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# Understanding and improving the functioning of stormwater nature-based solutions under climate extremes – Towards a unified modeling framework for the GreenStorm project

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## Abstract

The European GreenStorm project aims to better deploy nature-based solutions for the adaptation to different climate extremes. The project focuses on stormwater management solutions (NBS<sub>SW</sub>), across a diversity of types and climates. A key step in the project is to develop and use a unified modeling framework at the facility scale to improve both their design and performance assessment. Based on a set of previously monitored of NBS<sub>SW</sub> constituted by the GreenStorm project consortium, a generic hydrological operating diagram is first proposed, illustrating the main physical processes to consider. Drawing from this diagram, the Hydrus software has been selected but some limitations have at the same time been pre-identified, pointing to areas for consolidating the modeling approach. A single method for evaluating and using the modeling framework is also proposed, in a view to its use in predictive mode: for a given NBS<sub>SW</sub>, it combines a large number of simulations run with prior parameters intervals, the characterization of the observations corresponding to the climatic extremes of interest, a sensitivity study to identify influential and non-influential parameters, an identification of acceptable simulation and set of parameters, and an analyze how close/different is the accepted parameter distribution compared to prior one.

## Highlights

- Characterization of climate extremes of interest requires special attention
- Specific developments are needed to establish a unified modelling framework
- The evaluation method must be adapted to the use of the model in a predictive mode

## Introduction

Modeling the hydrological behavior of stormwater nature-based solutions (NBS<sub>SW</sub>) is needed to improve both the design and the performance assessment of these solutions. Their behavior is complex because it involves a large number of processes and parameters in the soil-plant-atmosphere

continuum. A great deal of scientific effort is therefore dedicated to developing models and determining how to evaluate and use them (Pons, 2023; Ouedraogo, 2025).

The European GreenStorm project (<https://arceau-idf.fr/en/projects/greenstorm>), started in 2024 and funded under the Driving Urban Transition partnership, aims to develop a unified modeling framework to predicting the performance of a diversity of NBS<sub>SW</sub> during different climate extremes (storms, heatwaves, and droughts). The model is planned to operate at the facility scale. It should integrate the significant hydrological processes and their interactions, and produce simulations at fine time steps (typically the minute) and over long durations (typically the year) to ensure the robustness of the results.

The aim of this communication is to provide preliminary insights on how to choose the desired modeling framework, how to develop it, and how to evaluate it for future use in “predictive” mode.

## Methodology

### Adapting the model to the diversity of solutions and benefits

One of the challenges is to devise a modeling framework that allows studying performance aspects of NBS<sub>SW</sub> for 3 types of issues associated with different climate extremes: runoff retention during storms, ability to cool the atmosphere via the evapotranspiration (ET) process during heatwaves, and vegetation resilience during drought periods. The ambition is also to develop a single modeling framework that can be adapted to a wide variety of NBS<sub>SW</sub> and under a wide variety of European climates, including future climates.

### Based on an analysis of hydrological processes

In order to guide the choice of the modeling framework, an analysis of the hydrological processes involved in a variety of NBS<sub>SW</sub> was carried out, in order to obtain a generic diagram of their hydrological functioning. This analysis is performed for a set previously monitored of NBS<sub>SW</sub> constituted by the GreenStorm project consortium, featuring a diversity of solutions and climates (Table I).

**Table 1. List of the NBS<sub>SW</sub> potentially used for developing and evaluating the modeling framework.**

NBS <sub>SW</sub>	Measure variables	Period of observation
Genoa Green roof (Italy)	Meteo, Rain, Drainage, Soil storage	09/2008 – 04/2010
Trappes Green roof (France)	Meteo, Rain, Drainage, Soil storage, ET	10/2012 – 07/2018
Umea Greenroof (Sweden)	Solar, Rain, Drainage	01/2018 – 12/2020
Athens Bioroof (Greece)	Meteo, Rain, Irrigation, Drainage, Soil storage	06/2014 – 01/2016
Sense-City raingarden (France)	Meteo, Rain, Inflow, Drainage, Soil storage	01/2021 – 01/2024
Breuil raingarden (France)	Meteo, Rain, Inflow, Drainage, Soil storage	05/2024 - present
Saclay detention basin (France)	Meteo, Rain, Inflow, Outflow, Soil & Surface storage, Groundwater	01/2021 - present
Växjö biofilters (Sweden)	Rain, Outflow	05/2021 - present
Skellefteå swale (Sweden)	Rain, Outflow, Soil storage, Groundwater	01/2015 - present
Sense-City storm trees (France)	Meteo, Rain, Inflow, Drainage, Soil storage	04/2022 – 04/2023

## Results and discussion

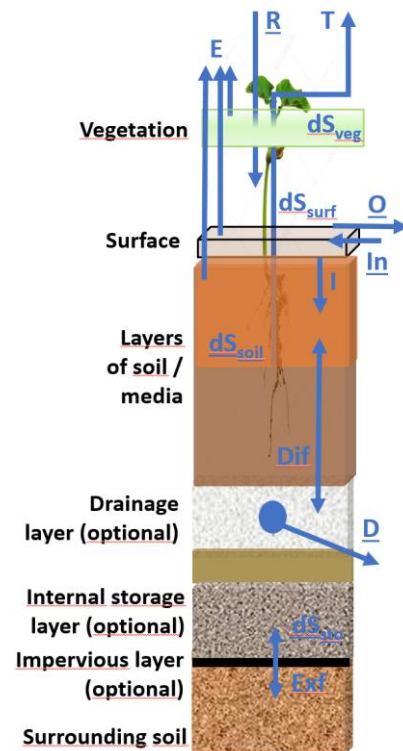
### A generic diagram of the hydrological functioning of a NBS<sub>SW</sub>

Figure 1 shows the generic hydrological operating diagram of NBS<sub>SW</sub>. The exercise necessarily involves simplifications, and a vertical 1D representation with compartments (in black) that store and exchange water (in blue) has been retained.

Starting from the atmosphere, rainfall (flux  $R$ ) is first intercepted by vegetation leaves (storage  $dS_{veg}$ ), then reaches the surface for temporary storage ( $dS_{surf}$ ).

At the surface, it is also possible for additional water to arrive (e.g. collection of runoff from adjacent surfaces;  $In$ ) and conversely for a quantity of water to be discharged downstream (typically, as overflow;  $O$ ). Water temporarily stored at the surface infiltrates ( $I$ ) and can then be exchanged between the different layers ( $Dif$ ) of soil or substrate. Some of this water may be directed to the atmosphere through evaporation ( $E$ , from the ground but also from the canopy) and plant transpiration ( $T$ ). A drainage layer is also sometimes present (flow  $D$  evacuated), as well as a dedicated internal storage layer ( $dS_{sto}$ ). An impervious liner may be placed at the bottom of the system. If not, exchanges occur between the system and surrounding soil (at the bottom but also laterally around the structure;  $Ext$ ).

The hydrological variables traditionally measured during a field experiment are underlined in Figure 1: these are mainly flows in pipes ( $O$ ,  $In$ ,  $D$ ), supplemented by rainfall ( $R$ ) which plays a predominant role and is also fairly easy to measure. More recently, soil water storage measurements (Tala, 2020) and to a lesser extent transpiration measurement (Thom, 2020), have also become more frequent.



**Figure 1.** Conceptual hydrological diagram of a generic urban NBS<sub>sw</sub> (see the text for the variable significance).

### The HYDRUS choice, with needs for enhancement

Based on a review of the literature (not shown here), on the expected objectives for the unified modeling framework and on the generic diagram of NBS<sub>sw</sub> hydrological functioning, the Hydrus software (Simunek, 1998) was selected. The major asset of Hydrus is the physically-based modelling of water fluxes in partially saturated porous media - which should allow a more realistic description of soil water content than already available conceptual frameworks. Hydrus also includes a description of root water uptake, which is seldomly the case in the models used in urban hydrology.

However, some limitations were pre-identified in Hydrus during this analysis, which constitute prospects for consolidating the modeling framework:

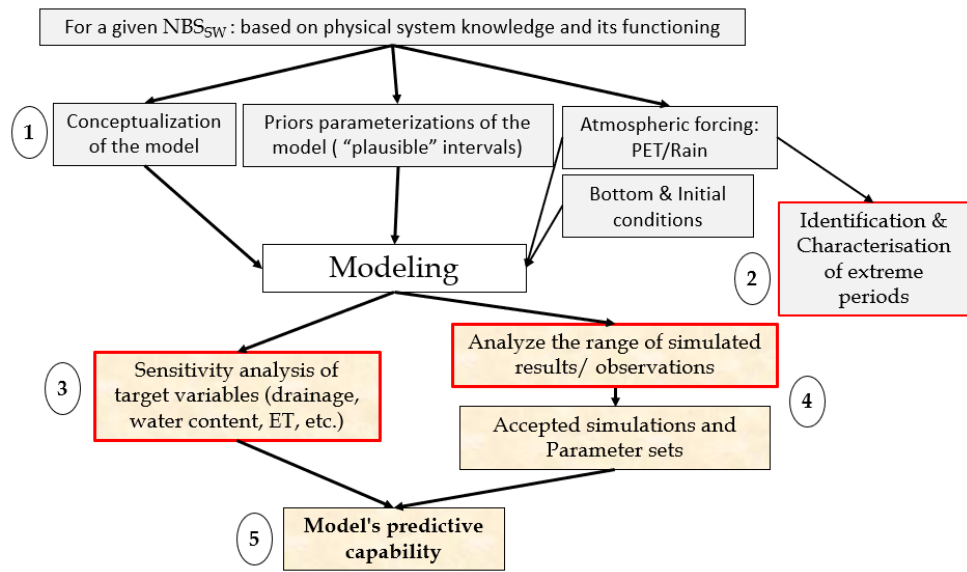
- The scheme for vegetation interception has been developed for agricultural context; it could be simplified, as the process is particularly important for urban NBS<sub>sw</sub> containing tall, dense vegetation and low loading ratio (i.e., for which rainfall represents a large fraction of the volume to be managed);
- The surface storage and/or internal water storage scheme must allow simulating the regulation (i.e., flow-rate control) of evacuated runoff ( $O$ ), which is not currently the case;
- The possibility of describing systems with uneven inflow distribution ( $In$ ) across their surface (due to localized inflow and topographic effects) should also be considered;
- Representing the role of a very coarse storage layer (e.g. ultralight honeycomb structures) is not obvious in Hydrus, as Darcy's equation, and therefore Richard's, hardly applies in such materials (Qin, 2016);
- Finally, while Hydrus 1D includes an option to describe drainage, the latter is associated with a zero-flux bottom boundary condition that does not allow considering drainage and exfiltration simultaneously, thus limiting its applicability.

### Initial thoughts on the methodology for evaluating the framework

Figure 2 presents methodological proposals for evaluating the modeling framework, with a view to its use in predictive mode (i.e. how to properly design a NBS<sub>sw</sub> in a real project, without

observation and the possibility of calibration). For a NBS<sub>SW</sub> database, a large number of simulations will be run with prior parameters intervals identified from the solution characteristics (step 1). The atmospheric forcing data, classically rainfall and potential ET series, will also be analyzed in order to identify the periods corresponding to the climatic extremes of interest (step 2). Once the simulations have been run continuously over long periods, a sensitivity study will be carried out to identify influential and non-influential parameters (on the variables of interest and during the periods of extremes; step 3). At the same time, the results will be compared with available observations. A sample of simulations deemed “acceptable” will be identified, together with the associated parameter distributions (step 4). Finally, the predictive capacity of the model will be assessed (step 5), in particular by checking for sensitive parameters how close/different is the accepted parameter distribution compared to prior parameter distribution.

**Figure 2.** Methodology to test and evaluate the modelling framework (numbers correspond to work steps)



## Conclusions and future work

A unique modeling framework for simulating the performance of NBS<sub>SW</sub> under climate extreme will be developed as part of the GreenStorm European project. The Hydrus tool has been selected, but development needs have been identified: these will be met either via independent modules coupled with Hydrus (e.g. canopy processes), or via adaptations within the code. The proposed methodology to evaluate the framework will then be implemented on different project's NBS<sub>SW</sub>, with recommendations on how best to use the modeling framework in predictive mode for other project tasks.

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