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A flexible modeling framework for hydraulic and water quality performance assessment of stormwater green infrastructure

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ABSTRACT

A flexible framework has been created for modeling multi-dimensional hydrological and water quality processes within stormwater green infrastructure (GI) practices. The framework conceptualizes GI practices using blocks (spatial features) and connectors (interfaces) representing functional components of a GI. The blocks represent spatial features with the ability to store water (e.g., pond, soil, benthic sediments, manhole, or a generic storage zone) and water quality constituents including chemical constituents and particles. The hydraulic module can solve a combination of Richards equation, kinematic/diffusive wave, Darcy, and other user-provided flow models. The particle transport module is based on performing mass-balance on particles in different phases, e.g., mobile and deposited in soil with constitutive theories controlling their transport, settling, deposition, and release. The reactive transport modules allow constituents to be in dissolved, sorbed, bound to particles, and undergo user-defined transformations. Four applications of the modeling framework are presented that demonstrate its flexibility for simulating urban GI performance.

Software availability: The distribution package for GIFMod including additional examples and a detailed user's manual are available at www.gifmod.com. The source code and installation package of the program can also be downloaded from the US EPA Github repository at: https://github.com/USEPA/GIFMod.

1. Introduction

Urban stormwater GI systems, also referred to as low impact development (LID) practices, are designed to reduce the volume, peak flow, and the contaminant loading associated with stormwater runoff. A GI design relies on processes such as infiltration, evapotranspiration, sedimentation, filtration, deposition, and plant uptake for mitigating stormwater runoff impacts. A variety of GI types are used for stormwater management, including dry and wet ponds, infiltration basins or trenches, constructed wetlands, bioretention systems, rain gardens, rain barrels, green roofs,, bioswales, and porous pavement; for a review (Ahiablame et al., 2012). Innovative or non-conventional approaches including combining multiple types of GI practices or using non-standard GI designs have also been proposed and proven to be effective in some cases (Dickson et al., 2011; Liu et al., 2015; Page et al., 2012).

To evaluate the long-term performance of GI design and explore potential improvements, it is important to model the processes affecting GI hydraulics and the fate and transport of contaminants fluxing through these facilities. This is particularly important because field studies have shown that the performance of stormwater GI practices can be highly dependent on their design configuration and the properties of the fill medium (Liu et al., 2014) as well as the intensity and duration of rain events (Qin et al., 2013). Furthermore, the recommended design standards for GIs are often different among jurisdictions in the United States and around the world (He and Davis, 2010).

Process-based mathematical modeling provides a cost-effective way to examine the effects of various design guidelines on the performance of GI practices tailored to specific sites and geographies. Modeling is also beneficial in characterizing the relative

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importance of various treatment processes within GIs and to optimize their performance at meeting hydraulic and water quality goals.

Most available models for GI performance analysis are either developed for catchment-scale applications or for specific LID practices with a pre-defined structure and limited scope. For a complete review, see Elliott and Trowsdale (2007). At the catchment scale, although there exist useful tools for large-scale assessment of the effectiveness of LID practices and for planning purposes, these tools often lack the details needed to consider site-specific design aspects or detailed processes occurring within one or more LID practices. For example, a LID feature was added in the Storm Water Management Model (SWMM) version 5.0 (Rossman, 2004, 2015); where different types of LID practices can be modeled as a combination of several compartments including surface, soil, storage and underdrain in which the downward infiltration is considered using the Green-Ampt equation (Green and Ampt, 1911) and first order decay of water quality constituents can also be modeled. The hydraulic retention time and the first order decay coefficient is used to calculate the effluent concentration based on the influent concentration to an LID. However, SWMM does not allow for more detailed considerations of how important internal reactive transport processes interact with GI structural design to influence contaminant removal or transformation to groundwater (Niazi et al., 2017). Similarly, the Soil and Water Assessment Tool (SWAT) 2009 (Neitsch et al., 2011); treats LID systems as storage blocks or reservoirs with given outflow, infiltration and evapotranspiration functions. Some other stormwater models that have the capability to consider GI practices include Source Loading and Management Model (WinSLAMM) (Pitt and Voorhees, 2004), and Model for Urban Stormwater Improvement Conceptualization (MUSIC) (Wong et al., 2002). Some simpler stormwater models (e.g., L-THIA-LID) (Lim et al., 1999) treat LID systems by considering alternate effective lumped parameters governing run-off generation and infiltration on modeled subcatchments (e.g., L-THIA-LID https://engineering.purdue.edu/mapserve/LTHIA7/lthianew/lidIntro.htm). Ackerman and Stein (2008) implemented best management practices (BMPs) into the HSPF hydrological model (Bicknell et al., 2001) by treating them as reservoirs with the capability to retain water through orifices and spillways or as water flowing through channels with bank overflow; the model then determines the load reduction of contaminants proportional to the volume reduction and first-order degradation. However, these models do not have the capability to consider detailed processes that can affect the performance of GI practices such as exfiltration, short-circuting, evapotranspiration, plant uptake, reactive-transport/biogeochemical transformation of constituents, or suspended/colloidal particle-associated transport within the GI systems.

As an alternative to catchment-scale models, LID-specific models have also been developed for specific types of GI with pre-defined structures including models representing bioretention systems (Brown et al., 2013; Dussaillant et al., 2004, 2005; He and Davis, 2010; Palhegyi, 2009) and Permeable Pavements (Lee et al., 2014) among others. Dussaillant et al. (2004) developed a model based on Richards equation called RECHARGE to evaluate the hydraulic performance of bioretention systems. Dussaillant et al. (2005) developed another model based on the Green-Ampt equation and compared it to the RECHARGE model. Brown et al. (2013) used DRAINMOD (Skaggs, 1990) to model the performance of bioretention systems. DRAINMOD is designed for the prediction of surface and subsurface drainage processes in agricultural land using the Green-Ampt equation for infiltration. WinDetPond (Pitt and Voorhees, 2003) is a process-based modeling tool designed mainly to evaluate the performance of detention-type GI systems with the main focus being pond hydraulic effects and particle capture through gravity settling. In this model, the hydraulic routing is done through weir outflow relationships and the stage-storage relationship can be explicitly entered by the user allowing modeling of irregularly shaped ponds with arbitrary topography. Regarding water quality, WinDetPond can evaluate the capture efficiency of ponds based on the particle size distribution of the incoming suspended solids, with water quality simulated by considering partitioning of contaminants onto particles. Although these models are intended to be applied to individual GI systems as separate entities, and in order to consider more detailed processes affecting performance, their application is restricted to a limited purpose and scope.

General purpose models such as those designed for modeling flow and transport in unsaturated soil or surface water hydraulics and water quality have also been used to study certain aspects of GI performance (Hilten et al., 2008; Massoudieh and Ginn, 2008; Meng et al., 2014). However, these general models, which are typically developed based on a single medium, cannot model the performance of real-world GI practices that are controlled by interactions among many processes in multiple media types. A convenient stand-alone model representation of GI performance is needed: One that models flow and transport in surface ponds, variably saturated soil, aggregate or underdrain layers, overland flow, and pipes, along with having the flexibility of coupling these multiple components.

In this paper, the development of a flexible process-based modeling framework, GI Flexible Model (GIFMod), is described. GIFMod can evaluate the hydrological and water quality performance of a wide range of GI practices with user-defined structure and levels of complexity. GIFMod was developed to allow user flexibility in modeling the following three critical aspects of GI performance: 1) hydraulics, 2) particle/colloid transport, and 3) dissolved and particle-bound reactive transport of contaminants. The flexibility of the hydraulic component allows for flow considerations in different media often seen in stormwater GI practices including ponds, overland flow, saturated and unsaturated porous media, storage layers or structures, pressurized or free-surface flow in pipes as well as evaporation and transpiration. GIFMod also allows users to introduce new media with user-defined head-storage (H-S) and head-flow (H-Q) relationships. The particle/colloid transport module within the GIFMod framework allows the introduction of multiple particle types, each with different transport properties. Particles are considered to be present in different phases including mobile, reversibly deposited, irreversibly deposited or bound to the air-water interface (AWI) while undergoing exchange between these phases. A user can specify the number and nature of the phases that each particle class can be present in as well as the exchange mechanisms/rates between the phases. Particle transport is especially important in predicting the water quality effects of GI practices because particle retention is one of the most important mechanisms for removal of contaminants with high affinity to solid materials. The contaminant reactive transport module allows consideration of multiple reactive components based on user-provided networks and stoichiometric coefficients. Contaminants can undergo sorption-desorption with the soil matrix as well as mobile and immobile particles. Build-up, wash-off, and atmospheric exchange of contaminants can also be considered. This paper summarizes the governing equations for modeling hydraulic, particle transport, and transport/transformation of water quality constituents using the GIFMod framework. The numerical approaches for approximating the equations are also presented as well as methods used to calculate model uncertainty. An overview of the Graphical Unser Interface (GUI) associated with the framework will also be presented. Finally, four demonstration