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A modelling framework for demand-oriented irrigation control using SWMM and SWMM-UrbanEVA

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Abstract

This study introduces a modelling framework integrating blue-green infrastructure modelling with demand-oriented irrigation management. By using Python-based applications, such as SWMM, SWMM-UrbanEVA and Smartin, the framework addresses key challenges, including insufficient representation of location- and plant-specific conditions or lack of integration for real-time control and model-predictive control. The framework supports dynamic irrigation control strategies, optimizing water use, enhancing evapotranspiration, and reducing urban runoff. In a case study in Münster, Germany, evapotranspiration increased by up to 60% for some BGI types, while sewer runoff decreased by up to 36%. The integration of rainwater harvesting and irrigation control demonstrates its capacity for resource efficiency. Flexible and adaptable, the framework enables practical applications across urban environments, allowing scenario analysis, efficient irrigation operations, and citizen engagement through real-time irrigation demand forecasting.

Highlights

- Development of a novel framework combining location- and plant-specific BGI modelling with demand-oriented irrigation management.
- Integration of dynamic irrigation control strategies (RTC and MPC) to optimize water use, increase evapotranspiration, and reduce urban runoff.

Introduction

Sustainable adaptation strategies using blue-green infrastructures (BGI) address the upcoming challenges of urbanization, climate adaption, and demographic change. However, only healthy vegetation can provide full functionality. This can be enhanced by irrigation from rainwater harvesting (RWH). In urban surroundings, the water demand can be significantly influenced by framing conditions such as location- (shading, soil characteristics) or plant-characteristics (demand, drought resilience) (Costello et al. 2000). A location- and plant-specific, which means demand-oriented irrigation management, is therefore recommended.

Irrigation can be executed through static and dynamic irrigation control strategies. Static irrigation is characterized by the implementation of a predetermined irrigation amount at regular intervals (e.g., daily or weekly). In contrast, dynamic irrigation is a demand-oriented approach that is either regulated based on real-time measurements, e.g., soil moisture (“real-time-control”, RTC) or model-predictive control (MPC), which accounts for precipitation-, temperature- and the associated demand-forecasts. A considerable number of studies have already examined the impact of irrigation control strategies on

the water and energy balance within model-based studies (e.g., Quinn et al. 2021). However, the existing model approaches have limitations, which can be attributed to one of three factors: (i) insufficient plant- and location-specific representation of BGI, (ii) the inability to integrate RTC- or MPC-approaches, and (iii) the inability to model full catchments due to the high model complexity.
For this reason, the present study aims to develop a modelling framework that addresses the existing limitations and enables the integrated study of irrigation control strategies. The framework should:

- enable location- (shading, soil characteristics) and plant-specific (demand, drought resilience) BGI modelling to accurately account for irrigation demand.
- allow the integration of different irrigation control strategies (RTC, MPC).
- enable the integration into rainfall-runoff models at catchment scale to examine the interaction and the effect on the sewer systems.
- use established model approaches.

Methodology

Model SWMM + SWMM-UrbanEVA

The SWMM (US EPA) (Rossman 2015) is used, upgraded with SWMM-UrbanEVA for optimized ET-modelling of BGI. In contrast to original SWMM, SWMM-UrbanEVA addresses previous limitations of the highly simplified evapotranspiration modelling in SWMM by integrating time-, location- and plant-dependent model approaches. This model is well-suited for BGI simulation, featuring two submodels (SM). SM 1 accounts for reduced evapotranspiration due to shading from buildings or vegetation, while SM 2 provides an evapotranspiration approach for vegetated areas, fully integrated into the LID (Low Impact Development) bioretention module. Model description and model validation can be found in Hörnschemeyer et al. (2021).

Python modelling framework for irrigation control

The framework consists of modular python applications which can be adapted manually. An overview is given in Figure 1.

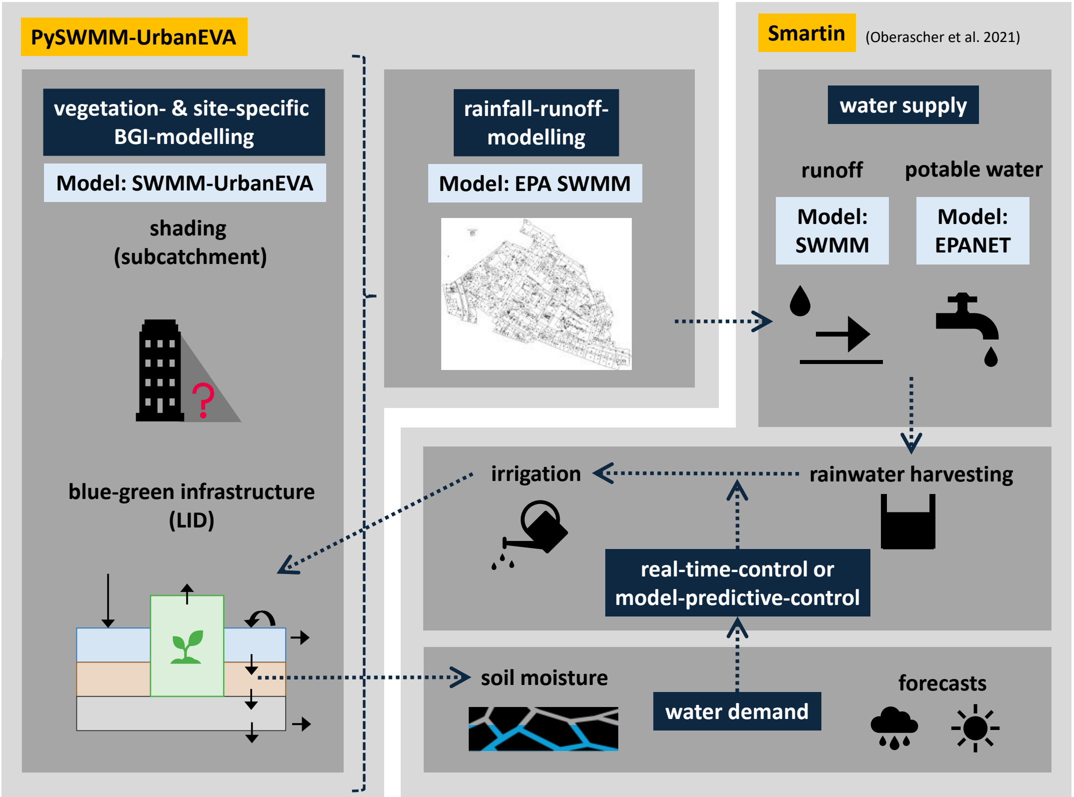

Figure 1. Structural overview on Python-based modelling framework

PySWMMUrbanEVA is developed as an Python Wrapper equivalent to PySWMM (McDonnell et al. 2020), containing the combined functionalities of SWMM and SWMM-UrbanEVA. The SWMM rainfall-runoff model is set up for the impervious surfaces as well as the sewer system. Pervious surfaces are mapped using the optimized LID module by SWMM-UrbanEVA. ET-reduction due to shading is applied to both, pervious and impervious subcatchments.

The "Smartin" Python package (Oberascher et al. 2021) is utilized for irrigation management. Smartin serves as a link between the water supply and water demand, incorporating RTC- or MPC-strategies for irrigation. Rainwater harvesting storages are fed by runoff from defined impervious surfaces, as modelled by SWMM. Alternatively, potable water is provided, modelled by the Python EPANET Toolkit (Open Water Analytics 2025). Water demand is calculated through the extraction of moisture conditions from the BGIs and/or the addition of forecasts. The results can be read at each routing step which allows flexible integration and adaption of various irrigation control strategies.

Case study

Study area

The modelling framework has been configured and evaluated for an urban catchment in Münster, Germany, using climate data with an average precipitation of 691 mm·a^{-1} and grass reference evapotranspiration of 490 mm·a^{-1}.The catchment area measures 10 acres and is predominantly characterised by impervious surfaces, such as roofs, asphalt and pavements, with a minor presence of green spaces, including gardens and street trees (Figure 2 a). The area is dominated by larger buildings, which result in significant shading within the street canyons (Figure 2 b).

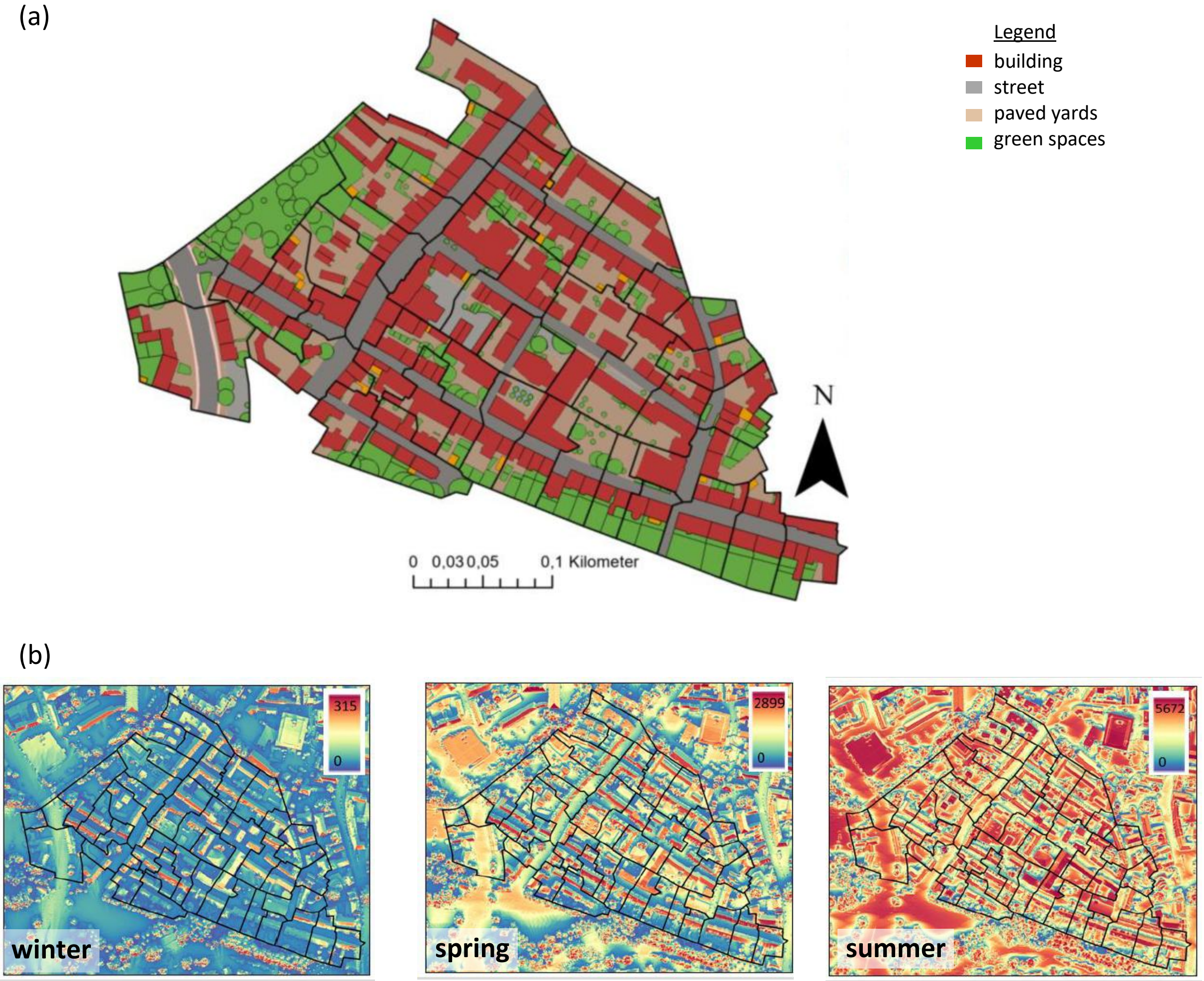

Figure 2. Overview on study area (a) and results of GIS shading-impact-analysis (b) for summer solstice (June 21st), equinox (March 20th) and winter solstice (December 21st)

Model setup

The rainfall-runoff-model is set up including impervious surfaces and the sewer system based on SWMM approaches, supplemented by SWMM-UrbanEVA LID-controls representing the pervious surfaces. Six BGI-types are defined (small/ medium/ high street tree, grass, mixed green spaces/gardens, hedges) and parameterized according to the parameterization toolsets previously developed by Hörnschemeyer et al. (2023). To enable the consideration of seasonal variations in shading impact, a GIS shading-impact-analysis is conducted for three days a year (winter solstice, equinox, summer solstice) (Figure 2 b) and integrated into the model for all impervious and pervious subcatchments. The "status quo" model version is then calibrated for discharge. For irrigation scenarios, RWH storages are placed decentralized to collect the roof's runoff. A target BGI is assigned to each storage. Irrigation is provided during the summer months, from April to September.

Scenarios

The modelling frameworks allows the comparison of several scenarios:

- irrigation control strategies: static irrigation, RTC based on soil moisture, MPC based on demand forecasts
- irrigation demand: variation of irrigation volume in terms of irrigation efficiency
- storage capacity: variation of storage volume in terms of demand coverage and runoff reduction

The simulation results are analyzed for (i) water balance and drought stress of the BGI as well as (ii) storage volume, demand coverage, irrigation efficiency (mm ET per mm irrigation) and runoff reduction through the RWH storages.

Results and discussion

Irrigation control strategies have been tested for several scenarios. First outcomes can be summarized as follows:

1. Irrigation can significantly reduce the drought stress of the BGI in the summer months and strengthen ET. Depending on the BGI type, ET can be increased by up to 60%.
2. Runoff volumes into the sewer system can be reduced by up to 36%, depending on the storage location. Overflow volumes in the sewer system can be reduced by 10% for the period under consideration. If the storage tank is emptied in advance based on a precipitation forecast, the area runoff can be reduced by a further 12%.
3. RTC depending on soil moisture shows a higher irrigation efficiency compared to static irrigation. MPC depending on water demand forecasts can further increase irrigation efficiency compared to RTC.

Current work includes (i) more detailed analysis of different irrigation control strategies with a particular focus on RTC- and MPC-strategies, (ii) development of recommendations for irrigation volume and configuration of irrigation control strategies, (iii) validation for a second study area in Münster, Germany, and (iv) application of the modelling frameworks for citizen information using dashboards for real-time forecasting of irrigation demand.

Besides, there is a need to investigate the impact of those irrigation control strategies on the overall urban water and energy balance. In addition, further discourse is required on the feasibility of implementing these strategies in urban areas, with particular emphasis on (i) data requirements, (ii) maintenance requirements and (iii) the integration of high-technology components.

Conclusions and future work

The developed modelling framework effectively bridges location- and plant-specific BGI modelling and irrigation management. By integrating demand-oriented strategies such as RTC and MPC, the framework helps to optimize water usage as well as urban water and energy balance.

Current and future work applies the modelling framework to comparative studies of irrigation control strategies with respect to water balance and climate adaptation. In this context, the framework will help to both: advance knowledge on sustainable urban development and enable practical applications. Its flexibility allows for seamless integration of RTC and MPC operations into RWH systems, while also providing opportunities for citizen information through real-time irrigation demand forecasting.

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