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Future Performance of Coastal Drainage Systems under Climate Uncertainty: A Sensitivity Analysis

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Abstract
Due to increased noticeable effects of climate change, coastal cities are urged to simultaneously protect against rising sea levels and maintain, and enhance, well-functioning stormwater drainage systems. Given the significant uncertainties associated with future projections, this work aims to evaluate the sensitivity of the drainage system to selected future scenarios. To achieve this, a total of 27 projected scenarios were generated for three time-horizons, combining sea level rise and rainfall in one-year long time series using openly available data from the Swedish Meteorological and Hydrological Institute (SMHI). These scenarios were tested using a hydrodynamic 1D model of the pipe system in Landskrona, Sweden.

The results indicate that the system performs well up until 2070 across all investigated scenarios. By 2100, however, performance indicators reveal the crossing of a threshold, resulting in greater variability between scenarios and a decline compared to earlier levels. Further analysis will focus on determining the exact threshold level and identifying the key contributing parameters. Additionally, more performance indicators will be incorporated, and the results will be analysed geographically to provide enhanced guidance for urban planners.

Highlights

- A 1D drainage model was utilized to evaluate system performance under three climate projections across three time-horizons.
- The system maintains satisfactory performance until a tipping point is reached between 2070 and 2100.
- Variations between the selected climate scenarios have a minimal impact on system performance until the tipping point is exceeded.

Introduction
Rising sea levels and changing rainfall patterns in northern Europe are placing significant pressure on existing drainage systems in coastal cities. These systems were often constructed using deterministic design principles (Haghighatafshar et al., 2020) and benefitted historically from land rise that offset sea level rise. However, in southern Sweden, the isostatic uplift is now negligible (Rosentau et al., 2012), creating major challenges for low-lying areas.

Stormwater drainage analyses typically focus on extreme events and the corresponding need for above-ground solutions capable of handling large volumes of water. These analyses take the functionality of the drainage systems under service level circumstances for granted, assuming that the system will always deliver the expected design performance under "normal" rainfall events. However, it is well understood that the future "normal rainfall" will be more intensive than that of today. Therefore, there is a pressing need to complement extreme event analyses with investigations of "normal" scenarios up to the service level for water and wastewater systems (Roth et al., 2024). In Sweden, the service level, established by the Water and Wastewater Association, are based on return periods of 10 or 30 years.

To adapt to future climate conditions, it is essential to further study how stormwater drainage systems will handle increased rainfall contributions alongside the reduced capacity caused by rising sea levels. While previous studies have addressed this issue using approaches such as surrogate models (Alipour et al., 2024) or limited scenario analyses (Bormann et al., 2024), there remains a gap in comprehensive sensitivity analyses.

This study addresses that gap by presenting a sensitivity analysis of the performance of the stormwater drainage system in Landskrona, Sweden, under future climate conditions. It examines three climate projections (SSP1, SSP2, and SSP5) from the IPCC AR6 report (Calvin et al., 2023) across three time horizons. The aim is to assess how variations in projections influence the performance of the drainage system, providing improved planning insights for relevant organizations.

Methodology

The methodology consists of three key components: the construction of future scenarios, model simulations and analysis of the resulting simulations. To represent common compound events, time series for rain intensity and sea level spanning a total of one year were used.

Scenario construction

Scenarios were developed using quality-assured data from rain gauge measurements recorded between January 1, 2023, and December 31, 2023, at 15-minute intervals. The data were collected by SMHI from the Helsingborg A station (see Figure 1). Sea level data for the same time period were obtained from the Barsebäck station with a resolution of 24 hours.

Projected scenarios were created by applying climate factors to rainfall data (*Fördjupad Klimatscenariotjänst | SMHI*, n.d.) and additive levels to sea level data, both provided by SMHI. The scenarios were based on the SSP1-2.6, SSP2-4.5, and SSP5-8.5 pathways, with the 25th, 50th, and 75th percentiles for rainfall and the 17th, 50th, and 83rd percentiles for sea level. This process yielded one reference scenario and 27 projected scenarios.

Modelling and result analysis

The projected scenarios were simulated using a calibrated 1D collection system model in MIKE+ by DHI (DHI, 2024). The model represents the drainage network, consisting of 4 679 nodes and 170 km of pipes, covering an area of approximately 20 km^2.

Performance analysis was carried out using the indicators specified in Table 1, which are derived from the model parameter of *water volume above ground*.

Table 1: Description of the performance indicators used.

Indicator	Abbreviation	Description
Number of Flooded Nodes	NFN	Number of nodes that are flooded at least once during the total simulation period
Flood Frequency	FF	How many times during the simulation period that the nodes are flooded
Normalised FF	FF/NFN	The flood frequency normalised by the number of flooded nodes over the simulation period. This indicates how many times a node is flooded per year on average

Case study

The model was developed for Landskrona (see Figure 1), a city located in southwestern Sweden near the Baltic Sea. Landskrona comprises a large number of residential areas, many of which are situated in risk zones prone to exposure from rising sea levels and flooding caused by rainfall, due to the area's low topographic slope.

The stormwater drainage system in Landskrona is already affected by rising sea levels. This has resulted in seawater entering the drainage system, thereby reducing its original design capacity and effectiveness.

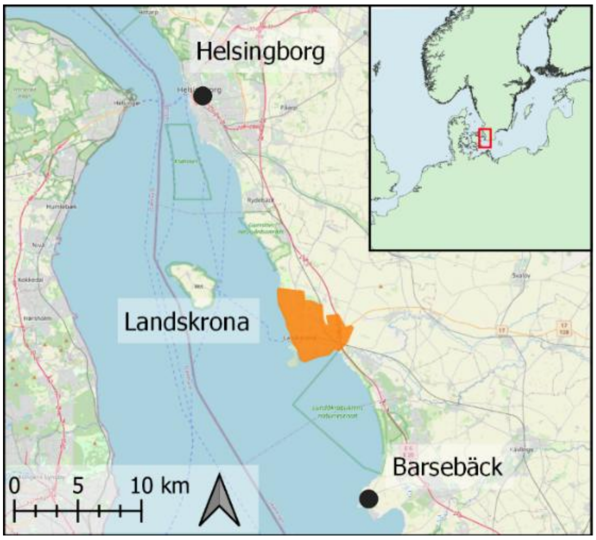

Figure 1: An overview map of the city of Landskrona, the rain gauge meter placement in Helsingborg and the sea level gauge meter placed in Barsebäck. The extent of the modelled area is shown in orange.

Results and discussion

The results are presented through graphs in Figure 2. Analysis of the performance indicator NFN in Figure 2a suggests that differences between the chosen climate projections remain minimal up to 2070, both relative to one another and compared to the reference time series. After 2070, a tipping point appears to be reached, resulting in increased uncertainty both within individual scenarios and between the various climate projections.

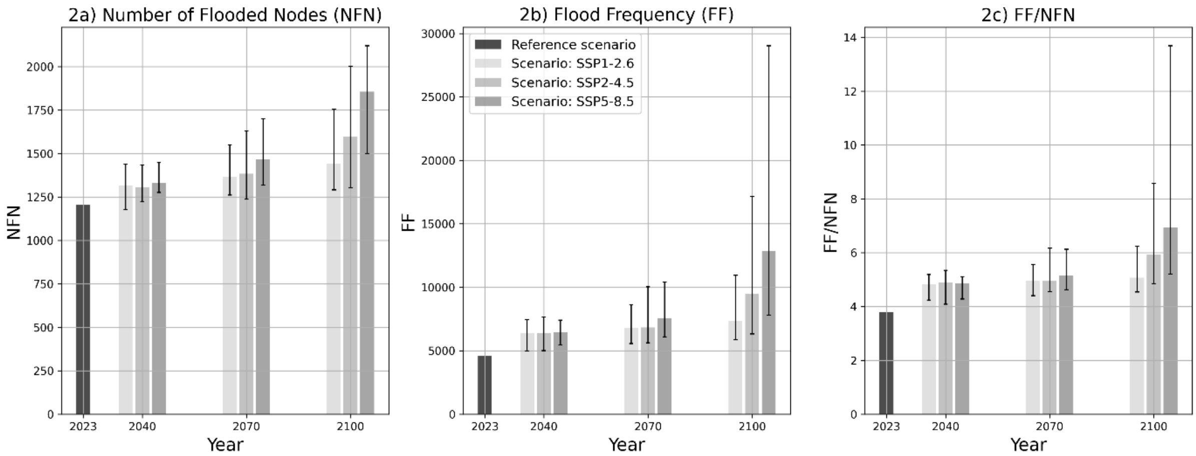

Figure 2: Graphs showing the performance indicators stated in Table 1 for all investigated scenarios. Graph 2a) shows number of flooded nodes, 2b) shows flood frequency and graph 2c) shows the normalized parameter FF/NFN.

For FF in Figure 2b, a similar trend is observed. However, the difference between 2070 and 2100 is significantly more pronounced than for NFN. Notably, the SSP5 scenario shows a substantial spread in results for 2100. When analysing the normalized indicator FF/NFN shown in Figure 2c, the findings reveal a drastic increase in the number of floodings per node beyond the tipping point. This indicates a sharp decline in drainage system performance for SSP5 after the tipping point, primarily expressed through an increase in the spread of uncertainties.

Up to the tipping point, the number of affected nodes remains relatively stable, and these nodes are also consistently the ones most prone to flooding. For city planners, this initial result implies that adaptation efforts can focus on the already identified flood-prone nodes for the period up to 2070.

It should be noted that this analysis does not account for potential land use changes or modifications to the drainage system. Any significant alterations in these areas could affect the conclusions drawn from this study.

Conclusions and future work

The initial results of this study suggest that the stormwater drainage system in Landskrona has a relatively strong capacity to manage increased rainfall volumes and rising sea levels until 2070. However, a tipping point is reached between 2070 and 2100, after which uncertainties increase significantly, requiring more extensive adaptive measures. These findings indicate that the drainage system performs similarly across all analysed climate scenarios (SSP1, SSP2 and SSP5) until the tipping point.

Further analysis will focus on statistical and geographical assessments to better understand the locations of flooded manholes and their changes over time. Additionally, seasonal variations, which have been shown to significantly affect flooding patterns, will be considered. The statistical analysis aims to evaluate the influence of selected parameters, providing city planners and water and wastewater utility managers with an enhanced foundation for climate adaptation planning.

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