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Research papers

Performance comparison of green roof hydrological models for full-scale field sites

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A R T I C L E I N F O

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A B S T R A C T

Green roofs can be valuable components in sustainable urban drainage systems, and hydrological models may provide useful information about the runoff from green roofs for planning purposes. Various models have been proposed in the literature, but so far no papers have compared the performance of multiple models across multiple full-size green roofs. This paper compared 4 models: the conceptual models Urbis and SWMM and the physically-based models Hydrus-1D and Mike SHE, across two field sites (Lyon, France and Umeå, Sweden) and two calibration periods for each site. The uncertainty and accuracy of model predictions were dependent on the selected calibration site and period. Overall model predictions from the simple conceptual model Urbis were least accurate and most uncertain; predictions from SWMM and Mike SHE were jointly the best in terms of raw percentage observations covered by their flow prediction intervals, but the uncertainty in the predictions in SWMM was smaller. However, predictions from Hydrus were more accurate in terms of how well the observations conformed to probabilistic flow predictions. Mike SHE performed best in terms of total runoff volume. In Urbis, SWMM and Hydrus uncertainty in model predictions was almost completely driven by random uncertainty, while parametric uncertainty played a significant role in Mike SHE. Parameter identifiability and most likely parameter values determined with the DREAM Bayesian algorithm were found to be inconsistent across calibration periods in all models, raising questions about the generalizability of model applications. Calibration periods where rainfall retention was highly variable between events were more informative for parameter values in all models.

1. Introduction

Green roofs are an increasingly popular design feature in urban areas that can limit the increase in runoff peaks and volumes caused by urbanization (e.g. Carson et al., 2013) while providing additional benefits for e.g. air quality (e.g. Tomson et al., 2021) and building insulation (e.g. Susca, 2019). The hydrology of green roofs has been studied both in full-scale roofs (for overviews see e.g. Carson et al., 2013; Cipolla et al., 2016; Mentens et al., 2006) and in purpose-built test beds (e.g. Stovin et al., 2012). Factors that influence the hydrologic performance include substrate properties (Berretta et al., 2014; Fassman-Beck et al., 2013; Szota et al., 2017), evapotranspiration (Cascone et al., 2019; Ebrahimian et al., 2019), roof slope (Getter et al., 2007), vegetation properties (Berretta et al., 2014) and roof dimensions (Hakimdavar et al., 2014). For example, Liu et al. (2019) found, based on irrigation lab experiments, that substrate material was the most important factor influencing the runoff retention in green roofs, followed by substrate depth, roof slope, and vegetation.

Planning of new green roofs and drainage systems that include green roofs requires predictions of roof runoff (e.g. Palla and Gnecco, 2020; Versini et al., 2015). This interest has led several authors to propose models of varying complexity and levels of detail. For specific green roofs, regression equations (e.g. Carson et al., 2013; Fassman-Beck et al., 2013) or unit hydrographs (Villarreal and Bengtsson, 2005) can be developed to quantify their long-term performance on either an event basis or for longer periods (Mentens et al., 2006). The downside of such approaches is that they remain site specific and thus might lack generality. Such simplified rainfall-runoff relationships may not be directly applicable in forecasting contexts.

A different approach is represented by conceptual models, i.e. simplified descriptions retaining a physical basis, which have been

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Nomenclature

List of symbols

Symbol	Description
A	Roof area [L^2]
A_{cell}	Area of a single cell in the SHE model domain (L^2)
A_{reg}	Coefficient controlling drainage flow (Urbis) [L^2]
B_{dr}	Fraction of potential evapotranspiration made available to the drainage layer (Urbis) [–]
B_{season}	Seasonal adjustment factor for evapotranspiration (Urbis) [–]
C_{sub}	Maximum water storage capacity of the substrate layer (Urbis) [L]
d_{sur}	Current depth of water on surface [L]
d_{dr}	Current depth of water in the drainage layer [L]
D_{dr}	Thickness of the drainage layer [L]
D_{sur}	Surface depression storage [L]
D_{sub}	Thickness of the substrate layer [L]
E_{dr}	Actual evapotranspiration from the drainage layer [$L\ T^{-1}$]
E_{pot}	Potential evapotranspiration rate [$L\ T^{-1}$]
E_{sub}	Actual evapotranspiration from the substrate layer [$L\ T^{-1}$]
E_{sur}	Actual evapotranspiration from the surface [$L\ T^{-1}$]
E_{tot}	Total actual evapotranspiration [$L\ T^{-1}$]
g	Gravitational acceleration, $g = 9.81\ m\ s^{-2}$
H	Sink term in Richards' equation [T^{-1}]
I	Infiltration rate into the substrate [$L\ T^{-1}$]
J	Accumulated infiltration volume during a rainfall event (SWMM) [L]
K	Hydraulic conductivity [$L\ T^{-1}$]
K_s	Saturated hydraulic conductivity [$L\ T^{-1}$]
L	Flow of water from substrate to drainage layer [$L\ T^{-1}$]
n	Manning's coefficient for surface flow (SWMM) [$T\ L^{-1/3}$]
n_{dr}	Manning's coefficient for drainage layer flow (SWMM) [$T\ L^{-1/3}$]
n_{she}	Manning's coefficient for surface flow (SHE) [$T^{-1}\ L^{1/3}$]
N	Number of observations
M	Roof slope [$L\ L^{-1}$]
P	Precipitation rate [$L\ T^{-1}$]
Q_{sur}	Surface runoff [$L^3\ T^{-1}$]
Q_{dr}	Drainage layer outflow [$L^3\ T^{-1}$]
Q_{ov}	Overflow from full drainage layer [$L^3\ T^{-1}$]
Q_{obs}	Observed roof runoff [$L^3\ T^{-1}$]
Q_{sim}	Simulated roof runoff [$L^3\ T^{-1}$]
Q_{stoch}	Simulated roof runoff with added random error [$L^3\ T^{-1}$]
R_{dr}	Coefficient controlling drainage flow (SHE) [T^{-1}]
R_U	Coefficient controlling drainage flow (Urbis) [-]
S_{eff}	Effective saturation [$L^3\ L^{-3}$]
t	Time [T]
V	Averjanov coefficient (SHE) [–]
W	Roof width [L]
z	Vertical coordinate [L]
α	Van Genuchten parameter [L^{-1}]
β	Van Genuchten parameter [–]
γ	Coefficient controlling change in K as function of θ (SWMM) [–]
η	Coefficient controlling relationship between water depth in the drainage layer and actual evapotranspiration (Urbis).
θ	Current substrate volumetric water content [$L^3\ L^{-3}$]
θ_{fc}	Volumetric water content of substrate at field capacity [$L^3\ L^{-3}$]
θ_r	Residual volumetric water content [$L^3\ L^{-3}$]
θ_s	Volumetric water content of substrate at saturation [$L^3\ L^{-3}$]
θ_{top}	Volumetric water content of top layer of the substrate [$L^3\ L^{-3}$]
θ_{wp}	Volumetric water content of substrate at wilting point [$L^3\ L^{-3}$]
λ	Van Genuchten parameter [–]
μ	Van Genuchten parameter [–]
σ	Standard deviation of the observation-simulation error distribution [$L^3\ T^{-1}$]
σ_0	Intercept of the heteroscedastic error model [$L^3\ T^{-1}$]
σ_1	Slope of the heteroscedastic error model [$L^{1/2}\ T^{-1/2}$]
σ_Q	Standard deviation of ensemble of flow values [$L^3\ T^{-1}$]
ϕ_{dr}	Void fraction of the drainage layer [$L^3\ L^{-3}$]
ϕ_{sur}	Void fraction of the surface layer [$L^3\ L^{-3}$]
ψ	Soil pressure head [L]
ψ_E	Threshold pressure head for evapotranspiration in Hydrus [L]
ψ_{init_bot}	Initial pressure head at bottom of substrate (Hydrus) [L]
ψ_{GA}	Green-Ampt suction head (SWMM) [L]
Ω_{spread}	Relative spread of model prediction ensemble [–]
Ω_{rel}	Reliability of model prediction ensemble [–]
$\mathscr{L}$	Log-likelihood [–]

proposed by several authors in the green roof context (e.g. Carbone et al., 2014; Herrera et al., 2018; Kasmin et al., 2010; Li et al., 2019; Locatelli et al., 2014; Rossman and Huber, 2016; She and Pang, 2010; Sherrard and Jacobs, 2012; Skala et al., 2019; Vesuviano et al., 2014). Some of these modelling approaches mainly focused on sub-models for specific parts or processes of green roofs, such as the drainage layer (Vesuviano and Stovin, 2013) and evapotranspiration (Feng and Burian, 2016; Jahanfar et al., 2018).

One commonly used model for green roofs is the U.S. E.P.A. Storm Water Management Model (SWMM), which has had official support for green roofs since version 5.1 (Rossman and Huber, 2016), although green roofs could be simulated in older versions using the curve-number approach or representing the green roof as a storage node in the drainage network (Alfredo et al., 2010). Attempts to model green roofs using the SWMM bioretention cell module were successful in some cases (Burszta-Adamiak and Mrowiec, 2013) but not in others (Versini et al., 2015). Different studies have confirmed that the SWMM green roof module added in version 5.1 is applicable to individual rainfall events (e.g. Hamouz and Muthanna, 2019; Palla et al., 2012) and over longer periods (e.g. Cipolla et al., 2016; Hamouz and Muthanna, 2019; Krebs et al., 2016). However, further studies have also raised concerns about this software, regarding e.g. the description of evapotranspiration (Feng and Burian, 2016; Hamouz and Muthanna, 2019; Peng and Stovin, 2017), the inability of calibrated parameters to be transferred to similar roofs in different locations (Johannessen et al., 2019), and the use of a large number of parameters to which the modelling outputs are insensitive (Leimgruber et al., 2018). Similar considerations are likely to apply to some other conceptual models as well, but have rarely been investigated in detail or reported.

Another type of descriptions used for green roof modelling are physically-based models, mainly based on the Richards equation, operating most commonly in one (i.e. the vertical) dimension (e.g. Avellaneda et al., 2014; Hilten et al., 2008; Peng et al., 2019; Sims et al., 2019; Skala et al., 2020), although two dimensional (Li and Babcock, 2015; Palla et al., 2009) or three dimensional (Brunetti et al., 2016) descriptions have also been reported. One frequently-named advantage of physically-based models is that parameter values represent physical characteristics which can be measured in situ (e.g. De-Ville et al., 2018b;

Sims et al., 2019) or in the lab (e.g. Brunetti et al., 2016; Peng et al., 2020). However, the representativeness of parameter values measured in the laboratory under controlled conditions has been questioned (Szota et al., 2017). This finding raises concerns about whether laboratory measurements of model parameters may also be applicable for roofs that have already been built. Another concern is that different models may interpret the same physical parameter in different ways in the model equations.

An ideal model would be capable of reproducing the runoff from green roofs with different designs, under different climatic conditions and for all times of the year. In addition, in an ideal situation models would be able to reliably predict runoff from green roofs without calibration, e.g. when considering the implementation of new green roofs. Comparing multiple models using the same dataset may be one way of generating insights into shortcomings of and potential improvements to model structures that might help achieve this goal. Some studies have tried to identify the best-performing models by applying multiple models to the same dataset. Carson et al. (2017) found that the (empirical) curve number method and characteristic runoff equation performed slightly better (0.03 difference in Nash-Sutcliffe Efficiency – NSE) than SWMM for two full-scale roofs. However, the site-specific nature of these first two models is less appealing in practice, and more complex models were not considered. Palla et al. (2012) performed event-based calibrations of a 16 × 22 m roof, comparing a simple conceptual model (consisting of three linear reservoirs) with the mechanistic model Hydrus-1D (Šimůnek et al., 2008). Both models closely reproduced the observed runoff hydrographs, but the mechanistic model's predictions were somewhat more accurate. By contrast, Soulis et al. (2017) reported better performance (for 2 × 1 m test modules) for the conceptual SWMM model than for Hydrus-1D. Xie et al. (2020) performed irrigation experiments on laboratory modules and found that Hydrus-1D obtained a higher NSE than SWMM in calibration, but worse scores for testing periods (with higher rainfall intensities), regarding runoff volumes and peak flows. Brunetti et al. (2020) performed a detailed calibration study of a month-long laboratory irrigation experiment with a 57 × 36 cm green roof module. They found that a conceptual model and a relatively simple mechanistic model were equally suited to describe the hydrological behaviour of the test module, while the use of more complex mechanistic models was not justified given the limited improvements in performance.

Although these studies contributed to elucidate some aspects of modelling green roofs, they might still present certain limitations. First, only one of them (Palla et al., 2012) is based on an actual green roof and not purpose-built lab or pilot modules, dismissing aspects of real green roofs such as scale effects, heterogeneity and non-vertical water movement. Second, the simulations were most commonly event-based descriptions (Palla et al., 2012; Xie et al., 2020), ignoring the processes that take place in the roof during dry periods and being sensitive to initial conditions. Brunetti et al. (2020) did use a continuous simulation, but their irrigation experiment only used block rainfalls of identical intensity which is not representative of the variability in natural rainfall and runoff from green roofs. Third, the mentioned comparative studies (Brunetti et al., 2020; Palla et al., 2012; Soulis et al., 2017) were all carried out under a Mediterranean climate (except Xie et al. (2020) who only simulated different rain intensities and ignored evapotranspiration), so their conclusions might not be applicable to other climates. Fourth, a number of the previous studies present a limited assessment of uncertainties in model parameters and predictions, which might also have a significant influence in the conclusions thereby reported.

Hydrological simulations of green roofs provided by reliable models seem to be an essential tool for the operation and design of these structures, which ultimately encourages more sustainable urban drainage systems. Therefore, the goal of this study is to propose a comparative evaluation of models of varying complexity (from simple conceptual to mechanistic ones), applied to two full-scale green roofs with different physical layouts and in two different climates. The models are compared under a context of continuous simulation, assessing modelling uncertainties and accuracy by means of Bayesian methods and monitored data of rainfall, potential evapotranspiration and output flow rate from different time periods. A formal Bayesian calibration approach is used to estimate values of model parameters that fit best with the observed flow data (including parameters that are not directly linked to observable characteristics of the green roof system or may be difficult to determine in-situ) while evaluating the inherent uncertainties in such estimates and the resulting uncertainties in the model predictions.

2. Methods

2.1. Green roofs & data sets

For this study two green roofs were selected, one in Lyon, France, and one in Umeå, Sweden, representing different designs and different climate conditions.

The green roof in Lyon was built in the Congress Centre of Lyon, France in 1995 and covers 280 m^2. The roof is flat and consists of a 50 mm egg-box shaped drainage layer underneath the substrate layer, which has a depth varying between 40 and 140 mm and is planted with sedum. Outflows from both the substrate and the drainage layer join in a single drain in which discharge was measured using an electromagnetic flow meter (Krohne Optiflux 2000), allowing to measure flow rates up to 330 L min^{-1}. The specified accuracy of the flow meter depends on the flow value and varies from 2.9% at 10 L min^{-1} to 1.0% at 30 L min^{-1} (i.e. for typical low and high flow rates for this roof). Rainfall was measured using a 0.2 mm tipping bucket rain gauge installed on the roof. Flow rate and rainfall measurements were reported with a constant one-minute time step from September 2012 to May 2013 (Bertrand-Krajewski and Vacherie, 2014). Other meteorological data (temperature, wind speed, atmospheric pressure, solar radiation and relative humidity) were provided by the French national meteorological office (Météo France), from the Bron weather monitoring station located 9 km from the green roof. The 2012–2013 green roof monitoring campaign was carried out for other objectives than model calibration and no local measurements of potential evapotranspiration were available. The Bron station is the closest station where daily measurements of potential evapotranspiration (E_{pot}) were also available. Therefore, E_{pot} values were initially estimated on an hourly basis from temperature, wind speed, atmospheric pressure, solar radiation and relative humidity records, employing the Penman-Monteith equation (e.g. Zotarelli et al., 2010). These hourly E_{pot} values were further corrected to sum to the Meteo France available total daily E_{pot} values considered as reference values. Afterwards, hourly E_{pot} corrected values were linearly interpolated to a one-minute time step (Principato, 2015).

The second roof was built in Umeå, Sweden in 2014 and covers 2469 m^2. A 25 mm drainage layer underlies a substrate layer whose depth varies between 42 and 80 mm with an average of 60 mm, planted with a mixture of grass and sedum. The original design depth of the substrate was 70 mm (BG Byggros AB, 2018a). The roof consists (see Fig. 1) of 7 V-shaped sections (i.e. 14 sloped sections in total, with half facing due north, half facing due south) that are angled between 15° and 38°. In the narrow section of the roof, a drain (receiving flow from both the surface and the drainage layer) is installed on either side of the roof at the bottom of the V; in the wider section drains are installed at ¼ and ¾ of the total width, each receiving flow from half of the V-shaped section. A network of pipes collects the water from these roof sections and from two small impervious roofs (169 m^2 in total). Flow was measured using a 1 L tipping bucket for flow rates up to 25 L min^{-1} (HyQuest, 2016) and an area-velocity flow meter for higher flow rates (Teledyne ISCO, 2010). The accuracy of the tipping bucket gauge was not quantified precisely, but based on a flow-rate dependent correction from the manufacturer (HyQuest, 2016) and in-situ checks of the volume per tip it is believed to be reasonably small. Previous laboratory tests of this model of area-

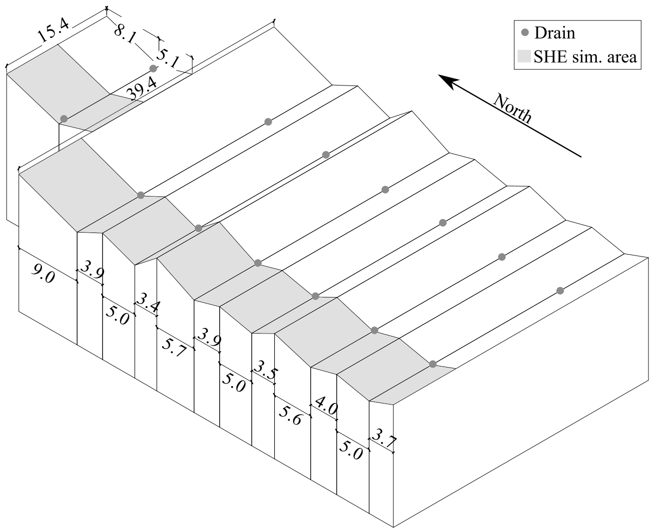

Fig. 1. Dimensions of the Umeå green roof, all measures in m. The part of the roof represented in Mike SHE simulations is indicated, the resulting flows were multiplied by 2 (narrow part of the roof) and 4 (wide part of the roof) to obtain flow rates for the whole roof. In SWMM the entire roof was simulated, while in Urbis and Hydrus (1-D models) the resulting flows given per m^2 were multiplied by the area of the whole roof.

velocity sensor showed that the accuracy of the flow measurement is typically within ±5% in the flow range of 120–540 L min^{-1}. (Broekhuizen, 2021). Rainfall was measured using a 0.2 mm tipping bucket. Measurements were carried out from late 2017 to early November 2020, although some gaps were present in the data. In addition, periods influenced by snow fall or snow melt (occurring as early as October, and as late as May) were excluded since they pose additional challenges outside the scope of this paper (e.g. Hamouz and Muthanna, 2019). Evapotranspiration was calculated using the Penman-Monteith equation and data from two stations from the Swedish Meteorological and Hydrological Institute (station 140,615 for solar radiation (approx. 2.7 km from the green roof) and 140,480 for other data (approx. 1.1 km from the green roof)).

For both sites, two independent one-month long periods were selected to calibrate and test different green-roof models. Independent calibrations were undertaken for each period and then cross-tested against the data for the other period. This was done to test whether a model calibrated for a given period is usable for other periods with potentially different meteorological conditions. For each site, one period was selected that showed high variability among the retention rates for individual events, while the other had similar total rainfall depth but with less varied retention. For Lyon, the selected periods were November 2012 (reporting low retention rates with a low inter-event retention variability) and April 2013 (with high variability of the inter-event retention rates). For Umeå, the selected periods were from 9 September 2020 to 11 October 2020 (reporting a high inter-event retention variability; hereafter referred to as just September) and from 29 June 2020 to 28 July 2020 (with low inter-event retention variability; hereafter July).

When analysing monthly time series including data from dry periods, zero-registered rainfall and flow-rate values were found to represent the majority of the values. However, the inclusion of these zero-registered values in the model calibrations might tend to favour the representation of low flow-rate values, penalizing the peaks of the hydrographs (e.g. Oliveira et al., 2018). In addition, the predictive capabilities of the models could also be overestimated during these dry periods, since almost any model will predict no flow if it has not rained for some time. On the other hand, close-to-zero flow rate values during rainy periods can also represent valuable information about the model performance, as models or parameter setups that predict flows when none occurred are not desirable. Therefore, flow rate values lower than the detection limit of the measurement devices (0.79 and 2 L min^{-1} for Lyon and Umea, resp.) were not considered in the calculations, as long as no rainfall was registered within the preceding 15 min.

2.2. Hydrological models

Four models of varying complexity were selected for this study. The model structures are shown visually in Fig. 2 and described in more detail in the sections below.

All models used in the study assume that flow through the substrate is vertical, with lateral flow occurring on the surface and in the drainage layer. The slopes of the roof in Umeå may give rise to some lateral flow in the substrate. However, this is believed to play at most a minor role for a number of reasons. First, water input (precipitation) and output (drainage) from the substrate take places uniformly across the entire roof. Second, the permeability of the geotextile separating the substrate from the drainage layer (90 mm hr^{-1} (BG Byggros AB, 2018a, BG Byggros AB, 2018b)) is higher than the observed rainfall intensities, so the formation of a saturated layer on top of the geotextile (i.e. in the bottom of the substrate) is unlikely. Third, the substrate is very thin compared to the length (in the direction of the slope) of the roof segments so water moving down through the substrate has little time to travel laterally before reaching the bottom of the substrate and the drainage layer. Fourth, the thin substrate means that should the drainage layer capacity be exceeded, the substrate will quickly become saturated at which point drainage outflow and surface runoff will be larger than lateral flow through the substrate. For these reasons, the assumption of only vertical flow in the substrate is considered appropriate. In addition, this is also the assumption most commonly used in green roof modelling studies, and it is therefore appropriate here given that the study goal is to test existing models.

2.2.1. Urbis

Urbis is a scenario simulation and decision support tool aimed at simulating long-term hydrological dynamics of different stand-alone and interconnected Stormwater Control Measures (SCMs), such as green roofs, swales, retention basins or permeable surfaces, at the block and building scales. This free software (https://deep.insa-lyon.fr/fr/content/urbis) was developed in the Python programming language, by INSA Lyon, France in collaboration with the companies Nidaplast, Siplast, and AS2C (Sandoval et al., 2019). The model is based on conceptual simplifications of these systems into a set of connected boxes or reservoirs that represent e.g. the storage zone or the substrate of each structure. Focusing on the case of green roofs, the option "alveolar flat green roof" was chosen in Urbis to model both the Lyon and Umeå green roofs. Urbis uses the term alveolar to refer to the egg box like layer of plastic compartments forming the bottom of the roof that allow for some storage volume and for drainage; SWMM uses the term drainage layer. Urbis was selected as an example of a simple conceptual model, because computer code for it was already available and the authors were already familiar with it, helping to avoid errors in the model setup. Other simple conceptual models have been proposed (see Section 1) and could be used as well, but given the large number of available models it was not feasible to compare all models here.

In the following lines a brief description is given of this "alveolar flat green roof" modelling setup in Urbis. The potential evapotranspiration is calculated according to:

$$E_{tot} = B_{season} E_{pot} \quad (1)$$

where E_{tot} is the total actual evapotranspiration, E_{pot} is a user-supplied potential evapotranspiration time series (e.g. calculated using the Penman-Monteith equation) and default values of the coefficient B_{season} are 0.5 for winter and 1 for summer. Evapotranspiration from the

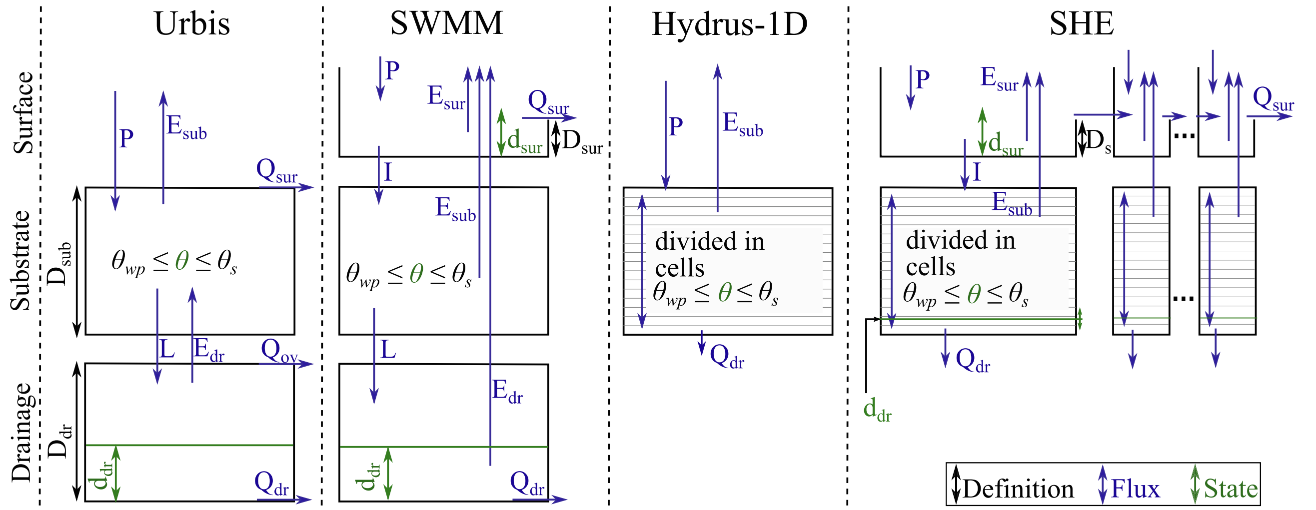

Fig. 2. Schematics of the models used in this study. The symbols are defined in the list of symbols at the beginning of the article. Note that for SHE two dimensions (the vertical and one horizontal dimension) are shown, but the model actually operates in three dimensions (vertical + two horizontal), and with more cells than shown here.

alveolus layer to the substrate is calculated from the following equations:

$$E_{dr} = \min\left(B_{dr}E_{tot}, d_{dr}\frac{3600}{\Delta t}\right) \quad (2)$$

$$B_{dr} = \left(\frac{d_{dr}}{\phi_{dr}D_{dr}}\right)^{\eta} \quad (3)$$

where B_{dr} is a fraction of the potential evapotranspiration that is available for the drainage (alveolus) layer, d_{dr} is the current water stored in the alveolus layer (since alveolus layers in Urbis are similar to drainage layers in SWMM, the subscript *dr* is used for both), D_{dr} is the drainage layer thickness (50 mm for Lyon and 25 mm for Umeå) and ϕ_{dr} is the void index of the layer structure, set as a calibration parameter for the case of Lyon and as a fixed value of 0.54 for Umeå based on available information from the manufacturer (BG Byggros AB, 2019). The coefficient η describes the relationship between water level in the alveolus layer and movement of water from the alveolus layer to the substrate, see next paragraph.

Furthermore, evapotranspiration from the substrate (E_{sub}) to the atmosphere is calculated according to:

$$E_{sub} = \begin{cases} E_{dr} & d_{dr} > 0 \\ \min\left(E_{tot}, \theta D_{sub}\frac{3600}{\Delta t}\right) & d_{dr} = 0 \end{cases} \quad (4)$$

where D_{sub} is the substrate depth and θ the current water content of the substrate. D_{sub} was set to 60 mm for Umeå and it was established as a calibration parameter for the green roof in Lyon, given the high variability of this value reported from in situ measurements. For the studied green roofs, no evapotranspiration or re-humidification occurs from the alveolus layer to the substrate and no storage exists in the drainage layer during dry periods. This was explicitly considered in Urbis by setting $\eta = 10000$ (a very high value) to make B_{dr} equal to zero (Eq. (3)), leading to set$E_{dr} = 0$ (Eq. (2)). Indeed, this conduces to cancel the water transfer from the alveolus (drainage) layer to the substrate, leading to estimations of E_{sub} (Eq. (4)) only dependent on the potential evapotranspiration and the substrate water content θ. Eq. (4) allows evapotranspiration to occur up to the potential rate, but reducing when the substrate moisture contents becomes low.

The maximum storage capacity of the substrate C_{sub} is calculated as follows:

$$C_{sub} = (\theta_{fc} - \theta_{wp})D_{sub} \quad (5)$$

where θ_{fc} and θ_{wp} are the field capacity and wilting point of the substrate, respectively. The wilting point was set to Urbis default value $\theta_{wp} = 0.05$ and θ_{fc} was established as a calibration parameter for both green roofs. If inflow into the substrate exceeds C_{sub} (saturation of the substrate), the excess water L from the saturated substrate, transferred to the alveolus (drainage) layer, is calculated as follows:

$$L = \max\left(\theta D_{sub}\frac{3600}{\Delta t} + P - E_{sub} + E_{dr} - C_{sub}\frac{3600}{\Delta t}, 0\right) \quad (6)$$

If the maximum storage capacity of the alveolus layer is reached, the excess becomes overflow (Q_{ov}), and if the maximum storage of the substrate is reached, any excess water on the surface of the substrate becomes runoff (Q_{sur}). This alveolar structure can also include a controlled outflow, aimed to simulate the output flows from the roof delivered to the pipe system. This flow rate Q_{dr} is then calculated by an orifice equation as follows:

$$Q_{dr} = R_U \bullet \mathrm{A_{reg}}\sqrt{2\mathrm{gd_{dr}}} \quad (7)$$

where R_U is a coefficient (set to 0.6 by default in Urbis). The area of the regulation orifice A_{reg} was set as a calibration parameter because A_{reg} is normally calculated in the software based on the design flow rate to be delivered from the roof to the drainage system, which was unknown in this case. It was not possible to calculate A_{reg} directly since conceptually the value of the parameter refers to an orifice in the wall of a tank while in the actual system the opening was a drainage outlet in the bottom of the roof. The regulation orifice is set to be located at the bottom of the alveolar layer in order to avoid stormwater storage in the drainage layer during dry periods, as neither roof was designed for this purpose. The roof runoff that was studied in this paper is the sum of Q_{dr}, Q_{ov} and Q_{sur}.

2.2.2. SWMM

SWMM (v 5.1.013; Rossman and Huber, 2016) is a conceptual model that still relies on some physically-based parameters and process descriptions. SWMM is commonly used in both research and practice and it is therefore of particular interest to evaluate its capabilities. A short description of the main process equations is given below, for details see Rossman and Huber (2016). Infiltration is represented using the Green-Ampt model (Green and Ampt, 1911):