Analysis of Urban Stormwater Control Measures Using Automated Modeling and Multi-criteria Evaluation

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Highlights

- An automated equation (model) discovery approach was applied to the field of rainfall-runoff modeling and stormwater control measures (SCMs) design.
- The proposed approach was used to design six SCMs and to assess their ability to achieve the target outflow.
- Multi-criteria analysis based on the obtained SCM design parameters is used to evaluate SCM performance with non-hydrological criteria.

Introduction

Stormwater control measures (SCMs) are technical elements that are designed to prevent and mitigate the negative effects of uncontrolled stormwater flow (e.g., urban floods or excessive combined sewer overflows) while providing ecosystem services and additional benefits for the city. Models are being used to design SCMs and predict SCM performance for different design and weather scenarios (Li, 2021). To investigate the impact of SCMs on the reduction of surface runoff at meso and macro scales, these models need to be integrated into or coupled with catchment-scale rainfall-runoff (RR) models. In this context, the open-source Stormwater Management Model (SWMM) (Rosmann, 2015) is one of the most widely used models enabling RR and hydraulic modeling of urban drainage. However, SWMM does not enable any automation that would speed up the calibration process of the RR model. Thus, search techniques (e.g., genetic algorithms, neural networks, etc.) (Niazi, 2017; Hu, 2018) and parameter optimization tools (e.g., PEST, OSTRICH) (Perin, 2020; Shahed Behrouz, 2020) are used to automate RR model calibration.

SCMs of predetermined design can be integrated into the RR model to simulate and evaluate their efficiency and performance through hydrological parameters (e.g., peak flow reduction, total volume, etc.). However, the performance of SCMs is merely observed, and their optimal design for reaching a target function (e.g., allowed surface runoff or determined hydrograph), can only be achieved through an iterative expert-driven process. Therefore, approaches that encompass auto-calibration of the RR model and objective-driven automated SCM design are more desirable. Zhu et al. (2019) investigated the coupling of SWMM and PEST to auto-calibrate the parameters of the RR model and two SCMs (i.e., bio-retention cell and permeable pavement). The authors reported promising results; however, the SWMM model has some limitations (e.g., a limited number of parameters representing SCMs). Moreover, an objective evaluation of SCM performance in terms of both, their hydrological (i.e., reduction of surface runoff) and co-benefits performance is of key importance for their wider uptake. While the SCM performance related to the reduction of surface runoff can be objectively assessed through relevant modeling techniques, the non-hydrological aspect of SCMs is many times neglected and/or assessed subjectively.

To overcome the above-mentioned drawbacks, a new approach is proposed in this study, which provides an integration of automated equation (model) discovery and domain-specific knowledge in the fields of RR and SCM modeling, together with multi-criteria analysis (MCA). More specifically, the goals of this study are: to develop a library of components for modeling RR and SCMs, compliant with the equation discovery tool ProBMoT (Process-Based Modeling Tool); to apply the proposed approach to find the optimal RR model for an urban sub-catchment in the city of Ljubljana, Slovenia, which fits best the pipe flow measurements; to find an optimal design of SCMs that would fit best the target catchment outflow; and to evaluate the co-benefits of the obtained SCM scenarios using MCA.

Methodology

Automated modeling

The proposed automated modeling approach is based on the Process-Based Modeling Tool (ProBMoT), developed by Čerepnalkoski et al. (2012). ProBMoT allows for the integration of domain knowledge, formalized as template components for the construction of process-based models, into the procedure of equation discovery from measured data. It automatically identifies both the structure and parameter values of an appropriate process-based model, given: a) a knowledge library (i.e., a mathematical formulation of the selected domain) in the form of model components, b) a conceptual model of the observed system, and c) measurements. Candidate model structures are generated from the knowledge library and a user-specified conceptual model of the observed system. The candidate models are transformed into equations, calibrated against provided data, and ranked according to their errors. To use ProBMoT within the presented case study of RR modeling and SCM design, the following steps were taken:

A.1) RR and SCM models were encoded in a modeling library.

A.2) Conceptual models of the case study and six SCM scenarios (i.e., bio-retention cell (BRC), rain garden (RG), green roof (GR), infiltration trench (IT), detention pond (DP), and the storage tank (ST)) were elaborated.

A.3) ProBMoT was used to discover the optimal model structure and parameters among viable RR models, following the conceptual model of the case study and flow measurements.

B.1) The RR model with the best performance was used to simulate catchment outflow for rainfall events with a duration of 1h and return periods of 5, 10, 25, and 50 years.

B.2) Three design events (i.e., data sets) that represent target catchment outflows were defined. The target outflows resulting from the precipitation with a return period of 10, 25, or 50 years were set to match the outflow typical for a 5-year return period event.

C.1) ProBMoT was used for the optimization of SCM parameters (i.e., to design the SCMs to achieve the desired outflow reduction) based on the conceptual model of each SCM scenario and the defined target outflows.

C.2) To determine the best SCM design, the conceptual models of SCMs were iteratively changed, based on the preliminary SCM design results.

Multi-criteria analysis

An evaluation system based on multi-criteria analysis (MCA) that will enable the assessment of SCMs with non-hydrological criteria (e.g., capital expenditure (CAPEX), operating expenses (OPEX), biodiversity …) is being developed. It will be based on the SCM design parameters. Namely, for non-hydrological criteria, a set of ranges will be defined and related to the obtained SCM design parameter values.

Preliminary results

Given the conceptual model and the modeling knowledge library, ProBMoT explored nine alternative RR models. The difference between the alternative models was in the mathematical formulation used for the calculation of infiltration (i.e., the SCS CN method, the Variable UK runoff equation, and the UK

Water Industry Research runoff equation were considered) in each of the two sub-catchments. All models were calibrated and validated against the measured data. Based on the criteria for assessing the goodness of fit, the models on average had »very good« performance (i.e., a Nash-Sutcliffe Efficiency coefficient (NSE) in the range between 0.75 and 1.00) for the four calibration and four validation periods. The best performance was achieved by two models that used a combination of two different infiltration methods.

The proposed approach enabled the design of six SCM scenarios and the assessment of their ability to achieve the target outflow. Detention ponds (DPs) and storage tanks (STs) provided comparable results. Namely, a near-perfect match (i.e., NSE value of 0.99) between the target and simulated outflow was achieved for both measures. These are the two most space-efficient measures, with an average area of approx. 1000 m^2. Infiltration trenches (ITs) also achieved a good fit between the target and simulated outflow (i.e., NSE value of 0.99). When compared to ST and DP, these elements on average take 2.5 times more space due to smaller max. depth, smaller max. voids fraction, and limited infiltration rate of the existing soil. Rain gardens (RGs) and bio-retention cells (BRCs) provided similar results, as they are both limited by the soil's saturated hydraulic conductivity. Therefore, both measures performed well only in the case of the design event with the lowest intensity. Among the SCMs that are placed within the existing pervious areas, these two SCM types take up the most space. The changes in the green roof (GR) area have a direct influence on the size of the impervious area. If 40% of the existing impervious area is replaced by GRs, the catchment outflow (i.e., from impervious and pervious areas) for the design event with a return period of 50 years almost matches the target outflow. We are currently considering the other criteria (i.e., CAPEX, OPEX, and biodiversity) for the SCMs that match the target outflows.

Conclusions and future work

The proposed automated model discovery approach was used to find the optimal structure among the viable RR models, based on pipe flow measurements. Next, ProBMoT was used for SCM design (i.e., for optimization of SCM parameters) and for catchment outflow reduction (i.e., for achieving the target catchment outflow), following the conceptual models of six SCM scenarios. An evaluation system that will enable the assessment of SCMs with non-hydrological criteria (e.g, CAPEX, OPEX, and biodiversity) based on the obtained SCM design parameters is still under development.

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