Modeling Long-Term Water Balances of Green Infrastructures using SWMM Extended with the Evapotranspiration Model SWMM-UrbanEVA

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Highlights

- SWMM upgraded with ET-model SWMM-UrbanEVA could be calibrated and validated with good model performance for long-term water balances of green roofs.
- Vegetation specific ET-modeling is essential when evaluating long-term water balances.
- Dry period's ET-modeling also influences available soil storage capacities for wet periods.

Introduction

Facing the upcoming challenges of urbanization, global warming and demographic change, green infrastructures (GI) are needed for developing sustainable adaptation strategies. Therefore, urban drainage models are used for decision support, evaluating (i) urban water balances (long-term) and (ii) single events (design storms). Urban hydrology has so far lacked a suitable model for long-term water balancing of GI, addressing evapotranspiration (ET) with vegetation-specific dynamics (e.g., Feng and Burian, 2016; Poë et al., 2015). The objective of this study is to test the applicability of SWMM extended with the ET-Model SWMM-UrbanEVA for simulating the hydrologic performance of GI.

Methodology

The study focused on long-term simulations of green roofs. Different exfiltration measurements were chosen for evaluating parameter sensitivities and calibrated model performance.

Measurements

Various green roofs were monitored since 2015 in Münster, Germany. The large-scale green roof at the Münster University of Applied Sciences Center (FHZ) has an area of 80 m². In addition, four test-bed green roofs with an area of 3 m² each (Leo 1, 4, 7 and 10) were investigated. The systems vary in substrate height (6 cm for Leo 1 & 4, 10 cm for Leo 7, and 15 cm for Leo 10) and drainage mats. The roofs are planted with a mixture of sedum species with herbs and grasses. Climate data were recorded at both locations since 2015 (FHZ, Δt=5 min) and 2016 (Leo, Δt=1 min). Runoff was measured volumetrically with an accuracy of Δh_R=0.1 mm and Δt=5 min (Scherer et al., 2017). Further information on the measurement setup will be provided in the presentation and in an additional full paper.

Model setup

The LID (Low Impact Development) bio-retention module of SWMM (US EPA) (Rossman, 2015) was used, upgraded with SWMM-UrbanEVA for optimized ET-modeling of GI (Hörnschemeyer et al., 2021). In contrast to original SWMM, SWMM-UrbanEVA can map shading impacts as well as dependencies on vegetation, soil and moisture conditions.

The sensitivity analysis was carried out globally with Latin Hypercube Sampling (McKay et al., 1979), varying all LID and SWMM-UrbanEVA variables with 100 simulations for each variable. The Pearson correlation coefficient cor was chosen for correlation evaluation.

The models were calibrated automatically for 6-month runoff measurements in 2017 using the Shuffled-Complex-Evolution Method University of Arizona (SCEUA) (Duan et al., 2003). Nash-Sutcliffe model efficiency coefficient NSE (Nash and Sutcliffe, 1970) and volume error Vol were selected to evaluate the goodness-of-fit. Both, sensitivity analysis and calibration were done using KALIMOD, an interface between simulation models and optimization algorithms (Henrichs et al., 2014, 2009). For validation two 3-month validation periods were analyzed. The results were compared with simulations using current SWMM.

Results and discussion

The results of the sensitivity analysis indicate that the newly added crop factor K_C is most influential on total ET (cor=0.84). To minimize volume errors, it must be derived very carefully according to Allen et al. (2005). Further sensitive model inputs are the soil characteristics (wilting point, field capacity, porosity, soil depth, conductivity slope), observing cor=0.27 for the available water capacity volume and cor=0.26 for the air capacity volume. The leaf area index LAI controls ET flux interactions (interception, transpiration, evaporation) and is therefore important for realistically modeling the soil-plant-atmosphere system.

Table 1. Calibrated parameter values for FHZ and Leo 10 with calibration boundaries Min and Max.

LID-Layer	Parameter	Unit	Min	Max	**FHZ**
vegetation	crop factor	-	1	3	**1.14**
soil	porosity	-	0.22	0.65	**0.40**
soil	wilting point	-	0	0.20	**0.07**
soil	conductivity slope	-	1	100	**37.6**
drain	flow coefficient	$1 \cdot h^{-1}$	0.25	120	**43**
drain	flow exponent	-	0.1	1	**0.2**

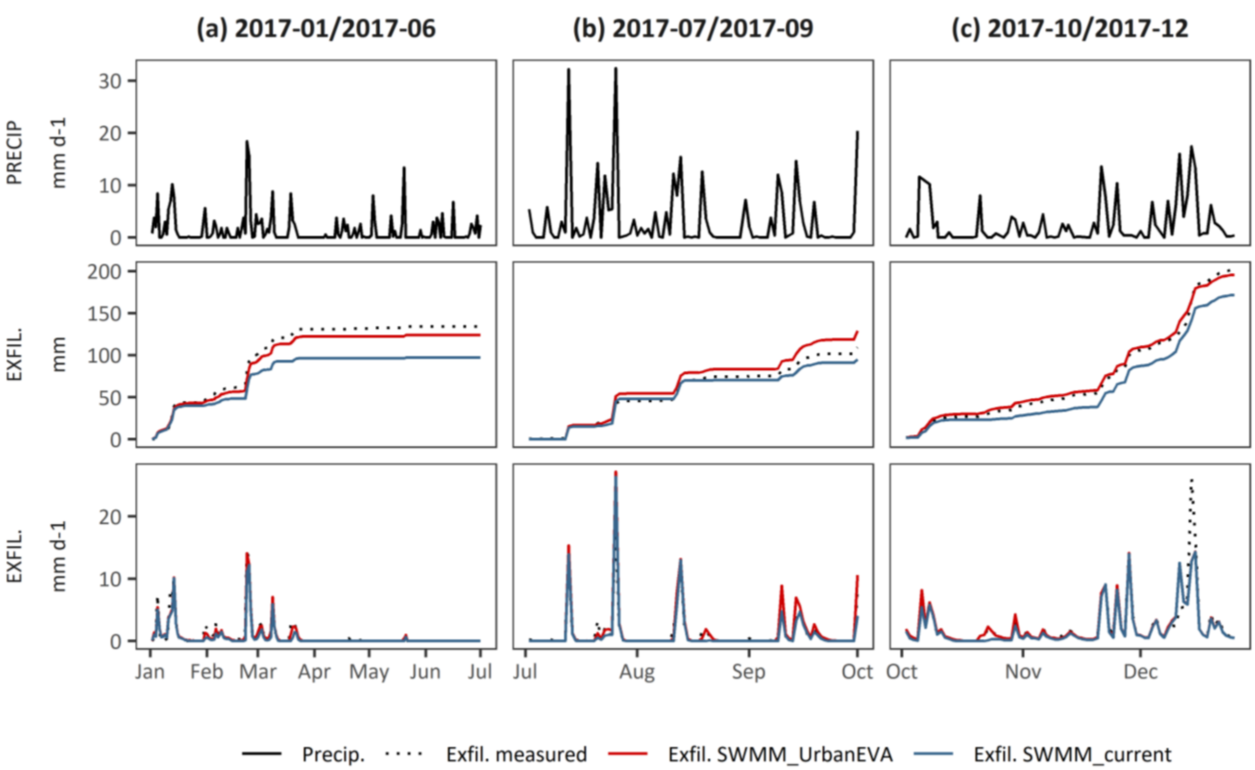

Figure 1. Measured and modelled exfiltration for green roof “FHZ”. Plotted periods are (a) calibration period and (b)/(c) two validation periods.

The calibration results are exemplarily given in Table 1 and Figure 1 for green roof "FHZ". The best-fit parameter sets of the calibration runs are within a realistic range (Table 1). Final goodness of fit criteria indicate good results for SWMM-UrbanEVA. Volume errors of $Vol_{UrbanEVA}$=-8% (Figure 1) are low in contrast to current SWMM ($Vol_{current}$=-28%). The underestimation of exfiltration at current SWMM goes back to lacks in ET-modeling during dry periods. Due to the missing dependencies of ET on soil and plant physiological parameters, ET is clearly overestimated. This underlines the relevance of suitable ET-modeling for long-term water balancing of GI.

In contrast, both models show very good adaption to measured exfiltration dynamics with $NSE_{UrbanEVA}$=0.95 and $NSE_{current}$=0.9. The slight change in model's process dynamics can be explained with different available soil storage capacities. Therefore, unlike during dry periods, soil storage and runoff concentration processes are the regulating ones during wet periods.

Similar results can be observed for the two validation periods.

Conclusions and future work

The LID bio-retention module of SWMM upgraded with ET-model SWMM-UrbanEVA could be calibrated and validated with good model performance for long-term water balances of green roofs. The results show that missing vegetation specific ET-modeling leads to distinct volume errors. Furthermore, impacts on wet period's available soil storage capacities can be observed. In the context of increasing relevance of green solutions in urban areas, this highlights the need of suitable models for long-term evaluations of GI. Future investigations must focus on parameterization and validation for different GI. Moreover, the integration of further aspects of urban water and energy balance to ET modeling (e.g., urban heat island) must be discussed.

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