Journal of Hydrology 554 (2017) 780–791

Contents lists available at ScienceDirect

Journal of Hydrology

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

Research papers

Unsaturated hydraulic behaviour of a permeable pavement: Laboratory investigation and numerical analysis by using the HYDRUS-2D model

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ARTICLE INFO

Article history:
Received 4 July 2017
Received in revised form 14 September 2017
Accepted 3 October 2017
Available online 4 October 2017
This manuscript was handled by Prof. P. Kitanidis, Editor-in-Chief, with the assistance of J. Simunek, Associate Editor

Keywords:
LID
Permeable pavement
Urban drainage
Sensitivity analysis
Infiltration

ABSTRACT

An adequate hydrological description of water flow in permeable pavement systems relies heavily on the knowledge of the unsaturated hydraulic properties of the construction materials. Although several modeling tools and many laboratory methods already exist in the literature to determine the hydraulic properties of soils, the importance of an accurate materials hydraulic description of the permeable pavement system, is increasingly recognized in the fields of urban hydrology. Thus, the aim of this study is to propose techniques/procedures on how to interpret water flow through the construction system using the HYDRUS model. The overall analysis includes experimental and mathematical procedures for model calibration and validation to assess the suitability of the HYDRUS-2D model to interpret the hydraulic behaviour of a lab-scale permeable pavement system. The system consists of three porous materials: a wear layer of porous concrete blocks, a bedding layers of fine gravel, and a sub-base layer of coarse gravel. The water regime in this system, i.e. outflow at the bottom and water contents in the middle of the bedding layer, was monitored during ten irrigation events of various durations and intensities. The hydraulic properties of porous concrete blocks and fine gravel described by the van Genuchten functions were measured using the clay tank and the multistep outflow experiments, respectively. Coarse gravel properties were set at literature values. In addition, some of the parameters (K_s of the concrete blocks layer, and α, n and K_s of the bedding layer) were optimized with the HYDRUS-2D model from water fluxes and soil water contents measured during irrigation events. The measured and modeled hydrographs were compared using the Nash-Sutcliffe efficiency (NSE) index (varied between 0.95 and 0.99) while the coefficient of determination R^2 was used to assess the measured water content versus the modelled water content in the bedding layer ($R^2 = 0.81 \div 0.87$). The parameters were validated using the remaining sets of measurements resulting in NSE values greater than 0.90 ($0.91 \div 0.99$) and R^2 between 0.63 and 0.91. Results have confirmed the applicability of HYDRUS-2D to describe correctly the hydraulic behaviour of the lab-scale system.

1. Introduction

In recent decades, due to rapid expansion of urbanization, urban areas have experienced an increase of impermeable surfaces such as roofs, roads and other paved surfaces. This urban development has diminished natural soil drainage and has increased runoff volumes (Finkenbine et al., 2000). This phenomenon, coupled with a progressive increase of precipitation, due to climate change, could likely increase floods in urban areas. In this way, traditional urban drainage techniques, seem to be inadequate for the purpose.

Recently, to mitigate the effects of urbanization, Low Impact Development systems (LID), an innovative stormwater management approach, have gained popularity, despite the debate in the scientific community about their advantages compared to traditional drainage systems (Burns et al., 2012; Shuster and Rhea, 2013). LID systems consist of a series of facilities whose purpose is to reproduce the site's pre-developed hydrological processes using design techniques that infiltrate, filter, store, evaporate, and detain runoff close to its source. The most common LID techniques are green roofs, bioretention cells, infiltration trenches, wetlands, wet ponds, swales and permeable pavements. Benefits of LIDs in terms of runoff reduction and pollutants removal have been widely discussed in the literature (Carbone et al., 2014a; Huang et al., 2016; Kamali et al., 2017). For example, Kamali

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https://doi.org/10.1016/j.jhydrol.2017.10.005
0022-1694/

et al. (2017) investigated the performance of a permeable pavement under sediment loadings during its life span by evaluating the temporal and spatial clogging trends of this facility and by finding its vulnerability to sediment loadings during rainfalls.

Considering the complexity of the physical processes involved, modelling tools able to accurately interpret the behaviour of LIDs are required. Although in the literature there are several stormwater models that can be used to analyze LIDs, most of them lack a comprehensive description of the hydrological processes involved, and often do not include any parameters optimization techniques. Therefore, the scientific community has recently focused its attention on physically based models to describe the hydraulic behaviour of LIDs.

The HYDRUS software package (Šimůnek et al., 2016), is one of the most widely used software to simulate water flow and solute/heat transport in two-dimensional vertical or horizontal planes, in axisymmetrical three-dimensional domains, or in fully three-dimensional variably saturated domains. Recently, the HYDRUS models have been used in the literature for the description of the hydraulic behaviour of LIDs such as green roofs and permeable pavements with optimal results (Brunetti et al., 2016a,b; Carbone et al., 2014a,b; Carbone et al., 2015a; Hilten et al., 2008; Palla et al., 2009; Qin et al., 2016; Yang et al., 2015). However, despite the satisfactory results of the cited studies, the development and use of these numerical tools for the description of LIDs is still limited.

Permeable pavements (PP) represent a good solution to solve stormwater management problems both in quantitative and qualitative terms. In general, PP systems are layered systems consisting of a wear layer, generally concrete, a filter layer, mainly constituted of coarse sand or fine gravel, a gravel aggregate base layer, and a crushed stones sub-base layer. The heterogeneity of the materials that compose PPs, and its strongly unsaturated hydraulic behaviour, pose significant modelling challenges. In this way, most of the works related with permeable pavement are focused on the hydrological performance of PP both in qualitative and quantitative terms (Al-rubaei et al., 2013; Brown and Borst, 2015a,b; Chandler and Wheater, 2002; Dreelin et al., 2006; Haselbach et al., 2014; Huang et al., 2016; Kamali et al., 2017; Kuang et al., 2011; Legret et al., 1996; Lin et al., 2016; Palla and Gnecco, 2015; Sansalone et al., 2012).

The sustainable management of water resources requires the identification of procedures to optimize the use and the management of resources (Maiolo and Pantusa, 2016). Moreover, a correct characterization/identification of the parameters controlling the water regime in construction materials is a crucial task (when using physically based models). Despite the hydrological benefits of permeable pavements, these techniques are not yet widespread probably because modelling tools often used simplified methodologies, based on empirical and conceptual equations, which do not take into account hydrological processes in a physical way. In addition, the hydraulic properties of pavement materials have not been investigated in a comprehensive manner, limiting the investigation only to specific properties. For example, Chandrappa and Biligiri, (2016) investigated the permeability characteristics of porous concrete mixtures using falling head permeameter method. This study showed the relationship between material porosity and permeability in order to have a good design of the concrete mixture. In another work, Zhong et al. (2016) recognized the influence of pore tortuosity on hydraulic conductivity of pervious concrete. This study showed that several parameters influenced the prediction of hydraulic conductivity and this parameter was not solely affected by effective porosity. A limit of this study is that it is only focused on the concrete material and also it does not explore other hydraulic properties different than hydraulic conductivity. In another paper, Huang et al. (2016) proposed a numerical model for permeable pavements and also proved its applicability by applying it to simulate both hydraulics and water quality. The results of this study demonstrated a good agreement between field measurements and modeled results for three types of pavement in terms of hydraulics and water quality variables including peak flow, time to peak, outflow volume and TSS removal rates. Although a variety of analytical and numerical models are now available to predict water through porous media, the most popular model (maybe the best way) remains the Richards equation for variably saturated flow. A limit in using Richards equation is that its numerical solution has been criticized for being computationally expensive and unpredictable. In this way, the HYDRUS program numerically solves the Richards equation for saturated-unsaturated water flow.

Thus, the aim of this work is to propose a technique/procedure on how to interpret water flow through the construction system using the HYDRUS model. This research will suggest experimental and mathematical procedures for model calibration, which consists of: (a) experimental design (system construction, and number and character of measured transient flow data); (b) methods for independently evaluating of material hydraulic properties; (c) additional optimization of material hydraulic parameters using the transient flow data; and (d) model validation. The van Genuchten-Mualem function (van Genuchten, 1980) included in HYDRUS-2D was used to describe the unsaturated flow within the system. Following the experimental procedures proposed by Kodešová et al. (2014), several analyses have been conducted on the wear and bedding material of the lab-scale porous system made of porous concrete blocks and fine gravel. Results of these analyses have been fundamental to obtain the Soil Water Retention Curve (SWRC) of the materials so as to limit the following parameter optimization phase. The effect of the remaining parameters has been investigated through a sensitivity analysis carried out using the Morris screening method. Therefore, a model calibration procedure using the parameter optimization procedure included in HYDRUS-2D, namely the Levenberg-Marquardt optimization algorithm, has been conducted. Finally, the calibrated model was validated on an independent set of measurements.

2. Materials and methods

2.1. Lab-scale permeable pavement system

In order to study the behaviour of a permeable pavement, a lab-scale test bed was constructed. It consisted of a Plexiglas container (dimensions of the bottom 59 × 59 cm, height of 41 cm) with a circular outlet in the centre of the bottom (diameter of 10 cm) and layers of construction materials (Fig. 1) for a total thickness of 41 cm. The main principle of a pavement design is that the constructed layers distribute the concentrated loads from wheels below the road. The pressure of the wheels on the wear layer is relatively high, thus it is necessary to adopt high quality materials for this layer. Conversely, pressure decreases with depth and allows the use of weaker materials in the lower layers of the pavement. For these reasons, the choice of constituent materials and their gradations are fundamental. Generally, the main layers of a permeable pavement are a wear layer, a bedding layer, a base layer and a sub-base layer. The layer types and their construction thickness for the lab-scale porous modular pavement were chosen according to the CIRIA report (Kellagher et al., 2015), considering a traffic category of 3 (small car parks subject to cars, light vans and motorcycle access) and a California Bearing Ratio index (CBR) of 5% or greater. The wear layer consists of porous concrete blocks characterized by high permeability. Sub-base and bedding layers were constructed following the suggestions of the Interlocking Concrete Pavement