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Exploring the effects of green infrastructure placement on neighborhood-level flooding via spatially explicit simulations

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ABSTRACT

State and local governments are increasingly considering the adoption of legislation to promote green infrastructure (e.g., bioswales, green roofs) for stormwater management. This interest emerges from higher frequencies of combined sewer outflows, floods and exposure of residents and habitat to polluted water resulting from growing urbanization and related pressure on stormwater management facilities. While this approach is promising, there are many unknowns about the effects of specific implementation aspects (e.g., scale, layout), particularly as urban settlements and climate conditions change over time. If green infrastructure is to be required by law, these aspects need to be better understood. We developed a spatially-explicit process-based model (the Landscape Green Infrastructure Design model, L-GriD) developed to understand how the design of green infrastructure may affect performance at a neighborhood scale, taking into consideration the magnitude of stormevents, and the spatial layout of different kinds of land cover. We inform the mechanisms in our model with established hydrological models. In contrast with watershed data-intensive models in one extreme and site level cost-savings calculators in the other, our model allows us to generalize principles for green infrastructure design and implementation at a neighborhood scale, to inform policy-making. Simulation results show that with as little as 10% surface coverage, green infrastructure can greatly contribute to runoff capture in small storms, but that the amount would need to be doubled or tripled to deal with larger storms in a similar way. When placement options are limited, layouts in which green infrastructure is dispersed across the landscape—particularly vegetated curb cuts—are more effective in reducing flooding in all storm types than clustered arrangements. As opportunities for green infrastructure placement increase and as precipitation increases, however, patterns that follow the flow-path and accumulation of water become more effective, which can be built on an underlying curb-cut layout. If space constraints prevented any of these layouts, random placement would still provide benefits over clustered layouts.

1. Introduction

Stormwater management is a challenge exacerbated by urban and agricultural development at all scales. As the percent of impermeable cover within a watershed increases, stormwater volume, peak flow, and concentration of non-point source pollutants increase (Athayde, Shelly, Driscoll, Gaboury, & Boyd, 1983). In urban areas, traditional gutter and storm sewer systems are often inadequate for reducing the quantity of stormwater runoff or decreasing pollutant loads (Hood, Clausen, & Warner, 2007). In agricultural or rural areas, drainage systems quickly channel large volumes of water, sediment, and dissolved pollutants to waterways (Nelson & Booth, 2002). In both urban and rural settings, inadequate stormwater management can lead to flooding, erosion, and impaired aquatic habitats (Finkenbine, Atwater, & Mavinic, 2000). Additionally, global climate change is expected to cause more heterogeneity in the frequency and/or intensity of storms (Bonebrake & Mastrandrea, 2010), further stressing existing stormwater systems. The climate models developed by the International Panel on Climate Change (IPCC) predict an increase in average annual precipitation for the Midwestern United States of up to 20% by the end of this century. For example, in the Chicago metropolitan area, Illinois, this could range from 5 to 9 additional inches of rain per year, and storms producing more than 2.5 in. of rain in 24 h are expected to more than double in frequency (Hayhoe & Wuebbles, 2008).

Best management practices (BMPs), which can include green infrastructure, are typically recommended by planning agencies to control discharge rates in developed and developing areas (Jaffe et al., 2010). In the context of stormwater management, green infrastructure is designed to minimize the generation of urban stormwater runoff and associated pollution by using and mimicking natural systems to collect, treat, and infiltrate rain where it falls (Montalto et al., 2007), i.e., at the site level. Examples of green infrastructure for stormwater management include swales, bioinfiltration devices, green roofs, constructed

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wetlands, or permeable pavement. Green infrastructure can facilitate stormwater management in several ways and at different scales. Runoff volume can be reduced through infiltration, evaporation, and evapotranspiration by plants (Hatt, Fletcher, & Deletic, 2009). Mechanisms for pollution removal include sedimentation, plant uptake (Vought, Dahl, Pedersen, & Lacoursière, 1994), filtration (Urbonas, 1999), biofiltration (Hatt, Deletic, & Fletcher, 2007), biodegradation, sorption and biosorption (Volesky & Hola, 1995). Different types of green infrastructure better optimize some of these functions over others. For example, while swales or constructed wetlands are designed to achieve both runoff quantity and quality goals, filters and green roofs are primarily designed to improve water quality, and rain barrels and permeable pavement aim to reduce runoff volume and/or peak flow (Larson & Safferman, 2008; US Environmental Protection Agency, 2000). Empirical studies show significant variability in the performance of green infrastructure, which may be attributed to a wide range of causes, from maintenance to weather to surrounding landscape (Gonzalez-Meler, Cotner, Massey, Zellner, & Minor, 2013). Although green infrastructure systems vary in their effectiveness, with proper design and maintenance, they may provide an effective complement to conventional stormwater infrastructure.

There has been, however, little examination of how green infrastructure interacts with the other components in the hydrological system, including roads and sewers, and their collective impact on the stormwater hydrology of an urban area. Empirical studies to this effect are costly and difficult to carry out because of the very nature of the experiment. Urban neighborhoods are unlikely to share land cover, gray infrastructure, and even rainfall intensity in the same storm. Consistent implementation and maintenance of green infrastructure would also have to be ensured for appropriate comparison across neighborhoods. Given the expense of such experimentation, numerous modeling tools have been created for planners and engineers to model stormwater runoff and water quality, ranging from simple site-specific, spreadsheet-based models that estimate runoff amounts, to data-intensive, watershed-scale models with multiple catchment areas that are capable of giving precise estimates of runoff and water quality, used to guide the construction of entire water management systems. These tools are all designed to address a variety of purposes and thus have varying data needs, provide different levels of detail in their outputs, and make assumptions about processes and spatial interactions in different ways. A review of existing tools is given below, and summarized in Table 1. We seek to expand the space of possible green infrastructure solutions with modeling tools that allow us to systematically experiment via simulation what would be too costly to test empirically. Our goal is to help policy-makers understand how different neighborhood-level green infrastructure designs may alleviate urban flooding, and contribute with generalizable strategies that can be effective in a broad range of neighborhood and climate conditions. This model could ultimately guide empirical testing of green infrastructure designs, once specific promising strategies are identified. We developed the Landscape Green Infrastructure Design (L-GrID) model with the characteristics needed for this purpose (outlined in Section 1.2).

1.1. Background: existing stormwater runoff modeling tools

Starting with the simplest models, spreadsheet models are designed to make simple and quick estimates. The Center for Watershed Protection's Watershed Treatment Model (WTM) (Caraco, 2011) and the US Environmental Protection Agency's (USEPA) Spreadsheet Tool for Estimating Pollutant Load (STEPL) (Tetra Tech, 2006) are both user-friendly for quick planning estimates about impacts of developments in terms of runoff volume and quality. The US Department of Agriculture's *Urban Hydrology for Small Watersheds*, *Technical Release 55* (*TR-55*) (US Department of Agriculture, 1986) is one of the most widely used worksheet models. It consists of a series of tables of values based on soil types and land covers, known as SCS curve numbers, that planners can use to produce quick estimates of runoff at specific sites.

Some simple planning tools are available online and are frequently updated with new information or scenarios. L-THIA (Long Term Hydrologic Impact Analysis), developed by Purdue University and the US Environmental Protection Agency, is a web-based spreadsheet model intended to show how land-use change affects runoff and water quality over the long term (Midwest Spatial Decision Support Systems (MSDSS) Partnership, 2010). It uses 30 years of rainfall data and soil information for all counties in the Midwest, and the TR-55 tables to estimate runoff for individual storms. The Green Values Calculator, developed by the Center for Neighborhood Technology, is another user-friendly, web-based model that uses the same TR-55 tables to estimate the effect of particular developments on runoff, and focuses on comparing the cost effectiveness of integrating different BMPs to reduce runoff (Center for Neighborhood Technology, 2010).

Rising in level of detail and complexity, other models were developed to provide greater customization for specific watersheds or development project, provide more information about implementation of BMPs, and include explicit spatio-temporal processes in their simulation. They tend to have more focused goals, such as sizing of BMPs or planning long-term water quality. The Partnership for Water Sustainability in British Columbia's Water Balance Model (WBM) (Partnership for Water Sustainability in British Columbia, 2013) is an online tool specifically calibrated for use in Canada and to plan for water quality at the site, watershed, or regional scales. Spatial representation is limited by the scale defined by the user, and runoff volumes are aggregated per subcatchment. RECARGA, developed by the State of Wisconsin, is intended for small watersheds as a tool to properly size bioretention and bioinfiltration facilities for new developments (Atchison & Severson, 2004). It uses the TR-55 tables in the same manner as the other models to estimate the runoff entering the BMPs. The P8 Urban Catchment model (Program for Predicting Polluting Particle Passage thru Pits, Puddles, & Ponds) was developed for the US Environmental Protection Agency and the States of Wisconsin and Minnesota to model runoff and water quality in urban watersheds for the purpose of evaluating development proposals and to select and size BMPs (Walker, 2007). It is a hybrid model, combining spreadsheet and watershed components, since it uses the TR-55 tables to estimate runoff but can still represent larger scales. It is, however, limited by its method of subdividing watersheds into pervious and impervious zones, and a surface flow mechanism that primarily simulates the routing of water through a chain of BMP devices (e.g. ponds and basins) to estimate the changes in flow and water quality through the removal of pollutants and solids. It does not, however, allow for spatially explicit representation of the location of BMPs.

Other stand-alone models require extensive data inputs and calibration. The outcomes involve more detailed representation of hydrological processes and comprehensive outputs. These models can often be integrated with other programs such as ArcGIS or run with extensions that further fine-tune hydrological processes. The AnnAGNPS (Annualized AGricultural Non-Point Source Pollution Model) was developed by the US Department of Agriculture primarily to model agricultural runoffs (Bingner, Theurer, & Yuan, 2010). It is a cellular model with user-defined cell sizes. It is thus spatially explicit, allowing better representation of surface flows and erosion. Besides being limited to agricultural areas, it is problematic to track data over time-periods longer than a day. This model also tends to overestimate sediments, is not readily customizable, and is very data intensive. WinSLAMM (the current Windows version of the Source Loading and Management Model) has been in use for nearly forty years (PV and Associates, 2013). It was designed as a planning tool for sizing and placement of BMPs for pollution control. Although its processes update in small time steps of at least six minutes, its flow processes focus on routing and flow rates over relatively large geographies. It also requires