turbidity	Strengthening natural habitats		
Measures:					
Dredging & extraction (1)	GE/NL	x			
Clay ripening for re-use of dredged material (2) *	NL			x	x
Raising agricultural land (3) *	NL			x	x
Broad green dyke (4)	NL		x		x
Bird nesting islands (5)	NL		x		
Rich dyke + reef blocks (6)	NL		x		x
Twin dyke and intermediate area (7)	NL	x	x	x	
Marconi (outside the dykes) (8)	NL	x	x		x
Sedimentation outside the dykes- Brushwood Groynes (9)	NL	x	x		x
Kleine polder (10) *	NL	(x)*	x*		
Breebaart polder (11)	NL	x	x		
Mussel bed recovery (12)	NL		x		x
Flexible tidal control on lower Ems (13)	GE	x			x
Tidal polder Coldemüntje (14)	GE	x	x		
Freshwater polder Stapelmoor (15)	GE		x		x
Improved connectivity at sluices in Knock, Oldersum, Herbrum (16)	GE		x	x	
Tidal habitat restoration at Coldemuntje (17)	GE		x		
Riparian habitat restoration 700 ha (18)	GE		x	x	
Sea grass restoration Hund-Paapsand (19)	GE/NL		x		
Integrated foreshore management and salt marsh expansion (20)	GE	x			x
Application of dredged material for agriculture (21)	GE	x		x	
Bird island at Pogum (22)	GE		x		

and engineering design by using locally sourced materials (Marijnissen et al., 2020). The excavation in the salt marshes, where a part of the extracted and ripened sediment came from, resulted in the formation of the Klutenplas, a shallow water body with an artificial nesting island (5) that now serves as habitat valuable bird species (Marijnissen et al., 2020). Sediment from the Ems-Dollard estuary has also been repurposed into making reef blocks to facilitate the settlement of mussels and oysters, thereby enhancing biodiversity and contributing to the flood safety function of the Rich Dyke (6). The Rich Dyke measure also includes the construction of tidal pools along the dyke that serve as additional habitat, and a vertical pole forest with suspended ropes promotes mussel attachment and growth.

Following on the coastal protection measures, an additional flood defence intervention is the Twin Dyke (7), consisting of a primary, seaward-facing high dyke and a secondary, lower inland dyke. Together, they provide a two-layer defence against storm surges and other multifunctional uses in the inter-dyke zone (Marijnissen et al., 2021). A tidal culvert in the sea dyke enables tidal exchange within the inter-dyke zone, creating a controlled tidal system in the area between the dykes, which is divided into two functional zones. The southern section (~10 ha) is designed as a tidal wetland for sediment deposition and brackish habitat development, acting as a natural filter that supplies clear, nutrient-rich water to the northern zone (~27 ha). The northern zone serves as a testbed for shellfish aquaculture and salt-tolerant agriculture, and the water flow between the zones is controlled.

Another example of sedimentation-focused infrastructure is the Marconi project (8), which involved the creation of a 16-ha pioneer salt marsh, a 13-ha elevated salt marsh, and a bird nesting island (5) (Baptist et al., 2021). Altogether, the Marconi project expands the area available for fine sediment deposition from the estuary, increases habitat areas, and provides space for recreation and leisure. To further stimulate sedimentation outside the dykes and mitigate erosion, Brushwood Groynes (9) are to be installed in the northwestern Dollard. The groynes, constructed from bundles of brushwood, are placed along a 2.5 km stretch within a 500-m offshore zone. The groynes are to be installed in meandering shapes aligned with the natural coastline rather than straight lines.

In addition to the previously described interventions, several other nature-based solutions have been implemented in the Ems Estuary and Dollard Bay region to enhance ecological function and climate resilience. In the Kleine Polder (10), the landscape was reconfigured to support both biodiversity and recreational use. A culvert was also installed to connect the site with the Termunterzijldiep, thereby improving fish migration pathways. While the contribution of Kleine Polder to habitats in the estuary is small, it is intended for scaling up into Groote Polder (adding up to 150 ha of wetland) where greater habitat gains would be achieved as well as acting as a sediment sink similar to Polder Breebaart. In Polder Breebaart (11), a former polder converted to wetland by reconnecting the polder to the estuary through a culvert, excessive deposition of fine material within the channels at the site prompted a pilot to dredge 70,000 m^3 of fine sediment for experimentation. This sediment was dredged, ripened, and matured for use into dyke-grade clay and was used in the Broad Green Dyke (4). Polder Breebaart aims to enhance sedimentation and habitat quality, for which purpose a channel was excavated to link the tidal zone with a freshwater pond, creating additional space for sediment deposition through a fine sediment trap. The moat between the bird island (5) and the dyke was widened to act as a barrier against predators (e.g., foxes) and parts of the island's surface were covered with shell material to improve nesting success. Fish migration was restored through the installation of a culvert linking the freshwater and tidal zones. The last of the Dutch nature-based solutions is the Hond-Paap shellfish restoration project (12). It aims to rebuild lost mussel beds using biodegradable nets pre-seeded with juvenile mussels (Glorius et al., 2021).

In relation to the German measures, the "Masterplan Ems 2050" lists a set of measures for the Ems River aimed at improving the hydromorphological and ecological conditions through tide management, sediment dynamics and habitat restoration. One of the central measures is the flexible tidal control with the Emssperrwerk (13), which seeks to limit the upstream propagation of tidal energy and to reduce flood dominant net upstream sediment transport into the Lower Ems.

The tidal polder Coldemüntje (14) is in operation since spring 2025, which has created about 35 ha of land for new habitat and biotopes as a result of water exchange with the lower Ems river during flood- and ebb-tides. Currently, the foreland area between the river and dyke has a marginal space for habitats. Therefore, this polder with the shallow oscillatory water level areas provides ample opportunities for the growth of biodiversity. According to the masterplan, such biotope areas will be increased up to 500 ha by 2050.

Stapelmoor is the second polder (15) under the "Masterplan Ems 2050", which is a freshwater area with no connection with the Ems river, however it provides benefits for the Ems habitat and biodiversity. This pond is mainly filled with rainwater reaching a maximum water level up to 1.35 m NHN, and having an average depth of 0.85 m. These conditions have supported to populate typical plants in the shore areas with changing water levels, and to accommodate adaptive species. Due to building up thick clay-layering at the bottom, water seepage to aquifers is prevented, which minimises the risk for the neighbouring drinking water facility.

The Masterplan also seeks improvement of ecological connectivity at key sluices (16), including those at Knock, Oldersum, and Herbrum. Specific state funding was allocated for improving ecological functionality at the Knock sluice, including evaluations of how modifications to the outer lock may contribute to habitat stability. Similar interventions have taken place at the Oldersum sluice, although its isolated location may limit connectivity benefits.

A broader objective under the Masterplan is the restoration of 700 ha of tidal (17) and river floodplain (18) for bird habitat expansion. This restoration includes the creation of estuarine habitats in tidal biotopes and polders, following a two-phase program: i) the development of riparian forests, reed beds, and tidal flats alongside significant reductions in turbidity; and ii) the establishment of inland meadow habitats for breeding birds. This measure is interdependent with others, such as improving connectivity at sluices (16).

Under the ANK (Action programme for natural climate protection) founded programm (C-HuPaSed) and continuesly discussed in WG Hund-Paapsand, NLWKN is preparing a pilot on how natural seagrass resettlement can enhance carbon storage in the Ems estuary (19). The project focuses on improving hydro- and morphological conditions using dredged material from Ems fairway maintenance. Sediment is applied to the Paapsand to support seagrass growth, aiming to boost carbon storage, reduce emissions, and enhance resilience to sea level rise.

There are two other climate resilience projects prepared by Germany in the Ems-Dollard estuary area: the first pilot is an integrated foreland management plan to expand saltmarshes and promote sedimentation called KliResDol (20). The second pilot project explores the use of fine material dredged mud and silt from the Ems fairway (1) for agriculture (21). A monitoring campaign is planned to gather necessary information (e.g., soil fertility, plant growth, crop production, nature conservation) to evaluate the overall potential contribution of dredged material for the climate resilience, raise land behind the dykes at the eastern German side of the Dollard, similar to the clay ripening (2) and raising of agricultural land (3) at the Dutch side. The third project carries out a feasibility study for implementing a bird island in the foreshore area at the eastern side of the Dollard near Pogum (22) to create favourable hydrodynamic conditions for the saltmarsh growth (C-VolDolSed). The goals are to enhance carbon sequestration, increase the elevation of the foreshore as a climate adaptation measure, and provide a safe habitat for birds.

4.3. Key lessons from pilots so far

The first pilot to be operational is the polder Beebaart. Connecting the former polder back to the estuary with a 2 by 1 m culvert has resulted in significant deposition within the polder, approximately 30 cm/year in the tidal channels and 10 cm/year in the flats between 2001 and 2003 (Tydeman, 2005). To restore its intended ecological functionality, eventually 70,000 m^3 of mud was dredged between 2018 and 2020. This demonstrated a possible method for the active removal of sediment from the Dollard to reduce turbidity in combination with nature restoration. Furthermore, it inspired the initiation of the (at the time of writing) yet to be completed Double Dyke pilot at Bierum.

Another method for sediment extraction was demonstrated in the Wide Green Dyke project. Sediment was removed form marsh in the Dollard in the form of a moat called the “klutenplas” to temporarily create a bird island for additional ecological benefits. Monitoring demonstrated rapid deposition of weakly consolidated mud of 70 cm on average within two and a half years. Initial deposition was rapid and slowed down to 5 cm in the final half year as inundation became less frequent (Esselink et al., 2020). The construction of the klutenplas did not affect marsh erosion or vegetation cover in the surrounding marsh (Esselink et al., 2020). This pilot demonstrates that, at least on a small scale, sediment can be extracted from the Dollard marsh without large adverse effects and effectively trap new sediment in the marsh naturally.

The Clay Ripening Pilot demonstrated that thin clay layers mature faster than thick ones, and mechanical treatments like ploughing and turning improved ripening rates significantly (ED2050, 2023). Despite not meeting all standard clay quality guidelines for salinity and organic matter content, it could still be suitable for dyke construction by incorporating the material's actual properties into the design of the flood defence. Applying dredged sludge on the test dykes showed promising initial results. The thickness decreased up to 70% following a decrease in water content to a constant thickness within two weeks and vegetation recovered after application of the dredged sediment (Leod et al., 2025). Experiments with dredged sediment from the Ems Estuary suggests desalination for agricultural use requires rinsing the sediment with fresh water followed by rapid drainage of the water to minimize nutrient loss (Barciela-Rial and van der Star, 2024), although more testing is required to find a practical procedure.

The Marconi pilot used dredged sediment to construct new marshes and successfully supported new pioneer marsh vegetation. The most important factor was the formation of tidal creeks at the restoration site for drainage, the supply of at least 20% mud into the bed sediment, and the supply of nutrients. Tidal creeks formed primarily following the topography and tidal prism with only a limited influence of the brushwood groynes. Further long-term monitoring is needed to assess sedimentation trends and determine the effectiveness of this constructed wetland as a sediment sink for the estuary (de Vries et al., 2021; Baptist et al., 2021).

The Ems barrier at Pogum (Emssperrwerk) has proven effective so far. It was closed 19 times between December 2005 and December 2024 to protect the lower Ems region from storm surges along a 110 km stretch of dyke. It also ensures adequate water depth for ship traffic between Papenburg and Emden, accommodating surge levels up to 2.7 m NHN (NLWKN, 2021). In 2020, a test with the barrier was conducted under the "Masterplan Ems 2050", demonstrating that barrier operations can influence the fluid-mud distribution and thereby water quality between Knock and Hebrum. Additionally, poldering efforts have enhanced biodiversity and helped remove suspended particles from the water. Continuous monitoring of these polders shows encouraging results, guiding future strategies within the "Masterplan Ems 2050".

The pilot projects also provided key insights into legislative and governance barriers. Existing legislation did not easily facilitate the implementation of measures; in all cases, exceptions were obtained by designating the activities as pilots. For instance, sediment extraction from salt marshes was initially prohibited, but permitted through consensus among stakeholders as pilots (pers. comm. M. Buurman, July 2025). Similarly, operations within wetlands protected by Natura (2000) and their potential expansion into zones beyond the established boundaries of the estuary were also accepted if framed as pilots (pers. comm. M. Buurman, July 2025). Once pilots have demonstrated ecological and operational benefits, new regulatory pathways for upscaling must be established.

5. From pilots to upscaling

5.1. Upscaling strategies for the Ems-Dollard estuary

Small-scale, hands-on projects can be effective in achieving targeted adaptation goals (as summarized in Section 4.3). However, their localized impact often limits broader systemic benefits. To enhance the adaptation of entire coastal regions a more integrated, large-scale approach is required rather than isolated interventions. Upscaling plays a central role in this transition by enabling the wider application of proven measures, amplifying their benefits and supporting the ecological and socio-economic functioning of the coastal system. In this study, upscaling refers to the strategic expansion and replication of effective local measures across broader geographic areas and ecosystems. It must build on proven knowledge and practices by integrating local insights from pilot sites.

Upscaling strategies for the Ems Estuary have been developed both on the Dutch and German sides. On the Dutch side, the Groeidelta (Growing Delta) Programme led by the Province of Groningen is an integrated upscaling plan with specific adaptation strategies and measures for the coming decade (2027-2037) (ED2050, 2021). On the German side, specific upscaling goals are set to continue to pursue the objectives of "Masterplan Ems 2050"): ecological restoration of the Ems River and the preservation of its economic functions (The State of Lower Saxony, 2015).

A sediment management strategy must consist of three components: (1) a sediment source, (2) a target area, and (3) a means of transport. In the Ems Estuary, suspended sediment in the water is both the source and a central challenge. Strategies can be distinguished by the location of the target site, i.e. landside or seaside of flood defences, and by whether sediment is transported naturally or artificially. Flood defences block the natural transport toward the hinterland, creating a transition across the landscape of strategies: from landside areas where only artificial placement is feasible, to foreshores where natural deposition occurs readily. Recognizing this transition and linking strategies to local challenges reveals three main scalable sediment management approaches (Fig. 5).

Strategy A emerges from using sediment to address challenges in the hinterland by artificially transporting sediment over flood defences.

The primary upscaled measure is the large-scale application of dredged sediment for agricultural land raising. The expectation is a reduced salinity load into the topsoil of the raised polders (see Section 2.3). Substantially raising the land directly behind the dykes also stabilizes the inner side of the flood defences against sliding during high water events, both from the added soil weight and higher inside groundwater table. Consequently, if a flood would occur the inundation depth reduces. For this strategy, the high turbidity in the Ems Estuary is a resource rather than an inherent problem. Measures including the extraction of sediment, either from dredging or taken from the intertidal zone, should be upscaled to meet the demand for clay. As an optimistic upper estimate disregarding sediment losses from processing and bulk dry density estimate of 1000 kg/m^3 for consolidated mud, meeting the current ED2050 goal of extracting one million tonnes of (dry) sediment per year, would equate to raising 1000 ha of land by 10 cm annually. The amount of sediment available for extraction depends on several factors, including the method of extraction, whether it's dredging from channels and harbours, direct removal from the (new) intertidal zone, or clay mining through pits in tidal marshes. However, as turbidity decreases over time and sea-level rise accelerates, locally dredged material can no longer support sufficient land raising, and thus alternative resources are needed. Moreover, the morphological response to large-scale clay extraction remains difficult to predict with our current system understanding.

In strategy B sediment management targets the flood defence zone itself, involving options to create pathways for the natural transport of sediment through floods defences (e.g. with culverts) as well as the artificial heightening of the flood defences themselves. The strategy combines traditional and multifunctional (e.g., NbS) flood protection approaches for enhancing coastal resilience. Coastal resilience is herein defined as ‘the capacity of the socioeconomic and natural systems in the coastal environment to cope with disturbances, induced by factors such as sea level rise, extreme events and human impacts, by adapting whilst maintaining their essential functions’ following Masselink and Lazarus (2019). Such a strategy builds on existing flood defence practices, such as dyke strengthening, but also incorporates multifunctional elements to address broader estuarine challenges. Examples include the use of extracted sediment in wide green dykes, habitat creation through the double dyke concept as in Polder Breebaart, and the proposed use of the Emssperrwerk for tidal control to reduce sediment inflow into the turbid Ems River. Such a strategy has benefits and disadvantages. A key advantage of strategy B is its ability to leverage well-established governance structures for flood protection to deliver additional ecological and sediment management benefits, e.g. in the case of the wide green dyke pilot (van Loon-Steensma and Vellinga, 2019). Secondly, its ability to (partially) adapt to rising sea levels may lead to reduction of coastal protection efforts which provides more safety at lower costs on the long term. A third advantage is that natural defences strengthened with natural elements have a residual performance (Piercy et al., 2021), resulting in incomplete failure upon dyke breaching in contrast to traditional coastal defences which fail completely upon breaching. However, multifunctional flood defences also have disadvantages. They can be more costly, complex to implement, and may introduce additional operational risks. Therefore, this strategy requires careful balancing of cost-effective short-term safety with long-term resilience and multifunctionality.

Finally, moving from strategies for flood defences to coastal foreshores, strategy C focuses on restoring estuarine ecosystems and enhancing biodiversity through the creation and expansion of natural habitats. As such it is more nature-based than strategy B, and located more seaward. Upscaled measures under this strategy include the direct construction of new habitats, e.g. bird islands and wetlands within the estuary, as well as the managed expansion of existing wetlands using structures like brushwood groynes. Additional efforts involve creating new wetland areas along the Ems River and within multifunctional flood defence systems, such as the double dyke concept. A central objective of this strategy is to improve water quality by reducing turbidity, while simultaneously enhancing the resilience of habitats to sea-level rise. By promoting natural sediment deposition in vulnerable intertidal zones,

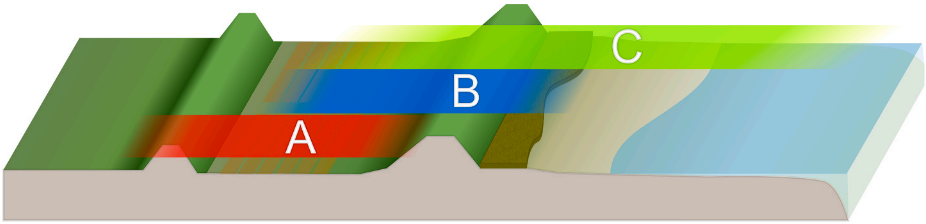

Fig. 5. Spatial prioritisation of climate resilience across the landscape by strategies A: land raising and agriculture within polders behind the primary dyke, B:flood protection, focused around the primary defences and C coastal resilience and habitat restoration, focused primarily seaward of the primary defences.

habitats can maintain their elevation and ecological function over time in spite of rising sea-levels. This approach also provides co-benefits for flood protection, as vegetated foreshores help attenuate wave energy and reduce hydraulic loads on dykes during storm events. However, the long-term success of this strategy depends on the ability of restored habitats to keep pace with rising sea levels. This requires a continuous supply of suspended sediment to support vertical accretion. Herein lies a key tension: while reducing turbidity improves water quality, it may also limit the sediment available for deposition in these habitats. Under the current system understanding, a sharp reduction in turbidity as a result of upscaling could undermine the resilience of existing and newly created wetlands.

The three upscaling strategies, land raising (A), flood protection (B), and habitat restoration (C), are not mutually exclusive. On the contrary, they can be complementary and mutually reinforcing for achieving the overall objectives and vision. For example, the creation of new inland wetlands (Strategy C), such as in Polder Breebaart, can serve multiple purposes: sediment can be extracted and processed for agricultural land raising (Strategy A), while another portion can be used to reinforce flood defences (Strategy B). In this way, individual measures can contribute to multiple strategic goals simultaneously. However, strategies may also compete over the long term. While sediment is currently abundant, ultimately it is limited and necessitates a holistic view for sediment management. For instance, large-scale extraction of sediment for land raising may reduce the availability of suspended material needed for natural deposition in tidal marshes, potentially undermining their resilience to sea-level rise. To address the full range of challenges in the Ems Estuary a combination of these strategies will be necessary. Prioritizing flexible, adaptive measures that can be adjusted over time is recommended to enhance co-benefits and minimize trade-offs.

5.2. Enabling factors for implementing cross-border upscaling

The success of upscaling in the Ems Estuary will not only depend on technical feasibility and spatial priorities across border, but also on the ability to align governance processes. Effective upscaling in the Ems Estuary hinges on cross-border collaboration between the Netherlands and Germany to overcome the fragmented governance of the estuary. This collaboration should continue to build on the synergies between the visions and objectives shared by both countries, and the corresponding strategies and measures. While developed independently, the Dutch "Ems-Dollard 2050 Programme" and the German "Masterplan Ems 2050" share aligned goals regarding coastal restoration and strategic upscaling (pers. comm. M. Buurman, also see Table 2). Both initiatives establish a long-term vision of “Ecology and Economy in balance” with specific objectives of reducing turbidity, strengthening natural habitats, sustainable agricultural and flood safety. As a result, strategies pursuing either initiative are well-positioned for coordinated upscaling across both countries.

Although a common vision for the Ems Estuary and the development of integrated cross-border strategies is feasible at the technical level, different management cultures between nations present a challenge for implementing such strategies. The Netherlands has long embraced a participatory governance model rooted in its traditional “polder model”, characterized by inclusive, consensus-based planning that actively involves a wide array of stakeholders, including governmental authorities at multiple levels, local communities, NGOs, water boards, and the private sector (Schreuder, 2001). Furthermore, the Dutch have focussed on long-term coastal adaption through a predominantly sectoral water management lens, facilitated through the Delta Program (Bauer and Steurer, 2015). In contrast, Germany's adaptation governance is more multi-sectoral and federal, with the national government only acting as a facilitator for provincial and federal adaptation strategies rather than a central authority towards them (Bauer and Steurer, 2015). Public participation is formalized with structured procedures, rather than being embedded throughout all stages of planning (Panten et al., 2018). While the Netherlands' sectoral, long-term, and collaborative planning may foster legitimacy and innovation in water management, Germany's more procedural structure facilitates implementation of adaptation measures once consensus is reached at provincial and federal levels. Bridging these governance cultures requires deliberate efforts to harmonize planning processes and encourage mutual learning.

So far, the Netherlands has focused on small scale pilots with upscaling potential in the estuary (from Dollard to the river mouth area), while Germany has prioritised measures within the river system, particularly in the lower Ems area. A formalized Ems-Dollard cross-border platform with common visions could serve as a governance backbone for implementing more integrated strategies at scale. Upscaling depends on identifying priority zones for the implementation of larger-scale and integrated adaptation measures, especially where co-benefits are greatest. Furthermore, standardizing indicators and harmonizing success criteria of a joint vision for the estuary (e.g., 1 Mtonnes per year of sediment extraction in ED2050 for sediment management, flood protection standards, nature restoration goals like 200 ha of additional bird habitat by 2050 in the "Masterplan Ems 2050") across borders enhances comparability and transparency in how cross border actions contribute to this shared vision. Shared indicators allow for agreement on the feasibility of strategies and measures as well as the long-term impact across the Ems Estuary. Existing platforms such as the tri-lateral Wadden-sea interreg EU projects, the G-commision, and the Trilateral Wadden Sea Cooperation (TWSC) offer precedents for formalized cross-border knowledge-sharing, cooperation and planning. On a local level. policy makers need to balance between ecosystem restoration goals and local socio-economic aspirations. To facilitate the implementation of upscaling strategies, agreed restoration activities can be presented as formal tasks within policy documents after stakeholder engagement. This supports the uptake of spatially complex strategies (particularly clay ripening and beneficial use of dredged material in strategy A) in subsequent legal and planning frameworks and ensures there is support once measures need to be implemented.

6. Discussion

The proposed upscaling strategies provide a promising framework for coordinated cross-border efforts in climate adaptation, nature restoration and the sustainable use of the economic benefits. However, implementing these strategies raises important questions about their feasibility and long-term resilience. One major uncertainty across all strategies is the future availability of sediment. The Wadden Sea is still adjusting to historical land reclamation and large-scale interventions, most notably the construction of the Afsluitdijk in 1932 and the closure of the Lauwerszee in 1969, both of which significantly reduced the tidal prism (Elias et al., 2012). Although land reclamation has ceased in recent decades, projected sea-level rise is expected to further alter the sediment balance, potentially leading to the submergence of tidal flats under high-end scenarios (Wang et al., 2018). The Ems Estuary itself is also undergoing long-term morphological change, shifting from a multi-channel to a single-channel system over the past century (Schrijvershof et al., 2024). This transformation, compounded by dredging and other human interventions (van Maren et al., 2016), will continue shifting sediment transport patterns in the future. As a result, the sediment budget available for upscaling strategies remains highly uncertain. Adding to the uncertainty of sediment management strategies is the resilience to sea-level rise of the Ems Estuary and the Wadden Sea more generally. Marshes in the Dollard have shown limited growth over the past decades, accreting about 8 mm/year with the most recent measurements suggesting a decrease to only 4 mm/year (Esselink et al., 1998, 2002, 2020). This is remarkably low compared to other mainland tidal marshes (e.g. along the Dutch Frisian coast) within the Wadden Sea (Elschot et al. 2020) considering the high turbidity within the Dollard and suggests the tidal marsh may be more vulnerable to sea-level rise. Reducing the sediment supplied to the marsh by extraction without restoration efforts would likely accelerate marsh loss. Finally, while mud is abundant in the Ems Estuary at present, it is ultimately a finite resource. Given the interconnected nature of the Wadden Sea, any cross-border initiative aimed at reducing turbidity or enhancing resilience in the Ems Estuary in the short term must also consider potential impacts on the broader sediment budget of the Wadden Sea system in the long term.

In the context of climate change and the global need to adapt to rising sea levels (Nicholls, 2018), the sediment-based approach to coastal adaptation explored in the Ems Estuary may offer a valuable example for other regions. While estuaries differ in their physical contexts, many share common sediment management challenges (de Vriend et al., 2011), particularly in responding to long-term morphological changes driven by interventions such as dredging and land reclamation (van Maren et al., 2025). Globally, these have amplified tidal ranges in estuaries (Talke and Jay, 2020). Positive feed-backs from tidal amplification in response to interventions have already fundamentally transformed estuarine systems such as the Pearl River Delta (Zhang et al., 2025) and Ganges-Brahmaputra Delta (van Maren et al., 2023). In some cases, like the Loire and Changjian Estuaries, channel deepening and land reclamation have triggered the same self-reinforcing hydro-morphological feedback mechanisms between sediment import and tidal amplification as found in the Ems Estuary, shifting the system towards an increasingly turbid state (Dai et al., 2016; Dijkstra et al., 2019; Dijkstra and de Goede, 2024; Lin et al., 2025). Under these conditions, similar sediment management schemes as piloted in the Ems Estuary to alleviate the rise in turbidity may provide added value by extracting and repurposing dredged sediment, recognizing its potential use for construction, ecological restoration, and soil enhancement (Carreira et al., 2025; Dorleon et al., 2024; Ulibarri et al., 2020; Baptist et al., 2019). However, these strategies are not universally applicable. Estuaries such as the Mekong, Mississippi, and Ebro Deltas already suffer from sediment deficits and widespread coastal erosion (Edmonds et al., 2023; Rovira and Ibàñez, 2007; Schmitt et al., 2017). In these cases, further sediment extraction would worsen erosion and further increase vulnerability, undermining rather than supporting coastal adaptation.

To overcome barriers in the implementation of climate adaptation strategies, further cross-border cooperation is essential. Challenges in cross-border cooperation are not isolated to the Ems Estuary, however. It is commonly reported as one of the major institutional barriers in coastal zone management (Ansong et al., 2023; Berzi and Ariza, 2018; Jones et al., 2021; Moodie and Sielker, 2022). According to van Tatenhove (2017), planning transboundary interventions should be an exercise in reflexive governance, where the act of mutual planning and collaboration in turn informs future governance arrangements facilitating further collaboration. He identifies three preconditions for successful cooperation: (1) learning from pilot projects, (2) producing and sharing knowledge, and (3) developing a shared regional approach that aligns with national governance structures. As described in this paper, all three of the preconditions described are met within the Ems Estuary and cross-border collaboration has increasingly been pursued in the last decade, making the estuary well-positioned to deal with environmental uncertainties in its transboundary governance. While cooperation can still be improved, the Ems Estuary can already demonstrate how transboundary cooperation can be fostered in estuarine and coastal management.

Building on this cooperation, the Ems Estuary also illustrates how Nature-based Solutions (NbS) can be scaled effectively across national boundaries. Although EU directives such as the Environmental Impact Assessment, Water Framework Directive, and Natura 2000 encourage restoration efforts as NbS, their uptake often relies on voluntary actions, and large-scale applications are still limited (Calliari et al., 2022). As of August 2024, the EU's Nature Restoration Regulation adds more regulatory incentives for coastal restoration through binding restoration obligations emphasizing concrete, measurable improvements (Marquard et al., 2025). Even with agreed restoration targets, institutional and regulatory differences between countries, including differences in responsible authorities, pose additional challenges to consistent implementation (Amirzada et al., 2023; Lise et al., 2025). An additional issue reported in some European projects is the lack of consensus among stakeholders on the specific problems NbS are meant to address (O'Sullivan et al., 2020). In contrast, the Ems Estuary paradoxically has benefited from containing disputed territory. A history of shared stewardship has led to a common knowledge base and established framework for cooperation, recently reinforced by the signing of the “Ecological Strategy for Sediment Management” between the Netherlands and Germany. This agreement establishes a basis for scaling up NbS and sediment management options tested through pilot projects. These pilots help reducing uncertainty in the performance of non-traditional measures, a common barrier to upscaling (Calliari et al., 2022; O'Sullivan et al., 2020; Sánchez-Arcilla et al., 2022). Furthermore, measurable restoration goals set by the Dutch "Ems-Dollard 2050 Programme" and the German "Masterplan Ems 2050" provide a framework for setting and evaluating pilot outcomes, addressing the need for robust targets and indicators to guide and monitor the success of measures (Debele et al., 2023; Lise et al., 2025; Marquard et al., 2025; San Jose et al., 2025). Harmonizing these criteria across borders would further enhance cooperation and the effectiveness of NbS implementation. Finally, coordinating restoration goals with other sectors is commonly accepted as an enabler for coastal restoration (Lise et al., 2025; Marquard et al., 2025). For the Ems Estuary aligning with goals for regional economic development (preserve agricultural production, efficient dredging of local harbours, and improving liveability) has helped to mainstream coastal restoration into adaptation plans.

7. Conclusion

The Ems Estuary is a transboundary system managed by both the Netherlands and Germany, with part of the estuary being disputed territory between the two nations. The estuary faces escalating challenges including rising turbidity, salt intrusion, and flood risk. Governance of the estuary is fragmented across various levels of national governmental bodies, complicated by various overlapping national and European legislation. Both nations have recognized these challenges and developed visions for the estuary in the "Ems-Dollard 2050 Programme" in the Netherlands (focusing primarily on the coastal stretch from the Eemshaven to the Dollard Bay), and the "Masterplan Ems 2050" in Germany (focusing on the Ems Estuary including the Ems River). Both nations share aligned goals in reducing turbidity, strengthening natural habitats, increasing climate resilience, and supporting economic activity prompting closer collaboration in pursuit of this shared vision for an Ems Estuary with “Economy and Ecology in balance”. Both nations have devised and implemented different pilot projects to achieve this goal including among others silt extraction, land raising, and artificial habitat creation.

Moving from small-scale pilots to upscaling strategies to tackle the adaptation of the estuary, three complementary sediment management strategies have been identified from the pilot measures focusing on different parts of the landscape. Strategy A involves land raising of agricultural lands from the re-use of sediment extracted from the estuary. Strategy B consists of multifunctional flood protection measures combining flood protection with building resilience from locally extracted sediment. Strategy C is concerned primarily with the ecological health of the estuary and consists of creating and preserving habitat within the estuary, e.g. with bird islands, or protecting and expanding marshes with groynes. A combination of all three is needed to achieve the shared vision of the estuary. These upscaling strategies require further cooperation across the countries and institutions, as well as a system to better translate the restoration goals and natural values of the estuary in effective legislation. This may be achieved by harmonizing indicators for restoration goals, identifying zones that should be prioritised, and strengthening cross-border institutional platforms like the

G-Commission. The Ems case demonstrates that adaptive, transboundary sediment management and climate adaptation strategies can emerge from pilot-based experimentation and a shared strategic vision, enabling coordinated action in complex estuarine systems under climate uncertainty.

The Ems Estuary case offers transferable lessons for other transboundary coastal systems, particularly regarding the integration of sediment management with climate adaptation and biodiversity restoration. The strategies discussed demonstrate how dredged material can be transformed from a waste product into a key asset for regional resilience. Moving forward, the establishment of formal cross-border governance structures, coupled with adaptive monitoring and stakeholder engagement, will be essential to realize the full potential of these strategies. Combining local experiences from pilots with cross-border knowledge sharing and cooperation has proven successful in initiating the development of long-term transboundary adaptation plans, providing a blueprint for managing estuarine systems under uncertainty in the face of global climate change.

CRediT authorship contribution statement

Richard J.C. Marijnissen: Writing – review & editing, Writing – original draft, Visualization, Methodology, Conceptualization. **Yuting Tai:** Writing – original draft, Methodology, Conceptualization. **Sara P. Cobacho:** Writing – original draft, Methodology, Conceptualization. **Martin J. Baptist:** Writing – review & editing, Writing – original draft, Validation, Conceptualization. **Dirk S. van Maren:** Writing – review & editing, Writing – original draft, Validation. **Pushpa Dissanayake:** Writing – review & editing, Writing – original draft, Resources, Conceptualization. **Dennis Oberrecht:** Writing – review & editing, Resources, Conceptualization. **Dirk Post:** Writing – review & editing, Resources, Conceptualization. **Matthijs Buurman:** Writing – review & editing, Writing – original draft, Resources, Conceptualization. **Jantsje M. van Loon-Steensma:** Writing – review & editing, Writing – original draft, Conceptualization. **Wei Chen:** Writing – original draft. **Joanna Staneva:** Writing – review & editing, Conceptualization. **Mindert B. de Vries:** Writing – review & editing, Supervision, Project administration, Conceptualization.

Declaration of generative AI in scientific writing

During the preparation of this work the authors used suggestions from Copilot for minor revisions in the manuscript in order to improve the overall structure, clarity and coherence in the writing. After using this tool/service, the authors reviewed and edited the content as needed and take full responsibility for the content of the published article.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Pushpa Dissanayake reports a relationship with Lower Saxony Agency of Water Management, Coastal and Nature Conservation (NLWKN) that includes: employment. Dennis Oberrecht reports a relationship with Lower Saxony Agency of Water Management, Coastal and Nature Conservation (NLWKN) that includes: employment. Dirk Post reports a relationship with Lower Saxony Agency of Water Management, Coastal and Nature Conservation (NLWKN) that includes: employment. Matthijs Buurman reports a relationship with Province of Groningen, "Ems-Dollard 2050 Programme" that includes: employment. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

All data used in this study are available in the cited literature and publicly accessible sources referenced throughout the manuscript. No new data was generated or analysed for this study.

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