Chapter 8
Synthesis
Coastal protection is becoming increasingly important worldwide because many coastal communities are currently facing flood risks due to accelerating sea level rise (IPCC 2014), land subsidence (Syvitski et al. 2009; Weston 2014) and extreme events such as storms surges (Kiesel et al. 2021), which will probably become more frequent with climate change (Menéndez and Woodworth 2010; IPCC 2014; Vousdoukas et al. 2018). Hard engineering structures such as dikes, sea walls, breakwaters and storm surge barriers, also known as ‘grey’ solutions, are commonly used for coastal protection. Nevertheless, these measures are often associated with negative impacts on coastal ecosystems and the loss of their ecosystem services (e.g. Lai et al. 2015). Furthermore, because conventional hard engineering is static, it can be increasingly challenged by climate change and the maintenance may become highly costly (Temmerman et al. 2013; Bouma et al. 2014; Morris et al. 2020). Alternatively, hybrid ecosystem-based coastal defence, or ‘green’ solutions, which combines conventional hard engineered barriers with coastal ecosystems, can be a more sustainable, ecologically valuable and cost-effective alternative to hard engineering alone (Shepard et al. 2011; Temmerman et al. 2013; Morris et al. 2018; Schoonees et al. 2019; Vuik et al. 2019). Natural ecosystems such as sand dunes, marshes, mangroves, seagrass, kelp forest, coral and shellfish reefs are able to attenuate waves and currents and stabilise the soil (Shepard et al. 2011; Bouma et al. 2014). Furthermore, ecosystems are capable of recovering from storm disturbances and be resilient against sea-level rise (Feagin et al. 2015; Kirwan et al. 2016; Fagherazzi et al. 2020; Morris et al. 2020). In addition to coastal protection, they provide a broad range of other ecosystem services including biodiversity conservation, nutrient cycling, support for fisheries and carbon sequestration (Orth et al. 2006; Gedan et al. 2009; Barbier et al. 2011; Duarte et al. 2013).

However, uncertainties about the actual effectiveness of these ecosystem-based measures still hampers the practical implementation. To safely implement natural ecosystems as part of the coastal protection programmes, we need to further address specific knowledge gaps regarding their functioning (i.e. coastal ecosystem dynamics in space and time), as well as providing thorough understanding of management effects on the safety value, ecological status and ecosystem behaviour (long-term dynamics), across connected habitat types.

In this thesis, I provided field evidence that supports the effectivity of foreshore ecosystems for coastal protection as well as the importance of the connectivity between ecosystems (Fig. 1). More specifically I investigated i) the importance of elevation and width of both tidal flats and marshes for wave run-up onto the dikes (chapter 2), ii) the importance of tidal flat elevation (changes) on the long-term marsh development (chapter 2), iii) topsoil and lateral erosion resistance across foreshore ecosystems, location, age and management type (chapters 3, 4, 5 and 6) and iv) the use of ‘green’ management measures to stabilise tidal flats and thereby facilitate marsh expansion (chapter 7). The first part of this chapter integrates the key findings of this thesis, unravelling knowledge gaps about coastal ecosystems dynamics and its management in relation to coastal protection. To conclude, I will discuss management implications and applications within the Dutch Flood Protection Program (HWBP).
Chapter 8

Fig 1. Illustration of the main results of this thesis.

**Integration of main findings**

Marshes effectively reduce wave run-up on the dikes but are hard to get where most needed.

In this thesis we show that the morphology of the foreshore is important for both i) run-up reduction by wave attenuation (reducing dike failure risk) and ii) marsh development (i.e. low wave exposure and minimum elevation for specific flooding regime necessary for the vegetation to establish) (chapter 2). Our field measurements show that foreshore sites with salt marshes reduced wave heights and halved wave run-up on the dikes during our monitoring period (2019 - 2021), even when the marshes had shorter and less dense vegetation during winter (Fig. 2). Differences of wave run-up between locations was mainly attributed to differences in elevational profile (i.e. higher elevation and/or marsh width). This is in accordance with previous studies that describe increased wave attenuation in wider and higher vegetated foreshores, even during severe storms (Vuik et al. 2016; Willemsen et al. 2020). Furthermore, locations with higher tidal ranges led to higher high-tide water levels causing higher wave run-up. Interestingly, wind direction and fetch length differences did not significantly explain differences in run-up between...
locations, so it was mainly driven by the topography. We expect that vegetation friction would also explain part of this attenuation (Vuik et al. 2016; Willemsen et al. 2020; Keimer et al. 2021). However, this was not disentangled in our model due to the high variability of vegetation parameters in time and space, which made it impossible to create a single vegetation variable to fit the statistics. Although vegetation was represented as marsh width in our models, future research could investigate the integration of these vegetation parameters that vary in time and space into a model to disentangle the real vegetation effect on run-up separated from the bathymetry.

Through analysis of vegetation and bathymetry maps we showed that the more vulnerable areas to wave run-up due to lower elevated tidal flats (< 0.5 m above mean sea level in the Dutch Wadden Sea) are also the areas where marshes are not able to develop (chapter 2). In these low elevated locations, the establishment of vegetation is challenging due to too high flooding frequencies and higher wave exposure, which also translates into higher run-up onto the dikes (Fig. 2). Furthermore, we show that marsh retreat in the past decade was related to the erosion of the tidal flats in front of the marsh. In contrast, accretion of tidal flats was correlated to an expansion of the marsh edge. This catch-22 problem implies that engineering measures will always be needed in the vulnerable areas: either to strengthen exposed dikes or to stimulate tidal flat accretion to induce marsh development at those exposed places where marshes cannot develop without our help. It also calls for better understanding of the erosion and sedimentation dynamics of the higher tidal flats, as this can ultimately promote the formation of salt marshes. Furthermore, it should be noted that although the effect of the marshes on wave attenuation in our field study was large, the effect may be lower during storms with higher water levels, as higher water levels are related to lower wave attenuation capacity (Vuik et al. 2016; Willemsen et al. 2020). Therefore, continuing the monitoring of run-up and wave attenuation until there is a storm with higher water levels would be a next step to quantify the effectiveness of the marshes in the field under extreme conditions.

Fig. 2. Comparison of the elevation of the highest beach wracks on the dikes (wave run-up height) after the storm of the 8th of January 2019 between a wide marsh in Uithuizen (~400 m width) and bare tidal flat in Eemshaven: run-up is higher when the marsh is absent. NAP is the Dutch ordinance level, which is similar to the local mean sea level.
Soil stability of foreshore ecosystems

In line with chapter 2, soil stability of coastal ecosystems is of key importance for maintaining the high elevation of the foreshore which in turn is beneficial for coastal protection (Le Hir et al. 2000; Hu et al. 2015; Zhu et al. 2020). Although it is known that coastal vegetation stabilises the soil (e.g. Coops et al. 1996; Christianen et al. 2013; Lo et al. 2017; Wang et al. 2017) there were prior to this thesis still knowledge gaps regarding how different ecosystems can stabilize the soil and how it is affected by their physical and biological properties as well as by their management. Furthermore, sediment stabilization is not only important in communities higher in the intertidal zone, such as marshes, which have more wave attenuating capacity (Bouma et al. 2014). The presence and development of such communities higher in the intertidal zone is related to the elevation of the adjacent tidal flats (Hu et al. 2015, chapter 2). Therefore it was also important to understand the role of lower lying communities, such as bare tidal flats and seagrass, on sediment stabilization.

We demonstrated that almost all types of saltmarshes, including marshes with sandy subsoil, were resistant to topsoil erosion under fast water flow (2.3 m s\(^{-1}\)), which could occur during a dike breach (chapter 3). This is important to reduce the chance of dike breaching during extreme events, and to reduce the size of dike breaches when dikes fail (Zhu et al. 2020). Resistance to erosion occurred as long as the marshes had a cohesive top layer of high root density and organic content. Saltmarshes trap sediment, organic content and belowground biomass through time, and this cohesive, fine-grained top layer is the most erosion resistant. This biogenic cohesive top layer is especially visible in soil profiles of marshes that developed from sandy intertidal flats, like in Griend (chapter 2 and 4) and Schiermonnikoog (chapter 2 and 6) (Fig. 3 and 4). Pioneer marshes with sandy soil and low organic content were the only marshes that completely eroded because were not cohesive. Furthermore, not a single tidal flat soil was erosion resistant. Contrary to the expected, grazing was not related to less topsoil erosion. If an artificial crack reaching the sandy subsoil (easily erodible) was created in resistant marsh samples, mimicking what could occur during a dike breach due to tension cracks or debris hitting the soil, the soil would collapse. Overall, chapter 3 highlights the importance of preserving and/or restoring saltmarshes in front of the dikes to decrease the size of the dike breach and increase the evacuation time. However, sandy marshes may be more vulnerable. Nevertheless they could still reduce the wave energy impacting the dike (chapter 2).
Fig. 3. Example of a sandy marsh soil profile (top), with easy erodible sand below the cohesive top layer of organic content, roots and fine sediment, and a silty marsh soil profile (bottom), which is erosion resistant.

In addition to the main findings in chapter 3, we also found an slight increase on topsoil erosion due to cracks formed in the sediment at four of the sampling locations during an unusually dry summer. These drought cracks were shallow (~4 cm depth), and led to a faster sediment erosion in form of small blocks of the surface layer. Nevertheless, the marsh was still stable. Therefore, in the case of a dike failure, this faster erosion of the most surface layer due to soil shrinkage may not be very important. However, if droughts or heat waves followed by storms become more frequent due to climate change (IPCC 2014; Vousdoukas et al. 2018; Perkins-Kirkpatrick and Lewis 2020), marshes may become less resilient and more fragmented (Silliman et al. 2005; Cahoon et al. 2011; Derksen-Hooijberg et al. 2019). In this case, the enhanced erosion seen in this experiment could contribute to marsh degradation. For this reason, future research could focus on the effect of increased drought periods on marsh degradability.
In chapter 4 we studied top and lateral soil erosion resistance at Griend, a back-barrier island, which is a sandy system consisting of low dunes with shells and beach wrack deposited by storms, sheltering a salt marsh (Cooper et al. 2007; Pilkey et al. 2009) (Fig. 4). Barrier islands and back-barrier islands are an important part of coastal protection in shallow soft-bottom coasts like the Wadden Sea because they are the first barrier attenuating waves coming towards the coast from the open seas, resulting in fetch limitation (Otvos 2020). These islands are sometimes managed by coastal engineering to prevent their complete erosion, like in the case of Griend (Govers and Reijers 2021). The past management of Griend through sand enforcement of the initial chenier barrier, which are the current dunes, led to a shelter area at the wake of the island suitable for marsh development. As expected, neither higher dune soil nor the bare tidal flat soil were resistant to lateral or top erosion due to the lack of cohesive sediment with organic matter and dense belowground biomass. Nevertheless, a salt marsh formed in the sheltered side, creating a cohesive erosion-resistant top soil layer through the accumulation of fine sediment, organic matter and roots by the marsh vegetation. Lateral soil stability increased when the marsh established nearer to a creek and at low elevations, due to more fine sediment deposition and thus thicker cohesive layers; and decreased near to the dunes or at higher elevations due to mostly sandy soil profiles (Fig. 3). Therefore, soil erosion resistance due to the presence of thicker cohesive top layers seems to be related to the topography and presence of creeks which enhances sediment input and drainage of the island, as seen in mainland marshes (Reed et al. 1999; Koppenaal et al. 2021).
Fig. 4. Study sites in the Netherlands (top), including the Wadden Sea and the Scheldt Estuary. Numbers indicate which chapters took part at each location. Aerial image of a part of the Wadden Sea (bottom) indicating examples of barrier islands, back-barrier islands, mainland marshes, back-barrier marshes and tidal flats. The dotted line indicates the mainland dike. It can be observed that some stretches of the dike are fronted by marshes and others by bare tidal flats. The aerial photograph was obtained from PDOK (Public Geodata Portal in The Netherlands).
Finally, we showed that eelgrass (*Zostera marina*) with developed roots and rhizomes (i.e. root-mat forming seagrass) can reduce top erosion by roughly halving the horizontal sediment transport compared to bare sediment samples (Chapter 5, Fig. 5). In contrast, turbidity within the eelgrass samples was higher than in the bare sediment. We attributed this to enhanced turbulence and scouring at meadow edges enhancing the resuspension of the most fine sediment particles (< 62.5 μm). Nonetheless, the overall effect was that belowground biomass of eelgrass with high root density reduce top erosion. Although eelgrass can provide stabilization to the foreshores it has declined worldwide due to human impact, and its restoration is challenging due to diverse factors such as hydrodynamic exposure and poor water quality (e.g. van Katwijk et al. 2016). Therefore future research effort should focus on conservation and restoration of these communities.

Fig. 5. Underwater photo of *Zostera marina*, commonly known as eelgrass. The mat of roots and rhizomes that *Z. marina* can create can be observed in the sides of a hole from where a soil sample was extracted.

In general, a clear message from our chapters is that belowground biomass of vegetation with high root density and organic content can increase sediment top and lateral erosion resistance even under strong hydrodynamic conditions. The most erosion resistant soils were the ones with cohesive sediment type (silt/clay) combined with high belowground biomass, specifically higher root density, found in marshes. However, sandy soils with dense root networks and organic content were also resistant to topsoil erosion. In contrast, vegetated soils with sandy non-cohesive sediment type and/or with low root density and/or low organic content,
such as dunes, pioneer sandy marsh with low organic content and seagrass from deeper depths in fluffy muddy sediment and low root density, were the most vulnerable to both lateral and top erosion. Finally, one important aspect to add is that in normal conditions, the topsoil is protected by the vegetation canopy, which reduces water flow and waves and creates a shield layer reducing shear stress at the soil surface (Nepf 2012). Although not studied in this thesis (the aboveground vegetation was clipped in our marsh erosion experiments), we also expect this to contribute to erosion resistance, especially because the marsh vegetation does not fully disappear in winter, only in the pre-pioneer and pioneer zones in some cases (chapter 2).

Grazing management can reduce marsh lateral erosion sensitivity

Wave flume experiments, described in chapter 6, revealed that lateral erodibility of the marshes (i.e. resistance to cliff erosion) is affected by grazing management in combination with marsh age and marsh elevation. First, the depth of the cohesive top layer of silt, clay, organic matter and roots (Fig. 3), develops stronger at intermediate elevations, due to more exposure to floods, when vegetation can trap fine particles, and in older marshes which had longer time to develop and accrete organic matter (Off et al. 1997; Van de Koppel et al. 2005, chapter 6). Overall, we showed that marshes with a thin cohesive top layer, such as found in high elevations or young or very low marshes, are more vulnerable to cliff erosion because they collapse as soon as the sandy subsoil is eroded. Secondly, the erosion-resistance of the cohesive top layer is enhanced by management practices that promote i) large grazers (cattle), in agreement with Pagès et al. (2018), which compact the soil by trampling and reduce soil-bioturbating arthropods, ii) mowing, which reduce soil-bioturbating arthropods and iii) small grazers (hares, geese) which promote vegetation types with higher root densities (Fig. 6). However, compaction by large grazers simultaneously leads to thinner cohesive top layers and lower soil elevation, potentially leading to more inundation under sea-level rise. This may be a problem in marshes without enough sediment supply to accrete vertically and keep up with sea level rise (Kirwan et al. 2016).

Although cattle grazing can reduce the silty soils erosion rate (chapter 6), cliff erosion at the marsh edge by toppling of blocks (larger scale) (Francalanci et al. 2013), which was not addressed in our experiment, may be differentially affected by grazing. In other words, the fact that the soil itself becomes more cohesive and more resistant to gradual lateral erosion, may not be related to the block toppling in the marsh edge fronting the tidal flats. For example, marshes in Ameland, a barrier island in the Dutch Wadden Sea, are retreating even being grazed (personal communication with a nature manager). Cliff erosion in grazed marshes may be explained by natural cyclic alternations between retreat and marsh expansion due to differences in elevation between the tidal flat and the accreted marsh edge (Van de Koppel et al. 2005), tidal flat erosion dynamics (Bouma et al. 2016, chapter 2) or sediment shortage (Ladd et al. 2019). Therefore, although cattle grazing may reduce erosion rates, all these other large scale factors may be overruling the grazing effect. In order to determine if grazing also reduces large scale erosion (i.e. mass failure) in the marsh edge adjacent to tidal flats, future research should
focus on the grazing effect on a bigger scale, following the work done by Wang et al. (2017) and Pagès et al. (2018).

Fig. 6. Example of grazers found in salt marshes: hare, geese and cattle (top). Exclosure in a salt marsh grazed by hare and gees (bottom-left) and a salt marsh grazed by cattle (bottom-right). Erosion sensitivity of the soil was reduced with both types of grazing.

‘Green’ management options to change the tidal flat bathymetry

Higher and convex foreshores may lead to higher wave attenuation and longer distance from wave breaking points toward the potential pioneer marsh zone (Mariotti and Fagherazzi 2013; Hu et al. 2015). This would reduce erosion in the pioneer vegetation zone of a salt marsh (Mariotti and Fagherazzi 2013; Hu et al. 2015; Bouma et al. 2016; Willemsen et al. 2017) as well as reduce wave run-up on the dikes (chapter 2). For this reason, management should not focus only on marshes but also on the tidal flats in front of the dikes or the marshes. A more ecological valuable alternative to ‘grey’ solutions for tidal flat management may be the restoration and protection of sedimentation-promoting foundation species (Angelini et al. 2011; van de Koppel et al. 2015; Schoonees et al. 2019) such as eelgrass meadows or mussel beds. These natural communities could attenuate waves and currents, provide an elevated and stable soil as well as changing tidal flat profile (e.g. Meyer et al. 1997; Borsje et al. 2011; Donker et al. 2013; Walles et al. 2016). In return, this could potentially aid marsh expansion (Chowdhury et al. 2019).
Hence, we tested the use of biodegradable artificial reefs, which were aimed as precursors to restore mussel beds, on wave attenuation and tidal flat stabilization in an exposed location (chapter 7). The results show that the structures, which were 20 cm high, reduced wave heights when the mean water level was < 50 cm. Furthermore, the reefs promoted local sediment accretion (Fig. 7), even when the structures were lower due to degradation as a result of harsh weather conditions including ices sheets. Lower structures where not as effective in wave attenuation, and the explanation for enhanced local sediment trapping even being low elevated may have been by their flow attenuation (Fivash et al. 2021). The effects on sediment dynamics was local (~10 m from the reefs). Therefore, an even larger implementation scale would be needed to affect long-term tidal flat morphology and promotion of large-scale connectivity between tidal flats and high intertidal systems such as salt marshes. Furthermore, large bedform dynamics should be considered when designing the dimensions of the reefs to expand their sediment trapping effect. Higher and more resistant structures may be useful to attenuate more waves in exposed locations but not necessarily for sediment trapping due to the possible enhanced scouring (chapter 7). Furthermore, in very exposed locations, stable mussel beds may not be able to develop (Paoli et al. 2015). This highlight the importance of distinguishing the application of these solutions depending on the aim: ecological (e.g. mussel bed restoration) or engineering (wave attenuation and stabilization of the tidal flat) (Morris et al. 2019, chapter 7). In some cases, both aims may just not be possible to combine.

Fig. 7. Effect of the biodegradable artificial reefs on tidal flat accretion. At this stage the reefs were already lower due to degradation, but still accreted sediment.
Management implications and applications within the Dutch Flood Protection Program (HWBP)

Benefits from salt marshes for nature-based coastal defence

Salt marshes should be protected and/or restored because they provide stable soils that are resistant to erosion (chapters 3, 4 and 6). Resistant soils provided by marshes may reduce breach dimensions if a dike fails (Zhu et al. 2020, chapter 3). Furthermore, these stable marsh soils effectively reduce wave run-up on the dikes independently of the vegetation species (chapter 2). Wider marshes (> 300 m) or more elevated marshes (> 1.5 m NAP) provide further reduction of wave loads in the dikes (chapter 2). Wave run-up reduction is important for preventing water flowing over the dike during storms (dike overtopping) and to reduce wave impact on the dike during more frequent moderate storms (Vuik et al. 2019). In this thesis we included a wide range of vegetation species (from short grazed marshes to reed marshes with high vegetation), so the effect of marsh width in reducing run-up may apply to other locations although the magnitude may differ.

In the context of The Netherlands, historical land reclamation works in the Dutch Wadden Sea strongly promoted salt marshes in the past and also explain where are current salt marshes located (Dijkema et al. 2011) (chapter 2, Fig. 8). Similarly, marshes have developed with human intervention in the Western Scheldt, although more natural marshes can be found there compared to the Wadden Sea (Van der Wal et al. 2008) (Fig. 4). We found variation in the marsh sediment type depending on the site (chapter 3, 4, 6): in the mainland saltmarshes of the Wadden Sea, the sediment was mostly silty and cohesive, while in Schiermonnikoog (barrier island) and Griend (fetch-limited island), we could distinguish an erosion-resistant top layer accreted on the top of readily erodible coarse sand (Fig. 3 and 4). In the Scheldt delta, few locations had soil profiles with only sand, such as Ritthem and Rilland and the others were silty and cohesive (Fig. 4). Silty marshes with cohesive soils are the most resistant to topsoil and lateral erosion (chapter 3 and 4). Finally, although sandy marshes may be less resistant to lateral erosion, they can still attenuate waves by the vegetation and higher soil elevation (Shepard et al. 2011) and therefore provide coastal protection.
Grazing management on salt marshes for coastal protection

Low intensity cattle grazing or rotational livestock grazing is recommended because it increases lateral erosion resistance of silty/peaty marsh soils (chapter 6) and provides other benefits such as increased biodiversity and carbon storage (Davidson et al. 2017). In contrast, topsoil erosion under fast-water flow was not affected by grazing although we could expect that in the case of a dike breach, cattle grazed soil would be more compact and more resistant to damages (chapter 3). High intensity cattle grazing should be avoided because it could be a risk for land subsidence due to soil compaction and have negative effects on soil properties (Nolte et al. 2013; Davidson et al. 2017; Keshta et al. 2020). This will be especially important in organogenic marshes with low sediment input sensitive to sea level rise as found in North America (Davidson et al. 2017). Extensive grazing is also preferred from their impact on diversity of plants (Bakker 1989), invertebrates (van Klink et al. 2015; Davidson et al. 2020) and breeding birds (Mandema et al. 2013). In European marshes dominated by Elytrigia atherica, like in Europe, promotion of small herbivores (e.g. hare and geese) in areas where they have declined (Dokter et al. 2018) could be investigated to avoid the encroachment of this species which has low root density and is related to less erosion resistance (chapter 6). However, in other marshes dominated by less palatable species such as Spartina spp. as found in America (Davidson et al. 2017), the effect of the small grazers may be different.

Marshes grazed by livestock, which have shorter vegetation (i.e Uihuizen, den Andel and Zwarte Haan), still reduce more waves and wave run-up on the dikes compared to the bare mudflats (chapter 2). This attenuation is due to the higher elevation and the roughness of the vegetation, even during winter state (chapter 2). Therefore, grazing does not suppose a risk for
the efficiency of marshes protecting the dikes, although marshes with taller vegetation may be even more effective (e.g. Möller et al. 1999; Bouma et al. 2010; Ysebaert et al. 2011).

Management of tidal flats for coastal protection (i.e. marsh expansion)

A limitation from the ecosystem-based coastal defence is that marshes may not be able to develop along all the foreshore, as discussed in chapter 2. One of the limiting factors for having a continuous marsh along all the dikes is that tidal flats with enough elevation for marsh establishment do not occur everywhere in front of the dikes (chapter 2). This is especially important in areas modified by humans where the foreshores have been engineered and the space for the ecosystems to develop is limited (Doody 2013). Furthermore, worldwide analysis show that tidal flats are being lost due to coastal development, reduced sediment input, sinking of riverine deltas, increased coastal erosion and sea level rise (Murray et al. 2019). These areas without elevated tidal flats have too high flooding frequency and inundation time for marsh to develop in addition to more wave and current exposure that can prevent seedling establishment (e.g. Hu et al. 2015; Balke et al. 2016; Bouma et al. 2016; Silinski et al. 2016).

In the case of the Dutch Wadden Sea, natural landward marsh migration is limited by the dikes, which results in coastal squeeze (Doody 2013). Our results support the conclusions in the map of potential saltmarsh formation in the Dutch Wadden Sea proposed by van Loon-Steensma (2015). Areas fronting the dikes with low elevations (< 0 m NAP), such as near Harlingen and Lauwersoog, may not be suitable for marsh development even with human intervention due to the lack of natural sediment deposition and/or high exposure, which is necessary to sustain long-term marsh development (Fig. 8, Box 1) (van Loon-Steensma 2015; Wang et al. 2018; Hu et al. 2021). These areas where marshes are not able to develop would need more reinforcement than areas with a dike protected by a marsh. In areas with elevated tidal flats but where marshes are currently missing or are very narrow, marsh expansion seaward could be facilitated by increasing the elevation of tidal flat, reducing incoming waves and supporting sediment supply (Hu et al. 2021), thus creating favourable conditions for marsh establishment (Box 1). This could be done for example at the south of Zwarte Haan, east of Holwerd or the west of Eemshaven (Fig. 8). However, it should be also taken into account that the creation of new marshes would go at the expenses of open mudflats which are important as feeding areas for migratory birds and for mussel beds among others (Compton et al. 2013).

In the past, marsh expansion through increasing the elevation of the tidal flats and reducing waves and currents has been achieved by interventions like building wave-breaking brushwood groynes (Fig. 9), digging drainage channels, or applying dredging material to create a wave attenuating foreshore (Dijkema et al. 2011; Hu et al. 2015; van Loon-Steensma 2015). Restoring stabilizing ecosystems like seagrass beds (chapter 5) or shellfish reefs (chapter 7) could be an alternative for hard engineering to attenuate waves and currents, increase tidal flats accretion (i.e. increase in elevation) and simultaneously increase ecological value (e.g. Meyer et al. 1997; Borsje et al. 2011; Donker et al. 2013; Walles et al. 2016). However, combining ecological aims (restoring an ecosystem) and engineering aims (reducing waves and trapping
sediment to promote suitable conditions for marsh expansion) may not always be possible (Morris et al. 2019, chapter 7). For example, in our experiment with biodegradable artificial reefs (chapter 7), the site was too exposed for the reefs to persist and develop into a stable mussel bed. Larger scale reefs, more resistant materials and the installation at higher elevations may be needed to resist the harsh conditions and have a larger effect on wave attenuation and tidal flat sedimentation. However these alternative characteristics may not be suitable for mussel bed restoration (Paoli et al. 2015). Unfortunately, most of the exposed locations that may benefit from marsh expansion may not be suitable for mussel or seagrass restoration as a management solution due to the high exposure. In these situations, other measures such as sedimentation fields with brushwood groyne (Fig. 9) (De Groot and Van Duin 2013), sediment nourishments (Baptist et al. 2019) or a combination of these ‘grey’ measures with the restoration of seagrass beds and shellfish reefs as an hybrid solution may be an option. Finally, the use of structures to facilitate marsh expansion may be temporal if the aim is to create a window of opportunity for the first stages of marsh establishment (Hu et al. 2015) (Box 1). However, in situations of coastal squeeze, where the space for ecosystem development is lacking, or is a very exposed area, such structures should be maintained to prevent marsh erosion (Bakker 2014; Siemes et al. 2020). For instance, in the Wadden Sea, management of the tidal flats should be continued to preserve a minimum marsh width in front of the dikes (e.g. ~ 300 m, chapter 2).

Fig. 9. Effects of brushwood groyne on sediment trapping and marsh vegetation establishment. The right side is the lee of the brushwood groyne (facing landwards), more sheltered and where more sediment has been trapped leading to an increase in marsh vegetation.

Lastly, in addition to restoring soil stabilising ecosystems or using man-made solutions for marsh expansion, it is recommended to continue monitoring the evolution of the sediment dynamics over time (e.g. with bathymetric and satellite maps) and detect the areas where tidal flats are eroding or accreting (chapter 2). This may be a predictor of future salt marsh retreat. Furthermore, suspended sediment in the water column should also be monitored at higher
spatial and temporal resolution, which is important for coastal ecosystems to keep up with sea level rise. In other words, we can focus on stabilising the tidal flats, but if sediment availability is reduced (Mariotti and Fagherazzi 2013; Ladd et al. 2019; Murray et al. 2019), ecosystems may have a problem to build up and keep up with sea level rise, especially if the ecosystems are not able to migrate inland due to human constructions (Doody 2013). Sediment shortage due human activities such as the creation of dams or river dredging is a current cause for tidal flats and marsh loss (Mariotti and Fagherazzi 2013; Murray et al. 2019). Therefore foreshore management may require actions in the land watershed such as opening upstream dams. If this is not possible, sediment nourishments in combination with the previous measures mentioned may be an option to consider (Baptist et al. 2019; Hu et al. 2021).

Further recommendations for salt marsh restorations

For future soil nourishments aimed at marsh restoration, using fine-grained sediment (mud), which will become more cohesive and erosion resistant, is recommended rather than the use of coarse sand that is non cohesive and erodes easily (chapter 3, 4, 6). This may not be possible in all the places due to the local sediment source, but it is recommended when fine sediment is available. Restored sandy marshes may take longer to become erosion resistant (chapter 3 and 6). Therefore future research could focus on sediment-type management, how long would it take for a sandy location to become stable and whether sediment-type management could have ecological impacts. Furthermore, marsh restorations should include a good drainage system with creeks to provide enough sediment supply (Reed et al. 1999) and promote the accretion of thicker erosion-resistant top layers (chapter 4).

**Concluding summary on ecosystem-based coastal defence**

Based on our findings together with previous studies, I conclude that marshes, compared to bare tidal flats, play an important role on coastal protection independently of the vegetation type or if they are in winter state (chapter 2, 3, 4, 6). Therefore, they should be included in coastal protection schemes. Marshes will be stable and attenuate more waves loads onto the dikes compared to bare tidal flats even if they are grazed (chapter 2). Furthermore, grazing may be interesting to reduce lateral erosion rates (chapter 6), but further research should focus on if there is an effect of grazing on reducing cliff erosion in form of toppling blocks, therefore at a larger scale. Nevertheless, I find very important to avoid high intensity grazing which can lead to land subsidence and affect the biodiversity.

A limitation of the nature-based protection by salt marshes is that they cannot be implemented everywhere, because their establishment is very location-specific and depends on environmental conditions (e.g. sediment availability, elevation profiles and wave exposure Box 1, Hu et al. 2021, chapter 2). When possible, ecosystem-based coastal defence should integrate connected ecosystems lower in the tidal range (for example tidal flats, seagrass beds and shellfish reefs), which can stabilise the soil and reduce waves (chapter 5 and 7), both
processes positively related to marsh expansion and increased ecological value. Unfortunately, restoration of mussel or seagrass beds in exposed locations is often difficult (chapter 7). In cases where natural options like restoring seagrass beds and shellfish reefs are not feasible, marsh expansion could be promoted by minimal engineering actions (e.g. building brushwood groyne) until a stable marsh able to withstand waves has developed. In locations with high exposure or low sediment supply, where marshes are not able to migrate inland, such measures should be maintained long-term to prevent marsh erosion. In some cases ecosystem-based solutions combining marshes and dikes may be too costly, not achievable, or going at the expense of other ecological values, such as causing the loss of mudflats that are important for migratory birds (chapter 2). In these situations, ‘hard engineering’ solutions may remain necessary. Finally, I believe that future research and management should go towards how to maintain coastal ecosystems in face of climate change (i.e. sea level rise and increased storms) and to monitoring sediment dynamics and sediment availability to be able to predict where the marshes may start eroding in order to have time to plan a response to that.
Box 2. Summary of research questions and answers

Chapter 2

Questions: Are marshes growing where we need them most? Which factors drive differences of run-up and beach wrack levels across different foreshore types?

Answer: Marshes were associated with higher elevations of adjacent tidal flats (above ~ 0.5 m NAP). Furthermore, marsh expansion offshore was associated with the accretion of the adjacent tidal flats. Marshes effectively protected dikes from wave loading, but also sites that are most vulnerable to high wave run-up were found in those areas where marshes typically do not develop spontaneously due to too low soil elevations and high hydrodynamic exposure.

Chapter 3

Questions: How do different foreshore types resist to fast flow erosion, which could occur during a dike breach?

Answer: Almost all types of saltmarshes, including marshes with sandy subsoil, were resistant to topsoil erosion under fast water flow thanks to the presence of an erosion resistant top layer of organic matter, roots and/or fine sediment accreted by the marsh vegetation. Only pioneer vegetation in sandy places was found without this resistant top layer and therefore were completely eroded. Furthermore, not a single tidal flat soil was erosion resistant.

Chapter 4

Questions: How resistant are soft-sediment ecosystems from fetch-limited barrier island to top and lateral erosion in relation to its management?

Answer: Neither higher dune soil nor bare tidal flat soils were resistant to lateral or top erosion. However, a salt marsh developed in the sheltered side of the dunes, creating an erosion-resistant top soil layer through the accumulation of fine sediment, organic matter and roots. Lateral soil stability increased when the marsh was nearer to a creek and at low elevations, due to more fine sediment deposition and thus thicker erosion-resistant top layers.
**Chapter 5**

**Questions:** What is the role of eelgrass on bed-load transport and sediment resuspension under wave conditions?

**Answer:** Dense root-mat forming seagrass, like *Zostera marina* growing in shallow waters, effectively reduced bedload transport of sandy sediment. However, small patches did not reduce water turbidity.

**Chapter 6**

**Questions:** How does grazing management in combination with abiotic factors, such as marsh age, marsh elevation and sediment layering, affect the susceptibility of marsh edges to lateral erosion?

**Answer:** Grazing by cattle and small herbivores (i.e. hare and geese) can reduce the erodibility of fine-grained soils, making salt marshes more resilient to lateral erosion. However, compaction by livestock simultaneously results into lower soil elevation, potentially leading to more inundation under sea level rise.

**Chapter 7**

**Questions:** Can we develop nature-based management on the tidal flats to stabilize the marshes?

**Answer:** Biodegradable artificial reefs have the potential to attenuate waves and change tidal flat morphology. However, to benefit connected foreshore ecosystems like salt marshes, the dimensions of the reefs should be larger and the structures should be more resistant.