Towards the production of guidelines to support the design of stormwater management practices for on- site pollution control

Jérémie Sage, Emmanuel Berthier, Marie-Christine Gromaire

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Vers la production de recommandations pour le dimensionnement de techniques alternatives permettant une maîtrise à la source des flux de polluants

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RÉSUMÉ

L'objectif de cette étude est d'illustrer l'intérêt d'une chaine de modélisation, développée dans des travaux antérieurs, pour le dimensionnement des pratiques de gestion à la source des eaux pluviales urbaines. Une approximation de la chaine de modélisation par un méta-modèle est dans un premier temps utilisée afin d'évaluer l'incidence du dimensionnement des techniques alternatives pour la maîtrise des flux de polluants pour un grand nombre de scénarios de conception. Une analyse plus approfondie est par la suite réalisée à partir du modèle initial pour un nombre limité de scénarios de dimensionnement afin d'étudier l'incidence de l'ouvrage sur la distribution des masses de polluants rejetées vers l'aval et de vérifier son bon fonctionnement hydrologique. Les résultats obtenus suggèrent qu'une réduction importante des flux de polluants dirigés vers les milieux aquatiques pourrait être obtenue en forçant l'infiltration d'une petite fraction du ruissellement. Néanmoins, dans le cas de sols faiblement perméables, le recours à des solutions donnant lieu à des niveaux d'efficacités acceptables ne garantit pas nécessairement que le fonctionnement hydrologique de l'ouvrage soit satisfaisant, du fait d'une sollicitation excessive de l'ouvrage se traduisant alors par un maintien en eau sur des durées excessives et saturation en profondeur du sol sous l'ouvrage.

ABSTRACT

This paper presents the application of a conceptual hydrological model (developed in previous studies) for the evaluation of different stormwater management strategies for on-site pollution control. A meta-modelling approach is first adopted to emulate the original model at a low computational cost and to investigate the influence of the design of stormwater source-control systems in terms of pollutant removal efficiency from a large number of simulations. The analysis is based the construction of "sizing diagrams" relating the performance of the facility to some design parameters and illustrates the applicability of the model for the production of simple design tools. A more detailed assessment of the behavior of the source control system is later conducted for a limited number of design scenarios, so as to better understand how stormwater management strategies affect the distribution of pollutant discharges and to verify that selected configurations result in a correct hydrological functioning of the facility. The analysis primarily indicates that noticeable load reductions may be achieved through the infiltration of a small fraction of runoff. The selection of configurations producing in satisfactory pollutant removal efficiencies may however result in a failure of the facility for low permeability soils, due to a limited drainage capacity. These results therefore indicate that the design of source control systems should not solely be based on pollution control criteria and that their hydrological functioning should also be investigated.

KEYWORDS

Flow-rate control, Guidelines, Sizing, SUDS, Urban runoff, Volume reduction

1 INTRODUCTION

Stormwater source control strategies, promoting infiltration and evaporation in small vegetated facilities (referred to as Best Management Practices, Sustainable Urban Drainage Systems or Green Infrastructure) are today recommended for the management of urban runoff pollution (Ahiablame et al. 2012; Fletcher et al. 2014). While the relevance of such solutions has clearly been demonstrated, recent literature results indicate that their performance often remains variable due to insufficient guidance or inappropriate design criteria (Bressy et al. 2014). In this context, mathematical modelling appears as a relevant option for the development of simple and easy-to-use guidelines or design tools supporting the implementation of efficient stormwater source control systems.

In this study, a conceptual stormwater management model is introduced and its applicability for the production of recommendations and simple design tools is investigated. The modelling system, which consists of a "production" and a "facility" sub-model, allows the simulation of different scenarios in terms of catchment characteristics and source-control system design. Within this framework, the performance of a pervious source control system (typically a swale or a bioretention facility) may be evaluated from long rainfall records under different pollutant wash-off dynamics. Despite promising results, the model essentially remains a computationally intensive research tool. Besides, a thorough model assessment, conducted through a global sensitivity analysis method (Sage et al. n.d.), has evidenced a relatively large variability of model outputs depending on the parameterization of each sub-model which prevents a direct application for operational purposes.

Here, a stepwise approach is adopted to identify the most relevant stormwater management strategies in terms of pollution control efficiency and hydrological functioning (for low to moderate hydraulic conductivity soils). A meta-model is first implemented to emulate the original model at a very low computational cost, so as to derive "sizing diagrams" from which the influence of the design of the source control system can be evaluated. A limited number of sizing scenarios is later selected for a more detailed assessment of the hydrological behaviour of the facility based on the distribution of various model outputs simulated for a 10 year rainfall period with the original modelling system. The variability of model outputs resulting from the uncertainty model parameterization is accounted for at both steps of the analysis using a Monte-Carlo approach.

2 METHODS

2.1 The conceptual stormwater management model

The modelling system may be described as the combination of an "urban catchment" and a "facility" sub-model. For the catchment sub-model, runoff volumes are generated using a 4-parameter linear reservoir scheme to simulate flow-routing and rainfall-runoff transformation. Hydrologic losses include surface depressions, constant-rate infiltration (which may occur though road surfaces) and evaporation which is here assumed to be proportional to the Penman-Monteith potential evapotranspiration. A generic water quality model, based on commonly used "asymptotic accumulation", "transport limited" and "source limited" wash-off equations (Alley 1981; Bai and Li 2013), is implemented to simulate the temporal variability of pollutant concentrations in runoff. In this study, two distinctive pollutant wash-off dynamics may be represented, considering either the removal of suspended solids from urban streets or the dissolution of zinc from zinc roofs. The applicability of the water quality equation for both urban surfaces has been discussed in other studies (Sage et al. *[in preparation]*, 2015b).

The source-control system consists in pervious storage unit collecting runoff, providing (1) volume reduction for frequent rain events (through evaporation and infiltration) and (2) temporary storage and flow-rate control for large infrequent storms. Infiltration rates are computed from the Green-Ampt equation and a redistribution scheme derived from the work of Milly (1986) is additionally implemented to simulate soil drying under the action of gravity, capillary forces and evapotranspiration. Evaporation is again assumed to be proportional to Penman-Monteith evapotranspiration records. Discharge from the facility may either occur as overflow or release at a controlled rate through a flow-limiting device.

The facility may primarily be described by its size b, expressed as ratio to the drainage area, a soil type based on the USDA classification (Rawls et al. 1982) which encompasses retention curve and hydraulic conductivity function parameters, a dead storage volume h_P (expressed as water elevation over the area of the facility) and a design outflow rate Q_{MAX} (expressed in l/s per hectare of contributing catchment) (cf. figure 1.a). Here, the source control system is assumed to be designed to capture the 10-years storm. The temporary storage volume above the flow-limiting device h_{SUP} is thus calculated using a conventional sizing approach, by selecting from intensity-duration-frequency the rainfall duration resulting in the largest required storage volume for the 10-year return period (Aron and Kibler 1990). Additional parameters include an evaporation coefficient (ratio between actual and potential evapotranspiration), surface depressions in the facility, a cross-sectional shape coefficient α (cf. figure 1.b) and two coefficients characterizing the behaviour of the flow-limiting device. A complete model description can be found in Sage et al. *[In preparation]*.

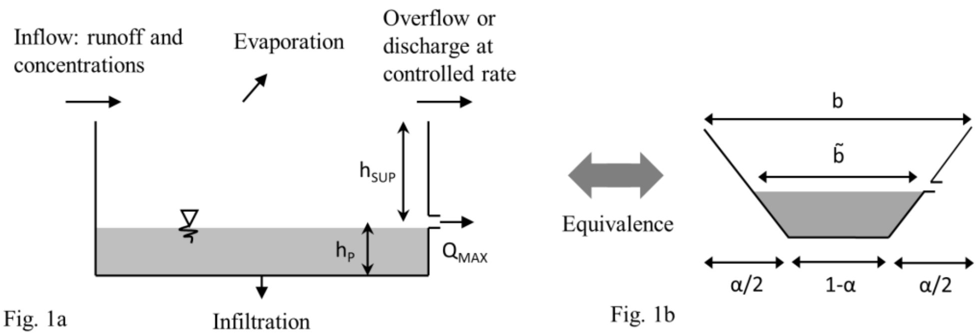

Figure 1 – 1a. Representation of the source control system 1b. Effect of the cross-sectional shape parameter α (the introduction of b̃ is justified later on)

2.2 Approximation of the original model

A meta-model (or surrogate model) may be described as an algorithm implemented to approximate at a low computational cost the outputs of a more complex mathematical function. Meta-modelling techniques have received significant attention for computationally demanding applications such as calibration, uncertainty or sensitivity analysis, propagation of uncertainties and, more generally, design space exploration (Razavi et al. 2012). In this study, a 2-layer neural network is adopted to replicate the pollutant load reduction efficiencies simulated for a 4-year rainfall period from Paris region as a function of model parameters. In the original modelling system, the use of a physically based infiltration-redistribution model requires the introduction of categorical “soil type” parameter for which the whole retention curve has to be specified. So as to facilitate construction of sizing diagrams, the saturated hydraulic conductivity K_S is used as a surrogate for the “soil type” parameter for the calibration of the meta-model (such approach thus assumes that K_S has a much larger influence on simulated efficiencies than other hydrodynamic parameters, which is consistent the results of Locatelli et al. 2015). The calibration of the neural-network is conducted from 65.000 evaluations of the original model (for a 4 year rainfall period) with 11 soil types with hydraulic conductivities ranging from 0.6 to 25.9 mm/h and the predictive power of the model (validation) is checked against 12.000 additional simulation results. A very good fit of the meta-model to the dataset is obtained for both calibration and validation (R^2>0.999).

2.3 Assessing the influence of the design of the source control system

The meta-model is adopted for the construction of sizing diagrams displaying pollution control efficiency estimates as a function of two design parameters as contour lines. Here, input factors referred to as “design parameters” include the relative area of the source control system *b*, the dead storage depth h_P, soil hydraulic conductivity K_S and the maximum outflow-rate Q_{MAX}. The results of the sensitivity analysis indicate that *b* is by far the most influential design parameter as it controls both the magnitude of infiltration or evaporation and the dead storage volume. K_S is also identified as an important input factor for which a wide range of values may be encountered by practitioners. The performance of the source control system is hence represented as a function of *b* and K_S whereas different h_P and Q_{MAX} values are selected for each sizing diagram. The variability in model outputs is accounted for by performing 20.000 simulations to propagate the uncertainty associated with the 14 “non-design” parameters (e.g. other than the four aforementioned parameters). Pollution control efficiencies presented in corresponding figures represent the 10th percentile of these 20.000 simulation results so as to provide an estimation of the minimum expected load reduction and to avoid an overestimation of the efficiency. The variability in model outputs is expressed as the difference between 90th and the 10th percentile of simulated efficiencies $\Delta E_{10\text{-}90}$.

A further analysis of the functioning of the source control system is carried out for a limited number of design scenarios identified from the sizing diagrams. Simulations are performed for a 10-year rainfall period in Paris region with the original model the variability in model output is again accounted for using a Monte-Carlo approach (the number of model evaluations is however limited to 400 due to significantly higher computational requirements). To facilitate the analysis simulations results are also presented for a specific parameterization regarding the 14 “non-design” parameters. The distribution of daily pollutant discharges at the outlet of the facility is first compared to the distribution simulated at the outlet of the contributing catchment so as to understand the effect of the source control system regarding frequent rain events as well as large infrequent storms. The hydrological behaviour of the facility is later investigated from (1) the distribution of the average water content in a 1-m thick soil layer below the surface (average values over 24h) and (2) the distribution of daily average water elevations in the facility.

3 RESULTS

3.1 General influence of design parameters

The source control system may incorporate or not a permanent pool volume to retain and infiltrate some fraction of the runoff volumes. In France, the maximum allowable outflow rate Q_{MAX} often remains the only criterion given to practitioners for the design of stormwater management practices (Petrucci et al. 2013; Sage et al. 2015a). Without any requirement regarding the management of frequent rain events, facilities exclusively dedicated to flow-rate control (e.g. h_P = 0) are likely to be implemented (Bressy et al. 2014). The performance of such source control systems is presented in Figure 2 for Q_{MAX} = 1 and 10 l/s/ha.

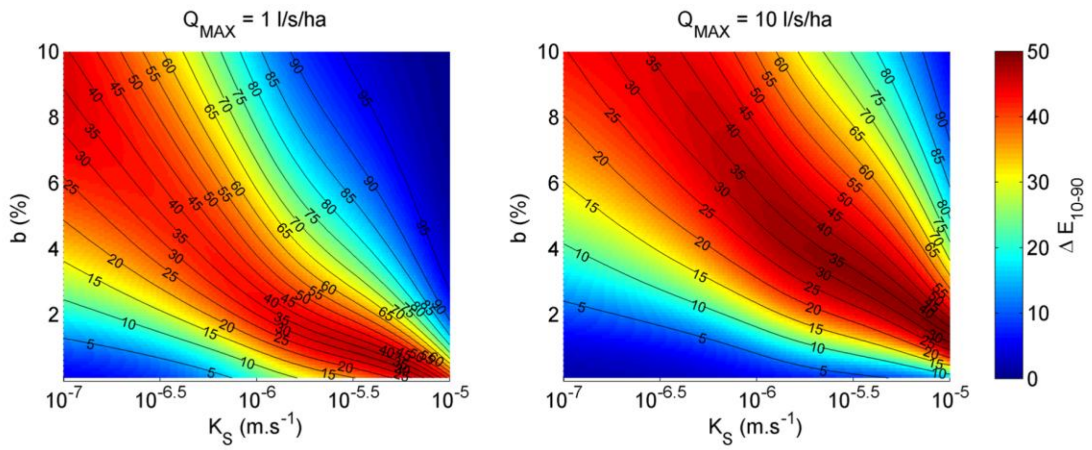

Figure 2 – Sizing diagrams for h_P = 0 and Q_{MAX} = 1 and 10 l/s/ha (contour lines = 10th percentile of simulated efficiencies, $\Delta E_{10\text{-}90}$ = difference between the 90th and the 10th percentile of simulate efficiencies)

Figure 2 primarily evidences a very large variability in simulated pollutant reduction efficiencies. While the results suggest that a high performance of the source control system might be obtained in many configurations, guaranteeing satisfactory pollution control efficiency is generally difficult, unless highly pervious soils and large infiltration areas are considered. The variability in model outputs here chiefly results from the uncertainty regarding the behaviour of the flow-limiting device, which may alternatively provide sufficient retention to promote infiltration or cause a direct release of captured volumes for frequent rain events. Here, this inability to retain runoff volumes for small storms is exacerbated at higher values of the design outflow rate and lower efficiencies are thus simulated for Q_{MAX} = 10 l/s/ha. The variability regarding the performance of the source control system for such “flow-rate control designs” is somewhat consistent with the observations of Bressy et al. (2014) and suggest that a better performance could probably be achieved if the facility incorporates a small permanent pool volume.

The sizing diagrams obtained for different h_P and Q_{MAX} values are presented in figure 3. Simulated pollutant reduction efficiencies are here represented as a function of K_S and the relative infiltration area above the level of the flow limiting device $\tilde{b}$ (cf. figure 1). As compared to the results obtained for h_P = 0, simulated efficiencies exhibit a moderate variability for most design scenarios (although not shown here, the variability observed for Q_{MAX} 10 l/s/ha and h_P = 5 cm is essentially related to the parameters of the water quality model).

As shown in figure 3, the performance of the source control system increases for higher values of the dead volume storage h_P and lower design outflow rates Q_{MAX} (which was again expectable as large Q_{MAX} values result in shorter detention times for frequent rain events). Regarding the effect of Q_{MAX}, further analysis suggest that the behaviour of the flow limiting device does not differ much from a simple overflow when Q_{MAX} = 10 l/s/ha (not shown here). As a consequence, lower design outflow rates would at first glance appear as a relevant option to achieve higher pollutant removal efficiencies. Surprisingly, previous results as well suggest that reasonable pollutant load reductions might be obtained for relatively impervious soils. In the next section, 3 design scenarios resulting in a 75% pollutant reduction efficiency (shown in figure 3) are selected to further analyse the effect of flow-rate control and better understand the hydrological behaviour of the facility for moderately pervious soils.

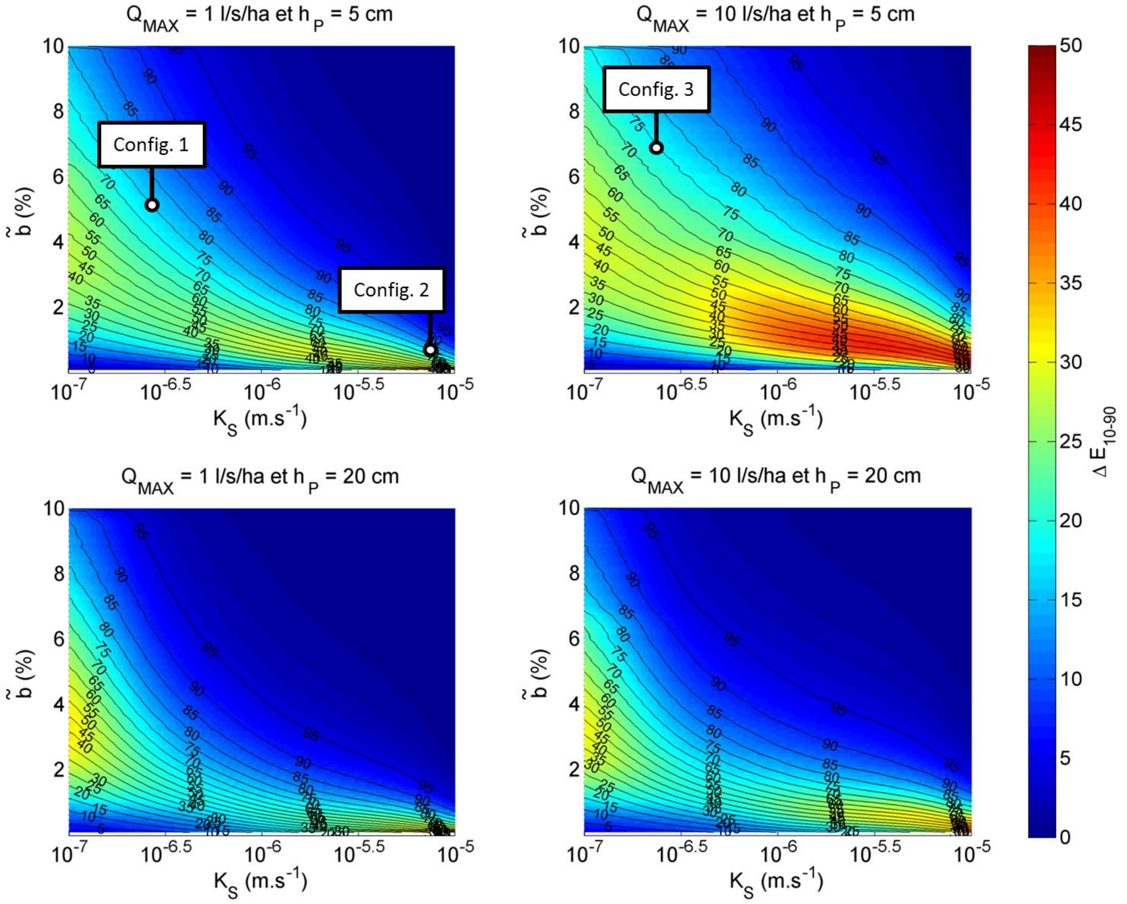

Figure 2 – Sizing diagrams for h_P = 5 and 20 cm and Q_{MAX} = 1 and 10 l/s/ha (contour lines = 10^th percentile of simulated efficiencies, $\Delta E_{10\text{-}90}$ = difference between the 90^th and the 10^th percentile of simulate efficiencies)

3.2 Further analysis for specific design scenarios

The 10-90% confidence intervals for the distributions of daily pollutant discharges simulated at the inlet and the outlet of the facility for the 3 design scenarios are presented in figure 4. The results indicate that, for a similar overall efficiency, the effect of the source control system may significantly differ from a management strategy to the other.

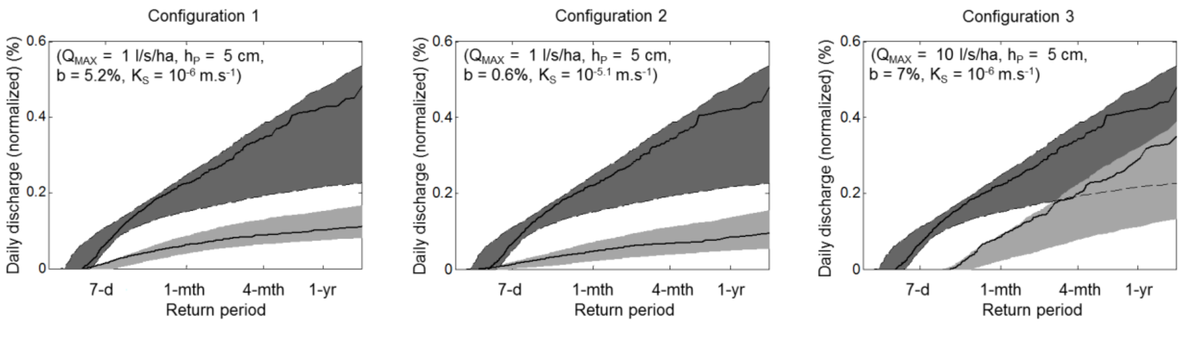

Figure 4 – Distribution of daily pollutant discharges (expressed as a percentage of total pollutant load simulated at the outlet of the catchment). Dark shaded area: daily load at the inlet of the facility. Light shaded area: daily load at the outlet of the source control system (10-90% confidence intervals). Solid black line = simulation results for a specific model parameterization (≈75% efficiency)

For Q_{MAX} = 1 l/s/ha (configurations 1 and 2), a high frequency of non-zero discharges is simulated and the facility provides a noticeable attenuation of pollutant loads for intermediate to long return period (e.g. greater than 2 months). Conversely, while the frequency of non-zero discharges is significantly reduced for Q_{MAX} = 10 l/s/ha (as a larger *b* value is needed to achieve the 75% reduction efficiency), their distribution tends to be less affected by the source control system at higher return periods. To achieve the similar level of pollution control, a more systematic capture of the small rain events is therefore needed for large design outflow rates to counterbalance the more limited mitigation of pollutant discharges for large infrequent storms. The choice of low Q_{MAX} values may hence be justified when stormwater management not only aims at controlling the overall pollutant load directed to receiving waters but is also intended to reduce the magnitude of pollutant discharges for infrequent rain events.

The distributions of the daily average water content in the first meter of soil as well as the distribution of daily average water elevations associated with the 3 design scenarios are shown in figure 5.

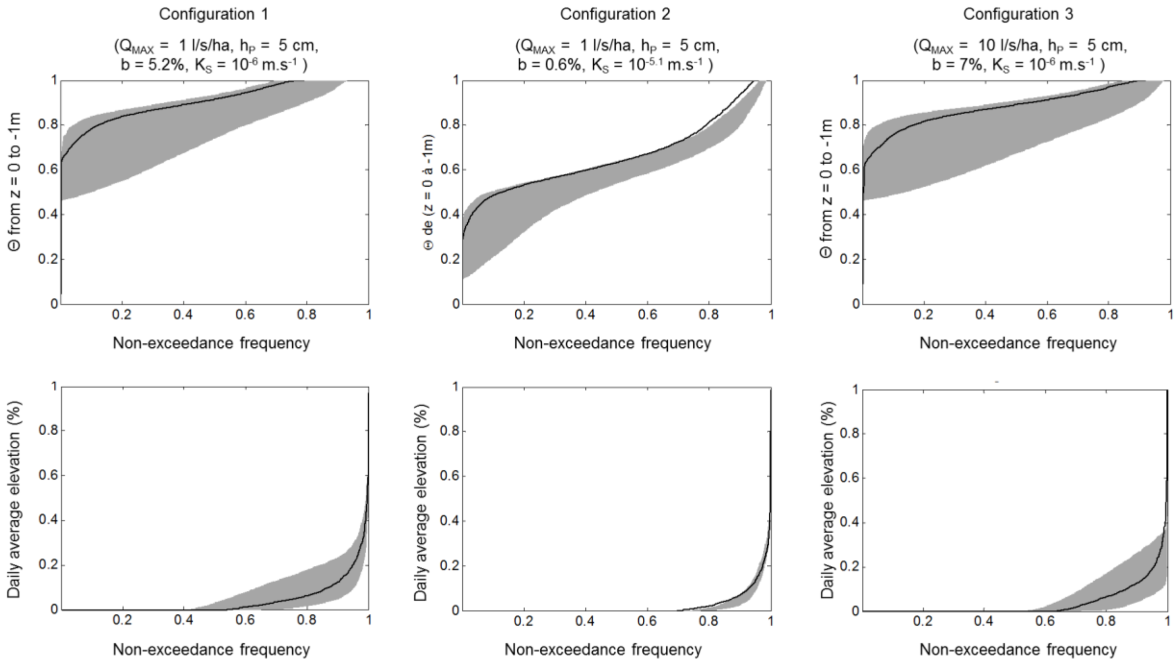

Figure 5 – Distribution of the average relative water content Θ in the first 100-cm of soil (average values over 24h) and distribution of the daily average water elevation (expressed as percentage of the maximum water elevation) (10-90% confidence intervals)

For the pervious soil (configuration 2), the facility believably exhibits a sufficient drainage capacity to avoid a deep saturation of the soil column for frequent rain events and the daily average standing water elevation in the facility often remains negligible. Conversely, the distributions computed for configurations 1 and 3 clearly indicate that failures such as water table rising or extended ponding durations could potentially occur in areas with low hydraulic conductivities. Here, the worst situation is obtained for Q_{MAX} = 1 l/s/ha which suggests that the adoption of low design outflow rate may not be desirable in the case of relatively impervious soils as it would result in (1) the accumulation of larger runoff depth above the level of the flow limiting device and (2) extended ponding duration. For such situations, the implementation of diffuse stormwater management practices (e.g. large infiltration and evaporation areas) with limited ponding depth (e.g. small h_P and sufficiently high Q_{MAX} values) to facilitate emptying during dry periods should hence probably be considered.

While previous examples illustrate the benefits of a detailed assessment of the hydrological behaviour of the source control system in addition to the estimation of pollution control efficiencies, a more systematic analysis is believably needed for the identification of the most relevant stormwater management strategies.

4 CONCLUSIONS

The influence of the design of stormwater source-control systems was investigated using a conceptual model. A meta-modelling approach was first adopted to illustrate the applicability of the model for the selection of efficient stormwater management strategies though the construction of sizing-diagrams relating design parameters to pollutant reduction estimates. Corresponding results primarily indicate that, when source-control systems are not only intended to provide pollutant reduction but also flow-rate control for large infrequent storms, the implementation of a small permanent pool volume (5 to 20cm) allows a more systematic abatement of frequent rain events and noticeably higher pollution efficiencies (e.g. larger than 75%). In many configurations, a satisfactory performance of the source-control system could also be observed for relatively impervious soils (with saturated hydraulic conductivities lower than 10^{-6} m.s^{-1}). For such situations, a further analysis of the behaviour of the source control system (based on the original model) however evidences possible failures of the facility due to a limited drainage capacity. This study therefore suggests that the selection of a design scenario cannot solely be based on pollutant reduction efficiency estimates and that the hydrological functioning of the facility should also be investigated.

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