Review

Enhancing the Ecological Value of Sea Dikes

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Abstract: Sea dikes protect low-lying hinterlands along many coasts all around the world. Commonly, they are designed as embankments with grass covers or grey revetments accounting for the prevailing hydraulic loads. So far, incorporation of ecological aspects in the dike design is limited. With regard to increasing environmental awareness and climate change adaptation needs, the present study reviews methods for ecological enhancement of sea dikes and discusses limitations and challenges related to these methods. In doing so, one key aspect is to maintain dike safety while increasing the ecological value. Potential for ecological enhancement of sea dikes has been found regarding natural or nature-based solutions in the foreshore, dike surface protection measures (vegetated dike covers, hard revetments and dike roads) and the dike geometry. While natural and nature-based solutions in the foreland are investigated thoroughly, so far only few experiences with ecological enhancements of the dike structure itself were gained resulting in uncertainties and knowledge gaps concerning the implementation and efficiency. Additional to technical uncertainties, engineers and ecologists meet the challenge of interdisciplinary collaboration under consideration of societal needs and expectations.

Keywords: green sea dikes; ecological enhancement; ecological engineering; nature-based solutions; ecosystem services

1. Introduction

Dikes, an integrated part of flood defense systems, have proven worldwide as effective protection against fluvial and coastal flooding. The dike form and alignment, building materials and associated structures vary depending on the boundary conditions, such as hydraulic loads, spatial restrictions and locally available materials. Commonly, dikes consist of an earth-filled core made of granular or cohesive soil materials with a grass cover as surface protection [1].

In Germany alone, around 1200 km of sea dikes and estuarine dikes protect an area of more than 12,000 km² and a population of more than 2,400,000 people [2]. Historical documentations give insight into continuous dike heightening and strengthening efforts after extreme storm surge events in the past [2,3]. Nowadays, sea dikes and revetments are designed and constructed according to the available guidelines for coastal structures, e.g., The International Levee Handbook [1], under consideration of hydraulic aspects, such as the design water level and design wave parameters, as well as geotechnical aspects, e.g., soil properties. So far, ecological aspects are not directly incorporated in dike design.

In times of climate change and growing awareness of environmental issues [4], increased design requirements and new adaptation strategies for coastal structures become necessary to account for increased loads on the one hand and nature conservation on the other hand [5–7]. Latest developments in coastal engineering integrate the utilization of ecosystem services and natural processes in engineering practice for more sustainable and adaptive design. Thereby, a wide range of new engineering disciplines, such as ecosystem-based engineering and building with nature, have been developed [8].

However, no integrated concept for ecologically valuable dikes is available so far. Dikes are conventionally built as hard engineering structures that withstand the forces of wind, waves and flooding, whereby constituting an interference with nature [9,10]. Standard seeding mixtures that consist of different grasses and a small percentage of herbs are known to ensure the main functions of the grass cover—protection against mechanical forces, such as wave impact, and influences of weather [11]—whereas ecological aspects are not considered sufficiently. Sites with higher hydraulic loads are usually equipped with grey revetments that directly impact the ecological connectivity [12,13].

Nevertheless, there is potential to make use of ecosystem services and enhance the ecological value of dike systems. Fundamental knowledge, e.g., on the erosion resistance of vegetated dike covers, has been gained and various methods applicable for enhancing the ecological value of dikes, such as vegetated revetments, have been developed. With reference to [14], the main objective is now to develop an integrated design concept for ecologically valuable dikes. In doing so, the aim of this review is

- to outline methods and approaches applicable to increase the ecological value of dikes,
- to show potentials, challenges and open research questions and
- to discuss the conception of ecologically valuable sea dike systems with regard to ecology, engineering and society.

First the ecological basics are explained and existing frameworks for integrating ecosystems in coastal engineering are summarized. Subsequently, components of sea dike design with potential for ecological enhancement are presented regarding their relevance for dike design and ecological aspects. Furthermore, existing dike reinforcement methods that are worth considering for ecologically valuable sea dikes are described. Finally, the conception and implementation of ecologically valuable sea dike systems under consideration of ecology, engineering and society are discussed.

2. Ecological Basics

2.1. Ecosystem Engineers

Ecosystem engineers are organisms that affect biotic and/or abiotic conditions by direct or indirect structural changes in the form of modification, maintenance or creation of habitats and thereby modulate the physical conditions and availability of resources to other species. Autogenic ecosystem engineers, such as corals or grasses, cause structural changes due to their physical existence alone. Allogenic ecosystem engineers, such as beavers or plants that affect the subsoil due to root growth, modify their environment due to direct structural changes [15,16].

2.2. Ecosystem Services

Ecosystems are defined as functional systems consisting “of all the organisms and the abiotic pools with which they interact” [17]. Benefits provided to people by ecosystems are so-called ecosystem services. According to the Millennium Ecosystem Assessment [18], these ecosystem services can be categorized into

- provisioning services (food, fiber, fuel, water, ...)
- regulating services (air quality regulation, climate regulation, water regulation, ...)
- supporting services (nutrient cycling, soil formation, photosynthesis, ...)
- cultural services (cultural diversity, education, aesthetics, ...)

Changes in ecosystems, which in turn lead to changes in ecosystem services, directly influence human well-being. Then again, human activities may cause changes in ecosystems, resulting in changes in ecosystem services and finally human well-being. Therefore, the assessment of ecosystem services has become a valuable planning and management tool [18–20].

Organisms of major importance in estuaries and coasts are dune plants, tidal marsh plants, mangroves, seagrasses, kelp and seaweeds, corals, reef-forming bivalves, burrowing crustaceans and infauna. Their effects on structural, abiotic and biotic factors are discussed in detail in [21]. Typical coastal protection ecosystem services provided by the resulting ecosystems (coral reefs, salt marshes, mangrove forests, etc.) are the attenuation and/or dissipation of waves, sediment retention and/or stabilization and the reduction of flooding and spray [22]. The use of ecosystems for coastal protection has attracted great interest in recent years [10,23–25].

2.3. Existing Frameworks for Integrating Ecosystems in Coastal Engineering

Various frameworks, namely building with nature [26,27], engineering with nature [28], living shorelines [29], etc. exist that deal with the integration or use of ecosystems for coastal protection purposes. While the concepts may differ in their focus, a common objective is to make use of ecosystem services and/or natural processes for ecological, economic and social benefits in relation to hydraulic engineering [8].

In general, nature-based coastal engineering approaches can be distinguished in (1) the systematic utilization of ecosystem engineers to initiate structural changes that finally result in coastal protection ecosystem services and (2) the adaption of conventional coastal structures with the aim to increase their ecological value [30]. Additionally, the framework building with nature pursues the principle of actively using not only nature's resources but also nature's dynamics for hydraulic engineering questions [26,27]. In general, using nature's engineers can be realized by restoring/maintaining ecosystems, integrating ecosystem engineers in new environments or imitating ecosystem engineers without direct use of the organisms [21].

One way of categorizing nature-based solutions is to distinguish between “fully natural solutions”, “managed natural solutions”, “hybrid solutions that combine structural engineering with natural features” and “‘environment-friendly’ structural engineering” ([31], similar categorization in [32]). To date, guidelines for the design, implementation, monitoring and maintenance of nature-based coastal engineering solutions are limited [31].

3. Sea Dike Design Aspects with Potential for Ecological Enhancement

The main function of sea dikes is to protect the hinterland from flooding. Therefore, dike safety has the highest priority in dike design. The dike must be able to withstand waves, currents and high water without failure due to erosion or insufficient dike stability while building a barrier between land and water. Environmental aspects are considered during dike design, e.g., aiming at minimizing/compensating environmental impacts and optimizing resources use [1,11], however the ecological value of the dike system itself is generally of secondary relevance. In the following, various components of sea dike design that allow for ecological enhancements of the dike system are presented regarding their relevance for dike design and ecological aspects. First the vicinity of the dike, i.e., the foreland, and subsequently the dike structure itself including slope inclination, dike roads, dike revetments and dike vegetation are explored.

3.1. Foreshore Vegetation and Fauna

Foreshore vegetation and fauna influence the ecological value of the coastal system and affect hydrodynamics and morphology. Comprehensive reviews on coastal ecosystems and their ecosystem services in terms of coastal protection and co-benefits are given e.g., in [21–23]. The main coastal protection services observed are (1) the attenuation of waves and (2) the stabilization of the shoreline and (3) accretion of sediments. Wave attenuation is ascribed to wave breaking due to water depth change (e.g., reefs) and wave damping due to increased bottom friction (e.g., mangroves or marshes) [24]. Sediment deposition is promoted due to reduced flow velocity and sediment binding by plant roots [21,22]. Moreover, soil accretion can be increased through the accumulation of organic matter produced by ecosystems, e.g., for marshes and mangroves [33].

Mangroves, salt marshes and sea grass show wave damping capacities that depend on vegetation properties, e.g., the vegetation height and width, and hydraulic conditions, e.g., the water depth [34–37]. Additionally, increased sediment accretion was observed for these foreshore vegetations [38–40]. Likewise, wave attenuation [41,42] and sediment trapping capacities [43,44] were documented for coral and oyster/mussel reefs. A recently published meta-analysis performed by Narayan et al. [24] shows average wave height reductions of 72% for salt-marshes and 70% for coral reefs followed by average wave height reductions of 36% for seagrass and 31% for mangroves. As average values for water depths and wave heights were used within this study, further analyses for extreme events are required to consider design cases. Carbon sequestration, water purification and habitat creation are valuable co-benefits provided by foreshore vegetation and fauna [21,22].

Due to spatial and temporal variation in ecosystems and not yet resolved knowledge gaps, integration of coastal protection services of ecosystems in design processes still poses a challenge [45,46]. However, combining hard coastal structures with foreshore ecosystems can decrease the hydrodynamic loads on the built infrastructure, thus increasing the design life and reducing necessary maintenance efforts [8,37,47].

3.2. Slope Inclination

While the dike height is determined based on the hydraulic boundary conditions (design water level and wave run-up), the dike slopes are designed as a compromise between optimal dike stability (mild slopes) and minimal material consumption and dike footprint (steep slopes) [1].

Using wide green dikes with a grass covered shallow seaward slope around 1:7 is assumed to have positive effects on nature, recreation and tourism compared to a standard sea dike with a steeper slope (around 1:3) and grey revetment [6]. However, as the dike footprint increases linearly with the slope inclination, the loss of original habitat increases accordingly [48]. At the same time altered habitat is created (e.g., grass meadows, see [6]), which may have an ecological value. Effects on coastal processes, such as reflection at the structure [48], are reduced with milder slopes.

3.3. Dike Roads

Roads on dikes are a crucial element for dike inspection, maintenance and defense purposes. Commonly, dike roads are built as asphalt-paved roads along the dike crest or the inner dike berm (above mean high water) with regular access from the hinterland via ramps. The dimension, foundation and materials of these dike roads have to enable crossing of heavy vehicles [1,11].

As a more natural alternative to asphalt-paved roads, vegetated geocellular containment systems (see Section 4.2.3 for further details) were used on the crest of a river dike in Germany [49]. Tests with similar soils showed that the traffic security was given even under extreme conditions [49].

3.4. Dike Revetments

If boundary conditions do not permit the use of grass covers for erosion protection, e.g., in the case of high hydraulic loads, hard revetments, such as rip-rap or placed block revetments, are necessary [1]. Design of hard revetments depends on the revetment type and its features, e.g., interlocking vs. no interlocking blocks and permeable vs. impermeable revetments. Design guidance is given e.g., in the Rock Manual [50] and the International Levee Handbook [1].

Vegetated or colonized revetments pose a possibility to increase the ecological value of grey revetments (Figure 1). However, yet little information exists on the ecological effectiveness and other positive or negative side effects of vegetating or colonizing revetments.

Along inland waterways, the use of grouted revetments filled with flowable topsoil and alginate was tested for establishment of vegetation and colonization of fauna within the cavities of the revetment [51]. In case of fully-grouted revetments, the colonization can be supported by using a loose rip-rap on top of the grouted revetment [52]. Similarly, concrete mats—double-layer interconnected geotextile mats filled with flowable concrete—can be covered with a vegetated topsoil

that acts as sacrificial layer and only serves ecological and aesthetic purposes [53]. Fully vegetated grouted revetments and concrete mats are pictured [52,53], though no deeper ecological analyses were conducted.

Figure 1. Vegetated and/or colonized revetments. (a) Vegetated grouted revetments after [52], (b) vegetated concrete mats after [53], (c) vegetated revetment blocks after [55], (d) vegetated block mats after [54] and (e) further surface and structure adaptations to promote colonization after [56–58].

With reduced sealed area, special concrete revetment blocks and block mats allow for vegetation of the revetment. Here, openings between the single blocks and open areas within the blocks enable the establishment of vegetation [54]. For further support of vegetation growth, concrete revetment blocks can be combined with geotextiles [55]. Increased stabilization of the revetment blocks is anticipated as the roots anchor the blocks with the underground soil [55]. Vegetation establishment is assumed to depend amongst others on the dimension of the opening. Open cell block mats presented by [54] have an open area of 20%, revetment blocks in [55] an open area of 25%.

Colonization of organisms, such as algae or mussels, can be supported by adapting the surface or general structure of revetments. Here, a range of small (e.g., texture and small grooves) to larger adaptations (e.g., water retaining features or elevations) is possible [56–58]. Measures have to be chosen with regard to the flooding frequency/tidal elevation and target organisms [58]. Water retaining features were found as most effective measure for increasing the number of sessile and benthic species, followed by intertidal pits for benthic species [58]. Detailed results of a meta-analysis on the effectiveness of the various measures on the abundance and number of organisms (sessile, mobile, benthic, fish and habitat-forming taxa) under consideration of the environmental settings (intertidal, subtidal) are given in [58]. When supporting the colonization of organisms on hard substrates, the species origin (native,

non-native, cryptogenic) and possible negative effects of the newly evolving ecosystem have to be considered [59,60].

3.5. Grass and Herbaceous Dike Covers

3.5.1. Practical Relevance and Current Practice

Dense grass covers have proven worldwide as simple, effective and simultaneously sustainable surface protection against erosion on dikes [1,11,61,62]. Besides functioning as surface protection, grass covers can have an ecological value and can increase the aesthetic appeal [1].

While the aboveground part of grass covers—the sward and the stubble—absorbs rainfall energy and can increase surface roughness and thereby protects against splash and interrill erosion, reduces hydrodynamic loads and catches sediments, the underground part—the roots—binds soil particles and modifies physical and chemical soil parameters and thereby affects infiltration, reinforces the soil and protects against rill and gully erosion [63–66], cf. Figure 2.

Figure 2. Structure and physical effects of a grass cover.

The grass species applied for dike covers have to be selected according to the local climate, soil and hydraulic conditions and should ideally correspond to native species [1,62]. To provide an erosion-resistant dike cover, the following requirements have to be fulfilled: (1) permanently green, dense grass cover with different root forms and depths, (2) combination of fast and slow germinating species, (3) adjusted to boundary conditions, e.g., salt tolerance or frost resistance, and (4) tolerance to cutting, step-resistance and regenerative capacity [11,67,68]. The optimal species composition is defined as a combination of 70% tussock-forming grasses, 15% of species with subterranean runners and 15% with rhizomes [69]. The network of horizontally creeping roots lying within the upper 15–20 cm results in strengthening of the soil structure while deep-reaching roots anchor the upper with the lower soil layers [70]. In Germany, standard seeding mixtures consisting of different grasses (perennial ryegrass, smooth meadow-grass and red fescue) and, if desired, a small percentage of herbs (yarrow) are recommended for sea dike vegetation [11]. Ryegrass provides a fast development of the grass cover, although insufficient root volume; fescues and meadow grasses lead to deep, fine roots and increase the erosion resistance significantly [71]. In tropical and Mediterranean regions, often vetiver grass is used for slope stabilization [72,73].

3.5.2. Erosion Resistance Against Overflow and Wave Overtopping

The erosion resistance of green dike covers has been investigated in wave flumes, within in-situ tests on real dikes and with model tests on artificial research dikes or dike covers. For full-scale model tests in wave flumes, natural grass sods were excavated and installed onto the dike model [74,75].

With the Dutch wave overtopping simulator (Dutch WOS) erosion tests on real dikes were made possible [76–79]. Investigations on artificial research dikes [80] and tests on top layers in planter trays with the fixed US wave overtopping simulator (US WOS) [81,82] complete the portfolio of overflow and wave overtopping erosion tests on vegetated dikes. Table A1 summarizes the conducted investigations, tested objects, applied loads and corresponding results.

While design guidance conservatively recommends tolerable overtopping discharges of 5 l/(sm) with significant wave heights of $H_{m0} = 1\text{--}3$ m for maintained and closed grass covers [83], physical model tests and in-situ analyses show that a good grass cover is generally able to resist mean wave overtopping discharges up to 30 l/(sm) or higher [75,76,78,82]. Weak points, such as rabbit holes, trees or poor grass condition, reduce the erosion resistance drastically [78,79,82].

Often only little information on the tested dike vegetation is given and test results cannot be generalized or transferred to other boundary conditions (vegetation type, grass condition, etc.). Though, by considering the duration of loading and quantitative vegetation parameters within the erosion analyses, a linear correlation between the cumulative overtopping volume V_{total} at failure and the product of root volume and root length was found [82]. Meanwhile, meta-data analyses on the soil resistance against concentrated flows revealed an exponential decrease in soil detachment ratios due to rill and gully erosion with increasing root density and root length density [64,65].

3.5.3. Erosion Resistance Against Wave Impacts

Grass covers on the seaward slope can be affected by wave impacts. No damages have to be expected for waves up to 0.75 m height for grass covers of good quality [66]. Weak spots, such as mice holes or dead plants, induce earlier erosion [75]. For grass sods with initial damage, a threshold wave height of 0.5 m is concluded, beyond which erosion starts [84]. Cracks, especially water filled cracks, increase the risk of greater damage due to wave impacts [85]. Generally, erosion due to wave impacts is influenced by the homogeneity and quality of the clay and grass, sand inclusions and weak points [84]. Detailed investigations, e.g., on the correlation of vegetation traits and wave impact resistance, are lacking.

3.5.4. Influence of Maintenance

Species diversity, vegetation coverage and root density on sea dikes strongly depend on the maintenance measures applied [66,86]. Species-rich communities were generally found in unfertilized areas. At the same time, highest erosion resistances were found for long-term unfertilized dikes [66]. Laboratory studies confirmed that erosion resistance increases with increasing species diversity [87]. Consequently, maintenance measures directly affect soil erodibility. Cessation of fertilization increases species-richness, root length, root weight and thus erosion resistance already after a short time [86].

3.6. Woody Vegetation on Dikes

Generally, dense well-maintained grass covers are recommended for dike vegetation [1]. However, as a result of natural progression or intended promotion, occasionally woody vegetation in the form of forest-like stocks, tree rows or solitary trees can be found on dikes [88]. Woody vegetation differs substantially from grasses and herbaceous vegetation or shrubs by their surface (stem and crown) and underground structure (root system). Thus, woody vegetation results in different biomechanical effects than grasses or herbaceous vegetation. According to [63], woody vegetation improves in particular mass stability due to deeper and stronger roots, while grasses and herbs provide especially increased surface erosion protection due to the dense ground cover.

The use of woody vegetation on dikes is widely debated. While woody vegetation offers ecological functions, e.g., providing habitats, balancing water quality and temperature, as well as cultural, recreational and aesthetic functions [89], the effects on dike safety are contrarily discussed. Table 1 summarizes reasons for and against woody vegetation on dikes. While established recommendations and guidelines vary from prohibiting woody vegetation on dikes as a general rule (e.g., [62,90]),

exceptions can be possible as long as the stability and functionality of the dike is not restricted or the risks are acceptable [91]. Adaptation measures for dikes with woody vegetation, such as dike oversizing, structurally effective sealings or securing of trees, represent options to ensure the structural safety [91,92].

Table 1. Reasons for and against woody vegetation on dikes.

Contra	Reference
Increased risk of vegetation-induced dike damage, e.g., holes due to tree failure, damage of dike sealing	[1,89,93,94]
Increased risk of erosion: trees as starting point for external erosion (flow concentrations, turbulences), increased internal erosion due to cavities as a result of root decay	[1,63,89,93,94]
Additional forces, e.g., wind forces, transmitted into slope	[1,63,93]
Hinder the development of an erosion-resistant surface cover due to shadowing	[1,93]
Effects on water flow: reduction of flow velocities through increased roughness, reduced flow cross section	[63,89]
Increased risk to attract burrowing animals	[1,93]
Complication of monitoring and maintenance	[1,63,89,93]
Obstacles during flood fighting operations	[1,63,93]
Pro	Reference
Increased soil stabilization due to root reinforcement	[1,63,89,95,96]
Increased (global) dike stability due to additional weight and/or deeper roots	[63,94,95,97]
Positive effects on soil moisture due to interception, water extraction and transpiration	[63,89,94]
Foreshore woody vegetation and woody vegetation on the outer slope can act as breakwater or protection against ice drift and reduce flow velocities	[88,94,97]
Positive effects on sediment transport	[89]
Ecological functions, e.g., providing habitats, balancing water quality, temperature etc.	[89,98]
Cultural, recreational and aesthetic functions	[89,95,98]
Reduced maintenance costs/efforts	[95,97]

4. Reinforcement Methods for Sea Dikes

To adapt to increasing design parameters or also to compensate for reduced dike resistance, e.g., in the case of lower erosion resistance of ecologically valuable sea dike vegetation, reinforcement measures might be worth considering. In the following, an overview on dike reinforcement methods (Section 4.1) and a detailed comparison of the various grass reinforcement methods (Section 4.2) are given.

4.1. Overview

Commonly, sea dikes consist of a sand core and a clay layer as sealing dike cover [1,11]. Latest innovations, however, show alternative dike designs with further dike strengthening potential, such as dike core reinforcements and new methods for dike sealing.

Studies on the use of geotextiles in the form of geotextile loops, horizontal and slope-parallel geotextile layers and geotextile tubes to increase dike safety against wave overtopping are reported by [99]. Testing the first three methods, wrapped loops and slope-parallel nail-anchored geotextiles (for slopes $\geq 1:2.5$) prove to be stable constructions with limited deformations [99]. Integrated continuous geotextile soil-filled tubes were found to offer an erosion resistant, stable dike core [100].

In case of reinforcement needs for existing dikes at limited space conditions, measures are necessary that do not increase the dike footprint further. Here sheet piles and concrete screens in the crestline or dike nailing and mixed-in-place columns along the landward slope are possible. Sheet piles

and concrete screens in the crestline improve the stability of the dike and help controlling seepage [1,6]. In case of an overflow or overtopping event and consequent erosion of the landside slope, the height of the dike and with this the flood protection function are still ensured when applying sheet piles [101].

Dike nailing, a modification of the traditional soil nailing, represents a cost-effective measure with which dike stability is improved due to increased structural integrity and increased shearing resistance [102,103]. A similar effect is given with the mixed-in-place method with which dike stability is increased due to columns of soil mixed with cement [6].

As an alternative to the valuable mineral clay sealing, geosynthetic clay liners can provide dike sealing and prevent from typical dike breaches [104]. Grass reinforcements represent another dike reinforcement method, which is described in detail in the following chapter.

Generally, alternative dike designs are associated with additional costs for material, machinery, etc. When assessing the cost-efficiency, resulting benefits, such as reduced necessary dike height or footprint, better adaptation to local conditions and social or ecological benefits, have to be considered.

4.2. Grass Reinforcement

As hydraulic loads exceed the strength of the natural grass cover, artificial grass reinforcement can be a possible solution to avoid dike failure and preserve the natural cover. Amongst others, erosion control meshes and blankets, fiber roving systems, turf reinforcement mats (TRM) and vegetated geocellular containment systems can serve as erosion control measures by reinforcing the cover layer [105]. In the following, an overview on selected up-to-date grass reinforcement methods and their resistance is given.

4.2.1. Smart Grass Reinforcement (SGR)

The concept of SGR uses a thin, three-dimensional geogrid that is placed underneath the grass surface by cutting and lifting the upper layer of the existing grass cover, installing the geogrid onto the underground and finally putting the grass layer on top of the geogrid. After regeneration of the grass cover, the intertwining of roots and geogrid leads to an increased erosion resistance and the geogrid itself provides a protective function against erosion of the underlying soil. Tests with the Dutch wave overtopping simulator [106] on a real dike section with a grass cover in poor condition showed no major erosion for mean overtopping rates of 50 l/(sm) over a 6 h testing period at the reference (unreinforced) and reinforced dike section. After initiating artificial damage in the form of holes, attached poles, etc., the additional erosion resistance due to SGR became apparent with less progressive erosion compared to the unreinforced dike section [107,108].

4.2.2. High Performance Turf Reinforcement Mats (HPTRM)

HPTRMs are three-dimensional, durable geotextile mats that are installed onto the underground and covered by grass seeds and a thin layer of soil. After roots have grown through the geotextile, an intertwined system with increased erosion resistance is formed. Thereby HPTRMs enhance the seed germination and vegetation growth through modifying the local micro climate.

Information on material properties (weight per unit area, tensile strength, etc.) and performance (erosion resistance due to overflow and ability to encourage seed germination and plant growth) were achieved from standardized tests of the National Transportation Product Evaluation Program (NTPEP). For example, maximum permissible flow velocities of 7.6 m/s for vegetated HPTRMs [109,110] and 3.8 m/s for unvegetated HPTRMs [110] were obtained while assessing the performance in protecting earthen channels from stormwater-induced erosion [111]. Tests on seed germination and plant growth showed biomass improvement of exemplarily 378% [110].

Tests at the Colorado Wave Overtopping Facility have shown no damage after 6 h testing of dormant HPTRM-reinforced Bermuda grass with maximum mean overtopping discharges of 370 l/(sm). Referred to the cumulative overtopping volume, the erosion resistance of HPTRM-reinforced grass covers against wave overtopping is found to be at least 2.8 times higher compared to unreinforced

grass covers [81]. After erosion of the top soil layer, the HPTRM still provides further protection against erosion and thereby increases the overall erosion resistance of the system [112,113].

4.2.3. Geocellular Containment Systems

Geocellular containment systems, i.e., three-dimensional geotextiles in the form of honeycombed cells connected to each other and filled with substrate, show an increased carrying capacity and improved deformation behavior due to the activation of passive earth resistance and tensile ring forces. Critical flow velocities are increased as erosion forces are absorbed by the network of cells and soil and the soil is held within the cells [49,114]. Design velocities of 0.9 m/s for geocells filled with unvegetated topsoil and 1.5 m/s for geocells filled with vegetated topsoil are recommended [115].

4.2.4. Comparative Analysis

Figure 3 summarizes the results of erosion tests and recommendations for design velocities of the SGR system, HPTRMs, ECRMs (Erosion Control Revegetation Mats) and geocellular containment systems. The SGR system and HPTMR-strengthened grass covers withstand maximum possible average overtopping discharges far beyond the commonly indicated 5 l/(sm) for preventing dike damage [83]. Still, the actual resistance is unknown as existing testing facilities lack of sufficiently high hydraulic power [81,107,112,113]. Compared to the design velocities for grass-only [116], the design velocities for vegetated geocells [105] seem to be very conservative and further research is required. Grass reinforcement with geotextiles has proven to be effective and feasible for sloped structures. However, the obtained testing results are only applicable to similar systems, i.e., similar geotextile, grass species and substrate.

Figure 3. Maximum mean overtopping rates and maximum flow velocities for the Smart Grass Reinforcement system (SGR), High Performance Turf Reinforcement Mats (HPTRMs), Erosion Control Revegetation Mats (ECRMs) and geocellular containment systems from literature.

5. Discussion

5.1. Technical and Functional Conception of Ecologically Valuable Sea Dikes

Coastal protection is the main function of sea dikes. Therefore, dike safety is the key factor during the design process. Developing an integrated design concept for ecologically valuable sea dikes, the ecological value of the system has to be enhanced while maintaining the dike safety. Table 2 summarizes methods for ecological enhancement of dikes and their limitations/challenges. Based on

the findings of the present review, potential for ecological enhancement of sea dikes has been found regarding the foreshore composition, dike surface protection measures (vegetated dike covers, hard revetments and dike roads) and the slope inclination. A schematic sketch of a sea dike system with nature-based solutions is given in [32].

Table 2. Summary of methods for ecological enhancement of dikes and their limits/challenges.

Dike Component	Common Design	Ecological Enhancement	Limitations/Challenges
Foreshore	Not directly integrated in dike design	Ecosystem engineering (marshes, reefs, etc.) or nature-based solutions (e.g., artificial reefs)	Little experience concerning establishment and management. Uncertainties concerning (constant) coastal protection function
Slope inclination	Slope design as compromise between dike stability and material consumption/footprint	Milder seaward slopes for positive effects on nature, recreation and coastal processes	Increased dike footprint, additional habitat loss/alteration
Dike roads	Asphalt roads	Alternative vegetated fortified paths (e.g., vegetated geocellular containment systems)	Little experience, mainly pilot projects. Assurance of stability and functionality
Revetments	Grey revetments (rip-rap, placed blocks, etc.)	Vegetated or colonized revetments	Little experience, mainly pilot projects. Assurance of stability and functionality
Vegetated dike cover	Dense grass covers, no woody vegetation	Adaptation of seeding mixtures towards more ecologically valuable vegetation	Assurance of consistent erosion resistance

The integration of ecosystem-based engineering in the foreshore, e.g., with natural ecosystems or nature-based breakwaters in the form of reefs, allows for ecological enhancement and decreased hydraulic loads at the dike structure [8,47]. The target species has to be chosen according to boundary conditions, such as climate, salinity, exposure to hydrodynamic loads, submergence time and substrate [8]. Colonization with corals e.g., depends on the availability of hard substrate; mangroves require muddy systems. Similarly, mangroves can only be found in tropical or subtropical regions, while salt marshes occur in temperate regions. Little experience with the establishment and management of natural solutions still poses a challenge. However, lately, innovative nature-based methods are investigated for foreshore restoration, such as wave breakers made of oyster-bags [117] and reef balls [118]. Furthermore, artificial sea grass beds are investigated regarding their potential to support the long-term rehabilitation of natural sea grass [119]. Uncertainties concerning the coastal protection function of ecosystems [45,46], e.g., due to their spatial and temporal variability, have to be considered in the design process. Depending on the ecosystem, aboveground biomass may vary over the year resulting in temporal differences in energy dissipation and sediment accretion. Exemplarily, a reduction of shoot densities from around 4600 shoots/m² in summer to 600 shoots/m² in winter was found for a seagrass meadow and largest wave height reductions were recorded in July when the shoot density was high [120]. Additionally, vegetation may break or fold under extreme wave loads resulting in reduced coastal protection benefits [121]. In case that the aboveground biomass disappears completely, only the trapped sediments can yield wave attenuation [45].

Adaptations of the general dike geometry, such as milder seaward slopes, can have positive effects on nature, recreation and coastal processes [6,48]. Considering milder slopes for ecological enhancement of sea dikes, the various aspects—additional habitat loss/alteration, alteration of coastal processes—have to be evaluated as well as further conflicts, e.g., due to space restrictions, have to be considered.

A more natural approach to asphalt-paved dike roads may be alternative methods, such as vegetated geocellular containment systems [49]. Considering alternative design methods for the construction of dike roads, more comprehensive investigations are required, especially concerning the assurance of stability and functionality under extreme conditions.

Dike revetments can be enhanced ecologically by introducing vegetation by means of provision of substrate within cavities [51] or reduction of surface sealing [55]. Experience with these approaches is, however, mainly limited to pilot projects. Colonization with organisms can be supported by means of surface adaptations, e.g., more inhomogeneous surface structures or water retaining features [58]. Yet, studies on the colonization of revetments mainly focus on the subtidal and intertidal zone while for dikes generally only the dike toe is affected by tidal water fluctuations. Colonization of dike revetments may therefore be limited. Generally, the stability and functionality of the revetment have to be ensured for every change of the original revetment system, e.g., changes in permeability or root growth within revetment cavities and possibly filter layers.

Based on experience and supported by comprehensive laboratory and field studies [74,76,82], commonly grasses are used for dike vegetation (Figure 4, left) since a dense grass cover is known to provide sufficient surface protection against moderate hydraulic, climatic and mechanical loads [1]. Enhancements of the ecological value of the dike vegetation are possible by adapting the seeding mixtures towards species compositions that offer more food sources for flower-visiting insects or more carbon sequestration (Figure 4, right). When adapting the vegetation on dikes, the erosion resistance still has to be assured. Currently, different vegetation mixtures are investigated concerning their ecological value, erosion resistance and vegetation development under coastal conditions within the EcoDike project [122]. Concerning maintenance measures such as mowing or grazing, the demands of coastal protection and ecology have to be reconciled, though dike safety is of primary importance. For compensation of probably decreased erosion resistance, the application of grass reinforcements may be possible. Woody vegetation on dikes is generally not welcome except special adaptation measures are taken [91,92].

Figure 4. **Left:** Typical grass-covered sea dike on Pellworm, Germany (Photo: Scheres, 2018); **Right:** Species-rich vegetation on a river dike along the Lower Rhine in Meerbusch, Germany (Photo: Scheres, 2019).

5.2. Bringing Together Ecology, Engineering and Society

Designing and implementing ecological enhancements and nature-based solutions in coastal protection not only requires the interdisciplinary collaboration of scientists (especially ecologists) and engineers, but also brings societal challenges, such as the necessity to consider different interests, knowledge and language of the various stakeholders in science, practice, policy and public [123,124]. The design and implementation of ecologically valuable sea dikes requires interdisciplinary cooperation acknowledging the demands and objectives of the different parties and focusing on the common interests of ecology, engineering and society. Developing an integrated concept for ecologically enhanced sea dikes, the dike system has to be understood and promoted as part of a greater ecosystem.

While a dike functions as a coastal protection structure (relevant for engineering and society, Figure 5), it can simultaneously provide habitat for coastal flora and fauna and thereby give ecological benefits (relevant for ecology and society, Figure 5). For enhancing the ecological value of coastal structures, ecological engineering as a merger of ecology and engineering (Figure 5) has to be applied.

To finally achieve ecologically valuable coastal protection, the interests of all stakeholders have to be brought together. Conflicts may arise if objectives, approaches or mindsets differ [125].

Figure 5. Bringing together the interests of ecology, engineering and society to achieve ecologically valuable coastal protection.

Overcoming knowledge and language differences [126,127], adjusted operational instruments, e.g., by involving knowledge brokers [123], direct participation of stakeholders, e.g., within participatory or collaborative modelling approaches [128], and cost–benefit analyses under consideration of ecosystem services [129,130] can form a basis for decision-making and help to overcome possible conflicts.

6. Conclusions

Sea dikes pose an important coastal protection element along coasts with low-lying hinterlands. For the design and maintenance of dikes, dike safety is the main factor to assure constant and sufficient protection against the forces of the sea. When adapting the original system, the dike safety has to be maintained.

Ecological enhancement of sea dike systems can be obtained by means of natural or nature-based solutions in the foreland or at the dike structure itself. Natural (marshes, reefs, etc.) or engineered approaches (artificial reefs, etc.) can support ecosystems in the foreland and can simultaneously decrease the loads on the dike structure resulting in longer design lives and reduced maintenance efforts. Ecological enhancements of the dike structure itself, e.g., vegetated revetments or ecologically valuable sea dike vegetation, allow for further increase of the ecological value of the sea dike system. Introducing new design methods, the stability and functionality of the coastal protection structure have to be assured, e.g., maintenance of the erosion resistance of vegetation covers when adapting the vegetation species applied.

While a wide range of studies focuses on natural and nature-based solutions in the foreland, so far only few experiences with ecological enhancements of the dike structure itself were gained resulting in uncertainties and knowledge gaps concerning the implementation and efficiency (technical and ecological). To account for increasing hydraulic loads and environmental awareness, engineers and ecologists from science and practice are obliged to take joint steps towards greener, adapted coastal protection.

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Appendix A

Table A1. Summary of studies on the erosion resistance of vegetated dike covers against wave overtopping and overflow. Abbreviations: q = mean overtopping/overflow discharge [l/(sm)], V_{total} = cumulative overtopping volume [m³/m], WOS = Wave Overtopping Simulator. * *Festuca Rubra*, *Lolium perenne* and *Poa pratensis*; ** *Trifolium repen* and *Medicago sativa*.

Ref	Test Object	Material of Cover	Vegetation	Loads	Results
<i>Model tests in wave flumes</i>					
[74]	sea dike model, 1:3 landward slope	3 different clays tested	no vegetation	q up to 10 l/(sm) H_S unknown	<ul style="list-style-type: none"> erosion initiation due to $q < 1.0$ l/(sm) [good clay]
[75]	sea dike model, 1:3 landward slope	clay	grass sods from Ribe, Denmark	q up to 30 l/(sm) $H_S = 0.75$ –1.0 m	<ul style="list-style-type: none"> no damage (visual assessment)
<i>In-situ tests on real dikes</i>					
[76]	sea dikes in the Netherlands, several test locations	clay	various grass conditions and maintenance strategies	Dutch WOS q up to 75 l/(sm) $H_S = 2$ m	<ul style="list-style-type: none"> no dike failure due to $q = 30$ l/(sm) one dike failure due to $q = 50$ l/(sm) [bad grass coverage] some dike failures for $q = 75$ l/(sm)
[77]	sea dikes in the Netherlands (here only Vecht dike)	90% sand	grass cover in a good condition	Dutch WOS q up to 50 l/(sm) $H_S = 1$ m and 3 m	<ul style="list-style-type: none"> erosion initiation due to $q = 30$ l/(sm) [$H_S = 1$ m] undermining and collapse of top layer due to $q = 50$ l/(sm) [$H_S = 1$ m] erosion initiation due to $q = 5$ l/(sm) [$H_S = 3$ m] head-cut erosion due to $q = 30$ l/(sm) [$H_S = 3$ m]
[78]	Vietnamese sea dikes, 1:3 & 1:15 landward slope	moderate clay	Bermuda grass	Dutch WOS q up to 70 l/(sm) $H_S = 1.5$ m	<ul style="list-style-type: none"> erosion initiation due to $q = 40$ l/(sm) [good Bermuda] erosion initiation due to $q = 10$ l/(sm) [poor Bermuda with Casuarina tree] erosion initiation due to $q = 20$ l/(sm) [very poor Bermuda]
		good clay	Bermuda and Vetiver grass	Dutch WOS q up to 120 l/(sm) $H_S = 1.5$ m	<ul style="list-style-type: none"> erosion initiation due to $q = 80$ l/(sm) [good and poor grass condition] erosion concentrated around a horizontal concrete beam
		good clay	young Bermuda grass (1-year, good condition)	Dutch WOS q up to 110 l/(sm) $H_S = 1.5$ m	<ul style="list-style-type: none"> erosion initiation due to $q = 100$ l/(sm)
		good clay	young Carpet grass (1-year, good condition)	Dutch WOS q up to 100 l/(sm) $H_S = 1.5$ m and 2 m	<ul style="list-style-type: none"> erosion initiation due to (1) $q = 60$ l/(sm) and (2) $q = 100$ l/(sm) [$H_S = 2$ m]

Table A1. Cont.

Ref	Test Object	Material of Cover	Vegetation	Loads	Results
[79]	tidal river dike in Belgium, 1:1.7 landward slope	clay	grass in poor condition	Dutch WOS q up to 25 l/(sm) H _S up to 1.2 m	<ul style="list-style-type: none">erosion initiation due to q = 10 l/(sm) at rabbit holedike failure due to q = 25 l/(sm)
		clay	grass in poor condition	Overflow simulator q up to 170 l/(sm)	<ul style="list-style-type: none">no/minor erosion due to q = 170 l/(sm)
Model tests on artificial research dikes/dike covers					
[81,82]	planter trays on 1:3 slope	clay	no vegetation	US WOS q up to 18.6 l/(sm) H _S = 2.44 m	<ul style="list-style-type: none">severe erosion after 1 h of q = 9.3 l/(sm)failure due to V_{total} = 56 m³/m
		clay	Bermuda grass	US WOS q up to 370 l/(sm) H _S = 2.44 m	<ul style="list-style-type: none">no damage due to V_{total} = 16,522 m³/m [well-maintained, dense Bermuda grass]minor erosion due to V_{total} = 11,338 m³/m [Bermuda grass with wheel ruts]minor erosion after 1 h of q = 186 l/(sm) [dormant Bermuda grass]failure due to V_{total} = 2,175 m³/m [dormant Bermuda grass]
		clay	Bahia grass	US WOS q up to 279 l/(sm) H _S = 2.44 m	<ul style="list-style-type: none">no damage due to V_{total} = 13,244 m³/m
[82]	planter trays on 1:3 slope	4 different sandy soils	Bahia grass, 50% and 30% grass coverage	US WOS H _S up to 2.44 m	<ul style="list-style-type: none">failure due to V_{total} = 301 to 1,354 m³/mcorrelation of hydraulic resistance and root parameters (average root length and volume)
[80]	research dike, 1:2 & 1:3 landward slope	fine-grained dredged material	standard dike seeding mixture * with added legumes **, good vegetation coverage	overflow tests max. q > 550 l/(sm) max. v > 4.6 m/s	<ul style="list-style-type: none">measured average cumulative soil loss did not exceed the critical amount of soil loss (1.27 cm)

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