A Decade after Bodil: Assessing Coastal Flood Adaptation in Roskilde, Denmark

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ABSTRACT

The 2013 Bodil storm caused severe coastal flooding in Roskilde city. This paper evaluates to which degree adaptation measures implemented or planned since Bodil reduce the flood risk under present and future conditions. Municipal climate plans are analysed, and the Bodil event is forensically reconstructed and re-simulated using hydrodynamic modelling under present and future scenarios. Results show that implemented measures, particularly the Inner Harbour Dike, effectively reduce inundation under Bodil-scale conditions, while their protective capacity is exceeded under more extreme water levels, with flooding occurring through indirect pathways. The study highlights the need for continuous reassessment of adaptation strategies using process-based flood modelling to support climate-resilient urban planning.

KEYWORDS: Flood adaptation; Storm surge flooding; Flood risk; Climate change.

1 INTRODUCTION

Coastal cities are increasingly exposed to flood risk as climate change intensifies storm surges and raises mean sea level, challenging existing protection standards and urban planning practices. In low-lying historic waterfronts, even moderate increases in sea level can lead to rapid inundation, prolonged flooding, and disproportionate damage to cultural heritage, infrastructure, and urban functions. Understanding whether current adaptation strategies remain sufficient to manage these evolving risks requires not only forward-looking projections, but also systematic evaluation against past extreme events and improved knowledge.

The 2013 storm surge event Bodil represents a critical reference point for coastal flood risk in Denmark. The event produced the highest recorded water levels in parts of the Roskilde Fjord in more than a century, resulting in extensive flooding in Roskilde city, particularly in the harbor area. In the aftermath of Storm Bodil, Roskilde Municipality developed and implemented climate adaptation measures, ranging from structural flood protection and hybrid defenses to spatial transformation and risk avoidance. More than a decade later, Bodil provides a narrative for assessing whether these measures have meaningfully reduced flood risk and whether they are robust under future climatic conditions.

The main objective of this paper is twofold. First, it evaluates whether the adaptation measures implemented or currently planned in Roskilde city are sufficient to prevent flooding during a recurrence of the 2013 Bodil event**.** Second, it assesses how these strategies perform under more extreme conditions associated with future sea-level rise, representing plausible high-end storm surge scenarios. To address these objectives, the study combines an analysis of municipal climate planning documents with a set of hydrodynamic simulations using the RIM2D model. The Bodil event is forensically reconstructed using observed water levels and pre-event topography, and then re-simulated under present-day conditions and future extreme water levels, incorporating implemented and planned adaptation measures.

By focusing on a single, well-documented city and a historically extreme event, the paper contributes to a growing body of research that seeks to bridge climate adaptation planning and process-based flood modelling using a storyline approach. The results provide empirical insight into how urban adaptation strategies perform in practice, highlight remaining vulnerabilities, and underscore the importance of continuous reassessment of coastal protection standards in the face of rising sea levels.

2 METHODOLOGY

2.1 Study Area

The Roskilde Fjord area in Denmark faces a growing set of climate-related hazards, with storm surges and coastal flooding posing as the most significant threat. The fjord's long, narrow, and funnel-shaped geography amplifies water levels when strong winds push water inland, highly exposing nearby towns and infrastructure. Roskilde Fjord extends approximately 42 km from its connection to the Kattegat to its southern inner reaches and hosts several urban settlements and critical infrastructures along its shoreline. In this study, the analysis focuses on the harbor area of Roskilde municipality (Figure 1).

The Roskilde harbor area is characterized by its low-lying waterfront directly adjacent to the historic city center. Large parts of the harbor and surrounding urban fabric are located only slightly above mean sea level, making them highly sensitive to even moderate storm surges. The area contains valuable cultural heritage assets, including a national museum featuring a unique collection of Viking ships, historic buildings, public spaces, and archaeological sites, which constrain the implementation of large-scale structural protection measures. Flooding in Roskilde therefore not only carries high economic risks but also irreversible cultural and social losses.

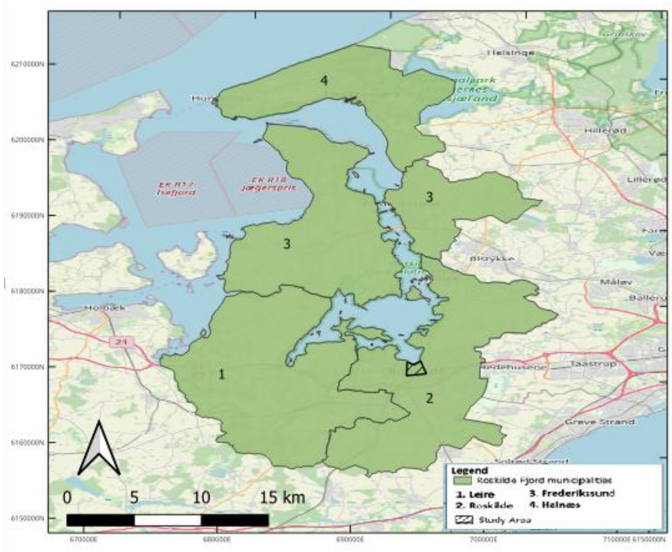


Figure 1 - Roskilde Fjord and selected study area at Roskilde municipality.

2.2 Flood Modelling

Flood simulations were carried out using the raster-based hydrodynamic model RIM2D, which solves an inertial formulation of the shallow water equations and is suitable for simulating fluvial, pluvial, and coastal flooding processes (de Almeida et al., 2013). The model has been widely applied in previous studies and is described in detail elsewhere (e.g. Apel et al., 2016; 2022; 2024). In this study, coastal inundation is driven by elevated water levels recorded at tidal gauges; wind and wave effects are not explicitly modelled due to limited data availability.

The model domain covers the Roskilde Fjord and adjacent land areas (approximately 1,379 km²) at a spatial resolution of 2 m. Land-surface roughness was derived from land-use data using standard Manning coefficients associated to land-use classes from literature, while buildings were represented using a building-hole approach based on OpenStreetMap footprints. Spatially distributed saturated infiltration rates were assigned using soil substrate maps. Urban drainage by the sewer system was accounted for using a capacity-based approach, assuming a drainage capacity of 20 mm/h. Simulations were performed on a high-performance computing system on Graphical Processor units (GPUs), allowing efficient execution of high-resolution scenarios.

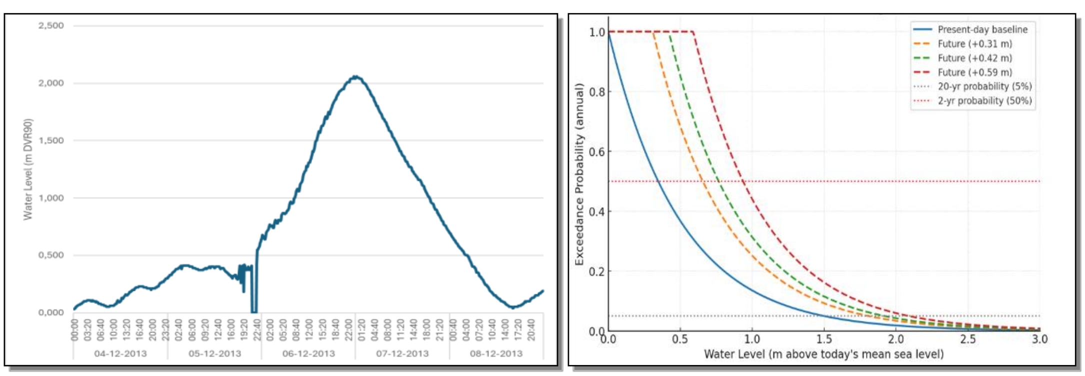
To evaluate flood risk evolution and the effectiveness of adaptation measures in Roskilde Harbor, a set of progressively structured scenarios was developed. First, the 2013 Bodil event was forensically reconstructed using observed hourly water levels from the Roskilde Harbor gauge (DMI station 30407) and a 2007 digital elevation model (DEM) representing pre-event conditions. Second, the Bodil event was re-simulated using its maximum observed water level (2.06 m) under present-day topography, incorporating implemented adaptation measures. A further scenario includes both implemented and planned measures. Finally, a future extreme scenario was simulated using a water level of 2.50 m, representative of a potential 100-year event under sea-level rise. Together, these simulations allow systematic comparison of baseline flooding, current protection performance, and robustness under more extreme future conditions.

2.3 Event Description

Storm surges are created by wind that pushes water towards coasts, which causes the water level to rise (Needham et al., 2015). Denmark has a long history of storm surges with the Bodil event of December 2013 representing the most severe storm surge event affecting the Roskilde Fjord area in recent decades. The event developed from a rapidly deepening low-pressure system over the North Atlantic and, upon reaching Denmark, strong northwesterly winds pushed large volumes of seawater into the narrow Roskilde Fjord, producing extreme storm surge conditions (Andrée et al., 2021). This wind-driven set-up led to sustained elevated water levels during 6–7 December 2013.

Observed water levels at Roskilde Harbour reached just more than 2 m above mean sea level, the highest levels recorded in more than a century. The event was characterized not only by a high peak but also by several hours of elevated water levels, substantially increasing flood exposure and damage potential (Figure 2a). The forensic reconstruction of Bodil shows a rapid and non-linear flooding response in the harbor area. Flooding began in the western harbor around 02:00 on 6 December, and a small additional rise in water level (approximately 0.10 m) was sufficient to trigger inundation of the inner harbor by 04:00. By 08:00, the entire harbor area is flooded, despite peak water levels occurring later, indicating that critical flooding thresholds are exceeded well before the event maximum (Figure 3).

The Bodil storm caused significant impacts in Roskilde city. The flooding primarily affected the harbor area and the adjacent historic city center, where the storm surge inundated waterfront quays, public spaces, and basements of historic buildings. Damage to cultural heritage assets, commercial properties, and waterfront facilities was reported, and access to central areas was temporarily disrupted during the peak of the event (Roskilde Municipality, 2014; *Politiken*, 2013).



a **b**

Figure 2a. Observed water level at Roskilde Harbour (DMI gauge 30407) during Storm Bodil, from 4 to 8 December 2013. Figure 2b. Projected mean sea-level rise under different emission scenarios translates into increased water levels in Denmark based on DMI (Klimataatlas, 2025).

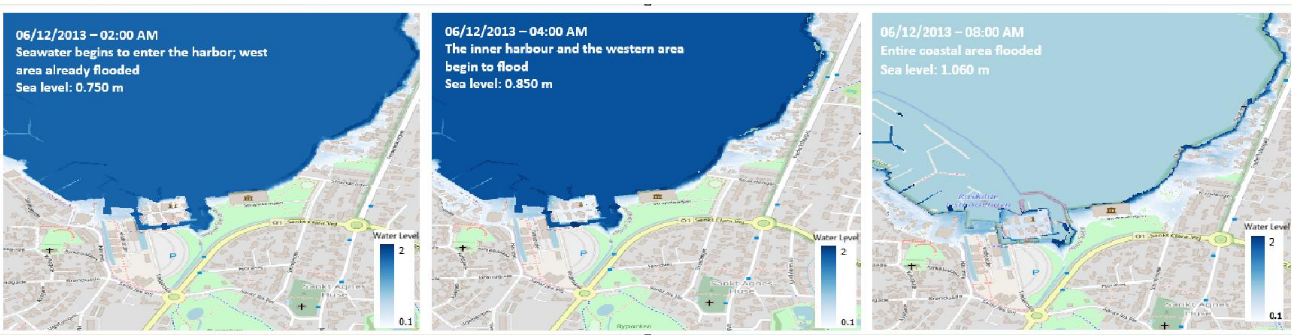


Figure 3. Simulated temporal evolution of flooding in the Roskilde Harbour area during the Bodil storm. Snapshots at 02:00, 04:00, and 08:00 on 6 December 2013.

According to the Danish Meteorological Institute (DMI), the frequency of storm surges of comparable or greater magnitude is expected to increase significantly in the future. Events that currently have a statistical return period of once every 20 years are projected to occur on average every second year. This shift is driven primarily by mean sea-level rise, which elevates the baseline water level from which storm surges develop, thereby increasing the probability that extreme thresholds are exceeded (DMI, Climate Atlas).

This mechanism is often described as a nonlinear frequency shift, whereby relatively small increases in mean sea level lead to disproportionate increases in the frequency of extreme coastal flooding events (Figure 2b). Consequently, events that are considered rare under present-day conditions may become commonplace within a few decades.

According to IPCC, by 2050, global mean sea level is expected to rise by additional 10-25cm, regardless of reductions in greenhouse gas emissions. Even under scenarios where net-zero emissions are achieved, thermal expansion of seawater and ongoing ice-sheet contributions ensure that sea-level rise will persist well beyond this century. For Denmark, regional projections provided by DMI's Climate Atlas indicate that under climate change scenario SSP3-7.0, mean sea level in Roskilde Fjord could rise by approximately 47 cm by 2071-2100. While this increase may appear moderate in absolute terms, it has disproportionate consequences for the potential impact of storm surges (Figure 2b). Such changes expose low-lying coastal regions, including areas around Roskilde Fjord, to recurrent flooding, undermining existing protection standards and challenging long-term adaptation strategies.

3 ADAPTATION MEASURES

Climate change adaptation has become a central concern in urban and spatial planning, as climate impacts are primarily experienced at the local level. Planning frameworks translate long-term climate risks into spatial strategies, land-use regulations, and infrastructure investments tailored to local conditions and capacities. Local governments play a key role in this process, as they are responsible for implementing national and international objectives through concrete planning decisions. As a result, municipal climate plans serve as a critical link between climate science, policy goals, and practical risk reduction.

In Denmark, the DK2020 initiative has for the first time introduced a common structure to municipal climate plans. DK2020 originally targeted a selection of Danish municipalities but has developed into a national platform designed to support local governments in developing comprehensive climate action plans aligned with the Paris Agreement. Based on the C40 Climate Action Planning Framework, DK2020 requires municipalities to combine climate mitigation targets with systematic assessments of climate risks and vulnerabilities, and to define adaptation measures across sectors. The framework emphasizes implementation pathways, monitoring, and periodic revision, thereby enabling an evaluation of both planned and realized adaptation actions.

Between 2013 and 2024, Roskilde Municipality developed and implemented a series of climate adaptation and urban planning documents in response to increasing flood risk and long-term climate change (Table 1). In the harbor area, adaptation is guided by a layered planning framework, in which strategic climate objectives are progressively translated into operational measures and spatial interventions. These documents range from high-level climate action plans aligned with national and international targets to detailed adaptation action plans and site-specific urban redevelopment projects. Together, they establish a coherent pathway from policy intent to physical implementation, with storm surge, sea-level rise, and compound flooding in Roskilde Harbor forming a central and recurring focus.

At the strategic level, Roskilde Municipality's Climate Plan (Klimaplan) 2024 (DK2020) defines the overarching climate objectives and identifies coastal flooding and sea-level rise as key long-term risks for low-lying waterfront areas. While primarily a strategic framework, the plan explicitly acknowledges that protection efforts in Roskilde Harbor are largely implemented yet emphasizes the need for continuous reassessment of protection levels in response to future sea-level rise and extreme events. This positions the harbor as an area where adaptation is ongoing rather than complete.

These strategic objectives are operationalized through the Climate Action Plan (Klimahandleplan) 2024, which specifies concrete adaptation actions relevant to the harbor area. A central measure is the protection of Roskilde Inner Harbor, where a new harbor promenade functions as an integrated coastal defense. The project combines permanent structural protection - a raised promenade with cast concrete paving and a continuous half-wall - with deployable flood barriers, allowing detachable aluminum boards to be installed during extreme events. This hybrid system raises the effective protection level for direct flooding, i.e. dike overtopping, to approximately +2.75 m, directly addressing storm surge impacts comparable to the 2013 Bodil event, while balancing flood protection with urban accessibility and heritage considerations.

Complementing these defenses, the climate plan also addresses compound flooding through targeted interventions such as the Tømmergrunden adaptation project, in the west part of Roskilde Inner Harbor. This project introduces a dike designed to protect against elevated fjord water levels while enabling controlled discharge of cloudburst runoff via a longitudinal depression and a closable opening. The measure explicitly recognizes the interaction between storm surge and extreme precipitation. However, this dike is still in the planning and design phase.

Table 1- Key climate and urban planning documents guiding flood adaptation in Roskilde Harbour

Document	Year	Type	Main focus	Relevance
Klimatilpasningsplan for Roskilde Kommune [1]	2014	Climate adaptation plan	Identification of flood risks (storm surge, cloudbursts, groundwater) and priority areas	Establishes Bodil as reference event and identifies Roskilde Harbour as a high-risk zone
Klimaplan 2024 – DK2020 [2]	2024	Climate action plan	Integrated mitigation and adaptation aligned with the Paris Agreement	Frames long-term adaptation objectives and acknowledges need for reassessment under sea-level rise
Klimahandleplan 2024 [3]	2024	Adaptation action plan	Concrete adaptation actions, timelines, and responsibilities	Specifies implemented and planned flood protection measures in Roskilde Harbour (e.g. Inner Harbour West, Tømmergrunden)
Kyststrategi – Administrationsgrundlag for kystbeskyttelse [4]	2023	Coastal strategy / regulatory framework	Principles, design guidelines, and decision criteria for coastal protection under sea-level rise	Defines protection standards, adaptable design requirements, and retreat logic applied in Roskilde Harbour projects
Kommuneplan (Municipal Plan) [5]	2016; 2019: 2009; 2026	Urban / spatial plan	Land-use regulation and urban development	Integrates flood risk into land use and constrains development in exposed harbour areas
Handleplan for klimatilpasning 2026–2029 [6]	2025	Adaptation implementation plan	Monitoring, model updates, and continuation of adaptation projects	Confirms harbour area as a priority and supports scenario-based evaluation
Harbour redevelopment & Viking Ship Museum relocation plans [7]	2017–ongoing	Urban project plans	Waterfront transformation, cultural heritage protection	Introduce accommodation and retreat strategies central to the harbour adaptation concept

[*] the numbers in brackets indicate the references

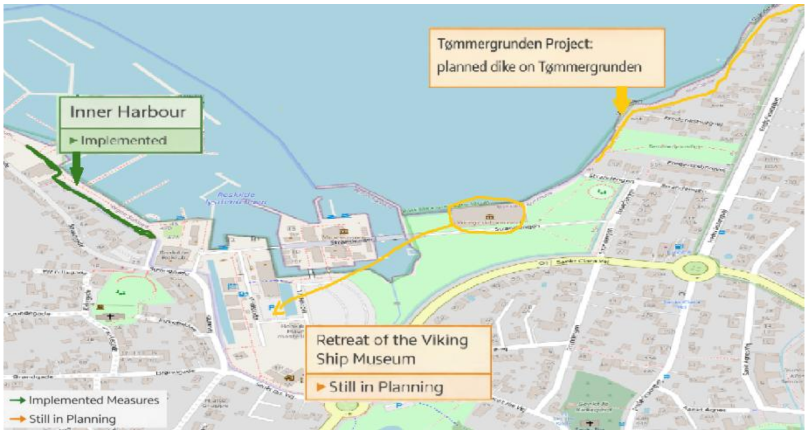


Figure 4 – Adaptation measures implemented and planned in the Roskilde's Climate Plan.

Beyond structural protection, Roskilde's adaptation strategy also incorporates elements of spatial transformation and risk avoidance. A prominent example is the decision to relocate the Viking Ship Museum to a safer location, reducing exposure of irreplaceable cultural heritage assets to future flooding. The redevelopment of the former museum area and adjacent harbor zones into Havneparken, a multifunctional public park, reflects an adaptive approach that accommodates periodic flooding while enhancing recreational and urban qualities. By transforming highly exposed waterfront areas into flexible public spaces rather than intensively used buildings, the municipality reduces potential damage while maintaining public access to the fjord.

The implementation and coordination of these measures are supported by the Action plan for Climate Change Adaptation (Handleplan for Klimatilpasning) (2026–2029), which consolidates adaptation projects and emphasizes the importance of maintaining and updating hydrodynamic and drainage models to evaluate local climate adaptation scenarios. This commitment to model-based assessment underlines the municipality's recognition that protection levels and spatial strategies must be revisited as sea levels continue to rise.

In addition, Roskilde's Coastal Strategy (2023) provides the regulatory and design framework for coastal protection, specifying protection heights, adaptability requirements, and the balance between hard protection, retreat, and public access, thereby shaping the form and limits of the harbor adaptation measures analyzed in this study.

The structural interventions described above form the basis for the modified topographic representation used in the hydrodynamic simulations presented in the following section.

4 RESULTS – ADAPTATION EFFECTIVENESS AND FUTURE SCENARIOS

The numerical simulations presented in this section are designed to evaluate how the implemented and planned adaptation measures for the Roskilde harbor perform under extreme coastal flooding conditions. Building on the preceding assessment, the simulations address two central questions: first, whether the adaptation measures implemented or currently planned are sufficient to prevent flooding during a recurrence of the 2013 Bodil event; and second, how these strategies respond to more extreme conditions associated with future sea-level rise (Figure 5).

The simulation results indicate that the Inner Harbor dike provides effective protection under a Bodil-scale maximum water level of 2.06 m, preventing direct inundation of the urban areas located behind the harbor promenade. Under this scenario, the dike blocks the primary flood pathways observed during the 2013 event, resulting in a substantial reduction in flood extent and water depths landward of the harbor front. However, when the maximum water level is increased to 2.50 m, representing a more extreme future event, the Inner Harbor dike cannot prevent flooding of the protected area behind it. The dike continues to prevent direct overtopping along the harbor edge, but flooding occurs indirectly via the area surrounding the Viking Ship Museum from where floodwaters propagate inland and inundate the protected area from the land side. This suggests that under higher water levels, secondary flood pathways bypass the main line of defense, indicating either the presence of additional protection measures not captured in the digital elevation model or an inherent limitation of the current protection system under extreme conditions. It also illustrates that system performance is controlled not only by the crest height of individual protection structures but also by the connectivity of surrounding low-lying areas.

In contrast, the Tømmergrunden dike exhibits limited influence on flooding patterns in the simulations. The area is inundated already under the 2.06 m scenario, primarily due to inflow from the harbor and museum area behind the dike, rather than from direct fjord overtopping at the Tømmergrunden frontage. Increasing the water level to 2.50 m leads to earlier and more extensive flooding, reinforcing the conclusion that the planned dike, as represented in the model, does not significantly alter the dominant flood pathways. This outcome may reflect missing design details in the model representation, such as crest height, continuity, or the operation of closable openings; alternatively, it may indicate that the planned measure is insufficient when considered in isolation. Overall, the results show that while current adaptation measures in Roskilde Harbour reduce flood impacts under Bodil-scale conditions, their effectiveness diminishes under more extreme water levels, highlighting the importance of addressing indirect inundation pathways and system-wide connectivity in future adaptation planning.

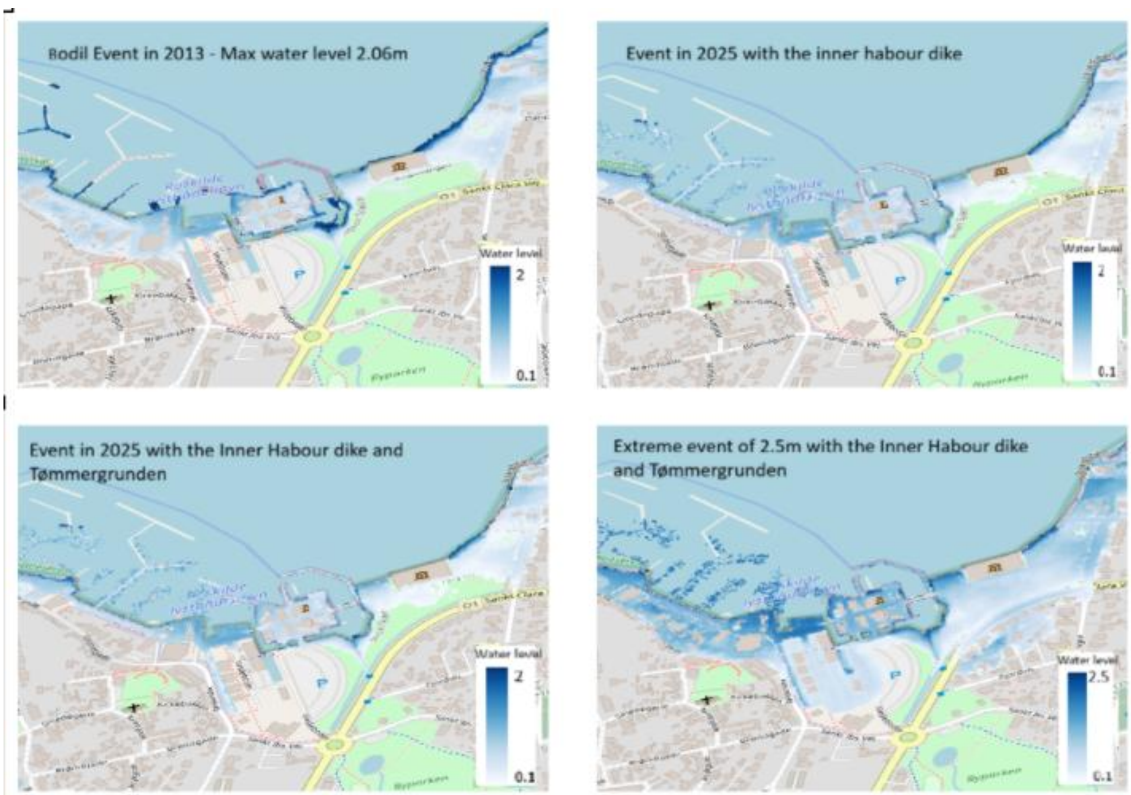


Figure 5 - Simulated flooding scenarios in the Roskilde Harbor area. *(a)* Forensic reconstruction of the 2013 Bodil event at its maximum observed water level (2.06 m). *(b)* Replication of the Bodil event under present-day conditions, including the implemented Inner Harbor Dike. *(c)* Replication of the Bodil event incorporating both implemented and planned adaptation measures - Inner Harbor Dike and Tømmergrunden dike. *(d)* Extreme future scenario with a water level of 2.50 m, simulated with both implemented and planned dikes.

5 CONCLUSION

This study evaluated the effectiveness of climate adaptation measures in Roskilde Harbor by reconstructing the 2013 Bodil storm and re-simulating it under present-day and future extreme water-level scenarios. The results show that adaptation measures implemented since Bodil, particularly the Inner Harbor Dike, substantially reduce flooding under Bodil-scale conditions. However, under more extreme water levels representative of future scenarios, the protective capacity of the system is strongly reduced, mainly by inundation occurring through indirect pathways rather than direct overtopping.

The planned Tømmergrunden dike shows limited additional benefit in the simulations, suggesting that either key design elements are not yet fully defined or that the measure alone is insufficient to address dominant flood pathways. Overall, the findings highlight that while current strategies improve resilience to present-day extremes, they do not fully prevent flooding under high-end future scenarios.

This underscores the importance of continuous, model-based reassessment of adaptation measures and of addressing system-wide connectivity and residual risk in coastal urban planning. Following the Bodil event, Roskilde Municipality developed a comprehensive set of climate adaptation and urban planning documents, reflecting a systematic effort to translate scientific knowledge into local planning and infrastructure measures. While these strategies uses Bodil as a benchmark, are grounded in current climate projections and aligned with frameworks such as DK2020, the simulation results indicate that protection measures implemented and planned may still be exceeded under higher water levels. Importantly, the findings show that system performance depends not only on the crest height of individual protection structures but also on the connectivity of surrounding low-lying areas, which may allow floodwaters to propagate through indirect pathways. Although hydrodynamic simulations inevitably involve uncertainty, the forensic reconstruction and re-simulation of past extreme events provide a practical methodological approach for municipalities to reassess existing protection systems and support iterative adaptation planning under changing climate conditions. These findings are generic and can be translated to other coastal communes facing the same problem of increasing flood risk.

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