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Sustainable and Resilient Coastal Cities (SARCC)
Interdisciplinary Flood Protection Strategies for Southend-on-Sea (UK)

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DOI
10.3850/IAHR-39WC252171192022518

Publication date
2022

Document Version
Final published version

Published in
Proceedings of the 39th IAHR World Congress (Granada, 2022)

Citation (APA)
Wüthrich, D., Teng, D., Ke, Q., Diaz, A., Bortolotti, A., Iuorio, L., & Hooimeijer, F. (2022). Sustainable and Resilient Coastal Cities (SARCC): Interdisciplinary Flood Protection Strategies for Southend-on-Sea (UK). In M. Ortega-Sanchez (Ed.), *Proceedings of the 39th IAHR World Congress (Granada, 2022): From Snow to Sea* (pp. 6370-6379). IAHR. https://doi.org/10.3850/IAHR-39WC252171192022518

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doi://10.3850/IAHR-39WC2521716X2022518

Sustainable And Resilient Coastal Cities (SARCC): interdisciplinary flood protection strategies for Southend-on-Sea (UK)

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Abstract

In a world influenced by climate change and consequently sea-level rise, extreme floods are expected to become more frequent in the future, representing a serious threat for riverine and coastal settlements. Therefore, flood protection is a large component of climate adaptation and should be closely related to other measures of climate adaptation and societal needs. In this context, SARCC (Sustainable And Resilient Coastal Cities) supports the use of integrated Nature Based Solutions into coastal management, urban planning and design, integrating them into existing infrastructure and flood defenses. This paper will focus on the strategy developed for Southend-On-Sea (UK), presenting the different approaches that were used to manage coastal flooding and make it part of a long-term large scale urban development strategy. In particular, this study estimated overtopping discharges during extreme storm conditions and analyzed their inland propagation using Delft3D FM numerical simulations. Based on these results, mitigation, and adaptation measures as a part of the spatial strategy were developed through a joint collaboration of hydraulic engineers, urban designers, maritime archaeologists and local authorities, pointing out the strength of interdisciplinary approaches for reliable and well-integrated flood protection strategies. Important highlight of the study is how flood risk management is integrated in spatial planning and how hydraulic engineering modeling is directly use as indicators to make spatial design decisions.

Keywords: Flood protection, hydraulic engineering, urban planning, resilient cities, interdisciplinary approach.

1. INTRODUCTION

In a world influenced by climate change and sea-level rise, extreme flow conditions represent a serious threat for riverine and coastal settlements. Already today, flood is the most common natural disaster in the world with more than 3,000 events between 1995 and 2015, representing 43% of all calamities (CRED 2015). Recent floods in Germany, Belgium and the Netherlands in summer 2021 proved conclusively the destructive nature of these events, responsible for severe damages to buildings and critical infrastructure (Korswagen et al. 2022). Similarly, with climate change and sea level rise, extreme coastal floods are expected to become more frequent in the future, exposing more people to these catastrophes. Therefore, flood protection is a large component of climate adaptation and should be closely related to other measures of climate adaptation and societal needs in urban coastal areas. In contrast with previous hard and invasive measures, recent research developed Nature-Based Solutions (NBS), *i.e.* actions that are inspired and supported by nature and are used to tackle societal challenges such as climate change whilst providing both benefits to humans and nature. However, practical applications of NBS remain, so far, limited and SARCC (Sustainable And Resilient Coastal Cities) investigated seven case studies in the North Sea and English Channel, supporting the use of NBS into coastal management urban planning and design, integrating them into – or replacing, existing grey infrastructure and flood defenses. This paper will focus on one of these pilot locations: Southend-On-Sea (UK), presenting the different approaches that were used to manage coastal flooding through an interdisciplinary approach, including hydraulic engineers, urban designers, maritime archaeologists and local authorities.

Southend-On-Sea is a coastal town in southeastern Essex (England), on the north side of the Thames estuary, ~64 km east of London (Figure 1). In the recent decades, Southend-On-Sea has become a popular summer holiday destination, incentivizing developments along the coastline and attracting a large number of visitors. However, the ground levels around 2-3m Ordnance Datum Newlyn (ODN) make this area more

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vulnerable to coastal flooding, as shown in Figure 1, where three main areas seem to be most affected. Among these, the Shoeburyness area, located in the south-eastern corner (Figure 1), was identified as the main pilot, because potential NBS would improve safety to residential properties, beach-front businesses and critical infrastructure, including roads, railway, and utilities services. The current defenses against coastal flooding in Southend-On-Sea mainly consist of a seawall along the coastline, with safety standards with a return period of ~100 years, thus pointing out the need for additional measures, which are the objective of the present study.

Figure 1. Map of Southend-On-Sea with area selected for the present case study. (AECOM 2017)

2. METHODOLOGY

The present study focuses on protection measure against coastal flooding, and its combined occurrence with an inland (riverine) flood is herein excluded. To minimize flood damages, the strategy developed for Southend-On-Sea involved using Gunners park and the adjacent green area (~400,000 m^2) to act as a flood diversion area, collecting the possible overtopping volumes coming from an extraordinary sea storm, thus protecting buildings, houses and other infrastructures.This approach is similar to that proposed by Hooimejier et al. (2022) for Vlissingen (Netherlands). The essence of the NBS in both cases is the acceptance of water coming over the existing dike into the area and reducing the risk by reducing the consequences (and not the probability) as a part of a changing paradigm. The objective of this study is therefore to estimate overtopping discharges during extreme conditions and analyze their propagation using numerical simulations. In particular, this study focusses on the hydraulic engineering modelling and design aspects that will later be implemented in the design of coastal areas, as hinted in Section 4. This has been crucial information for the development of the long term, large scale spatial strategy.

In particular, the following chapters discuss the modelling and effectiveness of various flood-protection measures in the Shoeburyness area of Southend-On-Sea. First the geometric input of the outer seawall, wave and tidal conditions are elaborated. Based on this, the critical overtopping discharge is determined out of several combinations with a joint probability of 1/200. Combined with a synthetic storm derived from previous events, these data will act as input for Delft3D Flexible Mesh (FM) models, simulating various scenarios corresponding to different flood protection measures. Results derived from these numerical simulation provide the starting point for an integrated design of flood defenses and urban developments.

2.1 Overtopping discharge

The overtopping discharge highly depends on the geometry of the seawall. A typical example of the cross section at Shoeburyness, with typical crown wall profiles against wave overtopping presented in Figure 2. Seawalls include an inclined revetment with a slope of 1:2.5, reaching an elevation of +4.25 m above the toe, *i.e.* the beach. On top of the revetment, a crown wall is installed reaching an elevation of 5.04 m.

According to EurOtop (2018), in the UK the overtopping conditions are calculated for a return period of 200 years. Table 2 shows the average overtopping discharge rate q_m computed for the 6 combinations of water levels and wave conditions having a joint probability of 1/200 (Pullen et al. 2007). Due to limited data available for the crest height of seawall, the level of crest was assumed to be uniformly distributed at an elevation of 5.04 m ODN. Note that Sea Level Rise (SLR) has not yet been taken into account in the water levels of Table 1 and SLR in the calculations and modelling is conservatively assumed to +0.6 m by 2100 (HM Government 2017).

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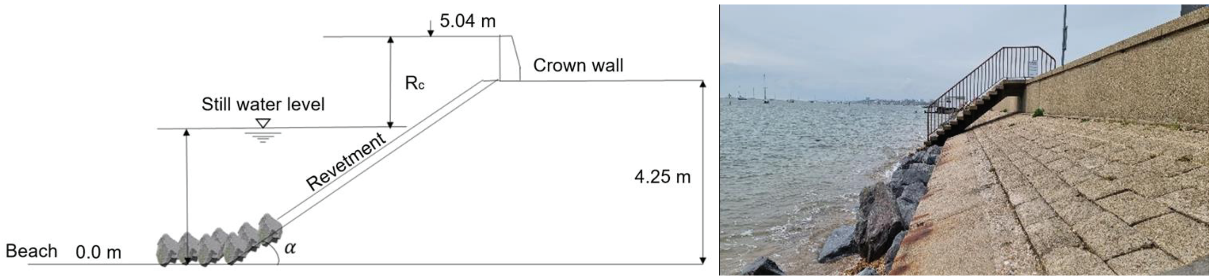

Figure 2. Geometric input of the outer sea wall at Shoeburyness (Southend-On-Sea, UK)

Table 1. Wave and water level conditions with a joint probability of 1/200. SLR : Sea Level Rise. Note that q_m is the mean overtopping discharge over the whole storm duration.

Condition	Water Level [m ODN]	$H_{m,0}$ [m]	$T_{m-1,0}$ [s]	q_m *(no SLR)* [m³/s/m]	q_m *(with SLR)* [m³/s/m]
S1	2.4	1.32	5.8	0.00016	0.00071
S2	2.9	1.6	5.4	0.00225	0.00673
S3	3.35	1.55	5.0	**0.00359**	**0.01049**
S4	3.75	1.25	4.5	0.00106	0.00527
S5	4.22	0.95	3.9	0.00028	0.00451
S6	4.7	0.5	2.9	0.00043	0.00480

The overtopping discharge is calculated using the empirical model EurOtop (2018) in Eq. [1] and [2], developed for design or assessment approaches:

$$\frac{q}{\sqrt{gH_{\mathrm{m0}}^3}} = \frac{0.026}{\tan\alpha}\cdot\gamma_b\cdot\xi_{\mathrm{m-1,0}}\cdot\exp\left[-\left(2.5\cdot\frac{R_c}{\xi_{\mathrm{m-1,0}}\cdot H_{\mathrm{m0}}\cdot\gamma_{\mathrm{b}}\cdot\gamma_{\mathrm{f}}\cdot\gamma_{\beta}\cdot\gamma_{\mathrm{v}}}\right)^{1.3}\right] \quad [1]$$

with a maximum of:

$$\frac{q}{\sqrt{gH_{\mathrm{m0}}^3}} = 0.1035\cdot\exp\left[-\left(1.35\cdot\frac{R_c}{H_{\mathrm{m0}}\cdot\gamma_{\mathrm{f}}\cdot\gamma_{\beta}\cdot\gamma^*}\right)^{1.3}\right] \quad [2]$$

Where:
- q the overtopping discharge [m³/s/m]
- H_{m0} the significant wave height [m]
- α angle of the slope of the embankment [rad or °]
- $\xi_{\mathrm{m-1,0}}$ breaker parameter [-]
- R_{c} freeboard [m]
- γ_{b} influence factor for a berm [-]
- γ_{β} influence factor for oblique wave attack [-]
- γ_{f} influence factor for roughness elements on a slope [-]
- γ^* influence factor for a storm wall [-]

The influence factor for the storm wall ($\gamma^* = \gamma_{\mathrm{v}}$) has an applicability range:

$$\gamma^* = \gamma_{\mathrm{v}} = \exp\left(-0.56\frac{h_{\mathrm{wall}}}{R_{\mathrm{c}}}\right) \quad \text{with} \quad 0.08 < \frac{h_{\mathrm{wall}}}{R_{\mathrm{c}}} < 1.00 \quad [3]$$

For certain scenarios (S4, S5, S6 in Table 1), there are points in time when influence factor γ_{v} falls outside of this applicability range. When this happens, the influence factor is conservatively assumed to be 1.

In case of negative freeboard, *i.e.* the water level is higher than the crest of the seawall, the amount of water flowing to the landward side of the structure is partially composed by overflow (q_{overflow}) and partially

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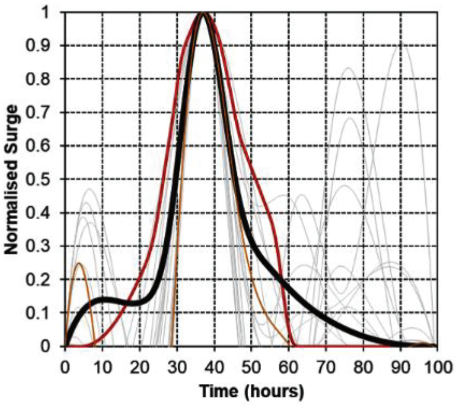
overtopping (q_{overtop}). The EurOtop (2018) suggests the use of Eq. [4] (broad crested-weir) to compute the overflow discharge (q_{overflow}), together with Eq. [2] for the overtopping discharge q_{overtop}, assuming $R_c = 0$.

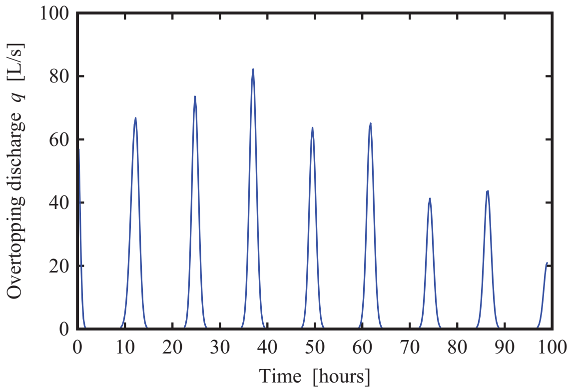
$$q_{\text{overflow}} = 0.54\sqrt{g \cdot |-R_c^3|} \quad [4]$$

Based on these formulae and assumptions, the average overtopping discharges are computed for all six scenarios in Table 1. Results showed that scenario S3 provided the highest discharges, thus representing the most critical.

Following the instruction of coastal flood boundary conditions design in UK, the designed time series of still water level (SWL) for scenario 3 was obtained for a time step of 15 minutes and for a storm period of 100 hours (Environment Agency, 2018). This assumption is based on the design-surge profiles derived in the UK using observed (total sea level) and predicted (tide) sea level data for UK NTGN sites in England, Wales and Scotland. From these data, the 15 largest surge events at each gauge site were extracted and interpolated, as shown in Figure 3a. These skew surge profiles typically had one large surge peak, lasting between 40 and 90 hours. The mid-point level between High Astro Tide (HAT = 3.55 m) and Mean high water spring (MHWS = 3.05m) at Southend-on-Sea is 3.3m. Therefore, we select a 100-hours duration of astronomic tide with a peak value of ~3.3m at sheerness (close to Southend-on-Sea) as base tide. Adding the scaled surge heights to the base tide levels gives the net design event tide curve. The overtopping discharge rate can be then calculated following eq.[1] and [2] and the results for the current scenario (*i.e.* crest level at 5.04 ODN without SLR) is presented in Figure 3b.



(a)



(b)

Figure 3. (a) Synthetic surge at Sheerness (UK). (b) Overtopping discharge over the crest length of 1,000 m and a storm duration of 100 hours.

2.2 Numerical simulations

The numerical simulations were conducted using Delft3D Flexible Mesh (FM), developed by Deltares (Netherlands), which is a hydrodynamic model 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. The same program was previously used by Hooimejier et al. (2022) for the case study of Vlissingen.

To provide reliable results, Delft3D FM needs a minimum of three inputs: 1) the bathymetry/topography, 2) the surface roughness coefficient and 3) the boundary conditions. For the area of Shoeburyness in Southend-On-Sea, an unstructured triangular grid with total number ~0.7 million nodes was built, with a resolution of ~10m. The bed level is assigned with the DSM in the model and the roughness value is uniformly assigned with a Manning coefficient of 0.06 [s/m$^{1/3}$], common for floodplain areas. The boundary condition is a time series of the overtopping discharge along the coastline, previously discussed in Section 2.1. The overtopping is assumed uniform over the whole coastline for a total coast length of 1 km and for comparison with the case-study of Vlissingen, only a storm from 0 to 44 hours is simulated herein.

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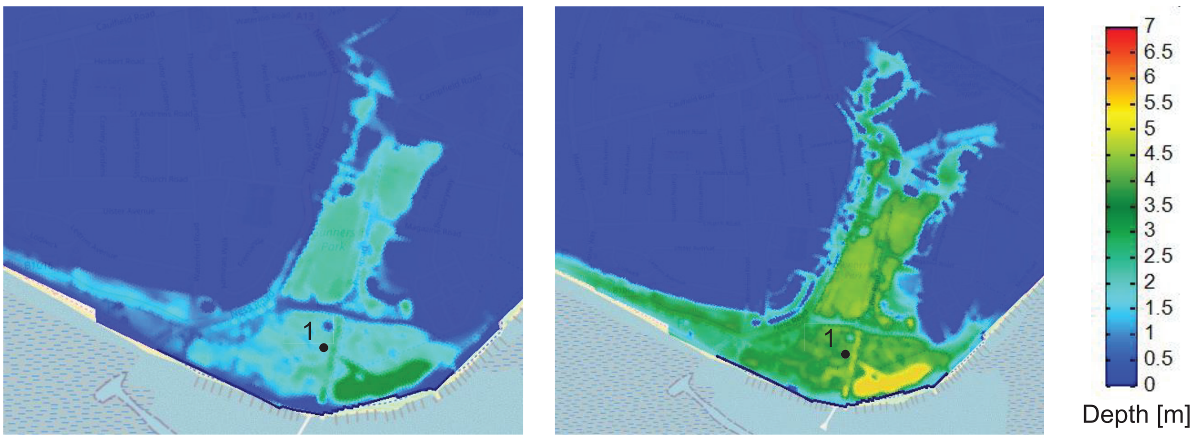
3. RESULTS OF HYDRAULIC ENGINEERING MODELLING

A total of seven different situations were simulated in the hydrodynamic model, varying four main aspects: (1) crest height; (2) presence of sea level rise (SLR); (3) presence of internal barriers around Gunners Park; and (4) roughness of the embankment. This resulted in the following simulations:

i. No measures (current situation), without SLR – Crest at 5.04m
ii. No measures (current situation), with SLR – Crest at 5.04m
iii. With measures (internal barriers), without SLR – Crest at 5.04m
iv. With measures (internal barriers), with SLR – Crest at 5.04m
v. With measures (internal barriers), with SLR – Crest at 5.04m (increased roughness)
vi. With measures (internal barriers), with SLR – Crest at 5.2m
vii. With measures (internal barriers), with SLR – Crest at 5.4m

3.1 No measures (current situation)

These scenarios provide a description of the current *status quo*. Both simulations with and with and without Sea-Level-Rise (*i.e.* +60 cm) were simulated and results are presented in Figure 4. The results show considerable flood depth in the Shoeburyness and the situation is expected to worsen by 2100, if a SLR of +60cm relative to the current situation is considered. Numerical values of flood depths over time are presented in Figure 9, where extremely large values can be observed, up to 4m in Gunners park (Point 1). For this scenario, the absence of secondary defenses allows the flooding water to propagate further inland, affecting the railway lines and Shoebury common road. The flood extent produced by Delft3D FM is compared to the result of modelled climate change flood zones in Shoeburyness due to overtopping by AECOM in 2018 (Figure 1), showing visually similar results. The numerical simulations for this scenario clearly showed that flood-protection measures need to be improved to protect the Shoeburyness area, especially in view of further housing development foreseen in this region.



(a) (b)

Figure 4. Results of Delft3D numerical simulations for the scenario without additional measures: (a) without SLR; (b) with SLR of +60cm by 2100.

3.2 With internal protection barriers

Some additional measures were implemented in the area behind the primary defense line, introducing secondary defenses in the form of protection walls to contain the overtopped water inside the area of Gunners park, therefore limiting its propagating in the surrounding neighborhoods. The water levels obtained after the implementation of this secondary defenses are shown in Figure 5 for both scenarios with and without SLR.

As expected, this configuration resulted in higher water level compared to the previous one without inner barriers (Figure 4). Water levels in point 1 are presented in Figure 9, showing that in case of SLR, these values at the end of the simulated storm can reach up to 5 m. From the urban planning and design perspective, it remains questionable if these protection barriers can be raised any higher than 3 meters and ground excavations are not possible in some parts of Gunners Park because of the presence of underground bombs from WW2. This implies that interventions are needed along the coastline to reduce the overtopping volume.

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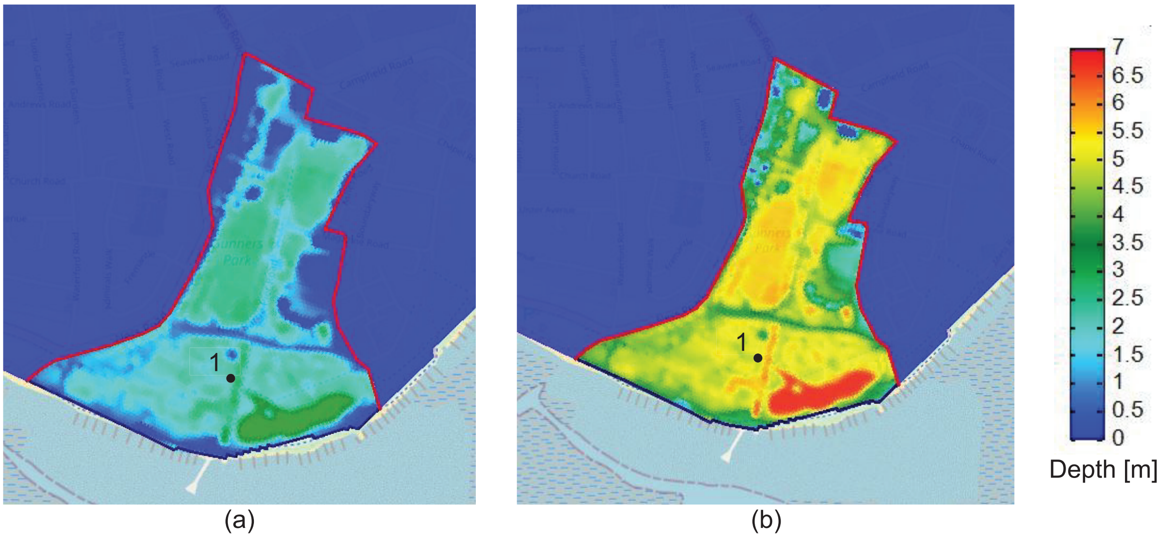


Figure 5. Results of Delft3D FM numerical simulations for the scenarios with additional internal barriers to contain the flooded water in the Gunners Park area: (a) without SLR; (b) with SLR of +60cm by 2100.

3.3 Higher coastal protections

The high-water levels that resulted from the numerical simulations in Section 3.2 called for interventions along the coastline to reduce the overtopping discharge and therefore the water volume stored inside Gunners Park. For this, an increase of the crest height from the current value of 5.04 m ODN to 5.20 m and 5.40 m is simulated, using the same methodology presented in Section 2. For this implementation only the scenarios with SLR +60cm were considered. As expected, the higher crest resulted in lower overtopping discharges and therefore in lower water depths, as shown in Figures 6. This allowed to reduce the water depth at point 1 from 5m to 3.2m and 1.8m, for crest heights of 5.2 m and 5.4 m, respectively.

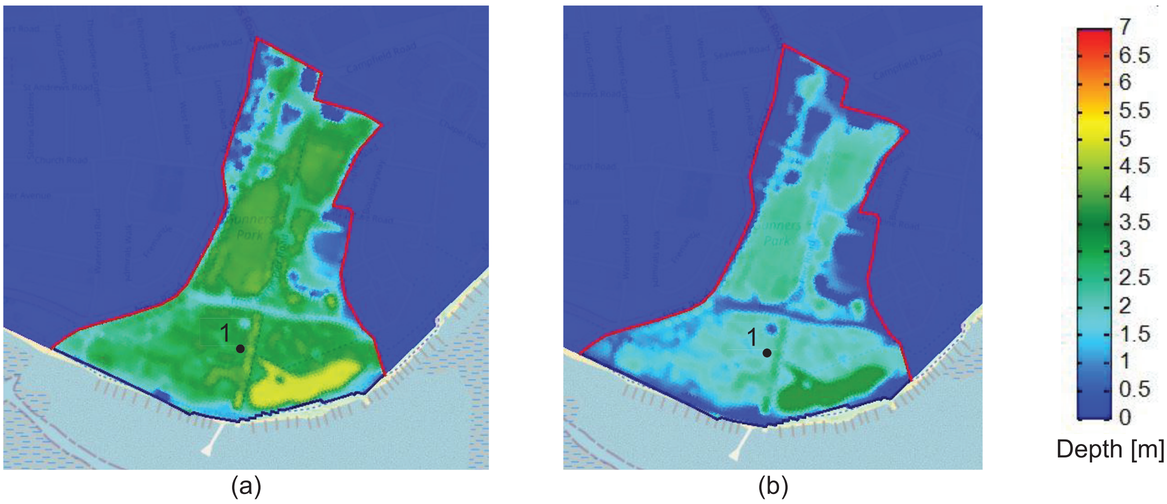


Figure 6. Results of Delft3D FM numerical simulations for the scenarios with additional internal barriers and increased crest heights: (a) crest at 5.2 m; (b) crest at 5.4 m. Both scenarios include SLR of +60cm by 2100.

Building on the concept of raising the primary coastal defense line, as part of a more conceptual exercise, the height of the wall required to reach ‘*zero overtopping*’ was developed and discussed. For the definition of ‘*zero overtopping*’, equation [5] was provided by EurOtop (2018), based on laboratory experiments:

$$\frac{q}{\sqrt{g \cdot H_{\mathrm{m}0}^{3}}} = 10^{-5} \qquad [5]$$

where H_{m0} is the significant wave height and g the gravitational constant. For the S3 scenario in Table 1, Eq. [5] gives overtopping discharge of approximately 0.06 L/s/m. In figure 7 the average overtopping discharge q is plotted against the crest height, taking into account a SLR of +60 cm by 2100. This showed that the discharge of 0.06 L/s/m corresponded to a crest height of 6.5 m, which is 1.46 m higher than the current primary defence line, *i.e.* 5.04 m. It is acknowledge that the concept of '*zero overtopping*' is an unnecessarily safe and extreme scenario, nonetheless, it is still a relevant information in the discussion on how much overtopping to accept versus how much to raise the seawalls.

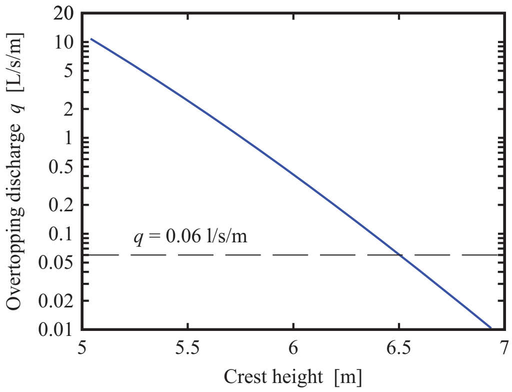


Figure 7. Relationship between overtopping discharge and crest height. Data shows that for an overtopping discharge q < 0.06 L/s/m, a crest height of ~6.5 m is necessary.

3.4 Increased roughness

An additional solution to reduce wave overtopping without increasing the crest height is the use of roughness elements on the outer revetment of the dike. This is in line with the development of Nature Based Solutions (NBS) in the context of the SARCC project. The increased roughness is simulated by using a roughness influence factor γ_f = 0.85 in Eq. [1] and [2], instead of the value for the current embankment γ_f = 1. A value of 0.85 can normally be achieved by using certain configurations of blocks or ribs on the revetment or placed block revetments, with more information can be found in chapter 5.4 of the EurOtop Manual (2018). Examples of potential '*building with nature*' solutions are shellfish reefs or nature rich revetments, as can be found on Ecoshape (2021), however more research on the effectiveness and on the durability of these solutions is needed for a safer and more reliable design.

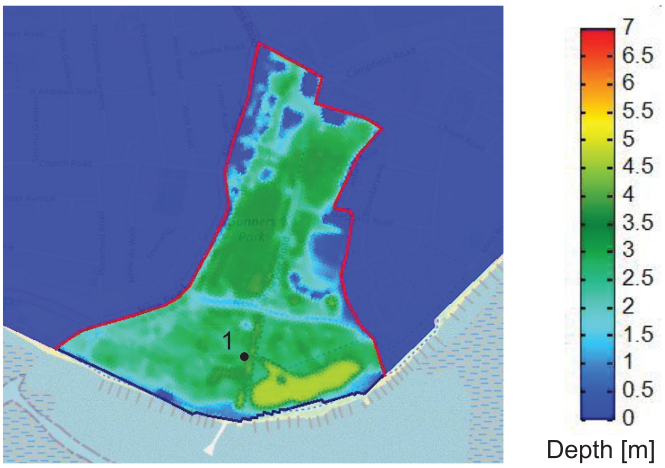


Figure 8. Results of Delft3D FM numerical simulations for the scenario with additional internal barriers and increased roughness on the outer revetment of the dike (γ_f = 0.85), including SLR of +60cm by 2100.

3.5 Discussion

Various configurations were simulated using Delft3D FM. The water depths in the middle of Gunners Park (location 1) are shown in Figure 9 as a function of the simulated storm time, *i.e.* 44 hours. The increase in water depth, and therefore in volumes, develops over time and it is consistent with the overtopping discharges in Section 2. For this study, no releases of water during low tides are considered, which is a conservative assumption, since in reality some water could be discharged in between storm peaks. Overall, water depths showed a great variability for the various configurations, showing the availability of multiple solutions to reach the desired safety levels. While safest solution is raising the crest of the dike, this might encounter the criticism of the population. The alternative of increased roughness of the revetment is very promising, but more information is needed on the effectiveness of these Nature Bases Solution as coastal protection measures. Finally, results showed a high influence of SLR, confirming the importance of relevant and effective policies to mitigate climate change.

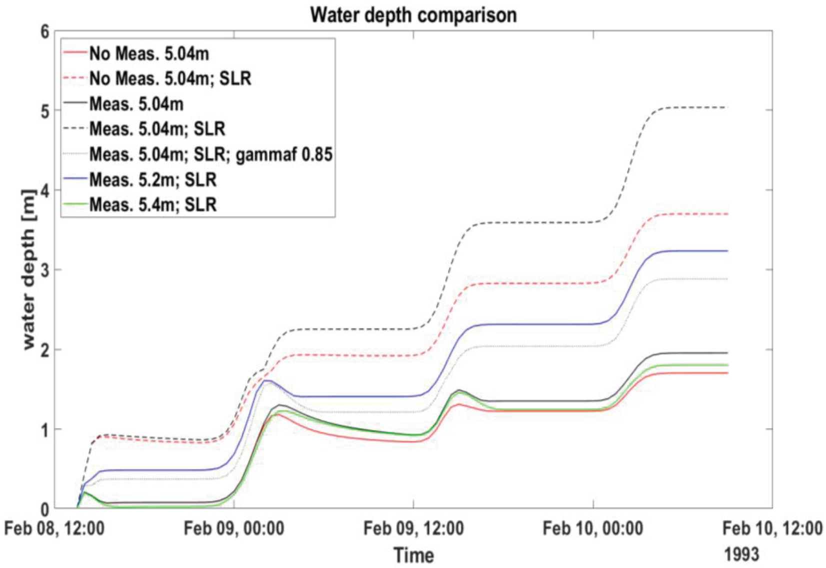


Figure 9. Water depths at location 1 as a function of time for all configurations tested in Sections 3.1 (no measures, current situation), 3.2 (internal protection barriers), 3.3 (Higher coastal protections), 3.4 (Increased roughness).

4. INTEGRATED DESIGN

During the research and design phases, the collaboration between hydraulic engineers and urban designers was highly interactive and demonstrated to be very fertile. The systematic sharing of research, integrated development of a visions and transferring this in a shared strategy created the basis for innovative design solutions, where the process of mutual and coordinated feedbacks supported integrated design activity. Integrating flood risk into spatial vision to strategy is a new approach in which technical and conceptual aspects are synergized in holistic and multidisciplinary solutions to a distinct problem (Godschalk and Milizia 2013). Especially new to these solutions is the aim for creating a flood risk approach (reduction of consequences) in which urban and ecological amenities are integrated.

For the specific case of Southend-On-Sea, the numerical simulations developed by hydraulic engineers were decisive to understand how the Garrison Park should be designed spatially to meet future climate change challenges and improve the urban quality. The above-discussed scenarios provide information on how water depths will be made beneficial for this future urban development of the area. Knowledge on the hydrodynamic aspects also touches economic and societal issues; which were considered and then integrated into spatial design within a systemic approach (Berger 2009).

To contain the propagation of water in the case of overtopping, the introduction of a secondary line of defense was defined, but the construction of a new embankment required a considerable amount of material. Furthermore, a new housing development in the area was recently approved by the Municipality, which creates safety problems for upcoming residents and for the usability of the area itself. To answer both complications two different but interdependent strategies were developed by Iuorio and Bortolotti (2021). The first one deals with re-profiling the area and the material used to build the new dike ring is excavated in certain locations of the site itself. This created new lower-lying areas able to store larger volumes of water in case of overtopping, reshaping the landscape to design a public park where potential floods could be controlled and confined into specific areas. This was also preparatory to the construction site and build foundations for the new the house development. The second measure focused the buildings themselves. In the design proposal, the ground level of the settlements was used as parking space – another relevant issue that afflicts the neighborhood. To do so the developments are built on stilts, as shown in Figure 10, implying that the ground floor can accommodate floods, enhancing the security of buildings themselves and human lives. Openings in lower parts of the buildings was shown to be effective measure to reduce the forces in case of flood (Wüthrich et al. 2018) and favor an integrated design between urban development and flood protection measures.

For an optimal design of these residential houses, a knowledge of the water levels in case of wave overtopping was needed and numerical simulations were used to obtain water levels at locations 4 and 9. Results showed similar values at both locations, as reported in Figure 11b. With the exception on the scenario without measures, including SLR, all other simulations revealed water levels that were lower than common height of stilts used parking garages (*i.e.* 2.5-3m), therefore confirming the feasibility of this integrated solution.

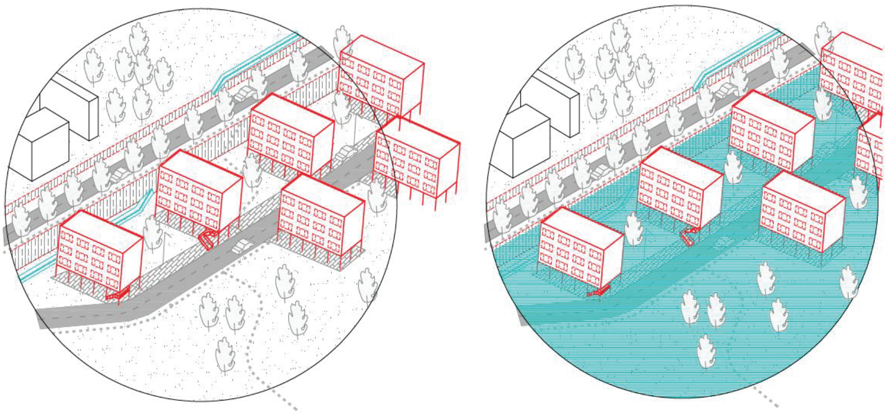
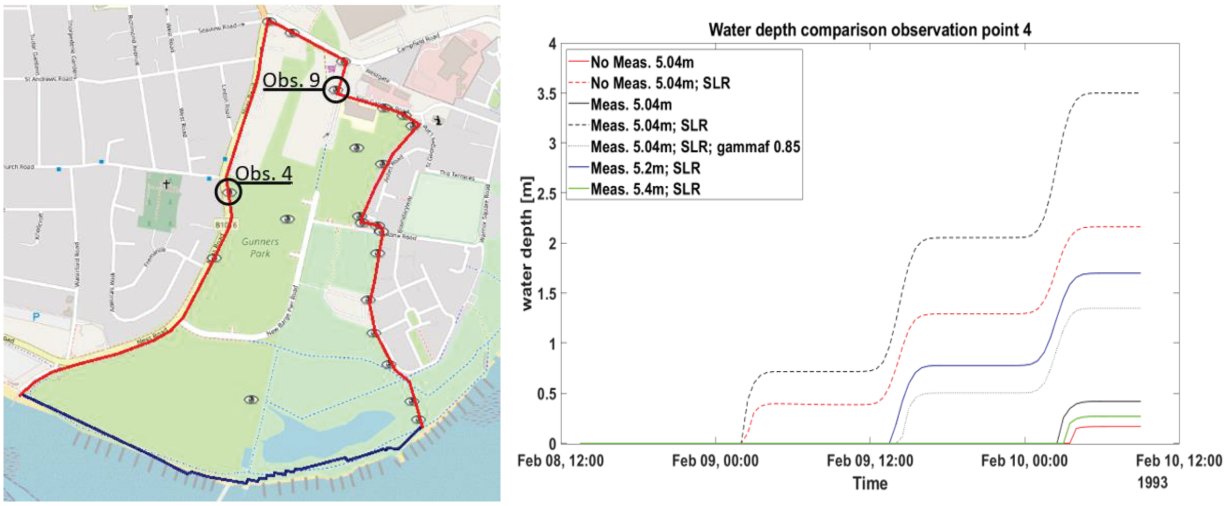


Figure 10. The second line of defence in the backgroud with flood-proof housing developments. [Drawings by A. Bortolotti and L. Iuorio]



(a) (b)

Figure 11. (a) Locations of the construction site for the new residential development and (b) water levels derived from the numerical simulations.

5. CONCLUSIONS

The project SARCC (Sustainable And Resilient Coastal Cities) supports the use of integrated Nature Based Solutions into coastal management and policy making, integrating them into existing infrastructure and flood defenses. More specifically, this research focused on the strategy that was developed to manage coastal flooding in Southend-On-Sea (UK), presenting the different solutions that were analyzed. In particular, this study estimated overtopping discharges during extreme storm conditions and analyzed their inland propagation using Delft3D FM numerical simulations. Results showed that the current situation would result in

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extensive overtopping volumes, responsible for severe inland inundations, thus pointing out the need for further action.

Mitigation and adaptation measures were developed through a joint collaboration of hydraulic engineers, urban designers, maritime archaeologists and local authorities, including the introduction of secondary defense lines to accept overtopping, and this not reduce flood probability, and instead reduce the consequences by accommodating the water in Gunners park that at the same time enhances urban development and quality in the area. The increase in elevation of the primary defense lines was shown to be an effective solution, but encountered the criticism of the population. A reduction of overtopping discharge through an increased roughness of the revetment was shown to be very promising, but more information is needed on the performance of these Nature Bases Solution as coastal protection measures. Overall, these results presented a successful methodology applied to the case study of Southend-On-Sea (UK), pointing out the strength of interdisciplinary approaches for reliable and well-integrated flood protection strategies.

6. ACKNOWLEDGEMENTS

This project was funded as part of the European project *Interreg 2 Seas Mers Zeeen*. The authors would like to acknowledge the participation and contribution of additional partners, including Mr. John Bennett (municipality of Southend-on-Sea, UK) and Mr. Gary Momber (Maritime Archaeology Trust, UK). Helpful discussions with Dr. Jeremy Bricker (University of Michigan, USA) are also acknowledged.

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