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Modelling of Three Permeable Car Parks with SWMM model

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Abstract

Three permeable car park systems were simulated with SWMM LID model. For the two vegetated permeable car parks (ECOVEGETAL Mousses and ECOVEGETAL Green), the choice was made to use the SWMM bioretention module while the permeable pavement module was used for a mineral permeable car park (ECOVEGETAL Minéral). One year of rainfall and potential evapotranspiration were used to simulated water flows through the structure of these parking lots. Calibration and sensibility analysis were conducted and quality of the simulations were estimated with a Nash–Sutcliffe efficiency coefficient and a water budget criterion. Good results were obtained for the mineral and ECOVEGETAL Mousses car parks. Bioretention module seems not suitable if the structure of the parking is too complex.

Highlights

- The SWMM bioretention module has too few soil layers
- Good simulations require calibration of soil parameters
- Potential evapotranspiration must be modulated by a coefficient for two of the car parks

Introduction

Permeable parking lot is one of the most common use of permeable pavements. A permeable car park allows stormwater to infiltrate into the permeable structure, to be stored and gradually released into stormwater networks or infiltrated into the subsoil. Permeable pavements can be vegetated in some case and be part of green infrastructure. A vegetated permeable car park differs from a mineral one in its components (some layers contain organic matter) and its ability to retain more water for reuse by plants and to increase evapotranspiration. Some studies tried to model permeable pavement (Illgen, 2008; Korkealaakso et al., 2014). However, few studies have attempted to model vegetated permeable car parks even if models are developed for other permeable pavements as in SWMM (**S**torm **W**ater **M**anagement **M**odel). In this model, only one parameter - the vegetation volume fraction – accounts for vegetation but is considered negligible, since the values are low (maximum of 0.2) (Korkealaakso et al., 2014). Thus, the objective of this study is to test the ability of some SWMM green infrastructure options to represent the hydrological behaviour of three different permeable parking lots. For that objective, rain and outflows were continuously measured in 2016-2018 for three permeable parking lots (1 mineral and 2 vegetalized). Firstly, the three experimental places and the monitoring will be described, as well as the way the car parks are represented in SWMM. Secondly, modelling results are compared with observations.

Methodology

Experimental parking lots and monitoring

Three types of lysimetric parking places of 13.26 m² each Figure 1), representative of the three permeable car park systems developed by ECOVEGETAL (Figure 1a) were monitored. Those places were lined (Figure 1b), to prevent water from exfiltrating into the subsoil and thus limiting the number of unknown parameters in the water balance. The ECOVEGETAL Minéral (EMin) place consists of plastic grids (5 cm thick) filled with gravels (< 10 mm) laid on a 4 cm bedding of gravel (< 10 mm), a 20 cm draining sub-base layer of 0/31.5 crushed stone and a 30 cm sub-base layer of 40/60 crushed stone. For ECOVEGETAL Mousses (EMo), the plastic grid (5 cm thick) is filled with a mineral substrate (3/15 mm, composed of crashed ceramics, compost, pozzolan) and planted with mosses (sedums, thymes, white clovers, fescues). It lies on a 4 cm thick bedding composed of the same mineral substrate as in the plastic grid, a 20 cm draining sub-base layer of 0/31.5 crushed stone and a 30 cm sub-base layer of 40/60 crushed stone. For ECOVEGETAL Green (EG), the plastic grid (5 cm thick) is filled with an organic substrate (0/3 mm) planted with grass. This layer lies on an organic substrate FERTILIT® (0/15 mm of crushed ceramics, compost, natural organic fertilizers) as bedding (4 cm), and a mixture between stones (30/60 mm) and HYDROFERTIL® (0/25 mm of crushed ceramics, compost, peat, natural organic fertilizers) as a fertile base (20 cm). A 30 cm sub-base layer of 40/60 crushed stone forms the last layer. Each place is drained by a 100 mm diameter drain at the bottom of the structures. The discharges are measured at the outlet of the drain with tipping buckets of 130 ml. Surface runoff was never observed on these parking lots.

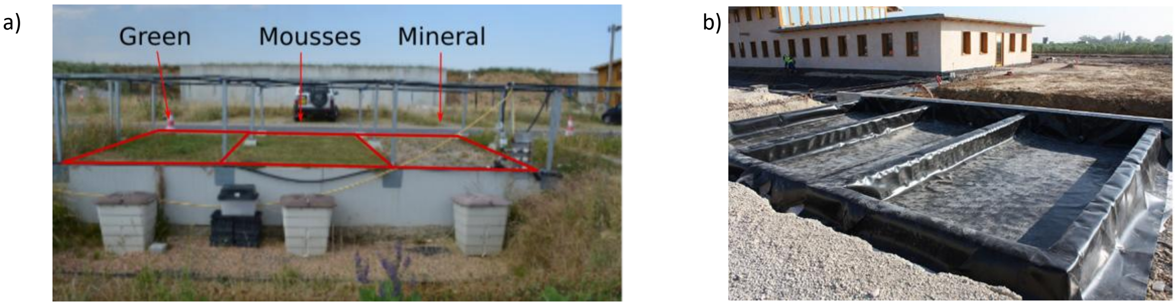

Figure 1. a) The 3 experimental places, b) the impermeable layer setup (Varnede et al., 2019)

Rainfall, wind speed, air temperature, relative humidity, and net radiation were recorded on site. Potential Evapotranspiration (PET) was calculated from Penman-Monteith equation. Due to missing data two different periods were used. For EMin, data run from September 21, 2016 to September 20, 2017 (total rainfall is 529 mm and total PET 825 mm) and for EMo and EG, data are from September 21, 2017 to September 20, 2018 (total rainfall is 739 mm and total PET 879 mm). Observed discharges were also available at a 1-min time step for the same periods.

SWMM model parametrization

Among the green infrastructure modelling options included in SWMM, the permeable pavement was used for EMin whereas bioretention module was used for EG and EMo. If layers of the permeable pavement module are suitable for EMin, first layers of EMo and EG contain finer substrate and organic matter which should be represented as soil. Pavement layer is therefore not necessary for these two parking lots. Table 1 presents how the different layers of the car parks are represented in SWMM. Due to the limited number of layers in the bioretention module, it's not possible to explicitly represent all the different layers. Substrate layer (inside the plastic grid), bedding and fertile base (for EG) that may play a role in water retention, were gathered and represented by the soil layer of the bioretention module. It should be noticed that although the total thickness of the three parking lots is the same, each layer modelled in SWMM may have a different thickness as a result of this aggregation. Aggregation of different layers makes it difficult to estimate the soil physical properties. Thus for the soil layer, 6 parameters were calibrated (Table 1): initial water content (θ_{ini}), porosity (Φ), field capacity (fc), wilting point (Wp), saturated hydraulic conductivity (Ks) and HCO, a coefficient used in conductivity versus soil moisture curve (Rossman and Huber, 2016).

As EMin has no vegetation, and the first EG simulations showed too much discharges due to an overestimation of water content in the soil layer, it was also decided to introduce an evapotranspiration coefficient (K_{pet}) in order to adjust the PET values for these two parking lots.

Table 1. Correspondence between the layers of bioretention module and permeable pavement in SWMM and the layers of the three permeable parking lots (the numbers in brackets indicate the total thickness of each layer). Details of each layers are given in Experimental parking lots and monitoring section. Parameters to calibrate are also shown with the range of potential values [min – max] and final value for the best simulation (see SWMM model parametrization section)

Permeable pavement module		Bioretention module		
SWMM	ECOVEGETAL Minéral	SWMM	ECOVEGETAL Mousses	ECOVEGETAL Green
Surface	Surface	Surface	Surface	Surface
Pavement	Plastic grids (5 cm)	-	-	-
Soil	Bedding (4 cm)	Soil	Plastic grid + bedding (9 cm)	Plastic grid + bedding + fertile base (29 cm)
Storage	Draining sub-base+ sub-base (50 cm)	Storage	Draining sub-base + sub-base (50 cm)	Sub-base (30 cm)
Drain	Drain	Drain	Drain	Drain
θ_{ini} (m^3/m^3)	[0 - 0.3] - 0.006	θ_{ini} (m^3/m^3)	[0 - 0.55] - 0.06	[0 - 0.8] - 0.02
Φ (m^3/m^3)	[0.1 - 0.7] - 0.62	Φ (m^3/m^3)	[0.15 - 0.6] - 0.47	[0.2 - 0.8] - 0.79
fc (m^3/m^3	[0.1 - 0.3] - 0.08	fc (m^3/m^3	[0.15 - 0.6]- 0.21	[0.2 - 0.8] - 0.48
Wp (m^3/m^3)	[0 - 0.1] - 0.001	Wp (m^3/m^3)	[0 - 0.1] - 0.02	[0 - 0.1] - 0.04
Ks (mm/h)	[100 - 300] - 267	Ks (mm/h)	[100 - 300] -130	[100 - 300] - 148
HCO (-)	[5 - 60] - 15	HCO (-)	[5 - 60] - 32	[5 - 60] - 57.5
K_{pet} (-)	[0.5 - 1]- 0.65	K_{pet} (-)	-	[1 - 1.5]- 1.35

Calibration was carried out using a multi-criteria method, in conjunction with a sensitivity study (see Ramier et al., 2011 for details). For each of the parameters a range (min-max) of potential values are given (Table 1) and a set of simulations is realized with a random selection of parameter values from among the potential values. Then final values of parameters are chosen from the *"good simulations"*. Quality of the simulations are estimated with Nash–Sutcliffe efficiency coefficient (NSE) on discharges and a water budget criteria (WB) defined as below:

$$WB = \frac{\sum_{t=1}^{n} Q_{sim}^{t} - \sum_{t=1}^{n} Q_{obs}^{t}}{\sum_{t=1}^{n} Q_{obs}^{t}}$$

where Q_{sim} is the simulated discharge, Q_{obs} the observed one, t the current time step, n the number of time steps. The two criteria are calculated for a 10-min time step, based on a simulation at 1-min time step. "*Good simulations*" are defined as those with NSE > 0.7 and WB between -0.05 and 0.05. For EMin and EG, a first set of 100 simulations was run to fix the value of K_{pet} at 0.65 for EMin and 1.35 for EG (Table 1), then 650 simulations were carried out for each parking lots.

Results and discussion

For EMin, only one "good simulation" was obtained. For this simulation WB is -0.01 and NSE= 0.81. Figure 2 a) shows the comparison between simulated and observed discharges for this simulation. Simulated discharges are overestimated specially for the lower values. The total cumulative discharge is 280 mm instead of 223 mm for observations. For EMo, 8 "good simulations" were obtained. However, for 5 of these simulations surface runoff was simulated even though it was never observed. These 5 simulations were rejected. Simulated and observed discharges are compared in Figure 2 b) for the best simulation (WB = -0.048 and NSE = 0.81). It can be observed than some of the lower observed discharges are not simulated but total cumulative discharges are similar (~ 290 mm). For EG, no "good simulations" were obtained. 9 simulations have a WB between -0.05 and 0.05 but NSE are between - 13.1 and 0.51. The simulated and observed discharges for the best simulation (WB=0.02 and NSE = 0.51) are shown in Figure 2 c). This comparison shows that the model underestimates the discharges and that many zero discharge values are simulated, even for the highest observed discharges. Moreover, it was also observed for EMin and EMo that better NSE values could be obtained when shifting simulated values respectively by 40 mn and 30 mn earlier in time. This reflects the difficulty of representing correctly the flow dynamics. It should also be noticed that for the 3 car parks, final values of θ_{ini} are very low (from 0.006 m^3/m^3 for EMin to 0.06 m^3/m^3 for EMo) and those for Φ are close to the maximum potential values (Table 1).

The sensitivity analysis shows low sensitivity to most of the parameters. This may reflect a phenomenon of compensation between the parameters and therefore an over-parametrisation or poor parametrisation of the model. In particular, the model is not directly sensitive to wilting point, field capacity or porosity, but rather to the difference between field capacity and wilting point, and to the difference between porosity and field capacity. To facilitate calibration, the model should either be reformulated to introduce only these two parameters, or the residual water content and porosity should be fixed so that only the field capacity can be calibrated. Similarly, the model does not appear to be sensitive to saturated hydraulic conductivity and HCO of the soil layer. As a high permeability is expected for permeable car parks, the saturated hydraulic conductivity could be set at a high value (between 200 and 300 mm/h) in order to only calibrate HCO.

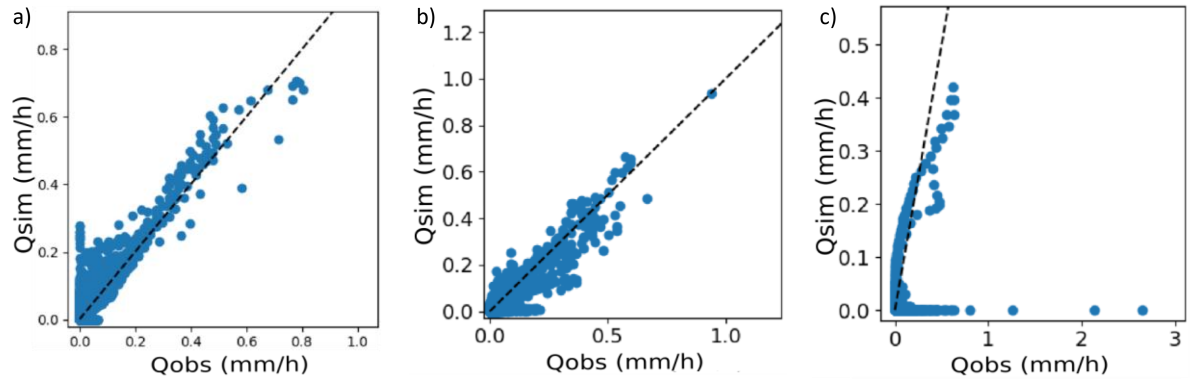

Figure 2. Comparison between simulated and observed discharges at a 10-min time step for a) ECOVEGETAL Minéral, b) ECOVEGETAL Mousses and c) ECOVEGETAL Green.

Conclusion

Using the SWMM permeable pavement module to simulate water transfer through a permeable car park such as ECOVEGETAL Minéral can give good results. However, it is necessary to calibrate certain parameters and decrease the evapotranspiration if potential evapotranspiration values are used and the dynamics of the discharges is still difficult to reproduce accurately. The SWMM bio-retention cell can be used for vegetated permeable car parks, but a calibration is also necessary. On the other hand, if the structure of the car park to be simulated is more complex, with multiple layers of soil having different properties like ECOVEGETAL Green, the limited number of layers present in the SWMM bio-retention module does not allow for a good representation. A model with a representation of different soil layers would be required.

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