Journal of Hydrology 548 (2017) 263–277

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol

Research papers

On the use of surrogate-based modeling for the numerical analysis of Low Impact Development techniques

Giuseppe Brunetti [a,*], Jirka Šimůnek [b], Michele Turco [a], Patrizia Piro [a]

[a] Department of Civil Engineering, University of Calabria, Rende, CS 87036, Italy
[b] Department of Environmental Sciences, University of California, Riverside, Riverside, CA 92521, USA

ARTICLE INFO

Article history:
Received 19 October 2016
Received in revised form 28 February 2017
Accepted 6 March 2017
Available online 8 March 2017
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Philip Brunner, Associate Editor

Keywords:
Urban hydrology
Surrogate-based modeling
Sensitivity analysis
Infiltration
LIDs

ABSTRACT

Mechanistic models have proven to be accurate tools for the numerical analysis of the hydraulic behavior of Low Impact Development (LIDs) techniques. However, their widespread adoption has been limited by their computational cost. In this view, surrogate modeling is focused on developing and using a computationally inexpensive *surrogate* of the *original* model. While having been previously applied to various water-related and environmental modeling problems, no studies have used surrogate models for the analysis of LIDs. The aim of this research thus was to investigate the benefit of surrogate-based modeling in the numerical analysis of LIDs. The kriging technique was used to approximate the deterministic response of the widely used mechanistic model HYDRUS-2D, which was employed to simulate the variably-saturated hydraulic behavior of a contained stormwater filter. The Nash-Sutcliffe efficiency (*NSE*) index was used to compare the simulated and measured outflows and as the variable of interest for the construction of the response surface. The validated kriging model was first used to carry out a Global Sensitivity Analysis of the unknown soil hydraulic parameters of the filter layer, revealing that only the shape parameter α and the saturated hydraulic conductivity K_s significantly affected the model response. Next, the Particle Swarm Optimization algorithm was used to estimate their values. The *NSE* value of 0.85 indicated a good accuracy of estimated parameters. Finally, the calibrated model was validated against an independent set of measured outflows with a *NSE* value of 0.8, which again corroborated the reliability of the surrogate-based optimized parameters.

1. Introduction

During the last few decades, stormwater management has become a major component of the prevention of floods in urban areas and for the preservation of water resources. An increase of impervious surfaces, connected with demographic growth, has altered the natural hydrological cycle by reducing the infiltration and evaporation capacity of urban catchments while also increasing surface runoff. In their report, the Organization for Economic Co-operation and Development (OECD) (2013) identified an expected increase in flash and urban floods in large parts of Europe as one of the major issues for the future.

In this context, urban drainage systems play a fundamental role in improving the resilience of cities. In recent years, an innovative approach to land development known as a Low Impact Development (LID) has gained increasing popularity. A LID is a 'green' approach to storm water management that seeks to mimic the natural hydrology of a site using decentralized micro-scale control measures (Coffman, 2002). LID practices consist of bioretention cells, infiltration wells/trenches, storm water wetlands, wet ponds, level spreaders, permeable pavements, swales, green roofs, vegetated filter/buffer strips, sand and gravel filters, smaller culverts, and water harvesting systems. Several studies have evaluated the benefits of LIDs. For example, Newcomer et al. (2014) used a numerical model to demonstrate the benefits of LIDs, and an infiltration trench in particular, on recharge and local groundwater resources for future climate scenarios. In another paper, Berardi et al. (2014) demonstrated how green roofs may contribute to the development of more sustainable buildings and cities. Green Roofs (GR) were able to significantly reduce peak rates of storm water runoff (Getter et al., 2007) and retain rainfall volumes with retention efficiencies ranging from 40% to 80% (Bengtsson et al., 2004). Permeable pavements offered great advantages in terms of runoff reduction (Carbone et al., 2014; Collins et al., 2008), water retention, and water quality (Brattebo and Booth, 2003). Even though the results of available studies are encouraging, more

* Corresponding author.
E-mail address: giusep.bru@gmail.com (G. Brunetti).

http://dx.doi.org/10.1016/j.jhydrol.2017.03.013

research is needed to precisely assess the impact of LIDs on the hydrological cycle.

As pointed out by several authors (e.g., Elliot and Trowsdale, 2007; Wong et al., 2006), there is a strong demand for predictive models that can be applied across a range of locations and conditions to predict the general performance of a range of stormwater treatment measures. In recent years, researchers have focused their attention on applying and developing empirical, conceptual, and physically-based models for LIDs analysis. In their review article, Li and Babcock (2014) reported that there were >600 papers published worldwide involving green roofs, with a significant portion of them related to modeling. Several studies demonstrated that physically-based models can provide a rigorous description of various relevant processes such as variably-saturated water flow, evaporation and root water uptake, solute transport, heat transport, and carbon sequestration. Brunetti et al. (2016a, 2016b) used a mechanistic model, HYDRUS-3D (Šimůnek et al., 2016; Šimůnek et al., 2008), to analyze an extensive green roof in a Mediterranean climate. The model, previously validated against field scale measurements, was used to investigate the hydraulic response of a green roof to single precipitation events and its hydrological behavior during a two-month period. Metselaar (2012) used the SWAP model (van Dam et al., 2008) to simulate the one-dimensional water balance of a substrate layer on a flat roof with plants. Li and Babcock (2015) used HYDRUS-2D to model the hydrologic response of a pilot green roof system. The model was calibrated using water content measurements obtained with TDR (Time Domain Reflectometer) sensors. The calibrated model was then used to simulate the potentially beneficial effects of irrigation management on the reduction of runoff volumes. The VFSMOD model (Munoz-Carpena and Parsons, 2004) was extensively used for the analysis of the hydraulic behavior and solute transport of vegetated filter strips (Abu-Zreig et al., 2001; Dosskey et al., 2002).

However, physically-based modeling often involves highly nonlinear, partial, differential equations that are solved using various numerical approximation methods, requiring a high computational cost. Moreover, a comprehensive simulation framework includes model calibration, sensitivity analysis, and uncertainty quantification aimed at enhancing confidence in the model and its ability to describe real world systems. These tasks require running the simulation model hundreds or thousands of times and thus the computational cost exponentially increases.

Surrogate modeling focuses on developing and using a computationally inexpensive *surrogate* of the *original* model. The main aim is to approximate the response of an original simulation model, which is typically computationally intensive, for various quantities of interest (Razavi et al., 2012). Surrogate models have been widely applied in various water-related and environmental modeling problems. Khu and Werner (2003) used artificial neural networks (ANN) in conjunction with genetic algorithms (GA) to reduce the computational budget required in the uncertainty quantification framework of the rainfall-runoff model SWMM. The GA was first used to identify the areas of higher importance in the parameter space and ANNs were then used to approximate the response surface in these areas (Khu and Werner, 2003). Borgonovo et al. (2012) tested a surrogate model for the estimation of the sensitivity indices of an environmental model. Zhang et al. (2009) evaluated ANN and Support Vector Machine (SVM) for approximating the Soil and Water Assessment Tool (SWAT) model in two watersheds. Keating et al. (2010) used a surrogate model to carry out a comparison between the null-space Monte Carlo sampling (NSMC) and the DiffeRential Evolution Adaptive Metropolis (DREAM) algorithm for parameter estimation and uncertainty quantification. In another study, Laloy et al. (2013) used Polynomial Chaos Expansion (PCE) to emulate the output of a large-scale flow model. The surrogate model was used in a Bayesian analysis framework to derive the posterior distribution of different parameters. In their study, Younes et al. (2013) used a surrogate model to estimate three soil hydraulic parameters from a drainage experiment. In particular, PCE was used to run a Monte Carlo Markov Chain (MCMC) analysis. However, although the widespread diffusion of surrogate modeling tools could drastically reduce computational budgets, their use for physically-based modeling of LIDs is still unexploited.

The primary objective of this paper is to investigate the suitability of surrogate modeling for the numerical analysis of LIDs techniques by analyzing data from a real case study. The mechanistic model HYDRUS-2D is first used to simulate the hydraulic behavior of a Stormwater Filter (SF) at the University of Calabria, Italy. The surrogate model, based on kriging, is then used to carry out a Global Sensitivity Analysis (GSA) and a Global Optimization of soil hydraulic parameters. The use of a surrogate model for the sensitivity analysis of model outputs to soil hydraulic properties represents a new application of this technique that can provide a significant contribution in this field.

The problem is addressed in the following way. First, the evaporation method is used to measure the soil hydraulic properties of the vegetated substrate above the gravel filter, for which the hydraulic properties were unknown. The measured soil hydraulic properties of the vegetated substrate and the selected ranges of parameters of the filter layer are then used in HYDRUS-2D to set up the model. A Latin Hypercube Sampling (LHS) plan is used to build a first trial of the surrogate model. Before continuing with the other tasks, the surrogate model is validated and improved by using specific infill criteria. Once validated, the surrogate model is first used for the GSA based on Sobol's method to compute the sensitivity measures, and then for the inverse parameter estimation carried out using the Particle Swarm Optimization (PSO) algorithm. Finally, estimated parameters are used in the original mechanistic model for the validation purpose.

2. Materials and methods

2.1. Stormwater filter and site description

The University of Calabria is located in the south of Italy, in the vicinity of Cosenza (39°18′ N 16°15′ E). The climate is Mediterranean with a mean annual temperature of 15.5 °C and average annual precipitation of 881.2 mm. The stormwater filter (SF) has a surface area of 125 m^2, an average slope of 2%, and a total profile depth of 0.75 m. Fig. 1 shows a schematic of the SF.

The filter layer is covered by a vegetated soil substrate with a measured bulk density of 1.59 g/cm^3. A high permeability geotextile with a fiber area weight of 60 g/m^2 is placed at the interface between the soil substrate and the filter layer to prevent fine particles from migrating into the underlying layer. The filter layer is composed of a gravelly material characterized by a high permeability. An impervious membrane is placed at the bottom of the profile to prevent water from percolating into deeper horizons.

The SF is used to treat stormwater runoff from the adjoining impervious parking lot, which is characterized by an area of 220 m^2. Stormwater runoff from the parking lot is first conveyed into a manhole and then to an instrumented channel where the flow rate is measured by a flux meter composed of a rectangular, sharp crested weir coupled with a pressure transducer. The pressure transducer (Ge Druck PTX1830) measures the water level inside the channel and has a range of measurements of 75 cm with an accuracy of 0.1% of the full scale. The pressure transducer was calibrated in the laboratory using a hydrostatic water column, linking the electric current intensity with the water level inside the