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SPECIAL ISSUE: INTEGRATING ECOSYSTEMS AND COASTAL ENGINEERING PRACTICE

Hard Structures for Coastal Protection, Towards Greener Designs

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Abstract

Over recent years, many coastal engineering projects have employed the use of soft solutions as these are generally less environmentally damaging than hard solutions. However, in some cases, local conditions hinder the use of soft solutions, meaning that hard solutions have to be adopted or, sometimes, a combination of hard and soft measures is seen as optimal. This research reviews the use of hard coastal structures on the foreshore (groynes, breakwaters and jetties) and onshore (seawalls and dikes). The purpose, functioning and local conditions for which these structures are most suitable are outlined. A description is provided on the negative effects that these structures may have on morphological, hydrodynamic and ecological conditions. To reduce or mitigate these negative impacts, or to create new ecosystem services, the following nature-based adaptations are proposed and discussed: (1) applying soft solutions complementary to hard solutions, (2) mitigating morphological and hydrodynamic changes and (3) ecologically enhancing hard coastal structures. The selection and also the success of these potential adaptations are highly dependent on local conditions, such as hydrodynamic forcing, spatial requirements and socioeconomic factors. The overview provided in this paper aims to offer an interdisciplinary understanding, by giving general guidance on which type of solution is suitable for given characteristics, taking into consideration all aspects that are key for environmentally sensitive coastal designs. Overall, this study aims to provide guidance at the interdisciplinary design stage of nature-based coastal defence structures.

Keywords Coastal structures · Green infrastructure · Building with nature · Ecosystem engineering · Nature-based solutions · Environment-friendly engineering · Ecosystem services

Introduction

Predictions indicate that the percentage of world population living in coastal areas will continue to increase (Neumann et al. 2015). Concurrently, the effects of climate change, i.e. regional sea level rise and its consequences, pose risks to coastal communities and coastlines. As a result, coastal safety is of increasing importance (Temmerman et al. 2013; Firth et al. 2014). To ensure acceptable levels of coastal safety, coastal engineering solutions are implemented which can be classified into grey and green infrastructure (Fig. 1).

Grey infrastructure refers to conventional hard solutions (e.g. seawalls, dikes or breakwaters), while green infrastructure can be classified into three subcategories, namely (1) environmental-friendly grey infrastructure, (2) hybrid infrastructure and (3) soft infrastructure. Whereas soft solutions are typically green infrastructure, hard solutions can also be regarded as green infrastructure (under the label of environment-friendly grey infrastructure; Fig. 1) if they are designed to contribute to restoring, conserving or mitigating

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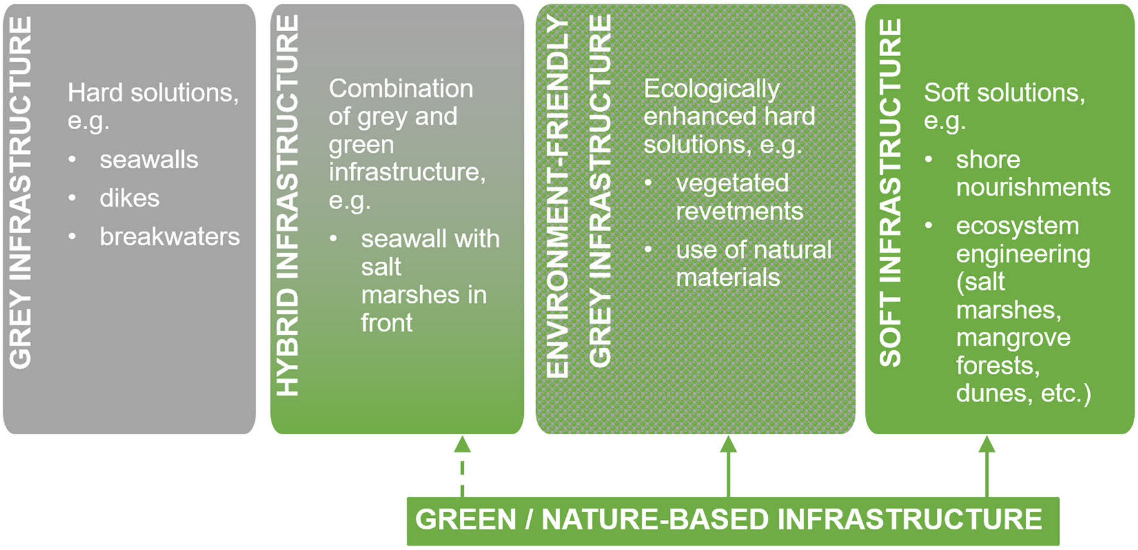

Fig. 1 Definition of infrastructure types

the loss of ecosystem services (David et al. 2016; van der Nat et al. 2016; Pontee et al. 2016; Silva et al. 2017). This can be achieved if the infrastructure mimics ecosystem functions (e.g. habitat provision) or induces or preserves connectivity as a natural system would (Silva et al. 2017). Thus, adaptations may be made to conventional grey infrastructure to increase their value as green infrastructure by allowing organisms to settle, and thereby offering ecosystem services (Borsje et al. 2011; Firth et al. 2014). The combination of coastal habitat (e.g. salt marshes) with hard solutions, known as hybrid infrastructure, is another way to implement green infrastructure (Sutton-Grier et al. 2015; Pontee et al. 2016).

Hard solutions, such as breakwaters, seawalls and dikes (Fig. 1), have been employed to offer coastal safety for years. Their designs are broadly based on recommended best practices and design guidelines developed over the last decades, e.g. in the Shore Protection Manual (CERC 1984), Coastal Engineering Manual (USACE 2002), Overtopping Manual (EurOtop 2018), International Levee Handbook (CIRIA 2013) or the Rock Manual (CIRIA 2007); see also Table 3 in the Appendix. It is expected that the number of hard coastal structures will continue to rise in response to climate change (Moschella et al. 2005; Chapman and Underwood 2011; Firth et al. 2013; Firth et al. 2016a). Simultaneously, with increasing awareness of the need for sustainable development and mitigating environmental impacts, implementing soft solutions, such as shore nourishments, has been increasingly considered (Capobianco and Stive 2000). Consequently, the following questions arise: (i) where and when are hard structures still preferred over soft solutions and (ii) if hard solutions are needed, how can they be made into green infrastructure, taking into consideration ecological and engineering aspects?

These questions are answered with the aim of bridging gaps between disciplines and thereby enhancing future collaboration and the definition of joint objectives. Challenges between disciplines may lead to the unsuccessful implementation of green infrastructure. Coastal engineers often lack understanding of the far-reaching effects of coastal infrastructure and what constitutes successful nature-based solutions, while ecologists may need a greater awareness of the aspects required to ensure coastal safety and to determine acceptable risks. The first question of this review aims to clarify to ecologists how hard structures provide coastal safety and under which conditions these structures are suitable vs. unavoidable ("Structure Types and Their Design Conditions" section). The focus of the second question aims to assist engineers in the consideration of the environmental impacts of hard structures ("Environmental Impacts and Concerns of Grey Coastal Infrastructure" section) and the incorporation of green infrastructure principles throughout the design process ("Possible Nature-Based Adaptations for Grey Coastal Structures" section).

This paper considers two groups/types of structures based on where they are employed. Breakwaters, groynes and jetties are grouped under the name of foreshore structures, while seawalls and dikes are classified as onshore coastal structures. The contents described are addressed through literature research and critically discussed in a review.

Guidelines and Policies on Nature-Based Coastal Engineering

The increasing recognition of green infrastructure has led to the development of policies and guidelines in a number of countries (e.g. the Netherlands, the UK, Germany and the USA) and international institutions. To give insight into existing approaches, Table 1 describes a selection of these guidelines and policies in terms of their main features and objectives.

In the Netherlands, the *Building with Nature* concept utilises the potentials of natural processes to develop multi-functional solutions that are aligned with the interests of nature and project stakeholders (De Vriend and Van Koningsveld 2012). Similarly, the *Engineering with Nature* approach of the United States Army Corps of Engineers (USACE) is based on the intentional alignment of natural and engineering processes to facilitate economic, environmental and social benefits for water infrastructure through collaborative processes, such as stakeholder communication and engagement (USACE 2012). On an international scale the *Working with Nature* philosophy of PIANC, the World Association for Waterborne Transport Infrastructure likewise aims at an integrated, proactive process to find and exploit win-win solutions

Table 1 Summary of selected guidelines and policies on nature-based coastal engineering

Guideline/policy (Reference)	Country/institution	Objective and main features
Building with Nature (De Vriend and Van Koningsveld 2012)	Netherlands	Programme carried out by a consortium of private companies, government agencies and research institutes. It aims to gather knowledge on ecosystems and to develop design rules for infrastructure in alignment with natural processes. This is done through pilot projects, which are implemented and monitored. Design guidelines are then developed, based on the analysis of the gathered data.
Engineering with Nature (US Army Corps of Engineers (USACE) 2012; Bridges et al. 2015)	USA	Aims to incorporate natural features and nature-based features (created by human design) into traditional engineering. It presents a framework to identify stakeholders, analyse the system and its vulnerability and propose and evaluate different alternatives, accounting for ecosystem service creation and comparing them through performance metrics. The report includes practical examples of the tools and evaluation methods.
Living Shorelines (SAGE 2015)	USA	Present coastal solutions that protect against storms and erosion while providing ecosystem services and preserving ecosystem connectivity. It considers different alternatives, consisting of vegetation alone or in combination with nourishments, stone fills and other structures. The alternatives are classified based on the environments where they are suitable, costs, advantages and disadvantages.
Shoreline Management Plans (DEFRA 2006)	UK	Developing strategies to reduce the threat of flooding and erosion that are beneficial to the environment, society and the economy, as far as possible. The environmental objective is to maintain, restore or, where possible, improve environmental and historic assets.
National Strategy for Integrated Coastal Zone Management in Germany (BMU 2006)	Germany	Balancing environmental, economic and social needs by developing and preserving coastal areas as ecologically intact, economically valuable and socially acceptable habitats.
Working with Nature (PIANC 2011)	Worldwide	Developing solutions for waterborne transport infrastructure, which are mutually beneficial to project and environmental stakeholders. Advocates an integrated, proactive approach from conception to project completion, which delivers project objectives by maximising opportunities for nature, rather than minimising ecological impacts.
Nature-Based Solutions and Re-Naturing Cities (European Commission 2015)	European Commission	Solutions, which are inspired, supported or copied from nature and that provide environmental, social and economic benefits. Wide range of areas of application. Aims to (1) enhance sustainable urbanisation, (2) restore degraded ecosystems, (3) develop climate change adaptation and mitigation and (4) improve risk management and resilience.
Nature-based solutions (IUCN 2016)	International Union for Conservation of Nature	Ecosystem-based measures to address societal challenges by protecting, managing or restoring ecosystems and making use of their services. Not restricted to any one area of application. Includes different approaches, e.g. ecosystem restoration, ecosystem-based infrastructure and ecosystem-based management.
Ecological Engineering (Cheong et al. 2013)	Miscellaneous	Coastal adaptation strategies which combine engineering structures and ecosystems, considering the societal functions and values of using synergies of the different measures, striving to increase coastal protection and make it more flexible.

in terms of environment quality and engineering goals, for instance a breakwater that ensures safe navigation and creates habitat opportunities (PIANC 2011).

A strategic approach for environmentally and economically sustainable management of coastal zones was introduced in 2002 by the European Parliament within their recommendation concerning the implementation of *Integrated Coastal Zone Management in Europe* (COM 2002). In Germany, these recommendations were implemented within the *National Strategy for Integrated Coastal Zone Management in Germany* that again was adopted at federal state level, within the master plans for coastal protection (BMU 2006). In the UK, sustainable policies for coastal management, such as the *Managed Realignment Policy*, are established through *Shoreline Management Plans* (SMPs) (DEFRA 2006). Furthermore, Naylor et al. (2011) provide background on the principles of including ecological enhancements in hard coastal structures, such as incorporating rock pools in vertical seawalls (Chapman and Blockley 2009) or using construction material with rougher surfaces (Moschella et al. 2005). Apart from general guidance, the guide offers a description of legal frameworks in the UK and Europe that supports these enhancements. In addition, Nesshöver et al. (2017) provide a review of the practice and policies of nature-based solutions within a European context.

Cheong et al. (2013) define the approach of *Ecological Engineering* that additionally considers societal functions and values as an integral part of nature-based solutions. The authors state that combined approaches to coastal adaptation, rather than a single strategy, such as seawall construction, is better preparation for the highly uncertain and dynamic coastal environment. They conclude that very few studies on practical implementations have examined the interactions, synergistic effects and co-benefits of combined approaches to adaptation.

The International Union for Conservation of Nature (IUCN 2016) and the European Commission (2015) focus on nature-based solutions for infrastructure in general, whereas the other policies discussed focus more specifically on hydraulic and coastal engineering applications. *Living Shorelines*, an innovative US approach, presents nature-based shoreline stabilisation techniques for erosion control (SAGE 2015).

Although the policies and guidelines in specific countries and institutions have different names, the desired outcomes of all are common: the use of natural processes and/or resources to achieve solutions that are socially, economically and environmentally beneficial. General guidelines are provided, while a need for detailed design guidelines in terms of effectiveness and performance of nature-based coastal solutions persists.

Structure Types and Their Design Conditions

This section presents a general description of two structure types (foreshore and onshore structures), and the design conditions relating to them. General design guidelines for the structure types are provided by different institutions, such as CIRIA (2007) and USACE (2002). A summary of the guidelines is included in Table 3 in the Appendix, in terms of the structures included, design processes and the aspects covered.

Foreshore Structures

Traditionally hard structures, such as groynes and breakwaters, are built on the foreshore to prevent or mitigate erosion (Hamm et al. 2002). A schematic overview of such structures and their effects on the physical environment is shown in Fig. 2.

Offshore breakwaters are built parallel to the shore and designed either to protect the coastline or to improve the recreational conditions behind them (Pilarczyk and Zeidler 1996). They may be constructed from materials such as concrete, rocks, sand bags or geotextiles and are designed to allow a certain amount of wave transmission by flow through the porous structure or overtopping. Part of the wave energy is reflected seawards, and part is dissipated by wave breaking on the slope or by friction losses inside the breakwater body (Pilarczyk 2003). The sheltering effect of breakwaters provides protection against storms but also affects the morphodynamics of the coast. The changes in the hydrodynamics induced by the presence of the structure (Mory and Hamm 1997) alter the gradients in sediment transport and thus cause morphological changes (Van Rijn 2013). The decrease of the longshore current behind the breakwater may induce a pattern of accretion on the updrift side, while the increase in flow velocity as the current leaves the sheltered area may result in erosion downdrift of the structure. Wave diffraction tends to increase erosion at the sides of the breakwater, and deposition in the middle part, since the diffracted waves curve towards the sheltered area and reduce in height inside of it (Hsu and Silvester 1990). Wave-induced set-up currents are caused by the changes of wave height away from and behind the breakwater. Variables, such as the number of structures, the distance between them (along the shore), their distance to the coastline, the structure crest height and the width of the surf zone, may induce different patterns of erosion and accretion (Ranasinghe and Turner 2006; Suh and Dalrymple 1987).

Groynes are structures that extend towards the sea perpendicularly, or obliquely, to the shoreline (USACE 2002) and are usually constructed of timber, rocks or concrete. Groynes prevent, or slow down, the longshore sediment transport,

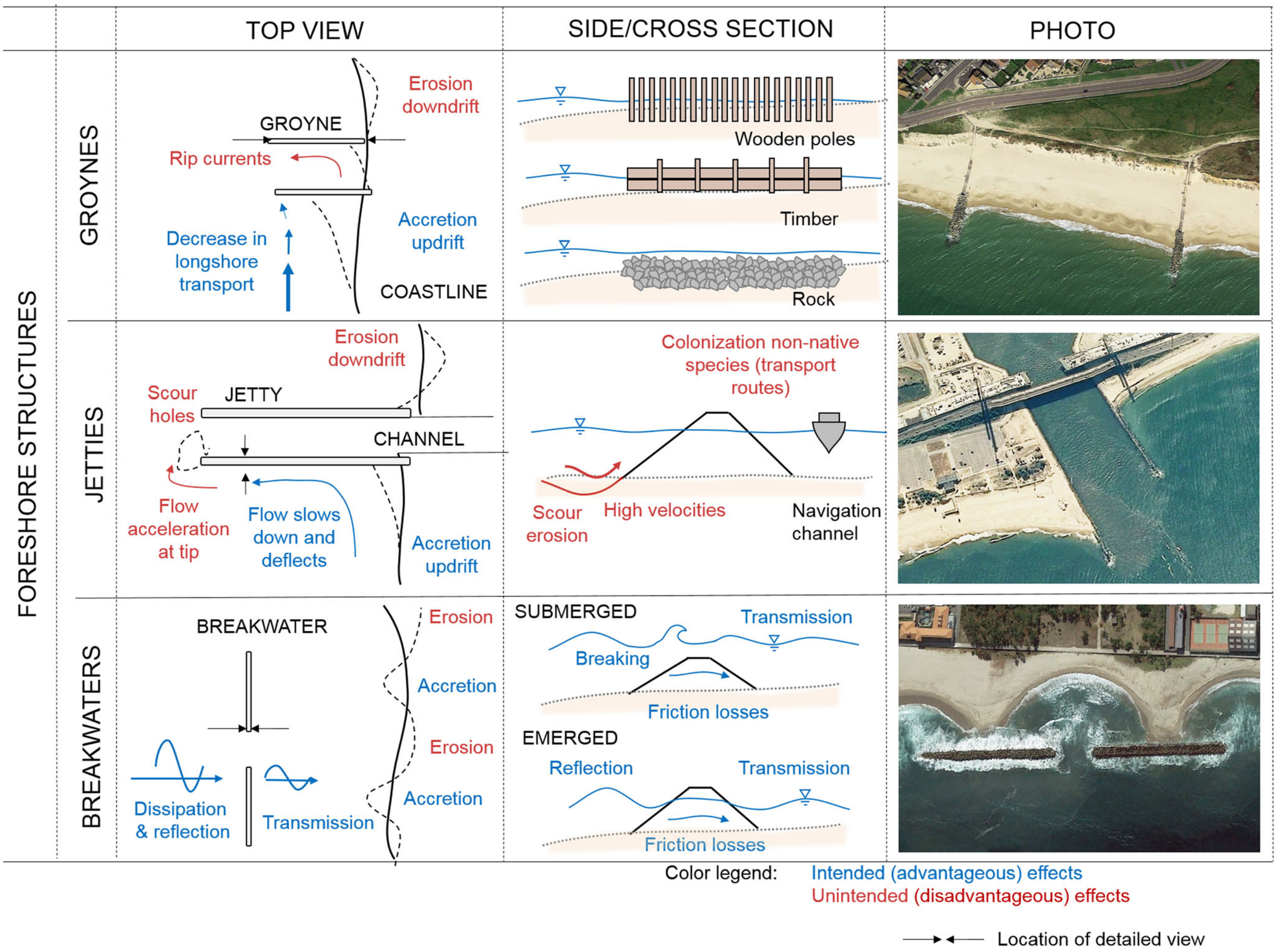

Fig. 2 Overview of hydrodynamic and morphodynamic effects of groynes, jetties and breakwaters. The left column has schematic plans of each structure type and its effects. The black arrows indicate the location of detailed views of the structures, shown in the central column. The right column shows actual examples of these structures (photos: GoogleEarth, Landsat/Copernicus (groynes and breakwaters); Google Earth, USDA Farm Service Agency (jetties))

resulting in accretion of sediment on the updrift side of the structure and erosion on the downdrift side (Van Rijn 2013), as illustrated in Fig. 2. Groups of groynes have been used to stabilise a stretch of coastline or for land reclamation purposes (Nienhuis and Gulati 2002). Jetties are also structures which are perpendicular to the coast, but these extend further seaward and have the purpose of protecting navigational channels. They divert tidal currents offshore and restrict the lateral transfer of sediment, reducing channel dredging costs (Van Rijn 2013).

Hard structures are designed to ensure structural integrity under extreme environmental conditions (not exceeding their design conditions). Different modes of failure are considered in the design, such as the erosion or breakage of the armour layer or geotechnical stability, i.e. sliding or settlement of the structure (e.g. Losada 1990). The amount of overtopping under normal conditions is limited to ensure the operability in the area sheltered by the structure. Further information on the existing design guidelines is included in Table 3 in the Appendix.

Foreshore structures have been seen to cause adverse long-term erosion effects on adjacent shores or nearby. These effects can be aggravated by implementing hard structures in unsuitable conditions or in cases where erosion is caused by socioeconomic practices, such as sand mining. Soft engineering approaches, such as sediment nourishments, can be applied alone, or in combination with traditional solutions (Capobianco and Stive 2000; Hamm et al. 2002). The periodic addition of sediment has been used as a way to counteract structural erosion or in by-passing schemes between groyne compartments.

Although hard foreshore structures and sediment nourishments may increase wave energy dissipation and mitigate erosion in medium- to high-energy environments, they do not provide protection against storm surge and flooding. When higher levels of protection are required, they can be complemented or replaced by shoreline structures such as seawalls or sea dikes.

Onshore Structures

Seawalls

Seawalls are shore-parallel, onshore structures designed to protect the coastal hinterland from overtopping and flooding. These structures fix the position of the shoreline, thereby preventing it from retreating landward. Seawalls can be vertical, curved, stepped or sloping structures. Revetments are sloping structures which cover the shoreline profile to offer erosion protection. Although there is a functional difference between seawalls and revetments (i.e. seawalls prevent inland flooding, while revetments prevent shoreline erosion), there are no distinct structural differences. Hence, in this paper, the collective term “seawalls” will be used. Seawalls are often considered the last line of defence on the coast and are typically constructed in areas where the natural protection of sandy or muddy beaches, ecosystems and/or other foreshore structures no longer provide an acceptable level of protection for landward infrastructure, such as promenades and roads.

Various types of seawalls, ranging from vertical to sloping, have been constructed on shorelines around the world using a variety of construction materials: reinforced concrete, rocks, concrete armour units, rock-filled gabions, steel piles, wood and sand-filled bags. Seawalls are often classified as permeable (rock revetment; Fig. 3) or impermeable, designed either to absorb or to reflect the wave energy. General design guidelines are offered by CIRIA (2007) and USACE (2002), while EurOtop (2018) provides guidance on crest level design, Table 3 in the Appendix. Seawalls are suitable for an open coast, exposed to high storm surges and large waves. They have the advantage of requiring little space, which makes them suitable for coastal defence in urban areas.

As seawalls form rigid barriers, they affect and alter coastal processes (see “Morphologic and Hydrodynamic Changes” section and Fig. 3). A seawall often leads to increased wave reflection, which may result in scour, due to the (partially) standing waves in front of the structure. This makes seawalls, especially impermeable ones, likely to cause sediment loss and in turn to structural instabilities (USACE 2002). To

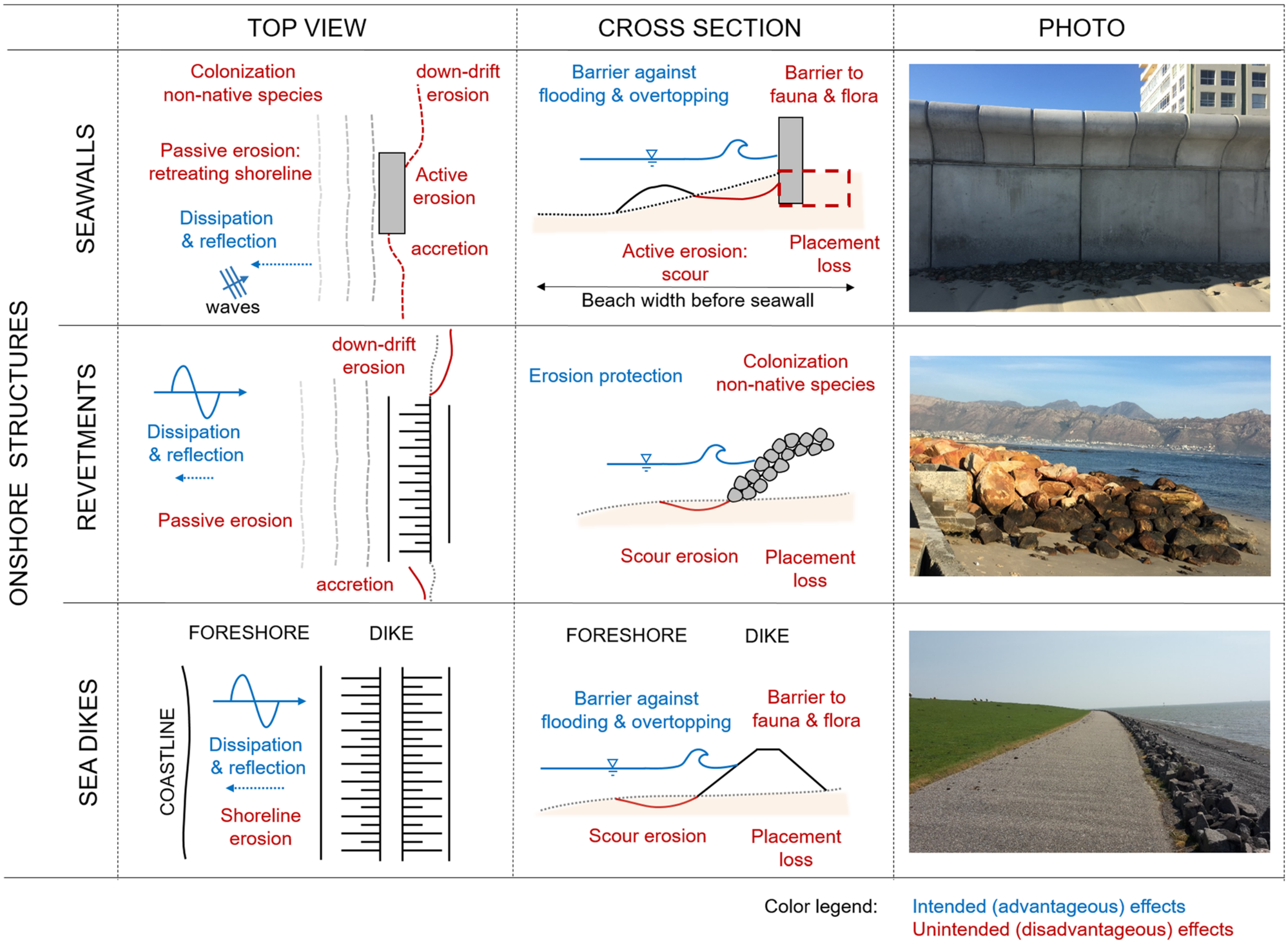

Fig. 3 Overview of grey onshore coastal structures and their hydrodynamic and morphodynamic effects

counteract the potential erosion effects, seawalls are often implemented in combination with foreshore structures such as groynes and shore nourishments, see "Foreshore Structures" section. Apart from scour, other typical damage modes that have to be considered in the design of seawalls include overtopping, flanking ("Morphologic and Hydrodynamic Changes" section), rotational sliding, overturning and corrosion of reinforcement steel (USACE 2002). A schematic overview of seawalls and their effects on the physical environment is shown in Fig. 3.

These structures provide short- to long-term protection (e.g. a sand-filled bag seawall: up to 5 years, a seawall with concrete armour units: up to 100 years). However, seawalls often cause a sudden shift in ecological balances at the site.

Sea Dikes

As with seawalls, sea dikes are considered a last line of flood defence. Also known as embankments or levees, sea dikes are shore-parallel coastal barriers which protect the low-lying hinterland from flooding, thanks to their raised ground level. A schematic overview of sea dikes and their effects on the physical environment is shown in Fig. 3 below.

Generally, dikes are composed of an earth-filled core with smooth slopes on both seaward and landward sides. Figure 4a shows a typical dike cross-section with its design water level (DWL) and the mean high water (MHW). Sealings, revetments, berms, crest walls etc. can complement the basic structure. If the hydraulic loads are low, sea dikes are covered with a vegetated clay layer. In the case of higher loads, i.e. due to breaking wave impacts, hard revetments, e.g. rock filled, are applied to induce friction and increase energy dissipation, thereby ensuring dike safety (EAK 2002; CIRIA 2013). Following storm surge experiences, sea dikes in Germany were heightened and broadened, resulting in the current characteristic dike profiles, with seaward slopes of between 1:3 and 1:7 and landward slopes of 1:2 to 1:5 (Schüttrumpf 2008). The footprint of a dike depends on the required crest height and slope angles, which in turn are determined by optimising dike stability (smooth slope), considering space restrictions and material consumption (CIRIA 2013).

To ensure the main function of coastal protection, dikes must be designed in such a way that they resist external loads (high water levels, waves, currents, human activities etc.) and consequent damage from erosion and mass instability (sliding). Design methods (Table 3 in the Appendix) consider hydraulic, morphological and geotechnical boundary conditions. Besides state-of-the-art design and construction, regular monitoring and maintenance are indispensable for dike safety (EAK 2002; CIRIA 2013). Sea dikes are generally built for long-term coastal protection, with a long design life, e.g. 50 years in the Netherlands (Pilarczyk 2017).

Environmental Impacts and Concerns of Grey Coastal Infrastructure

Environmental impacts depend on many site-specific aspects, related to structural design as well as ecological and physical conditions of the local system (Chapman and Underwood 2011; Nordstrom 2014). The following section discusses the general impacts of the structures defined in the "Structure Types and Their Design Conditions" section, based on (i) morphologic and hydrodynamic changes and (ii) changes in ecological communities, due to habitat modifications related to altered morphodynamics, substrate type and availability. Knowledge of environmental impacts and how they

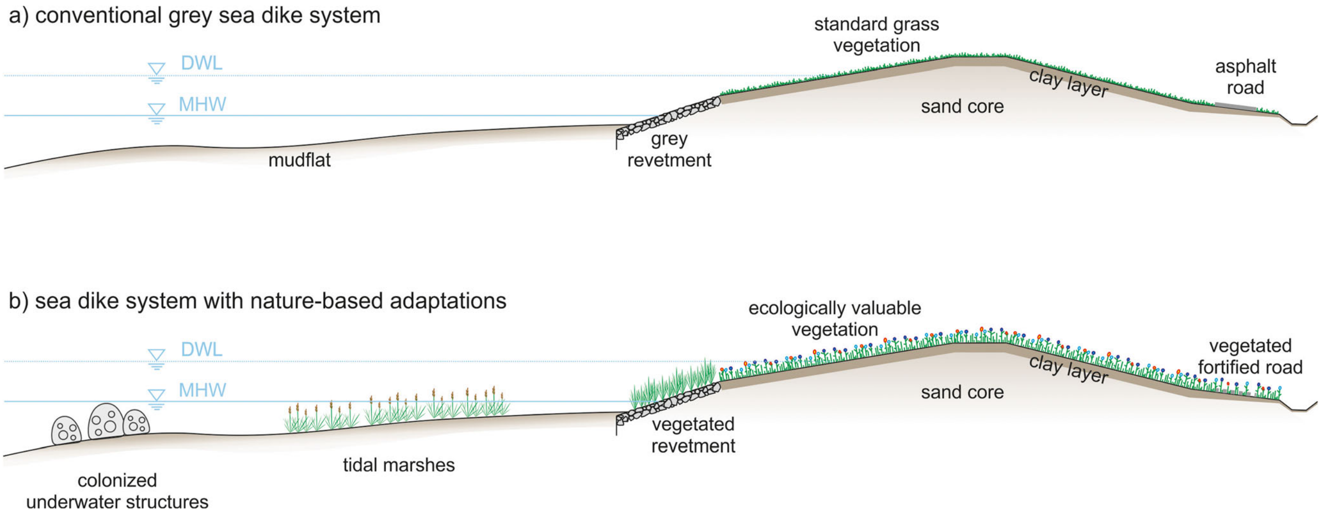

Fig. 4 **a** Conventional grey sea dike system. **b** Sea dike system with nature-based adaptations

evolve through the lifetime of a structure is still very limited. Systematic interdisciplinary research is thus required to fully incorporate impact mitigation in future infrastructure design.

Morphologic and Hydrodynamic Changes

The implementation of any coastal structure brings morphologic and hydrodynamic changes, such as alterations to wave regime, sediment dynamics and depositional processes (Dugan et al. 2011). Sometimes, they produce unintended morphodynamic effects, which may lead to structural deteriorations or sediment budget imbalances.

Wave reflection by emerged shore-parallel structures increases wave energy in front of the defence, increases scouring, and may result in erosion and the loss of intertidal areas (Douglass and Pickel 1999; Winterwerp et al. 2013). Submerged detached breakwaters became popular because of their low visual impact, but the lack of understanding of their hydraulic behaviour often resulted in erosion problems; a literature review conducted by Ranasinghe and Turner (2006) concluded that the majority of existing submerged structures have induced shoreline erosion on their lee side. Sediment trapping by shore normal structures produces shoreline advance on one side, but induces coastline retreat downdrift of their position. Moreover, currents are deflected seaward, which may cause a loss of sediment offshore and a danger for recreation activities, if the flow velocities are high enough (Scott et al. 2016). In addition, flow contraction at the end of shore normal structures leads to flow acceleration and scour at the tip (Lillycrop and Hughes 1993). Figure 2 illustrates the morphologic and hydrodynamic changes due to groynes, jetties and breakwaters.

Periodic shore nourishments on the foreshore, or beach face, may mitigate structural erosion problems induced by hard structures. However, they produce environmental effects, such as biota burial and an increase in turbidity and sedimentation, at both the site of extraction and placement. Additionally, it is improbable that any benthic fauna which survives the dredging process will be capable of reestablishment on the seabed (ICES 2016). The severity of the impact and the ability of the system to recover has not been systematically scrutinised, but depends on the intensity, duration and exposure of these effects and on the tolerance of the local species (Erftemeijer and Lewis III 2006; Erftemeijer et al. 2012).

Seawalls and sea dikes are rigid structures that act as a boundary between the land and the sea. Generally, their physical impacts on a beach increase the lower on the beach profile they are built (Dugan et al. 2011). These impacts can be classified as (1) placement loss, (2) passive erosion and (3) active erosion (Griggs 2010). Placement loss refers to the portion of beach that is lost when a structure is built, thus depending on the footprint of the structure. Although seawalls and dikes limit the extent of shoreline retreat, beach erosion in front of these structures continues on coasts subject to long-term net erosion. Consequently, the shoreline retreats towards (and possibly beyond) the structure, which results in gradual beach loss over time, known as passive erosion. This erosion is not a result of the structure itself, but continues as the structure does not address the underlying problems causing the erosion (Griggs 2010). Where no structure is present, the beach width would remain mostly the same, but the beach would shift further landwards with time (Dean 1987).

Active erosion occurs due to the interaction of the structure with coastal processes (Kraus and McDougal 1996). Since seawalls and sea dikes may create a cross-shore barrier effect by blocking the sand movement between the beach and the backshore, they consequently affect aeolian sand transport, and as a result, the natural dune system (Jackson and Nordstrom 2011; Nordstrom 2014). Moreover, the interruption of the sand supply from the backshore can potentially cause erosion at locations down drift of the seawall (Dean 1987; Kraus 1988; Nordstrom 2014). Analogous to emerged breakwaters, seawalls and sea dikes can further increase wave reflection and increase scour in front of the structure (USACE 2002). Locally increased erosion at the ends of a seawall, known as flanking, may also occur. Figure 3 illustrates the morphologic and hydrodynamic changes due to seawalls and sea dikes.

Effects Due to Changes in Habitat

The morphologic and hydrodynamic changes of coastal structures also have an impact on local species. The flow acceleration and scour at the end of shore normal structures ("Morphologic and Hydrodynamic Changes" section) may hinder the attachment of sessile organisms in the scour zone, and inhibit subtidal life near the base of the outer part of the structure (Britton and Morton 1989).

Loss of habitat is initially due to the placement loss and increases as the beach becomes narrower, as a result of passive erosion or scour due to active erosion (Dugan et al. 2011; Nordstrom 2014). Seawalls and sea dikes produce intertidal habitat loss, since the area flooded by the tide is obstructed by their presence, subsequently affecting the local biota (Dugan et al. 2008; Nordstrom 2014). The cross-shore barrier effect of onshore structures not only interrupts sand movement ("Morphologic and Hydrodynamic Changes" section), but may also hinder the movement of fauna (Nordstrom 2014). Consequently, fauna seeking refuge in the dunes are affected (Lucrezi et al. 2010; Nordstrom 2014) and inland habitat may be isolated, which also affects neighbouring habitats

(Chapman and Underwood 2011). Dugan et al. (2008) found that seawalls may produce a significant decline in the abundance, biomass and size of macroinvertebrates in the upper intertidal zone as well as in the species richness and abundance of shorebirds. Structures with slopes steeper than the natural shore offer reduced habitat area, resulting in a loss of local biodiversity and finally leading to a reduction in the total population size in a region (Chapman and Underwood 2011). In intertidal areas, a steeper slope means that species that used to live in different vertical zones are now located much closer together, causing changes in ecological interactions (Dugan et al. 2011; Nordstrom 2014).

Artificial coastal defences transform and often fortify soft-shore coastlines into static, hard structures, allowing colonisation by rocky shore species (Firth et al. 2014). When placed close to harbours or shipping routes, there is a higher risk of invasion by non-native species (neobiota), which could spread along a chain of groynes or breakwaters (Bulleri et al. 2006; Keith et al. 2011; Firth et al. 2012; Airoldi et al. 2015). Thus, the impacts of structures are not only confined to their location. Large-scale impacts may result from changes to ecological connectivity, which in turn affects biodiversity, as well as the ecosystem services in coastal zones (Dugan et al. 2011; Firth et al. 2014; Bishop et al. 2017).

Seawalls introduce new hard substrata that are notably less dynamic than muddy, rocky or sandy habitats (Nordstrom 2014). With reference to a number of studies, Chapman and Underwood (2011) reported that artificial habitat changes the mix of species, abundance, the size structures of population, reproductive output and competition or response to habitat. Sea dikes with a vegetated dike cover generally introduce less hard substrata than seawalls and therefore any ecological impacts are assumed to be less compared to seawalls, although, as yet, no scientific evidence of this is known to the authors. Nevertheless, alterations in the biotic structure through the construction of sea dikes are still to be expected as the dike vegetation usually diverges from the natural species (e.g. standard seeding mixtures in EAK (2002)).

Possible Nature-Based Adaptations for Grey Coastal Structures

Although the detrimental effects of hard solutions cannot always be avoided, certain nature-based adaptations can be made to mitigate or reduce these effects. This section describes (i) ecosystem engineering options as complement to traditional hard solutions, (ii) measures to mitigate morphologic and hydrodynamic changes and (iii) possible adaptations to ecologically enrich conventional grey structures. Nature-based measures should ideally be considered early on in project planning, to limit construction costs and to allow their implementation over larger spatial scales (Firth et al. 2013).

Using Ecosystems as Part of the Foreshore Structures Fronting Seawalls and Sea Dikes

General Considerations in Using Ecosystems Along the Foreshore

In planning ecosystems along the foreshore, two main generic principles, related to the habitat requirements of species, should first be considered. The first main principle is that species are typically either “aquatic” (seagrass meadows, mussel reefs, coral reefs) or “terrestrial” (e.g. salt marshes, mangroves), respectively, depending on whether they function the best underwater, tolerating regularly being shortly emerged from water, or whether they function best above water, tolerating flooding for part of the day. In general, species living higher in the intertidal system will be more efficient in attenuating waves (Bouma et al. 2014), as the surface area and structures they build are more likely to affect a larger part of the waves (see Bouma et al. 2014 for example calculations). The second main principle to keep in mind is that establishment and survival of species and ecosystems is typically limited by the maximum hydrodynamic forcing they can resist. This means that in green designs, the species should be selected based on their tolerance to hydrodynamic forcing. For example, corals and beach systems occur at higher energy levels than marshes and mangroves. In cases where hydrodynamic forcing creates unfavourable conditions for marshes and mangroves species to survive, hard structures or shore nourishments may be needed.

Ecosystems as Coastal Protection

Field studies show that coastal habitats have a significant potential for reducing wave heights that varies for habitat and site (Narayan et al. 2016). In general, coral reefs and salt marshes have the highest potential, producing an average of 70% and 72% attenuation, respectively.

Coral reefs are effective as they form a sharp transition from deep to shallow water (Ferrario et al. 2014), whereas intertidal vegetation like salt marshes and mangroves are effective since they grow high in the intertidal area and consequently increase bathymetric elevation (Bouma et al. 2014).

Reef-forming species, such as natural oyster reefs, act as natural breakwaters by attenuating waves (Meyer et al. 1997) and promoting sedimentation (Henderson and O’Neil 2003). Shellfish reef restoration has been implemented at a number of locations, such as the Oosterschelde in the Netherlands. Shellfish reefs were built in 2008 to prevent sediment loss from the tidal flats to the channels. Monitoring showed there was erosion prevention and accretion at the reefs compared to other, exposed locations (De Vriend et al. 2014). Scyphers et al. (2011) compared the bathymetric changes and vegetation retreat behind artificial oyster reefs with control locations, where reefs were not present. They concluded that although the experimental reefs created new habitat, they did not provide as much coastal protection as conventional solutions. This was partly attributed to their mesh not being rigid enough for the levels of wave energy. Natural reefs could also be installed in combination with hard structures to mitigate environmental impacts, such as loss of fish and shellfish habitat (Scyphers et al. 2011).

Submerged aquatic vegetation, such as seagrass, attenuates local currents (Gambi et al. 1990), dampens wave energy (Knutson et al. 1982; Fonseca and Cahalan 1992; Möller et al. 2014) and promotes sedimentation (Callaghan et al. 2010; Shi et al. 2012), subsequently acting as a buffer against flooding and erosion. Seagrasses have been observed to dissipate 40% of the wave energy, but have also shown negligible effects on waves when the water depth was considerably greater than the leaf length (Fonseca and Cahalan 1992). Thus, the ability of aquatic vegetation to dissipate wave energy depends on a combination of the hydrodynamic conditions and plant properties (Bradley and Houser 2009). Typically, the flexible structures of aquatic vegetation make them less effective in attenuating waves than the stiffer structures associated with salt marshes and mangroves (Bouma et al. 2005), although this may be compensated for by having a very high biomass (Bouma et al. 2010). It should also be noted that seagrass meadows may even contribute to flood safety when vegetation is extremely sparse and short, due to the fact that the dense rhizome mats will preserve an elevated bed level (Christianen et al. 2013).

Intertidal vegetation, like salt marshes, enhances sediment trapping and creates a platform that reduces the hydrodynamic loads behind them. Laboratory experiments by Möller et al. (2014) compared wave attenuation under storm surge conditions, with and without salt marshes, and observed that 60% of wave height reduction was attributed to the effect of the vegetation. Marsh creation can be conducted by displacing historical dikes landwards or building sluices at existing dikes, subsequently allowing tidal flooding behind the structures (Temmerman et al. 2013). The cyclic dynamics of ecosystems like salt marshes means maintaining sufficient marsh width for coastal protection difficult (Bouma et al. 2014, 2016). Measures that stimulate sediment accretion on the tidal flat fronting the marsh typically stimulate marsh expansion (Bouma et al. 2016; Cao et al. 2018). Mangrove ecosystems perform similar functions (protection against storms and sediment trapping) in tropical areas. Waves can be reduced between 13 and 66% over 100 m of mangrove forest (McIvor et al. 2012). Bamboo and brushwood structures have been used in restoration schemes at eroding coastlines to provide the morphodynamic conditions required for mangroves to establish (Winterwerp et al. 2013; Schmitt et al. 2013). This approach goes back to the kwelderwerken (salt marsh works), where marshes were historically created using brushwood dams to enhance sediment accretion on the tidal flats fronting the marsh (Dijkema 1987).

Even though coastal ecosystems provide multiple provisional and regulating ecosystem services, such as wave dampening or sediment trapping (Murray et al. 2002; Koch et al., 2009), it is still not known how to realistically design and assess green infrastructure (Costanza et al. 1997; MEA 2005). Verified parametrisation of the efficiency and performance of green infrastructure is lacking, e.g. wave attenuation depending on coastal system boundary conditions.

Towards an Integrated Approach by Combining Multiple Ecosystems

Although ecosystems located high in the intertidal zone, like salt marshes and mangroves, may contribute much more to flood safety than systems located lower, this does not mean the latter are unimportant. They can play an important role in stabilising and accreting upward the lower part of a foreshore. In doing so, these low intertidal ecosystems create favourable low-energy high-elevation conditions that allow the intertidal systems to expand (Bouma et al. 2014). This kind of mutual facilitative interaction was first suggested by De Vries et al. (2007; see Fig. 5) and later demonstrated for tropical coastal ecosystems by Gillis et al. (2014). Using a set of ecosystems rather than any single ecosystem as a foreshore system may thus provide a more resilient defence.

The spatial requirements of ecosystem engineering restrict its application to locations where there is sufficient space between urbanised areas (Temmerman et al. 2013). Besides this, although coastal vegetation (wetlands, dune vegetation and seagrass) may dampen part of the wave energy, it is not an impermeable barrier and it will be flooded during extreme high water. Coastal vegetation cannot stop storm surges, which behave similarly to tidal forces that penetrate the vegetation and raise water levels over several hours (Feagin et al. 2010). Large waves can also propagate further onshore during these extreme water levels. Due to the limitations in wave dampening and the potential detrimental effects of high-energy events on the ecosystems (SAGE 2015), ecosystem engineering is most suitable in environments of relative low energy. Whenever these conditions are not met, engineering measures may be needed to achieve the goals.

The long-term stability of coastal vegetation is an uncertainty that is still relatively poorly understood, which may hamper its implementation (Bouma et al. 2014). Fortunately, adaptations can also be implemented retrospectively, or incrementally, as discernible changes in design loads or other previously uncertain boundary conditions arise (such as sea level rise or increases in wave height impacts due to local morphological alterations).

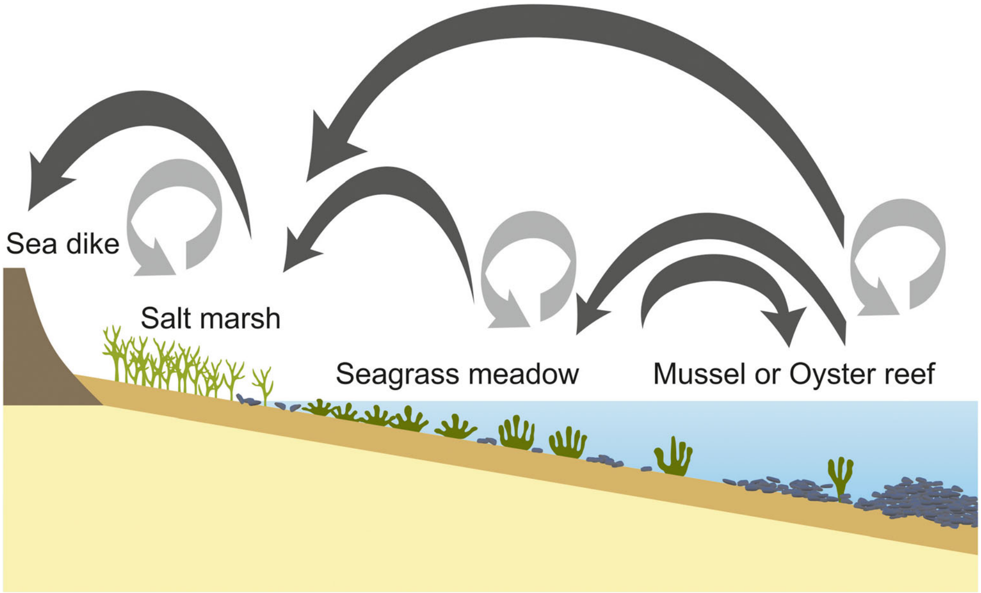

Fig. 5 Gradient of ecosystem engineering that stabilise the sediment and thereby protect the coast. Arrows indicate positive interactions. Adapted and translated from De Vries et al. (2007) and van Katwijk and Dankers (2001)

Impact Mitigation for Morphologic and Hydrodynamic Changes

To ensure minimal physical effects, recommended design guidelines and standards (Table 3 in the Appendix) should be followed. Numerical models predicting the shoreline response of coastal structures can help to optimise designs for mitigating physical changes on the adjacent coast. Moreover, monitoring of the physical impacts throughout the lifetime of the structure is important to identify unintended morphologic and hydrodynamic changes (USACE 2002).

The morphodynamic effects of foreshore structures can be reduced or mitigated in different ways. The undermining of structures due to scour can be prevented by appropriate scour protection design. However, although typical scour protections of rock or concrete would create new habitat, they would not compensate for the loss of the soft habitat they are placed on. Alternatively, structures of porous materials could produce less scour than impermeable structures. The impacts of erosion could be minimised in the design phase by increasing the structure porosity or in the dimensioning of the structures. An alternative is to mitigate the impacts of the design by shore nourishments or sand bypass systems (USACE 2002). However, sediment nourishments also produce negative environmental effects, as described in the “Morphologic and Hydrodynamic Changes” section.

The physical impacts of seawalls can potentially be reduced by burying the structure, or changing its location on the cross-shore profile. In USACE (2002), an example is presented where a rock seawall/revetment was completely buried under a beach and dune, which meant that the revetment would only become exposed during storm conditions. This proved to be more environmentally beneficial and had lower costs than a conventional rock revetment and could also be expected to have less adverse physical effects. Since the physical impacts of seawalls on a beach increase the lower they are located on the beach profile (Dugan et al. 2011), seawalls should be built as high as possible on the beach profile. In contrast, to promote habitat variety and diversity, the structure should be placed as low down in the intertidal zone as possible (Firth et al. 2014). The barrier effect of seawalls can possibly be reduced by modifying or lowering certain stretches along the seawall to restore sediment movement and ecological connectivity between the beach and the backshore (Nordstrom 2014).

The position of a sea dike influences how much wave energy reaches the dike and consequently how much the coastal processes are altered by the interaction with the dike structure. However, the process of selecting sea dike alignment involves various aspects, such as geomorphological and hydraulic conditions or land use, and is usually a compromise between the different issues (CIRIA 2013). Therefore, set-back positions of sea dikes are generally not the preferred solution.

Adaptations of the dike cross profile, such as the concept of wide green dikes with smooth seaward slopes (Van Loon-Steensma et al. 2014), can provide ecological enhancements and simultaneously reduce the effects on coastal processes, e.g. reflections at the structure (Dugan et al. 2011).

Ecological Enriching the Sub- and Intertidal Hard Substrates of Coastal Structures

As recommended by Firth et al. (2014), the selection of nature-based adaptations should be preceded by a thorough definition of the objectives and outcomes they should provide. A wide range of techniques for the ecological enhancements of artificial structures is described in literature (see Firth et al. 2016a for a critical review) and is highlighted here for foreshore structures, seawalls and dikes.

Impact Mitigation of Hard Foreshore Structures

Heterogeneity, from surface roughness to larger irregularities in a structure, offers a greater variety of habitats and promotes higher biodiversity compared to a smooth surface (Firth et al. 2012; Martins et al. 2010; Hall et al. 2018; Chapman and Underwood 2011; Naylor et al. 2011). Some heterogeneities are already present at coastal defences due to the construction procedure, such as holes/grooves in armour units, which retain water, or gaps between rocks or concrete blocks. Additional heterogeneities can also be incorporated in the design, for example, by adding tiles with different textures and microhabitats (Borsje et al. 2011; Coombes et al. 2015; Firth et al. 2016a). Drill-cored artificial rock pools can be an affordable, effective way to enhance the biodiversity of intertidal coastal structures (Firth et al. 2014; Evans et al. 2016).

Furthermore, Firth et al. (2013) suggest that rock structures should be constructed of both soft and hard rocks, since the weathering of carbonate rocks takes place faster than igneous rocks, thus creating additional surface roughness (Chapman and Underwood 2011; Firth et al. 2012). Mixed rock sizes provide different habitats that can lead to greater species diversity and abundance (Wiecek 2009). Porous coastal defences can form valuable habitats within their internal compartments, supporting greater species richness and diversity than external surfaces exposed to higher hydrodynamic forces (Sherrard et al. 2016). Artificial reef structures, for example Reef balls and WADs, have been built in many countries with this purpose. These elements are mound-shaped, concrete modules that imitate natural coral heads, providing a habitat for a variety of marine organisms (Barber 1999). Precast habitat enhancement units, for example BIOBLOCKS (Firth et al. 2014), are another option to increase local biodiversity (Chapman and Underwood 2011; Firth et al. 2013). BIOBLOCKS offer different, novel, micro-habitat types. To maximise species diversity, Firth et al. (2014) recommend that habitat enhancement units should include numerous novel habitat types, such as pits and pools of different depths and sizes, as well as ledges and overhangs.

Different types of artificial structures show different ratios of recruitment of non-indigenous versus native species, depending on their position and material (Glasby et al. 2007). Non-indigenous species were observed to recruit well on concrete surfaces near the water surface, while native species showed preference for locations closer to the shore and the seabed, such as rocky reefs and seawalls (Glasby et al. 2007). These factors should be analysed and considered in the design, to minimise threats to local biodiversity.

Adaptation Options for Seawalls

To minimise the environmental effects, adaptations for seawalls situated on rocky shores should ensure that the natural habitats are mimicked as far possible. As for seawalls on sedimentary coasts, their effects due to habitat changes should be mitigated as far as possible (Firth et al. 2014), e.g. lowering certain stretches of the seawall (see "Ecological Enriching the Sub- and Intertidal Hard Substrates of Coastal Structures" section). This subsection focusses on adaptation options that mimic rocky habitat.

Seawalls can be built or altered to enhance habitat diversity and complexity, without affecting the coastal safety offered, by maximising surface roughness and introducing microhabitats (Wiecek 2009; Borsje et al. 2011; Firth et al. 2014, 2016a; Hall et al. 2018). As with foreshore structures, smooth surfaces, such as concrete, should be avoided as far as possible (Wiecek 2009; Firth et al. 2014; Coombes et al. 2015) or can be made rougher by casting irregular finishes (Wiecek 2009) or by chiselling grooves or drilling holes (Martins et al. 2010; Nordstrom 2014; Hall et al. 2018). Naylor et al. (2017) showed how a rock revetment can be ecologically enhanced by informed selection and intentional positioning of armour rocks. Rock pools can be incorporated in seawalls to provide habitat for intertidal organisms by adding water-retaining features (Chapman and Blockley 2009; Firth et al. 2016b; Chapman and Underwood 2011; Firth et al. 2014). As for hard foreshore structures, precast habitat enhancement units can be included into seawall design to offer a range of novel habitat types (Firth et al. 2014; Chapman and Underwood 2011).

Since vertical seawalls decrease the area of intertidal habitat, sloping seawalls could be beneficial. A sloping structure, however, has a larger footprint and as such cannot be recommended over a vertical structure for this reason only (Chapman and Underwood 2011). Another way to increase intertidal habitat for seawalls is to construct a stepped seawall or alternatively cavities can be left between the seawall blocks or rocks (Wiecek 2009).

Careful consideration has to be given to the fact that invasive species favour hard structures and can use them as stepping stones (Airoldi et al. 2015; Bishop et al. 2017). For coasts with rocky shores, the probability of recruitment of local native species on seawalls can be increased by incorporating features that mimic their natural habitat (Airoldi et al. 2015). Measures can be taken to limit the colonisation of invasive species, such as using coating or smoother materials that hinder the settlement of fouling (Airoldi et al. 2015; Coombes et al. 2015) or by seeding the structures with native species (Firth et al. 2016a; Bishop et al. 2017). A higher diversity of native species may offer a resistance to settlement by invasive species (Firth et al. 2014).

Strain et al. (2018) conducted a quantitative meta-analysis and qualitative review of 109 studies to investigate which common nature-based adaptations (e.g. adding texture, crevices, pits and water-retaining units) have the greatest potential in increasing the biodiversity of key functional groups of organisms. The study found that adaptations in the intertidal zone that offer shade and provide moisture (e.g. crevices, pits and water-retaining features) had the largest influence on the richness of mobile and sessile organisms. Species whose body size was closest to the dimensions of the adaptations showed the greatest positive effects. Furthermore, intertidal adaptations that retain water had the largest impact on the richness of fish. Subtidal zone adaptations that added small-scale cavities resulted in higher abundances of sessile organisms, whereas elevated structures in the subtidal zone lead to higher numbers and abundances of fish. The results of the study provide valuable advice on selecting the most suitable adaptation type according to the desired goals, e.g. increasing biodiversity or enhancing certain ecosystem services.

Figure 6 illustrates examples of possible nature-based adaptations for seawalls. It is essential that adaptation options are positioned in the correct tidal zone, to ensure that they are submerged during high tide. Therefore, adaptations are often placed below mean high water spring tide (MHWS) (but see Firth et al. 2016b). As seawalls are often located on coasts exposed to high wave energy, adaptations should be adequately attached (Browne and Chapman 2011; Coombes et al. 2015; Hall et al. 2018).

Adaptation Options for Greening Dikes

To establish vegetated sea dike covers, standard seeding mixtures of different grasses and, if desired, a small percentage of herbs are commonly used (in Germany: *Lolium perenne*, *Poa pratensis*, *Festuca rubra* ssp. *trichophylla*, *Festuca rubra* ssp. *rubra* and *Achillea millefolium*). These mixtures are known to ensure the main functions of the grass cover: protection against mechanical forces, such as wave impact, and the influence of weather (EAK 2002). Although contemporary vegetated clay layers represent a green surface with a near-natural look, the ecological value of the dike cover is not sufficiently considered in the design process as indicated by the low biodiversity of the standard seeding mixtures. Nonetheless, the vegetated dike cover has the potential to become an ecologically valuable dike component by adapting the seeding mixtures towards more ecologically valuable plant compositions

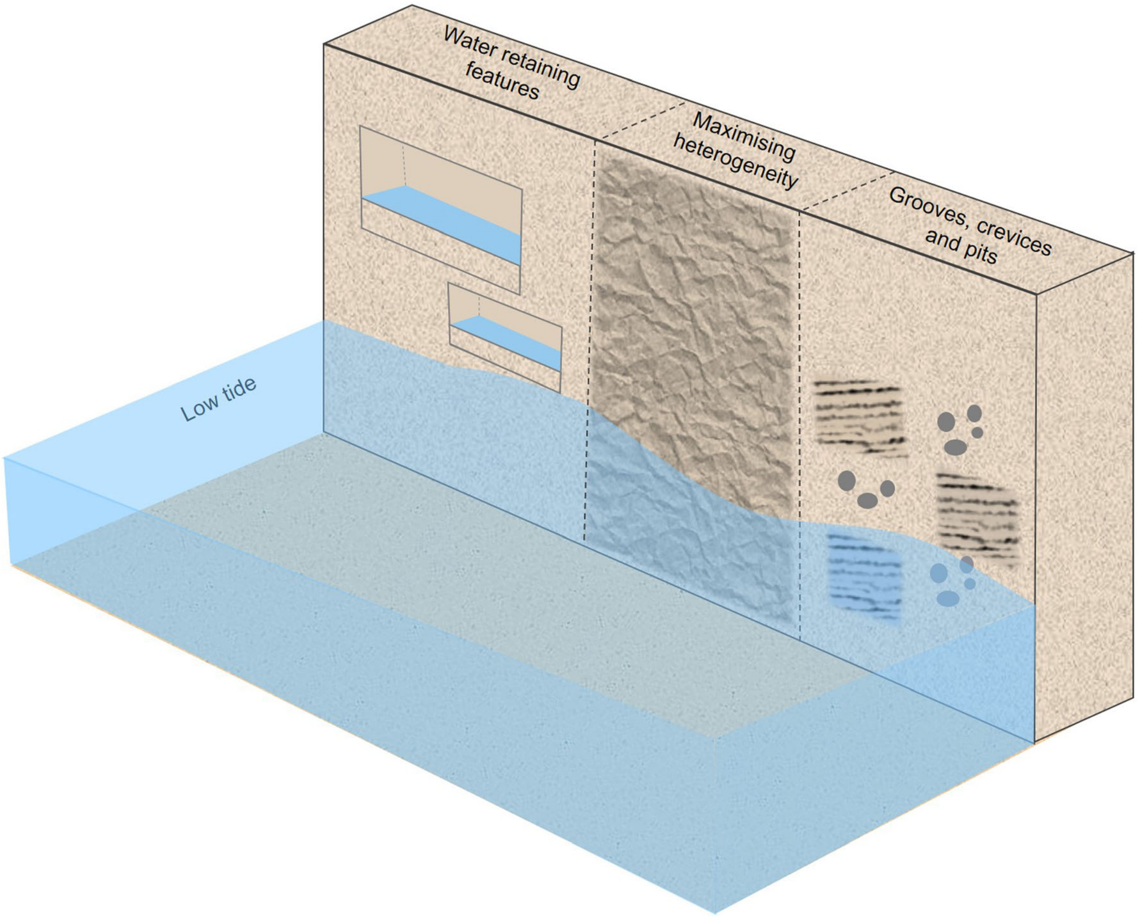

Fig. 6 Schematization of possible nature-based adaptations for seawalls. Interventions should be positioned to ensure that they are submerged during high tide

with an increased number of species and a higher amount of herbs and legumes. In doing so, the eligibility of the potential target vegetation, especially with regard to the erosion resistance and vegetation development under coastal conditions, has to be ensured (Scheres and Schüttrumpf 2017). Grass reinforcement methods, e.g. High Performance Turf Reinforcement Mats (Pan et al. 2015), can support the dike vegetation and increase the overall erosion resistance. Vegetated geocellular containment systems (Meyer and Emersleben 2009) increase the soil stability and allow the installation of dike paths with minimal soil sealing.

Given past experiences, grey revetments are usually employed for dike safety, in case of high loads that exceed the resistance of a grass cover. Common materials are rip-rap, asphalt and concrete (CIRIA 2013). Adaptations of the material of grey revetments, especially of the structure and texture, towards more natural, rougher and diverse-shaped surfaces allow for improved settlement and habitat conditions (Borsje et al. 2011). Alternatively, vegetated grey revetments, such as (partially) grouted rip-rap (Trentmann 2011), cellular revetment blocks (Mohamed et al. 2006) or geosynthetic concrete mattresses (Wilke et al. 2012), can increase the ecological value of the system due to cavities or grooves within the revetments or reduced surface sealing that allows for vegetation.

Figure 4b illustrates selected possible nature-based adaptations for sea dikes. When physically modifying the dike system, adaptations of the monitoring and maintenance strategies become necessary. In general, nature-based adaptations must not undermine the dike stability or its ability to offer coastal protection. Hence, a concept for ecologically valuable dikes should take into account conflicts between the ecological value and dike safety (Scheres and Schüttrumpf 2017).

Discussion

Nature-based solutions for coastal protection should generally be considered before hard solutions in order to minimise environmental impacts (see Table 2 for a summary of design considerations for hard solutions). The two main considerations to determine the applicability of nature-based solutions are (1) the suitability in relation to hydrodynamic forcing and (2) the availability for the spatial requirements necessary to obtain the desired level of coastal safety. Other considerations include ecological impacts, costs, construction methods, maintenance required, stakeholder support, visual impacts and climate change consequences.

Figure 7 illustrates in which conditions hard and soft solutions could be implemented. Ecosystem engineering may be suitable to provide coastal safety in areas with low to medium hydrodynamic forcing and elevated hinterlands (sufficiently high with respect to extreme water levels), given that there is enough space available. Wherever the wave energy is not sufficiently dissipated by coastal ecosystems, nourishments can increase the width of a beach and the amount of wave attenuation. In areas with structural erosion, periodic addition of sediment will be necessary to avoid net coastline retreat. Dunes, both natural and artificial, can provide additional protection against storms and serve as a physical barrier against flooding in lower lying areas.

Hard solutions should be considered a last resort and are suitable on coasts exposed to high wave energy and with reduced space available for changes in coastline position (e.g. urban areas). Beach nourishments can also be carried out in front of hard structures, in order to reduce the hydrodynamic loads acting on them. Hard foreshore structures offer wave attenuation and protection against erosion. For low-lying hinterlands, sea dikes/seawalls are generally the most appropriate solution, as these structures form a fixed barrier against inundation and provide a high level of safety. Besides building a hard barrier between the sea and hinterland, alternative coastal zone management approaches, such as retreat or elevated infrastructure, can be followed and may have ecological benefits, but is not discussed further in the present study.

When hard solutions are deemed necessary, it is advocated that they are ecologically enriched ("Ecological Enriching the Sub- and Intertidal Hard Substrates of Coastal Structures" section) to either restore, mitigate or conserve ecosystem services. Although these adaptations may minimise environmental impacts, some effects cannot be mitigated completely. Also, artificial habitats have shown different community structures and functioning compared to natural rock habitats (Firth et al. 2016a). It is recommended that adaptations are considered early on in the design as possible and are designed in close collaboration with ecologists (Firth et al. 2016b; Naylor et al. 2017). Knowledge gaps ("Conclusions and Future Avenues for Research" section) in the technical design of adaptations, in terms of dimensioning related to boundary conditions, persist and hence complicate application.

Engineers and ecologists are not only faced with a challenge regarding the functional design of nature-based solutions; societal issues are also relevant for the implementation of coastal structure projects (Naylor et al. 2012). Great advances in the field of nature-based coastal infrastructure have been made, with literature mainly originating from Australia, the USA, and Europe (Strain et al. 2018; Morris et al. 2018; Salgado and Martinez 2017), showing a bias to developed countries. Strain et al. (2018) suggests that, as is the case in terrestrial environments, socioeconomic status is a key indicator for the implementation of green infrastructure. The socioeconomic status depends in turn on factors such as level of education, willingness to invest in nature-based adaptations and available resources. This could explain the bias in literature. In the UK, Evans et al. (2017) studied stakeholder attitudes towards multi-functional coastal developments. The findings indicated that stakeholders favoured ecological

Table 2 Summary of nature-based design considerations

	Soft solutions	Hard solutions		
Structure type	Ecosystem engineering	Foreshore structures	Seawalls	Sea dikes
Purpose	Protection against flooding and shoreline stabilisation	Protection against flooding and shoreline stabilisation	Protection against overtopping and flooding and shoreline stabilisation	Protection against overtopping and flooding
Spatial requirements	High	Low	Low	Low–medium
Hydrodynamic conditions	Sheltered to exposed coast; mild to high wave conditions (depending on the coastal ecosystem type)	Exposed coast; large storm surges and waves	Exposed coast; large storm surges and waves	Exposed coast; large storm surges and waves
Design life	Short–long (greater uncertainty due to limited research)	Long	Short–long	Long
Environmental impacts and concerns	Possible negative effects if there is a replacement of a productive ecosystem by another (e.g. when planting species of a different ecosystem) Positive impacts due to higher biodiversity, restoration of ecological functions, ecosystem services	Changes to coastal processes, erosion Habitat loss Impacts due to introducing hard substrata Hazard for recreation Increase of turbidity (if complemented by regular nourishments)	Changes to coastal processes, thus active and passive erosion Habitat loss Impacts due to introducing hard substrata Interruption of ecological connectivity	Changes to coastal processes, thus active and passive erosion Habitat loss Changes in present plant communities (Impacts due to introducing hard substrata) Interruption of ecological connectivity
Nature-based adaptations	Building brushwood fences to emulate the effect of natural vegetation and restore ecosystems Hydrologic restoration through excavation and/or filling Sediment nourishments to increase wave damping in front of ecosystem Planting or transplanting seedlings	Maximisation of roughness and surface complexity Incorporation of micro-habitats Combination with ecosystem restoration (coral reefs, sea grasses, salt marshes, mangroves) If complemented with nourishments, reduce their frequency in time	Maximisation of roughness and surface complexity Incorporation of micro-habitats (e.g. rock pools; habitat enhancement units) Removal or alteration of seawall to restore sand movement Implementation in combination with other solutions (ecosystem restoration, shore nourishments)	Ecosystems and/or nature-based structures in the foreshore Adaptation of seeding mixtures towards more ecologically valuable vegetation Vegetated revetments Vegetated fortified dike paths Dike geometry adaptations

benefits over social, economic or technical benefits. Perceptions of coastal authorities and societies towards nature-based coastal protection schemes for areas with different socioeconomic statuses are however still largely unknown.

Site-specific knowledge (e.g. ecologic analysis, assessment of the local resources and construction materials) is essential for the success of nature-based solutions (Salgado and Martinez 2017). Considerable knowledge on green infrastructure was gained from pilot studies, monitoring and learning-by-doing principles. Reduced budgets and limited support may pose challenges for developing countries to gain site-specific knowledge through similar learning-by-doing approaches. Additionally, limited maintenance, monitoring (Silva et al. 2017) and social aspects (Salgado and Martinez 2017) could hinder the application of ecological enhancement of hard coastal structures and the conservation of existing foreshore ecosystems in emerging countries. Progress in overcoming these challenges must be made, before nature-based solutions can be readily implemented in developing countries.

Conclusions and Future Avenues for Research

There is significant evidence of the effectiveness of nature-based solutions (Narayan et al. 2016; Hall et al. 2018; Strain et al. 2018), but knowledge gaps and persistent uncertainties pose challenges. Current guidelines and policies (Table 1) provide general recommendations, while technical design guidelines with respect to the performance of nature-based solutions under different boundary conditions (abiotic and biotic) are still lacking. Overall, a comprehensive design basis to assess the lifetime, applicability and maintenance needs of nature-

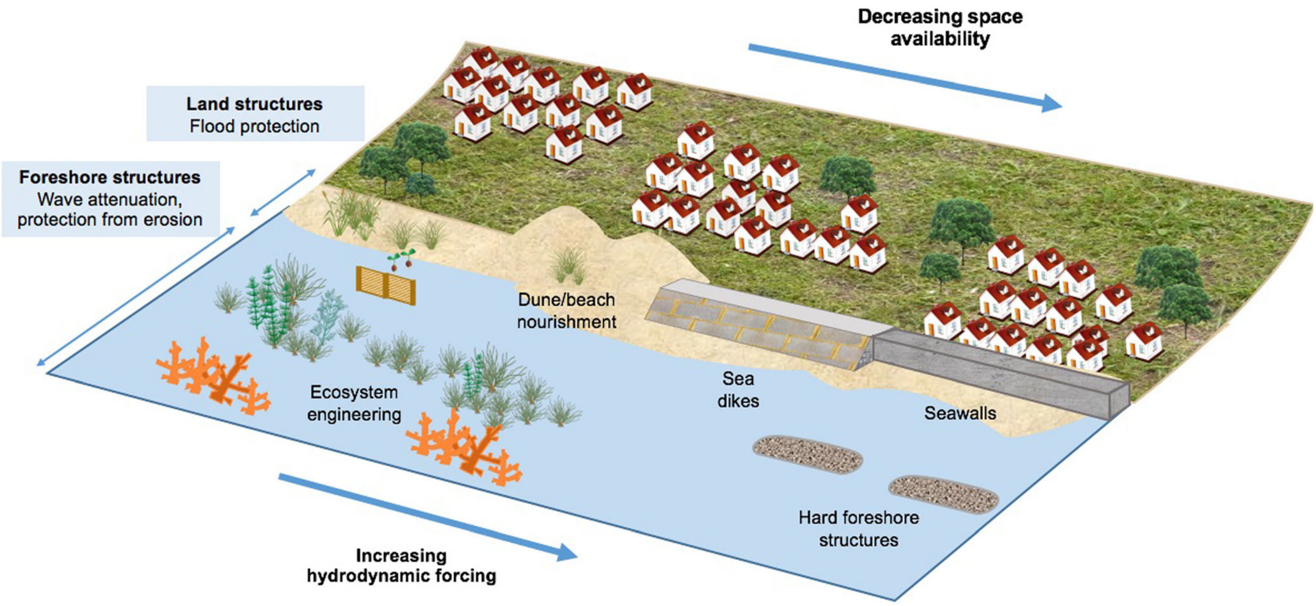

Fig. 7 Implementation of hard solutions related to land use and hydrodynamic forcing

based solutions is required to ensure that adaptations are readily included in designs in the future.

The uncertainties in the prediction of the wave height reduction of nature-based solutions are, firstly, due to the natural spatial variability in factors such as the plant height and diameter for different species. Secondly, current approaches to determine wave attenuation of plants are often based on a number of assumptions and simplifications and on site-specific calibration parameters. For example, the schematization of coastal vegetation as a number of vertical layers consisting of rigid cylinders with different densities and sizes (Suzuki et al. 2012). Additionally, the temporal availability of ecosystems makes it hard to predict their effectiveness for long time scales, thus impeding their use in coastal protection schemes (Bouma et al. 2014; Morris et al. 2018). There is also additional uncertainty on how aquatic ecosystems will adapt to climate change and sea level rise. For hybrid solutions, this means that the boundary conditions for structures sheltered by or placed behind coastal ecosystems are hard to determine and it is therefore not always possible to optimise their design by including the protection provided by ecosystems.

Considerable laboratory and field work is necessary to formulate comprehensive guidelines which ecologically enrich hard coastal structures for particular objectives in specific locations. For instance, as pointed out by Strain et al. 2018, research has mainly focused on determining the success of only one type of adaptation and is usually not applied across the whole structure. As such, it is unclear which intervention or combination of interventions for seawalls or foreshore structures would deliver optimal ecological benefits and what the benefits in relation to the adaptation area are (Strain et al. 2018). As for vegetated dikes, the design of optimal seeding mixtures to support higher biodiversity needs further research. Another aspect that requires attention, is the analysis of the proportion of native, non-native and cryptogenic species when evaluating micro-habitat adaptations (Strain et al. 2018).

Systematic interdisciplinary research is required to holistically quantify the environmental impacts of hard structures and understand the underlying processes on different temporal and spatial scales (Bishop et al. 2017). For example, understanding the migration of species along networks of structures could lead to better planning of dimensioning and spacing of hard structures (Firth et al. 2016a). Economic and social aspects involved in implementing nature-based solutions present further challenges.

To ensure that green infrastructure is applied more widely, including countries with limited budgets, future research should include economic optimization of nature-based coastal protection methods. Further studies are also required on the cost-effectiveness of green infrastructure compared to grey infrastructure under the same environmental conditions (Narayan et al. 2016; Morris et al. 2018). Additionally, cost-benefit analyses should include ecosystem services provided by grey and green infrastructure (Morris et al. 2018).

This review provides descriptions on how hard solutions function, where, when and why their use is required, thereby highlighting requirements related to coastal safety. The environmental impacts of hard solutions and adaptation options to reduce them are discussed, thus advocating the importance of environmentally sensitive engineering designs. Overall, recent studies have made large progress in understanding the coastal protection benefits of ecosystems (e.g. Bouma et al. 2014; Möller et al. 2014; Narayan et al. 2016) and in researching adaptation techniques to enhance biodiversity of coastal structures (e.g. Chapman and Underwood 2011; Firth et al. 2014; Strain et al. 2018). A greater interdisciplinary understanding is still required to move towards the inclusion of nature-based considerations in the standard practices and guidelines of coastal engineering, thus enabling a transition towards sustainable and environmentally friendly coastal solutions.

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Appendix

Table 3 Summary of selected design guidelines for coastal structures

Guideline (Reference)	Structure type	Country	Content
Shore Protection Manual (CERC 1984)	Seawalls, revetments. Groynes, breakwaters and jetties	International	Structure types, functions and limitations Design conditions and practices Construction materials
Recommendations for marine works [in Spanish] (ROM 2009)	Seawalls, revetments. Groynes, breakwaters and jetties	Spain	Structure types, functions and failure mechanisms Design guidance (planning, site conditions and data collection, geometry, building materials, construction, environmental considerations)
The Rock Manual (CIRIA 2007)	Rock structures including breakwaters, groynes, detached breakwaters, revetments and seawall toe	International	Structure types, functions and failure mechanisms Design guidance (planning, site conditions and data collection, geometry, building materials, construction, environmental considerations) Maintenance and monitoring
Coastal Engineering Manual (USACE 2002)	Sea dikes, seawalls, revetments. Groynes, breakwaters (various types) and jetties	International	Structure types, functions and failure mechanisms Design guidance (planning, site conditions, data collection, geometry, building materials, construction, environmental considerations) Maintenance and monitoring
Manual on wave overtopping of sea defences and related structures (EurOtop 2018)	Coastal dikes, revetments, seawalls and breakwaters	International	Wave overtopping limits Wave run-up and overtopping prediction including influence factors
The International Levee Handbook (CIRIA 2013)	Coastal, estuarine and river dikes	International	General information (functions, forms and failure mechanisms) Design guidance (from site characterisation and data collection to design and construction) Maintenance and monitoring
Design Guidance for Coastal Structures [in German] (EAK 2002)	Coastal and estuarine dikes	Germany	Loads on coastal structures Geotechnical investigations and processes Building materials Design and construction

References

Airoldi, L., X. Turon, S. Perkol-Finkel, and M. Rius. 2015. Corridors for aliens but not for natives: Effects of marine urban sprawl at a regional scale. *Diversity and Distributions.* 21 (7): 755–768. https://doi.org/10.1111/ddi.12301.

Barber, T. 1999. Reef balls TM: An advanced technique to mimic natural reef systems using designed artificial reefs. In *Abstracts of the 7th Scientific Conference on Artificial Reefs and Related Habitats, October, 1999, in San Remo, Italy.*

Bishop, M.J., M. Mayer-Pinto, L. Airoldi, L.B. Firth, R.L. Morris, L.H.L. Loke, S.J. Hawkins, L.A. Naylor, R.A. Coleman, S.Y. Chee, and K.A. Dafforn. 2017. Effects of ocean sprawl on ecological connectivity: Impacts and solutions. *Journal of Experimental Marine Biology and Ecology.* 492: 7–30. https://doi.org/10.1016/j.jembe.2017.01.021.

BMU. 2006. *Integriertes Küstenzonenmanagement in Deutschland*. Nationale Strategie für ein integriertes Küstenzonenmanagement (Bestandsaufnahme, Stand 2006). in German.

Borsje, B.W., B.K. van Wesenbeeck, F. Dekker, P. Paalvast, T.J. Bouma, M.M. van Katwijk, and M.B. de Vries. 2011. How ecological engineering can serve in coastal protection. *Ecological Engineering.* 37 (2): 113–122. https://doi.org/10.1016/j.ecoleng.2010.11.027.

Bouma, T.J., M.B. De Vries, E. Low, G. Peralta, I.C. Tánczos, J. van de Koppel, and P.M.J. Herman. 2005. Trade-offs related to ecosystem engineering: A case study on stiffness of emerging macrophytes. *Ecology* 86 (8): 2187–2199. https://doi.org/10.1890/04-1588.

Bouma, T.J., M.B. De Vries, and P.M.J. Herman. 2010. Comparing ecosystem engineering efficiency of two plant species with contrasting growth strategies. *Ecology* 91 (9): 2696–2704. https://doi.org/10.1890/09-0690.1.

Bouma, T.J., J. van Belzen, T. Balke, Z. Zhu, L. Airoldi, A.J. Blight, A.J. Davies, C. Galvan, S.J. Hawkins, S.P.G. Hoggart, J.L. Lara, I.J.

Losada, M. Maza, B. Ondiviela, M.W. Skov, E.M. Strain, R.C. Thompson, S. Yang, B. Zanuttigh, L. Zhang, and P.M.J. Herman. 2014. Identifying knowledge gaps hampering application of intertidal habitats in coastal protection: Opportunities & steps to take. *Coastal Engineering* 87: 147–157. https://doi.org/10.1016/j.coastaleng.2013.11.014.

Bouma, T.J., J. van Belzen, T. Balke, J. van Dalen, P. Klaassen, A.M. Hartog, D.P. Callaghan, Z. Hu, M.J.F. Stive, S. Temmerman, and P.M.J. Herman. 2016. Short-term mudflat dynamics drive long-term cyclic salt marsh dynamics. *Limnology and Oceanography* 61 (6): 2261–2275. https://doi.org/10.1002/lno.10374.

Bradley, K., and C. Houser. 2009. Relative velocity of seagrass blades: Implications for wave attenuation in low-energy environments. *Journal of Geophysical Research* 114 (F1): F01004. https://doi.org/10.1029/2007JF000951.

Bridges, T.S., P.W. Wagner, K.A. Burks-Copes, M.E. Bates, Z. Collier, C.J. Fischenich, J.Z. Gailani, L.D. Leuck, C.D. Piercy, J.D. Rosati, E.J. Russo, D.J. Shafer, B.C. Suedel, E.A. Vuxton, and T. V Wamsley. 2015. *Use of natural and nature-based features (NNBF) for coastal resilienc*e. ERDC SR-15-1.

Britton, J.C., and B. Morton. 1989. *Shore ecology of the Gulf of Mexico*. University of Texas Press.

Browne, M.A., and M.G. Chapman. 2011. Ecologically informed engineering reduces loss of intertidal biodiversity on artificial shorelines. *Environmental Science & Technology.* 45 (19): 8204–8207. https://doi.org/10.1021/es201924b.

Bulleri, F., M. Abbiati, and L. Airoldi. 2006. The colonisation of human-made structures by the invasive alga Codium fragile ssp. tomentosoides in the North Adriatic Sea (NE Mediterranean). *Hydrobiologia* 555 (1): 263–269. https://doi.org/10.1007/s10750-005-1122-4.

Callaghan, D.P., T.J. Bouma, P. Klaassen, D. van der Wal, M.J.F. Stive, and P.M.J. Herman. 2010. Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows. *Estuarine, Coastal and Shelf Science* 89 (1): 73–88. https://doi.org/10.1016/j.ecss.2010.05.013.

Cao, H., Z. Zhu, T. Balke, L. Zhang, and T.J. Bouma. 2018. Effects of sediment disturbance regimes on *Spartina* seedling establishment: Implications for salt marsh creation and restoration. *Limnology and Oceanography* 63 (2): 647–659. https://doi.org/10.1002/lno.10657.

Capobianco, M., and M.J.F. Stive. 2000. Soft intervention technology as a tool for integrated coastal zone management. *Journal of Coastal Conservation* 6 (1): 33–40. https://doi.org/10.1007/BF02730465.

Chapman, M.G., and D.J. Blockley. 2009. Engineering novel habitats on urban infrastructure to increase intertidal biodiversity. *Oecologia* 161 (3): 625–635. https://doi.org/10.1007/s00442-009-1393-y.

Chapman, M.G., and A.J. Underwood. 2011. Evaluation of ecological engineering of "armoured" shorelines to improve their value as habitat. *Journal of Experimental Marine Biology and Ecology* 400 (1-2): 302–313. https://doi.org/10.1016/j.jembe.2011.02.025.

Cheong, S., B. Silliman, P.P. Wong, B. van Wesenbeeck, C. Kim, and G. Guannel. 2013. Coastal adaptation with ecological engineering. *Nature Climate Change* 3 (9): 787–791. https://doi.org/10.1038/nclimate1854.

Christianen, M.J.A., J. van Belzen, P.M.J. Herman, M.M. van Katwijk, L.P.M. Lamers, P.J.M. van Leent, and T.J. Bouma. 2013. Low-canopy seagrass beds still provide important coastal protection services. *PLoS One* 8 (5): e62413. https://doi.org/10.1371/journal.pone.0062413.

CIRIA. 2007. *The rock manual: The use of rock in hydraulic engineering*. London: CIRIA.

CIRIA. 2013. *The international levee handbook*. London: CIRIA (CIRIA, C731).

Coastal Engineering Research Centre (CERC). 1984. *Shore Protection Manual (SPM)*. 4th ed. Washington, DC: U. S. Army Engineer Waterways Experiment Station, U. S. Government Printing Office.

COM. 2002. Recommendation of the European Parliament and of the Council of 30 May 2002 concerning the implementation of Integrated Coastal Zone Management in Europe. (2002/413/EC) *Official Journal of the European Communities L* 148/24, 662002.

Coombes, M.A., E.C. La Marca, L.A. Naylor, and R.C. Thompson. 2015. Getting into the groove: Opportunities to enhance the ecological value of hard coastal infrastructure using fine-scale surface textures. *Ecological Engineering* 77: 314–323. https://doi.org/10.1016/j.ecoleng.2015.01.032.

Costanza, R., R. D'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R.V. O'Neill, J. Paruelo, R.G. Raskin, P. Sutton, and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. *Nature* 387 (6630): 253–260. https://doi.org/10.1038/387253a0.

David, G.C., N. Schulz, and T. Schlurmann. 2016. *Ecosystem-based disaster risk reduction and adaptation in practice*. Cham: Springer International Publishing.

De Vriend, H.J., and M. Van Koningsveld. 2012. *Building with nature: Thinking, acting and interacting differently.* Dordrecht: EcoShape, Building with Nature.

De Vriend, H., M. van Koningsveld, and S. Aarninkhof. 2014. 'Building with nature': The new Dutch approach to coastal and river works. *Proceedings of the Institution of Civil Engineers - Civil Engineering* 167 (1): 18–24. https://doi.org/10.1680/cien.13.00003.

De Vries, M., T.J. Bouma, M. van Katwijk, and B.W. Borsje. 2007. *Biobouwers van de Kust. Technical report (Z4158)*. Delft: WL | Delft Hydraulics.

Dean, R.G. 1987. Coastal armouring: Effects, principles and mitigation. In *20th international conference on coastal engineering 1986, Taipei, Taiwan*. pp 1843–1857.

DEFRA. 2006. *Shoreline management plan guidance. Volume 1: Aims and requirements*. London: Department for Environment, Food and Rural Affairs.

Dijkema, K.S. 1987. Changes in salt-marsh area in the Netherlands Wadden Sea after 1600. In *Vegetation between land and sea*, ed. A.H.L. Huiskes, C.W.P.M. Blom, and J. Rozema, 42–49. Dordrecht: Dr W Junk Publishers. https://doi.org/10.1007/978-94-009-4065-9_4.

Douglass, S.L., and B.H. Pickel. 1999. The tide doesn't go out anymore: The effect of bulkheads on urban bay shorelines. *Shore & Beach* 67 (2&3): 19–25.

Dugan, J.E., D.M. Hubbard, I.F. Rodil, D.L. Revell, and S. Schroeter. 2008. Ecological effects of coastal armoring on sandy beaches. *Marine Ecology* 29 (s1): 160–170. https://doi.org/10.1111/j.1439-0485.2008.00231.x.

Dugan, J.E., L. Airoldi, M.G. Chapman, S.J. Walker, and T. Schlacher. 2011. Estuarine and coastal structures: Environmental effects, a focus on shore and nearshore structures. In *Treatise on Estuarine and Coastal Science*. Elsevier, pp 17–41.

EAK. 2002. Empfehlungen für Küstenschutzwerke. Korrigierte Ausgabe 2007. In *Kuratorium für Forschung im Küsteningenieurwesen (KFKI)*, ed. Die Küste, vol. 65. Karlsruhe: Bundesanstalt für Wasserbau (BAW).

Erftemeijer, P.L.A., and R.R. Lewis III. 2006. Environmental impacts of dredging on seagrasses: A review. *Marine Pollution Bulletin* 52 (12): 1553–1572. https://doi.org/10.1016/j.marpolbul.2006.09.006.

Erftemeijer, P.L.A., B. Riegl, B.W. Hoeksema, and P.A. Todd. 2012. Environmental impacts of dredging and other sediment disturbances on corals: A review. *Marine Pollution Bulletin* 64 (9): 1737–1765. https://doi.org/10.1016/j.marpolbul.2012.05.008.

European Commission. 2015. *Towards an EU Research and Innovation policy agenda for nature-based solutions & re-naturing cities*. Final report of the Horizon 2020.

EurOtop. 2018. Manual on wave overtopping of sea defences and related structures. An overtopping manual largely based on European research, but for worldwide application. In ed. J. W. van der Meer, N.

W. H. Allsop, T. Bruce, J. de Rouck, A. Kortenhaus, T. Pullen, H. Schüttrumpf, P. Troch and B. Zannutigh. Available online at www.overtopping-manual.com.

Evans, A.J., L.B. Firth, S.J. Hawkins, E.S. Morris, H. Goudge, and P.J. Moore. 2016. Drill-cored rock pools: An effective method of ecological enhancement on artificial structures. *Marine and Freshwater Research* 67 (1): 123–130. https://doi.org/10.1071/MF14244.

Evans, A.J., B. Garrod, L.B. Firth, S.J. Hawkins, E.S. Morris-Webb, H. Goudge, and P.J. Moore. 2017. Stakeholder priorities for multifunctional coastal defence developments and steps to effective implementation. *Marine Policy* 75: 143–155. https://doi.org/10.1016/j.marpol.2016.10.006.

Feagin, R.A., N. Mukherjee, K. Shanker, A.H. Baird, J. Cinner, A.M. Kerr, N. Koedam, A. Sridhar, R. Arthur, L.P. Jayatissa, D. Lo Seen, M. Menon, S. Rodriguez, M. Shamsuddoha, and F. Dahdouh-Guebas. 2010. Shelter from the storm? Use and misuse of coastal vegetation bioshields for managing natural disasters. *Conservation Letters* 3 (1): 1–11. https://doi.org/10.1111/j.1755-263X.2009.00087.x.

Ferrario, F., M.W. Beck, C.D. Storlazzi, F. Micheli, C.C. Shepard, and L. Airoldi. 2014. The effectiveness of coral reefs for coastal hazard risk reduction and adaptation. *Nature Communications* 5 (1): 3794. https://doi.org/10.1038/ncomms4794.

Firth, L.B., R.C. Thompson, and S.J. Hawkins. 2012. Eco-engineering of artificial coastal structures to enhance biodiversity: An illustrated guide.

Firth, L.B., N. Mieszkowska, R.C. Thompson, and S.J. Hawkins. 2013. Climate change and adaptational impacts in coastal systems: The case of sea defences. *Environmental Science: Processes & Impacts* 15 (9): 1665. https://doi.org/10.1039/c3em00313b.

Firth, L.B., R.C. Thompson, K. Bohn, M. Abbiati, L. Airoldi, T.J. Bouma, F. Bozzeda, V.U. Ceccherelli, M.A. Colangelo, A. Evans, F. Ferrario, M.E. Hanley, H. Hinz, S.P.G. Hoggart, J.E. Jackson, P. Moore, E.H. Morgan, S. Perkol-Finkel, M.W. Skov, E.M. Strain, J. van Belzen, and S.J. Hawkins. 2014. Between a rock and a hard place: Environmental and engineering considerations when designing coastal defence structures. *Coastal Engineering* 87: 122–135. https://doi.org/10.1016/j.coastaleng.2013.10.015.

Firth, L.B., A.M. Knights, D. Bridger, A.J. Evans, N. Mieszkowska, P.J. Moore, N.E. O'Connor, E.V. Sheehan, R.C. Thompson, and S.J. Hawkins. 2016a. Ocean sprawl: Challenges and opportunities for biodiversity Management in a Changing World Introduction: Context and background. *An Annual Review* 54: 193–269.

Firth, L.B., K.A. Browne, A.M. Knights, S.J. Hawkins, and R. Nash. 2016b. Eco-engineered rock pools: A concrete solution to biodiversity loss and urban sprawl in the marine environment. *Environmental Research Letters* 11 (9): 094015. https://doi.org/10.1088/1748-9326/11/9/094015.

Fonseca, M.S., and J.A. Cahalan. 1992. A preliminary evaluation of wave attenuation by four species of seagrass. *Estuarine, Coastal and Shelf Science* 35 (6): 565–576. https://doi.org/10.1016/S0272-7714(05)80039-3.

Gambi, M., A. Nowell, and P. Jumars. 1990. Flume observations on flow dynamics in Zostera marina (eelgrass) beds. *Marine Ecology Progress Series* 61: 159–169. https://doi.org/10.3354/meps061159.

Gillis, L., T. Bouma, C. Jones, M. van Katwijk, I. Nagelkerken, C. Jeuken, P. Herman, and A. Ziegler. 2014. Potential for landscape-scale positive interactions among tropical marine ecosystems. *Marine Ecology Progress Series* 503: 289–303. https://doi.org/10.3354/meps10716.

Glasby, T.M., S.D. Connell, M.G. Holloway, and C.L. Hewitt. 2007. Nonindigenous biota on artificial structures: Could habitat creation facilitate biological invasions? *Marine Biology* 151 (3): 887–895. https://doi.org/10.1007/s00227-006-0552-5.

Griggs, G. 2010.The effects of armoring shorelines—The California experience. In *Puget Sound shorelines and the impacts of armoring - Proceedings of a State of the Science Workshop*, May 2009. pp 77–84.

Hall, A.E., R.J.H. Herbert, J.R. Britton, and S.L. Hull. 2018. Ecological enhancement techniques to improve habitat heterogeneity on coastal defence structures. *Estuarine, Coastal and Shelf Science* 210: 68–78. https://doi.org/10.1016/j.ecss.2018.05.025.

Hamm, L., M. Capobianco, H. Dette, A. Lechuga, R. Spanhoff, and M.J. Stive. 2002. A summary of European experience with shore nourishment. *Coastal Engineering* 47 (2): 237–264. https://doi.org/10.1016/S0378-3839(02)00127-8.

Henderson, J., and J. O'Neil. 2003. *Economic Values Associated with Construction of Oyster Reefs by the Corps of Engineers*. ERDC TN-EMRRP-ER-01:

Hsu, J.R.C., and R. Silvester. 1990. Accretion behind single offshore breakwater. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 116 (3): 362–380. https://doi.org/10.1061/(ASCE)0733-950X(1990)116:3(362).

ICES. 2016. *Effects of extraction of marine sediments on the marine environment 2005–2011*. ICES Cooperative Research Report No. 330. 260 pp.

IUCN. 2016. Nature-based solutions to address global societal challenges. In eds. Cohen-Shacham, E Walters, G Janzen, C Maginnis, S. https://doi.org/10.2305/IUCN.CH.2016.13.en.

Jackson, N.L., and K.F. Nordstrom. 2011. Aeolian sediment transport and landforms in managed coastal systems: A review. *Aeolian Research* 3 (2): 181–196. https://doi.org/10.1016/j.aeolia.2011.03.011.

Keith, S.A., R.J.H. Herbert, P.A. Norton, S.J. Hawkins, and A.C. Newton. 2011. Individualistic species limitations of climate-induced range expansions generated by meso-scale dispersal barriers. *Diversity and Distributions* 17 (2): 275–286. https://doi.org/10.1111/j.1472-4642.2010.00734.x.

Knutson, P.L., R.A. Brochu, W.N. Seelig, and M. Inskeep. 1982. Wave damping in Spartina alterniflora marshes. *Wetlands* 2 (1): 87–104. https://doi.org/10.1007/BF03160548.

Koch, E.W., E.B. Barbier, B.R. Silliman, D.J. Reed, G.M. Perillo, S.D. Hacker, E.F. Granek, J.H. Primavera, N. Muthiga, S. Polasky, B.S. Halpern, C.J. Kennedy, C.V. Kappel, and E. Wolanski. 2009. Non-linearity in ecosystem services: Temporal and spatial variability in coastal protection. *Frontiers in Ecology and the Environment* 7 (1): 29–37. https://doi.org/10.1890/080126.

Kraus, N.C. 1988. The effects of seawalls on the beach: An extended literature review. *Journal of Coastal Research*. 1–28. https://doi.org/10.2307/25735349.

Kraus, N.C., and W.G. McDougal. 1996. The effects of seawalls on the beach: Part I, An Updated Literature Review. *Journal of Coastal Research* 12: 691–701.

Lillycrop, W.J., and S.A. Hughes. 1993. *Scour hole problems experienced by the Corps of Engineers*; Data Presentation and Summary. CERC-93-2.

Losada, M.A. 1990. Recent development in the design of mound breakwaters. In *Chapter 21*, ed. Herbich, J. Handbook of Coastal and Ocean Engineering, Vol. 1. Gulf Publishing.

Lucrezi, S., T.A. Schlacher, and W. Robinson. 2010. Can storms and shore armouring exert additive effectson sandy-beach habitats and biota? *Marine and Freshwater Research* 61 (9): 951. https://doi.org/10.1071/MF09259.

Martins, G.M., R.C. Thompson, A.I. Neto, S.J. Hawkins, and S.R. Jenkins. 2010. Enhancing stocks of the exploited limpet *Patella candei* d'Orbigny via modifications in coastal engineering. *Biological Conservation* 143 (1): 203–211. https://doi.org/10.1016/j.biocon.2009.10.004.

McIvor, A.L., I. Möller, T. Spencer, and M. Spalding. 2012. *Reduction of wind and swell waves by mangroves*. Natural coastal protection series: Report 1 Cambridge Coastal Research Unit Working Paper

40 Published by The Nature Conservancy and Wetlands International, 27 pages, ISSN 2050-7941.

Meyer, M., and A. Emersleben. 2009. Einsatz von Geozellen im Deich- und Wasserbau. In *3. Symposium* "*Sicherung von Dämmen, Deichen und Stauanlagen*", 431–443. Institut für Geotechnik der Universität Siegen.

Meyer, D.L., E.C. Townsend, and G.W. Thayer. 1997. Stabilization and Erosion control value of oyster cultch for intertidal marsh. *Restoration Ecology* 5 (1): 93–99. https://doi.org/10.1046/j.1526-100X.1997.09710.x.

Millennium Ecosystem Assessment (MEA). 2005. *Ecosystems and human well-being: Synthesis*. Washington: Island Press.

Mohamed, T.A., N.A. Alias, A.H. Ghazali, and M.S. Jaafar. 2006. Evaluation of environmental and hydraulic performance of bio-composite revetment blocks. *American Journal of Environmental Sciences* 2 (4): 129–134. https://doi.org/10.3844/ajessp.2006.129.134.

Möller, I., M. Kudella, F. Rupprecht, T. Spencer, M. Paul, B.K. van Wesenbeeck, G. Wolters, K. Jensen, T.J. Bouma, M. Miranda-Lange, and S. Schimmels. 2014. Wave attenuation over coastal salt marshes under storm surge conditions. *Nature Geoscience* 7 (10): 727–731. https://doi.org/10.1038/ngeo2251.

Morris, R.L., T.M. Konlechner, M. Ghisalberti, and S.E. Swearer. 2018. From grey to green: Efficacy of eco-engineering solutions for nature-based coastal defence. *Global Change Biology* 24 (5): 1827–1842. https://doi.org/10.1111/gcb.14063.

Mory, M., and L. Hamm. 1997. Wave height, setup and currents around a detached breakwater submitted to regular or random wave forcing. *Coastal Engineering* 31 (1-4): 77–96. https://doi.org/10.1016/S0378-3839(96)00053-1.

Moschella, P.S., M. Abbiati, P. Åberg, L. Airoldi, J.M. Anderson, F. Bacchiocchi, F. Bulleri, G.E. Dinesen, M. Frost, E. Gacia, L. Granhag, P.R. Jonsson, M.P. Satta, A. Sundelöf, R.C. Thompson, and S.J. Hawkins. 2005. Low-crested coastal defence structures as artificial habitats for marine life: Using ecological criteria in design. *Coastal Engineering* 52 (10-11): 1053–1071. https://doi.org/10.1016/j.coastaleng.2005.09.014.

Murray, J.M., A. Meadows, and P.S. Meadows. 2002. Biogeomorphological implications of microscale interactions between sediment geotechnics and marine benthos: A review. *Geomorphology* 47 (1): 15–30. https://doi.org/10.1016/S0169-555X(02)00138-1.

Narayan, S., M.W. Beck, B.G. Reguero, I.J. Losada, B. van Wesenbeeck, N. Pontee, J.N. Sanchirico, J.C. Ingram, G.-M. Lange, and K.A. Burks-Copes. 2016. The effectiveness, costs and coastal protection benefits of natural and nature-based defences. *PLoS One* 11 (5): e0154735. https://doi.org/10.1371/journal.pone.0154735.

Naylor, L.A., O. Venn, M. Coombes, J. Jackson, and R.C. Thompson. 2011. Including ecological enhancements in the planning, design and construction of hard coastal structures: A process guide. *Report to the Environment Agency (PID 110461)*. 66 pp.

Naylor, L.A., M.A. Coombes, O. Venn, S.D. Roast, and R.C. Thompson. 2012. Facilitating ecological enhancement of coastal infrastructure: The role of policy, people and planning. *Environmental Science & Policy* 22: 36–46. https://doi.org/10.1016/j.envsci.2012.05.002.

Naylor, L.A., M. MacArthur, S. Hampshire, K. Bostock, M.A. Coombes, J.D. Hansom, R. Byrne, and T. Folland. 2017. Rock armour for birds and their prey: Ecological enhancement of coastal engineering. *Proceedings of the Institution of Civil Engineers - Maritime Engineering* 170 (2): 67–82. https://doi.org/10.1680/jmaen.2016.28.

Nesshöver, C., T. Assmuth, K.N. Irvine, G.M. Rusch, K.A. Waylen, B. Delbaere, D. Haase, L. Jones-Walters, H. Keune, E. Kovacs, K. Krauze, M. Külvik, F. Rey, J. van Dijk, O.I. Vistad, M.E. Wilkinson, and H. Wittmer. 2017. The science, policy and practice of nature-based solutions: An interdisciplinary perspective. *Science of The Total Environment* 579: 1215–1227. https://doi.org/10.1016/j.scitotenv.2016.11.106.

Neumann, B., A.T. Vafeidis, J. Zimmermann, and R.J. Nicholls. 2015. Future coastal population growth and exposure to sea-level rise and coastal flooding - a global assessment. *PLoS One* 10 (3): e0118571. https://doi.org/10.1371/journal.pone.0118571.

Nienhuis, P.H., and R.D. Gulati. 2002. *Ecological restoration of aquatic and semi-aquatic ecosystems in the Netherlands: An introduction*. Springer, Netherlands.

Nordstrom, K.F. 2014. Living with shore protection structures: A review. *Estuarine, Coastal and Shelf Science* 150: 11–23. https://doi.org/10.1016/j.ecss.2013.11.003.

Pan, Y., L. Li, F. Amini, and C. Kuang. 2015. Overtopping erosion and failure mechanism of earthen levee strengthened by vegetated HPTRM system. *Ocean Engineering* 96: 139–148. https://doi.org/10.1016/j.oceaneng.2014.12.012.

PIANC. 2011. *Working with Nature- PIANC Position Paper*. https://www.pianc.org/workingwithnature.php. Accessed 4 May 2018.

Pilarczyk, K.W. 2003. Design of low-crested (submerged) structures – An overview –. In *6th international conference on coastal and port engineering in developing countries*, Colombo, Sri Lanka.

Pilarczyk, K. 2017. *Dikes and revetments: Design*. Maintenance and Safety Assessment, Routledge ISBN: 978-90-5410-455-1.

Pilarczyk, K.W., and R.B. Zeidler. 1996. *Offshore breakwaters and shore evolution control*. Rotterdam: Balkema ISBN: 90-5410-627-1.

Pontee, N., S. Narayan, M.W. Beck, and A.H. Hosking. 2016. Nature-based solutions: Lessons from around the world. *Proceedings of the Institution of Civil Engineers - Maritime Engineering* 169 (1): 29–36. https://doi.org/10.1680/jmaen.15.00027.

Ranasinghe, R., and I.L. Turner. 2006. Shoreline response to submerged structures: A review. *Coastal Engineering* 53 (1): 65–79. https://doi.org/10.1016/j.coastaleng.2005.08.003.

ROM. 2009. *Recomendaciones para obras maritimas, Serie I. Obras de abrigo frente a las oscilaciones de mar*. Puertos del Estado, Ministerio de Fomento, Gobierno de España.

SAGE. 2015. *Natural and structural measures for shoreline stabilization*. http://sagecoast.org/docs/SAGE_LivingShorelineBrochure_Print.pdf. Accessed 21 May 2018.

Salgado, K., and M.L. Martinez. 2017. Is ecosystem-based coastal defense a realistic alternative? Exploring the evidence. *Journal of Coastal Conservation* 21 (6): 837–848. https://doi.org/10.1007/s11852-017-0545-1.

Scheres, B., and H. Schüttrumpf. 2017. Conception of ecologically valuable sea dike systems. In *In Mediterranean Coastal Foundation. The thirteenth international MEDCOAST congress on coastal and marine sciences, engineering, management and conservation. MEDCOAST 17*, 893–904. Mellieha, Malta.

Schmitt, K., T. Albers, T.T. Pham, and S.C. Dinh. 2013. Site-specific and integrated adaptation to climate change in the coastal mangrove zone of Soc Trang Province, Viet Nam. *Journal of Coastal Conservation* 17 (3): 545–558. https://doi.org/10.1007/s11852-013-0253-4.

Schüttrumpf, H. 2008. *Sea Dikes in Germany. In Kuratorium für Forschung im Küsteningenieurwesen (KFKI)*. In ed. Die Küste, 189–199. 74 Heide i Holstein: Boyens Medien GmbH & Co KG.

Scott, T., M. Austin, G. Masselink, and P. Russell. 2016. Dynamics of rip currents associated with groynes — Field measurements, modelling and implications for beach safety. *Coastal Engineering* 107: 53–69. https://doi.org/10.1016/j.coastaleng.2015.09.013.

Scyphers, S.B., S.P. Powers, K.L. Heck, and D. Byron. 2011. Oyster reefs as natural breakwaters mitigate shoreline loss and facilitate fisheries. *PLoS One* 6 (8): e22396. https://doi.org/10.1371/journal.pone.0022396.

Sherrard, T.R.W., S.J. Hawkins, P. Barfield, M. Kitou, S. Bray, and P.E. Osborne. 2016. Hidden biodiversity in cryptic habitats provided by porous coastal defence structures. *Coastal Engineering* 118: 12–20. https://doi.org/10.1016/j.coastaleng.2016.08.005.

Shi, Z.H., N.F. Fang, F.Z. Wu, L. Wang, B.J. Yue, and G.L. Wu. 2012. Soil erosion processes and sediment sorting associated with transport mechanisms on steep slopes. *Journal of Hydrology* 454–455: 123–130. https://doi.org/10.1016/j.jhydrol.2012.06.004.

Silva, R., D. Lithgow, L.S. Esteves, M.L. Martínez, P. Moreno-Casasola, R. Martell, P. Pereira, E. Mendoza, A. Campos-Cascaredo, P. Winckler Grez, A.F. Osorio, J.D. Osorio-Cano, and G.D. Rivillas. 2017. Coastal risk mitigation by green infrastructure in Latin America. *Proceedings of the Institution of Civil Engineers - Maritime Engineering* 170 (2): 39–54. https://doi.org/10.1680/jmaen.2016.13.

Strain, E.M.A., C. Olabarria, M. Mayer-Pinto, V. Cumbo, R.L. Morris, A.B. Bugnot, K.A. Dafforn, E. Heery, L.B. Firth, P.R. Brooks, and M.J. Bishop. 2018. Eco-engineering urban infrastructure for marine and coastal biodiversity: Which interventions have the greatest ecological benefit? *Journal of Applied Ecology* 55 (1): 426–441. https://doi.org/10.1111/1365-2664.12961.

Suh, K., and R.A. Dalrymple. 1987. Offshore breakwaters in laboratory and field. *Journal of Waterway, Port, Coastal, and Ocean Engineering* 113 (2): 105–121. https://doi.org/10.1061/(ASCE)0733-950X(1987)113:2(105).

Sutton-Grier, A.E., K. Wowk, and H. Bamford. 2015. Future of our coasts: The potential for natural and hybrid infrastructure to enhance the resilience of our coastal communities, economies and ecosystems. *Environmental Science & Policy* 51: 137–148. https://doi.org/10.1016/j.envsci.2015.04.006.

Suzuki, T., M. Zijlema, B. Burger, M.C. Meijer, and S. Narayan. 2012. Wave dissipation by vegetation with layer schematization in SWAN. *Coastal Engineering* 59 (1): 64–71. https://doi.org/10.1016/j.coastaleng.2011.07.006.

Temmerman, S., P. Meire, T.J. Bouma, P.M.J. Herman, T. Ysebaert, and H.J. De Vriend. 2013. Ecosystem-based coastal defence in the face of global change. *Nature* 504 (7478): 79–83. https://doi.org/10.1038/nature12859.

Trentmann, J. 2011. Dichtung aus Wasserbausteinen mit Vollverguss aus hydraulisch gebundenem Vergusstoff. In *DWA (Ed.): KW Korrespondenz Wasserwirtschaft*. 4:452–458.

U.S. Army Corps of Engineers (USACE). 2002. *Coastal engineering manual, 1110th-2nd–110th edn*. Washington, D.C.: U.S. Army Corps of Engineers.

U.S. Army Corps of Engineers (USACE). 2012. *Engineering with nature fact sheet*. https://ewn.el.erdc.dren.mil/pub/EWNFactSheet_Final.pdf. Accessed 12 April 2018.

Van der Nat, A., P. Vellinga, R. Leemans, and E. van Slobbe. 2016. Ranking coastal flood protection designs from engineered to nature-based. *Ecological Engineering* 87: 80–90. https://doi.org/10.1016/j.ecoleng.2015.11.007.

Van Katwijk, M.M., and N. Dankers. 2001. *Ecological coastal protection; mussel beds, seagrass beds and salt-marshes. Poster at Symposium* "*Food for thought: structuring factors of shallow marine coastal communities*", 29–30. Texel: NIOZ. https://doi.org/10.13140/RG.2.2.30768.97286.

Van Loon-Steensma, J.M., H.A. Schelfhout, and P. Vellinga. 2014. Green adaptation by innovative dike concepts along the Dutch Wadden Sea coast. *Environmental Science & Policy* 44: 108–125. https://doi.org/10.1016/j.envsci.2014.06.009.

Van Rijn, L. C. 2013. *Design of hard coastal structures against erosion. Accessed online 22/10/2018*. https://www.leovanrijn-sediment.com/papers/Coastalstructures2013.pdf. Accessed 22 Oct 2018.

Wiecek, D. 2009. *Environmentally friendly seawalls: A guide to improving the environmental value of seawalls and seawall-lined foreshores in estuaries*.

Wilke, M., B. Krueger, M. Schuell, and P. Tschernutter. 2012. Erosion resistant construction of overflow sections by means of geosynthetic concrete mattresses. In *Proceedings 6th International Conference on Scour and Erosion (ICSE-6). Paris, France, 27.-31.08.2012: Société Hydrotechnique De France*, eds. J.-J. Fry, C. Chevalier, 1231–1238.

Winterwerp, J.C., P.L.A. Erftemeijer, N. Suryadiputra, P. van Eijk, and L. Zhang. 2013. Defining eco-Morphodynamic requirements for rehabilitating eroding mangrove-mud coasts. *Wetlands.* 33 (3): 515–526. https://doi.org/10.1007/s13157-013-0409-x.