The Intersection of Public Utilities and Private Ownership in Stormwater Management: A Case Study of Localized Flooding in Charlottesville, VA

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Abstract

At a site in Charlottesville, VA, runoff from two upstream properties flows down to the downstream properties, resulting in flooding problems. The City's public utilities have previously looked into new underground stormwater conveyance that would only require maintenance of right of way through the private properties. With GIS and EPA SWMM models, this paper analyzes scenarios that instead change the surface of one or both upstream properties in order to reduce runoff. The three different low impact development (LID) scenarios (rain garden, infiltration trench, and vegetative swale) are computed based on area needed to infiltrate runoff and cost of implementation. The three infiltration objectives used were 50% and 100% infiltration of one property and 100% infiltration of both properties. The analysis showed that of the three LIDs, infiltration trenches were the most efficient in reducing the total runoff per square foot, with rain gardens nearly as efficient. Cost analysis showed, however, that infiltration trenches would be more expensive to implement than rain gardens. Vegetative swales were not found to be effective in reducing runoff from the site. As a result, it is recommended that, of three LIDs, rain gardens or infiltration trenches be used to reduce flooding at the site.

Introduction and Background

Throughout the city of Charlottesville, there exist several areas that are prone to flooding during periods of heavy rain. Large portions of the stormwater conveyance system that is in need of maintenance or repair lies outside the city's right of way. While the utility services of Charlottesville are ready to provide resources and recommendations to private property owners, the current incentives have failed to generate interest in solving these problems. In many cases, water from upstream private properties are creating problems for downstream private properties. Because the problems generated downstream do not directly influence upstream owners, there is little motivation for these owners to take any course of action.

This situation is exemplified at a site on St. Clair Avenue in Charlottesville, in which runoff from two uphill properties leads to flooding on a downstream property. The conveyance pipe that serviced the runoff from the upstream properties has collapsed causing water to overflow onto the street and flood the downstream property. Furthermore, the addition of driveways to the upstream properties further concentrated runoff going into the now collapse pipe. The city however does not have the right of way to fix the collapse. The project serves to observe and analyze different potential solutions to develop a recommendation that will result in flood mitigation at the site. Using Geographic Information System (GIS) and the Environmental Protection Agency's (EPA's) Stormwater management Model (SWMM), three low impact developments (LIDs) are analyzed using social factors, cost, and ability to reduce runoff at the site.

LIDs are management approaches using or mimicking natural processes that result in infiltration, evapotranspiration, or use of stormwater in ways that protect water quality and aquatic habitats, with an emphasis on preserving, restoring, or creating green space (US EPA, 2015). The three LIDs that were chosen for analysis in this project were rain gardens, infiltration trench, and a vegetative swale (Figure 1). Rain gardens and infiltration trenches use depressions and ditches filled with aggregate to collect and infiltrate stormwater into the ground (Shamsi, 2012). Vegetative swales, in contrast, are more broad and shallow channels that convey and infiltrate stormwater (Shamsi, 2012). The objective of these LIDs is to minimize any runoff that would typically be directed to storm drains and removed using conventional stormwater management techniques.

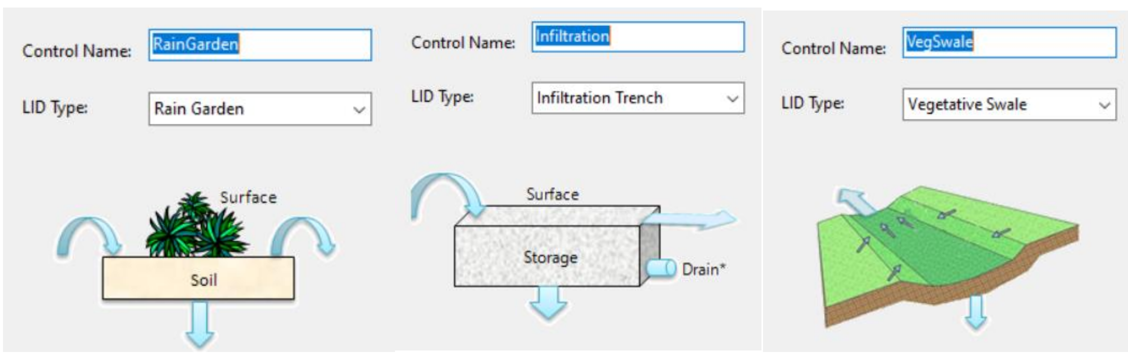

Figure 1. Visual representation of each LID according to EPA SWMM.

Methods

This project was conducted in three main parts: analysis of the area using GIS, determination of runoff with LIDs in SWMM, and analysis of external factors such as cost in determining a feasible solution.

GIS Analysis

For the GIS analysis, we selected to use ArcGIS, which includes a variety of tools, such as flow accumulation and pour point tools, used to determine the size of the watershed that was previously draining into the collapsed pipe. With this watershed delineated, the general percent slope of the area was determined by using the slope tool. Layers obtained from the city showing the roads, buildings, driveways, and land parcels were intersected with this watershed layer to find the amount of permeable and impermeable area on the entire site. Analysis of the site explored the options of implementing LIDs on just one property and on both properties. The size of the watershed for both of these options were calculated and applied to the models in SWMM.

EPA SWMM Modeling

The runoff and site conditions were modeled in EPA SWMM (Rossman, 2015). The watershed was assumed to be one subcatchment with one outlet. The parameter values of the subcatchment that were changed from the default values are listed in Table 1. Two storm return periods, 1-year and 10-year, each with a 24-hour duration, were considered. The rainfall depths for these synthetic storm events were obtained from the National Oceanic and Atmospheric Administration's (NOAA) website. For a 1-year storm, the rainfall depth was 3.03 inches and 5.55 inches for a 10-year storm.

Table 1. The values for the subcatchment parameters.

Subcatchment Parameters	
Width	140
% Slope	9
% Imperv	14.52
N-Imperv	0.01
N-Perv	0.2
Dstore-Imperv	0.05
Dstore-Perv	0.1
%Zero-Imperv	20

For the LIDs, the options were narrowed down to three possible scenarios: 1) rain gardens, 2) infiltration trench, and 3) vegetative swale. The setup of the SWMM model is shown in Figure 2. In analyzing each option, the typical parameter values (Table 2) according to the EPA SWMM guide for each LID were used as initial values and most parameters were held constant throughout each scenario and objective. Of the parameters, only berm height and soil media thickness were altered within a reasonable range as listed in the EPA SWMM guide to minimize the amount of runoff to the objective. These parameters were chosen because they are typically what is changed during design of the LIDs, as characteristics of the engineering soil and rip rap are more difficult to change. The ranges for these parameters are also listed in Table 2. In the first scenario, rain gardens, the berm height and thickness were altered between 6-12 inches and 18-36 inches, respectively. The second scenario, infiltration trenches, had alterations in berm height and thickness between the ranges of 6-12 inches and 36-100 inches. For the third scenario, vegetative swales, only the berm height was changed between a range of 6-12 inches.

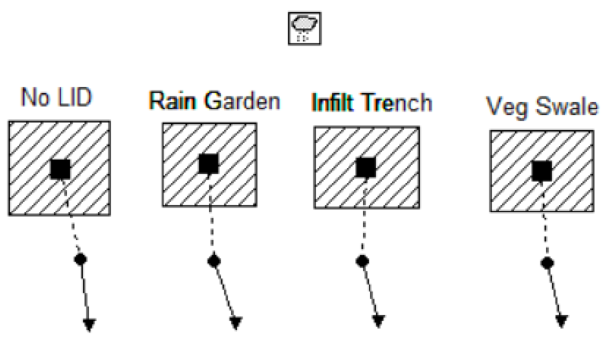

Figure 2. Setup of the SWMM model comparing each LID.

Table 2. Constant parameter values for each LID.

Constant Parameter Values					
Rain Garden		Infiltration Trench		Vegetative Swale	
Vegetation Volume	0.1	Vegetation Volume	0	Vegetation Volume	0.15
Surface Roughness	0.013	Surface Roughness	0.013	Surface Roughness	0.4
Surface Slope (%)	0	Surface Slope (%)	0	Surface Slope (%)	0.5
Porosity	0.52	Void Ratio	0.4	Swale Side Slope	3
Field Capacity	0.15	Seepage Rate (in/hr)	0.5	Berm Height (in)	6-12
Wilting Point	0.08	Clogging Factor	0.1		
Conductivity (in/hr)	1.6	Berm Height (in)	6-12		
Conductivity Slope	39.3	Thickness (in)	36-100		
Suction Head (in)	1.9				
Berm Height (in)	6-12				
Thickness (in)	18-36				

To determine how the different LID scenarios were able to mitigate flooding at the St. Claire site, the SWMM model was used and all LID parameters were then held constant except the area of the LID. Doing so, it was possible to determine the area necessary to achieve three objectives of 100% reduction of runoff from one property, 50% reduction of runoff from one property, and 100% reduction of runoff from both properties. The results for both peak runoff (cfs) and total runoff (gallons) were examined, both of which are zero for the objectives of 100% reduction of runoff. For 50% reduction of runoff, the aim of the LID was to reduce the total runoff (gallons) of the area by half, hence assuming that 50% of the runoff is infiltrated using the LID. While the area of the subcatchment and allowable peak flow changed to reflect each objective, the general procedures of analyzing each LID by changing different LID parameters were used for each LID scenario.

Analysis of Cost

For cost estimation, the costs of each LID were taken from various sources through research. The costs were approximated to reflect some of the characteristics known at the site. For rain gardens, the total cost mostly consists of excavating the site and filling it with soil. According to USDA's Web Soil Survey, the topsoil at the site is sandy loam and well drained soil, so the hydraulic conductivity of the soil is similar to what is modeled in SWMM. However, in order to ensure future performance of the rain garden, around 6 inches of compost soil and sand should be incorporated during construction to increase the infiltration rate and anticipate compaction. Displaced soil that is not returned to the rain garden is used to create the 12-inch berm as modeled in SWMM. Native plants to Virginia were chosen for the rain garden as they are adapted to local conditions, have deeper roots, and do not need extra care once planted (Fairfax County, 2009). For this project, seeds for plants that flourish in part sun- part shade conditions and are more tolerant of both drought and flooding were used to calculate the cost per square yard of the rain garden. To find the total cost, the amount of soil needed to fill the soil was found depending on the area of the rain garden and added to the cost of the surface layer of plants and mulch.

The vegetative swale has similar requirements to the rain garden. The native soil has 1adequate drainage and hydraulic conductivity. After excavation, a gravel layer is placed on the bottom along with a PVC underdrain that connects to the storm sewer. After the soil is backfilled in, the remaining soil can be used to build up a berm to allow for greater ponding. Grass is suitable vegetation on the swale, however, other vegetative covers can be used so long as they do not have high nutrient requirements.

The infiltration trench first needs to be excavated, and the soil will ultimately need to be hauled away as well. Filter fabric should be draped over the sides of the trench, going 2 feet in from the bottom edges. There should be 2 feet over coverage for any sections that overlap. An 8" layer of sand must be placed at the bottom to meet specifications covering the filter fabric base. The aggregate is then filled in on top and the filter fabric covering the top as well. Finer aggregate is added over the filter fabric and then finally a layer of sod. Observation wells are required every 50 feet for maintenance. The total cost was found by finding the amount of each aggregate needed to fill the infiltration trench according to the specifications.

The overall budget for the materials of constructing a rain garden is shown in Table 6. Cost of materials for an infiltration trench is shown in Table 7, and Table 8 for vegetative swale.

Table 3. Unit prices of each item for the rain garden.

Item	Unit	Unit Price
Compost soil/sand mix	yd^3	$30.50[a]
Earth excavation	yd^3	$15[b]
Mulch (2-inch layer)	yd^3	$20[c]
Plants	yd^2	$10[d]

Table 4. Unit prices of each item for the vegetative swale.

Item	Unit	Unit Price
Earth excavation	yd^3	$15[b]
1-½" Gravel Aggregate (AASHTO #57)	yd^3	$25[g]
PVC underdrain	10 ft	$10
Grass Seed	1000 ft^2	$15

Table 5. Unit prices of each item for the infiltration trench.

Item	Unit	Unit Price
Earth excavation	yd^3	$15[b]
½" Filter Gravel (AASHTO #8)	yd^3	$30[g]
1-½" Gravel Aggregate (AASHTO #57)	yd^3	$25[g]
Drainage Sand	yd^3	$50[i]
Non-woven Filter Fabric	yd^2	$1.40[f]
Sod	yd^2	$4.50[e]
PVC Observation Well (4"x10')	Per 50ft of trench	$75[h]

[a] Cost from https://cedar-grove.com/store/soil/60-40-lawn-mix
[b] Cost from https://www.homeadvisor.com/cost/landscape/excavate-land/#grading
[c] Cost from https://www.homeadvisor.com/cost/landscape/mulch-delivery-install/
[d] Cost from https://www.ufseeds.com/product/virginia-wildflower-seed/
[e] Cost from https://www.homeadvisor.com/cost/landscape/sod-prices/
[f] Cost from https://www.agriculturesolutions.com/agricultural-fabrics/drainage-filtration-and-weed-fabric?p=2
[g] Cost from https://www.paturnpike.com/Procurement/Purchasing/docs/BID%20TAB%20Aggregates%20801023_2015.pdf
[h] Cost from https://www.shop-esp.com/4-x-10-PVC-Well-Screen-020-Sch40-brMale-x-Female-Threads-P276.aspx?gclid=EAIaIQobChMImKeK7YjI6AIVBpyzCh2MYQtcEAQYASABEgKC4PD_BwE
[i] Cost from https://homeguide.com/costs/fill-dirt-sand-topsoil-cost#sand

Results

The total watershed area discharging to the property downstream was found to be 3.3 acres. The watershed area for just the south property was 1.58 acres (Figure 3). The total area consisted of 0.48 acres of impermeable area, resulting in 14.52% impermeable areas on the site.

The site was determined to have a 9% slope, and a width (the area of the subcatchment divided by the longest flow length) of approximately 140 ft.

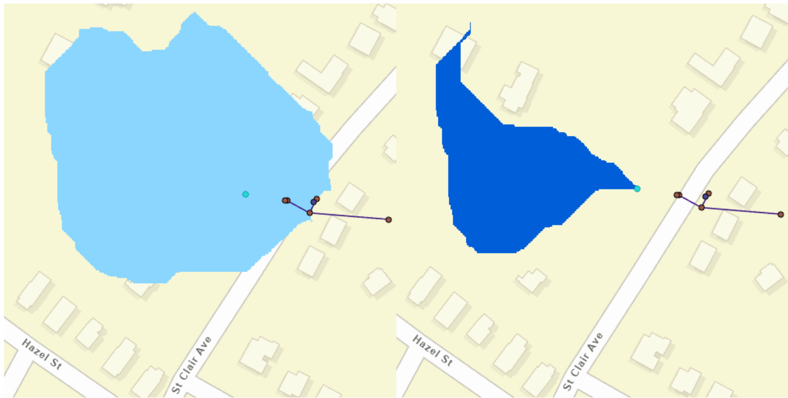

Figure 3. Watershed for both properties (left) and watershed for the south property.

Using EPA SWMM, the peak runoff for a 1-year storm and a 10-year storm for both of the properties are 3.19 and 9.84 cubic feet per second (cfs), respectively. The total runoff volume for a 1-year storm is 0.06x10^6 gallons and 0.17x10^6 gallons for a 10-year storm. Meanwhile, the peak runoff for the south property for a 1-year storm and a 10-year storm are 2.15 and 6.33 cfs, respectively (Figure 4). Similarly, the total runoff volume for just the south property given a 1-year storm is 0.03x10^6 gallons and 0.09x10^6 gallons given a 10-year storm.

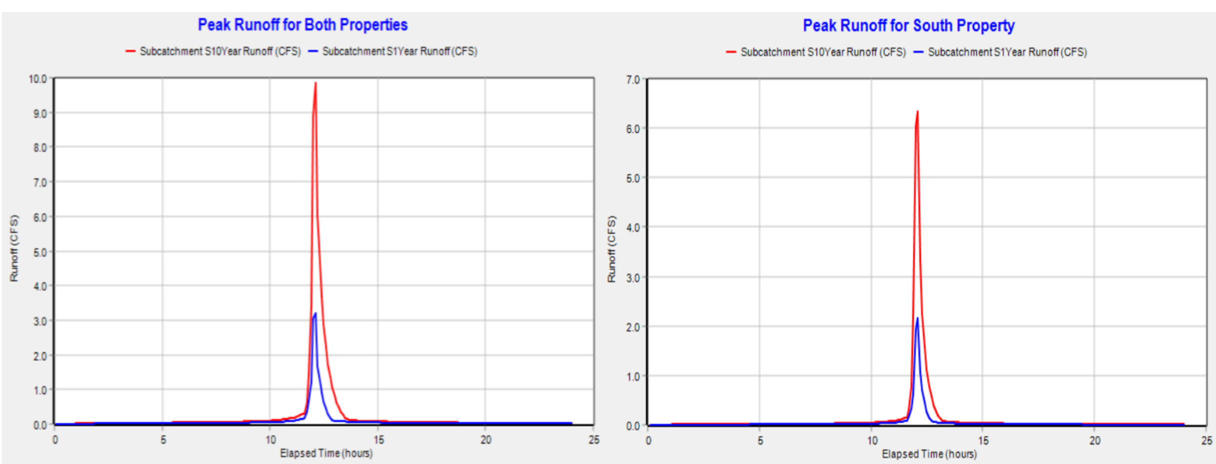

Figure 4. Runoff prior to LIDs for 1-year storm (blue) and 10-year storm (red) for both properties (left) and just the south property (right).

Using these values, the three LID scenarios as outlined in the Methods section were analyzed with the objectives of 100% reduction of runoff from one property and hence no peak flow, with results shown in Table 3 and 4. Required area for a rain garden and an infiltration trench during a 10-year storm is 0.156 acres and 0.122 acres, respectively (see Figure 5, values can be found in the appendix). The vegetative swale did not successfully infiltrate 100% of the runoff even when it occupied the entire property, so the result for the vegetative swale is the value of the entire property. For the rain garden, the final value used for the berm height was 12 inches, and the thickness of the soil was 24 inches. The infiltration trench had the same berm height but a thickness of 60 inches, as infiltration trenches can typically be deeper than rain gardens. When analyzing peak flow using a vegetative swale with a berm height of 10 inches, it was found that peak flow could not be reduced to zero even if it occupied the full subcatchment. Changing the berm height did not alter the results significantly and still required the entire subcatchment to be the vegetative swale to reduce peak flow.

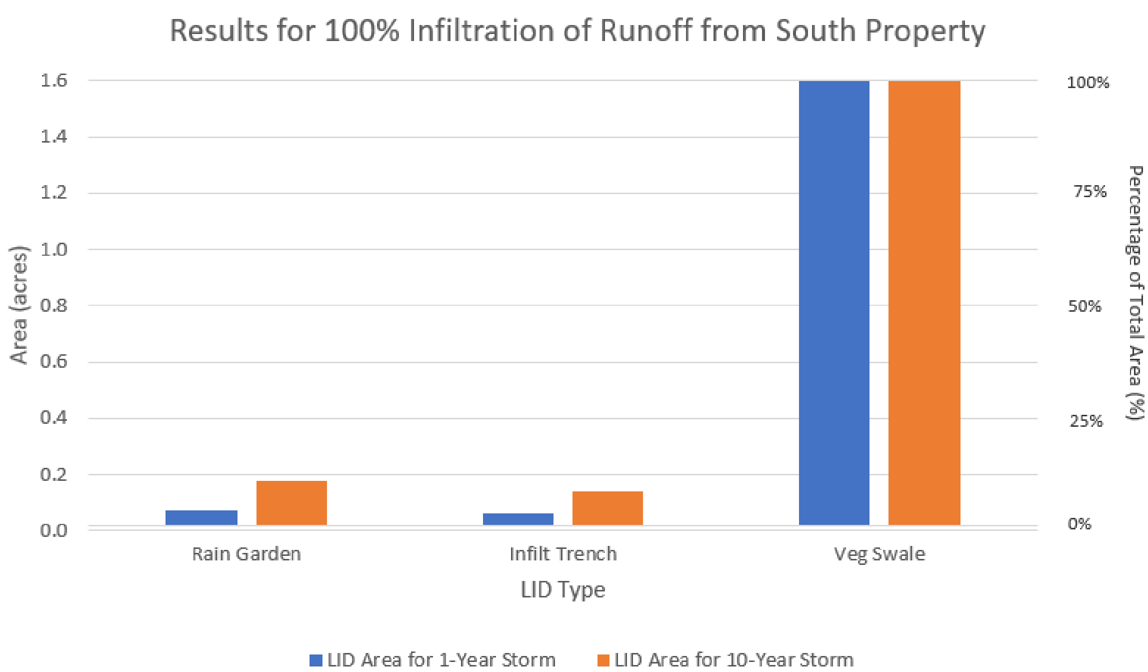

Figure 5. The results for 100% infiltration of runoff from the south property by LID type.

In the second objective, 50% reduction of runoff from only the south property, the volume of runoff should not exceed 0.02x10[6] gallons for the 1-year storm and 0.05x10[6] gallons for the 10-year storm. Given these values, the results for each LID are displayed in Figure 6. The third and final objective, 100% reduction of runoff from both properties, resulted in the values shown in Figure 7. The berm heights and thickness for each LID were not changed throughout the three objectives and were maximized within a range of values typical for each LID scenario. After looking at the effect of the two parameters on the runoff amount, it was found that berm height and thickness played an important role in infiltration and therefore the highest reasonable values were chosen for each parameter. For a rain garden, the berm height is typically 6-12 inches with a thickness of 24-48 inches (Rossman, 2015). Infiltration trenches have the same range for berm heights but thicknesses can range from 36-144 inches, but in order to keep the bottom of the trench a reasonable distance from the water table, the maximum depth of the infiltration trench was set to 60 inches.

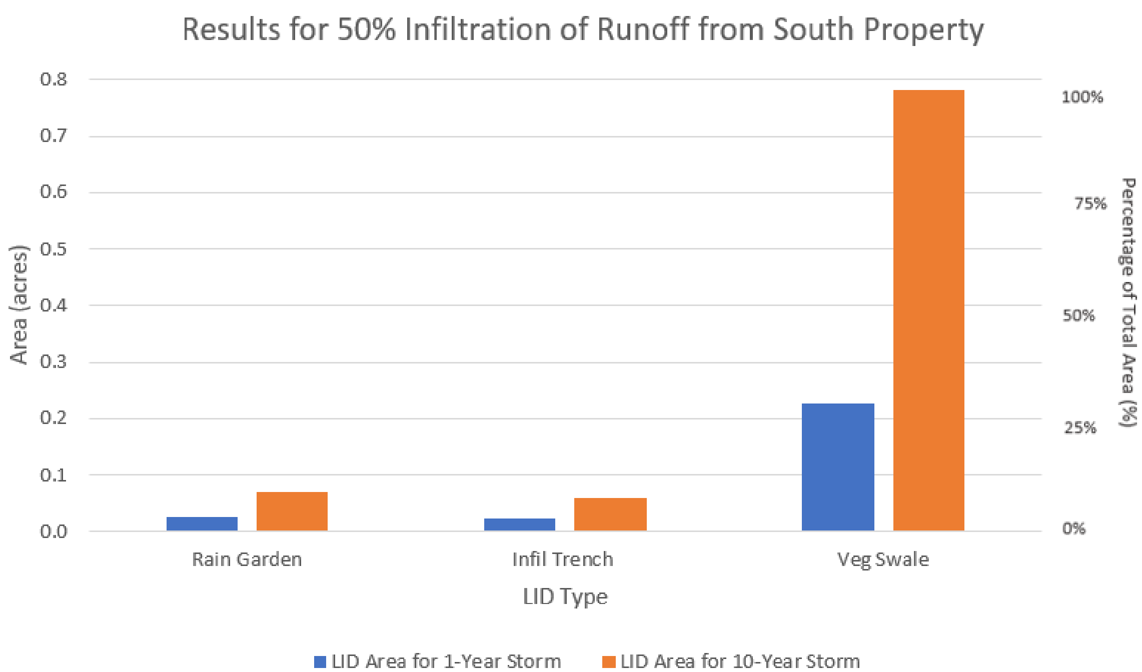

Figure 6. The results for 50% infiltration of runoff from the south property by LID type.

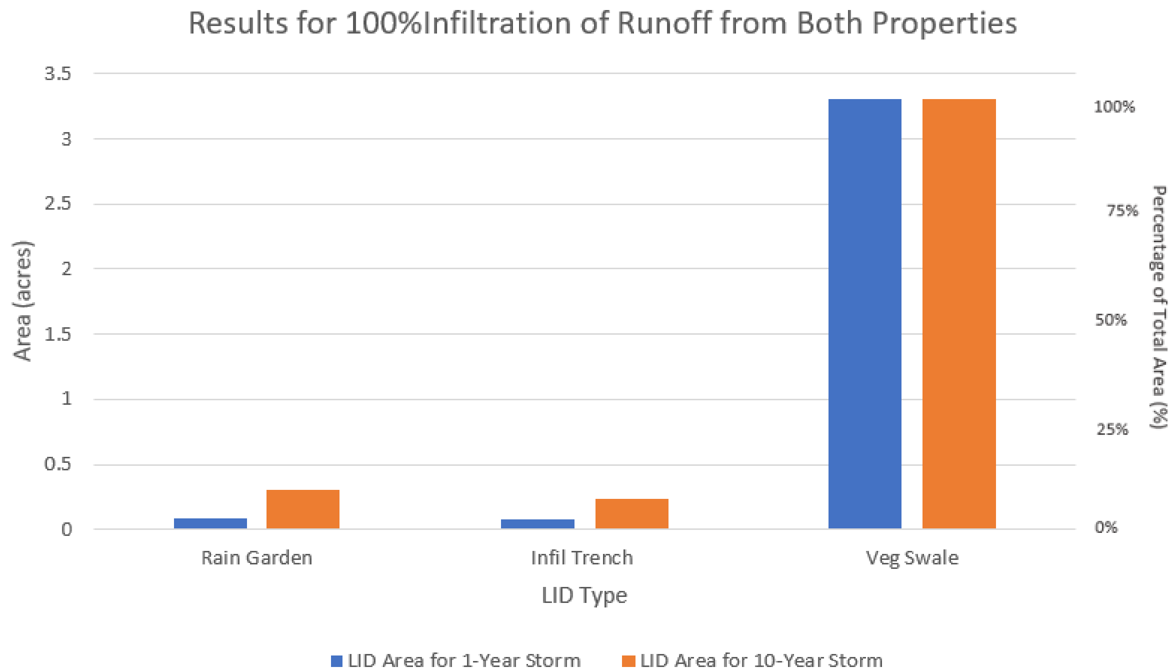

Figure 7. The results for 100% infiltration of runoff from both properties by LID type.

Cost Factors

The costs for the rain garden and infiltration trench for each scenario using the costs from the Methods section are shown in Table 9 and 10. The costs for a vegetative swale were not calculated as it did not fully infiltrate runoff even when it occupied the entire subcatchment.

Table 6. Cost for a rain garden for each scenario.

	100% infiltration - 1 property		50% infiltration - 1 property		100% infiltration - both	
	1-year storm	10-year storm	1-year storm	10-year storm	1-year storm	10-year storm
Cost	$5,400	$16,500	$2,700	$7,500	$9,800	$32,000

Table 7. Cost for an infiltration trench for each scenario.

	100% infiltration - 1 property		50% infiltration - 1 property		100% infiltration - both	
	1-year storm	10-year storm	1-year storm	10-year storm	1-year storm	10-year storm
Cost	$21,800	$64,100	$11,800	$31,500	$40,300	$124,000

Discussion

A large amount of area is required to reduce the peak runoff to zero for a 10-year storm. Designing to a 10-year storm would require around 10% and 8% of the total property area for a rain garden or infiltration trench, respectively. In comparison, designing the LID to a 1-year storm is more feasible since the areas are two to three times smaller, while still diverting runoff to alleviate flooding problems in more common rain events. Designing to a 1-year storm would require only around 3% and 2.5% of the total property area for rain gardens and infiltration trenches, respectively. Due to the ineffectiveness of a vegetative swale to reduce runoff during a 10-year storm, it is unlikely to be used as a means of reducing flooding at the site.

Using the cost estimate for the components of a rain garden, the cost for materials for a rain garden for each scenario ranged from $5,400 to $124,00. While the costs for a 1-year storm are lower, the rain garden would only help with flooding in more common, smaller rain events. If the property wishes to alleviate some flooding but is more limited in budget, an available option would be to choose to design the rain garden to a 1-year storm or aim for 50% infiltration instead of 100% infiltration. Overall, the costs for a rain garden are lower than for an infiltration trench, but also require more area for each scenario.

The infiltration trench performs best in the models and requires the least amount of area, however, it also has higher construction costs. Even for the most limited case with half runoff reduction for a 1 year storm, the cost still comes out to be approximately $11,800 for materials and excavation not including other labor costs. There is also the added factor of maintenance to ensure the pore spaces of the aggregate do not get overly clogged. Budget permitting, using an infiltration trench on the south property to reduce runoff is a feasible option.

The vegetative swale was the poorest performer in the model requiring the most area of any of the options; in the 100% infiltration cases a vegetated swale would require an area greater than the site itself. Given that it has comparable material costs to a rain garden but performs much more poorly, it should not be considered.

The quality of data going into the model could be improved. The soil data was gathered from the USGS Web Soil Survey and the NRCS synthetic hydrograph along with NOAA local precipitation data was used to create time series for design storms. The topographical data gathered from GIS was not very granular in the context of the size of the site, however, the general slope, shape, and size of the catchment were the important aspects that served the purposes of the model. The primary output variable used for sizing and optimization was peak runoff (cfs). The intent was by reducing the peak flow rate, the constrained flow through the damaged storm sewer would have more time to dissipate. Precipitation data was gathered from the Albemarle airport for one of the past storms on the site which was known to cause flooding. A time series was created from the data and found to be comparable to a 1-year storm. This time series was intended to be used as a baseline, however given the knowledge that there have been record storms in the past few years at the site, it was unlikely that the storm was the largest which could have caused flooding.

While none of the proposed scenarios may be the chosen solution for this site, the model can still offer useful insights for future stormwater management practices. While retrofitting LIDs has shown to be land intensive and costly, the LIDs' performances were demonstrated within the model with rain gardens infiltrating 1.7 cubic feet of stormwater per square foot and infiltration trenches 2.2 cubic feet per square foot. Trying to accomodate all the runoff was difficult in a finite space, so to avoid such cases in the future, less-intensive application of LIDs could reduce the load across the whole system. However, there are currently no incentives in place for private properties to landscape in a way that improves infiltration at the St. Claire site.

Conclusion

Stormwater management requires coordination between the City's public utilities and private property owners. While the City's public utilities have found ways to manage stormwater and reduce flooding without the help of private property owners, there are solutions that could be more effective in mitigating flooding with the cooperation of the private property owners. This is shown in a case study at St. Claire Avenue, where runoff from upstream properties is flooding downstream properties during rain events. The problem has been exacerbated by broken pipes that had previously diverted the runoff and the addition of impermeable area upstream. In order to address the problem, three LIDs were analyzed in the hopes of determining a potential solution that reduces runoff from the upstream properties. We found that the most effective way to reduce runoff at the site is through an infiltration trench, with rain gardens nearly as effective. However, in order for runoff to be zero during 10-year storms using the infiltration trench or rain garden, a large area of the property will need to be used for the LID. It may not be feasible or realistic to design a rain garden or infiltration trench to accomodate a 10-year storm due to requiring large amounts of area and resulting high prices of implementing the LID. If there is a desire to alleviate some flooding during more common 1-year storms, the rain gardens and infiltration trenches would be relatively small in size and could reduce the peak flow to zero. Vegetative swales were found to be inefficient in infiltrating runoff from the site.

Currently the greatest limitation is the lack of data on site specific hydrology. The rainfall data used in the model was a synthetic storm based on NOAA rainfall intensities. The topographical model was derived from city-level GIS data, not at the scale of the site.

Opportunities for future research could include obtaining GIS data and rainfall data that more closely reflects what is observed at the present site. Further investigation into dates when the site has flooded previously would clarify what the threshold for flooding is and the scenarios could be adjusted. In addition, installation of sensors to log both local precipitation and water level in the flooding storm drains would create a baseline for the model and would allow for further optimization of LID solutions. In addition, more research can be conducted so that costs include life cycle costs such as maintenance fees, replacement parts, etc.

Appendix

The results for 100% infiltration of runoff from the south property by LID type.

LID	Berm Height (in)	Soil Thickness (in)	LID Area for No Runoff (1-year storm) (sqft)	LID Area for No Runoff (10-year storm) (sqft)
Rain Garden	12	24	2,200	6,800
Infiltration Trench	12	60	1,800	5,300
Vegetative Swale	10	-	MAX	MAX

The results for 50% infiltration of runoff from the south property by LID type.

LID	Berm Height (in)	Soil Thickness (in)	LID Area for Half Runoff (1-year storm) (sqft)	LID Area for Half Runoff (10-year storm) (sqft)
Rain Garden	12	24	1,100	3,100
Infiltration Trench	12	60	975	2,600
Vegetative Swale	10	-	9,900	34,000

The results for 100% infiltration of runoff from both properties by LID type.

LID	Berm Height (in)	Soil Thickness (in)	LID Area for No Runoff (1-year storm) (sqft)	LID Area for No Runoff (10-year storm) (sqft)
Rain Garden	12	24	4,050	13,175
Infiltration Trench	12	60	3,330	10,315
Vegetative Swale	10	-	MAX	MAX

Works Cited

Fairfax County. *Rain Garden: Design and Construction.* (2009) Retrieved from https://www.fairfaxcounty.gov/soil-water-conservation/sites/soil-water-conservation/files/assets/documents/raingardenbk.pdf

Rossman, L. A. (2015, September). Storm Water Management Model User's Manual Version 5.1. 353.

Shamsi, U. M. (2012). Modeling Rain Garden LID Impacts on Sewer Overflows. Journal of Water Management Modeling. https://doi.org/10.14796/JWMM.R245-07

US EPA (2015, September 22). *Urban Runoff: Low Impact Development* [Overviews and Factsheets]. US EPA. https://www.epa.gov/nps/urban-runoff-low-impact-development