





 <https://doi.org/10.71573/m04sza71>

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Assessing hydrological behaviours of Sustainable Drainage Systems with the Town Energy Balance Model

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Abstract

The Sustainable Drainage System module of the Town Energy Balance model (TEB-SUDS) was developed based on the Equivalent Sustainable Drainage System (E-SUDS) approach and has previously been applied to assess the hydrological responses of individual SUDS types. This study extends the analysis by evaluating the hydrological responses of aggregations of different compartments within an SUDS facility using the TEB-SUDS module. The presented results are benchmarked against the well-established Low Impact Development (LID) module of Storm Water Management Model (SWMM), demonstrating the high capability of the TEB-SUDS module in modelling the hydrological processes of SUDS facility for stormwater management.

Highlights

- Assess the hydrological responses of SUDS facilities (permeable pavement with Storage–Regulation reservoir and/or Storage–Exfiltration reservoir) using the TEB-SUDS module.
- The TEB-SUDS module can effectively model the hydrological responses of SUDS facilities compared the SWMM model.

Introduction

In recent decades, Sustainable Drainage Systems (SUDS) have been recognised as an effective and sustainable strategy for managing stormwater (see Tunqui Neira et al., 2023, for a detailed typology). To evaluate the hydrological performance of SUDS facilities, hydrological models are commonly used (Qiu, 2021). However, these models often simplify the underlying hydrological processes, which may limit their accuracy in capturing the complexities of the hydrologic behaviour of SUDS facilities, and often do not cover the full variety of existing SUDS facilities' structures. Moreover, representing one by one each SUDS facility in an urban catchment model is not really feasible, and thus aggregation approaches, with the modelling of a limited number of equivalent SUDS facilities are needed. To address these challenges, Tunqui Neira et al. (2023) developed an equivalent sustainable drainage system (E-SUDS) approach to represent a broader variety of SUDS facilities, not only in terms of their individual configurations but also their aggregations.

The Town Energy Balance (TEB) model (Bernard et al., 2021), which integrates the ISBA-DF transfer scheme (Boone et al., 2000), provides a comprehensive framework for analysing energy and water transfers in urban settings. The TEB model has been used for urban hydro-climatic studies, which employs a grid-based approach based on street canyons to represent three key urban compartments: buildings, roads, and gardens. This enables a realistic depiction of hydrological processes across different spatial scales. In addition to its hydrological functions, TEB also retains the complex modelling of radiative and energetic phenomena from its original version, making it one of the few models that effectively combine hydrological, energetic, and radiative processes in an integrated manner at the city scale.

To address the limitations mentioned earlier, a SUDS module based on E-SUDS approach has been developed within the TEB model to systematically simulate the performance of various types of SUDS facilities (e.g., bioretention with or without underground storage, permeable pavement, surface water storage, lined and non lined retention basin). Tunqui Neira et al. (2024) assessed and validated the performance of a single type of SUDS facility (bioretention with underground water storage) using the TEB-SUDS module. However, further evaluation of the other types of SUDS facility defined in TEB-SUDS module is necessary. Such an assessment is particularly important for understanding their aggregations and the modelling techniques that enable their application at larger spatial scales. Therefore, this study focuses on assessing the hydrological responses of aggregation of SUDS facilities with different configurations (i.e. permeable pavement with Storage–Regulation reservoir and/or Storage–Exfiltration reservoir) by using the TEB-SUDS module. To achieve this aim, the well-established LID module of SWMM (Rossman, 2015) is adopted as a benchmark for comparison. Here, it is important to note that the purpose of this comparison is to evaluate the suitability of the developed TEB-SUDS module, rather than to determine which model produces more accurate simulations.

Methodology

The hydrological processes of SUDS in the TEB-SUDS module

The TEB-SUDS module was initially developed by Tunqui Neira et al. (2024) based on the E-SUDS approach. To develop the SUDS module and integrate it into the TEB model, the initial hydrological functions of the TEB model were adapted. More specifically, the substrates of different SUDS are modelled using the ISBA scheme (Boone et al., 2000), which simulates the soil column within the three main compartments (i.e., road, building and garden) defined in the TEB model. The interception process is represented by the reservoir mechanism inherent to the TEB model. The percolation of water from the substrate to the underground storage compartment follows the same methodology as the ISBA model, which calculates water flux to deeper layers of the soil column based on Richards' equation in its "mixed" form (Brooks and Corey, 1966). Regarding the hydrological processes of SUDS facility investigated in this study, they are represented by different reservoir types (Fig. 1). The principal reservoirs are described as follows:

- **Storage–Regulation reservoir (SR):** This reservoir temporarily stores rainwater, which is then released into the sewer network through a flow regulator. The operation of the SR reservoir is governed by the water balance equation, expressed as follows:

$$\frac{\partial W_{SR}}{\partial t} = (1-f_{SE}) \cdot [P_{SR}(t)+R_{SR}(t)] - F_{SR-SE}(t)-F_{SR-ovf}(t)- F^*_{SR-dr}(t) \quad (1)$$

where W_{SR} refers to the water level of the SR (mm), $P_{SR}(t)$ is the direct rainfall ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), $R_{SR}(t)$ refers to the collected runoff ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), f_{SE} represents the fraction of SUDS equipped only with the Storage–Exfiltration (SE) reservoir underground, and $F_{SR-SE}(t)$, $F_{SR-ovf}(t)$, and $F^*_{SR-dr}(t)$ represent the water flux going to the SE reservoir ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), the overflow from the SR ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), the regulated outflow ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), respectively.

- **Storage–Exfiltration reservoir (SE):** This reservoir collects water fluxes from the SUDS substrate. The stored water is then exfiltrated into the natural soil surrounding the SUDS or overflows if the reservoir’s capacity is exceeded. The equation governing the reservoir can be expressed as follows:

$$\frac{\partial W_{SE}}{\partial t} = F_{SR-SE}(t) - F_{SE-ovf}(t) - F_{SE-ex}^*(t) \quad (2)$$

where W_{SE} represents the water level stored in the SE (mm), $F_{SR-SE}(t)$, $F_{SE-ovf}(t)$, and $F_{SE-ex}^*(t)$ refer to the water flux from the SR ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), the overflow from the SE ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), and the exfiltration flux to the natural soil beneath ($\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$), respectively.

- **Soil reservoir:** This reservoir models the dynamics of water flow through the soil layer (see Decharme et al., 2011 for details on the ISBA-DF model).

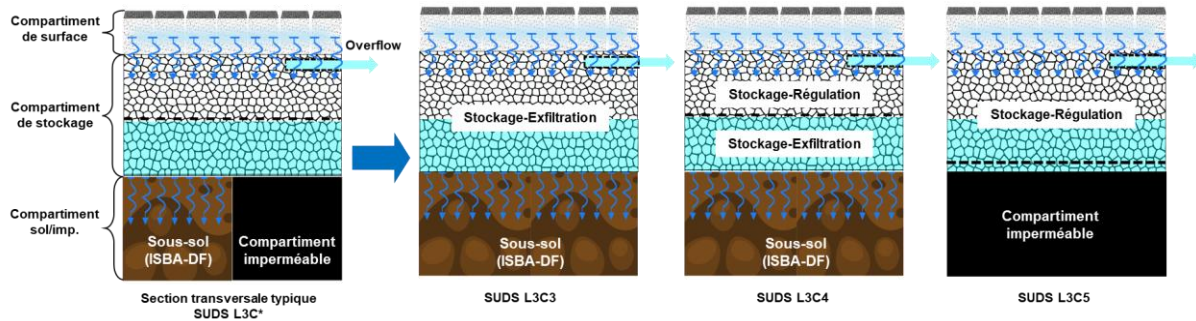


Figure 1. Example of the different reservoirs presented in an SUDS facility (permeable pavement), with details on the typology provided in L3C3, L3C4, and L3C5 of Tunqui Neira et al. (2023).

Assessing hydrological responses of SUDS facilities by TEB and SWMM

This study investigated the aggregations of different compartments within studied SUDS facility (i.e., Permeable pavement, PP). In total, three types of PP were analysed (Fig. 1): 1) PP with a SR reservoir (PP1; SUDS L3C5), where water can only be discharged in a regulated manner to the stormwater network. 2) PP with a SE reservoir (PP2; SUDS L3C3), which water is discharged solely through exfiltration into the underlying soil. 3) PP3 (SUDS L3C4), comprising both SR and SE reservoirs for water storage, regulation and exfiltration. The SWMM is a semi-distributed hydrological model (Rossman et al., 2015) widely used for stormwater management. Its Low Impact Development (LID) module enables the simulation of hydrological responses for various SUDS facilities at the urban catchment scale. This study adopts SWMM as a benchmark to evaluate and compare the performance of the TEB model in assessing the hydrological responses of PP1. The procedures for this comparison include: i) inflow from impervious areas connected to the SUDS, ii) SUDS regulated discharge (PP1 and PP3), iii) hydrological processes (e.g., exfiltration) within the SUDS (PP2 and PP3), iv) water storage in different reservoirs, v) water storage in the soil within the SUDS (PP2 and PP3), and vi) potential overflow from the SUDS.

Case study

In this study, a theoretical catchment with the surface area of 1 hectare (0.01 km^2) is used for the modelling experiments. Four scenarios are designed: 1) Scenario 1 includes roads, buildings, and gardens, with the urban road compartment in TEB divided into road and PP1. 2) Scenario 2 is identical to Scenario 1 but with PP2 instead of PP1. 3) Scenario 3 extends Scenario 1 by incorporating both PP1 and PP3 in the urban road compartment. 4) Scenario 4 extends Scenario 2 by incorporating both PP2 and PP3 in the urban road compartment. In SWMM, roads and buildings are represented as impervious surfaces, while gardens are represents as permeable surfaces. The meteorological forcing data (i.e., precipitation, temperature, specific humidity, atmospheric pressure, wind speed and direction, as well as incoming shortwave and longwave radiation) is aligned with the Pin Sec catchment in Nantes, France (Stavropoulos-Laffaille et al., 2018). This forcing data consists of time series with a temporal resolution of 1 hour, covering the period from May 2010 to September 2012. The same forcing dataset is applied in SWMM, and the Penman-Monteith equation is used to calculate potential evapotranspiration. The

main parameters used in both models include land use fractions, the height of the surface reservoir, substrate thickness, and the underground storage compartment (see details in Tunqui Neira et al., 2024 for an example of Bioretention).

Results and discussion

In this paper, we focus on presenting the results of the comparison of hydrological responses of Scenario 1 between the TEB model and SWMM. As shown in Fig. 2a, both models exhibit a consistent correlation for the inflow from impervious areas to the PP, the regulated discharge, and the substrate storage, with an R^2 value of 0.99. Comparing the hydrographs of these hydrological processes, the temporal evolution of inflow, regulated discharge, and water storage in SR shows similar variations (Fig. 2b), indicating that the TEB model shows performance comparable to that of SWMM.

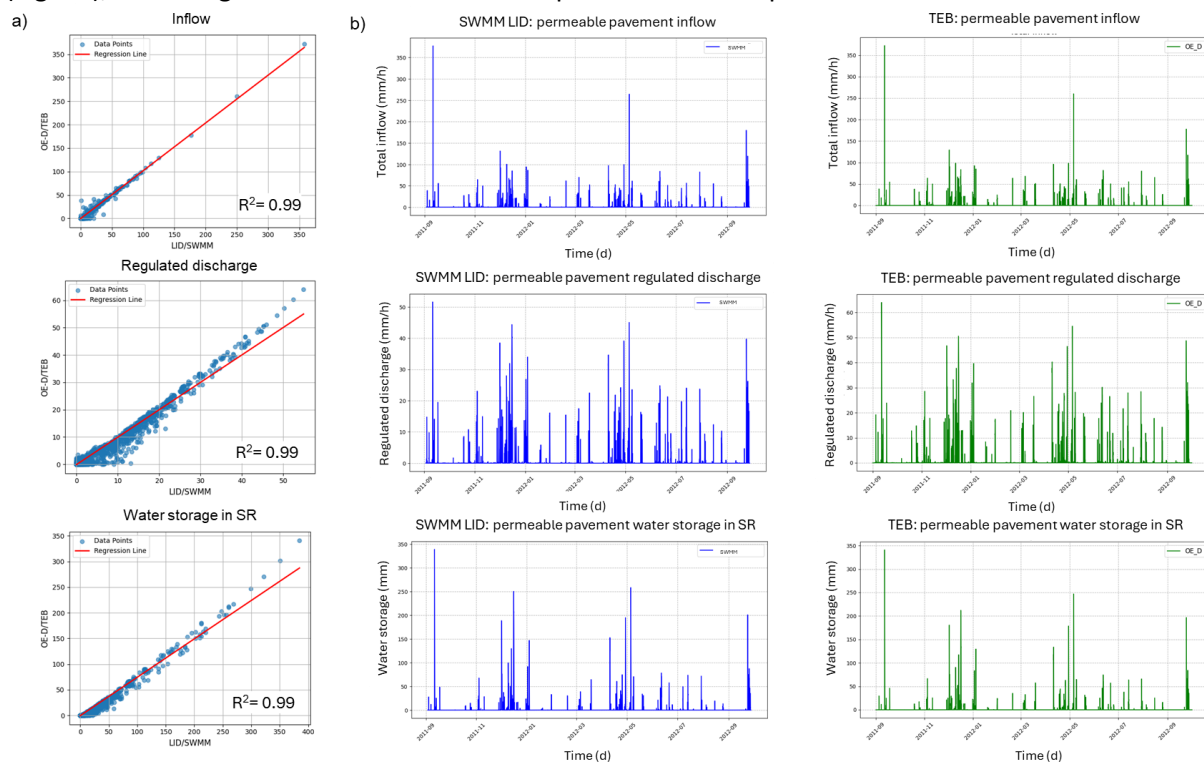


Figure 2. a) Comparison of main hydrological processes of PP simulated by SWMM and the TEB model. (b) Temporal evolution of hydrological processes of PP simulated by SWMM (presented in blue lines) and TEB (presented in green lines).

Conclusions and future work

This paper focuses on assessing the hydrological responses of aggregations of different compartments within an SUDS facility (permeable pavement) using the TEB-SUDS module. The results of Scenario 1 obtained from the TEB-SUDS module are compared with those from the LID module of SWMM, showing adequate consistency with respect to the inflow, regulated discharge and water storage in the regulation reservoir. While SWMM is widely used and serves as a practical benchmark, it has limited capability to represent detailed infrastructure-scale processes. Further work will consider the use of other physically based models (e.g., HYDRUS) as benchmarks for comparison with the TEB-SUDS. In addition, future studies will extend this assessment to other compartment aggregations within SUDS facilities developed in the TEB-SUDS module at the urban catchment scale.

Acknowledgement

The authors gratefully acknowledge the OPUR research program (<https://www.leesu.fr/opur/>) and the OPUR partners.

References

- Bernard, É., de Munck, C., Chancibault, K., Mosset, A., & Lemonsu, A. (2021). Hydro-climatic response of Paris metropolitan area through TEB-Hydro model simulation: multi-catchment calibration and model evaluation.
- Boone, A., Masson, V., Meyers, T., & Noilhan, J. (2000). The influence of the inclusion of soil freezing on simulations by a soil–vegetation–atmosphere transfer scheme. *Journal of Applied Meteorology*, 39(9), 1544-1569.
- Brooks, R. H., & Corey, A. T. (1966). Properties of porous media affecting fluid flow. *Journal of the irrigation and drainage division*, 92(2), 61-88.
- Decharme, B., Boone, A., Delire, C., & Noilhan, J. (2011). Local evaluation of the Interaction between Soil Biosphere Atmosphere soil multilayer diffusion scheme using four pedotransfer functions. *Journal of Geophysical Research: Atmospheres*, 116(D20).
- Rossmann, L. A. (2015). Storm water management model user's manual, version 5.1 (EPA-600/R-14/413b). *US EPA National Risk Management Research Laboratory, Cincinnati, Ohio, USA*.
- Qiu, Y. (2021). *Multiscale assessment of hydrological responses of Nature-Based Solutions to improve urban resilience* (Doctoral dissertation, École des Ponts ParisTech).
- Rossmann, L. A., & Huber, W. C. (2016). Storm water management model reference manual volume III–water quality. US Environmental Protection Agency: Cincinnati, OH, USA.
- Stavropoulos-Laffaille, X., Chancibault, K., Brun, J. M., Lemonsu, A., Masson, V., Boone, A., & Andrieu, H. (2018). Improvements to the hydrological processes of the Town Energy Balance model (TEB-Veg, SURFEX v7. 3) for urban modelling and impact assessment. *Geoscientific Model Development*, 11(10), 4175-4194.
- Tunqui Neira, J. M., Gromaire, M. C., Chancibault, K., & Chebbo, G. (2023). Toward a comprehensive functional typology of stormwater control measures for hydrological and water quality modeling purposes. *Blue-Green Systems*, 5(1), 41-56.
- Tunqui Neira, J. M. T., Gromaire, M. C., Chancibault, K., & Chebbo, G. (2024, June). Development and evaluation of Bioretention Stormwater Control Measures in TEB model to urban stormwater management. In *International Conference on Urban Drainage (ICUD)*.