# Setting up a SWMM-integrated model for the evapotranspiration of urban vegetation

Mise en place d'un modèle intégré SWMM pour l'évapotranspiration de la végétation urbaine

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## RÉSUMÉ

Dans les zones urbaines, le bilan hydrique et énergétique ainsi que le climat urbain ont changé. Dans le cadre du développement urbain durable, la végétation est considérée comme ayant une fonction d'ombrage et d'évaporation. Jusqu'à présent, l'hydrologie urbaine ne disposait pas d'un modèle de simulation approprié. Le modèle de simulation développé permet SWMM-UrbanEVA de simuler l'évapotranspiration de la végétation dans les zones urbaines. Pour les hydrotopes homogènes d'espaces urbains ouverts, la modélisation du bilan énergétique et hydrique du système sol-plante-atmosphère est réalisée sur la base de l'évaporation de référence FAO ($ET_0$). En incluant les caractéristiques météorologiques et végétales, il est possible d'effectuer un calcul spatio-temporel différencié qui montre également la dynamique annuelle de la végétation. L'infrastructure bleu-vert pour la gestion des eaux pluviales est explicitement prise en compte. Le lien avec le modèle hydrologique SWMM (US EPA) ainsi que l'intégration de normes internationalement acceptées, telles que l'évaporation de référence de la FAO ou l'indice de surface foliaire (LAI), garantissent une application simple. En raison de l'évolutivité à l'échelle micro et mésoéchelle, le modèle offre la possibilité d'analyser divers effets sur le bilan hydrique et énergétique urbain.

## ABSTRACT

In urban areas, the water and energy balance as well as the urban climate have changed. As part of sustainable urban development, vegetation is considered to have the function of shading and evaporation. Urban hydrology has so far lacked a suitable simulation model for this. The developed simulation model SWMM-UrbanEVA allows the site-specific simulation of the evapotranspiration of vegetation in urban areas. For homogeneous hydrotopes of urban green spaces, process modelling of the energy and water balance of the soil-plant-atmosphere system is carried out on the basis of FAO grass reference evaporation ($ET_0$). With including meteorological and vegetation characteristics, a spatio-temporal differentiated calculation is possible that also displays the yearly vegetation dynamics. Blue-green infrastructure for stormwater management is explicitly considered. The connection to the hydrological model SWMM (US EPA) and the integration of internationally accepted standards, such as the FAO grass reference evaporation or the leaf area index (LAI), ensure simple application. Due to the scalability to micro- and mesoscale investigations, the model offers the possibility of analysing various effects in the urban water and energy balance.

## KEYWORDS

blue-green-infrastructure, evapotranspiration, hydrological modelling, SWMM (US-EPA), urban, vegetation,

# 1 INTRODUCTION

In times of climate change, urbanisation and demographic change, cities as preferred habitats are increasingly facing new challenges. The water and energy balance is affected by major changes (Fletcher et al., 2013). Sustainable adaptation strategies should address these negative effects. For urban hydrology, evaporation represents a decisive parameter in water balancing. In the context of resource-efficient urban development, often only simple approaches for evaporation together with averaged area characteristics were chosen. Micro-scaled structures, such as various urban vegetation areas, found very little representation in the models, although sustainable strategy development takes place at this level.

So far, there is no product that models both adequately, the blue-green infrastructure and the sewer systems. The internationally widely used Stormwater Management Model (SWMM, US EPA), for example, can only differentiate between vegetation by using soil parameters. Therefore, the aim of this study was to develop a partial model for evapotranspiration of urban green that can be used within the framework of SWMM and other models. As far as possible, the complex relationships of the soil-plant-atmosphere system should be taken into account, so that dynamic modelling of different vegetation elements is possible.

# 2 METHODS

## 2.1 Methodology

Numerous modelling approaches have been investigated to establish the model. Central questions were the projection of the interception onto the entire surface or the fraction of covered soil (SCF, e.g.Šimůnek et al., 2013), the application of the approach of maximum possible evaporation already implemented in SWMM (Rossman and Huber, 2016), the interaction of interception and transpiration over the water-wetted leaf surface (e.g. Deardorff, 1978) as well as the modelling of soil evaporation and transpiration as a function of soil moisture (e.g. Zhao et al., 2013). To evaluate the plausibility and applicability, all approaches were combined and compared with each other with regard to system behaviour (water balance, proportion of evaporation components, annual variation etc.).

For the validation, measured data of the full scale lysimeter St. Arnold, Germany, were used, for which infiltration rates as well as climatic data for different vegetation forms (grassland, coniferous and deciduous trees) have been collected over five decades. The lysimeter has a long-term average of 793 mm precipitation and 460 mm $ET_0$ per year. Due to sandy soil in St. Arnold no surface runoff occurs (Henrichs et al., 2019). The simulation period was fixed at 20 years (1989 to 2009). In addition to validation using the vegetation forms of the lysimeter, further vegetation forms were simulated to test the general system behaviour. Choosing another global standard, FAO grass reference evaporation was used as input time series for potential evaporation rates.

## 2.2 Model description

SWMM-UrbanEVA is based on the open-source product SWMM (US EPA) where it is integrated into the Low Impact Development (LID) module. The existing three-layer system (surface - soil – storage) is retained. In addition, a so-called vegetation layer is integrated (Figure 1) for which various plant-specific properties can be defined. The evapotranspiration components are not fed from all three layers (as before) but are assigned to the different layers. Thus, the interception evaporation $E_I$ takes place out of the vegetation layer which means that the interception itself is also assigned there. Transpiration $E_T$ and (soil-) evaporation $E_S$ are interacting processes, both dependent on the soil moisture and are therefore fed from the soil layer. The last evapotranspiration component is the evaporation of free water surfaces $E_W$ which is assigned to the surface layer.

The leaf area index (LAI) is included into the model as a central vegetation parameter. For dynamically modelling the vegetation over the year, a monthly growth factor (gf) is implemented, so the average LAI entered can be calculated month-specifically. The soil-covered-fraction (SCF) can also be calculated dynamically by using the LAI. The calculation is done according to Bremicker (2000). Further vegetation-specific parameters in the model are the leaf storage coefficient (recommended 0,29) and the maximum interception capacity that is also calculated dynamically. Using this model structure, the only variable input parameter is the LAI.

An energetic uncoupling of the plant-bound processes interception and transpiration from the soil evaporation is ensured via the SCF. It is assumed that the soil evaporation under the vegetation is negligible and therefore only takes place in the uncovered part. For the interception height I the best results are obtained with a projection onto the SCF and calculation according to Braden (1985). His approach calculates the interception height as a function of the precipitation intensity P. The interacting processes transpiration and interception evaporation are calculated according to Deardorff (1978) and Dickinson (1984) via the fraction of the wetted leaf surface. Interception evaporation takes place only from the wetted part, while transpiration takes place from the dry surface. Soil evaporation is defined as a function of the relative soil moisture which describes the fraction of soil water present in the usable field capacity.

Further information about the model structure will be published in Hörnschemeyer et al. (in preparation).

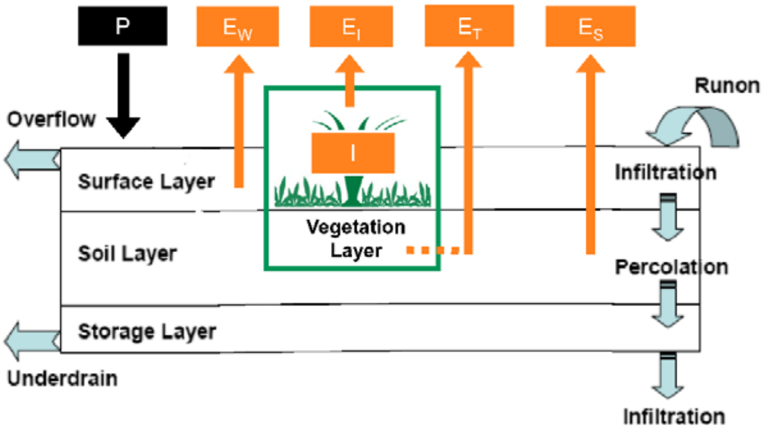


*Figure 1: Defining the vegetation layer and the evaporation components within the existing soilmodel (modified after Rossman and Huber, 2016)*

## 3 RESULTS AND DISCUSSION

Various evaluations show that the evapotranspiration of vegetation can be simulated well using SWMM-UrbanEVA. Figure 2 shows the monthly evapotranspiration for three different vegetation types which differ in the LAI. While the coniferous tree is set with LAI = 8, the deciduous tree has a LAI = 6 and the grass land LAI = 1 (Breuer et al., 2003). The differences between these plants represent a plausible system behaviour: the higher the LAI, the higher the evapotranspiration rate. This observation especially can be made during the summer months. The low evapotranspiration rates of all plants during the winter are due to the low potential rates.

Further evaluations show additional correlations to the LAI: By calculation with the SCF, the (soil-) evaporation rate is reduced as the LAI increases. At the same time, interception evaporation and transpiration increase.

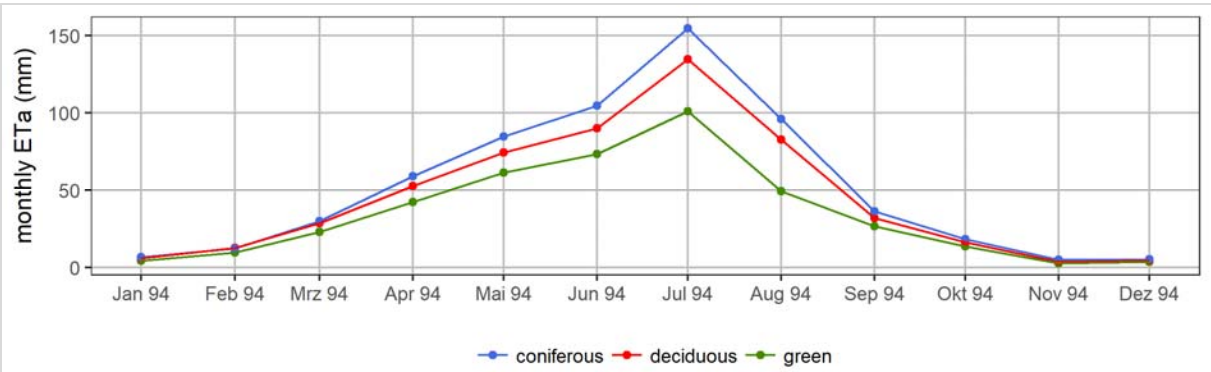


*Figure 2: Monthly evapotranspiration rates (ETa) for three different vegetation types*

Figure 3 shows the validation of the model using the infiltration rates of St. Arnold. The measured data are plotted as well as the simulation results of SWMM-UrbanEVA (Sim_Developed) and the existing SWMM version (Sim_SWMM). Both models have been calibrated before. For SWMM-UrbanEVA only very small volume deviations of the infiltration rate exist. The implementation of the LAI enables the model to calculate significantly higher evapotranspiration rates than the existing SWMM model which lacks the compensation for evaporation-intensive elements. Apart from the soil parameters, there is no possibility to adapt to different vegetation forms in this model.

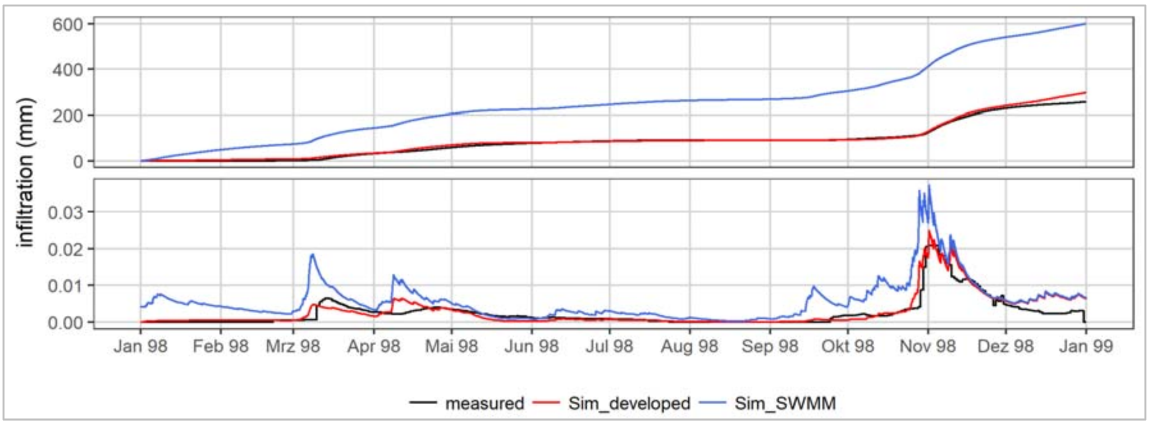


*Figure 3: Comparison of measured and simulated infiltration of a coniferous forest*

# 4 CONCLUSION

The new evapotranspiration model SWMM-UrbanEVA for urban vegetation was developed as a submodel for the LID module in SWMM (US EPA). In addition to the existing soil layers, it provides a vegetation layer, so the soil-plant-atmosphere system can be appropriately modelled. The model can depict different vegetation types in detail. The energetic coupling of the two processes $E_I$ and $E_T$ in the plant-atmosphere system and the soil moisture-dependent evaporation characteristics in the plant-soil-atmosphere system can be reproduced. The LAI is the central vegetation-specific input parameter. By defining a growth factor, the yearly dynamics of the vegetation can be expressed. The LAI proves to be a robust input parameter so the differentiation between the evapotranspiration components can be successfully described. In addition, it can be used to model various forms of vegetation with differences in evaporation characteristics. Moreover, the simple model structure allows a transfer to similar urban drainage models.

SWMM-UrbanEVA is currently being extended to integrate further typical urban effects on the water and energy balance especially shading by buildings and big vegetation and heat flow from ground and buildings. Further investigations on the parameterisation of vegetation in urban areas (e.g. LAI) are currently carried out. Urban EVA will be able to support the development and application of blue-green infrastructure in our cities. The SWMM-UrbanEVA model is available upon request.

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