Journal of Environmental Management 200 (2017) 434–445

Contents lists available at ScienceDirect

Journal of Environmental Management

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

Research article

Simulation of green roof runoff under different substrate depths and vegetation covers by coupling a simple conceptual and a physically based hydrological model

Konstantinos X. Soulis [a,*], John D. Valiantzas [a], Nikolaos Ntoulas [b], George Kargas [a], Panayiotis A. Nektarios [b]

[a] Department of Natural Resources Management and Agricultural Engineering, Division of Water Resources Management, Agricultural University of Athens, 75, Iera Odos Str., 11855, Athens, Greece
[b] Department of Crop Sciences, Lab. of Floriculture and Landscape Architecture, Agricultural University of Athens, 75, Iera Odos Str., 11855, Athens, Greece

ARTICLE INFO

Article history:
Received 16 December 2016
Received in revised form
26 May 2017
Accepted 6 June 2017

Keywords:
Urban water management
Extensive green roofs
Hydrology
Modelling
HYDRUS
Lysimeter

ABSTRACT

In spite of the well-known green roof benefits, their widespread adoption in the management practices of urban drainage systems requires the use of adequate analytical and modelling tools. In the current study, green roof runoff modeling was accomplished by developing, testing, and jointly using a simple conceptual model and a physically based numerical simulation model utilizing HYDRUS-1D software. The use of such an approach combines the advantages of the conceptual model, namely simplicity, low computational requirements, and ability to be easily integrated in decision support tools with the capacity of the physically based simulation model to be easily transferred in conditions and locations other than those used for calibrating and validating it. The proposed approach was evaluated with an experimental dataset that included various green roof covers (either succulent plants - *Sedum sediforme*, or xerophytic plants - *Origanum onites*, or bare substrate without any vegetation) and two substrate depths (either 8 cm or 16 cm). Both the physically based and the conceptual models matched very closely the observed hydrographs. In general, the conceptual model performed better than the physically based simulation model but the overall performance of both models was sufficient in most cases as it is revealed by the Nash-Sutcliffe Efficiency index which was generally greater than 0.70. Finally, it was showcased how a physically based and a simple conceptual model can be jointly used to allow the use of the simple conceptual model for a wider set of conditions than the available experimental data and in order to support green roof design.

1. Introduction

Among a variety of recently developed management practices aiming to ameliorate the environmental problems and hydrological risks associated with urbanization (Booth and Jackson, 1997), green roofs are emerging as one of the most promising alternatives (Carbone et al., 2014, 2015; Gnecco et al., 2013; Guo et al., 2014). Green roofs, also known as vegetated rooftops, eco-roofs, or living roofs, normally consist of three major components: a vegetation layer, a lightweight substrate medium, and a water storage/drainage layer placed on top of a waterproof membrane (Carbone et al., 2015; Carson et al., 2013; Yang et al., 2015). One of the most important advantages of green roof systems is related to their ability to retain a portion of the precipitation and to gradually release the remaining part, distributing storm runoff over a longer period of time. The retained precipitation is eventually released back into the atmosphere through evapotranspiration. In this way, green roofs facilitate storm water management in urban regions. The hydrologic performance (i.e. precipitation amount retained and runoff release rate) depends on many factors, such as storm characteristics, anteceded rainfall conditions, substrate depth and its hydraulic characteristics, storage/drainage layer characteristics, vegetation cover characteristics, and slope of the green roof (Carbone et al., 2015; Speak et al., 2013; Stovin et al., 2015a; Teemusk and Mander, 2007; Wong and Jim, 2014).

Green roofs are commonly classified as extensive or intensive

* Corresponding author.
E-mail address: soco@aua.gr (K.X. Soulis).

http://dx.doi.org/10.1016/j.jenvman.2017.06.012
0301-4797/

depending on the depth of the growing substrate layer. Green roofs with substrate depth less than 15 cm are classified as extensive and their vegetation consists of shallow rooting, drought resistant plants. Intensive green roofs with substrate depth more than 15 cm may support deeper rooting plants including shrubs and trees. Generally, extensive green roofs are lighter, cheaper, and require less maintenance. Accordingly, they have wider applicability, especially on older buildings where rooftop weight is an important limiting factor (Carson et al., 2013; Nektarios et al., 2011, 2015; Yang et al., 2015).

In spite of the significant and well-known green roof benefits, their widespread adoption in the management practices of urban drainage systems requires the use of adequate analytical and modelling tools (Carbone et al., 2015; Elliott and Trowsdale, 2007; Stovin et al., 2015b). Therefore, apart from the numerous studies focusing on the experimental investigation or the long-term monitoring of green roof hydrological performance, increased attention has recently been given in predicting their hydrologic effects at a watershed scale using hydrological models (Palla and Gnecco, 2015; Trinh and Chui, 2013) or analyzing their hydraulic functioning at a system scale (Carbone et al., 2014, 2015; Hilten et al., 2008; Palla et al., 2011, 2012; Stovin et al., 2013; Vesuviano and Stovin, 2013). Normally, the followed approach consists of two steps: a) estimation of the green roof runoff response and b) integration and routing of the estimated runoff response in the urban system using various methods.

Many studies aimed at modelling the hydrological behavior of green roofs using physically based numerical models that described the unsaturated flow in the porous matrix of the substrate such as HYDRUS software (Hilten et al., 2008; Palla et al., 2012) or other similar models (Carbone et al., 2015; Palla et al., 2009, 2011) based on numerical solutions of the Richards' equations. Other researchers utilized methodologies based on empirical relationships like curve number (CN) and rational coefficient (Getter et al., 2007; Moran et al., 2005; Fassman-Beck et al., 2016) or conceptual models based on cascades of reservoirs (Carbone et al., 2014; Locatelli et al., 2014; Palla et al., 2012; Stovin et al., 2013; Vesuviano et al., 2014).

Physically based models like HYDRUS are very well suited for green roofs planning and design and are generally more accurate than the conceptual and empirical models (Carbone et al., 2015; Palla et al., 2012). However, they are not widely used due to their prohibiting computational requirements as the numerical schemes used in these models require very fine temporal and spatial scales (De Munck et al., 2013). Palla et al. (2012) compared the performance of a mechanistic model based on HYDRUS-1D and a simpler, conceptual, linear reservoir model. They reported that even though the mechanistic model was more accurate, the conceptual model closely matched its performance. Several other studies presented efficient conceptual models simulating the hydrological functioning of several green roof configurations (Carbone et al., 2014; Locatelli et al., 2014; Palla et al., 2012; Stovin et al., 2013; Vesuviano et al., 2014; Vesuviano and Stovin, 2013). Accordingly, conceptual models seem to represent the best feasible alternative for the development of modeling tools for green roof planning, design, and management. However, conceptual models confront an important obstacle due to the lack of a clear physical meaning. As a result, the required parameters are generally difficult to be estimated without calibration while the calibrated models cannot safely be applied in other conditions or other locations.

In this context, the main objectives of this study were the following. Firstly, to investigate whether simplified model conceptualizations are still able to simulate extensive green roof hydrologic behavior. Secondly, to attempt to overcome the above hurdles by using a simple conceptual model jointly with a physically based numerical simulation model using HYDRUS-1D. This approach aims at combining on one hand the advantages of conceptual models, namely simplicity, low computational requirements, and ability to be easily integrated in decision support tools and on the other hand the capacity of physically based simulation models to be easily transferred in conditions and locations other than those used for calibrating and validating them.

Thus, a physically based numerical simulation model based on HYDRUS-1D and a simple conceptual model able to simulate the hydrological functioning of extensive green roofs were developed and tested using experimental data. Subsequently, the models were compared and possible relationships between their parameters were investigated. Finally, the physically based model was used to create a set of synthetic runoff data for various conditions. The conceptual model was calibrated using the synthetic data in order to thoroughly compare the two models and to investigate whether the simple conceptual model can reproduce the results of the physically based model for a wider set of conditions than the available experimental data. In this way, it was attempted to demonstrate that the physically based model may act as the basis for calibrating the simple conceptual model for a wider set of conditions than that of the available experimental data (e.g. climatic conditions, green roof configurations, substrate properties) in order to combine the advantages of both models.

2. Methodology

2.1. Experimental setup and data acquisition

The outdoor study was conducted from December 1, 2014 to April 5, 2015. Twenty two (22) orthogonal lysimeters having dimensions of 110 cm wide × 210 cm long × 35 cm height were placed on the roof of the library building at the Agricultural University of Athens, Greece (37°59′ lat., 23°42′ long). The lysimeters were set at an inclination of 5°. Each lysimeter was thermally insulated at the bottom and from all four sides by 5 cm extruded polystyrene slabs. Taking into account the width of the polystyrene slabs, the remaining space within each lysimeter was 100 cm wide × 200 cm long × 30 cm in height. On top of the polystyrene slabs a waterproofing membrane was lined. An outflow opening was constructed in the middle of their lowest part. The outflow opening was lined with the same waterproofing material and was connected to a pipe leading the runoff to a tipping bucket system. The size of the opening was sufficiently large to avoid the possibility of bottleneck effect even at extreme rainfall intensities.

A complete extensive green roof layering system was simulated within each lysimeter, starting with a protection mat placed on top of the water proofing membrane. The 3 mm protection mat was able to retain 3 L m^{-2} water as manufacturing instructed. A 25 mm high drainage board with 11.8 L m^{-2} water storing capability was laid over the protection mat. Then, the drainage layer was covered by a non-woven geotextile. The substrate for plant growth was placed on top of the non-woven geotextile. Half of the 20 lysimeters were filled with 8 cm substrate depth, while the other half with 16 cm substrate depth. The substrate comprised of pumice, attapulgite clay, zeolite and grape marc compost at volumetric proportions of 65:15:5:15 respectively, according to the patent 1008610. The physical and chemical capacities of the utilized substrate are listed in Table 1. Each lysimeter was equipped with autonomous automated subsurface drip irrigation system; however, during the study period no irrigation was applied.

The lysimeters were planted with two different vegetation types 8 months before the initiation of the study period. Eight (8) lysimeters were planted with 18 plants of *Origanum onites* L. each (Fig. 1c), and 8 more lysimeters were planted with 18 plants of *Sedum sediforme* (Lacq.) Pau each (Fig. 1b). During the study period