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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

Table 1
Summary of existing stormwater runoff models.

Model	Type	Purpose	Data and time needs	Inputs	Outputs	Time steps	Scale	Spatially explicit
Watershed Treatment Model (WTW)	Spreadsheet	Calculate runoff, apply future practices, estimate impact of future growth	Low	Land use, annual precipitation, soil types	Estimated runoff	N.A.	User defined	No
STEPL	Spreadsheet	Calculate nutrient and sediment loads from different land uses and the load reductions from BMPs	Low	Land uses, animals, precipitation, irrigation, soil data, septic systems, other discharge	Annual nutrient and sediment loads, load reduction	N.A.	Watershed, but could be smaller	No
TR-55	Worksheet	Prediction of changes in runoff	Low	Land use, soil type, rainfall	Runoff volume, peak rate of discharge, storage volumes, hydrographs	N.A.	Urban watersheds smaller than 2000 acres	No, uses SCS curve numbers to estimate runoff
L-THIA	Web-based program	Prediction of changes in runoff	Low	Geographic location, land use, soil type, acreage, type of land use changes taking place	Annual runoff volumes and depths, pollutant loading	N.A.	Small to large watersheds	No, uses historical data for the Midwest and TR-55 curve numbers to estimate runoff
Green Values Calculator	Web-based program	Prediction of relative impacts of alternative BMP projects	Low	General site specific data (e.g. number of lots, sidewalk width), soil type, precipitation, land cover, BMPs	Discharge, groundwater recharge, cost benefit analysis	N.A.	Site specific	No, uses TR-55 to estimate outcomes
Water Balance Model (BC)	Web-based tool requiring paid subscription	Planning water quality	Moderate	Drainage area, elevation, slope, soil types, land uses, surface conditions, network of surface enhancements for managing runoff	Runoff, nutrient loading, other biological data	Hourly	Sites, developments, or entire watersheds	Runoff volumes are aggregated per subcatchment.
RECARGA	Stand-alone program	Sizing of bioretention and bioinfiltration facilities for new developments	Moderate	Precipitation, soil type, land use, and cover properties	Sizing of BMPs to meet goals for infiltration and runoff rates	15 min	Small urban watersheds	No, uses TR-55 to estimate runoff into BMPs before routing through other processes
P8	Stand-alone program	Evaluating development proposals to select and size BMPs in treatment chains	High (substantial calibration)	Weather data, land area, land cover, soil type, SCS curve number, BMP values	Estimated runoff and water quality, estimated change in flow and water quality	Hourly	Multiple scales, but more appropriate for development scale	Not for BMP location, limited capability in flow and pollutant routing, watersheds are divided into pervious and impervious zones
AGNPS	Stand-alone program	Predict agricultural runoff during single events	High	Soil type, slope, fertilizer type used	Nutrients, pesticides, sediments	Daily	Small to large watersheds, up to 20,000 ha	Yes
WinSLAMM	Stand-alone program, driven by database not formulas	Assess effectiveness of BMPs in reducing pollutant concentrations during small and medium storms	High (substantial calibration)	Drainage area, land cover and uses, sewersheds, rainfall, runoff coefficients, sediment and pollution distribution	Pollutant concentrations, runoff volumes, hydrographs by source area, land use, or rainfall event	User-defined, unclear range of acceptable values	Site to watersheds	Yes, for flow routing
SWMM	Stand-alone program, can be supplemented with extensions	Design sewer systems (and BMPs) over large scales	High	Precipitation, land covers, and a subcatchment drainage network	Quantity and quality of runoff for each subcatchment, flow rate and depth, and quality of water in drainage network	User defined, 1 min or smaller	Site to watershed, subcatchments intended to be large	Yes
SUSTAIN	Stand-alone program	Placement and sizing of stormwater BMPs to meet cost, water volume, and water quality goals	High (substantial calibration)	Land use, watershed, precipitation, elevation, BMP configuration, routing network (extensive formatting required)	Average and range of flow volumes, flow reductions, sediment and pollutant loads in one assessment point in each subcatchment	Hourly or sub-hourly, as small as 1-minute increments depending on modules in use	Site to watershed	Yes

extensive field data for calibration. While it uses long-term precipitation records, it tends to correct for only small storm hydrology.

Among more intensive data-based and spatially-explicit watershed-scale models, the SWMM (Stormwater Management Model) is more frequently used. The US Environmental Protection Agency developed this tool to model sewer capacities over large scales by using subcatchment areas (Rossman, 2010). Landscapes in SWMM are divided into subcatchments and drainage networks. Processes can use time steps that are controlled by the user and can be smaller than a minute. Despite its widespread use, its limitations include a laborious setup of the drainage network and configuration process, and a limited ability to customize land coverages and to handle water quality. Its surface flow mechanism focuses on sewer drainage or flow to BMPs. Although users have control over sizing of subcatchments, it is time-intensive to create a subcatchment network with a fine enough resolution to investigate how small local variations in elevation, land cover, soils, or BMP placement affect runoff or lead to flow between subcatchments. One final watershed model, the System for Urban Stormwater Treatment and Analysis Integration Model (SUSTAIN) was developed for the USEPA to aid in placement and sizing of BMPs to meet cost, water volume, and water quality goals (Shoemaker, 2009). It is as data-intensive as SWMM, but it has a more user-friendly interface for managing the layout of the landscape and BMPs. It is also similar to SWMM in its representation of hydrological processes, but its runoff measurement focuses on single sites within subcatchments, or "assessment points," which are located in the lowest points of subcatchments. It thus narrows the assessment of impacts to these points. Like SWMM, it also requires extensive calibration and hydrological modeling expertise to run (Lee et al., 2012).

1.2. The case for a different model

While the tools described above are useful for the purposes for which they were created, they become harder to use to derive principles of green infrastructure design across urban neighborhood landscapes (i.e. beyond a site, but within the regional subcatchment scale) and storm conditions. Existing policies are based on unexamined assumptions about the effectiveness of green infrastructure, and require performance standards that may either not be attainable, or may be attainable at the site level but not solve the problem at the neighborhood level because they do not take into consideration spatial interactions during a storm. At the request of the Illinois Environmental Protection Agency, we sought to provide a tool to rapidly and systematically explore the effects of standards and guidelines to manage urban runoff, without the expense and highly technical expertise involved in calibrating a predictive tool to a wide range of conditions, or in empirical testing. Such tools are needed to inform the development of planning and regulatory recommendations for stormwater management with a fuller understanding of how green infrastructure may work (or not) in a variety of situations.

The specific research questions driving our work are organized in two parts. The first relates to the ideal proportion of green infrastructure on the landscape and whether there is a threshold beyond which the benefits of adding green infrastructure are marginal. The second set of questions relates to how the spatial configuration of green infrastructure over the landscape matters. To investigate these questions, we required a spatially explicit model that simulated how stormwater flow and accumulation is affected by different green infrastructure configurations in a variety of physical landscapes (e.g., slope, soil permeability) and storm characteristics. Thus, we required a high-resolution dynamic model that allowed non-modelers to easily experiment with green infrastructure placement, and that was friendly, fast and flexible enough that users could enter either real or hypothetical landscapes and scenarios, and translate the outputs into policy guidelines applicable to a variety of conditions. We wanted to recreate the ease of data input and tractability found in the simpler tools, and the spatio-temporal explicitness of the more complicated models, i.e. simpler and tested flow algorithms on more detailed landscapes. Recent studies have stressed the need for such parsimonious modeling tools for green infrastructure planning (Martin-Mikle, de Beursa, Julian, & Mayerc, 2015; Yang, Endreny, & Nowak, 2015).

To satisfy the requirements above, we built the Landscape Green Infrastructure Design (L-GrID), which allowed us to run a number of different green infrastructure scenarios varying in storm and landscape characteristics, and compare the outcomes in terms of flooded area and runoff volume. In the next sections, we describe the components and mechanisms of L-GrID, the simulation scenarios and results, and discuss implications for planning and policy.

2. Model components and processes

2.1. Model overview

L-GrID is a cellular model created in Netlogo (Wilensky, 1999). It was originally designed for the Illinois Environmental Protection Agency to investigate the effects of different green infrastructure configurations on urban stormwater management on a neighborhood scale. We chose to model a single, stylized form of green infrastructure that incorporates features common to various types, mainly the capacity to infiltrate and store stormwater. The model allows users to modify storm duration, landscape size, placement of green infrastructure, sewer configuration, and coverage ratios for different land cover types. After the configuration is set, the user can run simulations and compare the outcomes in terms of flooded area and runoff volumes directed to sewers, green infrastructure, and adjacent areas. L-GrID was specifically designed to run simulations to compare the effectiveness of different scenarios of green infrastructure allocation for stormwater management in a landscape, thus allowing us to derive generalized principles for green infrastructure configuration at a neighborhood or regional scale. L-GrID was not designed to predict stormwater runoff for a specific region, and should not be used in this manner. The predictive models described in Section 1.1 are better equipped for that purpose.

2.2. Landscape

The landscape is represented as a two-dimensional lattice of cells that are 10 m × 10 m each. We chose this resolution based on the width of our simulated streets, the narrowest channels through which stormwater could flow. The default landscape size for our simulations is a 200 × 200 cell grid or a lattice representing 4 km^2. Global variables describe characteristics that apply uniformly to the entire lattice. These include the time series for precipitation, based on storm magnitude and duration, and evaporation and evapotranspiration rates (Table 2). Cell variables describe the attributes of each cell relevant to infiltration and flooding. These include land cover, soil type associated to the land cover, and hydrological coefficients related to soil type (Table 3). We based our assumptions loosely on Cook County, Illinois, in which most of the city of Chicago is located. Although Cook County has 33% impervious cover (Cook & Iverson, 2000), we used 50% impervious coverage as a default value for our simulations because the county contains large areas of forest preserves and parkland, and we focus here on stormwater management in urban neighborhoods. Part of this cover is dedicated to roads, which also contain sewers. The proportion of green infrastructure in the landscape is a parameter that defines, in part, our scenarios (see Section 3). The remaining area is permeable surface. The following subsections describe the various landscape attributes in more detail.

2.2.1. Land cover

Cells in the landscape are one of two basic cover types: impervious surface (e.g. roads, buildings, parking lots), or permeable surface (e.g. lawns, parks, undeveloped land) (Fig. 1). For the various scenarios, green infrastructure land cover can be placed on permeable cells only. The soil type associated to each land cover type determines the

Table 2
Default values for global variables.

Variable	Value
Evaporation	3.5625 mm/day
Evapotranspiration	1.66 mm/day
Manhole volume	2.18 m^3
Manhole sump	25% of manhole volume
Sewer intake rate	0.51 m^3 per 30-second time step
Stormwater treatment rate	9.37 m^3 per 30-second time step
Maximum sewer system capacity	141,560 m^3

Table 3
Soil and surface flow variables by cover type or green infrastructure. Sources: California Department of Transportation (2009) (┼); Dallas, City of (1993) (▲); Gonzalez-Meler et al. (2013) (♦); Hunt and Lord (2006) (■); Morrow and Sharpe (2009) (*); Oram, n.d. (●); US Department of Agriculture (1986) (▼) ; Rawls et al. (1983) (Δ).

Soil variable	Green infrastructure (loamy sand soil)	Impervious cover	Permeable cover (silty clay loam soil)
Surface storage capacity♦	200 mm	0 mm	0 mm
Engineered soil depth■	1019 mm	0 mm	0 mm
Depth to water table*	1019 mm	1219 mm	1219 mm
Capillary suction●	61.3 mm	n/a	273 mm
Effective porosity Δ	0.401	n/a	0.437
Saturated hydraulic conductivity●	59.8 mm/h	n/a	2 mm/h
Roughness coefficient	.24┼	.0175▲	.15▼

average capillary suction, saturated hydraulic conductivity (Oram, n.d.), and effective porosity (Rawls et al., 1983), and they all affect infiltration rates (see Section 2.3.2, Table 3). Impermeable surfaces do not allow infiltration. Permeable surfaces are assumed to be silty clay loam soils, which are the dominant soil type in Cook County and have moderate-to-low permeability (Krumm, Nelson, & Beaverson, 1984). Green infrastructure soils are typically engineered to contain between 85% and 88% sand for optimal infiltration (Hunt & Lord, 2006). Thus, in our model, the soil of cells containing green infrastructure is assumed to be loamy sand. In addition to enhancing infiltration, many types of green infrastructure (with the notable exception of permeable pavement) are built to allow some detention or retention of water on the surface. Accordingly, cells with green infrastructure have their elevation lowered by 200 mm to simulate this storage capacity. This value was within the range of depths of infiltration devices used in urban areas, excluding wetlands and detention basins (Gonzalez-Meler et al., 2013). The green infrastructure's engineered soil extends to 1019 mm below the elevation, for a combined depth of 1219 mm (4 ft) from the land surface, which is recommended for optimal pollutant removal and cost effectiveness (US Environmental Protection Agency, 1999; Hunt and Lord, 2006). For simplicity, we assumed the same total combined depth of the soil (1219 mm) for permeable cells as for green infrastructure, based on the average depth to the water table in Cook County, Illinois (Morrow & Sharpe, 2009). For our purposes of generalization, we modeled stylized green infrastructure with common attributes rather than specific types, assuming that all green infrastructure installations are well maintained and thus perform with equal effectiveness and according to specifications. Table 3 summarizes the parameter values for both land cover types and for cells with green infrastructure.

2.2.2. Slope and outlets

The landscape has a slope of 0.25%, which is within the range of what is observed in Cook County (Illinois State Geological Survey, 2011). In our default scenario, the slope is oriented toward the lower left-hand corner of the lattice, where a primary outlet allows surface runoff to leave the landscape. Additional secondary outlets exist at intersections

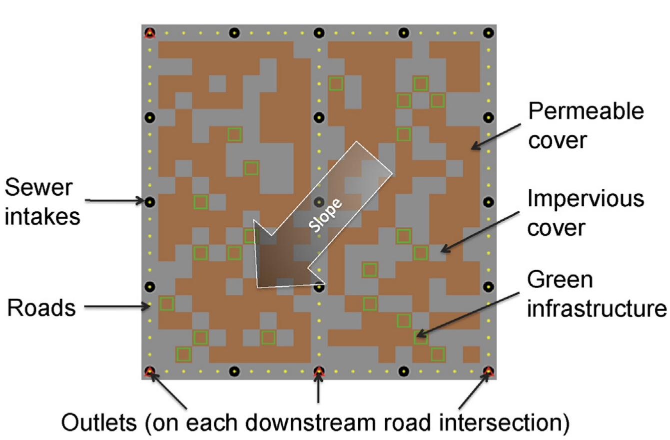

Fig. 1. Landscape features of L-GrID.

along the left and bottom side of the landscape (see Section 2.3.7). Without secondary outlets, the landscape would essentially work as a detention basin (Fig. 1).

2.2.3. Roads and city blocks

Urban landscapes are engineered to direct water toward drains, with roads designed to be the primary conduit for surface water to reach sewer intakes. It was important to mimic this basic design concept. Roads in our landscape are 10 m (or 1 cell) wide, surrounding city blocks that are 200 m × 100 m (20 × 10 cells, or 20,000 m^2), the approximate size of city blocks in Chicago (Fig. 1). Blocks are assumed to have curbs with a height of 150 mm, the average height required by the City of Chicago and the State of Illinois (City of Chicago, 2007), but due to the fact that roads are graded to be higher in the center in order to direct stormwater to the edges, a height of 127 mm is used to simulate the reduced area for street storage that the grading creates. Therefore, road cells are 127 mm lower than other cells. Curbs direct runoff from impermeable surfaces toward sewer intakes on the streets. If a green infrastructure cell is located next to a road however, it acts as a curb cut due to its lower elevation (see Section 2.2.1), and allows water to flow off the street and into the green infrastructure's surface water detention area. Under this condition, sewers and green infrastructure would compete for surface runoff water. In practice, stormwater does not flow unimpeded through the landscape and down the streets to its outlets. A common strategy is to build street berms to contain the runoff locally and prevent excessive flow downstream, as mandated by Illinois law (Carr, Esposito, & Walesh, 2001). In L-GrID, the downstream neighboring road cells from road intersections are thus raised 101.6 mm (4 in.).

2.2.4. Sewers

Sewer intakes are located on each road, at 5 cell intervals (Fig. 1). This arrangement is based on our own surveys of several streets in the neighborhoods around the campus of the University of Illinois at Chicago. Cells with sewer intakes each have a manhole that locally stores some of the water that flows into the drains. The volume of the manholes in the model is 2.18 m^3, which is the volume of a typical basin in the Chicago region (John Watson, Metropolitan Water Reclamation District of Greater Chicago, personal communication, October 17, 2014) (Fig. 2). The sump, or the volume of the manhole below the outlet pipe, is 25% of the total manhole volume. Outlet pipes are assumed to have a diameter of 45 cm. Water does not begin to enter the sewer system until it reaches the outlet pipe height, and water stored below the pipe inlet stays there for the duration of the simulated storm.

2.3. Processes and order of events

Processes represented in L-GrID are the ones identified in the literature as most relevant to the performance of green infrastructure for stormwater management (see Section 1). The processes run in the following order: 1) precipitation, 2) infiltration, 3) sewer intake, 4) evaporation, 5) evapotranspiration, 6) surface flow, and 7) drainage through the outflow (Fig. 3). Each sequence runs in time intervals of

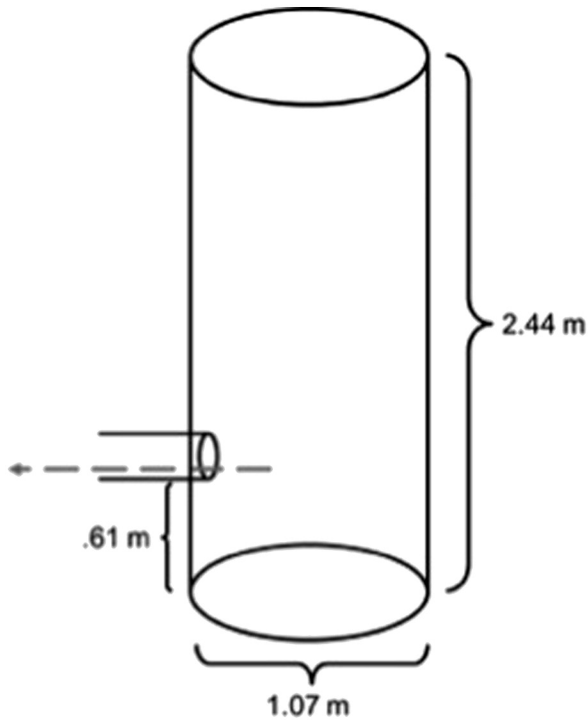

Fig. 2. Sewer intake assumptions in L-GrID.

30 s until stop conditions are met, as detailed in Section 2.3.8. Sensitivity tests showed that, for the current spatial resolution, the model produced continuous flow when the temporal resolution was 30 s or less; the fastest flow processes at this spatial scale were adequately represented. Longer time steps led to discontinuous flow and, similar to other numerical approximation hydrological models, would require larger cell sizes. Our focus on discrete storm events led us to dismiss groundwater recharge and flow. The soil type and flat slope of northeastern Illinois would result in little appreciable movement of infiltrated water over single storm event, vertically or horizontally (Howard Reeves, US Geological Survey, personal communication, April 8, 2010).

2.3.1. Precipitation

Test runs were conducted for 24-hour storm events of 5- and 100-year magnitude, the former being the design storm for new sewer construction, while the latter has increased in occurrence in the last few years. Other urban areas besides Chicago are experiencing similar effects of climate change, raising concerns among state legislators and local policy makers about how to best handle these effects (Jaffe et al., 2010).

Precipitation rates were calibrated for Chicago, Illinois (National Oceanic and Atmospheric Administration, 2014). A 24-hour duration 5-year storm has a precipitation total of 95.76 mm (3.7 in.). A 24-hour 100-year storm has a precipitation total of 182.88 mm (7.2 in.). The model uses an input table to simulate the rainfall rate at each time step, corresponding to a triangular hyetograph, where the peak rainfall rate occurs one third of the way through the storm and the peak is twice the average intensity (Akan, 1993; Yen & Chow, 1980) (Fig. 4).

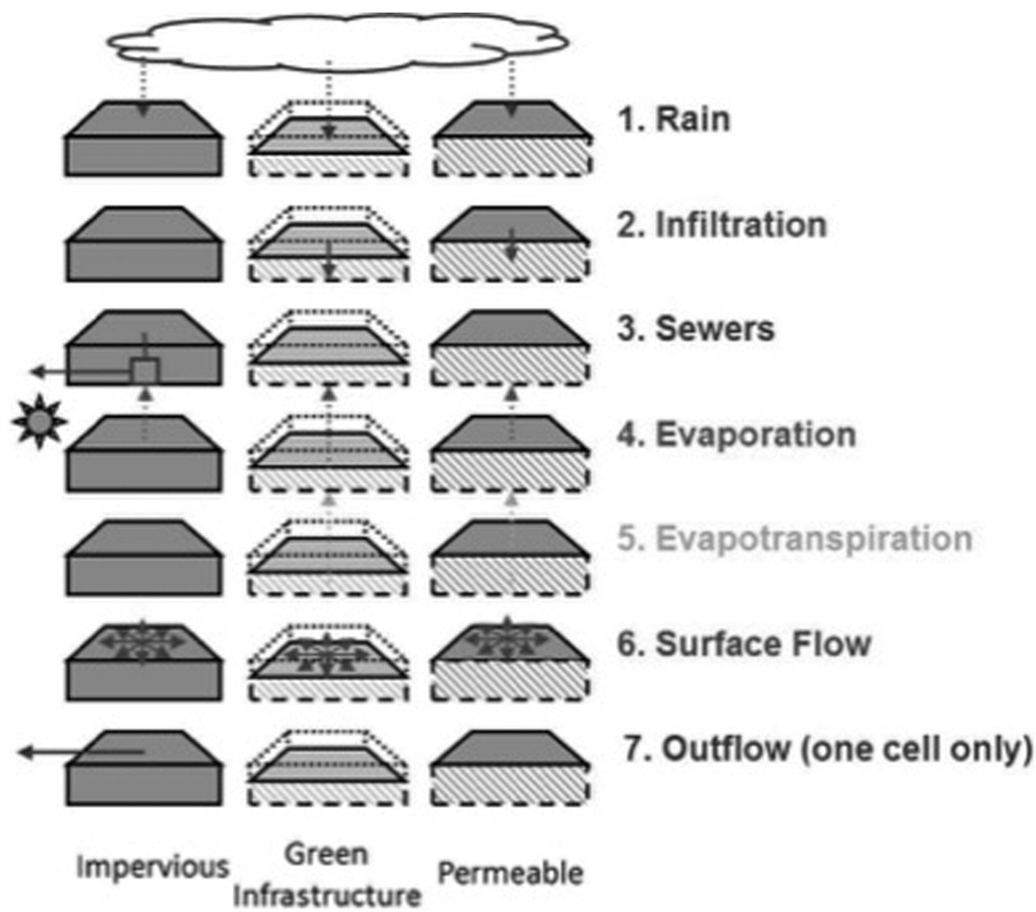

Fig. 3. Order of events in L-GrID.

2.3.2. Infiltration

Infiltration rates are calculated using the Green-Ampt formula (Albrecht & Cartwright, 1989; Green & Ampt, 1911), which is used by many of the existing watershed models, including SWMM and RECARGA. An advantage of Green-Ampt over other methods, including the TR-55 SCS curves, is that it allows for estimates of infiltration rates over time, and takes into account the soil type and amount of water that has already infiltrated in previous time steps.

On the first iteration only, infiltration is equal to the rainfall rate. The high proportion of impervious surface immediately produces runoff and water accumulation or ponding. In these conditions, the infiltration rate for subsequent time steps until saturation is calculated as follows:

$$f = K_s\left[1 + \frac{(\theta_s - \theta_i)\psi_f}{F}\right], \quad (1)$$

where:

- f infiltration rate at time t (cm/s);
- F total amount of water infiltrated at time t (cm);
- K_s saturated hydraulic conductivity (cm/s);
- Ψ_f suction at wetting front (negative pressure head, cm);
- θ_i initial moisture content;
- θ_s saturated moisture content.

In the above equation, θi − θs equals the effective porosity of the soil. Only green infrastructure and permeable surface cells can infiltrate water. During model initialization, each cell will have computed and stored the maximum amount of water that can infiltrate over the course of the storm, corresponding to the cell's land cover, soil type, and soil depth to the water table. While the wetting front does not reach the water table depth, each cell calculates at each time step the maximum amount of water that can infiltrate given the soil type and current degree of saturation. The actual amount of precipitation that infiltrates is the volume on the surface of the cell, up to the calculated maximum. The engineered soils of green infrastructure are designed to have more than sufficient capacity to infiltrate all the water that falls on them during a range of 24-hour storm in the Chicago region, including 100-year storms. The green infrastructure soils have extra capacity to retain runoff from surrounding pervious and impervious areas. However, once completely saturated, the green infrastructure itself will produce runoff.

2.3.3. Sewer intake

Sewer intakes in the Chicago area are designed to capture stormwater at a rate of 1.2 cubic feet per second (0.034 m^3/s). Most intakes tend to be blocked by 50% (John Watson, Metropolitan Water Reclamation District of Greater Chicago, personal communication, October 17, 2014), so that the sewer intake rate in L-GrID is set to 0.51 m^3 per 30-second time step. After the water level in the manhole reaches the outlet pipe, it enters the sewer system at the same rate as it enters the basins from the streets. Since our focus was on spatial interactions of the water on the landscape and not in the pipes, L-GrID assumes that the water that enters the sewer system is processed by treatment plants, but does not represent the transport and treatment explicitly. The treatment rate is based on operating data for the Stickney Water Reclamation Plant, a Metropolitan Water Reclamation District facility near Chicago and one of the largest treatment plants in the world. The plant handles water for an urbanized area that covers 673.4 km^2, and has an average daily capacity of over 4.5 million m^3 of water (Metropolitan Water Reclamation District of Greater Chicago, 2014). This translates into 9.37 m^3 of runoff per time step being removed from the simulated sewer system for treatment, thus freeing up capacity for further sewer intake (Table 2).

In Chicago, the sewer system is ideally engineered to handle 24-hour, 5-year storms without backing up or producing combined sewer overflows (CSOs). In practice, however, due to aging infrastructure and other constraints, the sewer system can accommodate 24-hour 2-year storms without flooding or CSOs (John Watson, Metropolitan Water Reclamation District of Greater Chicago, personal communication, November 14, 2014). We did not consider CSOs in our scenarios, so that we could assess under what conditions green infrastructure could prevent their occurrence. Without CSOs, if the assumed sewer infrastructure is full, the sewer intake rate is reduced by 98.2%, to the rate at which the treatment plant removes water from the sewers (Table 2). To determine how much water the sewer infrastructure would handle before saturating, the model was run with a 24-hour, 2-year storm, which has a total precipitation of 77.216 mm (Angel, 1989), with 0% green infrastructure and 50% impervious cover, an approximation of land cover conditions in Chicago. The maximum volume of water in the simulated sewer infrastructure at any time was used as an approximation for the sewer capacity for all simulation runs presented here. The maximum sewer volume for this landscape was 141,560 m^3. For a landscape of different size or land cover, or for a different sewer and treatment system, this maximum volume would need to be recalculated.

2.3.4. Evaporation

After the 24-hour storm event is over, evaporation occurs in all cells, regardless of cover type. We use rates derived from pan evaporation

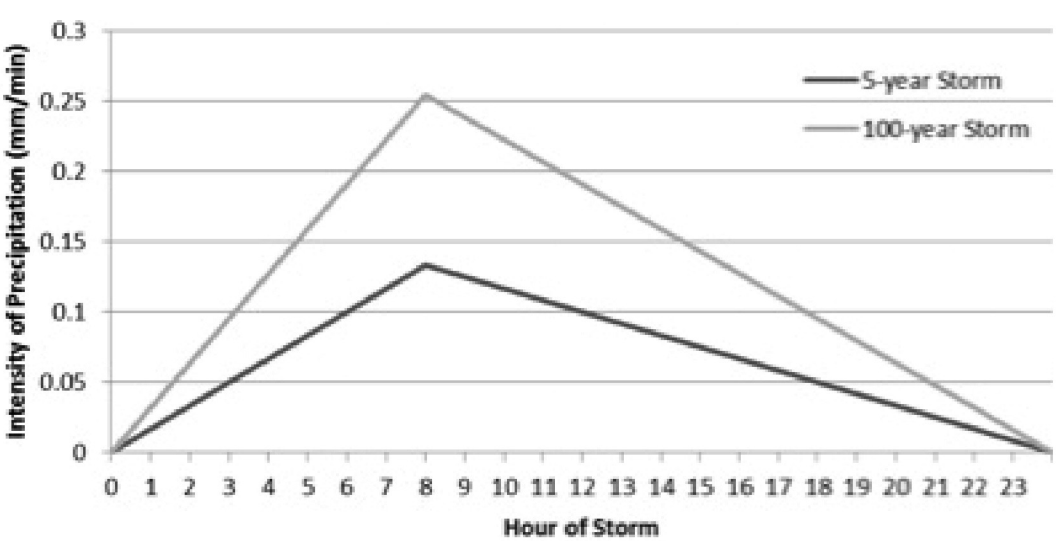

Fig. 4. Storm hyetographs.

rates, an estimate used by other models, including SWMM and RECARGA. In Illinois, the State Climatologist Office collects evaporation data from sites around the state. The only site located in northeastern Illinois is located at the Chicago Botanic Gardens and has data from 1997 to 2008 (Illinois State Climatologist Office, 2008). We chose to use the average monthly evaporation for June because its rate is closest to the average rate for summer months, the season when 65% of the top-ranked 1-day storms in Illinois occur (Huff & Angel, 1992). The monthly evaporation rate is 142.748 mm, which was multiplied by 0.75, as recommended by the State Climatologist's Office, to compensate for higher evaporation due to ideal pan conditions, resulting in an adjusted average daily evaporation rate of 3.5625 mm.

2.3.5. Evapotranspiration

Water evapotranspires from all green infrastructure cells at a set rate of 5.8E − 4 mm per 30-second time step, an average of reported data from several types of green infrastructure installations (e.g.Lazzarin, Castellotti, & Busato, 2005, Li, Sharkey, Hunt, & Davis, 2009). Different types of vegetation may have different evapotranspiration rates, but here we use the same average rate for all cells as representative aggregates of many types of vegetation present in green infrastructure.

2.3.6. Surface flow

The process of surface flow computes flow volumes between cells by solving Manning's equation for volume, adapting the equations for shallow concentrated flow when flow occurs between block cells, and to open channel flow when flow is between road cells (Eqs. (2) and (3)) (US Department of Agriculture, 1986). Each iteration, cells are ordered in ascending order of elevation, and interact with each one of its upstream neighbors, also in ascending order of elevation. This order of events for flow ensures that water can travel at most one cell per time step. The amount of flow between cells ordered in this way is determined by Manning's equation, which is a function of hydraulic slope, surface roughness, and water depths in a cell and its neighbor. Backwater flow naturally happens when lower elevation cells have higher hydraulic heads than their upstream neighbors. L-GrID limits this flow to not exceed the equilibrium water level between two neighboring cells (Ben O'Connor, University of Illinois at Chicago, personal communication, February 14, 2014) (Eq. (2)). If water depth is greater than 24.5 mm (1 in.), the Manning's roughness coefficient is halved to represent the reduction in friction from the underlying surface cover (Ben O'Connor, University of Illinois at Chicago, personal communication, February 14, 2014) (Eq. (3)).

$$Q = v \times A, \tag{2}$$

where:

- Q flow volume per unit time;
- V velocity (from Eq. (3)), and
- A cross-sectional area, computed as $w \times c$, where w is the smallest of: (1) the water depth of the cell from which water is flowing, or (2) half of the difference in the cells' heads, and c is: (1) the channel width for road flow, or (2) the distance between the center of each cell and its neighbor for shallow flow on the blocks.

Velocity in Eq. (2) is computed as follows:

$$V = 1/n \times r^{2/3} \times s^{1/2}, \tag{3}$$

where:

- r hydraulic radius, calculated as A/p for open channel flow in roads, where p is the wetted perimeter of the cell from which water is flowing, or as w for shallow concentrated flow over blocks (Ben O'Connor, University of Illinois at Chicago, personal communication, February 14, 2014);
- s hydraulic slope between the cell and its neighbor, and.
- N Manning's roughness coefficient, according to the cell's land cover (Table 3) and up to a water depth of 25.4 mm; at deeper water levels, the roughness coefficient is halved.

2.3.7. Outlet drainage

The outlet cells function as a drain for runoff. The model uses Manning's equation for open channel flow (Eqs. (2) and (3)), to determine outlet flow volumes. The slope is the same as between the outlet cell and its neighboring upstream road cell in the direction of outflow, assuming that the road continues with the same slope beyond the outlet. Water is discharged at this rate through each outlet cell and away from the system. The outlet product of the model is used as an estimate of runoff discharged downstream of the area simulated. The primary outlet on the lower left corner of the landscape will contribute a higher share of runoff than any other secondary outlet, being the lowest point at which runoff leaves the system.

2.3.8. Stop conditions

After a storm event, the model will run for up to one additional day but will stop earlier if all accumulated water leaves the surface. Once each simulation is completed, the model reports the volume of water leaving the system by the various mechanisms described above (e.g., infiltration via green infrastructure and soils, evaporation, and evapotranspiration). Evapotranspiration, often stressed as an important advantage of green infrastructure, had a very minor effect on our outputs of interest within single storms, and was thus not further included in our analyses below. We note, however, that this mechanism becomes more important in the long run, as it reduces soil water content and increases infiltration capacity in between storms.

3. Scenarios and simulation results

We conducted simulations to compare the effectiveness of different green infrastructure configurations for stormwater management in urbanized neighborhoods. We evaluate each scenario in different ways, to provide a fuller picture of the stormwater problem and how each allocation scenario might address this problem in multiple dimensions. All scenarios are evaluated relative to a baseline, without any green infrastructure for the first set of simulations (Section 3.1), or with random placement for the second set (Section 3.2). Our metrics include: (1) the amount of water infiltrated by green infrastructure, (2) the volume of runoff directed to the sewer system ("sewer runoff"), (3) the volume of runoff flowing to outside areas through the outlet cell ("outlet runoff"), and (4) the maximum area flooded. To determine if a cell is flooded, each cell records its greatest water depth during a run. Road cells or green infrastructure cells on road curbs are considered flooded at 50.8 mm (2 in.), while block cells are flooded at 24.5 mm (1 in.), the threshold at which damage is expected to start to accrue in each case (John Watson, Metropolitan Water Reclamation District of Greater Chicago, personal communication, November 8, 2013). We measure flooding of green infrastructure cells from the top of its surface storage, i.e., from where the cell elevation would have been without the green infrastructure (see Section 2.2.1).

The default settings used in all scenarios are listed in Table 4; variables in bold show the variables that changed across scenarios. Sensitivity tests showed that the effect of randomness in initial land cover allocation tends to cancels out in larger landscapes, producing little variability across runs. All scenarios were thus run only one time to reduce computation time. All scenarios were also tested for both 5-year and 100-year storms.

Table 4
Parameter settings for simulations (note: scenario settings are shown in bold).

Variable	Value
Outlet	on
Sewers	on
Slope of landscape	0.25%
Curbs	on
Curb height	127 mm
Intersection berm height	101.6 mm
Percent impervious	50%
Allow CSOs?	No
Sewer spacing	Every fifth road cell
Cell dimensions	10 m by 10 m
Road width	10 m (1 cell)
Block dimensions	200 m by 100 m (20 by 10 cells)
Landscape dimensions	2 km by 2 km (200 by 200 cells)
Storm duration	24 h
Storm intensity	**5- and 100-year (total precipitation of 95.76 mm and 182.88 mm, respectively)**
Percent green infrastructure	**0–50%**
Green infrastructure placement	**Baseline: sorted random** **Upstream–downstream** **Adjacent to roads–away from roads** **Hybrid**

3.1. Proportion of green infrastructure on the landscape

Our initial hypothesis was that there are optimal proportions of green infrastructure with respect to other cover types, so that beyond a certain threshold the improvements would only be marginal. We also expected that, since the sewer systems are calibrated to handle 2-year storms, there would be much lower levels of flooding or sewer intake after a 5-year storm in the absence of green infrastructure. With more intense 100-year storms, however, green infrastructure would help manage stormwater and minimize the burden on the sewer systems and the neighborhood. To explore these questions, we conducted model runs using the default conditions, varying the percentage of cells that are dedicated to green infrastructure (Table 4). We placed green infrastructure in cells sorted in descending order by number of upstream impervious neighbors, until the target green infrastructure cover was reached for each scenario (0%, 10%, 20%, 30%, 40%, and 50%). Since the initial allocation of land covers is random, so is the resulting green infrastructure scenario.

Our simulations show that at around 10% of green infrastructure coverage, more water would be directed to green infrastructure than to sewers in 5-year storms, and all surface flooding and runoff to downstream areas would be eliminated (Fig. 5). At around 20% of green infrastructure coverage sewer intake begins to level off, and the marginal benefit of adding green infrastructure beyond 20% begins to decrease.

At least 10–15% green infrastructure coverage would be needed to outpace the sewers and the discharge downstream in larger storms, and to significantly reduce block flooding. Road flooding would require 20% coverage to be reduced. At about 30% coverage, green infrastructure would begin to alleviate the sewer system from operating at full capacity and eliminate downstream outflow (Fig. 5). The overall marginal benefit of adding green infrastructure greatly decreases at higher values, although it would free up treatment and storage capacity in the sewer system.

3.2. Spatial placement of green infrastructure

The simulations described above allowed us to identify a range of values for green infrastructure cover that would have the greatest effectiveness over different storm types: 5–15% coverage for 5-year storms, and 15–30% coverage for 100-year storms. We proceeded by exploring the influence of spatial configuration within this range of cover on the ability of green infrastructure to handle stormwater generated by both 5-year and 100-year storms. This range also better aligns with the reality of most urban areas: limited space and funding to invest in stormwater management.

We organized our discussion first around archetypical configuration scenarios, often discussed in environmental planning circles, to examine how specific locational characteristics might influence the simulation results, against our sorted random baseline. Traditional stormwater management directs rainwater toward the streets, which act as stormwater collectors due to their lower elevation, and in turn direct

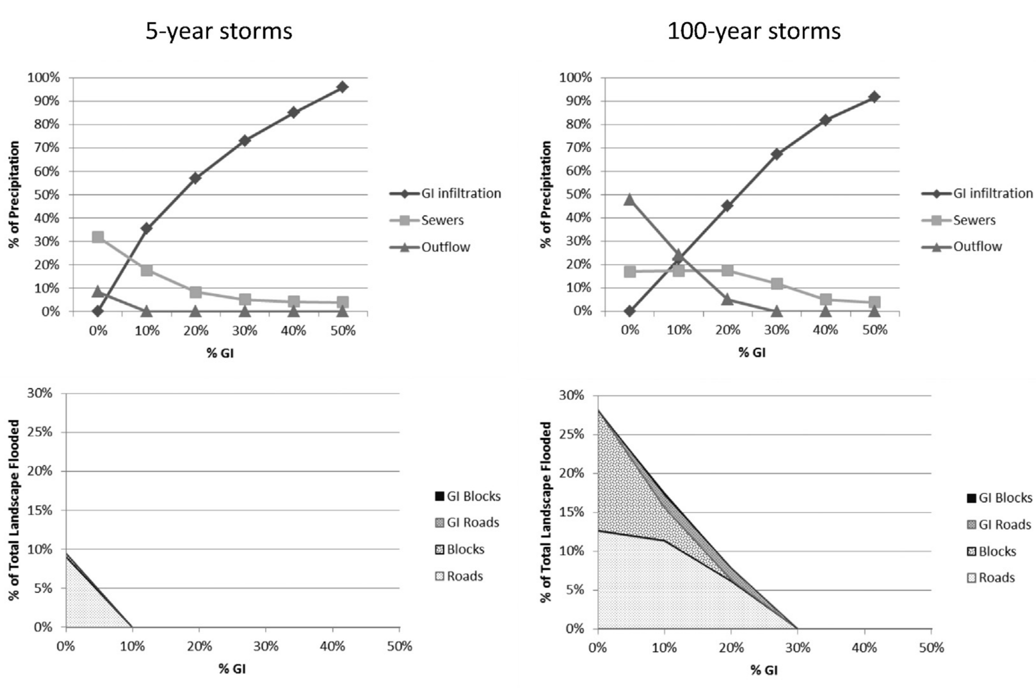

Fig. 5. Effect of percentage of green infrastructure coverage on infiltration, sewer intake, outflow runoff, and flooding.

the runoff toward sewers. One type of low impact development includes creating curb cuts to allow water on the streets to flow into green infrastructure. We expected that having green infrastructure adjacent to roads would produce better outcomes by allowing these structures to compete with sewers for water, thereby reducing the burden on the sewer system and flooding. To explore this effect, we created two scenarios: one with green infrastructure placed only adjacent to roads and one with green infrastructure placed away from roads. Green infrastructure located downstream is also expected to intercept and infiltrate more of the water as it flows down the slope toward the primary outlet, especially in more intense storms. While this may be true, one argument for placing green infrastructure upstream is to prevent the production of runoff that will end up accumulating in downstream locations.

Running the model with archetypical green infrastructure scenarios allowed us to examine how specific layouts perform differently for the various ways in which water flows and accumulates in a range of storms. With this in mind, we designed a hybrid layout that combines the perceived benefits of locating green infrastructure adjacent to roads, the concentration of these structures downstream, and the dispersion of structures upstream in the landscape. In this scenario, 10% of the total green infrastructure is located downstream, 45% is scattered upstream, and 45% is located along roads in the middle section of the landscape.

We present in the next section the simulation results of all the scenarios we tested for smaller and larger storms: (1) sorted random (baseline), (2) adjacent to roads (curb cuts), (3) away from roads, (4) upstream, (5) downstream, and (6) hybrid (Fig. 6). We conducted sensitivity tests around assumptions of green infrastructure storage capacity, and found that the results are robust within the range of 100 mm to 300 mm storage capacity (depth).

3.2.1. Effects of placement in smaller storms

In smaller storms, clustering green infrastructure downstream or upstream was similarly ineffective in reducing sewer runoff (Fig. 7). Concentrating green infrastructure reduces its effectiveness in routing runoff away from the sewer system, while spreading it out in the landscape increases exposure, storage and infiltration. For this reason, with lower amounts of precipitation, scattering green infrastructure eliminated flooding in the simulated landscape and runoff to neighboring areas, and reduced sewer intake. It is worth noting that even at 5% coverage, improvements are already noticeable. Among the dispersed scenarios, increasing coverage results in greater effectiveness in diverting water from the sewer system toward infiltration, by those layouts that include curb cuts (baseline, adjacent to roads and hybrid) relative to the layout without (away from roads).

3.2.2. Effects of placement in larger storms

In the larger storms and at lower levels of green infrastructure coverage, the landscape flood depths frequently exceeded the 127 mm curb height, thus overwhelming the green infrastructure irrespective of its configuration (Fig. 8). This reduced effectiveness can be partially compensated by increasing green infrastructure coverage, which needs to be at least doubled to obtain results closer to those generated in smaller storms. Sewers are less capable of capturing all precipitation in larger storms, and runoff instead floods the landscape and is directed to neighboring areas through the outlets. In all levels of coverage, upstream and downstream clustering scenarios perform poorly compared to the dispersed scenarios. At 20% coverage and above, green infrastructure adjacent to roads shows an advantage over other dispersed patterns by greatly reducing neighborhood flooding, followed by the hybrid and baseline scenarios. Simulated time series with L-GrID confirm the increased capacity of layouts with curb cuts to handle runoff peaks by effectively coordinating with the sewer system, both routing water toward sewers and slowing down intake. At 25% and above, however, the hybrid scenario is more successful in diverting runoff from both sewers and the outflow into neighboring areas. While very effective, placing green infrastructure adjacent to roads also directs more water toward roads, and therefore contributes to sewer intakes (desirable) and outlet flows (less desirable). The hybrid and baseline scenarios allow for water to be diverted from the streets via curb cuts, but also intercepts water before it reaches the roads and, in the hybrid layout, before it reaches the neighborhood downstream. For this to have an impact, however, higher green infrastructure coverage is needed.

The above simulations suggests that dispersion of green infrastructure throughout the landscape is a better strategy than increasing clustering and connectivity, taking fuller advantage of excess storage and infiltration capacity to capture runoff from adjacent land cover types. Among the dispersed scenarios, locations adjacent to roads

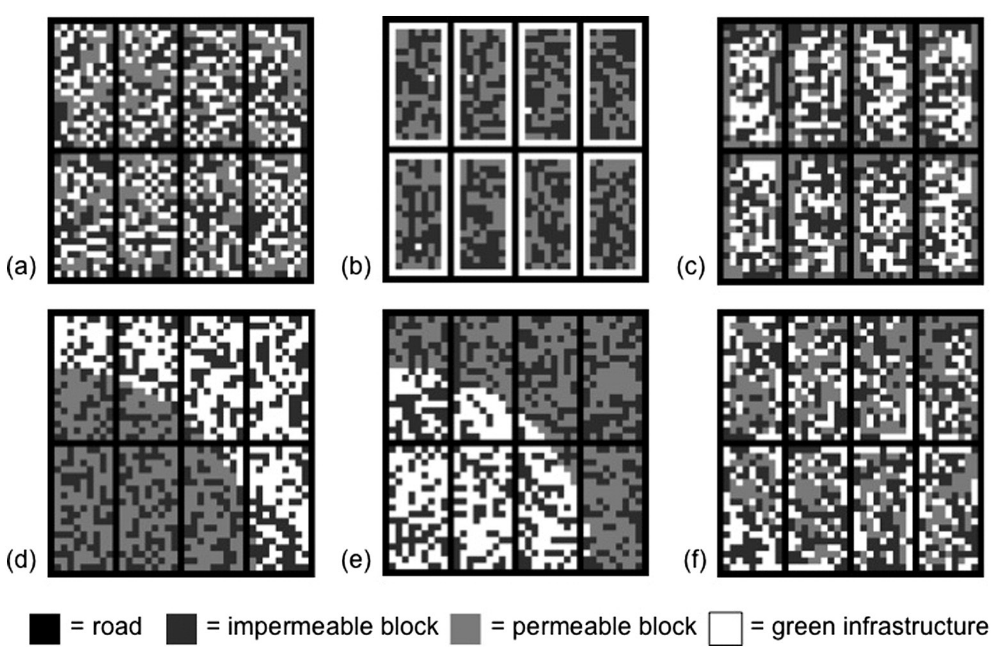

Fig. 6. Green infrastructure placement scenarios: (a) sorted random (baseline), (b) adjacent to roads, (c) away from roads, (d) upstream, (e) downstream, and (f) hybrid.

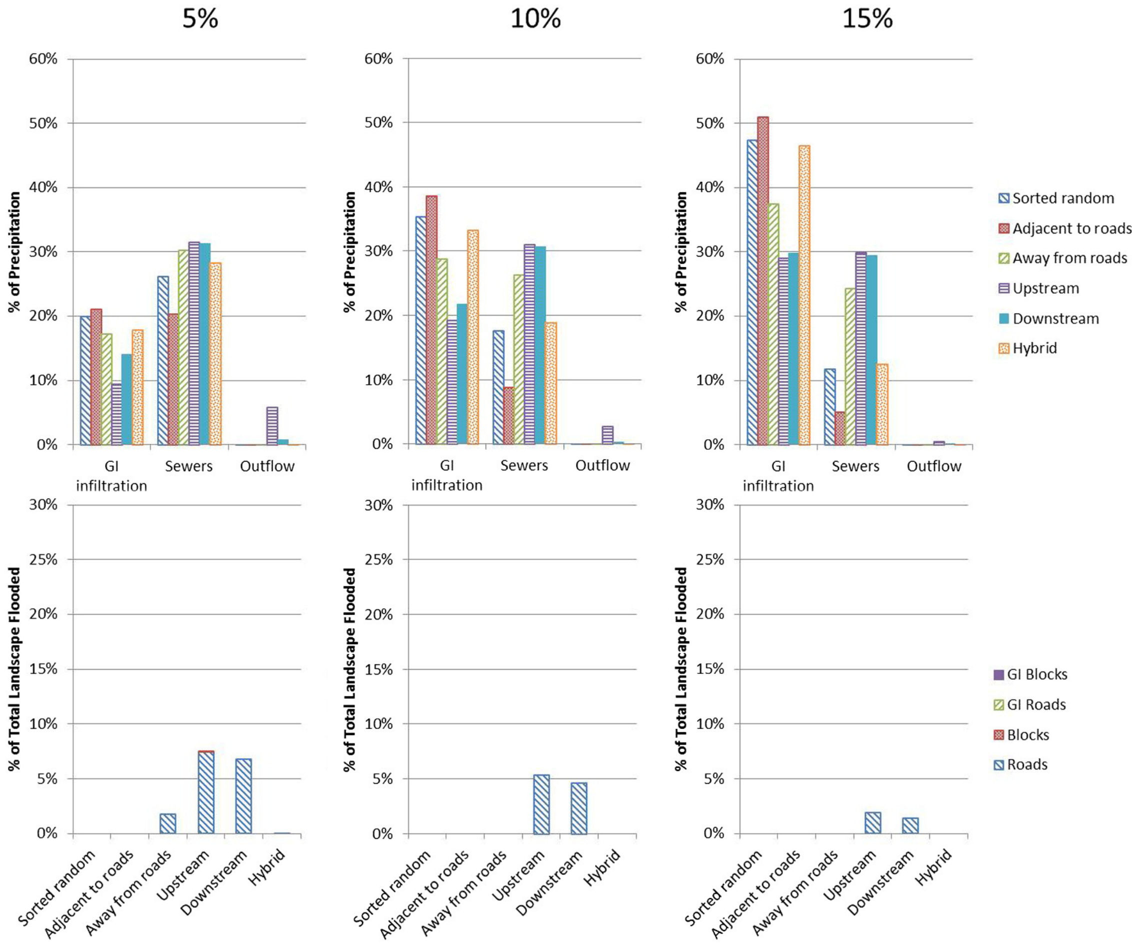

Fig. 7. Effect of the spatial arrangement of green infrastructure on infiltration, sewer intake, outflow runoff, and flooding in 5-year storms, at 5%, 10% and 15% green infrastructure coverage.

seem to provide the greatest advantage for both storm types, particularly when there are few locations available to install them. Since curb cut installations do not encroach on private property, this layout has the added benefit of greater flexibility for installation, as well as increased guarantees of appropriate maintenance by public agencies, rather than relying on private owners. As opportunities for adding green infrastructure increase—and as storm severity increases—a hybrid approach can be built on an underlying layout of curb cuts. If space constraints prevented any of these layouts, random placement would still provide benefits over the remaining layouts.

4. Implications and future work

We aimed to explore assumptions about the effectiveness of green infrastructure, and identify some general design principles for green infrastructure placement in urban areas. We developed L-GriD to explore some of these questions through simulation, and inform policy about green infrastructure allocation for stormwater runoff management in an urbanized landscape. It is difficult and costly to empirically contrast the effectiveness of green infrastructure layouts across neighborhoods that vary in landscape characteristics, infrastructure placement opportunities and constraints, and storm exposure. These same challenges make model validation, which should ideally follow model development, expensive and difficult to control. L-GrID could be validated at a smaller scale, using the model itself to design the field experiments to generate the data needed. It would not be possible, however, to account for critical neighborhood-level spatial interactions. In the absence of better data, models like L-GrID can still guide policy informed with the best of our knowledge (Yang et al., 2015). According to the dynamic and spatial interactions represented in L-GrID, green infrastructure could effectively assist in diverting stormwater from the sewer system and prevent flooding. Moreover, some layouts have greater potential to alleviate flooding than others. These findings may be used as reference for green infrastructure design.

Results presented here suggest that benefits of green infrastructure are seen at a minimum threshold of land area used for green infrastructure, but the marginal benefits start to decrease after a certain amount is allocated in the landscape. Our simulations suggest that these cover area thresholds exist, but we stress that the thresholds presented here are hypothetical. Further simulation and empirical research should be conducted to estimate these values on a given landscape.

It is important to assess the effectiveness of these approaches in a variety of both climate and landscape conditions, as a higher occurrence of 100-year storms has been observed in recent years, and as policy is designed and implemented at higher levels of enforcement. To ensure the robust performance of green infrastructure at the landscape level, and to reduce water flow into sewers and downstream areas for a variety of storms, a combination of configurations that conform to landscape heterogeneity should likely be promoted, but simpler approaches may still be effective. For instance, locating green infrastructure adjacent to roads, and particularly close to sewer outlets, would enhance the performance of green infrastructure in a range of storm types, and reduce the burden on sewer systems and areas outside the focal neighborhood. As precipitation increases and with greater opportunities for green infrastructure placement, a hybrid approach that follows the flow and accumulation of water in the landscape promises to be

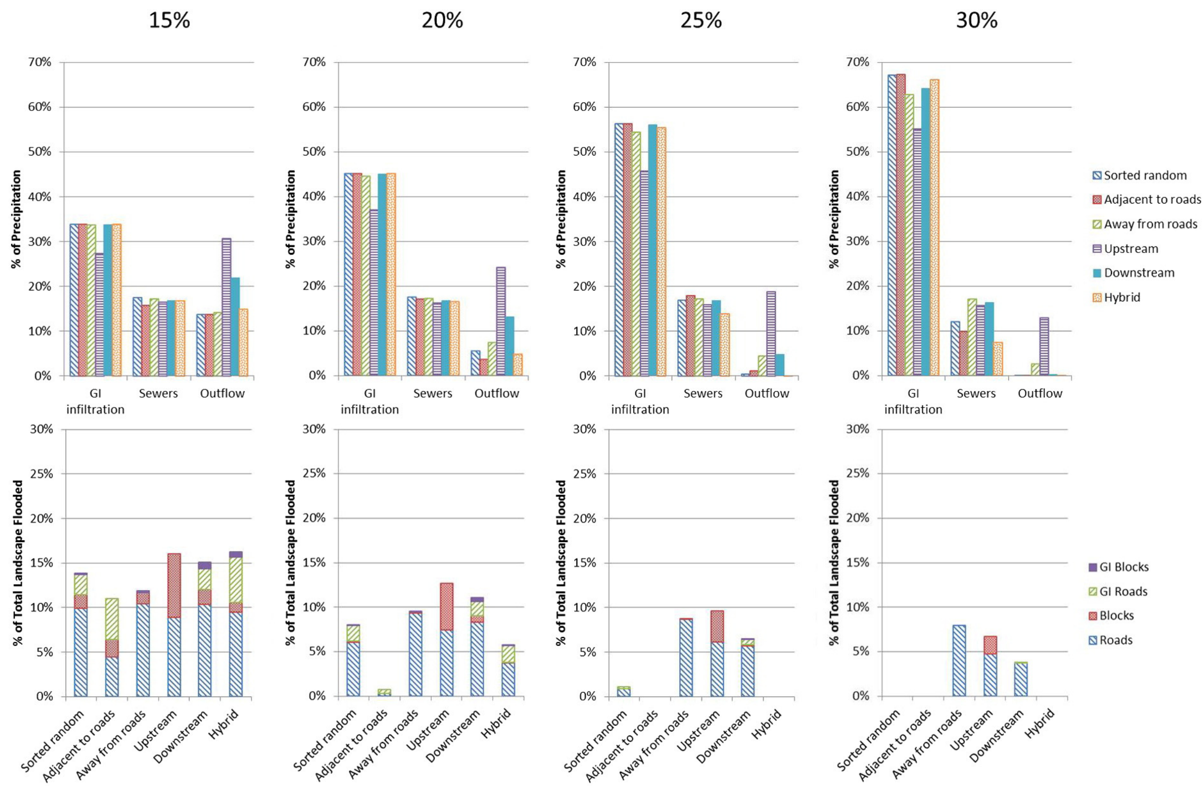

Fig. 8. Effect of the spatial arrangement of green infrastructure on infiltration, sewer intake, outflow runoff, and flooding in 100-year storms, at 15%, 20%, 25%, and 30% green infrastructure coverage.

more effective. These implications are in line with the recommendations of another recent study to locate green infrastructure along the flow path of stormwater (Yang et al., 2015). If such targeted allocations were not possible (e.g., due to utility constraints or neighbors' opposition), even random placement (the baseline scenario) would still provide some alleviation, particularly compared to large neighborhood clusters. If, due to space limitations, clustering were inevitable, downstream placement should be favored over upstream placement.

In its current version, L-GrID can be used to test other scenarios and incorporate variability and heterogeneity in the landscape (e.g., different land cover arrangements, varying slopes). The model could also be transferred to other regions and infrastructure specifications by changing the relevant default parameters, such as the sewer and treatment capacity, precipitation rates, and soil-related and green infrastructure storage and infiltration rates. It should be emphasized that deriving a "best solution" cannot be done through simulation alone, however. Increased effectiveness is not always attainable across all variables of interest, especially if costs (e.g., installation, operation, damage) are considered, which can widely vary in space (including the downstream neighborhoods) and across scenarios. Utility constraints are also present in actual landscapes, limiting placement options. The modeling tool in its current version allows for such discussions to take place with an appreciation of the tradeoffs of each placement strategy, within a range of biophysical contexts, including landscape characteristics, spatial constraints, and stakeholder values.

Significant, but possible, model extensions would be required to include aspects of water quality of the stormwater runoff. Having explicitly modeled water flow, chains of devices, pollutant dilution, flow, and removal can be incorporated in a future version of L-GrID. Further development could also include individual agents (e.g., residents and developers) making decisions about green infrastructure placement, as they respond to incentives and policies that might directly or indirectly target green infrastructure. Given that the hybrid and road-adjacent placement of green infrastructure seem to be the most effective approaches, a combination of public and private decision-making around the construction and retrofitting of sidewalks and driveways, backyards and front lawns would have to be represented, in turn motivated by different preferences toward the various individual and neighborhood-level benefits and costs of green infrastructure. Research is ongoing to include these and other new features in future versions of L-GrID.

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