Using Spatially-Identified Effective Impervious Area to Target Green Infrastructure Retrofits: A Modeling Study in Knoxville, TN

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Abstract

There is a need for enhanced guidance in siting distributed, infiltrative green infrastructure (GI) practices, especially in densely developed urban watersheds where retrofits come at a high cost. To maximize the hydrologic benefit of GI practices on urban streams, the disconnection of Effective Impervious Areas (EIA), or those impervious areas hydraulically connected to the stormwater network, has been identified as a strategic management approach that is expected to have the greatest impact. The overall effect of full disconnection of spatially-identified EIA on watershed hydrology is uncertain because this type of full disconnection is rarely brought to full-scale implementation. In this study, spatial EIA identification is used to parametrize an urban runoff model using the United States Environmental Protection Agency's Storm Water Management Model (SWMM). The calibrated model is used to assess runoff reductions resulting from GI practices distributed through the watershed via different placement strategies, both spatially-informed and not. Full treatment of the spatially-identified EIA using bioretention cells was compared to two scenarios treating the same area of impervious surfaces, but with random placement either among all impervious areas or placement focused in areas of higher imperviousness. Model results indicate that substantially higher runoff reduction could be realized by targeting EIA, with a median runoff reduction of nearly 30% more than other treatment scenarios across storm events ranging from 1.27 to 20.7 mm using this strategic siting. Further improvements in optimizing distributed infiltrative GI practice placement are needed and targeting of spatially-identified EIA appears to be a viable method for increasing the hydrologic improvements realized through watershed scale implementations.

Keywords: Stormwater, green infrastructure, distributed restoration, effective impervious area

1. Introduction

In an effort to protect and restore ecological health and pre-development hydrology in urban streams worldwide, watershed managers seek to reinstate more natural flow regimes in highly developed watersheds. Streamflow has been recognized as a “master variable” defining ecological potential in riverine systems (Poff et al. 1997), and the impacts of impervious surfaces on urban hydrology and a range of other symptoms of degradation have been well established (Brabec et al. 2002, Leopold 1968, Shuster et al. 2005, Walsh et al. 2005b) The value of healthy streams as both financial and cultural assets (Assessment 2005) has led urban watershed managers to seek strategies that both maintain flood protection from stormwater but also undo the effects of intense development on local hydrology. Increasingly worldwide, this is accomplished with distributed, nature-inspired, infiltrative green infrastructure (GI) retrofits. Specifically, these at-source, smaller-scale, infiltrative surface runoff treatment practices are being used in urban watersheds in attempts to restore pre-development runoff frequencies and volumes (Bernhardt and Palmer 2007). By shifting hydrology back to more natural patterns and addressing runoff production at the source, it is believed that urban stream systems will have a better chance of supporting thriving ecosystems without the need for ongoing active channel restoration projects; that is, restoration efforts will better match the scale of the degrading process (Walsh et al. 2005a).

Research on the effectiveness of distributed GI practices to collectively produce this hydrologic shift at the watershed scale is limited and it remains as an important research focus area (Jefferson et al. 2017). Several studies have begun to add to the knowledgebase and demonstrated the complexities of managing urban runoff with distributed GI practices. Modeling has shown that site runoff dynamics are sensitive to the location, type, and number of practices installed (Gilroy and McCuen 2009). For instance, comparisons of hydrologic response to rainfall for developed catchments with different stormwater management strategies (centralized vs. distributed) revealed that distributed GI practices can yield more natural runoff dynamics than centralized stormwater systems (Loperfido et al. 2014). A growing number of monitoring studies have also been conducted to measure the efficacy of distributed GI retrofit strategies at several different scales. Notably, though not exhaustively, these studies include investigation at the small residential scale (0.53 ha) (Page et al. 2015), larger development tracts (2-6 ha) (Bedan and Clausen 2009), and catchment-wide studies with Shepherd Creek in Cincinnati, USA (180 ha) (Roy et al. 2014, Shuster and Rhea 2013), and Little Stringybark Creek (450 ha) in Melbourne, Australia (Walsh et al. 2015). Additional examples are presented by Jefferson et al. (2017). The results of these studies indicate improvements in stated goals, though they are difficult to compare due to differences in study approaches, stormwater control measures (SCMs) employed, the timeline of installation, and siting strategies. These are nonetheless valuable studies, as the lack of adequate supporting evidence for distributed SCMs to effectively address watershed-wide goals remains an impediment to widespread use of this multi-benefit management strategy (Roy et al. 2008).

Another impediment to wider use of distributed SCM retrofits in existing urban areas is that these practices carry a higher cost related to land value in densely developed areas. Costs are further increased when you consider the opportunity costs of land used for stormwater management as opposed to other uses in the urban setting (Roy et al. 2008). Because of this, distributed GI practices have mostly been sited in an opportunistic, empirical manner where public land is available or where redevelopment occurs. The high costs for urban retrofit projects warrants strategic siting of these practices so that they impart the greatest good to stream hydrology, especially considering limited water resource budgets and increased urbanization (Barbosa et al. 2012).

Research has shown that the effective impervious area (EIA), a subset of the total impervious area (TIA) representing the impervious areas hydraulically connected to the stormwater network, has a much greater effect on stream hydrology than TIA due to rapid surface drainage along hydraulically-efficient stormwater infrastructure (Brabec et al. 2002, Shuster et al. 2005). Streams exhibit declining conditions as TIA increases, but these declines have been shown to be even more tightly coupled to increases in impervious connectivity (i.e., a higher EIA/TIA ratio) (Hatt et al. 2004, Lee and Heaney 2003, Leopold 1968, Walsh et al. 2005b). Because of this, the EIA should be leveraged to optimize the hydrologic benefits of GI retrofits by intercepting runoff from these areas first and foremost. However, quantifying and identifying EIA is more difficult than TIA because it can be subject to ambiguous urban drainage patterns and variable conditions that influence runoff production (Alley and Veenhuis 1983, Boyd et al. 1993, 1994, Brabec et al. 2002, Chiew and McMahon 1999, Ebrahimian et al. 2016a, Han and Burian 2009).

Although disconnection of EIA by implementation of GI practices can theoretically maximize the effectiveness of watershed restoration efforts, rapid and reliable identification of these areas is often time-consuming (Roy and Shuster 2009). Recently developed methodology by Epps and Hathaway (2018) provides spatially explicit identification of EIA that is informed by geospatial data and observed runoff trends. The results of this method account for spatial differences in runoff pathways and land cover along these pathways to identify areas most likely to be EIA in a GIS framework that can be used to prioritize stormwater management projects for runoff reduction. This method (Epps and Hathaway 2018) uses EIA quantity estimates from rainfall-runoff data analysis that build upon the work of Boyd et al. (1993) and Ebrahimian et al. (2016b). These quantity estimates for EIA are then spatially-identified with GIS flowpath analysis that differentiates impervious areas based on the connectivity of runoff produced by them via interceding surfaces and infrastructure towards the watershed outlet. Calibration is accomplished using a runoff attenuation parameter, varying this until the spatially-identified EIA quantity matches the quantity estimate from the observed data. Readers are encouraged to read Epps and Hathaway (2018) for further methodology details and a discussion of the limits of the results. The requirement of gaging a watershed to produce these results is a strong limitation on this methodology, but efforts are underway to investigate how this approach can be adapted to be used on ungaged watersheds. Determining the connectivity or lack thereof of rooftops is a concern with geospatial approaches to EIA identification, another area for future research. A final limitation is that it is difficult to assess the accuracy of the results of this new methodology or determine what the hydrologic effects might be given implementation of GI retrofits (as full disconnection of the EIA with these would take several years). Modeling can provide an initial means to assess the potential for this type of watershed-wide deployment of GI retrofits, assess how targeting spatially-identified EIA for disconnection compares to other less spatially guided strategies, and determine what level of changes in storm-event response should be expected given watershed-wide implementation.

One of the most widely-used urban stormwater runoff models is the United States Environmental Protection Agency's (EPA) Stormwater Management Model (SWMM) (Rossman 2004). Like most urban runoff models, SWMM is very sensitive to impervious parameter inputs. The need for accurate representation of impervious characteristics in urban runoff models has been noted, in particular in relation to EIA (Alley and Veenhuis 1983, Lee and Heaney 2003). A recent review of research applying SWMM to urban hydrologic investigations and the modeling of management paradigms for planning and decision-making (Niazi et al. 2017) has identified several gaps and opportunities for future studies to strengthen the use of this model. This review points to the gap in knowledge in accounting for hydrologic continuity and GI spatial orientation as one of the most important foci for future research due to the importance of assessing different GI retrofit configurations to support current urban watershed management approaches. Incorporating spatially-identified EIA information into a SWMM model to compare different siting strategies for GI retrofits forms the basis of the study presented here. Results can be used to guide better approaches for assessing distributed restoration initiatives, optimized GI planning, and the potential performance related to locational siting and configuration on a watershed-scale basis. This information will be pursued in this study using SWMM to model First Creek, a large urban watershed in Knoxville, TN. This will help determine what level of runoff reduction may be possible by installing GI practices strategically to disconnect EIA and how this targeted strategy using spatially-identified EIA compares to runoff reductions using less-informed spatial siting for the same level of treatment with GI.

Objectives

The main goal of this study is to utilize the spatial identification of EIA areas from Epps and Hathaway (2018) to assess the runoff volume reduction that might be realized given targeted application of GI practices to these locations. Results will be compared to other scenarios, of similar treatment level, that use different criteria for site selection not related to EIA location to help quantify the potential advantage of using this spatial EIA information. A secondary goal is to verify the importance of the results of spatial EIA identification using the methods of Epps and Hathaway (2018) pertaining to the use of this high-resolution data. This will be accomplished by assessment of model results and discussion of this important modeling parameter and its use in SWMM as it relates to surface runoff and GI models.

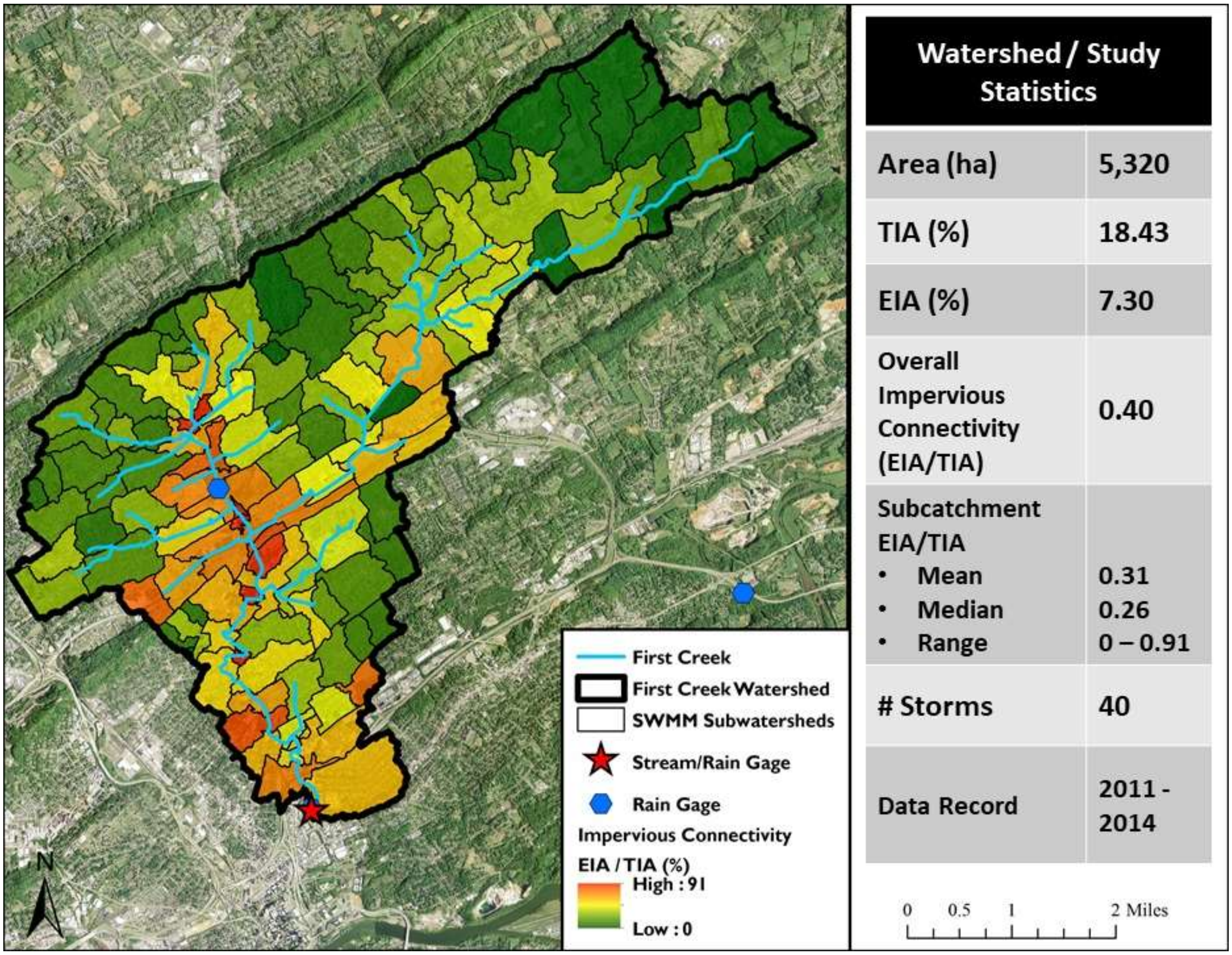

Figure 1. Map of study watershed, First Creek in Knoxville TN, U.S.A. with summarized characteristics related to imperviousness and rainfall-runoff analysis used to estimate EIA. EIA spatial locations determined per Epps and Hathaway (2018).

2. Methods

2.1 Study Site and Data

The focus of this study was the First Creek watershed in Knoxville, TN, United States (Fig. 1). First Creek is a mixed-development watershed (5,320 ha) with an upland tributary that runs through rural areas with sparse residential development and some agricultural lands and a main stem that flows through a densely developed urban corridor following a main arterial road with flood-protection channelization. Watershed statistics have been summarized in Figure 1. EIA quantity estimates were developed from rainfall-runoff data using rainfall and streamflow records for the period of March 2011 – June 2014 from the City of Knoxville Stormwater Engineering department (Epps and Hathaway 2018). Rainfall data (15 min. timestep) was obtained from three locations near the First Creek watershed and storm event depths for the watershed were calculated based on a Thiessen polygon weighted-average. Storm events with total rainfall depth above 1.27 mm and below 25.4 mm with at least 6 hours of separation from any additional rainfall were considered in the analysis. Local stormwater management goals require capture of runoff from the first 25.4 mm of rainfall for any size event. Focus on events of this size or smaller will demonstrate how distinctions in GI retrofit placement impact runoff capture for the storm events of this size or less. Additionally, this event size is approximately equal to the 90th percentile storm event size for the region (Sylvester et al. 2016). Storm events were further screened for use in GI modeling using best professional judgement to focus on events where all rainfall fell mostly in close temporal succession (12 hours or less) to focus on simpler single-peaked hydrographs with a more uniform runoff response over the watershed. While it has been shown that the effectiveness of GI practices can be greatly reduced for subsequent peaks of complex storms (Versini et al. 2016), these dynamics are better explored in studies of SCM design effectiveness. The stipulation for simpler single-peaked events is made in this study to reduce temporal rainfall effects on SCM performance and focus on differences in spatial distribution as much as possible in evaluating differences between placement scenarios. From the full record of data, 68 distinct rain events were identified. Nine of these were removed because they exceeded 25.4 mm in depth and 19 events were removed because they had multiple peaks. The largest storm in the remaining 40 events to be analyzed was 20.7 mm. Of the 40 events, 20 were less than 6 mm in depth, 11 events were in the range of 6-12 mm, and 9 events were larger than 12 mm.

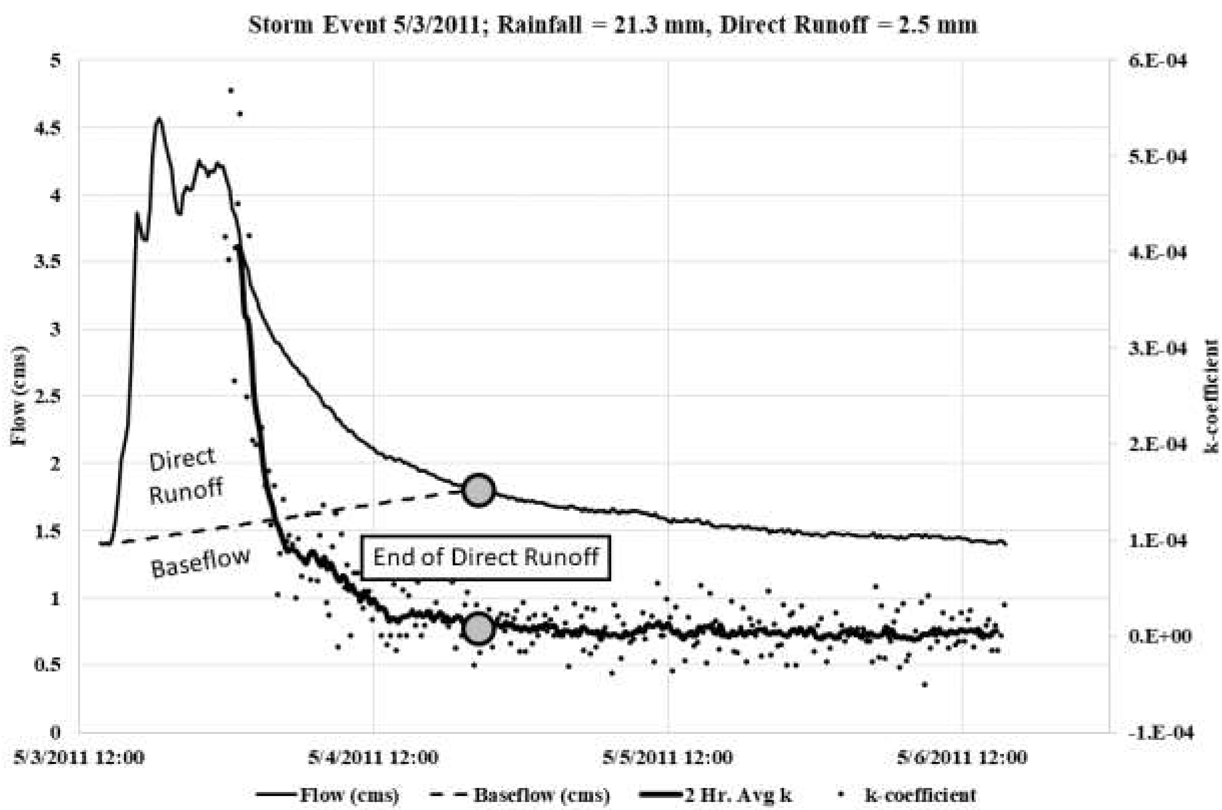

Figure 2. Demonstration of hydrograph separation used to develop rainfall-runoff pairs for the estimation of EIA.

Direct runoff depths for these storm events were estimated by hydrograph separation using the constant-k method of Blume et al. (2007). This method assumes that baseflow discharges from a linear reservoir with exponential decline such that the point on the receding limb of the hydrograph when the recession coefficient (*k*) becomes nearly constant represents the end of direct runoff and the streamflow's return to solely baseflow sources (Fig. 2). The recession coefficient was calculated for all points on the receding limb of the storm-event hydrographs via the equation from Blume et al. (2007):

$$k = -\frac{dQ}{dt} * Q(t) \qquad (1)$$

Flow data were assessed against the k-coefficient data using a 2-hour moving average to visually select the point in the receding limb of the hydrograph at which *k* stabilized to a near constant value. This point in the hydrograph was then connected by straight-line to the point just before hydrograph rise to complete hydrograph separation (Fig. 2). The volume of water above this line was then summed and converted to a depth through division by the watershed area so that rainfall-runoff trends could be used to quantify EIA. The quantity of EIA in the First Creek watershed was estimated in the same manner used in Epps and Hathaway (2018), employing regression analysis of rainfall-runoff data by the methods of Boyd et al. (1993) and Ebrahimian et al. (2016) as a guide. This EIA quantity was used as a target for calibration of spatial EIA models presented in Epps and Hathaway (2018). This spatial EIA data both: (1) forms the impervious connectivity input for a SWMM model (as opposed to using impervious connectivity as a calibration parameter), and (2) is the focal point of various SCM siting methodologies that are compared herein to evaluate how volumetric runoff reduction varies based on restoration approach. Spatial differences in the ratio of EIA/TIA (as a measure of impervious connectivity) for the First Creek watershed are shown in Figure 1, summarized at the subcatchment level used in the SWMM model.

2.2 Surface Runoff Model

A previously developed SWMM model for First Creek was provided by the City of Knoxville Stormwater Engineering for this study. This model had been developed for flooding analysis and did not include a groundwater component. Because the goal of the study was to assess the representation of impervious connectivity and the disconnection of EIA using GI retrofits as they pertain to surface runoff, the development of a groundwater component was deemed unnecessary. The existing SWMM model disaggregated the First Creek watershed into 125 subcatchments based on infrastructure location and grouping of homogeneous surface cover and topography. All surveyed channel information, stormwater infrastructure, hydraulic parameterization, and internal storage portions of the model were preserved for this study. Subcatchment boundaries were also preserved and the impervious area for each subcatchment was updated to ensure model parameters were consistent with high-resolution data used by the spatial EIA models.

2.3 SWMM Model Setup and Parameterization

Aside from subcatchment geospatial data, the SWMM model parameters were adapted based on guidance from SWMM documentation (Rossman and Huber 2016). The Green-Ampt method was used to represent infiltration in the model and runoff routing was modeled using the kinematic wave approximation. Rainfall observations (15 min. timestep) from the three tipping bucket gages (Fig. 1) used in EIA quantity estimation were used in the model, being assigned to subcatchments based on which representative Thiessen polygon area for the three gages that the subcatchment was located in.

Model parameters were developed from literature values in most cases, though a few were based on the assumptions of the spatial EIA model (Table 1). Infiltration parameters for the Green-Ampt model were taken from literature values based on subcatchment soil properties obtained from the National Resources Conservation Service's SSURGO soil survey database (SSURGO 2017). The distribution of each subcatchments soils among different Hydrologic Soil Groups (HSG) was used to produce weighted values for the literature-based Green-Ampt parameters. Average monthly evaporation values were used for evapotranspiration modeling and derived from pan evaporation measurements for local gages in eastern Tennessee (Farnsworth and Thompson 1983). Impervious routing parameters were parsed between TIA and EIA according to the amount of EIA identified in each subcatchment from the previously described spatial models (Epps and Hathaway 2018). For each subcatchment, the EIA was routed directly to the outlet while the balance of TIA was routed to pervious areas representing the disconnected portion of impervious surfaces. The original SWMM model obtained from the City of Knoxville had routed impervious and pervious areas directly to the outlet, utilizing model calibration of other surface runoff parameters to achieve adequate model fitting. The inclusion of the spatially-identified EIA routing is an improvement over this representation that reflects site-specific impervious connectivity data and addresses a concern for SWMM models as described by Niazi et al. (2017).

Table 1. Summary of pertinent SWMM model parameters and guidance used to develop the uncalibrated base models. Bolded values represent final parameters values for the calibrated model. Starred parameters indicate those that were varied during simple manual calibration.

Parameter	Description	Initial Value	Range Lo	Range Hi	Guidance/Source
Subcatchment Parameters					
Nimp*	Manning's n for Impervious	**0.015 (avg. Impervious)**	0.01	.018	Yen (2001)
Nperv*	Manning's n for Pervious	0.05 (avg. grass)	**0.038**	0.12	Yen (2001)
Simp (mm)	Depress. Storage for Impervious	**0.3**	---	---	(Ebrahimian et al. 2016b)
Sperv* (mm)	Depress. Storage for Pervious	6.4	**2.5**	10.2	ASCE (1992)
%Zero	Portion of IMP w. no Simp	**0**	---	---	Accounted for in EIA Spatial Model
%Routed	Portion of IMP routed to PERV/Outlet	**EIA %**	---	---	EIA % within each Subcatchment
Infiltration Parameters					
Suction (mm)	Suction head at wetting front	ψ_s=0.127*K_{sat}^(−0.328)			Brakensiek et al. (1981)

Ksat* (mm/hr)	Sat. hydraul. conductivity	Avg. value from soil composition	**Low value from soil composition**	High value from soil composition	Musgrave (1955); based on soil HSG comp.
IMD*	Max moisture deficit avail.	Based on K_{sat}/soil classification	**Low value from table range**	High value from table range	Rawls et al. (1983)

2.4 Model Calibration and Assessment

Surface runoff was modeled continuously and reported at a 15-minute timestep over the period from March 2011 to June 2014 during which records for streamflow and three rain gages existed. A subset of 40 of the identified storm events that had been used to estimate the watershed EIA were selected for analysis of potential runoff volume reduction. Analysis of overall GI practice runoff reduction was constrained to these storms since larger storms would likely be associated with runoff from more than just EIA areas. This focus on storm events most likely producing runoff from just EIA areas provides a greater assurance that different GI retrofit placement scenarios (described more below) will capture the differences in runoff reduction possible under strategic siting using spatial EIA identification versus other less-targeted guidance. Rainfall depths for these 40 storms ranged from 1.27 mm to 20.7 mm with an average storm size of 8.3 mm. While more than 40 valid storm-events occurred during the period of record, only storms that had been identified to derive from predominantly EIA in regression analysis were used. Modeled runoff from the equivalent timeframe of each of these observed storm events was summed to produce a runoff volume that was normalized to a depth over the watershed area for comparison to the observed runoff depth over the same equivalent timeframe. Model fit for storm-event runoff depths was used for calibration and assessed using the Nash-Sutcliffe efficiency index (NSE) (Nash and Sutcliffe 1970) and the Kling-Gupta efficiency (KGE) (Gupta et al. 2009).

Simple manual calibration for selected storm event runoff volumes was performed to improve the SWMM model fit by varying the starred parameters in Table 1 between their high, mean, and low values identified in the literature to determine model sensitivity and provide a suitable model of surface runoff. This calibration was simple in that the parameters for all 125 subcatchments were assigned the same value class (low, median, high) for the parameter of interest for each calibration iteration. Further calibration was not deemed necessary because the focus of the study was on GI practice placement. A reasonably accurate runoff model provided a consistent baseline for these different GI practice placement scenarios to be studied and compared. Final model parameters are noted in bold (Table 1). Calibration was assessed for the storm event runoff depths during 2011 – 2012 (23 events) and verified by the remaining event runoff depths during 2013 – 2014 (17 events).

2.5 Green Infrastructure Scenarios

To study differences in runoff reduction that may be realized given alternative approaches to SCM application, the calibrated SWMM base model was used to assess runoff reduction under different siting strategies for GI retrofits in the First Creek watershed. Since EIA was estimated as 7.3% of the watershed, this forms the targeted amount of impervious area to be treated by GI practices in all scenarios. Three scenarios of GI practice siting were compared and a schematic representation of these is shown in Figure 3.

- The first scenario ("EIA") applied GI practices only to the spatially-identified EIA areas (treating 7.3% of the watershed). This represents the targeted scenario where spatial models of EIA are used to identify locations for GI practices to disconnect EIA runoff from the stream network.
- The second scenario ("Random") distributed GI practices randomly by first using a random number generator to apportion the 7.3% treatment level amongst the subcatchments, and then using a second random number generator to divide that apportioned percentage for a given

subcatchment between EIA and non-EIA areas (subject to availability of each of these impervious types). In this scenario, it is assumed that the equivalent area of impervious surfaces (7.3% of the watershed) are treated for disconnection, but that the placement of practices among the TIA is not guided by any spatial information (i.e., random).

- The third scenario ("TIA-weighted") was guided by subcatchment imperviousness wherein the 7.3% treatment level was apportioned amongst subcatchments using a weighted average of the TIA in each subcatchment to the overall watershed TIA. This TIA-weighted impervious percentage was then divided between EIA and non-EIA areas in each subcatchment based on a random number generator. This scenario represents an intermediate guidance strategy in which the treatment amount in each subcatchment is proportional to the TIA distribution over the watershed, but that there is no further spatial differentiation between EIA and non-EIA areas receiving treatment. This scenario was chosen as an intermediate level of spatial guidance since distributed GI retrofits are typically placed more often in the most highly impervious areas of a watershed.

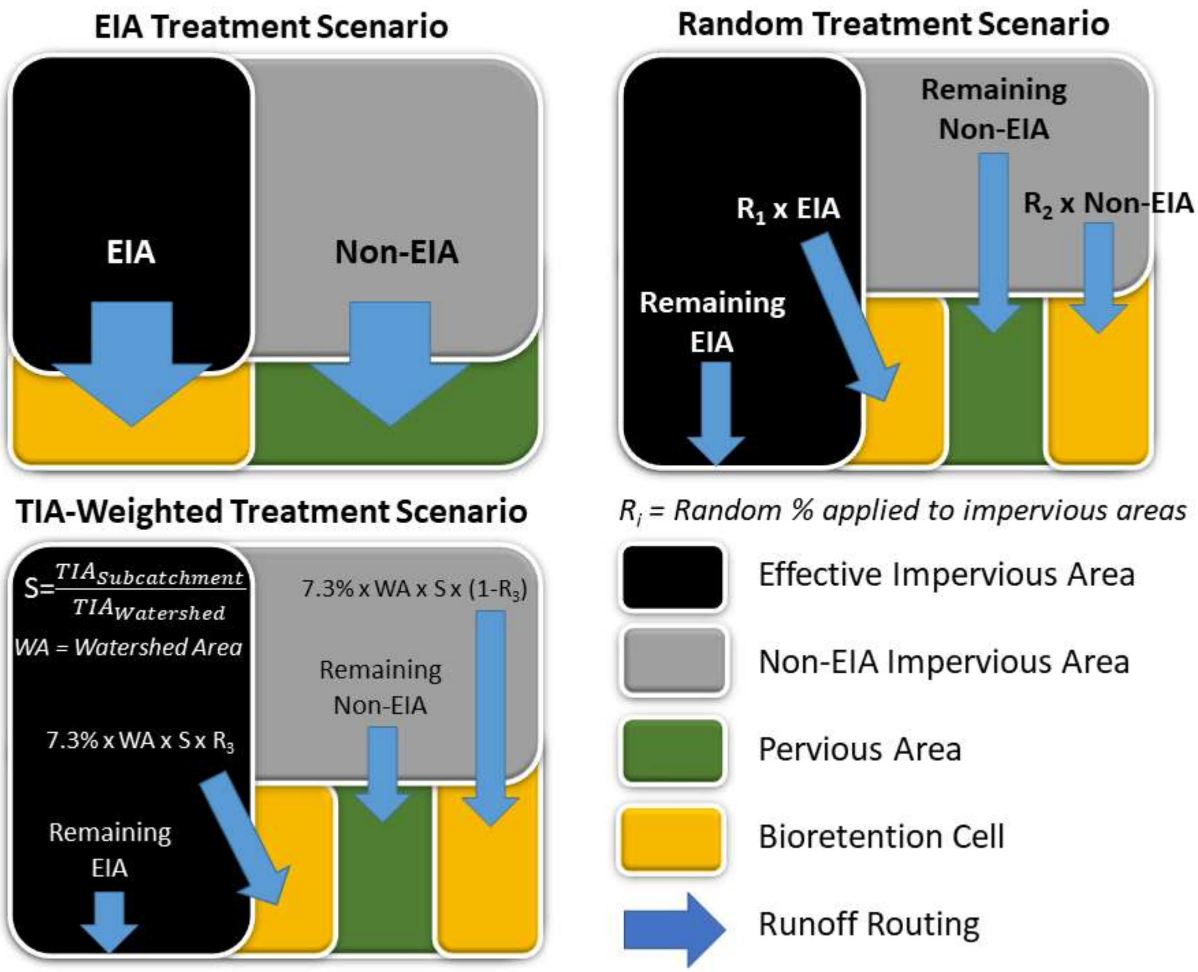

Figure 3. Schematic representation of GI siting scenarios used for comparison.

This process was iterated for each alternative siting strategy (Random and TIA-weighted) with different randomization to produce 30 different applications of GI practices for each to be compared to the EIA-focused siting strategy. Each of these scenarios was then modeled in SWMM by placing practices appropriately within the model to identify differences in runoff reduction between each model. Median and maximum reductions over the 30 model iterations for each alternative siting strategy were then compared to the EIA scenario results to assess differences in performance between the three. This was done to compare both the average and the best performance for less spatially-informed siting methods to quantify the advantage (or lack thereof) that utilizing spatial EIA data might provide over the alternative siting scenarios. Runoff volume reductions were compared using a storm-event pairwise Wilcoxon signed rank test (Wilcoxon et al. 1970) due to non-normality to assess whether GI siting scenarios exhibited dissimilar runoff reductions on average and thus demonstrate whether a given siting strategy might be advantageous.

2.6 Green Infrastructure Modeling

To apply the appropriate GI treatment in each scenario, a generic bioretention cell was modeled to treat both EIA and non-EIA impervious areas separately in each subcatchment. Bioretention cells were modeled using the LID editor in SWMM (version 5.1). A single, lumped bioretention cell receiving runoff from each impervious area subset was modeled for a total of two bioretention cells per subcatchment and these were sized distinctly with enough storage to capture the runoff from a 25.4 mm storm for the given impervious area each was determined to treat. Parameterization of these bioretention cells is summarized in Table 2. Bioretention cells were sized vertically per guidance from municipal stormwater management manuals (Table 2). For each GI practice scenario, the impervious surface area identified for treatment (EIA and non-EIA separately) was used to calculate the runoff volume for a storm event of 25.4 mm. The required surface area of bioretention cells to treat this amount of runoff was then calculated based on the total storage available in the bioretention cell to accommodate this volume. SWMM allows a given bioretention cell to receive runoff from a subset of the subcatchment impervious areas. Thus, two bioretention cells were defined and sized for each subcatchment (one for EIA, one for non-EIA), and the appropriate percentage of the impervious area was routed to each based on the EIA and non-EIA impervious areas to be treated in each scenario. SWMM also allows underdrain flow and excess water from the bioretention cell to be routed back to pervious areas or directly to the outlet. This option was utilized to maintain the model representation of surface routing, with the bioretention cell treating non-EIA routed to pervious areas and that treating EIA routed to the outlet. Storm event runoff depths were calculated from model outputs and the percent runoff reduction was calculated by comparison to surface runoff depths for the base model with no GI practices. The percent reduction of runoff for the 40 storm events was calculated for the 30 iterations in each alternative scenario to compare to the EIA-focused runoff reductions. Further, pairwise comparison of storm event runoff reduction between the three siting strategies was then used to assess whether there were statistical differences. This was done for all storm events as well as by three groupings of storm event size (< 6 mm, 6 – 12 mm, and 12+ mm) to aid in discussion of differences in runoff reduction by storm size. These grouping represent storm sizes for the area of approximately 54%, 72%, and 89% frequency ranks, respectively, (Fig. 4) based on rain data from the Tyson-McGhee airport station for the years 1981 – 2010 and are consistent with the results presented in Sylvester et al. (2016). The EIA scenario was compared to the median and maximum runoff reduction scenarios (of the 30 randomizations) for each of the Random and TIA-weighted scenarios to demonstrate the range of performance and sensitivity to placement for these alternate siting strategies in comparison.

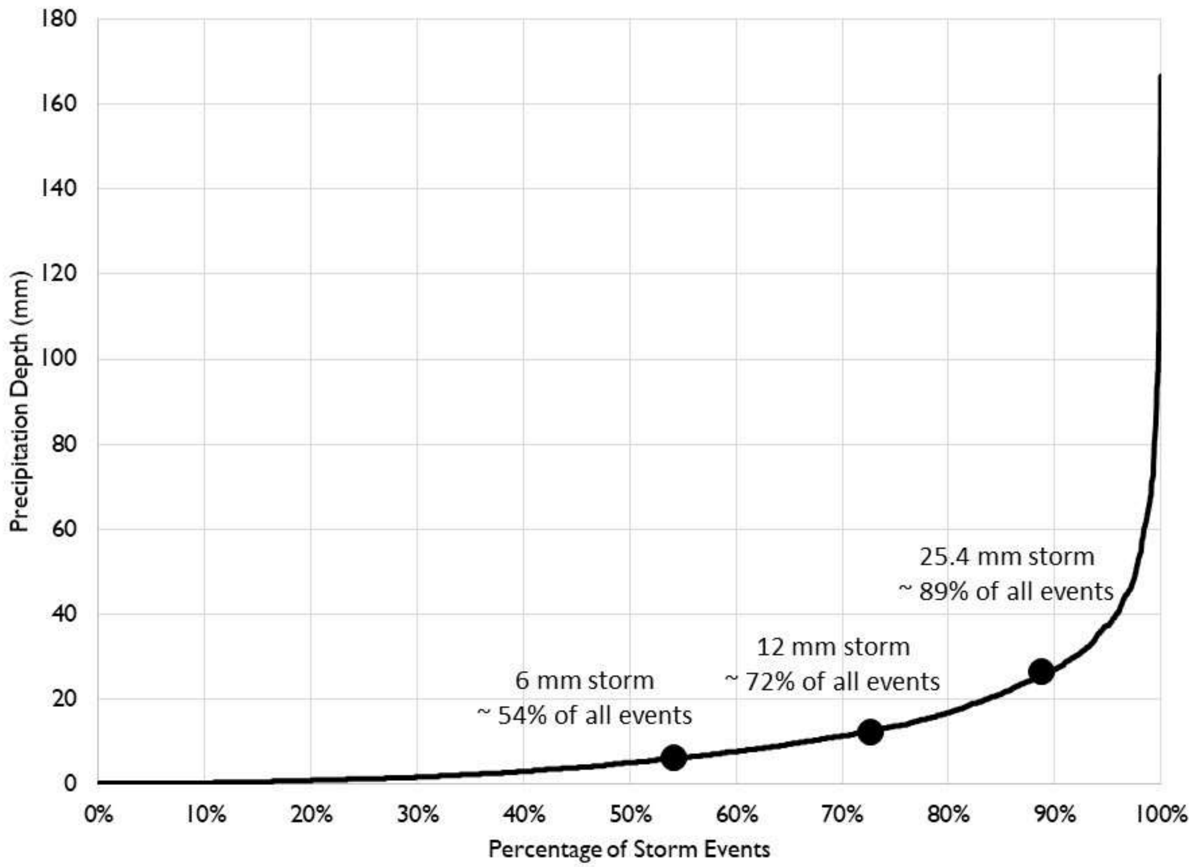

Figure 4. Storm depth frequency distribution for McGhee-Tyson airport, Knoxville, TN.

Table 2. Summary of bioretention cell parameterization and source of information for application of SCMs in different siting scenarios.

BIORETENTION CELL SCM (Type = BC)			
Parameter	**Description**	**Value Used**	**Rationale**
Surface Layer Parameters			
StorHt	Max depth water can pond (cm)	15.24	County (2008)
Soil Layer Parameters			
Thick	Thickness of soil layer (cm)	60.96	County (2008)
Por	Soil porosity (pore space/total volume)	0.44	Committee (2005)

FC	Soil field capacity (volume pore water/ total volume when fully-drained)	0.09	Committee (2005)
WP	Soil wilting point (vol. pore water/ total volume for well-dried soil)	0.04	Committee (2005)
Ksat	Saturated hydraulic conductivity (cm/hr)	1.27	County (2008)
Kcoeff	Slope of curve of log(conductivity) vs soil moisture content (dimensionless)	50	Rossman (2004)
Suct	Soil capillary suction (cm)	10.31	Brakensiek et al. (1981)
Storage Layer Properties			
Height	Thickness of storage layer (cm)	30.48	County (2008)
Vratio	Void ratio (porosity = vr/(1+vr))	0.4	Miller (1978)
Seepage	Rate of drainage into native soil (cm/hr)	Ksat	Model parameter for subcatchment
Vclog	Clogging parameter	0	Clogging ignored
Drain System Properties			
Coeff	Determines rate of flow through drain as a function of hydraulic head (C)	0.6	County (2008)
Expon	Determines rate of flow through drain as a function of hydraulic head (n)	0.5	County (2008)
Offset	Ht. of drain above bottom of storage layer (cm)	30.48	Miller (1978)

3. Results and Discussion

3.1 SWMM Model Results

The base model performed well in matching storm event runoff volume given simple manual calibration. Model performance results over the entire period and the calibration and verification periods are summarized in Table 3, and modeled runoff depth versus the observed runoff depth has been plotted in

Figure 5. The model typically performs well, but shows some underprediction of larger storm events, an expected outcome given the lack of a groundwater component within the model.

Hydrograph separation distinguishes total runoff between a baseflow component and direct runoff, the latter which may contain some portion of interflow, or shallow subsurface return flow not related entirely to surface runoff dynamics (Beven 1989). This portion is not easily discernible through graphical analysis and may over-estimate true surface runoff for any given event. Manual parameter adjustment for this SWMM model used mean literature values as a starting point and adjusted parameters to minimum and maximum literature values for all subcatchments to identify the greatest sensitivities in the model for surface runoff to arrive at the final calibrated base model. Parameters that were adjusted in this process away from the mean value were all related to soils and pervious area runoff, and the calibrated values were all on the low end of the literature ranges. It is possible that this reflects the condition of urban soils which typically have poorer infiltration and thus contribute to greater surface runoff. However, this may also be due to the potential overestimate of surface runoff from the inclusion of interflow portion which is not included in the SWMM model. Overall, these results demonstrate that the model is well-suited to serve as a basis for comparing runoff reduction between SCM placement scenarios.

Table 3. Summary of SWMM base model performance for prediction of storm event runoff depth.

Model Period	**Nash-Sutcliffe Efficiency**	**Kling-Gupta Efficiency**
Overall (2011 – 2014)	0.77	0.88
2011/2012 (23 events)	0.79	0.72
2013/2014 (17 events)	0.74	0.73

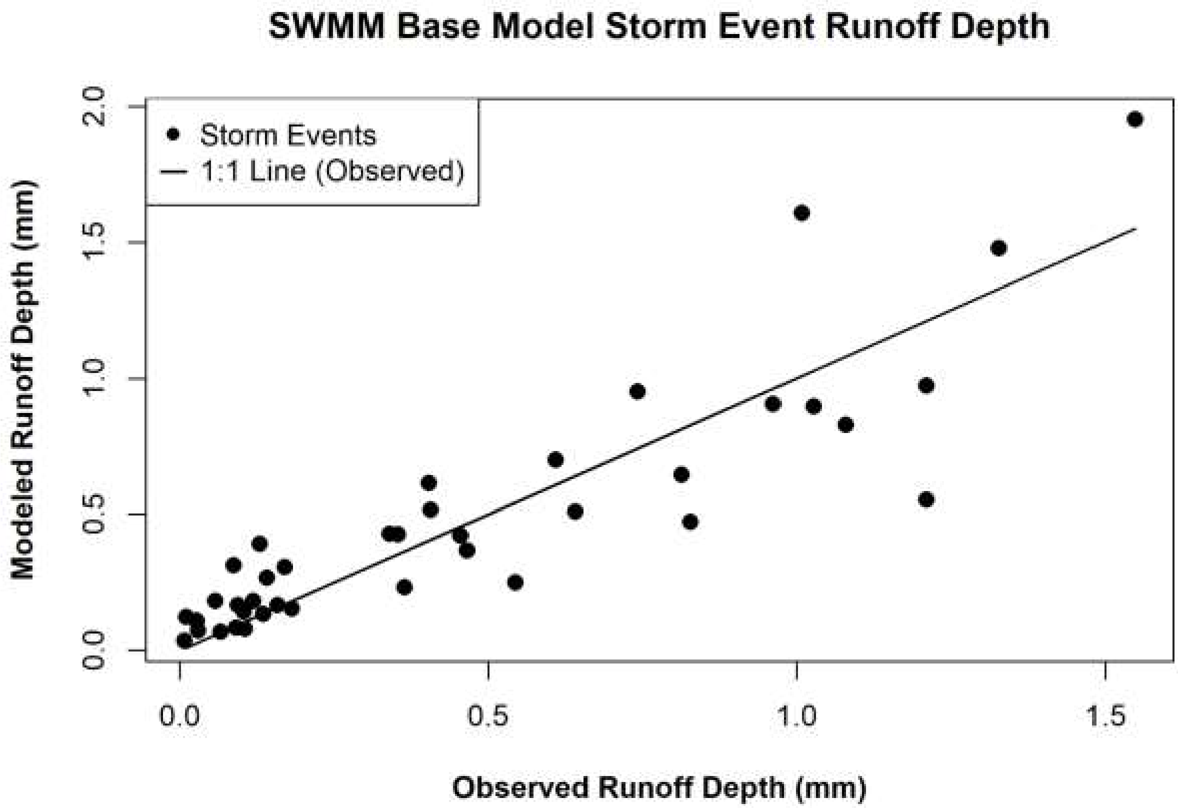

Figure 5. Observed runoff versus predicted runoff depth for the final SWMM runoff model for First Creek.

3.2 Spatial EIA Distribution among Subcatchments

The inclusion of spatially-explicit estimates of EIA that are informed by physical geography and hydrologic trends in this SWMM model produced acceptable model results with only simple manual calibration. EIA has been identified as one of the most sensitive parameters in SWMM models, and its accurate representation in the model can allow more efficient and accurate calibration for other important urban runoff parameters in the model (Mancipe-Munoz et al. 2014). Comparing the spatially-derived results of EIA from Epps and Hathaway (2018) to those from literature regression estimates offers a demonstration of the range in EIA values that varies based on the method of estimation (which can greatly impact surface runoff modeling results). A plot of the EIA versus TIA for the SWMM model subcatchments (Fig. 6) derived from spatial analysis in Epps and Hathaway (2018) demonstrates a very different relationship for the First Creek watershed than predicted by literature regression equations sometimes used for EIA estimation (Alley and Veenhuis 1983, Roy and Shuster 2009, Wenger et al. 2008). This plot indicates that EIA would be mostly overpredicted by regression equations for the First Creek watershed, especially for intermediate values of TIA.

The use of these regression equations to predict EIA in catchments other than where they were developed has been demonstrated to poorly reflect actual EIA measurements (Roy and Shuster 2009). While this is not the focus of this paper, it demonstrates that the method utilized to estimate EIA can vary greatly, and because runoff modeling results are sensitive to this parameter, it makes sense to use the most site-specific information available. Spatial EIA estimates used in this study were conducive to incorporation into SWMM model subcatchment discretization for more accurate runoff production and routing information. Implemented within typical GIS analysis for model parameterization, they were easily summarized by subcatchment in the same way as TIA typically is. Estimations of EIA using regression equations developed elsewhere or by using EIA as a model calibration parameter (that is, when it is one of many calibration parameters) may provide a less accurate representation of impervious connectivity and urban runoff processes.

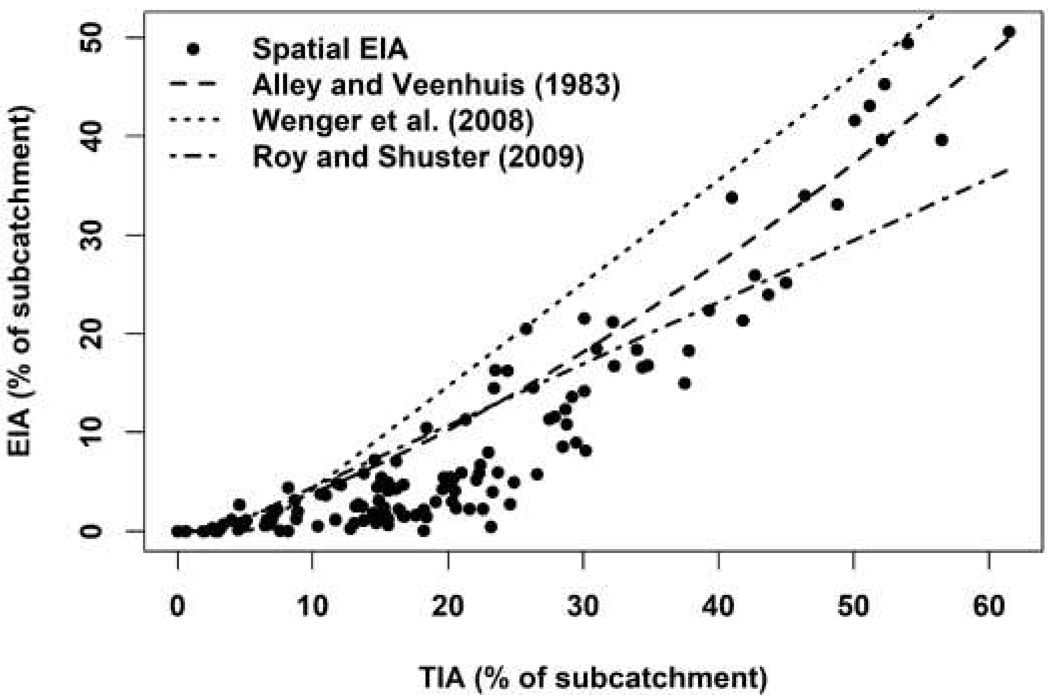

Figure 6. The spatial distribution of EIA among SWMM model subcatchments as a function of TI are not well represented by literature regression equations.

Table 4. Summary of mean/median percent runoff reductions for different treatment scenarios for all storms and by size groupings.

Percent Runoff Reduction	EIA Treatment		Random Treatment		TIA-weighted Treatment	
	Mean	Median	Mean	Median	Mean	Median
All Storms	37.3	39.8	27.2	28.7	27.0	28.6
< 6 mm	49.2	49.4	34.7	33.4	34.6	33.6
6 – 12 mm	32.2	34.6	25.0	27.9	24.4	27.4
12+ mm	16.9	17.8	13.3	12.5	13.1	12.6

3.3 Runoff Reduction for GI Placement Scenarios

Average percent runoff reductions achieved via different GI placement scenarios are summarized overall and by storm size groupings in Table 4. These values represent the mean and median reductions by scenario and storm size for all modeled events (40 events for EIA and the 30 randomization scenarios of 40 events for the alternative siting scenarios). Runoff reduction for the 40 storms are presented as boxplots to demonstrate differences in the range of values between GI siting strategies. These have been summarized for both the median runoff reduction scenario for the Random and TIA-weighted treatments over the 30 randomizations (Fig. 7) and the maximum runoff reduction scenario over the 30 randomizations as well (Fig. 8). The results of pairwise comparison for each grouping by the Wilcoxon signed-rank test (Wilcoxon et al. 1970) are presented in Table 5 for EIA runoff reduction and the maximum runoff reductions under the 30 randomizations of the alternative strategies. Results indicate that focusing GI applications in locations identified as EIA can result in greater runoff reduction, especially for smaller storms up to 12 mm. Over all storm events, GI placement focused on EIA resulted in nearly 4-10% greater runoff reductions (Table 5) than those for less spatially guided strategies with an overall mean runoff reduction of 37.3% (Table 4). This is in comparison to mean reductions of 27.2% and 27.0% for the random and TIA-weighted placement scenarios over all storm events, respectively. The differences in runoff reduction when storms are partitioned by size offers insight on modeled runoff dynamics and the performance of GI treatment over a range of conditions. This information can inform future model parameterization and utilization of this information for application of distributed GI practices in terms of runoff reduction potential and management strategies.

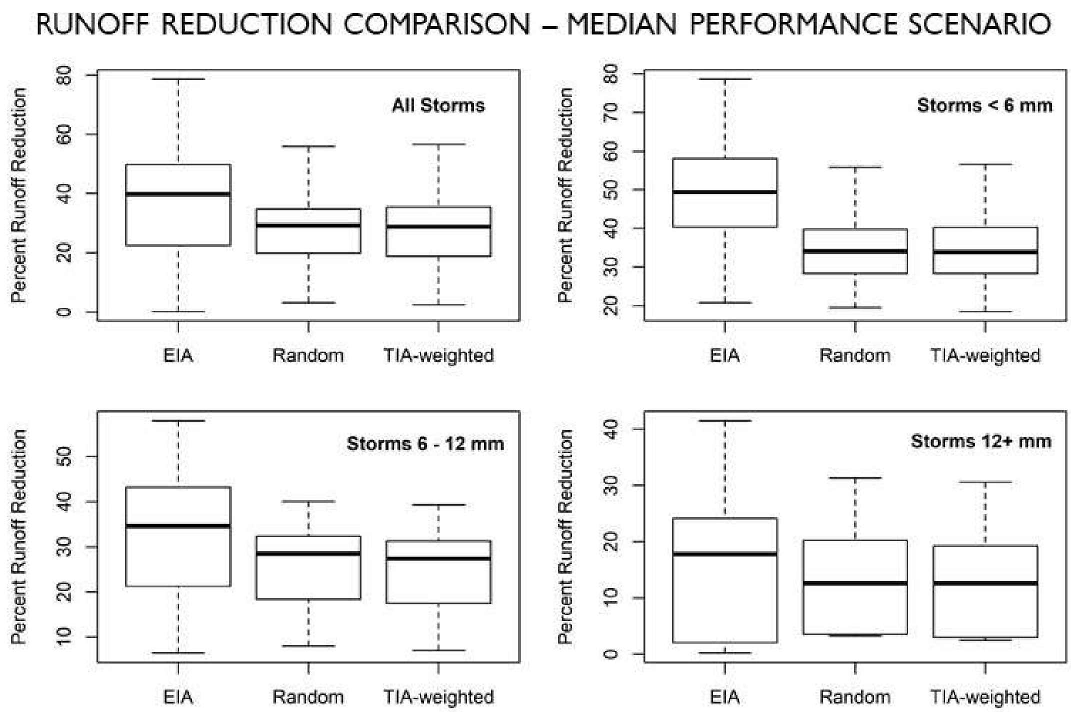

Figure 7. Comparison of EIA-siting to median values of runoff reduction for alternative strategies.

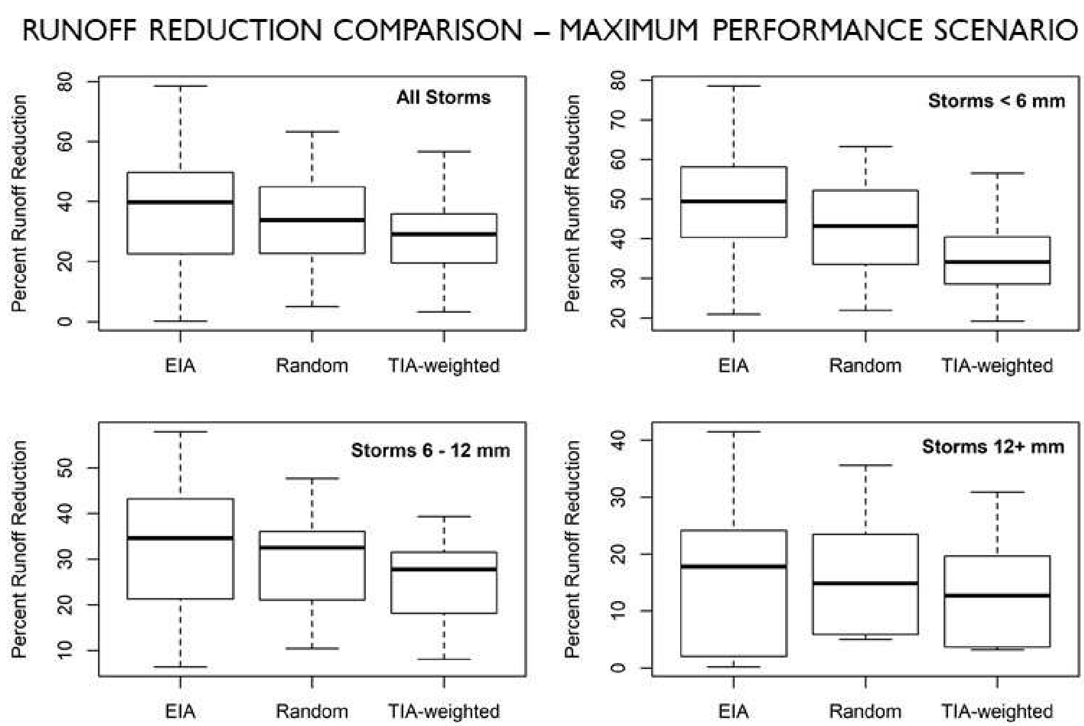

Figure 8. Comparison of EIA-siting to maximum values of runoff reduction for alternative strategies.

For smaller events (less than 6 mm), runoff reduction is highest when practices are placed according to spatially-identified EIA with a mean runoff reduction of 49.2%. Runoff from connected impervious surfaces during such events is well-handled by the modeled bioretention cells and precipitation is sufficiently small that pervious areas do not likely produce substantial runoff, if any. This is important to note when you consider that the higher frequency of runoff from smaller storm events is one of the indicators of urban hydrologic regime shift. Substantially greater runoff reduction for small storm events using EIA-focused placement may have a large impact on decreasing runoff frequency overall. While runoff would not be eliminated entirely, the amount would be negligible considering the size of the events.

Table 5. Summary of Wilcoxon signed-rank tests for maximum runoff reductions between GI siting strategy overall and for storm size groupings.

Storm Events	Comparison	Statistical Difference (p-value)	Pseudo-Median Difference	95 % Confidence Interval	
				Lower Bound	Upper Bound
All Storms	EIA to Random	< 0.001	4.24	2.37	5.40
	EIA to TIA-weighted	< 0.001	10.05	7.67	12.48
	Random to TIA-weighted	< 0.001	5.70	4.37	6.98
Storms < 6 mm	EIA to Random	< 0.001	5.76	4.85	8.78
	EIA to TIA-weighted	< 0.001	14.72	12.18	16.74
	Random to TIA-weighted	< 0.001	7.80	6.23	9.59
Storms 6–12 mm	EIA to Random	0.15	No statistical difference at α = 0.05		
	EIA to TIA-weighted	0.010	7.09	3.07	11.70
	Random to TIA-weighted	< 0.001	4.23	3.21	6.59

Storms 12+ mm	EIA to Random	0.820	No statistical difference at α = 0.05		
	EIA to TIA-weighted	0.055	No statistical difference at α = 0.05		
	Random to TIA-weighted	0.004	3.19	2.07	4.41

For intermediate events greater than 6 mm but less than 12 mm, runoff reduction using EIA-focused siting was greater than the maximum TIA-weighted scenarios with an average runoff reduction of 32.2%, but not statistically higher overall than the maximum runoff reductions for Random siting scenarios. While results were inconclusive for this intermediate range of storm sizes, a comparison of EIA runoff reductions and median runoff reductions for alternate strategies indicate that on average, less-spatially informed strategies resulted in approximately 7% less runoff reduction ($\alpha < 0.01$) on average. Runoff reductions for these intermediate storm events were moderately greater for the EIA treatment scenario, though with diminishing returns relative to the smallest storms. Events in this size range are typically frequent, especially in more humid climates like the southeastern United States. Full treatment of all EIA with distributed practices could thus reduce runoff by greater than 30% annually for storms less than 12 mm in size. While the magnitude of this reduction overall would be dependent on local precipitation frequencies, it could represent a substantial amount of annual runoff reduction if a larger percentage of storm events for a given urban watershed were in this range.

When rainfall exceeded 12 mm, runoff reductions appear to be greater when using EIA-focused siting based on mean and median percent reduction statistics (Table 4). However, there was not a statistically significant difference in storm event runoff reduction between siting strategies at the $\alpha = 0.05$ confidence level. There was greater variability in runoff reductions for EIA treatment scenarios for these larger storm events than for the other storm size groupings, and this is also evident in the Random and TIA-weighted treatment scenarios. One possible explanation for this could be the influence of antecedent moisture conditions and pervious areas on runoff production for larger storm events in the SWMM model. When rainfall exceeds infiltrative capacity, pervious areas begin to produce runoff, and this is more likely to occur for larger storm events. Further, infiltrative capacity for pervious areas ranges based on soil moisture conditions and thus varies by storm event depending on recent rainfall. This could also be related to performance of the bioretention cells as well for the same reasons since previous saturation may cause these practices to handle less runoff for storms falling in close temporal succession

Runoff from impervious areas routed onto pervious areas (as in the case of non-EIA portions of the watershed) would additionally influence soil saturation and further increase runoff from pervious areas for larger events. For the EIA treatment, all runoff from non-EIA is routed to pervious areas without treatment. For larger storms, and especially those falling when soil saturation is higher due to recent rainfall, all runoff from these non-EIA areas is routed to pervious areas in the SWMM model, which may produce runoff for these events. This effect would be lessened in the random and TIA-weighted scenarios which treat a portion of non-EIA runoff and thus would contribute less to intra-event pervious saturation. For larger storms, surface runoff thus becomes the sum of interactions between pervious conditions and surface runoff routing from different portions of the TIA that are subject to a range in antecedent moisture conditions. Treatment location may become secondary to simply the level of treatment for maximum runoff reductions as pervious influences impact surface runoff more for these larger events. This is also influenced by model parameterization and the scale of subcatchment disaggregation. While the results of the study are specific to the specific watersheds, they do indicate some advantage in targeting EIA with GI practices over other siting strategies, though the magnitude in other watersheds may be unclear. Despite this, the results highlight important foci for research development in urban stormwater management planning and areas where improved data and model representation may be warranted.

3.4 Limitations and Sources for Error

Table 6 provides a summary of important assumptions, uncertainties, and sources of error in this study. Acknowledgement of the limitations of these findings serves to point to important opportunities for future research that this study hoped to illuminate. While many of these have already been discussed throughout the text, it is important to consider them together as they can have a compounding effect on the results. Each of the items in Table 6 point to further lines of inquiry as watershed managers continue to improve data collection and modeling efforts in support of urban watershed management.

Table 6. Summary of relevant sources for error in this study.

Potential Source of Error	Description	Impacts on Results
Spatial Rainfall Variability	Thiessen-polygons may not accurately capture the distribution of rainfall over the watershed based on differences in observed rainfall at 3 gage locations	Rainfall estimates used in EIA estimation may bias foundational numerical targets of study
Hydrograph Separation	Baseflow and interflow components are difficult to separate from surface derived runoff	Runoff depths used for EIA estimation and model fitting may not accurately represent surface runoff well
Storm Event Selection	Focused screening of storm events in the record based on size and compact temporal distribution of rainfall and single-peaked hydrologic response	May bias results and conclusions to a smaller subset of realized storm events
EIA Quantity Estimate	Graphical analysis is subject to accuracy of data (rainfall and runoff, as discussed above)	Results may be biased based on data accuracy
EIA Spatial Identification	Spatial EIA determination by new methodology is not well-vetted or easily verified	Results and Conclusions may be influenced by incorrect spatial distribution of EIA
SWMM Parameterization	Literature values may not apply to specific site hydrology or land cover	Model may not reflect realistic hydrologic characteristics of watershed
Subcatchment Scale	The size and resolution of subcatchments may not match process scale of impervious runoff connectivity and GI applications	Simple model calibration may be associated with some level of equifinality
Lack of Groundwater in SWMM model	Shallow surface runoff and groundwater interactions are not accounted for	Runoff reductions focusing on surface runoff may not provide the full hydrologic effect of GI and pervious runoff processes
Uniform Bioretention Cell Parameters	Certain GI types may not be applicable or feasible in all locations; multiple practices may not behave ideally in series or parallel compared to lumped	Runoff reductions might be very different given more fine-resolution of system drainage, GI type, and treatment train

SWMM LID representation	SWMM model representation of GI may not be adequate to capture GI practice performance	Results may demonstrate less or more runoff reduction and impacts on hydrology than actual practices may attain in-situ

3.5 Modeling Considerations and Further Opportunities

While the results of this study indicate that utilizing spatial EIA information for GI practice placement can result in greater runoff reduction, some considerations should be made regarding model representation in Table 6 that will point to areas for further study. This modeling exercise utilized a single idealized bioretention cell for EIA and non-EIA areas to represent runoff reduction potential given watershed wide application. However, the routing of runoff deriving from EIA and non-EIA areas needs to be further studied considering the results for runoff reduction from larger storms. Model results suggests interactive effects in surface runoff processes (as modeled) that may be at play in urban hydrology, however it could also be a function of the modeling structure itself or possibly the scale of subcatchment disaggregation and representation. Realistic application of GI practices in this watershed would likely necessitate the disaggregation of the idealized bioretention cells into smaller units that were further distributed within each subcatchment, i.e., modeling at a finer scale for both the GI practices and their contributing watersheds. To holistically model this interactivity at the watershed scale, investigation of the relationship between groundwater conditions and surface runoff may also be warranted. Additionally, bioretention may not always be the most applicable or feasible type of GI for all areas. Detention-based GI may be more effective than infiltrative practices given certain site conditions and objectives, and vice versa. The use of a single type of GI practice with uniform design might be expanded in the future to assess how different GI types and designs might perform in conjunction with the additional information on runoff routing that is offered by the high-resolution EIA data.

Another consideration is the feasibility for GI retrofits in areas identified as EIA. Placement of GI where EIA has been identified may not always be feasible due to site constraints not identified by the spatial model. This could be related to poor infiltration rates, difficult topography, or adequate space. For the First Creek watershed, 3.1% of the watershed was identified as EIA in the public domain, less than half of the total EIA. Targeting these areas first for any GI retrofit efforts in the watershed would be a good strategy to begin implementation of distributed restoration efforts based on these modeling results. This would represent the intersection of opportunistic GI applications with spatially-informed siting that would provide watershed managers with the best hydrologic benefit for the watershed using readily available spaces for distributed restoration. Spatial EIA models could then be revised given the added GI to reassess impervious connectivity and further identify areas where runoff reductions would be greatest given the disconnection of those where GI has been established over the timeline of implementation.

4. Conclusions

There is a need to prioritize areas for GI retrofits in urban watersheds that enable cities to place (often limited) resources in areas where they will have the greatest impact on urban streams. Watershed assessment using high-resolution geospatial data can provide robust information concerning priority areas for distributed watershed restoration when coupled with hydrologic information. Modeling that incorporates the best information from both of these sources can be used to assess management options and refine approaches in order to optimize results for urban watershed improvement. The results of this study indicate that spatial EIA information can be applied to a SWMM model to adequately predict surface runoff using literature-based parameters with simple manual calibration. The calibrated model was used to investigate three GI placement scenarios. The strategy specifically targeting EIA within the watershed showed moderate differences in runoff reduction compared to more random GI placement strategies which treated both EIA and less-connected portions of TIA. The EIA based strategy was estimated to average approximately 37% runoff reduction over all storm events at about 10% more than the other two methods. However, the difference between the siting strategies weakened as storm size increased, indicating that treating effective impervious area is most advantageous for mitigating small, frequent rainfall events. Further study is warranted, in particular on watersheds with varying impervious connectivity, and especially those with a very high EIA/TIA ratio or where GI opportunities are constrained by dense development. These results highlight the importance of focusing GI applications to areas identified as EIA to optimize urban hydrologic benefits and point to how this methodology can help watershed managers prioritize restoration efforts. Further investigation with higher-resolution runoff modeling should lead to management recommendations that fully account for the spatial variability of urban runoff production, but this initial study demonstrates that the utilization of spatially-identified EIA data can be used as a basis for GI retrofit siting when runoff reduction is the primary objective.

4.1 Acknowledgements

The authors would like to acknowledge employees at the City of Knoxville Stormwater Engineering for providing data and models that form the basis of this study. This material is based upon work supported by the National Science Foundation under Grant Nos. 1634975 and 1553475.

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