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Investigating Urban Drainage System Robustness Using Multi-Storm Design Approach

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Abstract

Traditional urban drainage system design typically relies on a single design storm, which may not adequately capture the range of potential rainfall patterns. This study builds upon previous research investigating the effects of hyetograph shape variability by introducing a multi-storm design approach. We examined the robustness of urban drainage system designs by comparing systems developed using single and multiple design storms. Our methodology involved investigating model responses to an ensemble of 1000 hyetographs with varying temporal patterns but consistent duration and total precipitation. Students designed systems using a computer model, optimizing pipe dimensions, retention basin volume, and weir dimensions while minimizing costs and preventing flooding. We compared designs created with one versus three design storms. Results revealed that systems designed with three design storms showed lower flooding and overflow volumes, with average reductions of 75% and 35% respectively compared to single-storm designs. However, the overall system robustness was only marginally enhanced. This research highlights the limitations of current urban drainage system design approaches and suggests the need for more comprehensive methodologies to address climate variability and design uncertainty.

Highlights

- Multi-storm approach reveals limitations in traditional urban drainage system design
- Introducing more design storms can reduce flooding volumes by up to 75%
- Increased system robustness is connected to increased costs

Introduction

Urban Drainage Systems (UDS) play a crucial role in managing stormwater and preventing flooding in urban areas. It is common to use computer models, when designing such systems, to simulate different scenarios and arrive at an acceptable UDS design. Traditional UDS design often relies on a single design storm, which may not adequately capture the range of potential rainfall patterns.

This study builds upon our previous work (Pritsis et al., 2024), which investigated the impact of hyetograph shape variability on UDS robustness, by introducing a multi-storm design approach. The robustness of a design is defined by its ability to withstand a wide range of conditions, which are expected to occur during the system's operation (Blanchard and Blyler, 2016). Our previous research revealed that UDS designs based on a single hyetograph shape may not be sufficiently robust, as they can exhibit significant vulnerabilities (flooding and overflow) when exposed to diverse rainfall patterns.

This study expands upon our previous work by incorporating multiple design storms in the UDS design process and comparing the resulting UDS designs to the ones created using a single design storm. We applied this approach to the same urban catchment used in our initial study, allowing for direct comparison of results.

Methodology

We investigated the response of different UDS designs of the same catchment to an ensemble of 1000 hyetographs. The storms in the ensemble also have the same duration and total precipitation volume, but varying temporal patterns. The methodology followed for creating the ensemble, as well as a description of the catchment can be found in Pritsis et al. (2024).

To obtain a range of different designs following the same guideline, an exercise was provided to students as part of a MSc course. The students were provided with a SWMM file for a proposed UDS (Gironás et al., 2010), a cost function for the pipes and basin volume, and three design storms. The objective of the exercise was to minimize the cost of the UDS, without causing any flooding or overflow for the three design storms. The system variables that could be changed during the design to optimize the UDS were: pipe dimensions and elevation (within regulations), retention basin volume, and weir dimensions. These designs were then compared to the ones from Pritsis et al. (2024), where students were only provided with a single design storm.

Results and discussion

Our findings demonstrate that UDS designs based on three design storms exhibit better performance for the storms used compared to those based on a single storm (Figure 1). This was expected. When evaluating the designs using the ensemble however, it is not clear that the designs based on three design storms are more robust.

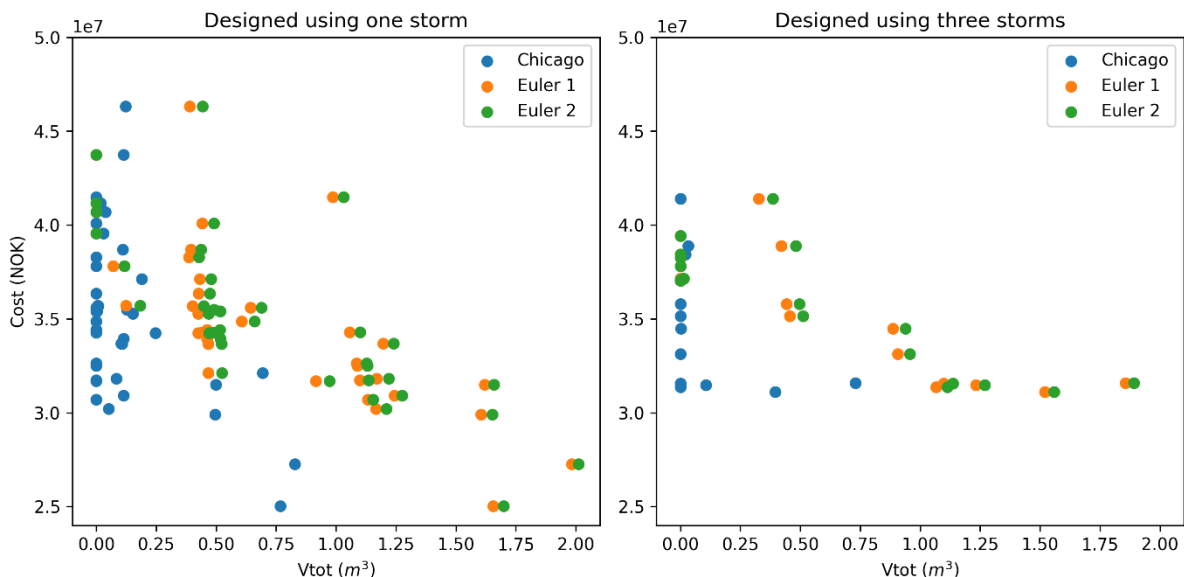


Figure 1 Flooding and Overflow (V_{tot}) for all systems when stressed with different design storms. Systems on the left were designed using only a Chicago design storms, for the systems on the right, three storms were used. Each system is represented by 3 dots in the plots.

The new systems (using three design storms) showed lower volumes of flooding and overflow across the ensemble of rainfall events, with average reductions of 75 and 35% respectively compared to single-storm designs. However, when we shift our focus from the magnitude of failure to the binary outcome of whether a system flooded or not, all systems, regardless of their design methodology, appear to fall within the same Pareto front (Figure 3). This observation indicates that systems designed

with three design storms fail with roughly the same frequency as those designed with a single storm. The key distinction lies in the severity of these failures.

Comparison of model performance and cost

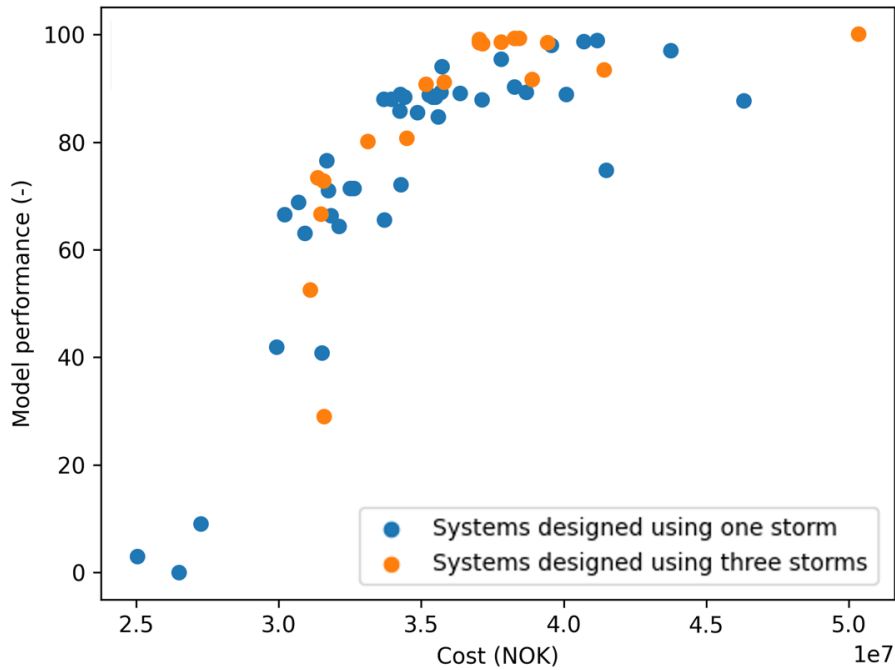


Figure 2 Comparison of model performance plotted against cost, between the systems designed using one and three design storms. Model performance is calculated as the percentage of storm events in the ensemble for which the system's model produces no flooding or overflow

By incorporating the Euler type storms in the design process, the size of the retention tank in the systems is chosen to be larger than the systems designed based on one storm (3863 vs 4374 m³) (Figure 3). The effect of this choice is seen in the reduced resulting overflow when the systems are tested with the ensemble.

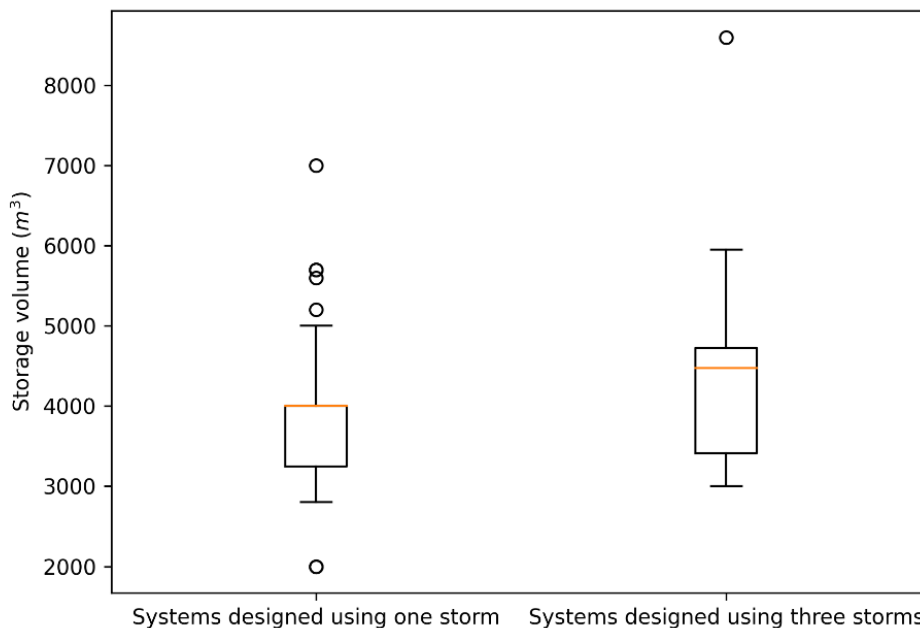


Figure 3 Comparison of storage (retention basin) volume between systems designs using one and three design storms

Conclusions and future work

Our study demonstrates that incorporating multiple design storms in UDS design enhances system robustness, albeit slightly. This approach provides a more comprehensive assessment of system performance under various rainfall conditions, addressing the uncertainty introduced by relying on a single hyetograph shape. The multi-storm designed systems, while not eliminating failure events entirely, mitigate their impact. When these systems do experience flooding or overflow, the volumes are smaller. This nuanced improvement in performance highlights the potential of multi-storm design approaches to enhance the overall robustness and effectiveness of urban drainage systems. However, the modest improvement suggests that three design storms may be insufficient to fully capture the range of expected conditions.

Future work should focus on optimizing the selection and number of design storms to better represent the expected rainfall variability. Additionally, research could investigate the relative contribution of other sources of uncertainty in UDS design, such as spatial rainfall variability and system description accuracy. These efforts could lead to the development of more robust design guidelines that account for the complexities of urban hydrology and the challenges posed by climate change. By advancing UDS design methodologies, we can create more robust and adaptable urban drainage systems that are better equipped to handle the challenges of changing climate patterns and urban development, ultimately improving flood protection and water management in cities (Balmforth et al., 2006).

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