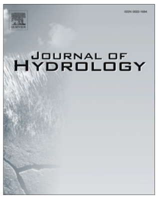
Journal of Hydrology 533 (2016) 15–27

Contents lists available at ScienceDirect

Journal of Hydrology

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



Temporal evolution modeling of hydraulic and water quality performance of permeable pavements

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ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 14 October 2015
Accepted 26 November 2015
Available online 30 November 2015
This manuscript was handled by Corrado Corradini, Editor-in-Chief, with the assistance of Renduo Zhang, Associate Editor

Keywords:
Low impact development
Modeling
Permeable pavements
Stormwater management
Urban hydrology
Water quality

SUMMARY

A mathematical model for predicting hydraulic and water quality performance in both the short- and long-term is proposed based on field measurements for three types of permeable pavements: porous asphalt (PA), porous concrete (PC), and permeable inter-locking concrete pavers (PICP). The model was applied to three field-scale test sites in Calgary, Alberta, Canada. The model performance was assessed in terms of hydraulic parameters including time to peak, peak flow and water balance and a water quality variable (the removal rate of total suspended solids). A total of 20 simulated storm events were used for model calibration and verification processes. The proposed model can simulate the outflow hydrographs with a coefficient of determination (R^2) ranging from 0.762 to 0.907, and normalized root-mean-square deviation (NRMSD) ranging from 13.78% to 17.83%. Comparison of the time to peak flow, peak flow, runoff volume and TSS removal rates between the measured and modeled values in model verification phase had a maximum difference of 11%. The results demonstrate that the proposed model is capable of capturing the temporal dynamics of the pavement performance. Therefore, the model has great potential as a practical modeling tool for permeable pavement design and performance assessment.

1. Introduction

Traditionally, stormwater runoff from impervious surfaces has been intercepted by sewer systems and discharged to receiving water bodies. Due to rapid expansion in recent years, urban areas have experienced an increase of impermeable surfaces such as roofs, roads and other paved surfaces. This change in the impervious-pervious surface balance has caused significant changes to both quality and quantity of stormwater runoff leading to degraded urban water systems (Arnold and Gibbons, 1996; Brabec, 2002; Finkenbine et al., 2000). Permeable pavement, one of the widely used Low Impact Development (LID) technologies in urban areas, presents a feasible solution to the above issues as it provides in situ restoration of the urban hydrologic cycle and reduces the needs for traditional stormwater facilities. Permeable pavement not only reduces runoff and flooding, enhances groundwater recharge, and filters and treats infiltrating runoff, but also provides the load carrying capacity of the conventional pavement. (Sansalone et al., 2008; Scholz and Grabowiecki, 2007). Porous asphalt (PA), porous concrete (PC) and permeable inter-locking pavers (PICP) are currently three very popular permeable pavements and have been widely applied in driveways, parking lots and low-speed roads (Balades et al., 1995; Watanabe, 1995).

Due to the massive application of permeable pavement in urban areas, many studies have been conducted to address its applicability on hydraulic and water quality performance. The hydraulic performance focuses on runoff attenuation, peak reduction and surface infiltration capacity, while water quality performance focuses on removal of various pollutants including total suspended solids (TSS), nutrients (i.e. nitrogen and phosphorus), heavy metals (i.e. Cu, Pb and Zn) and hydrocarbons. Most studies of water quality and quantity performance in the literature use field investigations under different testing conditions such as pavement age and structure, inflow characteristics and climate. The results showed that permeable pavement is capable of reducing stormwater runoff and can maintain its surface infiltration capacity at a satisfactory level with proper maintenance after as much as 10 years of service (Al-Rubaei et al., 2013; Ball and Rankin, 2010; Bean et al., 2007; Booth and Leavitt, 1999; Brattebo and Booth, 2003; Lucke and Beecham, 2011). In water quality performance, permeable pavement has been consistently shown to remove considerable amounts of TSS, heavy metals (Cu, Pb and Zn) and hydrocarbons from stormwater runoff (Brown et al., 2009; Eck et al., 2011a;

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http://dx.doi.org/10.1016/j.jhydrol.2015.11.042
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Newman et al., 2002; Roseen et al., 2011). However, reported performance for removing nutrients (nitrogen and phosphorus) has been inconsistent (Collins et al., 2009; Gilbert and Clausen, 2006; Huang et al., 2012; Pagotto et al., 2000; Rushton, 2001). Several studies employing laboratory experiments in order to better control testing conditions showed similar findings to those from the field investigations (Fach and Geiger, 2005; Huang, 2015; Tota-Maharaj and Scholz, 2010).

Previous studies on hydraulic and water quality performance of permeable pavements have primarily focused on the analyses and interpretation of field and laboratory-based observations (Brattebo and Booth, 2003; Huang et al., 2012; Pezzaniti et al., 2009; Roseen et al., 2011; Sansalone et al., 2008). This information is critical for understanding performance and thus, necessary for predicting the performance in existing pavement systems and for design of future systems. In order to utilize this information for design purposes, designers need robust modeling tools that can quantitatively predict both the hydraulic and water quality performance over the short-term and long-term horizons before pavement construction. Therefore, this paper aims to develop a numerical model, which is robust and can capture the temporal variation of pavement performance, for the engineering design of different types of permeable pavements. The literature shows that sufficient research has been conducted to understand how permeable pavements function to mitigate water quantity attenuation and mitigation of TSS (Al-Rubaei et al., 2013; Ball and Rankin, 2010; Bean et al., 2007; Brown et al., 2009; Eck et al., 2011a; Newman et al., 2002). Engineering permeable pavements for long-term performance with minimal maintenance requires accurate computer modeling of sediment accumulations in the pavement so engineers may be able to determine the appropriate design for the desired mitigation levels. A handful of studies have simulated the performance of permeable pavements by modeling techniques (either numerical or empirical), but fewer still have compared their predictions to data obtained through field investigations and lab experiments.

In modeling hydraulic performance, permeable pavements are often considered a porous media made of various surface materials (PA, PC and PICP) with one or more sub-surface gravel layers. Previous studies have simulated the hydraulic conductivity and porosity for surface and gravel layers of permeable pavements. Tan et al. (2003) modeled the reduction of porosity in the base layers for permeable pavements using the Kozeny–Carman equation in conjunction with experimental data. Montes and Haselbach (2006) established a quantitative relationship between porosity and hydraulic conductivity of a PC surface using a similar methodology to Tan et al. (2003). Deo et al. (2010) developed a model to simulate the degradation of surface infiltration rates (SIR) for a PC system based on a probabilistic particle capture approach and experimental data. Kuang et al. (2011) compared the hydraulic conductivity of the surface layer of a PC with that simulated by different models using various pore-structure equations. The comparison showed that Kozeny–Carman equation can successfully simulate the hydraulic conductivity with proper calibration of porosity and tortuosity. Yong et al. (2013) developed a black-box regression model to predict the degradation of porosity for a PA surface using laboratory experimental data.

A few studies have also focused on simulating the surface runoff, infiltration and outflow of permeable pavements. Macdonald et al. (1979) modeled the flow through a gravel media using a revised version of the Ergun equation and the results from the model were consistent with those obtained from lab experiments. Zhu et al. (1999) developed a numerical model based on Smoothed Particle Hydrodynamics (SPH) to describe the flow through a gravel media. Schluter and Jefferies (2002) developed a computer model to simulate the outflow (peak rate and volume) from porous pavement using the stormwater software package ERwin®. Eck et al. (2011b) developed a numerical model using the Boussinesq equation to simulate the surface runoff mitigation during storm events by applying mass conservation for the surface layer of a PA.

In water quality performance, previous studies have modeled pollutant removal (mostly TSS) by filter units of a gravel media in water and wastewater treatment. The removal mechanisms of TSS for gravel are mainly by sedimentation and interception (Yao, 1968; McDowell-Boyer et al., 1986; Urbonas, 1999). Yao et al. (1971) developed a numerical model in TSS removal for a gravel media, rapid sand filter by assuming that the major removal mechanisms are sedimentation, interception and diffusion. Based on the study by Yao et al. (1971), Tufenkji and Elimelech (2004) developed a regression model to describe the sedimentation, interception and diffusion processes for gravel media and model results were in good agreement with experimental data. Wu (1994) developed a numerical model simulating TSS removal from a gravel media given constant water pressure head. Several studies applied the theory developed for sand filters to stormwater management. Siriwardene et al. (2007) modified the model created by Yao et al. (1971) and applied the modified model to successfully simulate the sediment transport in gravel layers installed in a stormwater pond and sediment basin. Wong et al. (2006) introduced a first order kinetic decay model to estimate the overall TSS removal in stormwater ponds with the presence of a gravel media. Huang (2015) developed a regression model to predict the overall TSS removal efficiency for permeable pavements using experimental data. However, no study has applied the developed methodologies from filter units to numerically model the TSS removal in permeable pavements, even though the removal mechanisms between filters and permeable pavement are similar.

The above review shows that the aforementioned hydraulic models mainly targeted one or more hydraulic parameters (e.g. porosity, hydraulic conductivity and outflow) for a specific layer of permeable pavement (either the surface or subsurface gravel layer). From a water quality perspective, the previous models cited above were mostly developed for modeling the treatment efficacy of gravel media in sand filters or stormwater ponds but not for permeable pavements. As permeable pavements become more and more popular and more widely used, design requirements that achieve peak flow reduction will be required, and thus, accurate models that predict performance are required. In addition, pollutant removal becomes an important index for permeable pavement performance and it is necessary to have this information available at the design stage. This necessitates the development of numerical models that can predict both hydraulic and water quality performance of complete permeable pavement systems (both surface and gravel sub-layers) in order to help stormwater engineers optimize design and operation. Therefore, the twofold objectives of this paper are to: (1) propose a numerical model for permeable pavement systems that can accurately and realistically simulate both water quantity and quality (focusing on TSS) of outflow, and (2) to prove the applicability of the proposed model by applying the model to simulate three different types of permeable pavements (PA, PC, and PICP), which were tested in a field study in Calgary, Alberta, Canada.

2. Mathematical model development

A permeable pavement usually consists of a surface layer and one or more sub-surface gravel layers. The material specifics used in the surface layer and sub-surface layer are different due to the structural requirements and the purpose of the engineering structure. The surface layers of PA and PC are normally formed of coarse aggregates that are bonded together by bituminous asphalt and cement, respectively. The surface layer of PICP typically consists