Journal of
Marine Science and Engineering

MDPI

Article

Spatial Design Thinking in Coastal Defence Systems: Overtopping Dikes in Southend-On-Sea

Luca Iuorio [1,*], Davide Wüthrich [2], Djimin Teng [2] and Fransje Hooimeijer [1]

1 Faculty of Architecture and the Built Environment, Department of Urbanism, TU Delft, 2628 BL Delft, The Netherlands; f.l.hooimeijer@tudelft.nl
2 Faculty of Civil Engineering and Geoscience, Department of Hydraulic Engineering, TU Delft, 2628 CN Delft, The Netherlands
* Correspondence: l.iuorio@tudelft.nl

Abstract: Coastal dikes have been built for millennia to protect inhabited lands from exceptional high tides and storm events. Currently, many European countries are developing specific programs to integrate the construction of new dikes (or the raising of existing ones) into the built environment to face sea level rising. Technical difficulties in succeeding in this operation are questioning the paradigm of protection for the long term, pointing out the need for alternative strategies of adaptation that are not yet fully explored. This paper elaborates on innovative models to deal with coastal flooding, presenting the results of an interdisciplinary research and design process for the case-study of Southend-on-Sea (UK). Detailed numerical simulations are used to develop a spatial strategy to accommodate water during extreme events, introducing different prototypes of dike designs that include seawalls, enhanced roughness through rock and stepped revetments, as well as vegetation. The overall goal is to push forward the traditional approach of planning water protection infrastructure within the solely field of civil engineering. It elaborates on the integration of the disciplines of spatial design and engineering and presents novel advances in terms of spatial design for the revetment of overtopping dikes.

Keywords: engineering; spatial design; interdisciplinary; coastal dikes; roughness

check for updates

Citation: Iuorio, L.; Wüthrich, D.; Teng, D.; Hooimeijer, F. Spatial Design Thinking in Coastal Defence Systems: Overtopping Dikes in Southend-On-Sea. *J. Mar. Sci. Eng.* **2024**, *12*, 121. https://doi.org/10.3390/jmse12010121

Academic Editors: Kendra Dresback and Christine M. Szpilka

Received: 16 November 2023
Revised: 22 December 2023
Accepted: 3 January 2024
Published: 8 January 2024

1. Introduction

Most recent scientific reports agree that our climate is changing and that the next decades will experience a rise in sea-water levels [1–4]. While sources may provide scattered and conflicting data on the extent of this increase, this ongoing phenomenon will certainly result in more intense and more frequent storms that will increase the pressure on our coastal defences and flood protection measures. Already, today, floods represent the most common natural disaster in the world, comprising over 3200 events from 2000 to 2019 and representing 44% of all recorded calamities [5]. Following behind, storms constitute the second most common type of disaster event, accounting for 28% [5]. Some recent extreme events have hit the United Kingdom, including storms Eunice and Franklin in February 2022 and Ciaran in November 2023, showing the large amount of damage associated with these extreme events. Therefore, the need for climate adaptation stands out also in the field of coastal flood management and the chances for combining flood defences with other measures catering to societal needs in urban coastal areas seems opportune.

Traditional coastal protection measures include hard and invasive infrastructure in the form of quay walls, shore protection barriers (walls) and coastal dikes. While these structures have proved to be efficient, their spatial adaptation to the new climate scenarios is more challenging, since they are characterized by a strong footprint on the environment [6]. In certain cases, dike maintenance and (sur)elevation can have an enormous impact on historical structures, landscape, mobility networks and accessibility to the sea, particularly in those areas that heavily rely on tourism. For that, many recent research projects focused on the development of techniques inspired and supported by nature (the so-called nature-base solutions NBS), used to tackle societal challenges such as the mitigation of CO_2 emissions, protection from pluvial and fluvial floods, as well as coastal floods associated with sea level rise, providing both benefits to humans and to the natural environment [7–11]. The expansion and restoration of sand dunes, creation of wetlands, organic material groynes and reefs to support flora and fauna repopulation are sustained by a wide range of professional figures and supported by public international institutions. However, nature-based solutions cannot always be used. For example, sand dunes—that have been proved to be extremely favourable for coastal protection [12,13]—require a lot of space in coastal areas, enormous amounts of (dredged) material, and a long time to be developed. This means that nature-based solutions in coastal areas may only be used where there is available unbuilt space and not in dense urban settlements.

Urbanized coastal cities are generally characterized by high density, industrial developments, recreational areas, ports, mobility and supply networks. These are in continuous change and, when expanding, they claim more space and development that might collide with the space needed to increase the performance of the flood defence systems to cope with future standards of protection. Eventually, one of the two systems, i.e., urbanization on one side and engineering structures on the other, will have to be resituated. To combine both feasibility and profitability, new approaches in flood management—ranging between multifunctional dikes and the acceptance of water in the case of extreme weather events—have been developed [14–16]. It goes without saying that these new approaches need to be strategically planned because current infrastructure and coastal communities are still characterized by the traditional flood risk paradigm of protection. The development and implementation of alternative measures require the participation of multiple agents: local communities, governmental and administrative entities, and mostly the collaboration among different professional figures. From the perspective of the spatial design field, it is about conceiving of flood management as a spatial factor and not as a basic condition for urban development. From the flood risk management perspective, it means working in more complex situations that require the integration of more qualitative aspects of the built environment.

The Sustainable And Resilient Coastal Cities (SARCC) Interreg project explored the use of nature-based solutions in urban coastal zones through the spatial and engineering (interdisciplinary) design in seven pilots located in France, Belgium, the Netherlands and United Kingdom. Among these, the long-term objective for the pilots of Vlissingen (NL) and Southend-on-Sea (UK) was to reduce the spatial impact of the existing hard grey infrastructure and to introduce more flexible interventions that will also enhance the connectivity between the land and sea. Both designs are based on the concept of living with water [17,18], where public space is used as a flood retention area in case of extreme weather events. The essence of accepting water overtopping coastal defences and storing it in designated floodable zones (and therefore reducing the risk by limiting the consequences and not its occurrence probability) is part of a key paradigm shift that will lead to a better adaptation to climate change of existing urban areas [19–21].

This study focuses on the design exploration for the pilot of Southend-on-Sea, UK [22] that is aligned to the solutions proposed for Vlissingen, NL [23]. More specifically, it focuses on measures to overcome coastal flooding and adapt to climate change induced by sea-water level (SWL) rise. Its combined occurrence with an inland riverine flood is therefore excluded in the present study. To minimize flood damage, the strategy developed for Southend-on-Sea involves using Gunners Park and the adjacent green area (400,000 m^2) to act as a flood retention area, collecting the potential overtopping volumes resulting from an extreme sea storm, thus protecting buildings, houses and other infrastructures. While coastal protections have been extensively investigated from a technical perspective (including TAW [24], van der Meer [25] and van Gent et al. [26] among others), their integration in the urban landscape has often been overlooked, hence pointing out the need for more trans-disciplinary research. In particular, the design (geometry and material) of the revetments of dikes has shown to be a crucial factor to reduce wave-induced overtopping [27,28]. Hence, this study discusses the multifunctionality of coastal dikes, questioning how the shape of the revetment can affect the roughness of the dike and therefore reduce the volume of overtopping water. It is argued that a different design of the dike profile might provide spatial qualities and public functions to the urban built environment when no extreme events occur. For that, this study presents different prototype examples of dike designs that overcome the traditional approach of planning water protection infrastructure within the solely field of civil engineering. Finally, it elaborates on the integration of the disciplines and presents novel advances in terms of spatial design strategies for future coastal dikes.

2. Flood Risk (Protection) in Shoeburyness, Southend-on-Sea (UK)

Southend-on-Sea (181,800 inhabitants) [29] is one of the most densely populated areas in south-eastern Essex (England), 64 km east of London. It is located at the estuary of the Thames River (Figure 1), and it is accessible through a transportation system, featuring several railway stations and highways. Historically, its waterfront was a significant hub for leisure and recreational activities. Currently, the city's layout is characterized by a sprawling arrangement, mainly consisting of individual homes with gardens. Meanwhile, public, commercial and recreational services are concentrated around the main streets and along the coast. The ground levels—between 2 and 3 metres above the sea level (Ordnance Datum Newlyn)—make the city particularly vulnerable to coastal flooding. In addition, pluvial and riverine floods may occur in urban areas, mostly due to massive development processes after World War II, where many natural areas have been urbanized to provide affordable houses to the growing population, resulting in less space for water to be accommodated and drained. To date, the city faces significant pressure from property development driven by its substantial economic worth, especially along the coast [30]. Because of its critical setting, the Shoeburyness area, located in the south-eastern part of the municipality, has been identified as the main potential area for this pilot design project. Here, residential properties have been developed during the last two decades and new developments are planned to be built in the next few years despite its vulnerability to floods. Currently, Shoeburyness is protected against coastal flooding by a seawall (Figure 2), with safety standards with a return period of 100 years, pointing out the need for additional interventions to raise the level of protection of current infrastructure [31,32]. Recently, the municipality of Southend-on-Sea, together with the Association of the South Essex Local Authorities, developed a vision for the year 2050 [33], in which potential strategies, measures, policies and locations of the future developments of the region were discussed. Part of the 2050 Vision is the Essex Green Infrastructure Strategy [34] that aims at reinforcing the ecological restoration of the region to engage with the loss of biodiversity and improve the development of public spaces such as parks, gardens and sport facilities as well as cycling paths along the coastline.

The multidisciplinary team of researchers and designers of the SARCC project proposed the design of a floodable area at Gunners Park (Shoeburyness) in light of the interest of the municipality to include this area within an ecological regional corridor, while still implementing new housing developments. A closer examination of the urban context and the landscape of Shoeburyness showed that the morphology of this area is well suited for testing a new approach in dealing with coastal flooding. The approach for the Shoeburyness area was already tested in the pilot of Vlissingen (The Netherlands); however, there, the acceptance of overtopping over the dike was a main condition and was not based on an interdisciplinary vision of engineers and spatial designers [23]. The decision of applying the same approach in Southend-on-Sea was the result of a series of workshops, where via an interdisciplinary design process the main long-term and large-scale spatial flood defence strategy was developed. Another key difference with the Vlissingen case is that the city council and the maritime archaeologies were also included in the process to develop the plan for the Shoeburyness area.

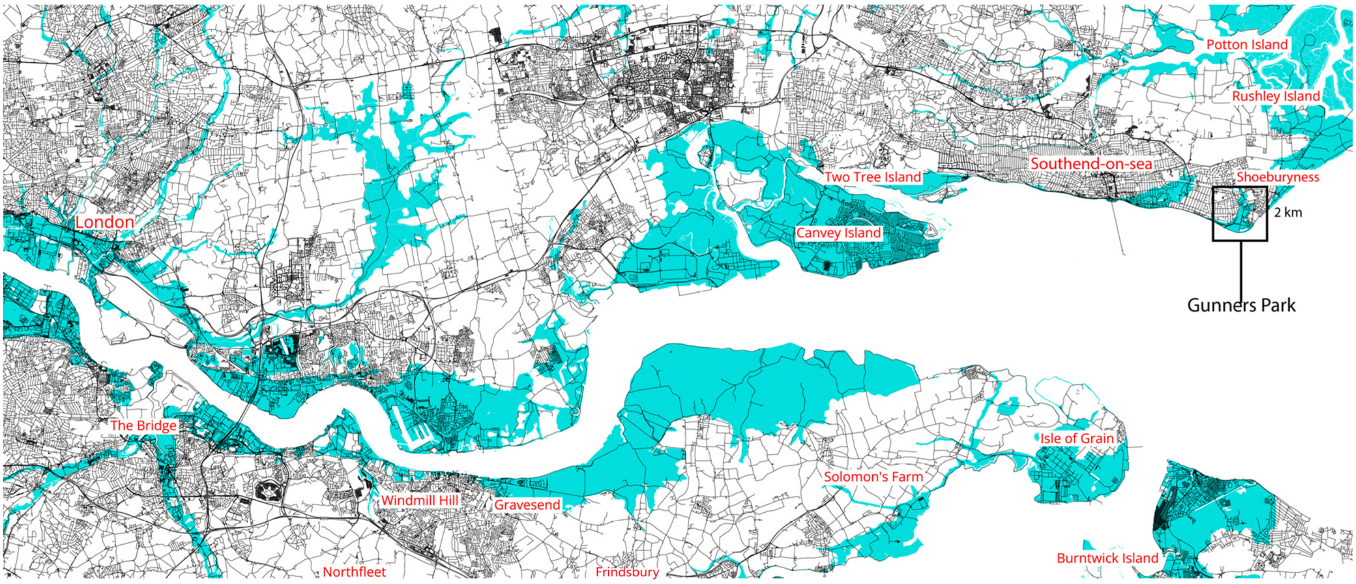
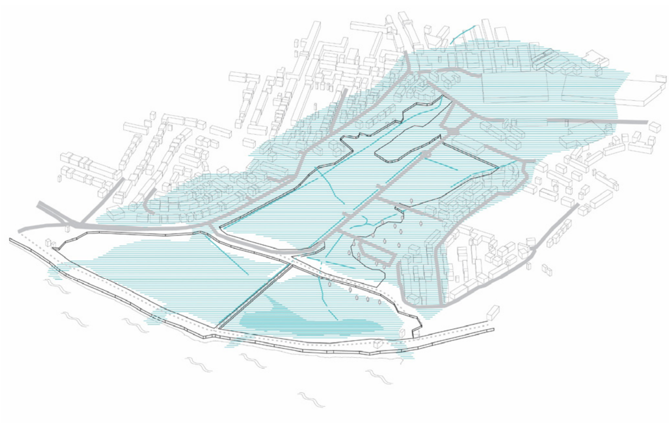


Figure 1. The Thames River estuary from Southend-on-Sea to London. Main mobility infrastructure and floodable areas (2100) are highlighted.

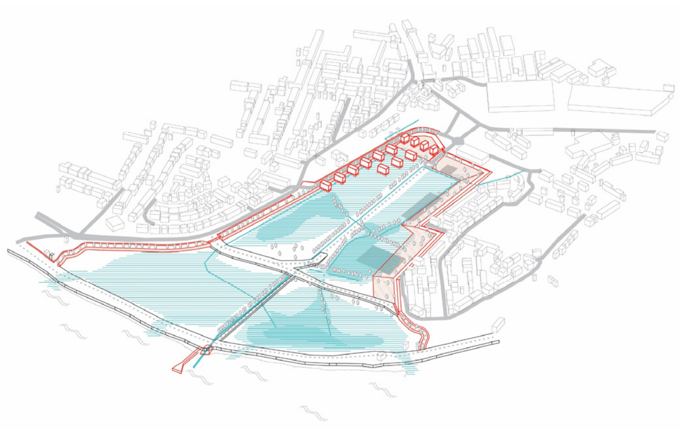
(**a**) (**b**) (**c**)

Figure 2. Current coastal defences in Southend-on-Sea (March 2023): (**a**) vertical seawall in Gunners Park; (**b**) concrete steps on Rampart Terrace; and (**c**) sand dunes in East Beach.

The floodable Gunners Park consists of a designated area where, during extreme weather events, water can overflow by establishing a secondary line of defence (Figure 3). The lower-lying zone is specifically designed with salt-tolerant crops and developed as a recreational area organized by open structures, pathways and vegetation potentially subject to flooding. Existing infrastructure, e.g., elevated roads, divides the area into two parts, enabling the flooding to take advantage of the decelerating cascade effect. The core concept behind this approach is to construct a new embankment that serves as both protection and a recreational space. Simultaneously, the new urban development within the area is designed to be resilient to flooding, including high constructions on stilts, while allocating ground floors for other purposes, e.g., storage or parking [20,22,35]. Accepting water overtopping coastal defences and storing it in floodable areas is a strategy to reduce the risk by limiting the consequences and not the occurrence of probability. In the case of Shoeburyness, it is also an opportunity to envision a spatial development of the area in which engineered structures are integrated within a system of public, private and recreational spaces.



(a)



(b)

Figure 3. (**a**) Flood risk area in Shoeburyness [31] and (**b**) spatial strategy for the floodable Gunners Park.

3. Methods and Tools

Previous studies [26–28] showed that the design of the dike's revetment can reduce the impact of waves during storms and therefore minimize the volume of water in the case of overtopping. Most of the research on the reduction of wave overtopping at coastal dikes focused on the roughness of the revetment with the aim of maximising the energy dissipation. This resulted in a series of alternative geometries and materials that can be employed in revetment constructions. Among these, the last decades saw the development of several blocks' typologies and patterns (e.g., Haringman, Basalton and Ronaton blocks, Hydroblocks, Hillblocks, and chessboard or ribbed patterns) widely used to cover the top layer of coastal structures in the Netherlands as well as in other European countries [36–38]. Advancements in the implementation of nature-based solutions have also been made. The construction of wide green dikes in Germany and the Netherlands, as well as the implementation of wide zones of marshlands next to the main dikes, were found to be particularly efficient in reducing the impact of waves on structures and therefore increasing the overall stability and protection of coastal systems [39–41]. Despite the innovation of such approaches, the implementation of both new geometries on the dike revetments and nature-based solutions increased the mono-functionality of the system. Essentially, these measures reduce the accessibility of coastal protection dikes when no extreme events occur, intensifying the already existing separation between engineering structures and urbanization. In this study, the revetment of the dike is analysed and designed in its spatial perspective to envision new forms of integration. The challenge of increasing the roughness of the revetment is seen as an opportunity to bring engineering structures closer to urbanization, enhancing the multifunctionality of coastal dikes. This has been investigated using numerical simulations for the case of Southend-on-Sea. The performance of four spatial configurations of the revetment of the coastal dike that currently protects the area of Shoeburyness is analysed, comparing the resulting overtopping volumes in the design proposal for the floodable Gunners Park.

Numerical Approach

In this study, engineering tools were used to estimate overtopping discharges during extreme events and numerical simulations were implemented to analyse their propagation within the built environment. The overtopping maximum discharge of the current dike at Shoeburyness was calculated for a scenario in 2100. This led to the definition of the crest level of the inner dike (the second line of defence) of the design proposal for the floodable Gunners Park. To estimate the volumes of water overtopping the coastal defence, the geometric input of the outer seawall, wave characteristics, sea-water level (SWL) rise prediction and storm conditions were elaborated. A typical cross section of the current coastal protection in Gunners Park is shown in Figure 4. Flow conditions and wave characteristics were determined based on a joint probability of two hundred years (1/200) [25,42] with an elevation of 3.35 metres over sea level (SWL, Ordinance Datum Newlyn), significant wave height ($H_{m,0}$) of 1.55 m and a period ($T_{m1\text{-}0}$) of 5 s. In addition, a SWL rise prediction of 0.7 m was added, based on the IPCC-AR5 scenario in 2100 [43–45].

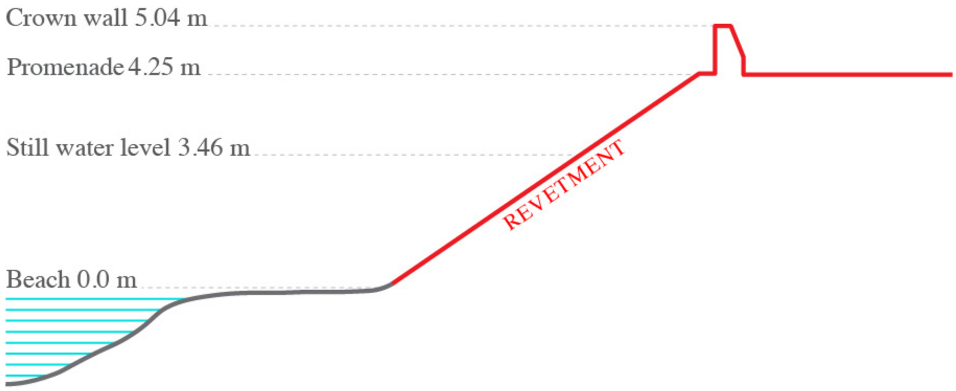


Figure 4. Profile of the current sea wall at Shoeburyness (Southend-On-Sea, UK).

The information on wave characteristics and SWL rise were combined with a 'synthetic' storm with a duration of 100 h and an astronomical tide with a peak value of 3.3 m at Sheerness (close to Southend-on-Sea), as detailed by Wüthrich et al. [22]. These data were then used as inputs in numerical simulations using Delft3D Flexible Mesh (FM), developed by Deltares (NL), which is a hydrodynamic model that solves the discretised shallow-water equations, commonly used to calculate non-steady flows that result from different hydro-meteorological conditions like storm surges, hurricanes, tsunamis, detailed flows and water levels, waves, sediment transport and morphology on a regular grid. Simulations used an unstructured triangular grid with ~0.7 million nodes and a resolution of 10 m.

The roughness value in the urban areas is uniformly defined using a Manning coefficient of 0.06 [$s/m^{1/3}$], common for floodplain areas. These data were used to calculate the overtopping discharge following the empirical model EurOtop [25] with a crest level of 5.04 m, typical of the current coastal defences at Shoeburyness. Various scenarios corresponding to different heights of the internal barriers used to limit the spread of the flood were simulated. Eventually, the inner dike was designed to be implemented with a crest level of 5.20 m to be able to accommodate 2,229,137 cubic meters of water within the park in case of extreme weather events (Figure 5). Nevertheless, this reference baseline scenario provided the starting point for a follow-up integrated design of the revetment of the coastal dike, which is the objective of this study. Starting from the design proposal for the floodable Gunners Park, four different variations of coastal dike (seawall, rocks, steps, vegetation) were tested and evaluated. The main objective was to define the effectiveness of certain solutions in reducing the impact of waves on the revetment—still allowing a maximum amount of water overtopping—and how roughness can be interpreted in its spatial characteristics to better integrate the dike into the urban environment.

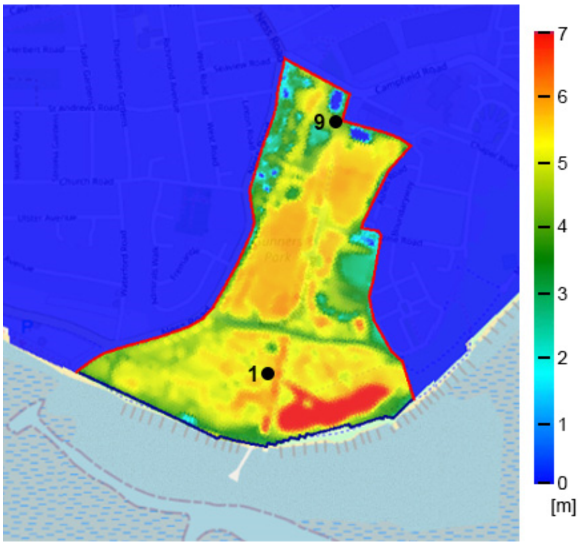


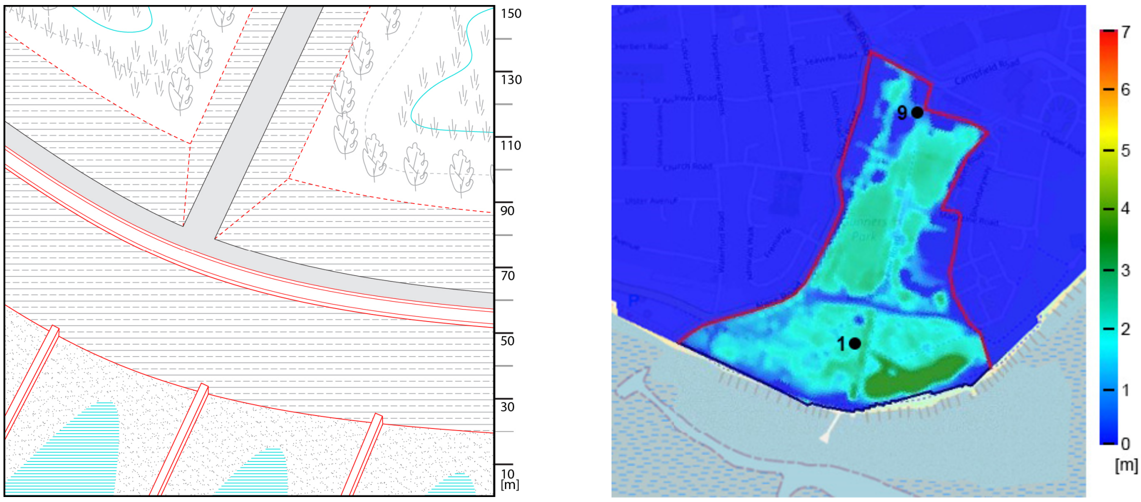
Figure 5. Water depth at the floodable Gunners Park. Numerical simulations for the baseline scenario. The inner dike (with the crest level at 5.20 m) creates a retention basin that might accommodate 2230 cubic meters of water in case of extreme weather events. Note that the red contour line represents the boundary of the domain.

4. Results

While there exist many engineered approaches to reducing overtopping during extreme events, the most traditional has always been the increase in elevation of protecting barriers. With current predictions of SWL rise, alternative solutions to raising seawalls need to be found to better integrate engineering structures within the landscape. This study focuses on four alternatives (seawall, rocks, steps, vegetation) to explore and compare how the design of the slope can reduce water overtopping, while still providing spatial qualities to the dike. Rock revetments have been widely employed during the last decades to dissipate wave energy along the coasts [46]. Stepped revetments and vegetation have been selected based on current research and practise on multifunctional dikes in Europe [14,47,48]. These alternatives are elaborated in the next sections with the description of the intervention and the analysis of the performance of these measures (water depth map) in the context of the floodable Gunners Park design proposal. The impact on the spatial functionality and quality of the area of the alternatives is elaborated in the discussion.

4.1. Seawall

The increase in sea wall height represents a 'business as usual' strategy to overcome challenges related to sea level rise and coastal flood risk. In this case, an increase in the crest height from the current value of 5.04 m (SWL, Ordinance Datum Newlyn) to 5.40 is simulated, using the methodology presented in the section titled Numerical Approach. As expected, the higher crest element resulted in lower overtopping discharges, and therefore in maximum water depths of 2.05 m at Point 1 inside Gunners Park (Figure 6), which is significantly lower compared to the 4.05 m observed for the baseline scenario (Figure 5). Similar considerations can be made for Point 9 (the inland part of Gunners Park), where water levels are significantly reduced to approximately 0.52 m. These results show the technical effectiveness of this 'business as usual' strategy, but also point out the lack of functionality and integration within the built environment, therefore demanding the development of additional solutions.

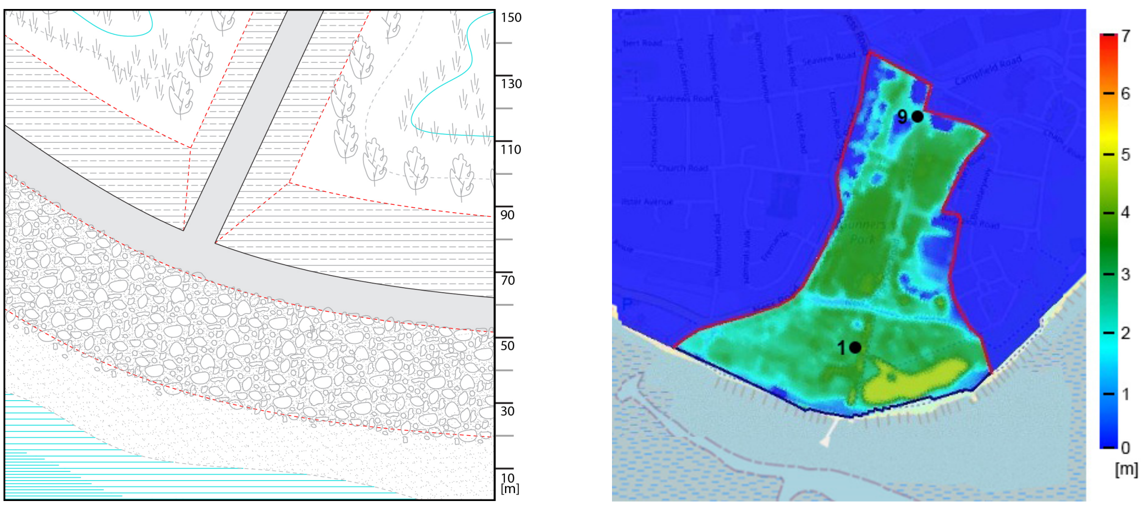


(**a**) (**b**)

Figure 6. (**a**) Axonometric view for the scenario with increased crest heights of 5.40 m and (**b**) numerical simulations (water depth map). Stored volume in Gunners Park is of 717,285 m^3. Note that the red contour line represents the boundary of the domain.

4.2. Rock Revetments

An alternative to reduce overtopping is to add rough elements (e.g., natural rocks or concrete elements) on the outer slope of the dike. Guidelines such as TAW [24] and the EurOtop Manual [25] provide roughness coefficients for different types and configurations of roughness elements on coastal dikes. For this alternative, an influence factor for roughness (γ_f) of 0.85 is used, which corresponds to a slope revetment with Vilvoorden stone or small concrete blocks in a chequered configuration. The results for this rocky configuration are presented in Figure 7b, showing a reduction in maximum water depths at Point 1 inside Gunners Park to 3.32 m, compared to the 4.05 m obtained with the baseline scenario. While this solution is less effective than the higher seawall (max water level at point 1 was 2.05 m), the fact that the crest of the dike is maintained at 5.04 m means that the view remains unobstructed, indicating a better connectivity between the coastal protection and the sea. The effectiveness of this solution can also be seen at Point 9, where the water depth is reduced from 2.5 m (baseline scenario) to 1.8 m.

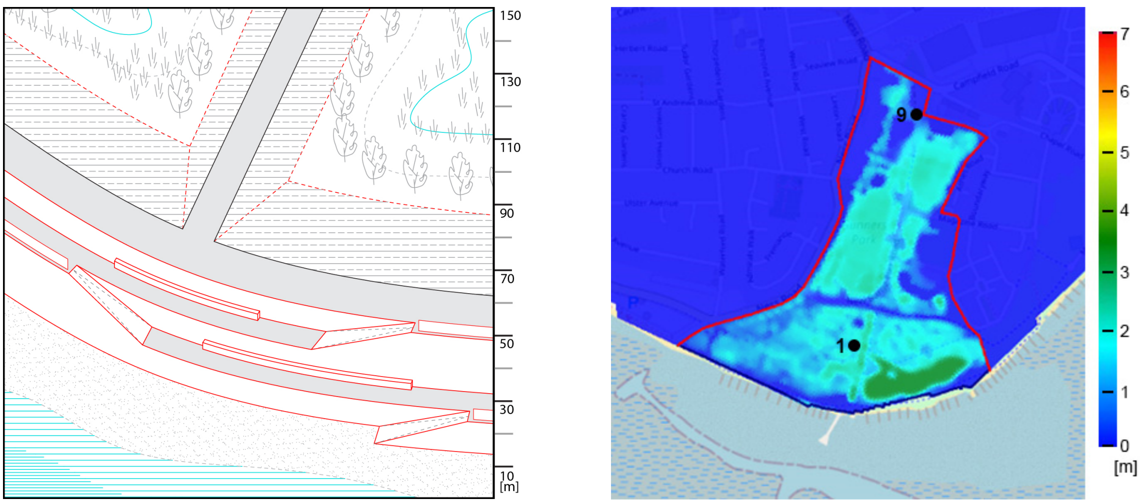


(**a**) (**b**)

Figure 7. (**a**) Axonometric view for the scenario with rocks on the revetment of the dike and (**b**) numerical simulations (water depth map). Stored volume in Gunners Park is of 1,229,801 m^3. Note that the red contour line represents the boundary of the domain.

4.3. Stepped Revetment

A relatively new and innovative alternative is the use of stair-shaped (or stepped) revetments. While stepped chutes are widely used as energy dissipators in hydraulic structures [49,50], their application to coastal defences is limited and their performance has not yet been incorporated in currently available guidelines. Despite this, recent studies have shown that stepped revetments can be an effective way to reduce wave overtopping [28,51]. This last study performed full-scale laboratory experiments and proposed a new expression for the roughness influence factor that can be applied to formulae proposed by the EurOtop manual [25]. These experiments resulted in an influence factor of roughness (γ_f) between 0.43 and 0.73. Based on this study, herein, a factor (γ_f) of 0.70 is conservatively chosen for the stepped revetment and used to compute the overtopping discharge for the numerical simulations. The results for this configuration are presented in Figure 8b, revealing water depths at point 1 ranging between 0 and 1.51 m, in line with those previously obtained for the seawall. This is a promising result because it shows that the use of steps along the dike's seaward revetment can be as effective as raising the seawall, while maintaining the same crest height. The use of stepped slopes also reduces the total water volume inside Gunners Park to 519,243 m^3, preventing the water from reaching Point 9. The use of steps also opens the possibility of integration within the built environment.

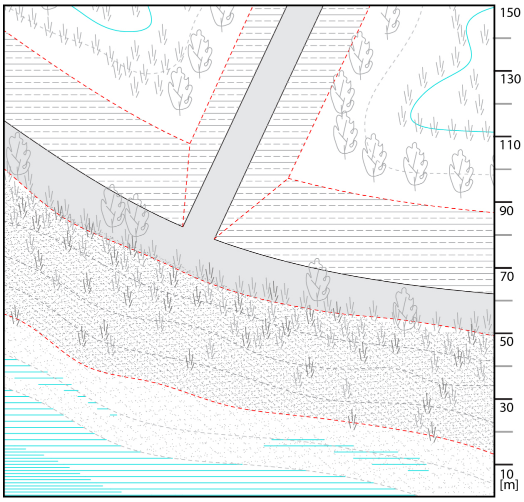


(**a**) (**b**)

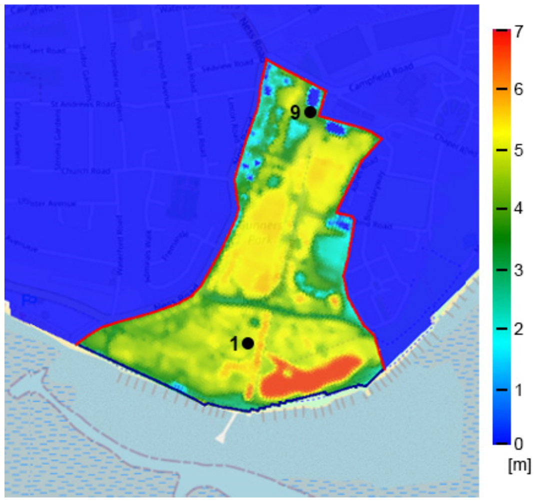
Figure 8. (**a**) Axonometric view for the scenario with stepped revetment and (**b**) numerical simulations (water depth map). Stored volume in Gunners Park is of 519,243 m^3. Note that the red contour line represents the boundary of the domain.

4.4. Vegetation

The fourth alternative is to use vegetation to reduce overtopping at the sea dike. Nature-based solutions for coastal protection is an active research topic and, therefore, no general guidelines are available yet. Here, the study by van Wesenbeeck et al. [41] was used as a reference, in which large-scale flume experiments were used to investigate the dissipation of waves by placing willow trees in front of a dike. Van Wesenbeeck et al. concluded that the willow trees reduce wave and run-up heights while hardly being damaged, even for wave heights of up to 2.5 metres. The most extreme wave conditions tested by van Wesenbeeck et al. are comparable to those determined by Wüthrich et al. [22] for Southend-on-Sea. Hence, for this study, it is assumed that placing vegetation along the coastline will dampen the incoming waves by 5%, which is slightly less than the results found by van Wesenbeeck et al. [41]. The overtopping discharge is then computed using this reduced wave height, which leads to the results of the numerical simulations presented in Figure 9b. The water levels still show values up to 6.5 m, which is higher compared to configurations with rougher revetments (e.g., rocks or steps). More specifically, the values in the most inland part of Gunners Park (3.3 m at Point 9) are still relatively high, which means that a combination of these measures is needed to optimise technical effectiveness and spatial quality and functionality.



(**a**)



(**b**)

Figure 9. (**a**) Axonometric view for the scenario with integration of vegetation on the revetment of the dike and (**b**) numerical simulations (water depth map). Stored volume in Gunners Park is of 1,867,849 m^3. Note that the red contour line represents the boundary of the domain.

5. Discussion

Climate change and sea level rise are expected to affect the coastline of southeast England. Latest predictions reveal a potential sea-water level rise of 0.7 m along the coast of Southend-on-Sea, which means that coastal protections around Shoeburyness need to be redesigned to prevent flooding during future storms. From a purely engineering perspective, raising the seawall from its current level of 5.04 m (Ordinance Datum Newlyn) to 5.40 represents the most effective solution; however, this approach negatively impacts the accessibility of the beach from the city. It also might include the redefinition on a bigger scale of the mobility (cars, bikes and pedestrians) system that currently lays on top of the main dike. In addition, this hinders the functionality of the coastline as public space and green corridor as envisaged by the 2050 Vision for the Essex Green Infrastructure Strategy, asking for the development of new integrated solutions. A possibility to limit the overtopped volumes entering Gunners Park includes the enhancement of the roughness on the seaward side of the existing coastal protection. Elements commonly used in coastal engineering include rocks (rubble-mount breakwaters), stepped revetments and, most recently, vegetation like marshlands or constructed wetlands. Numerical simulations were used to compare the effectiveness of these solutions in the case of Gunners Park taking into the account that a certain amount of water can be accepted and stored withing the retention area. A summary of the engineering performance (water depths and volumes), the spatial functionality and quality, and the level of integration of the single measures within the landscape is presented in Table 1.

Table 1 shows that rocks and stepped revetment lead to results comparable to the 'business as usual' strategy of raising the seawalls while providing different opportunities to enhance the multifunctionality of the dike. Rocks, not providing an even and safe surface, are not always suitable for activities like walking or sunbathing. However, because of the geometrical complexity, distributed gaps, voids, and small chambers might provide new space for the colonization of species of maritime flora and fauna, increasing the biodiversity of the engineered coast. The use of local material, as well as specific spatial compositions (curves and slopes) of the revetment, can implement the aesthetic quality of the structure that helps in perceiving the dike as part of the landscape, in connection with the surroundings. On the other hand, stepped revetments offer many opportunities to implement activities that usually are done in places like public parks, coastal promenades or waterfronts. Spatial design can provide numerous alternatives when developing linear spaces in which the use of fixed elements (like stairs, ramps, benches or parapets) might be employed to further enhance the roughness of the dike. On the stepped revetment, elements like small cabins or food stands can access the area, contributing to the commercial and recreational program of the Gunners Park. It goes without saying that the seasonal access to the dike needs to be carefully planned and monitored with appropriate safety standards, measures and evacuation plans that can be integrated into the design. The use of vegetation has limited impact on the overtopping discharge during extreme events, but its application has a deeper influence on the ecological dimension of these coastal protection measures, especially during more common chronicle events. Native flora can be used to enhance biodiversity and repristinate the land–water continuity that is currently interrupted by coastal protection infrastructure. As it happens in the case of rocks, vegetation might provide new habitat for fauna. It might offer opportunities for public activities in designated and limited areas to preserve the natural development of the species.

Table 1. Summary of maximum water levels inside Gunners Park at Point 1 and Point 9, defined in the previous figures.

Measure	Water Depth at Point 1 [m]	Water Depth at Point 9 [m]	Stored Volume [m^3]	Spatial Functionality and Quality	Integration of Measures within the Urban Landscape
Seawall	2.05	0.52	717,285	The wall obstructs the view and access to beach; it requires the redefinition of the mobility systems	The wall enhances the separation between the engineering protection infrastructure and the urban settlement
Rocks	3.32	1.79	1,229,801	Rocks are not accessible to humans but provide habitats for maritime flora and fauna	The use of local material (rocks or stone) may result as a good solution to aesthetically integrate the dike within the landscape
Steps	1.51	-	519,243	Steps might provide new space for public functions when no extreme events occur	Steps might enhance the use of the dike in its multifunctional dimension while still appearing as a separation between land and water
Vegetation	4.83	3.29	1,867,849	Vegetation provides a new habitat for fauna; limited access for activities	Native flora can recreate the lost ecological and functional land–water connection

It is important to mention that the results of the numerical simulations are based on the use of a single solution along the entire coastline of Gunners Park (approx. 1000 m). This has been methodologically carried out to test the performance of the specific measure. However, it might represent a limit, especially when discussing the possible implementation of such measures in complex environments in which legal, economic, safety and spatial aspects overlap. The goal of integrating the dike in the urban environment calls for more diverse and flexible solutions that can adapt to the specific spatial, safety and ecological needs of the current coast of Shoeburyness. Four combinations of the previous analysed configurations for the dike revetments have been identified and briefly discussed to understand the impact of the combination on the general performance synthetized in Table 2.

Table 2. Summary of maximum water levels at Point 1 and Point 9 inside Gunners Park for the spatial configurations with combined roughness. The percentage refers to the length of the section of the total coastal dike around Gunners Park (~1000 m).

Spatial Configuration	Max Water Level at Point 1 [m]	Max Water Level at Point 9 [m]
25% wall (5.4 m) + 25% rock revetment + 25% stepped revetment + 25% vegetation	2.97	1.44
50% step + 50% vegetation	3.23	1.70
50% seawall (5.4 m) + 50% steps	1.78	0.25
50% rock + 50% vegetation	4.07	2.54

The above-mentioned configurations were tested with Delft 3D, where the overtopping discharge was computed for each segment of the coastline and used as inputs in the numerical simulations. The results revealed some very interesting and encouraging results, showing that combining various solutions can be a very effective way of reducing overtopping discharge, and therefore the volumes that need to be stored during extreme storms. In particular, the combination of 50% seawall (5.4 m) + 50% steps was shown to be the most effective in reducing the water levels inside Gunners Park. With water levels of 0.25 m at point 9, this opens up to the possibility for new housing developments, as well as new activities that would be hindered by the 2.54 m needed for the configuration with 50% rock revetment + 50% vegetation. It is important to mention that the solutions in Table 2 were chosen as examples and that other combinations of lengths and roughness are possible, depending on the level of integration within the urban landscape that is desired.

6. Conclusions

Based on the case study of Southend-on-Sea (UK), this research focuses on innovative and more diverse approaches to deal with coastal protection that takes into the account the spatial quality and ecological value of the Shoeburyness area. It resulted to be beneficial in supporting the academic development of cooperation among disciplines, specifically engineering and spatial design. Basically, interdisciplinary research and design call for new forms of coexistence between the built environment and natural spaces. Climate change makes it urgent to transition away from the traditional approaches used to shape and design urban areas and engineered infrastructure. The floodable Gunners Park is a pilot designed, in its interdisciplinary setting, to understand how cohabitation with water can be achieved, while still providing quality to the space and high levels of safety for the citizens. As the results show, the goals of adapting to climate change while still protecting vulnerable urbanized areas can be combined with other human activities or natural land use. Furthermore, the study demonstrates that coastal protection needs to be planned and designed considering long time frames (climate projections, standards of protection, returning periods, etc). The implemented measures have effect in the long term on the space in quality and the use of the protected areas and are not always adaptable to societal, economic and climate changes and needs. This means that the planning and the design of water protection infrastructures solely within the field of engineering is not favourable anymore. The interdisciplinary design presented in the paper illustrates how on-the-way collaborative approaches can contribute to innovation and make use of the best of both disciplines.

This paper addresses a peculiar niche that deals with the design of the roughness of coastal dikes and how this factor can be used both to increase protection from coastal flooding and provide opportunities for developing new public spaces. More specifically, this research used numerical simulations to investigate the use of seawalls, rocks and stepped revetments, and vegetation to reduce overtopping during extreme events, affecting the volume of water entering the floodable park. Overall, the preliminary results of this research show that targeted flood protection standards can be achieved through a combination of measures that have the potential to enhance the systemic connectivity between the sea and the city, as well as a better integration of the infrastructures with the urbanized areas and the natural landscape. However, the study presents some limitations. A series of assumptions were made when defining the roughness coefficient (γ_f) to simulate overtopping water during coastal storms in the four different conditions. Current methods, tools and manuals that support the numerical modelling of floods refer to hypothetical coastal settings that do not always reflect the complexity of the potential design for the dike revetment. For examples, the use of vegetation for coastal protection is a relatively new research topic and specific guidelines are currently not yet available. The issue becomes even more challenging when integrating the numerous possibilities offered by the spatial design that might positively affect the engineering performance of longer segments of coastal dikes. In conclusion, the paper demonstrates the urgency of advancing collaboration within the disciplines to find innovative ways to deal with the challenges posed by climate change and sea level rise. Interdisciplinary design should not only be embedded in our current academic activity and practise during final design phases, but also during the initial fundamental stages of research, analysis, testing and modelling.

Author Contributions: Conceptualization, L.I. and D.W.; methodology, D.T, D.W. and L.I.; software, D.T. and D.W.; validation, D.T., D.W., L.I. and F.H.; formal analysis, D.T., D.W. and L.I.; investigation, L.I. and D.W.; resources, D.T., D.W., L.I. and F.H.; data curation, D.T. and D.W.; writing—original draft preparation, D.T., D.W., L.I. and F.H.; writing—review and editing, L.I. and D.W.; visualization, L.I. and D.T.; supervision, L.I., D.W. and F.H. All authors have read and agreed to the published version of the manuscript.

Funding: This project was funded as part of the European project Interreg 2 Seas Mers Zeeen, Sustainable and Resilient Coastal Cities (SARCC) [2S06-050].

Acknowledgments: The TU Delft research team was composed of F. Hooimeijer, D. Wuthrich, J. Bricker, A. Diaz, Q. Ke, A. Bortolotti, L. Iuorio and D. Teng. The authors would like to acknowledge the participation and contribution of additional partners, including John Bennett (municipality of Southend-on-Sea, UK) and Gary Momber (Maritime Archaeology Trust, UK).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. IPCC. Climate Change. Synthesis Report. Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. 2023. Available online: https://www.ipcc.ch/report/sixth-assessment-report-cycle/ (accessed on 2 January 2024).
2. Lowe, J.A.; Bernie, D.; Bett, P.E.; Bricheno, L.; Brown, S.; Calvert, D.; Clark, R.T.; Eagle, K.E.; Edwards, T.; Fosser, G.; et al. *UKCP18 Scientific Report*; Met Office: Exeter, UK, 2018. Available online: https://www.metoffice.gov.uk/pub/data/weather/uk/ukcp18/science-reports/UKCP18-Overview-report.pdf (accessed on 2 January 2024).
3. US Department of Commerce; National Oceanic and Atmospheric Administration. Global and Regional Sea Level Rise. Scenarios for the United States. Scientific Report. 2022. Available online: https://oceanservice.noaa.gov/hazards/sealevelrise/sealevelrise-tech-report-sections.html (accessed on 2 January 2024).
4. KNMI. Klimaatscenario's Voor Nederland. Scientific Report. 2023. Available online: https://www.knmi.nl/kennis-en-datacentrum/achtergrond/knmi-23-klimaatscenario-s-voor-gebruikers/ (accessed on 2 January 2024).
5. CRED Center for Research on the Epidemiology of Disasters. *The Human Cost of Disasters: An Overview of the Last 20 Years (2000–2019)*; UN Office for Disaster Risk Reduction: Geneva, Switzerland, 2020; Available online: https://www.preventionweb.net/files/74124_humancostofdisasters20002019reportu.pdf?_gl=1*1t4cp8b*_ga*OTI2NDU2NTMuMTcwNDYyOTQ0OQ..*_ga_D8G5WXP6YM*MTcwNDYyOTQ1MS4xLjAuMTcwNDYyOTQ1MS4wLjAuMA.. (accessed on 2 January 2024).
6. Hood, G. Indirect Environmental Effects of Dikes on Estuarine Tidal Channels: Thinking Outside of the Dike for Habitat Restoration and Monitoring. *Estuaries* **2004**, *27*, 273–282. [CrossRef]
7. Guerry, A.D.; Silver, J.; Beagle, J.; Wyatt, K.; Arkema, K.; Lowe, J.; Hamel, P.; Griffin, R.; Wolny, S.; Plane, E.; et al. Protection and restoration of coastal habitats yield multiple benefits for urban residents as sea levels rise. *Urban Sustain.* **2022**, *2*, 13. [CrossRef]
8. Doelle, M.; Puthucherril, T.G. Nature-based solutions to sea level rise and other climate change impacts on oceanic and coastal environments: A law and policy perspective. *Nord. J. Bot.* **2021**, *1*, 1. [CrossRef]

9. Lafortezza, R.; Chen, J.; Van Den Bosch, C.K.; Randrup, T.B. Nature-based solutions for resilient landscapes and cities. *Environ. Res.* **2018**, *165*, 431–441. [CrossRef] [PubMed]
10. van Loon-Steensma, J.M.; Schelfhout, H.A. Wide Green Dikes: A sustainable adaptation option with benefits for both nature and landscape values? *Land Use Policy* **2017**, *63*, 528–538. [CrossRef]
11. Leone, E.; Kobayashi, N.; Francone, A.; Bartolo, S.D.; Strafella, G.R. Use of Nanosilica for Increasing Dune Erosion Resistance during a Sea Storm. *J. Mar. Sci. Eng.* **2021**, *9*, 620. [CrossRef]
12. Lawlor, P.; Jackson, D.W.T. A Nature-Based Solution for Coastal Foredune Restoration: The Case Study of Maghery, County Donegal, Ireland. In *Human-Nature Interactions*; Misiune, I., Depellegrin, D., Egarter Vigl, L., Eds.; Springer: Cham, Switzerland, 2022.
13. Hanley, M.E.; Hoggart, S.P.G.; Simmonds, D.J.; Bichot, A.; Colangelo, M.A.; Bozzeda, F.; Heurtefeux, H.; Ondiviela, B.; Ostrowski, R.; Recio, M.; et al. Shifting sands? Coastal protection by sand banks, beaches and dunes. *Coast. Eng.* **2004**, *87*, 136–146. [CrossRef]
14. Marijnissen, R.; Kok, M.; Kroeze, C.; van Loon-Steensma, J. Re-evaluating safety risks of multifunctional dikes with a probabilistic risk framework. *Nat. Hazards Earth Syst. Sci.* **2019**, *19*, 737–756. [CrossRef]
15. Anvarifar, F.; Zevenbergen, C.; Thissen, W.; Islam, T. Understanding flexibility for multifunctional flood defences: A conceptual framework. *J. Water Clim. Chang.* **2017**, *7*, 467–484. [CrossRef]
16. Anvarifar, F.; Oderkerk, M.; van der Horst, B.R.; Zevenbergen, C. Cost-effectiveness study on preventive interventions: A survey of multifunctional flood defences. In *Comprehensive Flood Risk Management: Research for Policy and Practice*; Klijn, F., Schweckendiek, T., Eds.; CRC Press: London, UK, 2013.
17. de Jong, J.; van Rooy, P.T.; Hosper, S.H. Living with water: At the cross-roads of change. *Water Sci. Technol.* **1995**, *31*, 393–400. [CrossRef]
18. Schoeman, J.; Allan, C.; Finlayson, C.M. A new paradigm for water? A comparative review of integrated, adaptive and ecosystem-based water management in the Anthropocene. *Int. J. Water Resour. Dev.* **2004**, *30*, 17–30. [CrossRef]
19. Hurlimann, A.; Wilson, E. Sustainable Urban Water Management under a Changing Climate: The Role of Spatial Planning. *Water* **2018**, *10*, 546. [CrossRef]
20. Iuorio, L.; Bortolotti, A. Integrated coastal flood design strategies. Changing paradigm in flood risk management. *Int. Forum Urban.* **2021**. [CrossRef]
21. Franco-Torres, M.; Rogers, B.C.; Harder, R. Articulating the new urban water paradigm. *Crit. Rev. Environ. Sci. Technol.* **2021**, *51*, 2777–2823. [CrossRef]
22. Wüthrich, D.; Teng, D.; Ke, Q.; Diaz, A.; Bortolotti, A.; Iuorio, L.; Hooimeijer, F. Sustainable and Resilient Coastal Cities (SARCC): Interdisciplinary flood protection strategies in Southend-on-Sea (UK). In Proceedings of the 39th IAHR World Congress, Granada, Spain, 19–24 June 2022.
23. Hooimeijer, F.; Diaz, A.; Bortolotti, A.; Ke, Q.; van der Heuvel, J.; Bricker, J. Design & Assessing the flood risk management paradigm shift: An interdisciplinary study of Vlissingen, The Netherlands. *J. Urban.* **2021**. [CrossRef]
24. TAW. *Technical Report Wave Run-Up and Wave Overtopping at Dikes*; Technical Advisory Committee on Flood Defence: Delft, The Netherlands, 2002.
25. Van der Meer, J.W.; Allsop, N.W.H.; Bruce, T.; De Rouck, J.; Kortenhaus, A.; Pullen, T.; Schüttrumpf, H.; Troch, P.; Zanuttigh, B. *Manual on Wave Overtopping of Sea Defences and Related Structures*; An Overtopping Manual Largely Based on European Research, but for Worldwide Application; EurOtop; 2018. Available online: http://www.overtopping-manual.com/assets/downloads/EurOtop_II_2016_Pre-release_October_2016.pdf (accessed on 2 January 2024).
26. van Gent, M.R.; Wolters, G.; Capel, A. Wave overtopping discharges at rubble mound breakwaters including effects of a crest wall and a berm. *Coast. Eng.* **2022**, *176*, 104151. [CrossRef]
27. Chen, W.; Van Gent, M.R.A.; Warmink, J.J.; Hulscher, S.J.M.H. The influence of a berm and roughness on the wave overtopping at dikes. *Coast. Eng.* **2020**, *156*, 103613. [CrossRef]
28. Schoonees, T.; Kerpen, N.B.; Schlurmann, T. Full-scale experimental study on wave overtopping at stepped revetments. *Coast. Eng.* **2021**, *167*, 103887. [CrossRef]
29. Southend-On-Sea, City Council. Available online: https://www.southend.gov.uk/equality-diversity-0/within-southend (accessed on 2 January 2024).
30. Southend-On-Sea Borough Council. *Character Study*; Urban Practitioners: Southend-On-Sea, UK, 2011.
31. AECOM. *South Essex Level 1 Strategic Flood Risk Assessment*; Final Report; 2018. Available online: https://localplan.southend.gov.uk/sites/localplan.southend/files/2019-02/South%20Essex%20Strategic%20Flood%20Risk%20Assessment%20Level%201.pdf (accessed on 2 January 2024).
32. Thames Estuary 2100. *Managing Flood Risk through London and the Thames Estuary*; Report; Environmental Agency: Bristol, UK, 2012.
33. ASELA. *Growth and Recovery Prospectus*; Report; Association of South Essex Local Authorities, 2020. Available online: https://localplan.southend.gov.uk/sites/localplan.southend/files/2021-08/ASELA%20Growth%20and%20Recovery%20Prospectus%2013%20July%202020%20(1).pdf (accessed on 2 January 2024).
34. Essex County Council. Essex Infrastructure Strategy. A Strategy That Champions for High Quality Green Space and Green Infrastructure in Essex. Report. 2020. Available online: https://www.placeservices.co.uk/media/325323/EGIS_MainStrategy_09062020-LR.pdf (accessed on 2 January 2024).

35. Wüthrich, D.; Pfister, M.; Nistor, I.; Schleiss, A.J. Experimental study on forces exerted on buildings with openings due to extreme hydrodynamic events. *Coast. Eng.* **2018**, *140*, 72–86. [CrossRef]
36. Pilarczyk, K. *Dikes and Revetments: Design, Maintenance and Safety Assessment*; Routledge: London, UK, 2017.
37. Hofland, B.; Arefin, S.S.; van der Lem, C.; Van Gent, M.R. Smart rocking armour units. In Proceedings of the 7th International Conference on the Application of Physical Modelling in Coastal and Port Engineering and Science, Coastlab 18, Santander, Cantabria, Spain, 22–26 May 2018.
38. Vieira, F.; Taveira-Pinto, F.; Rosa-Santos, P. Single-layer cube armoured breakwaters: Critical review and technical challenges. *Ocean. Eng.* **2020**, *216*, 108042. [CrossRef]
39. Vuik, V.; Jonkman, S.N.; Borsje, B.W.; Suzuki, T. Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes. *Coast. Eng.* **2016**, *116*, 42–56. [CrossRef]
40. Maza, M.; Lara, J.L.; Losada, I.J. Experimental analysis of wave attenuation and drag forces in a realistic fringe Rhizophora mangrove forest. *Adv. Water Resour.* **2019**, *131*, 103376. [CrossRef]
41. van Wesenbeeck, B.K.; Wolters, G.; Antolínez, J.A.; Kalloe, S.A.; Hofland, B.; de Boer, W.P.; Bouma, T.J. Wave attenuation through forests under extreme conditions. *Sci. Rep.* **2022**, *12*, 1884. [CrossRef]
42. Pullen, T.; Allsop, N.W.H.; Bruce, T.; Kortenhaus, A.; Schüttrumpf, H.; Van der Meer, J.W. *EurOtop Wave Overtopping of Sea Defences and Related Structures*; Assessment Manual; 2007. Available online: https://www.researchgate.net/publication/256197945_EurOtop_Wave_Overtopping_of_Sea_Defences_and_Related_Structures_Assessment_Manual (accessed on 2 January 2024).
43. Church, J.A.; Clark, P.U.; Cazenave, A.; Gregory, J.M.; Jevrejeva, S.; Levermann, A.; Merrifield, M.A.; Milne, G.A.; Nerem, R.S.; Nunn, P.D.; et al. Sea Level Change. In *Climate Change 2013: The Physical Science Basis*; Contribution of Working Group 1 to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2013.
44. Palmer, M.; Howard, T.; Tinker, J.; Lowe, J.; Bricheno, L.; Calvert, D.; Edwards, T.; Gregory, J.; Harris, G.; Krijnen, J.; et al. UKCP18. Marine Report. 2018. Available online: https://www.metoffice.gov.uk/binaries/content/assets/metofficegovuk/pdf/research/ukcp/ukcp18-marine-report-updated.pdf (accessed on 2 January 2024).
45. Meinshausen, M.; Smith, S.J.; Calvin, K.V.; Daniel, J.S.; Kainuma, M.L.T.; Lamarque, J.-F.; Matsumoto, K.; Montzka, S.A.; Raper, S.C.B.; Riahi, K.; et al. The RCP Greenhouse Gas Concentrations and their Extension from 1765 to 2300. *Clim. Chang.* **2013**, *109*, 213. [CrossRef]
46. Pranzini, E. Coastal erosion and shore protection: A brief historical analysis. *J. Coast. Conserv.* **2018**, *22*, 827–830. [CrossRef]
47. van den Hoven, K.; Kroeze, C.; van Loon-Steensma, J.M. Characteristics of realigned dikes in coastal Europe: Overview and opportunities for nature-based flood protection. *Ocean. Coast. Manag.* **2022**, *222*, 106116. [CrossRef]
48. Marijnissen, R.J.C.; Kok, M.; Kroeze, C.; van Loon-Steensma, J.M. Flood risk reduction by parallel flood defences. Case-study of a coastal multifunctional flood protection zone. *Coast. Eng.* **2021**, *167*, 103903. [CrossRef]
49. Chanson, H. *The Hydraulics of Stepped Chutes and Spillways*; Balkema: Lisse, The Netherlands, 2001.
50. Wüthrich, D.; Chanson, H. Hydraulics, air entrainment, and energy dissipation on a Gabion stepped weir. *J. Hydraul. Eng.* **2014**, *140*, 04014046. [CrossRef]
51. Kerpen, N.B.; Schoonees, T.; Schlurmann, T. Wave overtopping of stepped revetments. *Water* **2019**, *11*, 1035. [CrossRef]