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# Looking under the canopy: Modelling how single trees contribute to runoff reduction in cities

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## Abstract

Urban trees provide a wide range of ecosystem services, including urban cooling, flood control, biodiversity, and air quality improvement. However, their impact depends on their physical attributes, seasonality, placement, and distribution in urban settings. This study focuses on the role of trees in stormwater management. Using the modified Gash and Rutter formulation, we developed a spatially distributed model to simulate individual tree's interception capacity and throughfall. The model was applied to individual trees with time-varying leaf area index (LAI) under different rainfall intensity, and canopy saturation conditions. Model validation against measurements showed strong agreement for total throughfall ($R^2 \simeq 0.83$) and interception ($R^2 \simeq 0.61$). At the urban scale, applying the model to a pilot area in Copenhagen, Denmark, resulted in a total runoff reduction of 15.2%, with local contributions varying between 2% and 43% based on tree characteristics. However, tree effectiveness was primarily driven by rainfall intensity and tree seasonality. Further research is needed to refine species-specific interception capacity and improve LAI-based parameterization in tree interception. Integrating this approach with hydrodynamic simulations could enhance understanding of trees' local flood control contributions, supporting urban planning and tree-planting strategies to optimize city resilience.

## Highlights

- A spatially distributed model was developed to simulate the local impact of urban trees on runoff reduction across various rainfall events.
- Using measurement data, model validation showed strong agreement for throughfall ($R^2$ = 0.83) and interception ($R^2$ = 0.61) using measurement data.
- The model demonstrated up to 43% local runoff reduction by individual trees, with effectiveness varying by tree characteristics and location.

## Introduction

Nature-based Solutions (NbS) have been increasingly proposed for urban areas where human activities and high population densities have intensified climate-related hazards. However, optimizing the spatial planning of NbS remains a challenge for effective implementation and investment decisions. There is a need for local assessment of NbS to support this optimization, ensuring that planning strategies are tailored to site-specific conditions and maximize benefits (Veerkamp et al. 2021). Trees stand out among various types of NbS due to their broad range of long-term ecosystem services yet significant land, planting, and maintenance investment requirements. In the context of stormwater management, trees contribute to runoff reduction through canopy storage, interception, and evaporation processes. These processes have been widely studied and implemented in hydrological models on coarse resolutions. However, the local effect of sparse trees (specifically street trees) on small-scale runoff has been overlooked (William et al. 2022; Rahman et al. 2023). Existing models often fail to account for interception, throughfall, and evaporation processes within the tree canopy and their spatial distribution. This study highlights the impact of individual trees on local runoff dynamics, providing a foundation for integrating tree hydrological processes into conventional urban hydrological models.

## Methodology

For this study, following the modified Rutter and Gash (Rutter et al. 1971; Gash et al. 1975, 1995) formula for single rainfall events, we calculated the interception and throughfall values for sparse trees. The method determines a specific storage capacity for trees as a function of tree LAI, Bark Area Index (BAI), and gross rainfall. For canopy intercepted rainfall evaporation, following (Pereira et al. 2009, Huang et al. 2017) the diffusion equation was adopted based on wind velocity, precipitation, temperature, and relative humidity data. The model was initially validated on measurement data from the study by Smets et al. (2019) for throughfall and interception during (2016 - 2017) in Belgium. The model was then applied to a distributed tree dataset in Copenhagen, Denmark. The tree dataset, including LAI, crown diameter, tree height, and crown vitality, was derived from LiDAR data collected in 2019 and used as an input to this model. Individual trees' interception capacity and total throughfall were then calculated and spatially distributed across the study area for rainfall events in 2023.

## Results and discussion

The model applied to the dataset for trees in Belgium demonstrated an adequate representation of throughfall for two individual Norway maple and small-leaved lime trees ($R^2 = 0.83$). Comparing the results with the modelled interception and throughfall from Smets et al. (2019), showed improvements in throughfall modelling due to the use of diffusion method. As Pereira et al. (2009) described, the diffusion equation performs better in saturated canopy conditions than the conventional Penman-Monteith (1965) method for single trees. For interception, the model's performance was lower ($R^2 = 0.61$) as it was primarily determined by an empirical formula based on LAI values, which are highly dependent on tree species and leaf type. Applying the model to Copenhagen showed a total runoff reduction of 15.2% at the urban scale. However, depending on tree characteristics, the local contribution ranged between 2% and 43%. This assessment was carried out for a summer rainfall event in 2023, assuming the leaf-on season for trees in the study area. In the case of deciduous trees, rainfall events during the leaf-off season would lead to significantly lower interception and storage capacities.

## Conclusions and future work

This study highlights the local impact of individual trees on storm runoff. While trees can reduce total runoff in urban systems, the magnitude of their effect is heterogeneous and dependent on temporal rainfall patterns, tree physical attributes and their positioning within the urban canopy. The proposed model can be integrated into rainfall processors for urban hydrodynamic models, incorporating the localized effects of tree canopies in spatially distributed inundation simulations. Our study demonstrated improvements in throughfall modelling through diffusion equations for the evaporation of intercepted rainfall. This study underscores the limitations of available methods for species-specific parameters representing tree interception capacity. Future work will focus on enhancing data accuracy, coupling the model with other urban hydrological processes, and studying long-term rainfall patterns for future projections and tree seasonality to assess the benefits of urban trees in stormwater management in cities.


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