Long-Term Water Balances of Green Roofs under Varied Climate Conditions

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Highlights

- Hydrologic behaviour of different green roofs under varied climate conditions were evaluated.
- Depending on design and climate conditions, green roof performance differs clearly.
- Climate conditions must always be considered when efficiently designing a green roof.

Introduction

Sustainable adaptation strategies using blue-green infrastructures address the upcoming challenges of urbanization, global warming and demographic change. Green roofs are being increasingly chosen to meet those problems. While numerous studies focus on runoff peak reduction and short-term water balances (e.g., Fassman-Beck et al., 2013; Stovin et al., 2015), long-term investigations support further understanding of green roof efficiency and enable the identification of influential factors on their water balance and their potential to contribute to cooling the urban environment by evapotranspiration (ET). Therefore, this study focuses on long-term effects of (i) different system designs and (ii) the influence of varied climate conditions. The range of resulting hydrologic performance as well as recommendations for further green roof design should be derived.

Methodology

The study is carried out in two steps. Starting with the analysis of different measurements, calibrated models were used for long-term simulations for three different locations.

Figure 1. Overview of test-beds "Leo"

Measurements

Starting in 2015, various green roofs green roofs in Münster, Germany, were monitored. In addition to a large-scale green roof at the Münster University of Applied Sciences Center (FHZ 1) with an area of 80 m², four test-bed green roofs with an area of 3 m² each (Leo 1, 4, 7 and 10) were investigated for this study (**Figure 1**). 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. All green roofs have a slope of 3%. The vegetation consists of 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. Additionally, the soil moisture of test-beds "Leo" was monitored (Scherer et al., 2017).

Long-term Simulation: SWMM-UrbanEVA

The Model SWMM-UrbanEVA (Hörnschemeyer et al., 2021) was used for calibration and long-term simulation for all green roofs. The LID bio-retention module of SWMM was calibrated for runoff measurements in 2017 using the Shuffled-Complex-Evolution Method University of Arizona (SCEUA) (Duan et al., 2003). Further information can be found at Hörnschemeyer et al. (2021). The calibrated models were used for 20-yr long-term simulations (1998-2017) with data of the German Weather Service. Location “Airport Münster/ Osnabrück” (FMO) has similar climate conditions as the measurement site, situated 20 km north-east of Münster (mean annual precipitation h_P=751 mm·a^{-1}, ET_0=465 mm·a^{-1}). To consider contrasting climate conditions, two more locations were added to the study: “Freudenstadt” (FRE) with high mean h_P=1501 mm·a^{-1} (ET_0=493 mm·a^{-1}) and “Gruenow” (GRU) with low mean h_P=487 mm·a^{-1} (ET_0=398 mm·a^{-1}).

Results and discussion

Measured water balance

The results (**Table 1**) show a total precipitation of 814 mm in 2017 (421 mm in summer and 393 mm in winter) with potential evapotranspiration ET_0 being 478 mm. For 2017, runoff coefficients vary between 41% and 57% depending on the substrate heights. For summer months significantly smaller runoff coefficients can be identified, ranging from 22% to 36%. For “Leo” test-beds, the two roofs with 6 cm substrate (Leo 1 and 4) and the roof with 10 cm substrate (Leo 7) have comparable runoff and ET heights. The roof with a substrate height of 15 cm (Leo 10) shows slightly lower runoff. This results from both the higher storage volume of the substrate and the more ET-active vegetation volume of this green roof (**Figure 1**).

Table 1. Measured heights for precipitation (h_P), grass reference evapotranspiration (ET_0) and runoff (h_R). Resulting runoff coefficients h_R/h_P are added.

	2017		Summer*		Winter*	
PRECIPITATION	h_P (mm)		h_P (mm)		h_P (mm)	
All green roofs	814		421		393	
POT. EVAPOTRANSPIRATION	ET_0 (mm)		ET_0 (mm)		ET_0 (mm)	
All green roofs	478		358		120	
RUNOFF	h_R (mm)	h_R/h_P (-)	h_R (mm)	h_R/h_P (-)	h_R (mm)	h_R/h_P (-)
FHZ 1 (6 cm)	467	0.57	150	0.36	316	0.80
Leo 1 (6 cm)	405	0.50	138	0.33	266	0.68
Leo 4 (6 cm)	412	0.51	146	0.35	266	0.68
Leo 7 (10 cm)	398	0.49	130	0.31	269	0.68
Leo 10 (15 cm)	333	0.41	91	0.22	242	0.62

*Summer = May-October, Winter = November-April

Simulated observations

The calibrations were successfully carried out for the green roofs under consideration. Final goodness-of-fit criteria indicate good behaviour of calibrated models with Nash-Sutcliff-Coefficients NSE > 0.70 and low volume errors Vol < 10%. Calibrated parameter values are in a realistic range (Hörnschemeyer et al., 2021). The results show decreasing runoff with increasing substrate heights, which is similar to measured observations. Exemplarily plotted for green roof FHZ 1, the measured runoffs (**Table 1**) can be validated for similar climate conditions at FMO (quantiles h_R between 344 and 456 mm·a^{-1} and h_R/h_P between 0.53 and 0.58) (**Figure 2**). For locations with high annual h_P (FRE) the runoff coefficients go up to 0.80, since the green roof has little retention storage. For low annual h_P (GRU) the runoff coefficients decrease to 0.43. These differences underline the distinct dependence of green roof efficiency on climatic conditions.

The frequency plot (**Figure 3**) shows the relative soil moisture SM_{rel} which is defined as the ratio of mean daily soil moisture and available water capacity volume. SM_{rel} > 1 indicates exfiltration. A clear difference between summer and winter conditions can be observed for all locations. Summer is clearly dominated by very dry situations with SM_{rel} < 0.2 while during winter exfiltration is most frequent. The high number of days with very low SM_{rel} leads to distinct ET-reduction, up to the standstill of ET-processes in continuously drought periods. No cooling effect can be expected then. With increasing annual h_P (FRE), the frequency of very low SM_{rel} during summer decreases while the exfiltration during winter increases. The opposite can be observed for locations with low annual h_P (GRU). With further analysis of green roof’s system behaviour this knowledge will result in recommendations for green roof design for different climate conditions.

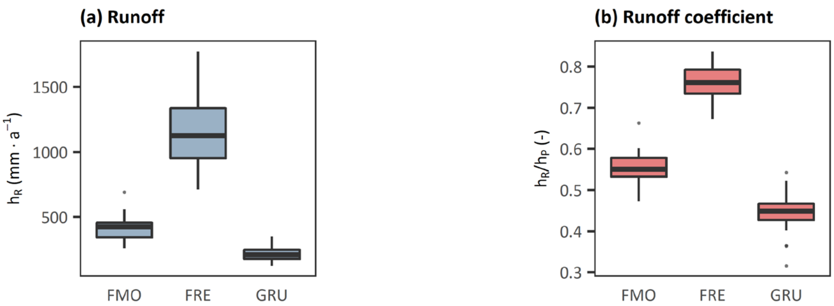

Figure 2. Annual simulated runoff h_R (a) and runoff coefficient h_R/h_P (b) of green roof FHZ 1 for a 20-years timeseries (1998/2017) at three locations FMO, FRE and GRU.

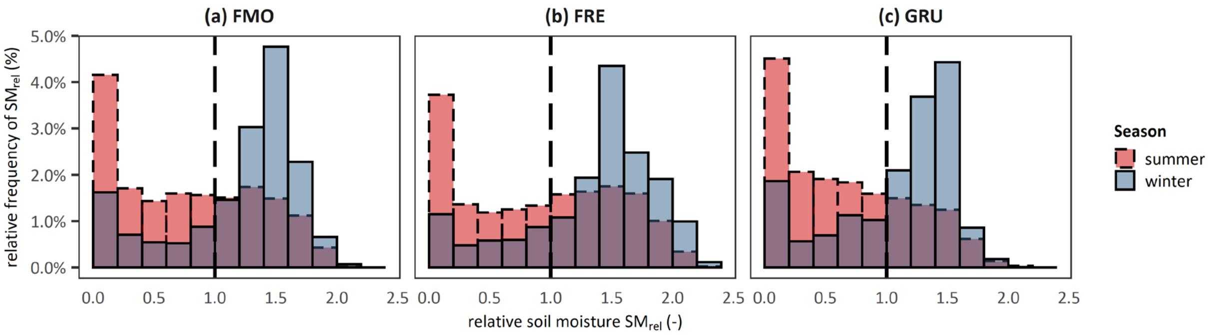

Figure 3. Relative frequencies of daily mean relative soil moisture (SM_{rel}) of green roof FHZ 1 for a 20-years timeseries (1998/2017) at three locations FMO (a), FRE (b) and GRU (c).

Conclusion and future work

Based on long-term simulations of the water balance and the soil moisture of green roofs, the influence of climate conditions on daily soil moisture and water retention of different types of green roofs was studied. Data were generated by a calibrated green roof simulation model with 20-yr times series of three weather stations with different climatic conditions in Germany. The annual retention depends on the substrate height and mainly on the difference of annual h_P and ET_0. The frequency analysis of the soil moisture shows clear seasonal dependencies. During summer low soil moisture is frequent. During those periods ET decreases and even stops so that no cooling effects can be expected. At the same time, a high storage capacity for potential precipitation is maintained, which leads to a high retention effects in summer. During winter ET is low resulting in high soil moistures and low retention effects during rainfall.
The observed dependence of green roof efficiency on local climatic conditions underlines the need of new design guidelines for green roofs as cost-effective instruments of the blue green infrastructure. Further investigations must be carried out on that topic. Moreover, connecting hydrological efficiency with cost-benefit analysis and life cycle assessment could give further indications on effective use of green roofs in urban design.

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