

# Development and evaluation of Bioretention Stormwater Control Measures in TEB model to urban stormwater management

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## Highlights

- Development of an innovative Stormwater Control Measures (SCM) module within the TEB model.
- TEB accurately replicates the hydrological interactions between the SCM and the surrounding urban environment.
- Comparative analysis with the SWMM model demonstrates the effectiveness of the proposed SCM approach.

## Introduction

In the field of stormwater management, the modelling of Stormwater Control Measures (SCM) is paramount for understanding their impacts on urban runoff mitigation. However, prevalent stormwater models often oversimplify hydrological processes in SCM modelling. These limitations raise crucial questions about the capacity of SCM models in representing the complex interaction between stormwater and the multifaceted hydrological phenomena shaping urban ecosystems. To address these challenges, a careful examination of modelling limitations is imperative to enhance the precision and applicability of stormwater management strategies.

The TEB (Town Energy Balance) model (Bernard et al., 2021), integrating the ISBA-DF transfer scheme (Boone et al., 2000), offers a comprehensive view of energy and water transfers in urban environments. Tailored for urban hydro-climatic analysis, it utilizes a grid-based approach based on canyon street, to depict three key urban components: buildings, roads, and gardens, providing a realistic representation of hydrological processes at various scales. TEB's capabilities extend beyond hydrological considerations, incorporating from its original version, complex modelling of radiative and energetic phenomena within urban landscapes. The model perfectly combines hydrologic, energetic and radiative processes, making TEB one of the few models capable of performing this integrated form of modelling.

Recognizing the distinctive features of the TEB model, we have chosen to employ it in developing a Stormwater Control Measures (SCM) module. This strategic decision aims to overcome the limitations discussed earlier, enhancing the precision and performance of SCM modelling. TEB's SCM module allows us to develop a versatile modeling framework adaptable to various types of SCMs. This framework links hydrology and urban climate effectively, providing a more detailed description of hydrological processes such as evapotranspiration. In addition, this SCM module is designed for modeling at large spatial scales.

This paper specifically details the development of bioretention (only with an exfiltrating underground storage compartment) within the SCM module. To evaluate the hydrological performance of the proposed SCM approach in TEB model, the well-established LID bioretention module of SWMM (Rossman, 2015) has been utilized as a reference for comparison.

## Methodology

### Development of the hydrological processes to be modelled in the TEB SCM module.

For the development of this SCM module, we initially integrated the established hydrological processes from the TEB model. Regarding the SCM substrate, all hydrological processes associated with this compartment are governed by the ISBA model (Boone et al., 2000), which concurrently oversees the soil column in the various urban road, building, and garden compartments within TEB. Rainfall interception by vegetation will be simulated utilizing the reservoir mechanism inherent in TEB. The percolation of water from the substrate to the underground storage compartment adopts the same methodology employed by ISBA to compute water flux to the deeper layer of the soil column. Conversely, processes absent in the TEB model were introduced through a reservoir-type approach. The key new processes include:

- **storage – infiltration reservoir (SI):** this reservoir serves as a temporary storage for water derived from direct rainfall and runoff from impervious areas drained by the SCM. The stored water later either infiltrates into the substrate or evaporates to the atmosphere. In cases where the water collected on the

SCM surface surpasses the reservoir capacity, the overflow is directed to the garden compartment of the TEB mesh. The equation governing the reservoir can be written in the following form:

$$h_{SI}(t) \cdot \Delta t = DR_{SI}(t) + R_{SI}(t) - F_{SI-ovf}(t) - F^*_{SI-evp}(t) - F^*_{SI-inf}(t) \quad (1)$$

where  $h_{SI}(t)$ : water level of the SI reservoir [L];  $\Delta t$ : time step [T];  $DR_{SI}(t)$ : direct rainfall collected by the SCM [ $LT^{-1}$ ];  $R_{SI}(t)$ : runoff from impervious areas drained by the SCM [ $LT^{-1}$ ];  $F_{SI-ovf}(t)$ : overflow [ $LT^{-1}$ ];  $F^*_{SI-evp}(t)$ : water evaporation [ $LT^{-1}$ ];  $F^*_{SI-inf}(t)$ : water infiltration [ $LT^{-1}$ ].

The equations for calculating water infiltration and evaporation have been adapted from existing equations in TEB model.

- **Storage – exfiltration reservoir (SE):** This reservoir collects water fluxes from the SCM substrate. The stored water will then be exfiltrated into the natural soil surrounding the SCM or by possible overflow of the reservoir. The equation governing the reservoir can be written in the following form:

$$h_{SE}(t) \cdot \Delta t \cdot \phi_{SE} = F_{subst-SE}(t) - F_{SE-ovf}(t) - F^*_{SE-ex}(t) \quad (2)$$

where  $h_{SE}(t)$ : water level of the SE reservoir [L];  $\Delta t$ : time step [T];  $\phi_{SE}$ : void ratio [-];  $F_{subst-SE}(t)$ : water flux from SCM substrate [ $LT^{-1}$ ];  $F_{SE-ovf}(t)$ : overflow [ $LT^{-1}$ ];  $F^*_{SE-ex}(t)$ : water exfiltration [ $LT^{-1}$ ].

The equation for calculating exfiltration has been adapted from Błażejowski et al. (2018), which allows to take into account, in addition to the permeability of the natural soil, the contribution of the lateral surfaces of the subway storage compartment, which is very important in this type of SCM.

Finally, SCM compartment for bioretention, result in a TEB soil column, structured in different created reservoirs or existing modules (Figure 1).

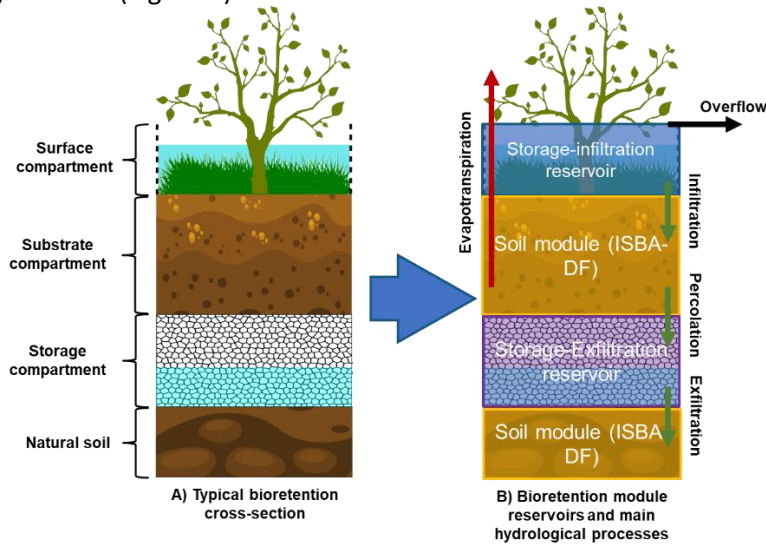


Figure 1: A) Typical bioretention cross-section. B) Bioretention conceptualized through reservoirs created and existing modules in TEB

### Comparison between TEB and SWMM

SWMM is a widely utilized software tool for simulating and analyzing stormwater runoff and drainage systems. SWMM supports various Low Impact Development (LID) practices, such as bioretention, green roofs, and permeable pavements. It enables users to strategically place and evaluate LID practices within a catchment, facilitating the assessment of their effectiveness in reducing stormwater runoff, mitigating flood risk, improving water quality, and promoting sustainable stormwater management.

For the comparison with the TEB model, we utilized the bioretention-type Low Impact Development (LID). The processes under comparison include: i) inflow from impervious areas linked to the SCM, ii) SCM hydrological processes (infiltration, evapotranspiration, percolation, exfiltration), iii) water storage in various reservoirs and the substrate, iv) potential overflow from the SCM. The aim of the comparison is to assess the adequacy of the approach used to conceptualize SCM within the TEB model.

### Case study

For comparing the SWMM and TEB models, a theoretical catchment of 1 hectare ( $10,000 \text{ m}^2$ ) was created. The catchment is segmented into four land use zones: buildings, roads (both representing the impervious surface in SWMM), garden (the permeable surface in SWMM), and SCM (LID Surface in SWMM). Meteorological data used align with that employed by Stavropoulos-Laffaille et al. (2018) in the Pin Sec

catchment in Nantes, France, covering the temporal series (1-hour time step) from May 2010 to September 2012. TEB model input meteorological data include precipitation, temperature, specific humidity, atmospheric pressure, wind speed and direction, as well as incoming shortwave and longwave radiation. In SWMM, precipitation is used, and based on the additional meteorological data provided for TEB, Penman-Monteith potential evapotranspiration (PET) is calculated. The SCM dimensions for both models are specified as follows: the surface reservoir has a maximum height of 100 mm, the substrate is 600 mm thick, and the underground storage compartment has a maximum thickness of 400 mm. Thus, in TEB, the substrate is discretized into eight soil layers of different sizes, while in SWMM, it is represented by a single soil layer. The parameters governing water movement in the substrate are computed by the TEB model and are also applied (or adapted) in the SWMM model. Table 1 summarizes all the main parameters needed in TEB and SWMM for SCM modelling.

**Table 1: Main parameters required for the modelling of bioretention-type SCMs in TEB and SWMM models**

TEB				SWMM			
Description		Quantity	Unity	Description		Quantity	Unity
General	Specific			General	Specific		
<b>Principal Catchment parameters</b>							
Land use fractions	Garden	0.208	-	Subcatchment surfaces	Pervious	2200	m <sup>2</sup>
	Building	0.500	-		Impervious	7800	m <sup>2</sup>
	Road	0.280	-		LID	120	m <sup>2</sup>
	SCM	0.012	-		Impervious surface percentage	78	%
Height of depression storage on impervious area	Impervious surface fraction	0.78	-				
	Building	2	mm	Height of depression storage on impervious area	---	2	mm
	Road	2	mm				
<b>SCM/LID principal parameters</b>							
<b>Surface compartment</b>							
Storage-infiltration reservoir	$h_{SIMAX}$	100	mm	Berm height	---	100	mm
<b>Substrate compartment</b>							
Thickness	$e_{MAX}$	600	mm	Thickness	---	600	mm
Porosity	$\omega_{sat}$	0.44	m <sup>3</sup> ·m <sup>-3</sup>	Porosity	$\omega_{sat}$	0.44	m <sup>3</sup> ·m <sup>-3</sup>
Field capacity	$FP$	0.28	m <sup>3</sup> ·m <sup>-3</sup>	Field capacity	$FP$	0.28	m <sup>3</sup> ·m <sup>-3</sup>
Wilting point	$WP$	0.11	m <sup>3</sup> ·m <sup>-3</sup>	Wilting point	$WP$	0.11	m <sup>3</sup> ·m <sup>-3</sup>
Conductivity	$k_{sat}$	102.34	m·h <sup>-1</sup>	Conductivity	$k_{sat}$	102.34	m·h <sup>-1</sup>
Initial water content	$\omega_{ini}$	0.19	m <sup>3</sup> ·m <sup>-3</sup>	initial water content	$\omega_{ini}$	0.19	m <sup>3</sup> ·m <sup>-3</sup>
<b>Storage compartment</b>							
Storage-exfiltration reservoir	$h_{SEMAX}$	400	mm	Thickness	---	400	mm
Void ratio	$\phi_{SE}$	0.4	-	Void ratio	---	0.4	-
Exfiltration rate	$k_{sat}$	102.34	m·h <sup>-1</sup>	Exfiltration rate	$k_{sat}$	102.34	m·h <sup>-1</sup>

## Results and discussion

Comparison of various hydrological processes between the two models during the study period (March 2010 - September 2012) is analyzed (Figure 2). Both models exhibit a consistent correlation for the inflow from impervious areas to the SCM, as well as the resulting overflow ( $R^2 = 0.98$ ). Concerning evapotranspiration, TEB tends to generate higher evapotranspiration flows than SWMM. This difference may arise from the more complex processes used by TEB for evapotranspiration calculation compared to the simpler approach of SWMM, which relies solely on PET. In terms of infiltration, a proper correlation is observed between the two models up to 100 mm·h<sup>-1</sup> ( $R^2 = 0.88$ ). Beyond this threshold, TEB appears to produce higher infiltration quantities than those calculated by SWMM. Percolation and exfiltration exhibit similar behavior in both models ( $R^2 = 0.92$ ), but at the maximum value reached (100 mm·h<sup>-1</sup>), the two models tend to operate differently. Regarding surface storage, there is a suitable correlation between the two models. It is evident that, during the study period, SWMM can store water up to the maximum capacity of the surface reservoir (100 mm), whereas this does not occur in the TEB model. This is attributed to overflow being the first process subtracted from the equation governing the SI reservoir in TEB (Eq. (1)), whereas in SWMM, for the LID

reservoir, it is the last process. In the case of water storage in the underground compartment, for both models, it is zero due to the high exfiltration rate (Table 1), avoiding water retention. Finally, comparing the water content of the SCM substrate in TEB and SWMM, we observe a similar performance between both models between field capacity (0.28) and substrate porosity (0.44), with soil humidity globally weaker for SWMM. However, between the wilting point (0.11) and field capacity (0.28), SWMM tends to underestimate soil water content values compared to TEB, whereas it is known to have difficulty in simulating very dry (and very wet either) soils. This may be due to the detailed representation of hydrological processes related to the root zone in TEB, while such processes are practically non-existent in SWMM.

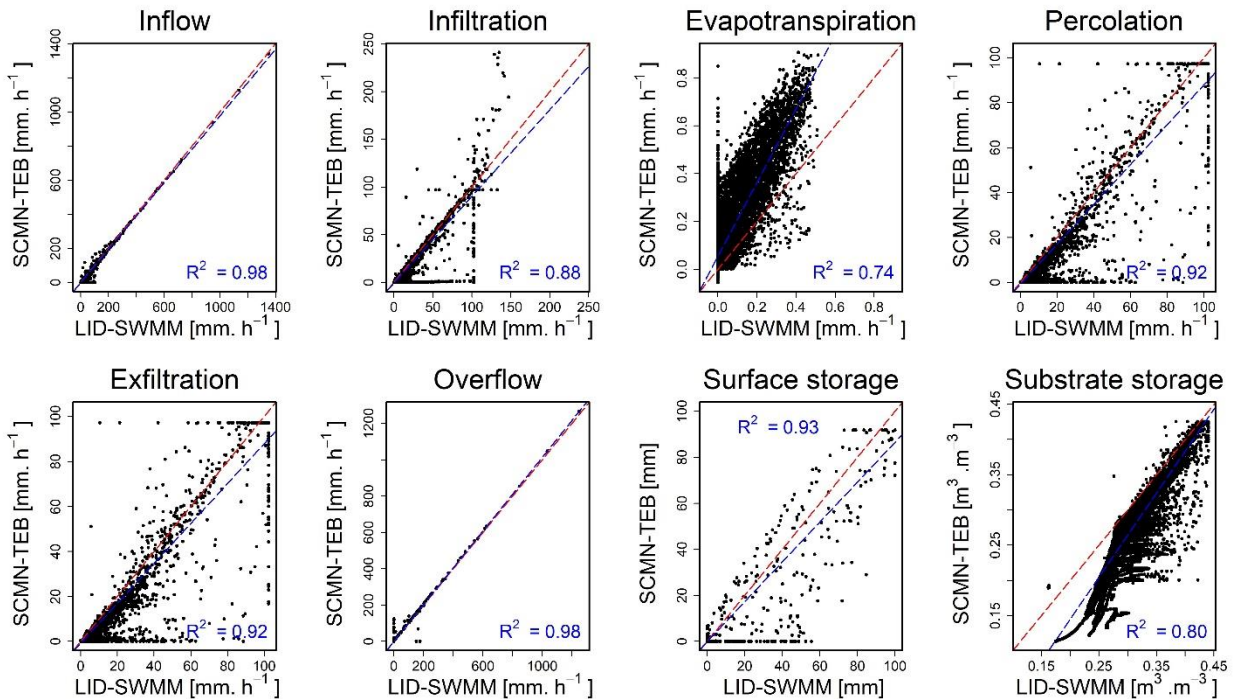


Figure 2: Comparison of different SCM hydrological processes between SWMM and TEB model

## Conclusions and future work

This paper details the creation of a bioretention-type Stormwater Control Measure (SCM) within the TEB model. The SCM's conceptualization integrates existing hydrological processes in TEB and introduces new processes with a reservoir-type approach. Performance assessment involves comparing various SCM hydrological processes in TEB with those calculated by SWMM's bioretention Low Impact Development (LID) module. The initial comparison affirms the adequacy of the SCM development in TEB, prompting a more detailed exploration of hydrological differences between TEB and SWMM. Future steps include extending this evaluation to other SCMs developed in TEB, utilizing any reference model or observed data. At the urban scale, the application of the TEB SCM module will be realized through the grouping of SCMs with similar hydrological functions into a single equivalent SCM.

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