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A model for simulating the performance and irrigation of green stormwater facilities at residential scales in semiarid and Mediterranean regions

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A B S T R A C T

Impervious areas change hydrological processes, reducing infiltration and evapotranspiration, and increasing direct runoff. Stormwater practices using green infrastructure are implemented locally to control runoff and preserve the hydrological cycle. Applying these techniques in semiarid and Mediterranean regions requires accounting for aspects related to the maintenance of green areas. This study develops the Integrated Hydrological Model at Residential Scale, a continuous model for representing the performance and irrigation of green stormwater facilities at residential scales. Among other relevant process, the model simulates evaporation from bare soil and redistribution between soil layers. Different components of the model were tested using laboratory and numerical experiments, and then an application to a case study and a sensitivity analysis were carried out. The model identifies significant differences in the performance of a rain garden with different vegetation, climate and irrigation practices and provides good insight for the maintenance needs of green infrastructure for runoff control.

Software availability

Name of software: IHMORS
Developer: Josefina Herrera and Jorge Gironás
Contact address: Jorge Gironás, Departamento de Ingeniería Hidráulica y Ambiental and Centro de Desarrollo Urbano Sustentable (CEDEUS), Pontificia Universidad Católica de Chile, Av. Vicuña Mackenna 4860, Santiago, Chile. Email: jgironas@ing.puc.cl
Availability: Free download at http://jorge-gironas.weebly.com/software.html (personal website)
First available: 2016
Software required: MS Excel (the MATLAB Runtime compiler is provided). Matlab codes can be obtained from the developers upon request

1. Introduction

Urban development reduces infiltration rates and surface storage capacity, producing higher direct runoff volumes and peak flow discharges (Xiao et al., 2007; Freni and Oliveri, 2007). To reduce these effects, different practices known as sustainable urban drainage systems (SUDS), low impact development (LID) and best management practices (BMP) have been developed (Fletcher et al., 2014). These practices replicate natural processes of capture, retention and infiltration to preserve the hydrological cycle and control runoff quantity and quality from frequent events (Huang et al., 2014; Fletcher et al., 2014; Walsh et al., 2014; Everett et al.,

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2015; Houdeshel et al., 2015).

SUDS, BMP and LID typically consider green areas that receive precipitation and runoff from impervious areas (Sample and Heaney, 2006; Xiao et al., 2007), which irrigate them to some extent. Such property may be very relevant in semiarid and Mediterranean regions as it can lead to lower maintenance costs (Sample and Heaney, 2006; Houdeshel and Pomeroy, 2013; Sample et al., 2014). Moreover, considering this supplemental irrigation can drastically change the design in these climates as compared to humid areas (Ascione et al., 2013), as well as the selection of the vegetation (Houdeshel and Pomeroy, 2013; Houdeshel et al., 2015). Finally, and despite the results of these drainage practices can vary substantially due to different climate conditions (Huang et al., 2014), their performance and effectiveness have been less often tested in semiarid and Mediterranean climates (Houdeshel et al., 2015).

Hydrological models are tools for assessing the performance of stormwater facilities. Models like SWMS-2D, HYDRUS and SWAP simulate water and/or solutes and heat transport to model runoff control (Li and Babcock, 2014). Nonetheless, despite their complete treatment of the soil-vegetation-atmosphere processes, none of them are suitable for simulating complex systems with storage structures, drainages or connections among areas which are able to alter the water movement (Li and Babcock, 2014). SWMM v5.1 (Rossman, 2010) is a more suitable model for stormwater facilities thas has been implemented in semiarid and Mediterranean areas (e.g., Huang et al., 2014; Walsh et al., 2014). Its LID module to simulate LID practices (e.g., rain gardens, green roofs, infiltration trenches) has been reported to produce both unsatisfactory results when simulating stormwater runoff hydrographs (Burszta-Adamiak and Mrowiec, 2013; Li and Babcock, 2014; Carson et al., 2017) as well as successful results after calibrated using observations (Palla and Gnecco, 2015; Rosa et al., 2015; Yang et al., 2015). Nonetheless, the model calculates Evapotranspiration (*ET*) on a daily basis using temperature data, and thus neither the type of plant nor the available soil moisture control the process (Rossman, 2010; Carson et al. 2017). Moreover, SWMM does not explicitly compute bare soil evaporation, which requires certain particular considerations (Allen et al., 1998, 2005). Furthermore, it is not possible to capture and visualize the soil water dynamics within multiple soil layers in different LIDs, nor in contributing subcatchments. Finally it is neither possible to explicitly enter an irrigation schedule, nor to design one using the dynamics of *ET* or the soil moisture. Overall, models able to simulate the surface/subsurface processes and the continuous dynamics of the soil water content controlled by *ET* and irrigation dynamics are essential when studying the performance of green infrastructure in semiarid and Mediterranean regions (Sample and Heaney, 2006; Houdeshel et al., 2015). These capabilities permit the evaluation of plant survival and the analysis of the sustainability of drainage techniques.

From our literature review of available models, only the SPAW model (Saxton and Willey, 2005), which simulates water transport with an agricultural focus (Li and Babcock, 2014), is able to explicitly consider the irrigation needs and has been used in urban settings (Lucas, 2006). However some of its characteristics affect its suitability for urban areas, as it runs on a daily basis and explicit connections among areas are not possible. Nonetheless, other studies have developed original models to deal explicitly with the issue of irrigation of drainage control practices. Sample and Heaney (2006) compared and integrated different irrigation management options within the context of LIDs modeling to perform an economic analysis in Boulder, USA. Alternatively, Xiao et al. (2007) developed and assessed a numerical model on an hourly basis to simulate hydrological processes at residential scales. They analyzed rain gutters, cisterns, law retention basins and driveway interceptors, and studied runoff reduction and their efficient use of irrigation water. Despite these studies successfully simulated the dynamics of soil water content, they did not focus on the soil moisture regime so as to determine percentages of time in which soil water content reaches critical levels for vegetation survival, or to assist decision making in irrigation. Such characterization would allow a better quantification of the time involved in irrigation, which translates into maintenance costs that are time dependent.

This paper presents the Integrated Hydrological Model at Residential Scale (IHMORS), a software to evaluate, in a continuous manner, the rainfall-runoff processes and stormwater control at residential scales, together with the irrigation of green areas by means of an irrigation module. Thus, the model is particularly suitable for Mediterranean and semiarid areas in which irrigation is essential for the vegetation's survival through the year. The model simulates surface and subsurface processes and accounts for the water content dynamics in different soil layers. Its different components were first tested using laboratory and numerical experiments, and then an application to a case study was carried out. In this application we assess the long-term performance in terms of runoff control and irrigation needs of rain gardens with different vegetation, under different climates and irrigation practices. Finally, a global sensitivity analysis of the model parameters is also presented.

2. Methodology

IHMORS is a physically-based continuous hydrological model for simulating rainfall-runoff processes in urban areas, which focuses on the performance of stormwater runoff control facilities, as well as irrigation practices at a residential scale. The model was developed in MATLAB and uses a MS Excel spreadsheet for data input. Common SUDS techniques like rain gardens, green roofs, surface retention areas and driveway interceptors can be simulated by combining and connecting different subareas, each with different properties. Input data include: (1) meteorological information, (2) time step information, (3) subareas' spatial configuration, (4) physical properties of subareas, and (5) an optional user defined irrigation program, although IHMORS also computes irrigation programs based on *ET* demands or a required minimum soil water content.

The model partially builds on the framework proposed by Xiao et al. (2007) for the representation of both surface and subsurface processes together with watering needs. Nonetheless, IHMORS implements several changes and improvements including: (1) the explicit and flexible representation of the connectivity among subareas, (2) the simulation of water redistribution among soil layers during dry-weather, (3) the evaporation from bare soil linked to subsurface processes to correctly simulate the soil moisture in each layer, and (4) the simulation of storage and subsurface runoff transport through conduit elements.

IHMORS considers a cascade of permeable and/or impermeable subareas with one or more soil layers each, which are conceived as rectangular planes interconnected through horizontal runoff flows. These flows are distributed uniformly over the downstream subareas as an additional form of precipitation. Fig. 1 shows all of the hydrological processes the model can simulate at each time step Δt (h) defined by the user. Water entering each subarea in the form of rainfall, run-on and/or irrigation, can be intercepted by vegetation or stored by the surface storage capacity. The water that reaches the surface can infiltrate or return to the atmosphere by evaporation from bare soil or *ET* from vegetated soil. Water moves through the soil layers by percolation and/or redistribution during dry weather days. Water reaching the last soil layer, can either go to the drainage system, and/or become deep percolation. Note that a free boundary