A hydrological model to study the performance and irrigation of stormwater facilities

Un modèle hydrologique pour étudier la performance et l'irrigation des installations d'eaux pluviales

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RÉSUMÉ

Le développement de l'urbanisation peut avoir un impact significatif sur l'hydrologie à l'échelle locale, en réduisant l'infiltration et l'évapotranspiration, et en augmentant le volume de ruissellement direct. Des techniques de réduction du ruissellement sont mises en œuvre à l'échelle locale pour contrôler les flux d'eau et préserver le cycle hydrologique. Ces techniques sont généralement des infrastructures vertes et leur utilisation en région semi-aride et méditerranéenne nécessite de prendre en compte certains aspects relatifs à la maintenance de ces zones vertes, comme leur irrigation ou le choix des espèces végétales. Ce travail présente la Modélisation Hydrologique Intégrée à l'Échelle Parcellaire, qui permet d'évaluer, en continu, les processus pluie-débit et le contrôle des volumes produits à l'échelle de la parcelle urbaine, ainsi que l'irrigation des zones vertes en fonction des espèces végétales utilisées. Le modèle simule les processus de surface et souterrains, et prend en compte la dynamique de l'humidité du sol. Plusieurs composantes du modèle ont été évaluées à l'aide d'expériences numériques et de laboratoire, puis une étude de cas a été conduite. Le modèle identifie des différences significatives en termes de performances pour des jardins de pluie avec des différences de végétation, climat et pratiques d'irrigation, et donne une bonne idée des besoins en maintenance des infrastructures vertes de contrôle du ruissellement.

ABSTRACT

Urban development can produce great impacts on local hydrology reducing infiltration and evapotranspiration, and increasing direct runoff volumes. Runoff control practices are implemented at local scales to control flow discharges and preserve the hydrological cycle. These techniques usually have green infrastructure therefore the application in semiarid and Mediterranean regions requires accounting for aspects related to maintenance of green areas, such as the irrigation needs and the selection of the vegetation. This study develops the Integrated Hydrological Model at Residential Scale, which allows evaluating in a continuous manner the rainfall-runoff processes and stormwater control at residential scales, together with the irrigation of green areas and the vegetated LID's involved. The model simulates surface and subsurface hydrological processes and accounts for the soil water content's dynamics. Different components of the model were tested using laboratory and numerical experiments, and then an application to a case study was carried out. The model identifies significant differences in the performance of a rain garden with different vegetation, climate and irrigation practices, and provides a good insight for the maintenance needs of green infrastructure for runoff control.

KEYWORDS

Green infrastructure, hydrological continuous simulation, irrigation, residential scale, soil water content

1 INTRODUCTION

To control the direct runoff from frequent events and preserve the hydrological cycle, runoff control practices have been implemented at local scales (Everett et al., 2015). These practices are identified with names such as sustainable urban drainage systems (SUDS), low impact development (LID) and best management practices (BMP) (Fletcher et al., 2014). Such techniques can be very useful in Mediterrenaean and semiarid environments because they can treat urban runoff while simultaneously using stormwater as the primary irrigation source, which ultimately may lead to lower maintenance costs (Sample and Heaney, 2006).

Hydrological models are valuable tools when assessing the performance of stormwater facilities in semiarid and Mediterranean regions because they allow evaluating the effects of runoff reduction and the efficient use of water. One of these models is the U.S. Environmental Protection Agency's Stormwater Management Model (SWMM), which simulates rainfall-runoff process in urban areas (Rossman, 2010). The new version of this model includes evaporation of standing surface water, infiltration and percolation (Rossman, 2010), but the model is not strongly suitable for capturing and visualizing the soil water content dynamics in different LIDs, nor in contributing subcatchments. Furthermore, it is neither possible to enter an irrigation schedule as an input nor to design one based on the dynamics of evapotranspiration or the soil moisture content. Sample and Heaney (2006) and Xiao et al. (2007) propose other models which consider and simulate both watering needs and soil moisture behavior together with stormwater runoff control. 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 decission-making in irrigation. Such characterization would allow a better quantification of the amount of time involved in irrigation associated with economic costs (i.e. personnel expense, maintenance, number of days for which certain maintenance activity is needed, etc.).

This work presents the Integrated Hydrological Model at Residential Scale (IHMORS), which allows evaluating in a continuous manner the rainfall-runoff processes and stormwater control at residential scales, together with the irrigation of green areas and the vegetated LID's involved.

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 residential scale. The model was developed in MATLAB and considers data input through a MS Excel spreadsheet. Input data include: (1) meteorological information, (2) time step information, (3) subareas' spatial configuration, (4) physical properties of each subarea including vegetation properties if necessary, and (5) an optional irrigation program defined by the user, although IHMORS also can compute irrigation programs based on evapotranspiration *ET* demands or a minimum soil water content.

IHMORS works with a cascade of subareas which can be permeable or impermeable. These subareas are conceived as rectangular planes interconnected through horizontal runoff flows, which are distributed uniformly over the downstream subareas as an additional form of precipitation. Each subarea can have different soil layers. Figure 1 shows all of the hydrological processes considered in the model. Each process involved is updated according to the time step selected by the user. Water enters each subarea in the form of rainfall, run-on and/or irrigation, to then 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* (if the soil is covered by vegetation). In the subsurface, water moves through the soil layers by percolation and/or redistribution during dry weather days. Water reaching the last soil layer, can then either move to the deep percolation and/or go to the drainage system, depending on type of SUDS, LID or green area represented. In parallel, non-infiltrated water becomes runoff and flows downstream to another subarea defined in the model or the drainage system. Such flow is simulated with a non-linear reservoir.

3 MODEL CALIBRATION AND VALIDATION

Three experimental tests were performed to validate critical components of the model: bare soil evaporation, subsurface runoff and soil moisture redistribution. None of these three processes are often explicitly considered by rainfall-runoff models for urban settings. To evaluate the quality of the calibrations and/or validations, the Modified Coefficient of Efficiency (MCE) (Legates and McCabe, 1999) was use. A value of 1 indicates an exact match with the observations.

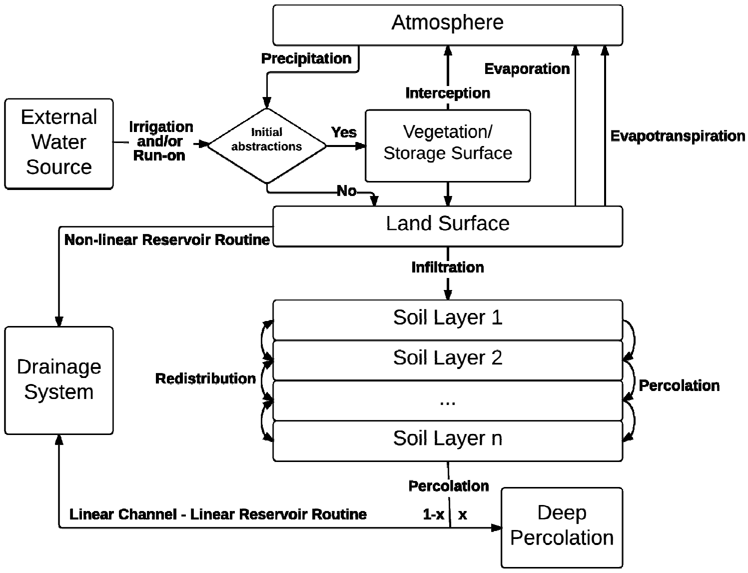

Figure 1: Conceptual representation of the physical processes at a residential scale simulated in IHMORS

To test and calibrate evaporative parameters, five different soil samples used as substrates in green roofs were dried under ambient conditions. The samples were weighed on a daily basis to measure evaporative water loss. Simulated soil water content closely compared to observations (MCE > 0.8).

Two experiments were performed to validate the capability of the model to simulate subsurface flow and the corresponding hydrograph. In each experiment a constant rain pulse was applied during 15 minutes over a sample of soil in a square box. Both water content in the mind point and the flow discharge drained from the box were measured. The subsurface flow was well simulated, and both the calibration and validation hydrographs produced by IHMORS match the observations well (MCE > 0.6).

HYDRUS-1D, a model to simulate water flow and solute transport into non-uniform soils (Simunek et al., 2013) was used to validate the water redistribution flux through the soil layers. To validate this component of IHMORS, a 0.6 m depth soil composed of a 0.2 depth top layer over a second layer of 0.4 m depth was simulated. We simulated 3 cases with different initial water content in each layer. MCE > 0.5 in all three cases imply that the soil water content dynamics simulated by both models in each layer are in reasonable agreement, despite the simpler approach adopted in IHMORS.

4 APPLICATION TO A RAIN GARDENS

After validating its properties IHMORS was used to simulate and assess the long-term performance (2 years, 2012-2013) of rain gardens. In particular, it was used to study the soil water content dynamics and the overall long-term water balance, exploring the impacts of irrigation schedules and the design practices (i.e. the selection of the vegetation and connection or disconnection of upstream contributing areas) on its maintenance needs. Two rain gardens assumed to be in 2 different cities in Chile were designed and modeled. One was located in the city of Santiago (33°26'S 70°39'W) and the other one in Temuco (38°46'S 72°38'W). Santiago has a warm temperate climate with dry summers (Peel et al., 2007) while Temuco has a warm temperate humid climate with warm summers (Peel et al., 2007). Both cases adopted a 2 m^2 rain garden receiving runoff from a 10 m^2 rectangular impervious surface. Two layers of the same soil with depths of 0.2 m (top layer) and 0.4 m (bottom layer) were considered. *Sedum* and grass were chosen as the rain garden's vegetation. Surface storage depths of 50 mm for Santiago and 60 mm for Temuco were defined, as precipitation in Temuco is 5 times greater than in Santiago.

4.1 Results and discussion

Figure 2 and 3 shows the soil water content duration curves, which represent the percentage of time that a given water content is equaled or exceeded. Figure 2a and 2b compare the soil water content performance for each city when varying the vegetation type (*Sedum* or grass). The figures also show the performance for bare soil, as well as the condition of a totally dry summer in Temuco (GS in Figure 2b). Figure 3a compares the effect of different irrigation plans on the duration curve for the rain garden with *Sedum* in Santiago. These plans include: a constant irrigation program (P1), a constant irrigation program with soil moisture sensor reporting field capacity (P2), an irrigation plan that replicates the previous day *ET* (P3), and finally no irrigation at all (WI). Figure 3b compares the duration curves of the rain garden with and without the connection with the upstream contributing area.

This exercise provided a comprehensive understanding of the performance of this type of drainage practice. Despite all the rain gardens control the totality of the runoff, they differ in terms of the soil water content dynamics and irrigation needs for maintenance. For example, irrigation is more essential in semiarid climates (Santiago) than humid climates (Temuco), as the soil water content is lower than the wilting point (θ_{WP}) for a longer time, regardless the vegetation used (Figure 2a and 2b). On the other hand, the resulting soil water content dynamics depend largely on the frequency and amount of irrigation (Figure 3a) as well as the connectivity with other contributing areas (Figure 3b).

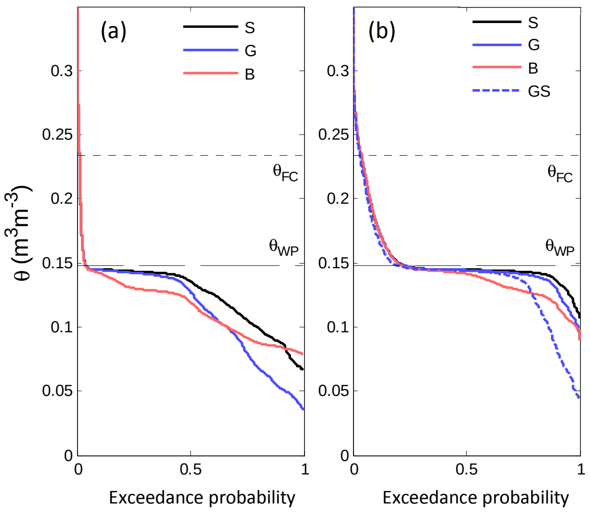

Figure 2: Soil water content duration curves comparing gardens with *Sedum* (S), grass (G) and no vegetation (B) for Santiago (a) and Temuco (b). In Temuco a garden with grass without summer precipitation is also considered (GS).

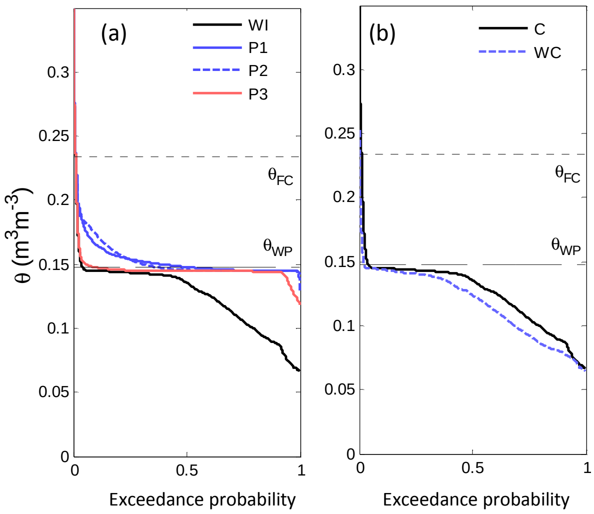

Figure 3: (a) Soil water content duration curves in Santiago for irrigation plans P1, P2, P3 and no irrigation (WI), (b) Santiago with *Sedum* connected (C) and disconnected (WC) with the contributing impervious area.

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