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Distributed Stormwater Controls for Flood Mitigation within Highly Urbanized Watersheds: Case Study for the Rocky Branch Watershed in Columbia, SC USA

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Abstract

For highly urbanized watersheds where space is limited, distributed Low Impact Development (LID) stormwater controls could offer an effective retrofit measure for addressing flooding problems. The objective of this study is to determine the feasibility of using distributed LID controls within an urbanized watershed for flood mitigation. The Rocky Branch watershed in Columbia, SC is an excellent case study because it experiences flash floods on an annual basis and has limited space for traditional, centralized stormwater controls to mitigate these floods. The Storm Water Management Model (SWMM) was used to model flooding and rain gardens were selected as the LID approach for flood mitigation due to their storage potential. Results of the study suggest that rain gardens with 30 cm berm heights and a total area equal to 20% of the impervious surfaces within the watershed would provide sufficient storage to mitigate up to and including a 10-year storm event. Once sufficient storage is available, the challenge is diverting runoff generated from impervious surfaces into rain gardens. Results of this study suggest that approximately 15, 27, and 38% of the runoff generated from impervious surfaces would need to be diverted to the rain gardens in order to mitigate flooding from a 2, 5, and 10-year storm event, respectively. Given prior work on adoption of LID approaches for other watersheds, rain gardens could be effective at mitigating up to a 5-year storm event within the watershed, although further research on possible adoption rates in the study watershed is needed to more fully support this claim.

Introduction

Low Impact Development (LID) approaches are drawing increased attention in stormwater management (Dietz, 2007). LID as a concept integrates land development and environmental concerns with the goal of minimizing the negative impacts of land development on the environment (Davis, 2005). LID approaches differ from traditional stormwater management approaches in a number of key ways including (i) they seek to minimize disturbance of the site, (ii) they emphasize maintaining the pre-development runoff volume rather than mitigation of peak flow rates alone, and, a primary focus of this study, (iii) they empathize decentralized, small-scale controls for runoff infiltration, storage, and detention (Abi Aad et al., 2010; Dietz, 2007). One of the more commonly used LID approaches for stormwater management is bioretention technology (e.g., bioinfiltration and rain gardens) (Davis et al., 2009). For flood mitigation in particular, which is the focus of this work, rain gardens have been found to be an effective LID approach given their ability to store and infiltrate runoff (Abi Aad et al., 2010).

Most research on the application of LID approaches has been for new developments rather than as a retrofit measure in urbanized watershed (e.g., Bedan and Clausen, 2009; Line et al., 2014). Some studies have taken a watershed-scale perspective looking at paired-basins where one basin has LID approaches for stormwater management and the other basin has traditional stormwater best management practices (BMPs). These studies concluded LID techniques are more effective at reducing runoff volumes (Bedan and Clausen, 2009; Selbig and Bannerman, 2008), which suggests they could be useful as a retrofit measure for urbanized watersheds. However, while important for new developments, these studies have some limitations in that they do not directly address the potential to use LID approaches as retrofit measures in urbanized watersheds and they focus on relatively small watersheds (less than 1 km^2).

Only a few studies have looked into the effectiveness of distributed stormwater controls at a watershed-scale in an urbanized setting. Loperfid et al. (2014) analyzed data from different watersheds in suburban Washington, DC and suggested that, during extreme precipitation events, distributed BMPs are effective at reducing runoff volumes. A related study investigated the potential for LID techniques to mitigate changes in precipitation projected under climate change scenarios for New York City found that retrofits with LID controls have a significant impact on reducing peak flows and runoff volumes (Zahmatkesh et al., 2015). This conclusion was supported by a study in Wilmington, North Carolina that showed stormwater control measures used as retrofits could have a hydrologic impact by reducing the runoff coefficient and the peak discharge from storm events (Page et al., 2015). Lastly, research in a suburban watershed in Cincinnati, Ohio showed evidence that the adoption of rain gardens and barrels at the parcel level had a significant effect on the watershed hydrology (Shuster and Rhea, 2013).

The purpose of this study is to improving understanding of distributed stormwater controls as a retrofit measure within urbanized watersheds. Shuster and Rhea (2013) showed that the adoption of distributed stormwater controls in urbanized watersheds can significantly reduce runoff volumes, but questions remain as to the potential of distributed stormwater controls for mitigating existing flooding problems within urbanized watersheds. For example, the Rocky Branch Watershed in Columbia, SC faces a recurrent flooding problem that, unfortunately, is common in many other older cities with insufficient stormwater controls. The objective of this study is to understand whether distributed stormwater controls could be used to mitigate the flooding problem facing Rocky Branch. More specifically, the objective is to determine how much total rain garden volume is needed for storage and how much runoff generated from impervious surfaces must be diverted to rain gardens in order to mitigate flooding for storms with different return periods.

Study Area

The Rocky Branch watershed is approximately 10.75 km^2 and is located in downtown Columbia, South Carolina, USA (Figure 1). Rocky Branch is approximately 6.5 km long and discharges into the Congaree River. The watershed has long experienced recurrent flooding problems, in particular in a low-lying commercial district called Five Points (highlighted in Figure 1a). Flooding typically occurs during intense summer thunderstorms. There have been significant efforts to mitigate these flooding problems using stormwater controls, but flooding still occurs on a regular (approximately annual) interval (Monk and Holleman, 2010; NOAA, 2010; Santaella and Gillbert, 2011; The State, 2014, 2012; WIS TV, 2015). The headwaters include residential communities and a portion of the University of South Carolina campus where it would be feasible to install rain gardens as stormwater controls.

Due to the high percentage of impervious surfaces and steep slopes from being located on the fall line, Rocky Branch has a very flashy response to rainfall events. The time to peak for an observed storm event that caused flooding at the Pickens St. station (shown in Figure 1) was approximately 1 hour. According to the 2011 National Land Cover Dataset (NLCD), 97% of the watershed is developed (17% high intensity, 37% medium intensity, 31% low intensity, and 12% developed open space) and much of the watershed is impervious (Figure 1b). Taking just the impervious surfaces within the watershed, the maximum slope is 42% and approximately one-fifth of the area has a slope greater than 5%. It is well known that impervious surfaces, and in particular connected impervious surfaces, increase runoff and flooding if not mitigated through stormwater controls and best management practices (BMPs) (Arnold Jr and Gibbons, 1996; Lee and Heaney, 2003; Roesner and Urbona, 1998; Schueler, 1995).

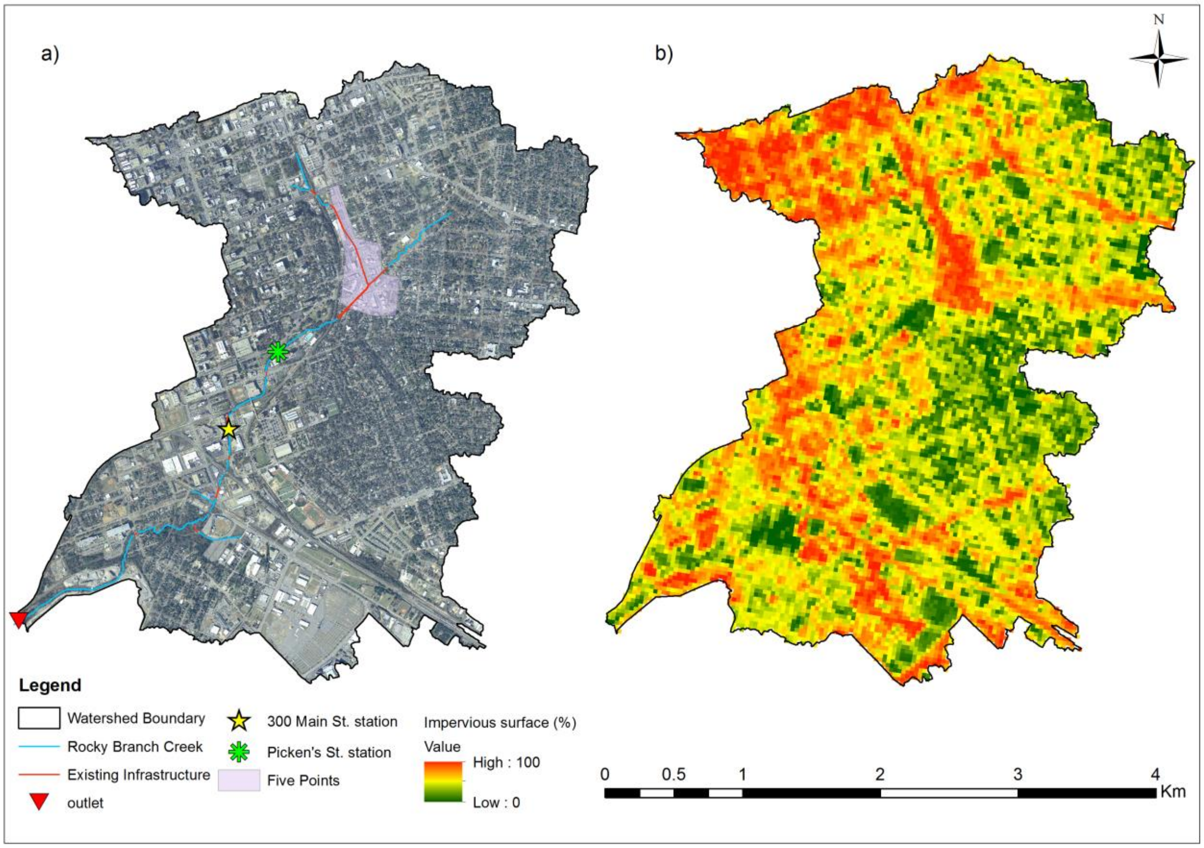


Figure 1. a) The Rocky Branch watershed in downtown Columbia, SC USA. b) Impervious surfaces according to the NLCD (Data Sources: The orthoimagery was collected on March, 2014 and obtained through the USGS National Map; The impervious surfaces layer was obtained through the 2011 NLCD)

Materials and Methods

Model Description and Setup

The EPA's Storm Water Management Model (SWMM) version 5.0.022 was used to model the stormwater runoff. SWMM is a dynamic, open source computer model that tracks the quantity and quality of the runoff in urban watersheds for either single event or continuous simulations (Rossman, 2012). SWMM routes runoff from subcatchments through a network system consisting of pipes, channels, storage/treatment devices, pumps, and regulators. SWMM is widely used and appropriate for this study because of its ability to model urban watersheds and the hydrologic performance of specific LID implementations.

The SWMM model simulates three primary processes: infiltration, surface runoff, and flow routing. The infiltration method used is an approach adopted from National Resource Conservation Service (NRCS) CN method for estimating runoff. Manning's equation was used for overland flow. The dynamic wave routing method was used for channel routing because it has the ability of accounting for channel storage, backwater, entrance/exist losses, flow reversal, and pressurized flow. This method solves the one-dimensional Saint Venant flow equations, which consist of the continuity and momentum equations for the conduit and a volume continuity equation at nodes that allows to represent a full closed conduit pressurized flow.

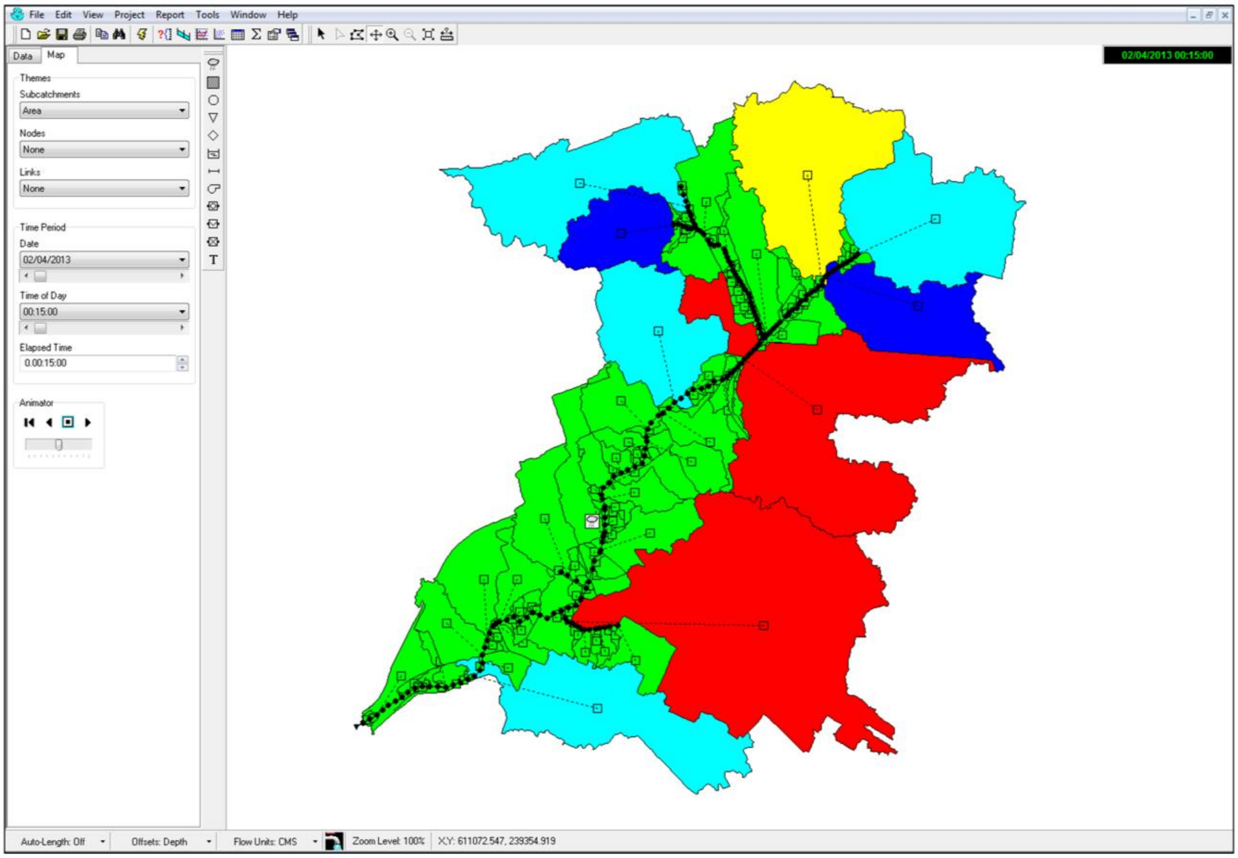
Rain gardens were selected as the LID implementation because they could be adopted widely within the watershed and offer significant storage and volume reduction capacity. The rain garden properties and characteristics were obtained from three resources: Wisconsin Department of Natural Resources Conservation Practice Standard (Bannerman and Considine, 2003), Maryland 2000 Stormwater Management Design Manual (MDE2000) (Schueler and Claytor, 2000), and Delaware Green Technologies Design Manual and Model (DNREC2005). Lucas (2004) includes easy to follow guidance for siting, sizing, installing, and planting a rain garden. A rain garden consists of three layers: surface, soil, and storage (Table 1). In the model, the total depth used for the soil and storage layers are 1200 mm, which is the maximum recommended depth, while the surface layer storage depth (ponding depth) is varied between the minimum and maximum recommended depths of 10 and 30 cm.

Table 1. Specifications and characteristics of rain gardens to be implemented in Rocky Branch Watershed

Layer/Parameter	Value
Surface	
Storage depth (mm)	100 - 300
Vegetation (volume fraction)	0.5
Surface roughness	0
Surface slope	0
Soil	
Soil thickness (mm)	900
Porosity	0.44
Field capacity	0.15
Wilting point (volume fraction)	0.1
Conductivity (mm/h)	30
Conductivity slope	10
Suction head (mm)	60
Storage	
Storage height (mm)	300
Storage void ratio	0.75
Storage conductivity (mm/h)	250

Data Preparation

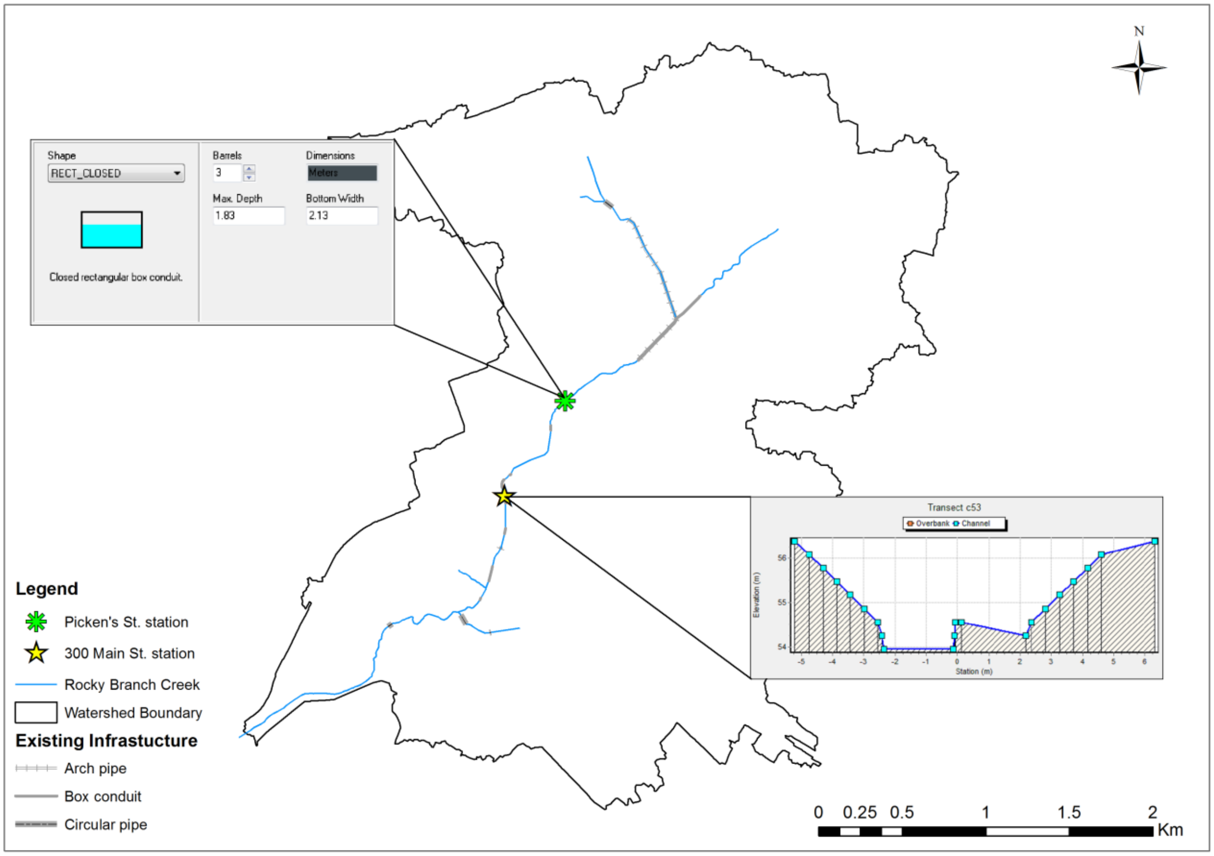
The Rocky Branch watershed was delineated into 134 subcatchments using a LiDAR-derived 3 m resolution Digital Elevation Model (DEM) (Figure 2). The discretization was done by placing subcatchment outlets at 50 m intervals along natural (irregular) portions and at 30 m intervals along the concrete-lined and conduit portions of the stream channel. Stormwater inlets along the streamline were also designated as subcatchment outlets. Standard GIS procedures were used to delineate the subcatchment boundaries. The delineated subcatchments were verified by available orthoimagery data.



Subcatchments: Area
Nodes: None
Links: None
Date: 02/04/2013
Time of Day: 00:15:00
Elapsed Time: 0.00:15:00
Auto-Length: Off
Offsets: Depth
Flow Units: CMS
Zoom Level: 100%
X,Y: 611072.547, 239354.919

Figure 2. Depiction of the Rocky Branch watershed in the SWMM model with 134 subcatchments and 188 conduits

Rocky Branch consists of natural (irregular) channels, pipe sections, and concrete-lined channels that were represented in the model as 188 conduits (Figure 3). The Manning's roughness coefficient for the natural cross sections was assumed to be between 0.03 and 0.04, while the Manning's roughness coefficient of the concrete lining cross sections was assumed to be between 0.011 and 0.015. The pipe sections include circular, box, and arch cross sections. Each of the 188 conduits in the model was assigned a cross section profile. The cross section profiles were obtained from a combination of LiDAR and on ground survey data, and a sample were verified by site visits. Figure 3 shows example cross sections as they appear within the model for the two locations along the branch where there are stream gauges.



Shape: RECT_CLOSED
Barrels: 3
Dimensions: Meters
Max. Depth: 1.83
Bottom Width: 2.13
Closed rectangular box conduit.

Figure 3. Rocky Branch showing stormwater infrastructure lines and cross section types. Example cross-sections are shown for the two stream gauge locations.

Land use, soils, slope, and curve number (CN) values were derived using publically available geospatial datasets and geographical information system (GIS) processing. Land use and imperviousness datasets were obtained from the NLCD 2006 (Fry et al., 2011), the latest available version at the time of the initial model development activities. The 2011 and 2006 NLCD data were compared and no significant differences were found for the study area. NCLD are raster data where each pixel is 30m by 30m. The Soil Survey Geographic (SSURGO) datasets were downloaded from the U.S. Department of Agriculture for Richland County, SC (SSURGO, 2012). The SSURGO dataset is a vector polygon dataset with attributes describing soil properties including Soil Hydrologic Groups. According to this data, 72% of the watershed area is Group B soils, 22% Group A, and 6% Group C. The land use and soils data were used to derive CN values for each subcatchment using NRCS values (Cronshey, 1986) and the processing steps shown in Figure 4. Finally, average slopes for each subcatchment were obtained using the DEM used for watershed delineation.

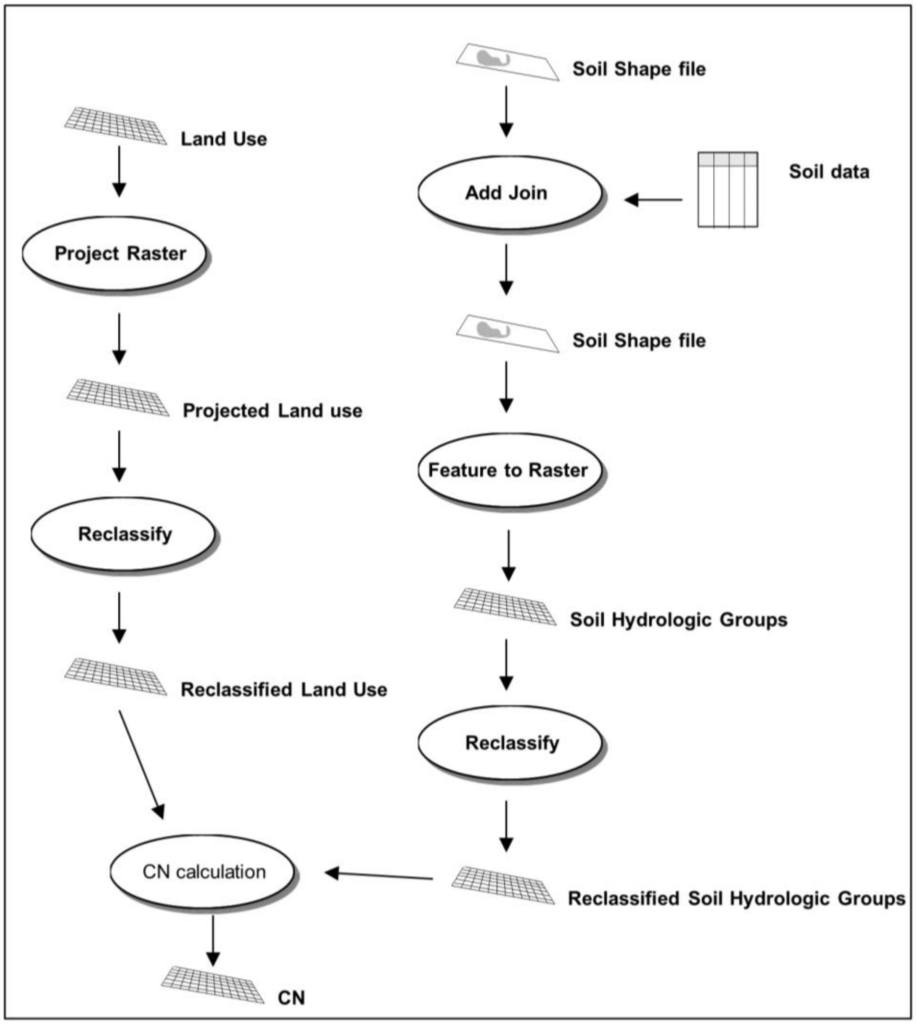


Figure 4. GIS workflow for CN computation using land use and soil hydrologic group datasets

Observed Storm Events

Rainfall data were collected during the study period June 2012 - June 2013 using a tipping bucket gauge (TR-525USW) located at the University of South Carolina’s 300 Main

Street engineering building (Figure 1a). The factory calibration of the gauge is 0.1 mm per tip. The gauge was connected to an electronic data logger (Sutron 8210A Data Collection Platform). The gauge was installed in a clear and unobstructed mounting location. Stage was measured at the 300 Main Street station for the study period using a bubbler water level gauge (Sutron 8210A). Stage and streamflow data were obtained from the USGS (station number 02169505) for the Pickens Street station. This streamflow data was obtained using an Acoustic Doppler Current Profiler (ADCP) (Levesque and Oberg, 2012). Figures 5 and 6 show the observed data for two rainfall events at the two stations: the July 10, 2012 storm that caused flooding and the February 7, 2013 storm that did not cause flooding. Baseflow at the start of the storm events, which is typically very low, was subtracted from the hydrographs for easier comparison between storm events.

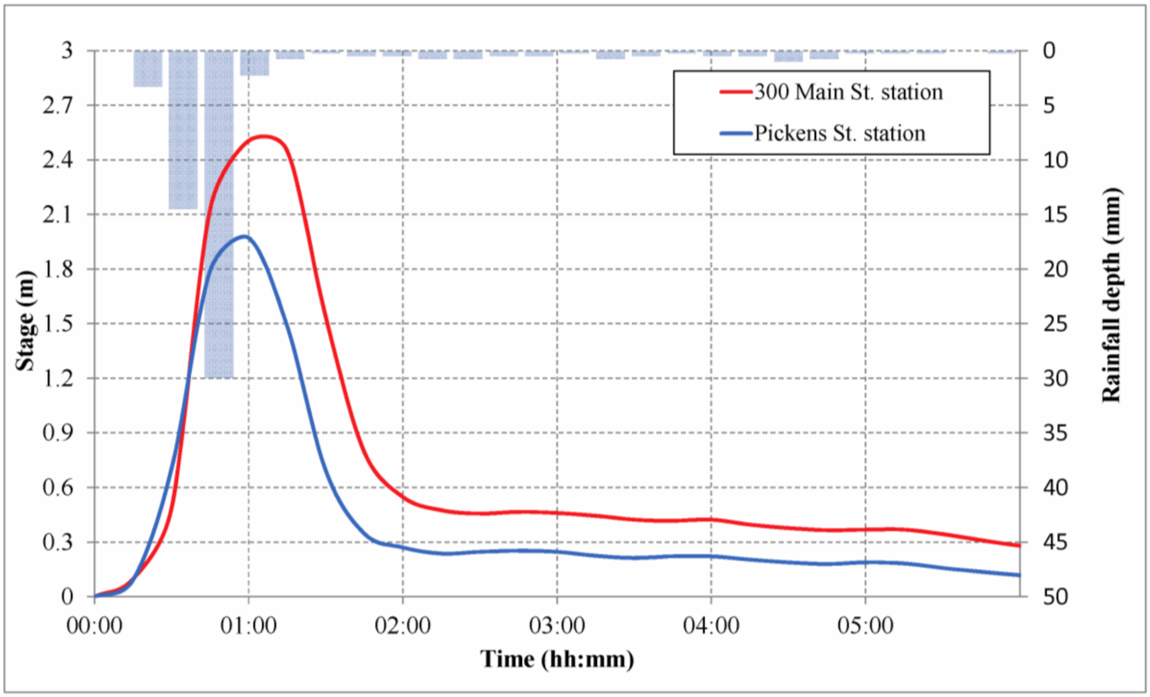


Figure 5. Rainfall intensity and corresponding stage for the July 10, 2012 event

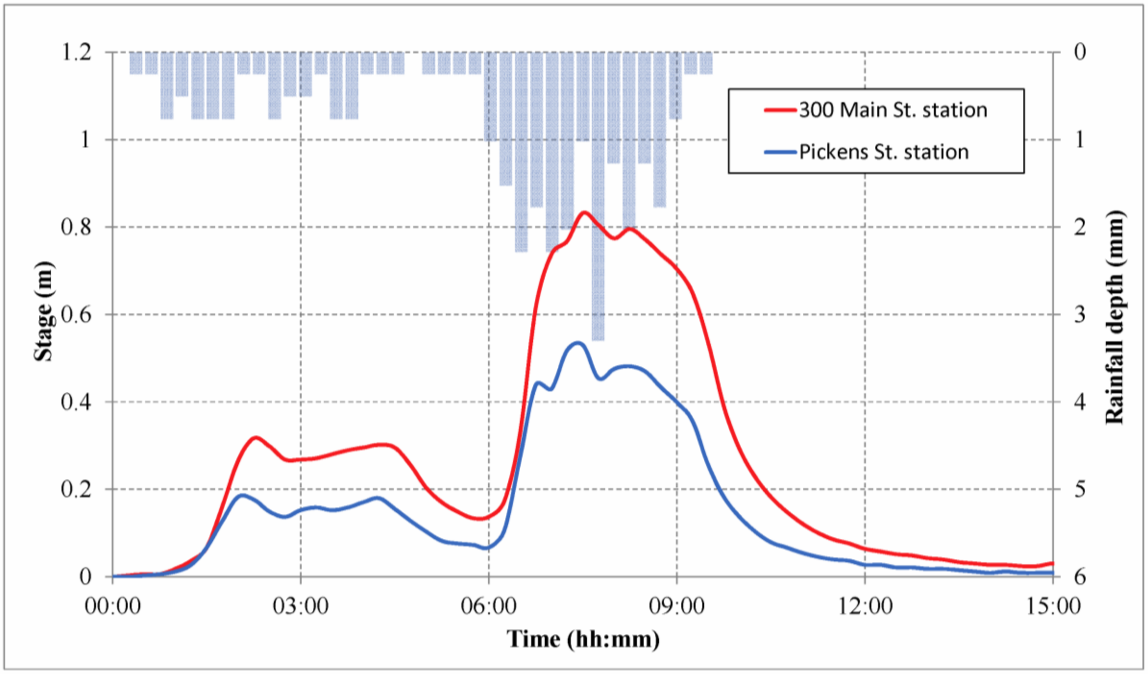


Figure 6. Rainfall intensity and channel stage for the February 7, 2013 event

Model Calibration and Evaluation

Model calibration was conducted using the subcatchment CN values as the calibration parameter. Each subcatchment in the study area was assigned a specific CN value using the workflow presented in Figure 4. The CN values were uniformly changed by a percent increase or decrease while also insuring the adjusted values were within the allowable range of 25 to 98. The objective of the calibration was to minimize relative error between observed and modeled stream stage and flow peaks available at the two gauging locations. This was done for three of the six observed storm events (Table 2) using a manual calibration procedure that prioritized accuracy for the large storm event on July 11, 2012 that caused flooding. The three storms selected for calibration were chosen to cover different rainfall depths, durations, and seasons. The calibrated model was evaluated by comparing predicted and observed peak flow and stage values for the remaining three observed storm events. The results of the model calibration and evaluation are described in the Results and Discussion section.

Table 2. Properties of observed storm events used for model calibration and evaluation

Storm date	Duration (hh:mm)	Cumulative rainfall depth (mm)
7/11/12	00:55	35.05
9/04/12	04:23	10.41
2/07/13	09:40	33.02
7/10/12	01:02	50.29
8/20/12	06:33	16.26
9/18/12	01:09	7.37

Model Scenarios

Three model scenarios were conducted to better understand the relationship between the modeled peak stage and three key model variables: ponding depth, rain garden area, and diverted runoff. **Ponding depth** is the maximum depth water can pond in the rain garden before overflowing (i.e., the rain garden berm height). **Rain garden area** is the total rain garden area as a percentage of the watershed impervious area. Together, these two variables control each rain garden's storage potential. **Diverted runoff** is the percentage of the runoff generated from impervious surfaces that is diverted to rain gardens. Three general scenarios were conducted in the study.

Scenario 1: Assume 100% diverted runoff meaning all runoff generated on impervious surfaces is diverted to rain garden (best case scenario). Model the reduction in stage at the 300 Main St. station for the July 10, 2012 event if rain gardens equaled 10% and then 20% of the impervious surface area.

Scenario 2: Let ponding depth vary between 20 and 30 cm and rain garden area vary from 15 to 30% of the impervious surfaces in the watershed. Use the model to determine the diverted runoff required to reduce the peak stage at the 300 Main St. station below bank overflow stage for these various combinations of ponding depth and rain garden area.

Scenario 3: Assume ponding depth equals 30 cm for maximum storage potential. Use the model to determine the combination of rain garden area and diverted runoff required to reduce peak stage at the 300 Main St. station below bank overflow stage for larger storm events (5 to 50 year return periods).

According to the Precipitation Frequency Data Server (PFDS) and using the COLUMBIA UNIV OF SC, 38-1944 station, the July 10, 2012 storm was equivalent to a 2-year, 1-hour event (Bonnin et al., 2006). We used information from PFDS to upscale the July 11, 2012 event to 5-, 10-, 25-, and 50-year, 1-hour duration synthetic events.

Results and Discussion

Model Calibration and Evaluation

The final calibration resulted in the CN values for all subwatersheds being reduced by 15% from their initial value uniformly throughout the watershed. This calibration resulted in the July 10, 2012 event having the lowest error with the two stage depth predictions within 1% relative error and the discharge within 8% relative error (Table 3). The relative errors were greater for the other two storms used in the calibration stage. The highest relative errors were for the September 4, 2012 event at the Pickens Street monitoring station with relative errors of 30-35% for both stage and flow. For the same event, the stage relative error was only 8% for the 300 Main St. station. The September 4, 2012 was a relatively minor event so this was deemed acceptable error given that the primary objective was to match the larger July 10, 2012 storm event that actually resulted in flooding.

Three independent storm events not considered when calibrating the model were used for evaluating the model. Results of the model evaluation show the relative errors of both stage and discharge were less than 12% for two of the three storm events (Table 3). The third storm, which occurred on August 20, 2012, had higher relative errors showing the model under-predicted both stage and flow at both observation stations for this event. A likely explanation for this is differences in antecedent moisture conditions (AMC) between the August 20, 2012 storm and the other two storm events. The model assumes normal AMC, which is consistent with the two storms that had lower relative errors. Rainfall records for the five days prior to the August 20, 2012, however, suggest wet AMC. To account for this, CN parameters in the model for the August 20, 2012 storm could be adjusted to account for wet AMC conditions, and this would reduce the relative error because it would increase the amount of runoff predicted by the model. Given that the model scenarios performed in this study assume normal AMC, the model was considered acceptable for the purposes of the study.

Table 3. Relative error between modeled and observed channel stage and flow at two stations for storm events used in model calibration and evaluation

	Calibration			**Evaluation**		
Storm events	7/11/12	9/04/12	2/07/13	7/10/12	8/20/12	9/18/12
<u>300 Main St. Station</u>						
Stage (m)						
Observed	1.63	0.70	0.84	2.45	0.79	0.66
Modeled	1.62	0.76	0.78	2.15	0.58	0.59
Relative error (%)	-0.65	8.88	-7.58	-12.17	-26.81	-10.14
<u>Pickens St. Station</u>						
Stage (m)						
Observed	1.33	0.38	0.53	1.97	0.50	0.27
Modeled	1.34	0.51	0.46	2.05	0.27	0.27
Relative error (%)	1.06	33.60	-12.66	4.02	-45.73	-2.22
Flow (m3/s)						
Observed	22.80	3.05	5.00	-	4.65	2.80
Modeled	24.61	4.13	5.46	38.35	3.05	2.76
Relative error (%)	7.95	35.36	9.27	-	-34.46	-1.31

Impact of Rain Garden Area on Flood Mitigation

Figure 7 show results from the first model scenario. Here the channel stage for the July 10, 2012 event at the Main Street monitoring station is reduced through the introduction of rain gardens into the watershed. The cases where rain garden area equals 10% and 20% of the watershed impervious area are presented. The results suggest that including rain gardens in the watershed with a total area just above 10% of the impervious area within the watershed would reduce the peak stage to below bank full conditions. If the rain garden area increased to be 20% of the impervious area within the watershed, then the flood peak would be further reduced to approximately 0.2 m below the bank full stage. Prior studies and guidelines focusing on the water quality and groundwater recharge benefits of rain gardens suggest rain garden areas of 10-

20% of the impervious area within a watershed (University of Wisconsin Guidelines, http://www.bioretention.com/recarga.html; Dussaillant et al., 2004), which interestingly would also be sufficient for flood control in this scenario.

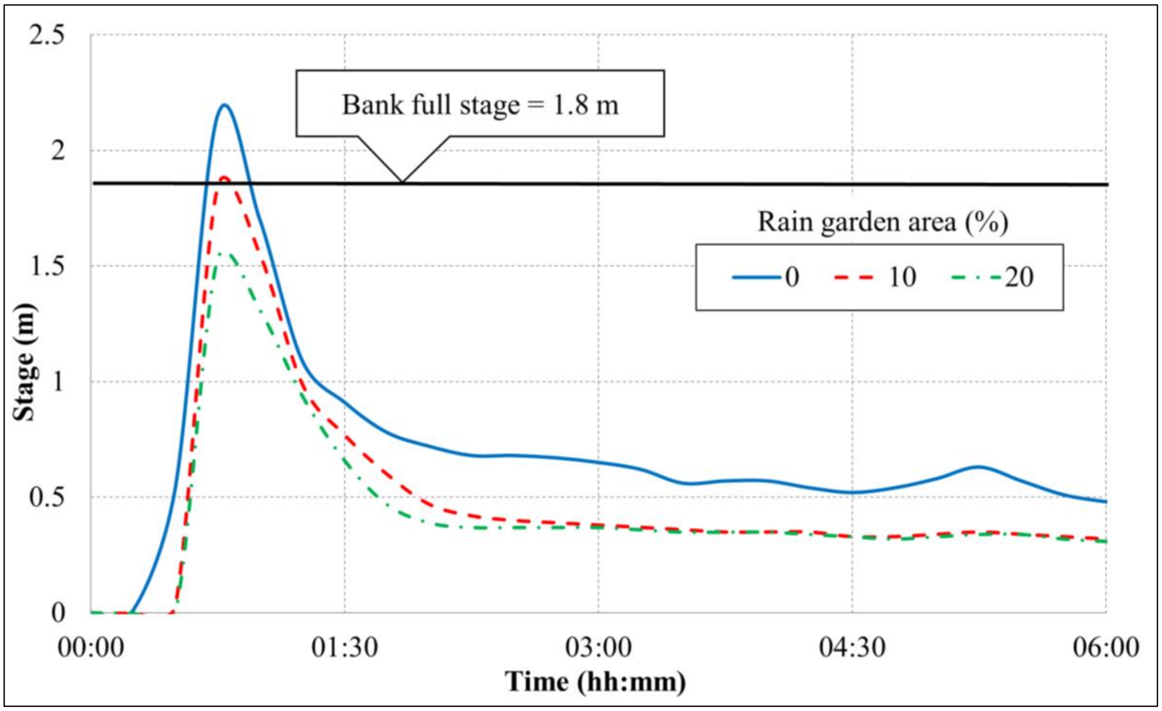


Figure 7: Simulated reduction in channel stage for the July 10, 2012 storm event at 300 Main St. through introduction of rain gardens into the watershed

Runoff Contribution to Rain Gardens for Flood Mitigation

Results from the second model scenario show the relationship between rain garden area, diverted runoff, and ponding depth for mitigating the July 10, 2012 flood event (Figure 8). As an example, consider the case from the prior analysis where ponding depth was equal to 10 cm and the rain garden area was equal to 10% of impervious surfaces. Figure 8 shows that the required diverted runoff for flood mitigation is equivalent to that found before: 100% of the runoff from impervious surface would need to be diverted to the rain gardens. When the rain garden area is increased to 20%, the diverted runoff required for flood mitigation decreases significantly to only

20%. This result shows the importance of sufficient rain garden storage to capture excess runoff volume. Figure 8 also shows that, once sufficient storage is achieved either from increasing the ponding depth or increasing the rain garden area, the diverted runoff needed to mitigate flooding approaches approximately 15% for this storm event. This 15% represents the runoff reduction required to mitigate flooding for the July 10, 2012 storm event. Finally, Figure 8 shows that if a ponding depth of 30 cm is used, then the required storage volume is achieved with rain garden area of 20% and no additional rain garden area is needed to mitigate flooding from this storm event.

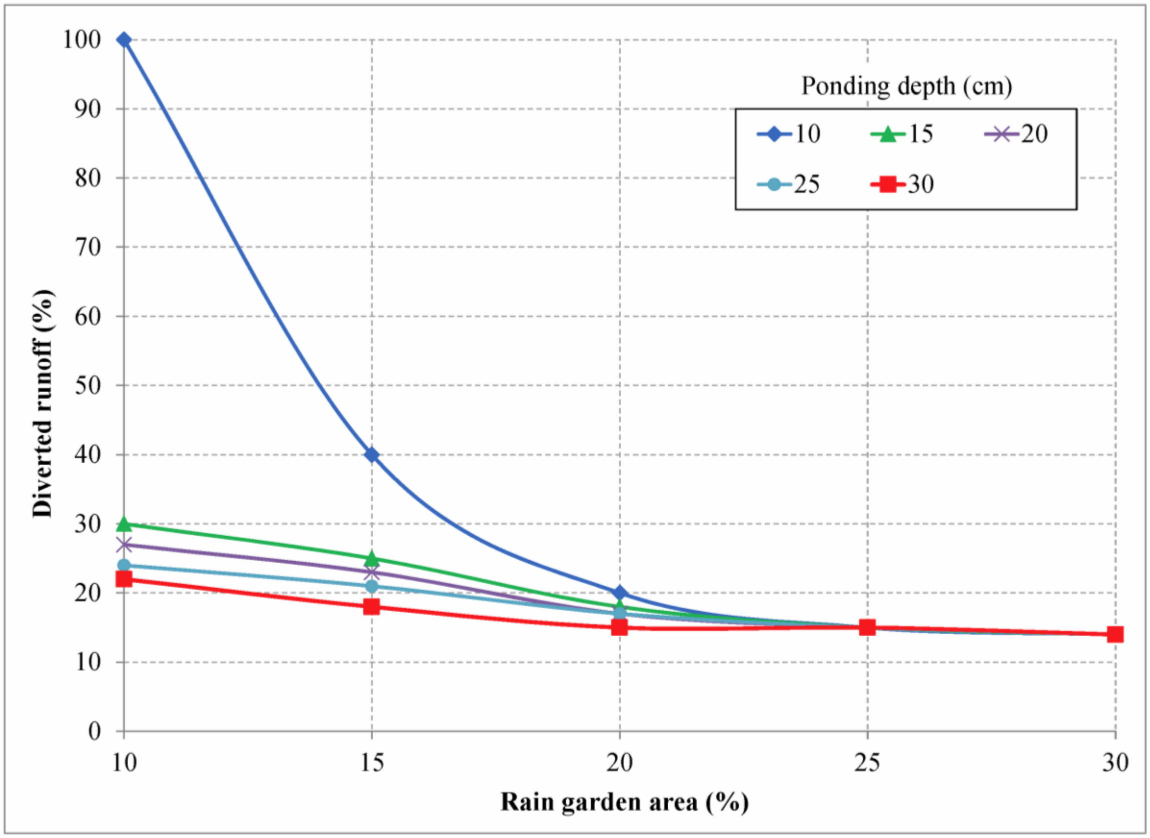


Figure 8: Required runoff diversion to mitigate flooding from the July 10, 2012 event as a function of rain garden area and ponding depth

Impact of Storm Return Period on Flood Mitigation

Results from third model scenario show how rain gardens could mitigate flooding for larger storm events. While the prior analyses focused on the July 10, 2012 event, which we determined was a 2-year 1-hour event, in this scenario synthetic storm events with higher return periods are used in the model. The cumulative hyetographs for these synthetic storms were generated by upscaling the July 10, 2012 event to have a total rainfall amount consistent with larger storm events as shown in Figure 9. Using these hyetographs and assuming a 30 cm rain garden ponding depth for maximum storage, Figure 10 shows the relationship between rain garden area and diverted runoff required for flood mitigation. Again this result shows a steep curve when rain garden storage is limiting. Each return period has a diverted runoff value that is approached once sufficient volume is achieved. These diverted runoff values represent the runoff reduction required to mitigate flooding for the larger storm events.

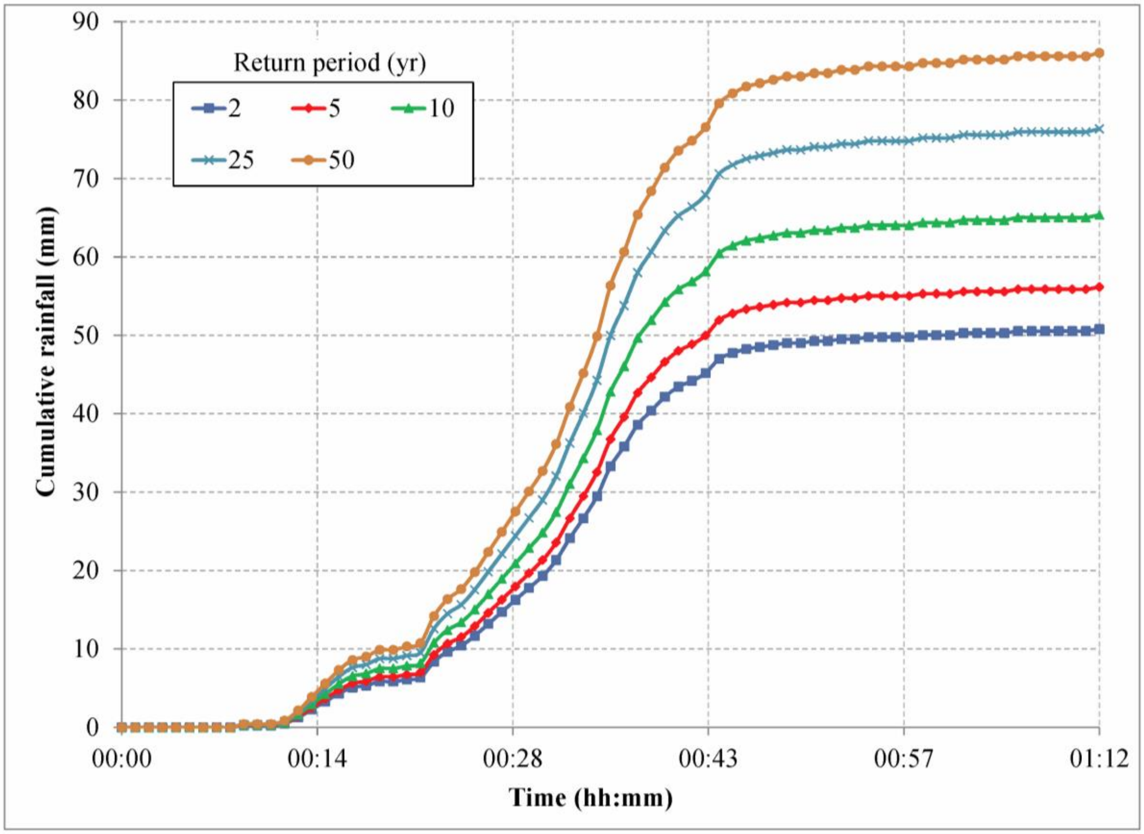


Figure 9: Results from upscaling the July 10, 2012 storm event to larger return periods while maintaining a 1-hour duration

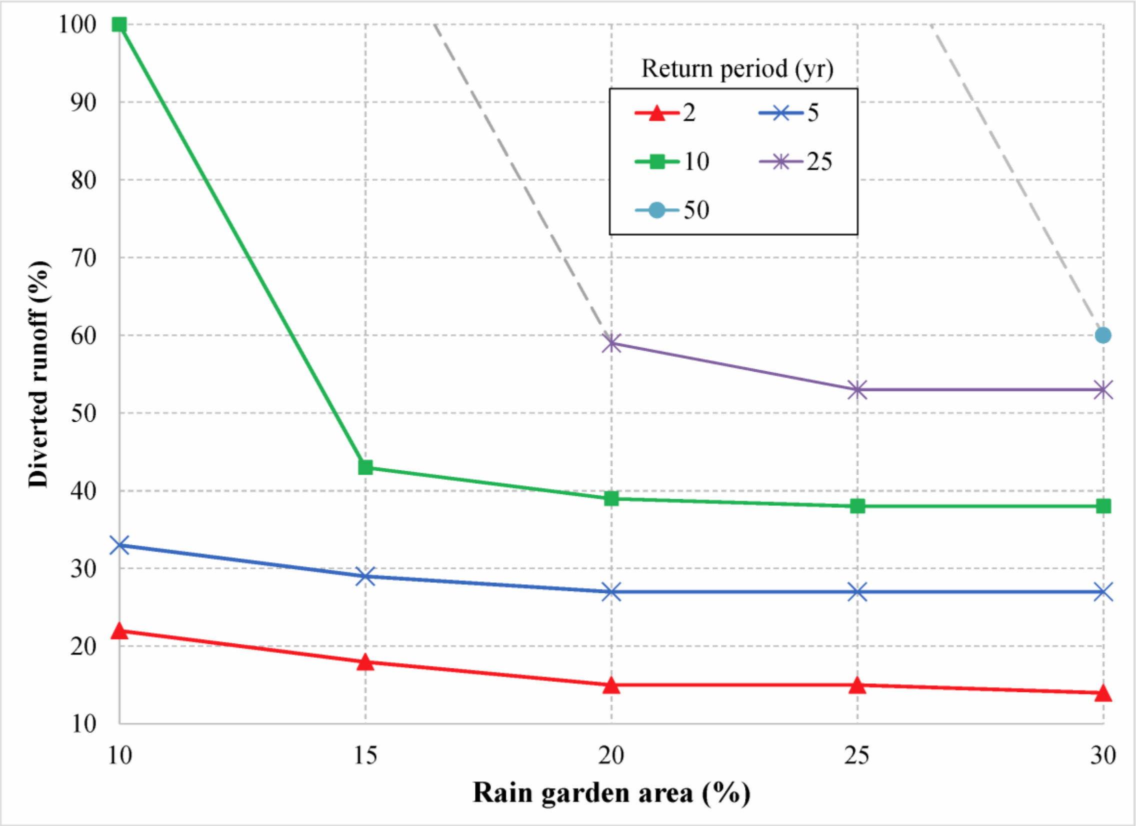


Figure 10: Percentage of runoff from impervious surfaces that must be diverted to rain gardens to mitigate flooding as a function of rain garden area (assumes a 30 cm ponding depth for the rain gardens)

Assuming a given rain garden area and ponding depth, it is possible to determine the required diverted runoff (or runoff reduction) required to mitigate flooding for different return period storms (Figure 11). Figure 11 reports results for rain garden area equal to 20% and 30% of impervious cover. For both cases, ponding depth is set to 30 cm for maximum storage potential. For return period storms less than 10 years, there is little difference between 20% and 30% rain garden areas. This suggests that both scenarios have sufficient storage to mitigate flooding for storms with these return periods. Therefore, there is not much benefit gained by adding rain gardens above 20% of the watershed’s impervious cover for storms with return periods less than or equal to 10 years. For the 10-year return period storm, approximately 38% of the runoff from impervious surfaces should be diverted to rain gardens to mitigate flooding. For the 5-year storm, runoff would need to be reduced by approximately 27% and this value drops to 15% for the 2-year storm. Storms with greater than a 10-year return period require more than 50% runoff reduction.

Given these required rain garden areas and diverted runoff amounts, the question becomes what level of LID adoption is reasonable within the watershed. Bakacs et al. (2013) found that, following an educational training program, 48% of respondents in Virginia and 58% of respondents in New Jersey adopted a stormwater best management practice at their home. The majority of the respondents that took action re-directed downspouts to gardens or mulched areas (64% and 54%, respectively). A much smaller fraction of the respondents (12% and 4%, respectively) went as far as installing a rain garden. Given that 35% of the watershed’s impervious cover is rooftop area, redirecting downspouts to existing gardens or mulched areas with sufficient storage to reduce runoff could have a significant impact. Furthermore, efforts by public entities including the university to reduce runoff from impervious surfaces could likewise be significant. Thus, while it is difficult to determine what level of runoff reduction through adoption of LID techniques is possible in the watershed, we believe it is reasonable to suggest that adoption of LID approaches could achieve the storage increase and runoff reduction required to mitigate up to a 5-year storm (rain gardens with total area equal to 20% of the impervious surfaces within the watershed; 27% of the runoff generated from impervious surfaces diverted into rain gardens).

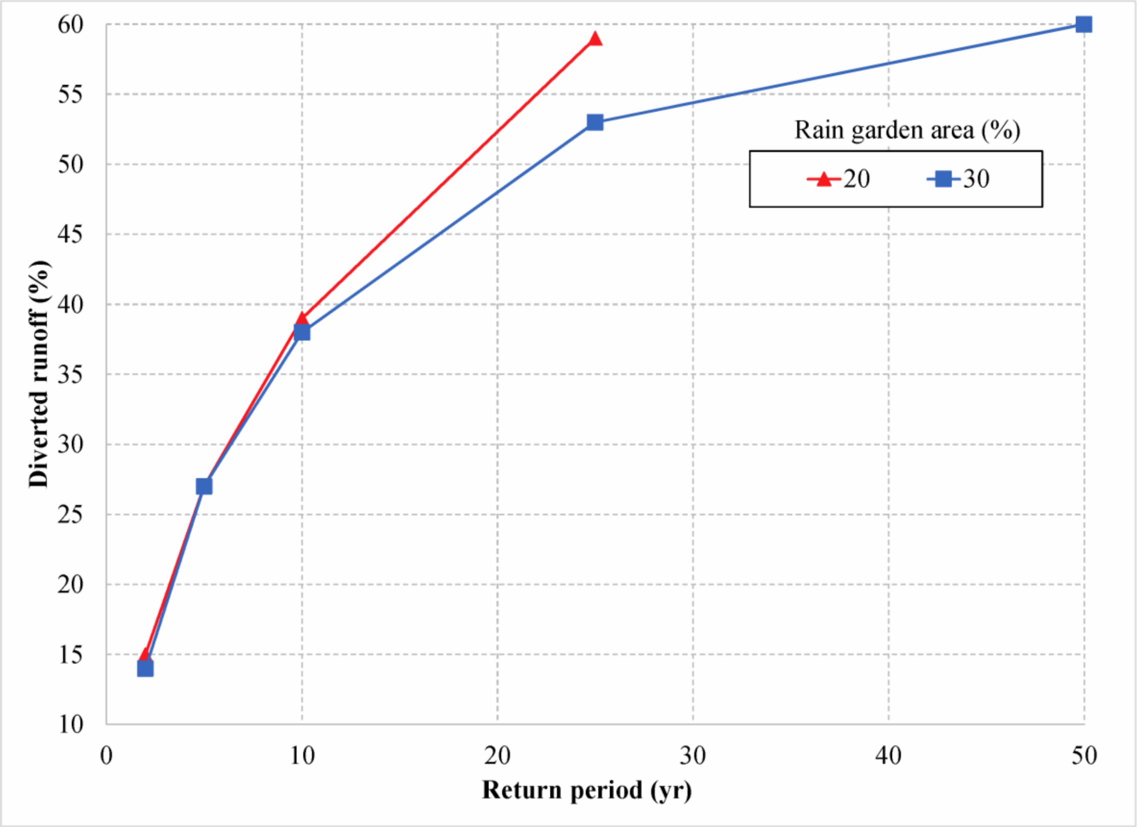


Figure 11: Percentage of runoff from impervious surfaces that must be diverted to rain gardens to mitigate flooding as a function of storm return period (assumes a 30 cm ponding depth for the rain gardens)

Conclusions

The objective of this study is to increase understanding of the LID techniques, using rain gardens as an example, as a retrofit measure to address flooding problems within urbanized watersheds. By understanding the required conditions under which distributed storm water controls like rain gardens could mitigate flooding, it is possible to suggest the potential and limitations of the approach. Ultimately stormwater control measures are used in combination for addressing water quality and quantity issues in developed watersheds, so these modeling scenarios are meant more for providing bounds on LID techniques, and rain gardens in particular, as a flood mitigation strategy.

The first challenge in addressing flooding in an urbanized watershed is to provide sufficient volume for storing runoff generated from impervious surfaces in the watershed. In our study, the storage volume added by the rain gardens was the product of two model variables: the total area of the rain gardens in the watershed as a percentage of the total impervious surface and the ponding depth (or berm height) of the rain gardens. Typical values for rain garden area cited in prior work focusing on water quality and groundwater recharge benefits of rain gardens have been 10-20% of the impervious area (Dussaillant et al., 2004). We found 20% to be a sufficient area to mitigate flooding for storm event with less than or equal to a 10-year return period, if the maximum recommended ponding depth of 30 cm is used.

Once sufficient storage is available, the next challenge is runoff reduction by diverting runoff generated from impervious surfaces into locations where it can infiltration, such as rain gardens. Using modeling scenarios for the study watershed, we determined that 15% of the runoff from impervious surfaces would need to be diverted to mitigate flooding for a 2-year return period, 1-hour duration storm. For a 5-year, 1-hour storm, there would need to be a 27% runoff reduction. Storms with 10-year return period would require 38% runoff reduction while higher return periods would require over 50% runoff reduction. Given that rooftop area accounts for 35% of watershed's impervious cover and research suggests approximately 50-60% adoption rates by homeowners of LID techniques following an outreach campaign (Bakacs et al., 2013), we suggest that distributed LID approaches could potentially be used to mitigate up to a 5-year return period storm. However, further research on possible adoption rates within in the study watershed is needed to verify this claim.

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