# Meadow Creek Water Management Plan

Technical Report
Presented to the Faculty of the
School of Engineering and Applied Science
University of Virginia

By

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On our honor as University students, we have neither given nor received unauthorized aid on this assignment.

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## 1. Project Problem Statement

The purpose of this design project is to address current issues affecting Meadow Creek, including the effects of excess sedimentation and the inequitable distribution of green infrastructure (GI). Meadow Creek receives stormwater runoff from the northern half of Charlottesville, which composes a 5,800-acre drainage basin (see Figure 1). Stormwater runoff comes from a variety of sources, including neighborhoods, schools, and shopping centers along U.S. Route 29. Prior to the stream restoration conducted in 2012, Meadow Creek was listed as an "impaired waterway" by the Virginia Department of Environmental Quality (DEQ), mostly due to excessive sedimentation from stream bank erosion. Sedimentation is a significant issue, as it increases turbidity, inhibits the growth of aquatic vegetation, harms aquatic wildlife, and transports more nutrients into waterways. Following the completion of the primary restoration effort, there remains concern for waterway health and reduction of sediment and nutrient loadings to acceptable levels, as key sources of detrimental stream impacts are largely generated outside of the channel, in the watershed itself. However, if stream restoration occurs in conjunction with the implementation of GI systems, also known as best management practices (BMPs) or low impact development controls (LIDs), within developed areas of the watershed, degraded waterways are able to more fully recover and revert to pre-development conditions. This is because GI reduces the volume of stormwater and associated pollutant loading delivered to the waterway by treating stormwater at its source. Common examples include green roofs, rain barrels, and rain gardens.

In addition to the benefits GI can provide related to water quality improvements and runoff reduction, they also provide many environmental and social co-benefits including improved air quality, increased wildlife habitat, enhanced community livability, reduced energy demand, and many others (Elkington, 1994; Center for Neighborhood Technology, 2010). However, inequitable distribution is an issue when implementing GI due to systemic issues embedded in guiding policies for GI projects. As a result of this inequitable distribution, disadvantaged communities do not get to reap the benefits GI provides. To address these issues, the team targeted subbasins within the Meadow Creek watershed that illustrated both a high level of need for stormwater management and a high level of social need based upon numerous social context variables, such as race, housing characteristics, and income. The proposed solution to the problem includes a multi-objective watershed analysis, a recommendation for optimal levels of GI implementation in the subbasins identified as having high sociotechnical need, and a site-scale design for one of these subbasins. The objectives of the project are to maximize environmental and socioeconomic benefits while minimizing costs associated with the GI placement.

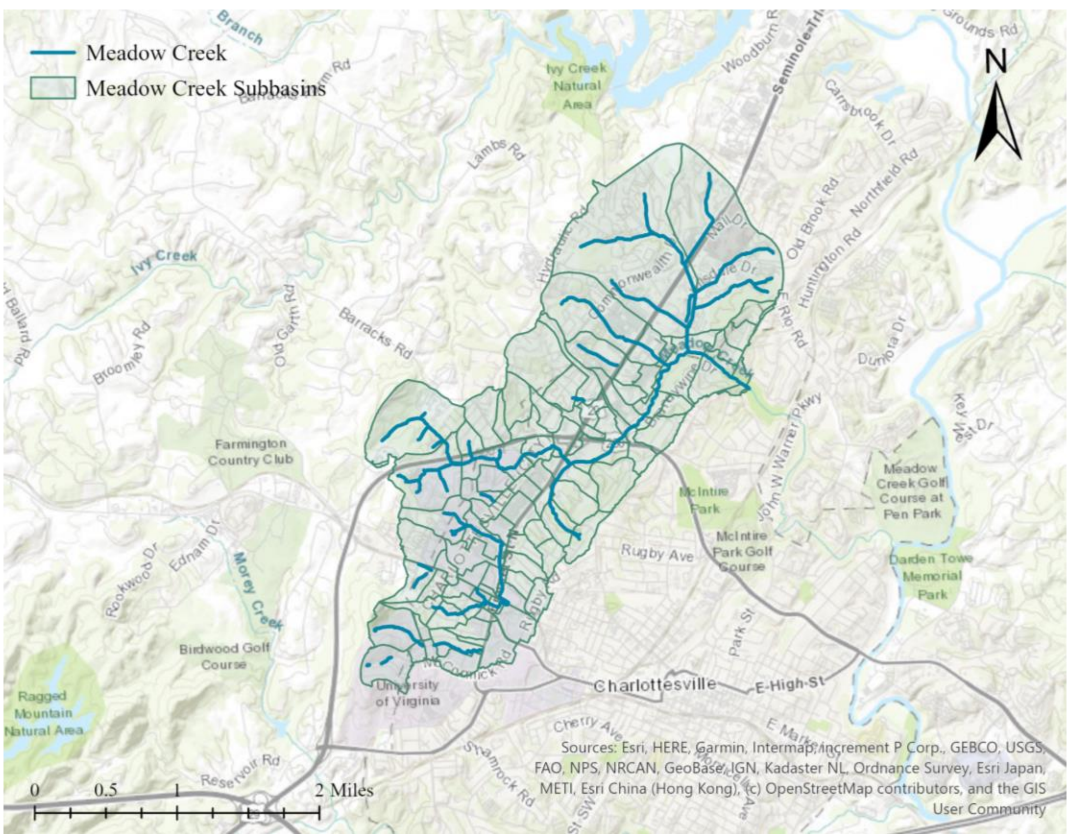


**Figure 1.** Meadow Creek watershed, located in Charlottesville, Virginia.

## 2. Project Scope

To accomplish these objectives, the team pursued four main areas of work: characterization of existing conditions, broad optimization of the general hotspot area, completion of site-scale design for a select subbasin, and outreach to understand community perspectives. First, the team prioritized a target area within the watershed by assessing environmental and social needs. This was completed through modelling and analysis of Meadow Creek watershed using Geographic Information Systems (GIS) data and the United States Environmental Protection Agency's Stormwater Management Model (SWMM). Fieldwork, including measuring stream discharge and nutrient loading at various sites along Meadow Creek, has been conducted by the team and Seth Herbst to support SWMM modelling. Once identified, the target area was optimized by determining feasible types of BMPs and associated areas for each type which proved to be advantageous from a cost-benefit standpoint. This was completed by developing sets of various scenarios for SWMM and comparing results using PySWMM, a software which combines Python and SWMM for more ready analysis and comparison. Following this optimization stage, one subbasin was selected for a site-scale design of best management practices (BMPs). Goals for the site were to bring the site total phosphorus (TP) loads within the state of Virginia's guidelines, provide requisite treatment volume as calculated using the Virginia Runoff Reduction Method (VRRM) for pre-BMP conditions, and achieve a 20% reduction in energy balance for channel protection given a 24-hr, 1-year storm and a 24-hr, 2-year storm. To inform GI designs in the watershed, the team facilitated community engagement through a survey and has incorporated feedback into this report. Community survey results were not received before the BMP selection occurred, so results were summarized primarily to provide valuable information for future GI projects.

The deliverables for this project include GIS maps and summarized results characterizing Meadow Creek watershed, an optimal distribution of GI for target subbasins, site-scale BMP designs for a selected subbasin, including AutoCAD drawings, expected cost for implementation, VRRM spreadsheets to illustrate water quality goals were met, SWMM results to display that water quantity goals were met, and the responses from the community survey.

## 3. Watershed Characterization

To select subbasins for optimization, and ultimately the subbasin for site-scale design, a target area that illustrated high social and technical need was identified using maps created with ArcGIS Pro. Technical need was determined by computing the percentage of impervious area per subbasin and the percentage of untreated acreage per subbasin. Percentage of impervious area was found using land use data, and percentage of untreated acreage was found by assuming the amount of impervious area treated by the BMP facilities documented by Albemarle County, the City of Charlottesville, and the University of Virginia (UVA). Further, land use and zoning data were used to determine land use percentages within each subbasin to inform SWMM modelling, as land uses have associated pollutant buildup values which can be used to simulate nutrient loadings after a storm event. The buildup values used in the SWMM model came from a relatively local watershed study for B. Everett Jordan Lake, a reservoir in North Carolina (Tetra Tech, 2003). Social need was determined through compiling demographic data from the U.S. Census, and the methods used for this analysis were based on a study completed by Mandarano and Meenar in that classified communities to determine where disadvantaged communities were located (2017).

In addition to these analyses of GIS data, background economic information, including guidelines for grant programs and presence of stormwater utility fees, was collected to determine any relevant incentives or disincentives for specific types of green infrastructure or for green infrastructure as a whole.

## A. Technical Characterization

### *Land Use*

An important consideration when assessing a given watershed is the current land use, as preliminary prioritization can be completed based upon results of SWMM modelling using anticipated pollutant loadings for subbasins. Two land cover datasets were used to characterize and provide context for hotspot identification, which were the National Land Cover Database (NLCD) and the Chesapeake Bay (CBay) Land Use Data. Each dataset provides advantages to the watershed analysis. The NLCD data differentiates between various levels of development and includes a land cover classification which allows the viewer to see what areas are developed open land, rather than general open land. CBay, on the other hand, provides higher resolution data which distinguishes between many pervious land cover classifications, allowing for more accurate pollutant loadings to be assigned and thus increasing the accuracy of the SWMM model (see Figure 2).

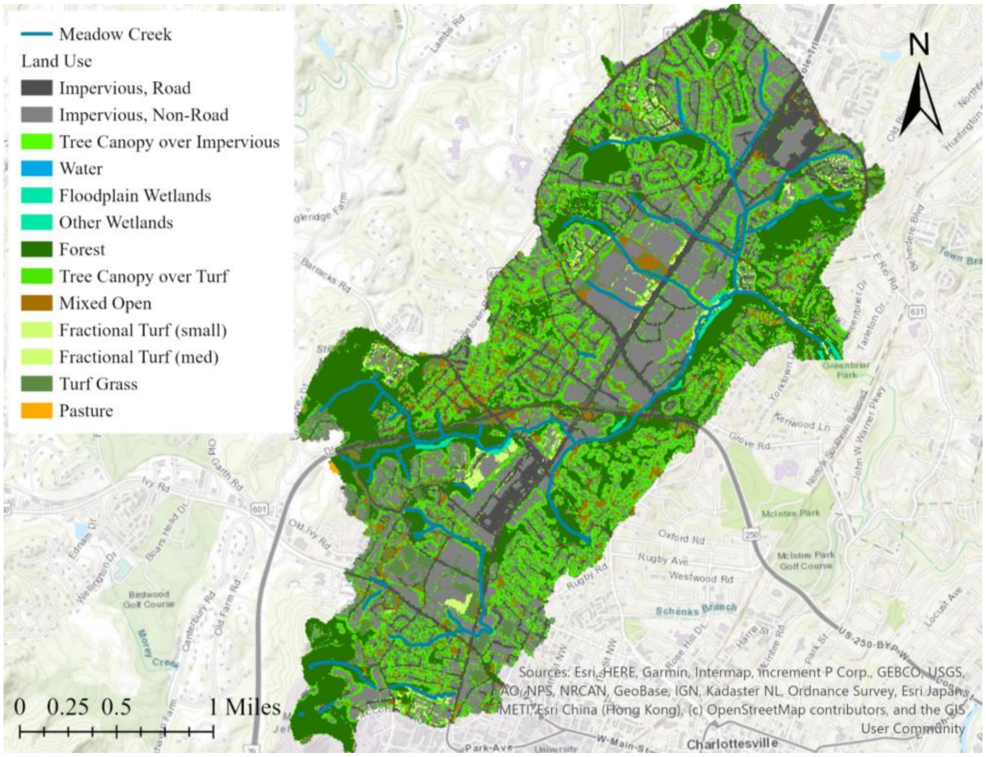


**Figure 2.** Chesapeake Bay (CBay) land use data for Meadow Creek watershed.

As seen in the above map, the majority of the watershed is impervious due to development along U.S. Route 29. The shopping centers along Route 29 are bordered mostly by residential areas and the roadways and open spaces which link them. Both land cover datasets identified developed, or impervious, land as being the most common land cover classification.

Using these results, subbasins which had comparatively high proportions of impervious cover were identified (see Figure 3). Doing so is important, as it illustrates which subbasins have a significant amount of stormwater runoff that is conveyed without infiltration opportunities that could reduce nutrient concentrations in the runoff. Two regions stand out: Seminole Square Shopping Center and Barracks Road Shopping Center. Seminole Square Shopping Center is composed of the northern concentration of impervious area, and Barracks Road Shopping Center is composed of the southern concentration of impervious area. This is most likely due to the large amount of surface parking provided for customers and employees at each location, as well as the fact that these developments were constructed prior to the establishment of enhanced stormwater management requirements. Additionally, it is important to note that the concentrated areas of impervious cover surround most of the tributaries to Meadow Creek, posing an increased threat to Meadow Creek's health due to close proximity and potential for untreated discharge.

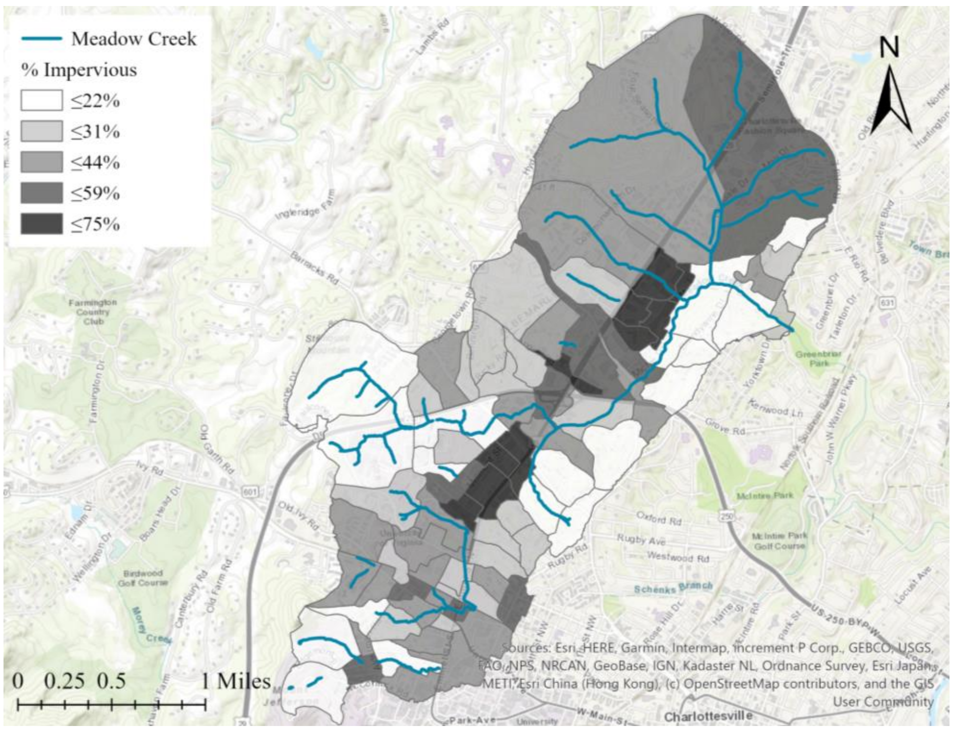


**Figure 3.** Percentage of impervious cover within Meadow Creek watershed subbasins.

To match pollutant loadings from the B. Everett Jordan Lake TMDL Watershed Model Development report to land uses of the subbasins within Meadow Creek watershed, the impervious land use categories provided by the NLCD and CBay data had to be further categorized into residential, commercial, and industrial areas. To do so, land use data was combined with zoning data for the City of Charlottesville and Albemarle County (Figure 4). To determine the impervious classifications which contributed to the impervious road areas, a 100 ft buffer was created in GIS to ascertain what pervious land uses and zoning bordered roadways. It was assumed that the land use and zoning that bordered the roadways approximated the associated pollutant loading of these roadways. The results of this analysis and the associated pollutant buildup values for nitrogen and phosphorus were entered into SWMM (see Appendix A). In the model, these values will determine the concentrations of these pollutants present in the runoff of each subbasin.

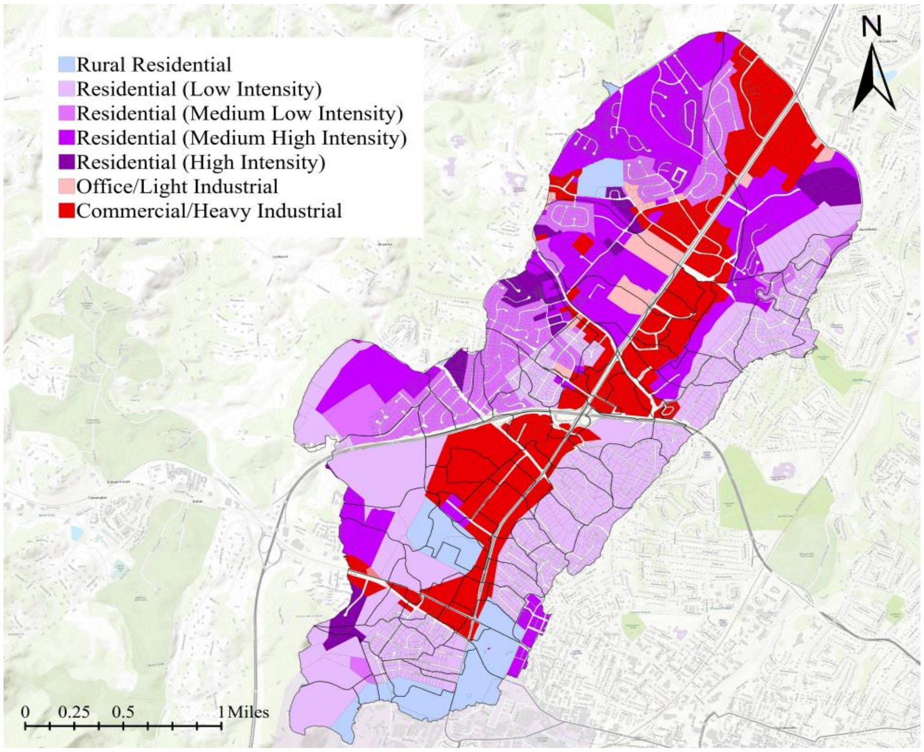


**Figure 4.** Zoning classification of Meadow Creek watershed.

The Meadow Creek watershed is constituted largely by residential zoning areas of various intensities, as denoted by the purple areas on the map above. Directly surrounding Route 29, however, there are high concentrations of commercial/heavy industrial areas. Just north of the U.S. Route 250 (Route 250) Bypass, these commercial/heavy industrial areas are bordered by medium/high intensity residential areas. This section of the watershed has high stormwater potential, due to the highly impervious land uses and the practices associated with these land uses.

***Fieldwork***

Beginning October 30th, students participated in weekly trips to 1-3 stations along Meadow Creek. Fieldwork involved taking discharge measurements using a portable velocity flow meter, as well as retrieving grab samples to measure nutrient concentrations. The discharge measurements will be used to develop rating curves for each of the stations along Meadow Creek, which will allow for the SWMM model of Meadow Creek to be accurately calibrated for a variety of storms. The grab samples will be used to more accurately characterize water quality in the SWMM model of the watershed by tracking spatial and seasonal trends of nutrient concentrations. Thus far, rating curves (see Figure 5 and Appendix B) have been developed for three of the nine stations along Meadow Creek (MC 4, MC 7, and MC Kip).

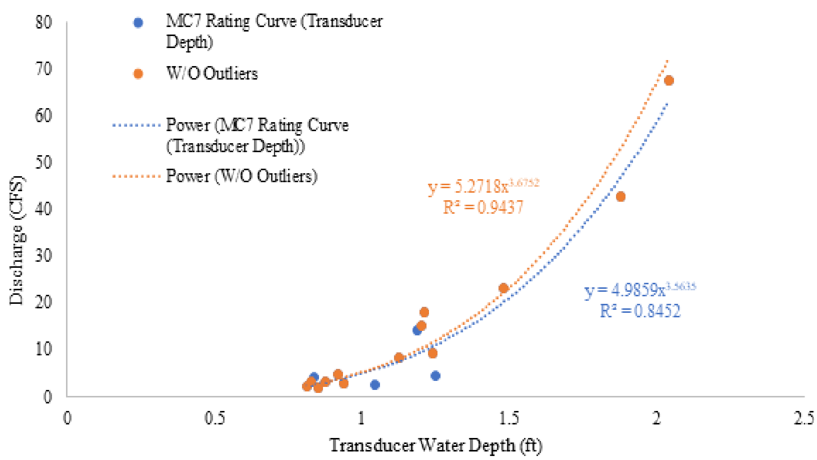


**Figure 5.** Rating curve produced for station MC 7 using results of fieldwork.

### *Untreated Acreage*

To understand if there is existing GI in Meadow Creek watershed and to what extent that GI treats the surrounding area where it is installed, the stormwater facilities documented by the City of Charlottesville, Albemarle County, and UVA were mapped using ArcGIS Pro. To determine what amount of area is currently being treated, an assumption for the contributing drainage area of each stormwater facility was made based upon the Virginia (VA) Best Management Practice (BMP) Clearinghouse guidelines. The total treated acreage within each subbasin was found and compared to the total area of the subbasins to determine the percentage of acres which are untreated. Figure 6 displays the results of this process and the points which represent the documented stormwater facilities (see Appendix C for detailed methodology and assumptions). It is important to note that many of these stormwater facilities correspond either to new developments along Route 29, such as the Shops at Stonefield, or to UVA properties, and that the majority of areas without stormwater facilities were developed prior to the establishment of more stringent stormwater management guidelines in recent years.

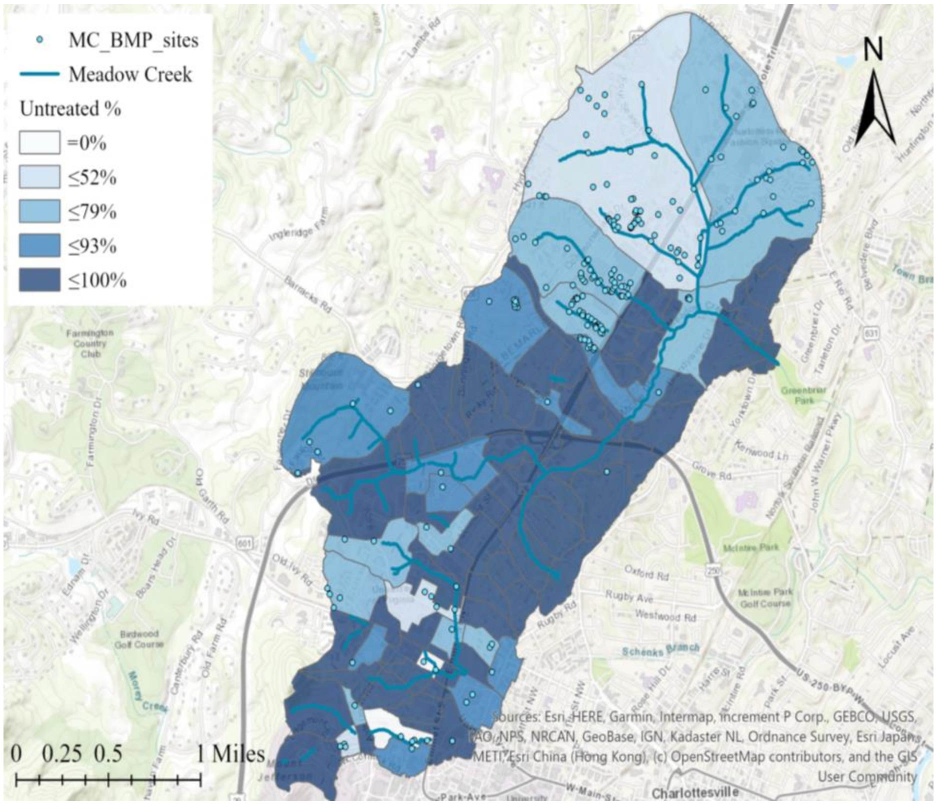


**Figure 6.** Percentage of untreated area within Meadow Creek watershed subbasins.

### B. Social Characterization

The social factors data analysis for this project was modeled after a study completed by Mandarano and Meenar (2017). In that study, they classified areas of Philadelphia, Pennsylvania based on community context and capacity variables to determine where disadvantaged communities are present and if they have the capacity to implement green stormwater infrastructure. Context variables include demographic data such as race, ethnicity, housing characteristics, income, violent crime, and children-household relationship. Capacity variables included presence of community organizations, education level, public property, and green space. For our purposes, only a context variable composite map of Meadow Creek was created, as capacity data was more limited for a watershed in comparison to a large city. The context variable data used in this study came from the U.S. Census and was downloaded at the block group level, which is the highest resolution format publicly available. For each context variable used, the number of people exhibiting that variable was divided by the total number of people in the block group, resulting in a percentage providing the prevalence of each variable in each block group. For example, the number of Asian people was divided by the total number of people in each block group to determine the percentage of Asian people in each block group. Then, the percentages were classified into five groups (1-5) using the Natural Breaks method, with 1 being the lowest magnitude of a variable and 5 being the highest. The violent crime data had to be processed in a different manner as it came from Charlottesville GIS Open Data instead of the U.S. Census. Detailed steps as to how the violent crime layer was created, as well as this process, can be found in Appendix D-1 and D-2. Once individual maps for each variable were created, a composite ranking was obtained by summing the ranks for each variable within a block group and then dividing by the total number of variables (see Figure 7).

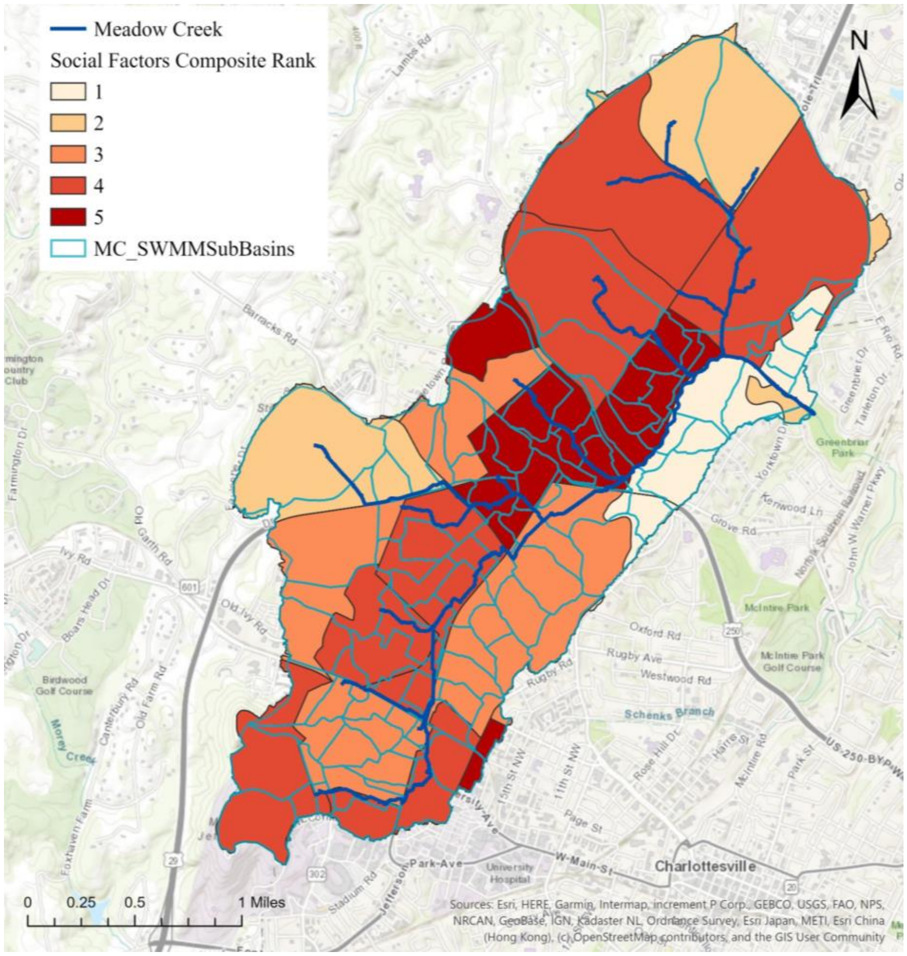


**Figure 7.** Composite ranking of social factors by U.S. Census block group in Meadow Creek watershed.

## C. Economic Characterization

The economic information found for Meadow Creek includes discussion and valuation of the direct and indirect benefits of stormwater facilities and Charlottesville-specific incentives and fees for stormwater management. An important consideration for this study is understanding the cost benefit analysis of green versus grey infrastructure; grey infrastructure being the traditional stormwater systems. To do so, one must consider the direct cost, indirect savings, and stormwater value generated throughout the infrastructure's life-cycle (Jaffe, 2010).

In developing a design for Meadow Creek, it is vital to consider the factors of private and public investments in GI, and it is especially important to understand how these investments are equitable for all communities, given community context and capacity to facilitate and manage these green projects. The public sector rarely owns enough of the impervious land, so government initiatives usually require the participation of private stakeholders to be successful. Underserved communities can be more difficult to facilitate engagement with, as they may require resources such as childcare or meals for their families in order to fully participate Nevertheless, it is important to build community trust and internal capacity because these communities often face the hardest environmental challenges.

The goal of GI programs is to reduce and manage stormwater flows to prevent flooding and improve water quality, as well as to achieve broader environmental and public benefits than traditional infrastructure. With these goals in mind, the added benefits include social outcomes, such as reduction in heat-related deaths and stress, promotion of physical activity, and improved safety. Economic outcomes include increased job creation, increased residential property values, and a reduction in infrastructure construction cost.

With green infrastructure improving the water quality, there comes added benefits such as better air quality, energy conservation, and greenhouse gas reduction. There are studies that value these diverted costs, such as the Intergovernmental Panel on Climate Change (IPCC), which found that $12 per million gallons of stormwater diverted attributed to carbon dioxide emissions avoided. Research has also found there to be an increase in property values when trees are planted. Evaluating these indirect costs comes with its complexities, as it is difficult to measure every indirect benefit associated with the development of green infrastructure since many are interconnected to other costs, causing the analysis to be extremely broad. Notably, grey infrastructure lacks indirect benefits and illustrates how GI can be significantly greater in value. However, GI's indirect benefits can take a long time to come to fruition, which makes it difficult to compare when evaluating in present terms (Vandermeulen, 2011).

The fundamentals of an economic analysis include a cost-benefit analysis, evaluating the Net Present Value (NPV) of the project to evaluate the risk associated with taking on the project, using a multiplier analysis which observes that an input (the GI) will have multiple output effects on the economy, such as labor, demand, and production (Vandermeulen, 2011).

The local incentives for types of GI in Virginia and the Charlottesville area are as follows. The Virginia Conservation Assistance Program (VCAP) has incentives corresponding to the treatment and control of stormwater runoff; bioretention facilities and infiltration chambers are reimbursed 75% of costs up to $15,000. Green roofs are also reimbursed up to $15,000. Impervious surface removal, vegetated stormwater conveyance channels, rainwater harvesting systems and permeable pavers are covered up to $10,000. Conservation landscaping, rain gardens and dry wells are reimbursed up to $3,500. Another incentive is green mortgages, which small businesses can apply for. These are loans to retrofit green infrastructure with the help of the U.S. Small Business Administration. A similar program is the Clean Energy Commercial Loan Fund which provides loans to small businesses owners investing in renewables, energy audits, and energy management controls.

There is a Charlottesville Stormwater Fee in which properties are charged for their impervious area. A program that can assist in lowering the initial cost of green roofs is the Green Roof Building Fee Reduction, in which a 50% reduction to the building permit fee is applicable to the construction of a "green roof" as defined by Virginia Code.

## D. Selection of Target Area

Based upon the results of these analyses to determine social and technical need, the team identified a target area. To visualize overlapping areas of high social and technical need, social and technical maps were combined to create a composite map which encompasses an equal weighting between percent imperviousness, percent untreated acreage, and the previously combined social factors (race, ethnicity, housing characteristics, income, violent crime, and children household relationship). Based upon these composite rankings (see Figure 8), the subbasins composing Fashion Square Mall, Seminole Square Shopping Center, Barracks Road Shopping Center, and the area surrounding Lambeth Field Apartments illustrate the highest sociotechnical need. Although each of the aforementioned regions should be factored into a holistic green infrastructure plan for this watershed, a set of 10-20 subbasins was desired for the subsequent optimization stage. Therefore, the team decided to target a cohesive unit of 20 subbasins within high need areas. This unit comprises the majority of Seminole Square Shopping Center and the Route 250 Bypass, and the subbasins within this target area are highlighted in Figure 8.

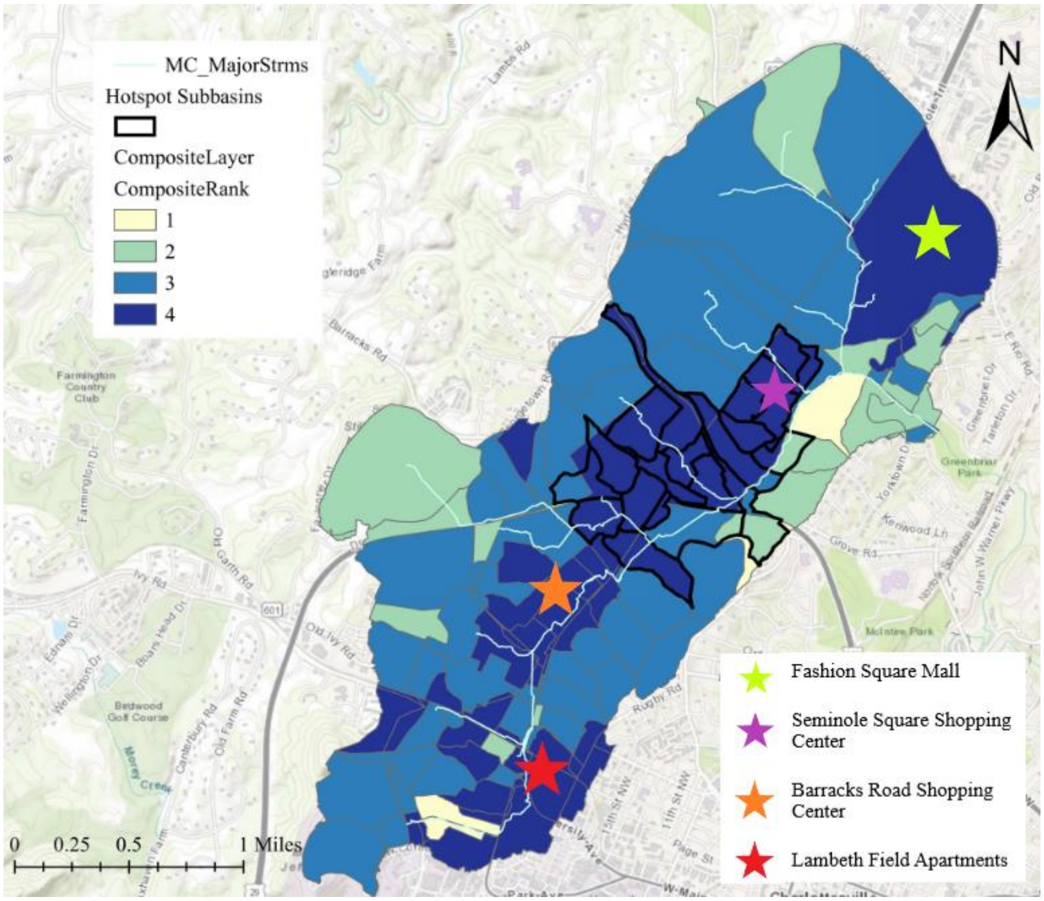


**Figure 8.** Sociotechnical rank for Meadow Creek watershed subbasins.

***Green Infrastructure Feasibility***

A primary consideration in developing an equitable green infrastructure plan in the Meadow Creek watershed is site feasibility. BMPs have specific design requirements related to site topography and the hydrologic landscape including minimum and maximum slopes, maximum contributing drainage areas, building setbacks, soil type, and land use. These specific design criteria, as stated in the VA BMP Clearinghouse guidelines, were used by Seth Herbst, the graduate student working with the team on this design project, to create maps of raster data displaying feasible area within the watershed for rain gardens, green roofs, and permeable pavement. The undergraduate team later developed feasibility layers for grass swales and larger bioretention systems using this same method. Raster cells which did not align with criteria were set to 0, and those which met criteria were set to 1. Using raster multiplication, feasible raster cells were found by identifying which cells remained after multiplication with a value equal to 1. Only sites that fit all five criteria listed above for each BMP type were accepted as feasible (see Figure 9). It is imperative for this project that target locations have comparatively high levels of green infrastructure feasibility.

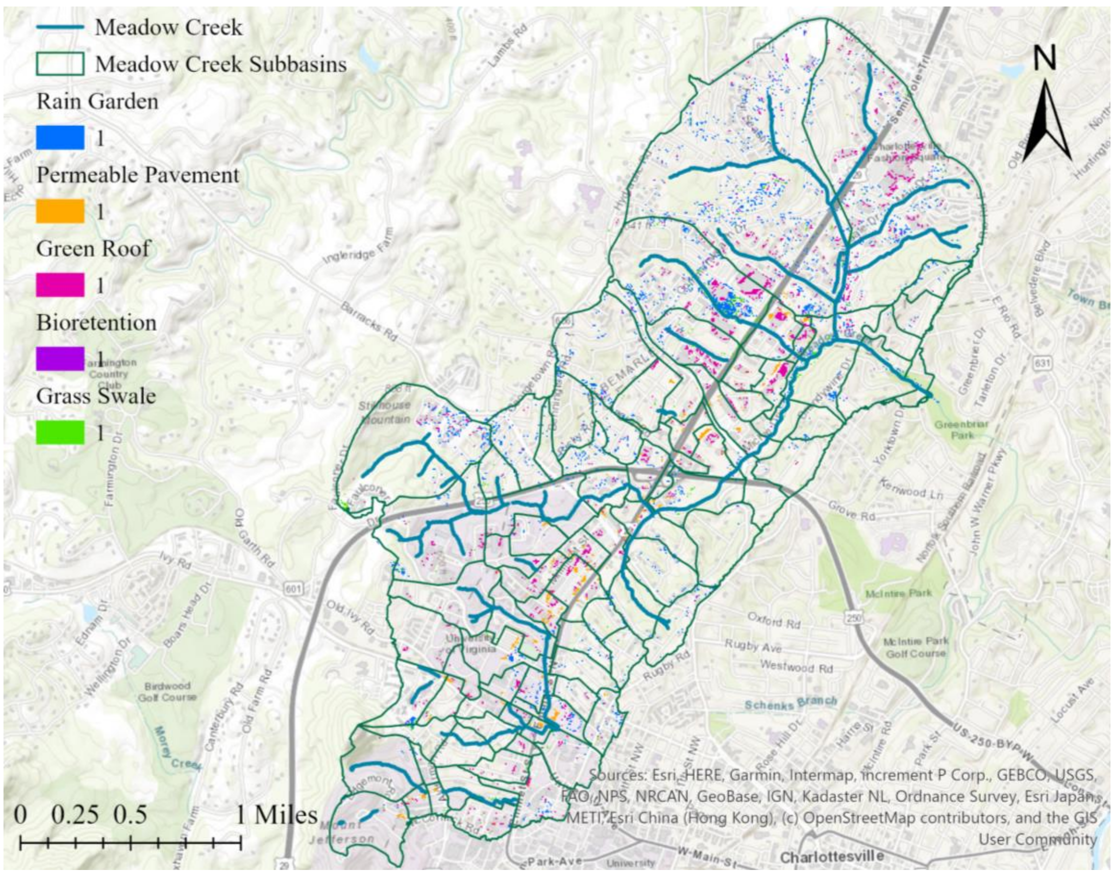


**Figure 9.** Feasible areas for rain gardens, permeable pavement, green roofs, bioretention systems, and grass swales in Meadow Creek watershed subbasins.

To better illustrate the overall density of feasible GI within the watershed and the target area, Figure 10 was developed. The density values were obtained by dividing the total potential area of green infrastructure within a subbasin by the total area of the subbasin. Successively darker green shading corresponds to increasing density of feasible green infrastructure spaces. Density was calculated to find which subbasins have the most potential per unit area, as it would be more feasible to design for smaller, more compact areas than larger subbasins where feasible areas are widely dispersed throughout the subbasin. Although there is an outlier subbasin located in Barracks Road Shopping Center that displays high feasible GI density, it was not integrated into the target area due to a lack of connectivity with other high potential areas in Seminole Square Shopping Center.

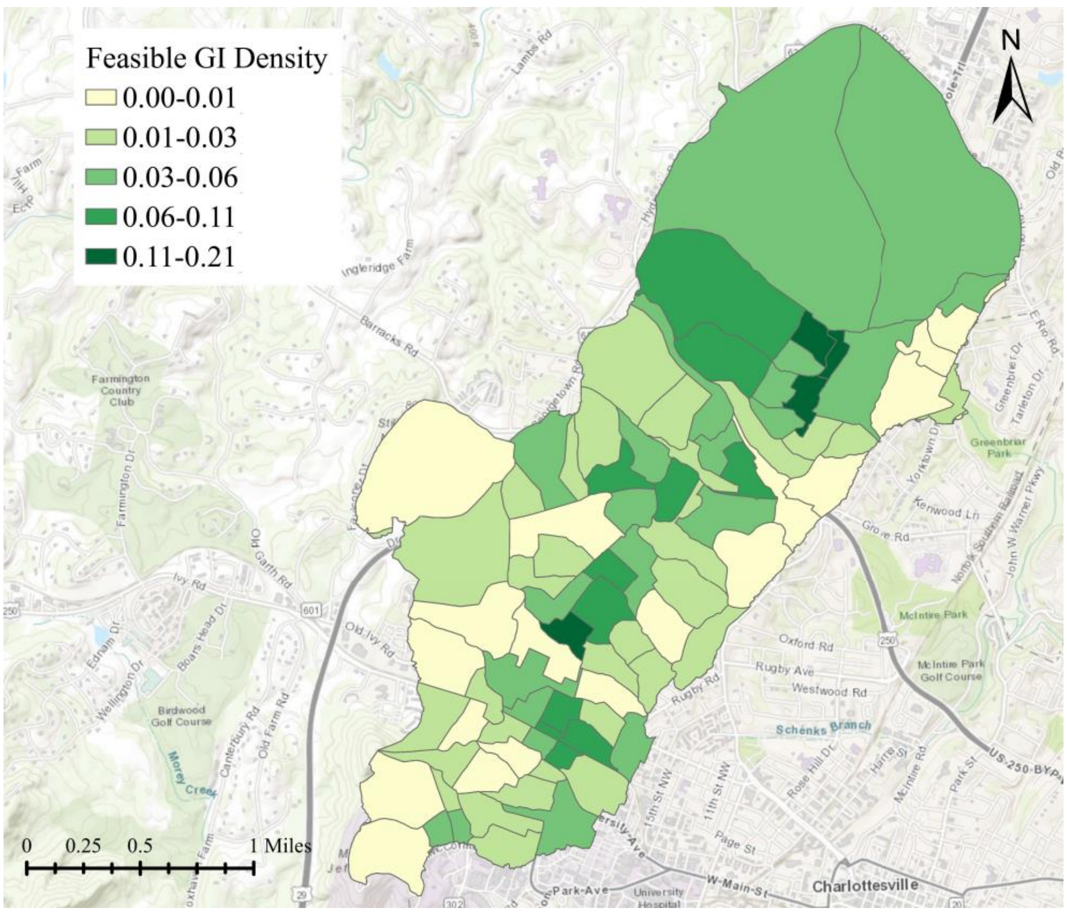


**Figure 10.** Feasible green infrastructure density of Meadow Creek watershed subbasins in terms of fractions.

Mild slopes, Hydrologic Soil Groups (HSG) A or B, and less buildings contribute to a higher feasible GI density. Associated land use was also a factor used to determine feasible areas, but both pervious and impervious land uses allow for various types of GI, so this would not significantly affect density. There appears to be some correlation between subbasin area and feasible GI, as the smaller subbasins within the middle of Meadow Creek watershed that compose the areas between Seminole Shopping Center and Barracks Road Shopping Center have high densities of feasible GI space. However, this correlation is weak because large subbasins that compose the Shops at Stonefield and Fashion Square Mall also exhibit a decent amount of feasible GI density. Rather, this correlation is most likely due to smaller subbasins composing a specific region within the watershed that contains compatible characteristics. It is important to note that feasible GI density should not be confused with existing GI density; the information displayed in Figure 10 only shows potential for rain gardens, green roofs, permeable pavement, bioretention systems, and grass swales. To provide the maximum amount of feasible space for input into PySWMM and to compare numerical results, the total feasible area within each subbasin was summarized for each type of GI (see Table 1).

**Table 1.** Feasible types of green infrastructure in target subbasins, ordered by subbasin number.

| Subbasin | Area (ac) | Rain Garden (ac) | Green Roof (ac) | Permeable Pavement (ac) | Grass Swale (ac) | Bio-retention (ac) | Total Feasible GI Space (ac) | Feasible GI Density (%) |
|---|---|---|---|---|---|---|---|---|
| 72591 | 21.36 | 1.28 | 0.05 | - | 0.05 | 0.02 | 1.40 | 6.55% |
| 72631 | 21.86 | 0.45 | 0.30 | 0.08 | 0.07 | 0.02 | 0.93 | 4.27% |
| 72671 | 23.23 | 1.01 | 0.03 | - | - | 0.02 | 1.07 | 4.59% |
| 72731 | 21.91 | 0.48 | 0.67 | 0.23 | - | 0.07 | 1.45 | 6.62% |
| 72781 | 37.88 | 0.53 | 0.17 | 0.29 | 0.00 | - | 0.99 | 2.61% |
| 72951 | 40.99 | 0.99 | 0.22 | 0.33 | 0.25 | 0.02 | 1.82 | 4.44% |
| 73081 | 35.16 | 0.32 | 0.49 | 0.22 | 0.17 | - | 1.21 | 3.43% |
| 73121 | 34.02 | 0.55 | 0.21 | 0.29 | 0.05 | 0.12 | 1.23 | 3.62% |
| 73171 | 15.55 | - | 0.37 | 0.22 | - | - | 0.60 | 3.85% |
| 73181 | 14.37 | 0.08 | 0.16 | 0.17 | - | - | 0.41 | 2.86% |
| 73201 | 21.18 | 0.21 | 0.70 | 0.69 | - | - | 1.61 | 7.60% |
| 73211 | 30.60 | 0.29 | 0.03 | 0.02 | - | - | 0.35 | 1.14% |
| 73301 | 31.68 | 0.01 | 0.38 | 0.40 | - | - | 0.79 | 2.50% |
| 73321 | 14.45 | 0.02 | 0.60 | 0.15 | - | - | 0.77 | 5.32% |
| 73391 | 17.50 | 0.22 | - | 0.02 | 0.23 | 0.02 | 0.50 | 2.85% |
| 73421 | 15.45 | - | 0.47 | 0.17 | - | - | 0.64 | 4.16% |
| 73461 | 16.26 | 0.13 | 1.64 | 0.59 | - | - | 2.36 | 14.53% |
| 73531 | 15.56 | 0.48 | 1.21 | 0.75 | - | 0.02 | 2.47 | 15.85% |
| 73551 | 13.85 | 0.26 | 0.23 | - | - | - | 0.49 | 3.57% |
| 73571 | 8.46 | 0.20 | 0.86 | 0.48 | 0.12 | 0.10 | 1.75 | 20.72% |

Nearly all subbasins within the target area have the potential to employ rain gardens, green roofs, and permeable pavement systems, but many do not have the potential to employ grass swales or bioretention systems. This is a result of the requirements used to generate feasibility layers, as grass swales and bioretention systems require both a larger setback from existing buildings and a larger contributing drainage area to be considered feasible.

## 4. PySWMM Optimization

The next stage of the project was to develop PySWMM scenarios to optimize the twenty subbasins composing the target area. However, due to technical difficulties with PySWMM resulting in only one undergraduate team member being able to run the entirety of the code, the team decided to further narrow down the subbasins to optimize to ensure a manageable workload for this team member. To begin this process, the base scenario reflecting the existing conditions for the subbasins in the target area was run, and runoff and nutrient loadings for each subbasin were compiled to determine the subbasins with the highest technical need (see Table 2). This scenario uses a 1-inch, 24-hour SCS Type II design storm. The results being compared include peak runoff, total runoff, total nitrogen (TN), and total phosphorus (TP). Areas are noted in Table 2, and results were also scaled by area to determine relative technical need. Each set of results has been formatted such that increasingly darker shading represents increasing magnitude.

**Table 2.** PySWMM results for the target area using the base scenario of existing conditions. Subbasin cells which are highlighted blue indicate the seven subbasins chosen for optimization.

| Subbasin | Areas (ac) | Peak Flow (CFS) | Peak Flow/Area (CFS/ac) | Total Runoff Volume (CF) | Total Runoff Volume/Area (CF/ac) | TN Load (g) | TN/Area (g/ac) | TP Load (g) | TP/Area (g/ac) |
|---|---|---|---|---|---|---|---|---|---|
| 72591 | 21.36 | 6.52 | 0.3053 | 21573 | 1010 | 210.90 | 2.27E-04 | 67.67 | 7.27E-05 |
| 72631 | 21.86 | 11.74 | 0.5371 | 39705 | 1817 | 654.52 | 6.87E-04 | 181.96 | 1.91E-04 |
| 72671 | 23.23 | 8.25 | 0.3552 | 27668 | 1191 | 379.70 | 3.75E-04 | 128.49 | 1.27E-04 |
| 72731 | 21.91 | 13.60 | 0.6207 | 47384 | 2162 | 678.72 | 7.11E-04 | 194.86 | 2.04E-04 |
| 72781 | 37.88 | 14.80 | 0.3907 | 50077 | 1322 | 683.93 | 4.15E-04 | 212.70 | 1.29E-04 |
| 72951 | 40.99 | 11.88 | 0.2899 | 39284 | 958 | 320.88 | 1.80E-04 | 92.41 | 5.18E-05 |
| 73081 | 35.16 | 15.36 | 0.4367 | 51659 | 1469 | 835.49 | 5.46E-04 | 269.21 | 1.76E-04 |
| 73121 | 34.02 | 15.65 | 0.4600 | 63325 | 1861 | 1181.83 | 7.98E-04 | 372.98 | 2.52E-04 |
| 73171 | 15.55 | 10.94 | 0.7037 | 37063 | 2383 | 649.07 | 9.58E-04 | 183.42 | 2.71E-04 |
| 73181 | 14.37 | 9.92 | 0.6901 | 38669 | 2691 | 839.10 | 1.34E-03 | 227.67 | 3.64E-04 |
| 73201 | 21.18 | 12.63 | 0.5961 | 45619 | 2154 | 828.54 | 8.98E-04 | 226.41 | 2.45E-04 |
| 73211 | 30.60 | 11.99 | 0.3920 | 40660 | 1329 | 438.40 | 3.29E-04 | 126.87 | 9.52E-05 |
| 73301 | 31.68 | 15.21 | 0.4801 | 57276 | 1808 | 1271.55 | 9.21E-04 | 366.29 | 2.65E-04 |
| 73321 | 14.45 | 11.45 | 0.7928 | 40647 | 2814 | 903.09 | 1.44E-03 | 230.94 | 3.67E-04 |
| 73391 | 17.50 | 4.65 | 0.2656 | 15323 | 875 | 145.82 | 1.91E-04 | 44.26 | 5.80E-05 |
| 73421 | 15.45 | 14.05 | 0.9098 | 47784 | 3094 | 1050.62 | 1.56E-03 | 262.65 | 3.90E-04 |
| 73461 | 16.26 | 13.72 | 0.8440 | 49319 | 3034 | 1201.68 | 1.70E-03 | 310.46 | 4.38E-04 |
| 73531 | 15.56 | 12.75 | 0.8194 | 44181 | 2840 | 925.46 | 1.37E-03 | 239.79 | 3.54E-04 |
| 73551 | 13.85 | 11.11 | 0.8026 | 38728 | 2797 | 811.94 | 1.35E-03 | 210.89 | 3.50E-04 |
| 73571 | 8.46 | 6.08 | 0.7181 | 22943 | 2711 | 971.18 | 2.63E-03 | 127.44 | 3.46E-04 |

It is important to note that the unscaled highest peak flow, total runoff, TN, and TP typically correspond to subbasins of the greatest area, yet the scaled results do not correspond to these same subbasins. To investigate the optimization outcomes which would correlate to subbasins with high unscaled results and to subbasins with high scaled results, three of the largest area subbasins were chosen (73081, 73121, and 73301) alongside four of the subbasins with higher relative contributions (73421, 73461, 73531, and 73571). These four subbasins constitute the central region of Seminole Square Shopping Center.

After determining which subbasins to use in the optimization, the last step to finalize the code was to input unit costs for each type of GI with a feasibility layer. The cost calculations were estimated through referencing multiple cost estimation reports for capital and operation and maintenance costs and adjusted for location to Virginia and inflation (see Appendix E). Using these results (see Table 3), cost calculations were developed based upon the cost unit. Rain gardens, bioretention systems, and grass swales were calculated based upon the square footage of impervious drainage area (IMP DA) which they were expected to treat, while green roofs and permeable pavement were calculated based upon the square footage of each system. To determine specific costs for green roofs and permeable pavement, specifications employed during the creation of LID controls in the PySWMM code were used to differentiate between design options. From these, it was found that green roofs best resembled extensive green roofs, and that permeable pavement best resembled porous concrete.

**Table 3.** Unit costs for different types of green infrastructure.

| Type of LID | Base Unit Cost | Cost Unit |
|---|---|---|
| Rain Garden | $2.34 | /sf IMP DA |
| Bioretention | $2.34 | /sf IMP DA |
| Grass Swale | $1.45 | /sf IMP DA |
| Green Roof | $11.66 | /sf green roof |
| Permeable Pavement | $9.79 | /sf permeable pavement |

The employed scenarios were based upon altering the amount of assigned area for each type of GI in each subbasin (see Appendix F). The maximum allowable area which could be assigned was based upon the total feasible area for each type of GI within a given subbasin. Therefore, the amount of treatment provided by GI in this analysis is limited primarily by the feasible GI area and the assumptions used to create the feasibility layers and corresponding LID controls in SWMM. Scenarios were run for each subbasin, starting with existing conditions, where no feasible GI is employed, and ending in the condition where 100% of feasible GI is employed. For each subbasin, total costs for each scenario were calculated, as well as total reduction of peak runoff, runoff volume, TN, and TP. To determine the optimal percentage of employed feasible GI for each subbasin, a cost-benefit curve (see Figure 11) for total percent reduction associated with each scenario was produced using a similar methodology to that of the multi-objective watershed optimization conducted by Eckart, McPhee, & Bolisetti (2018). Total percent reduction was calculated using the sum of percent reductions for peak runoff, runoff volume, TN, TP, and mean runoff. Figure 12 shows the corresponding percent reduction of only TP per subbasin per scenario.

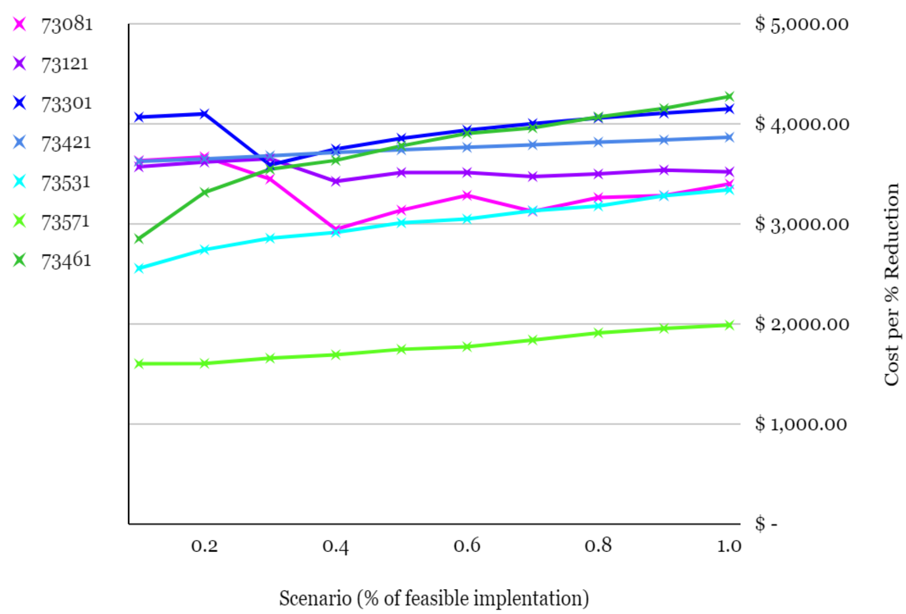


**Figure 11.** Cost per % reduction ($) versus PySWMM scenario (% of feasible implementation).

The majority of subbasins exhibit a positive linear relationship between cost per percent reduction and percentage of feasible GI implemented, which is expected, as implementing more GI is expected to cost more. However, subbasins 73081, 73301, and 73121, which are the three largest subbasins, display a downward trend before increasing linearly like the other, smaller subbasins. These downward ticks are due to large increases in the percent reductions of TP and TN (see Appendix F-3). These increases could be attributed to the increase of types of GI that effectively remove more runoff than other practices, as SWMM currently only models the reduction in runoff mass load based on the reduction in runoff flow volume (U.S. EPA, 2015). The types of GI which allow for infiltration and removal in SWMM are grass swales, bioretention, rain gardens, and permeable pavement. Comparing the types of feasible GI for 73081, 73301, and 73121 versus types of feasible GI for the other subbasins, they have significantly more feasible area for permeable pavement and rain gardens, which are two of the practices necessary for infiltration in SWMM. Although the remaining four subbasins have feasible area for practices with infiltration, those practices may not be as effective or may not constitute a significant amount of area within the subbasin. However, the PySWMM optimization code must be altered to output more thorough cost-related results to determine the root of the cause and explain the nonlinear trend. Another notable trend is that subbasin 73571 appears to be significantly more cost-effective than any other subbasin at every level of feasible implementation by approximately $1,000 per scenario. This is most likely due to the high feasible GI density in this subbasin as well as the significant feasibility of each type of GI, where more than half of the feasible area is composed of practices capable of infiltration. Lastly, for each subsequent scenario, the cost per percent reduction only increases slightly. The average difference between the cost per percent reduction at 10% and 100% implementation is $376.33, which is about 10% of the average total cost per percent reduction at 10% implementation.

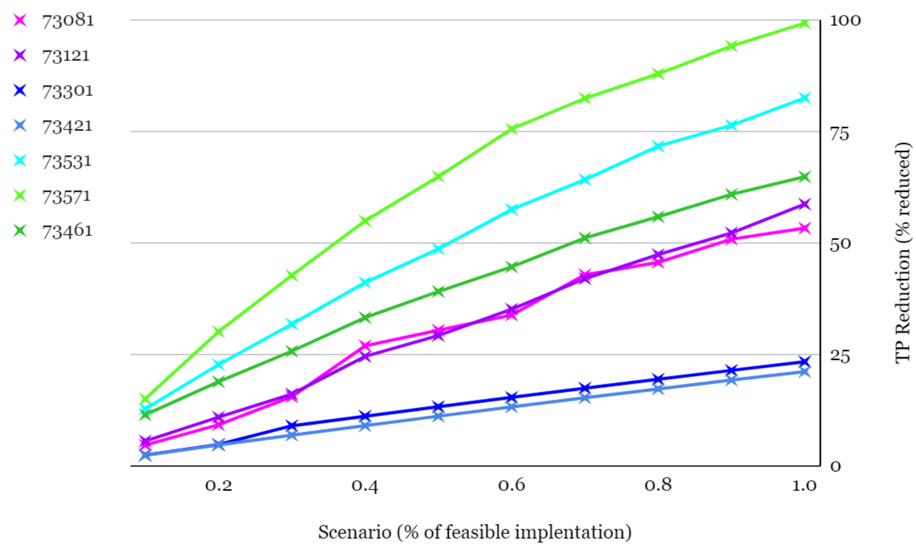


**Figure 12.** Total phosphorus (TP) reduction (% reduced) versus PySWMM scenario (% of feasible implementation).

Based on the above figure, all subbasins also exhibit a roughly positive linear relationship between percent TP reduction and percentage of feasible GI implemented, which is expected due to the linear increase in feasible GI space being implemented. Larger increases in percent TP reduction, and thus larger slopes between two points, correspond to the downward trends seen for subbasins 73081, 73121, and 73301. As aforementioned, these increases reduce cost per percent reduction for a given scenario.

Table 4 details a summary of the optimization results for the most cost-effective scenario for each subbasin, including total cost and total and percent reduction of peak runoff, runoff volume, and TP. Table 5 displays the types and amounts of feasible GI employed for the scenarios given in Table 4. From these results, reduction efficiency amongst the most cost-effective scenarios can be compared. Considering that the most cost-effective scenarios for subbasins 73081 and 73121 implement 40% of feasible GI, the associated percent reduction is significantly larger than most other subbasins. However, subbasins 73531 and 73571 have comparable percent reductions even though only 10% of feasible GI is implemented for these subbasins. In Table 5, these subbasins are seen to implement similar percentages of feasible GI for their respective cost-effective scenarios, which accounts for the observed level of reduction. Thus, subbasins 73531 and 73571 should be highly prioritized in future GI planning of Meadow Creek watershed, especially since these subbasins have a smaller associated area and involve less coordination than deploying GI in larger subbasins like 73081 and 73121. Subbasins 73301, 73421, and 73461 each have relatively low percent reduction associated with the most cost-effective scenario. The decreased efficiency of GI in these subbasins is due to the type of feasible GI being implemented; none of these three subbasins have a significant amount of feasible area for rain gardens, grass swales, or bioretention systems, which increase the infiltration potential of a subbasin. Subbasin 73421 is especially inefficient, as there is no infiltration of stormwater runoff by green roofs, which comprise 73% of the implemented GI. Finally, it is important to remember that a larger percentage of feasible GI area within a subbasin will always improve its efficiency, as a larger amount of GI will be implemented in all scenarios. This is observed for both subbasins 73531 and 73571, as these subbasins had the highest and second highest feasible GI densities.

**Table 4.** Summary of most cost-effective solutions based upon the sum of percent reductions for peak runoff, runoff volume, TN, TP, and mean runoff.

| Subbasin | Cost per % Reduction ($) | Scenario | Peak Runoff Reduction (CFS) | Peak Runoff Reduction (%) | Runoff Volume Reduction (CF) | Runoff Volume Reduction (%) | TP Reduction (g) | TP Reduction (%) | Total Cost ($) |
|---|---|---|---|---|---|---|---|---|---|
| 73081 | $ 2,946.76 | 0.4 | 1.75 | 11.41% | 6728 | 13.02% | 72.53 | 26.94% | $ 268,876.83 |
| 73121 | $ 3,425.86 | 0.4 | 2.85 | 18.21% | 11046 | 17.44% | 91.61 | 24.56% | $ 350,187.16 |
| 73301 | $ 3,589.15 | 0.3 | 0.63 | 4.17% | 2553 | 4.46% | 33.04 | 9.02% | $ 111,314.31 |
| 73421 | $ 3,624.91 | 0.1 | 1.31 | 1.31% | 632 | 1.32% | 6.25 | 2.38% | $ 31,246.48 |
| 73461 | $ 2,852.80 | 0.1 | 0.62 | 4.53% | 3157 | 6.40% | 35.67 | 11.49% | $ 114,851.00 |
| 73531 | $ 2,556.35 | 0.1 | 0.95 | 7.43% | 3252 | 7.36% | 30.71 | 12.81% | $ 122,446.18 |
| 73571 | $ 1,602.22 | 0.1 | 0.59 | 9.74% | 2400 | 10.46% | 19.19 | 15.06% | $ 92,670.37 |

**Table 5.** Summary of employed green infrastructure for most cost-effective solutions.

| Subbasin | Area (ac) | Scenario | Rain Garden (ac) | Green Roof (ac) | Permeable Pavement (ac) | Grass Swale (ac) | Bio-retention (ac) | Total GI Space (ac) | Implemented GI Density (%) |
|---|---|---|---|---|---|---|---|---|---|
| 73081 | 35.16 | 0.4 | 0.128 | 0.196 | 0.089 | 0.069 | - | 0.482 | 1.37% |
| 73121 | 34.02 | 0.4 | 0.219 | 0.086 | 0.118 | 0.020 | 0.049 | 0.492 | 1.45% |
| 73301 | 31.68 | 0.3 | 0.004 | 0.115 | 0.119 | - | - | 0.238 | 0.75% |
| 73421 | 15.45 | 0.1 | - | 0.047 | 0.017 | - | - | 0.064 | 0.42% |
| 73461 | 16.26 | 0.1 | 0.013 | 0.164 | 0.059 | - | - | 0.236 | 1.45% |
| 73531 | 15.56 | 0.1 | 0.048 | 0.121 | 0.075 | - | 0.002 | 0.247 | 1.59% |
| 73571 | 8.46 | 0.1 | 0.020 | 0.086 | 0.048 | 0.012 | 0.010 | 0.175 | 2.07% |

## 5. Site-Scale Design for Select Subbasin

### A. Subbasin Selection

To choose one of these seven subbasins to design, PySWMM results, community visibility, proximity to Meadow Creek, and preliminary estimates of TP reduction required (found using VRRM) were assessed.

From the PySWMM optimization, subbasins 73531 and 73571 would be prioritized over the other subbasins due to the high percent reduction achieved when implementing 10% of feasible GI. Moreover, 73571 had the lowest associated cost per percent reduction, and 73531 had the second lowest associated cost per percent reduction. These subbasins are also smaller in area and thus more feasible to design for due to less coordination between property owners and a more limited space to propose GI facilities.

Visibility in this context refers to how often the surrounding community would visit the subbasin and is largely based on the businesses and amenities present. Visibility is an important factor for success of GI, as demonstration projects are vital for increasing awareness and implementation. Additionally, GI system maintenance is typically prioritized according to visibility, as property owners and government officials desire to minimize potential backlash or complaints from community members. Community visibility of each subbasin was assessed and ranked relatively. A close-up view of the seven subbasins is depicted in Figure 13. As seen in this map, subbasins 73121 and 73301 run parallel to Hydraulic Road, which is heavily trafficked; subbasins 73421, 73461, 73531, and 73571 are all primarily accessed by Route 29; and subbasin 73081 is largely residential and thus accessed only by local roads. All subbasins except 73081 are used mostly for commercial and light industrial purposes. Within this group, subbasins 73301, 73461, and 73531 have the highest visibility due to the presence of popular stores and restaurants, such as Whole Foods Market, Marshalls, Sushi King, Outback Steakhouse, and Plaza Azteca. It should also be noted that one of the reasons contributing to the high social need in this region is the presence of Hearthwood Apartments along Michie Drive, located between subbasins 73301 and 73461, as many community residents are low-income, racial/ethnic minorities.

Concerning proximity to Meadow Creek, subbasins 73461, 73571, and 73531 either include or are directly adjacent to longer stretches of Meadow Creek. Due to their high percentage of impervious area, the stormwater runoff generated at these subbasins, as well as any stormwater runoff conveyed to these subbasins, will accumulate pollutants and will not undergo any significant treatment for quantity or quality before entering the stream. Thus, these subbasins pose a critical threat to the health of Meadow Creek.

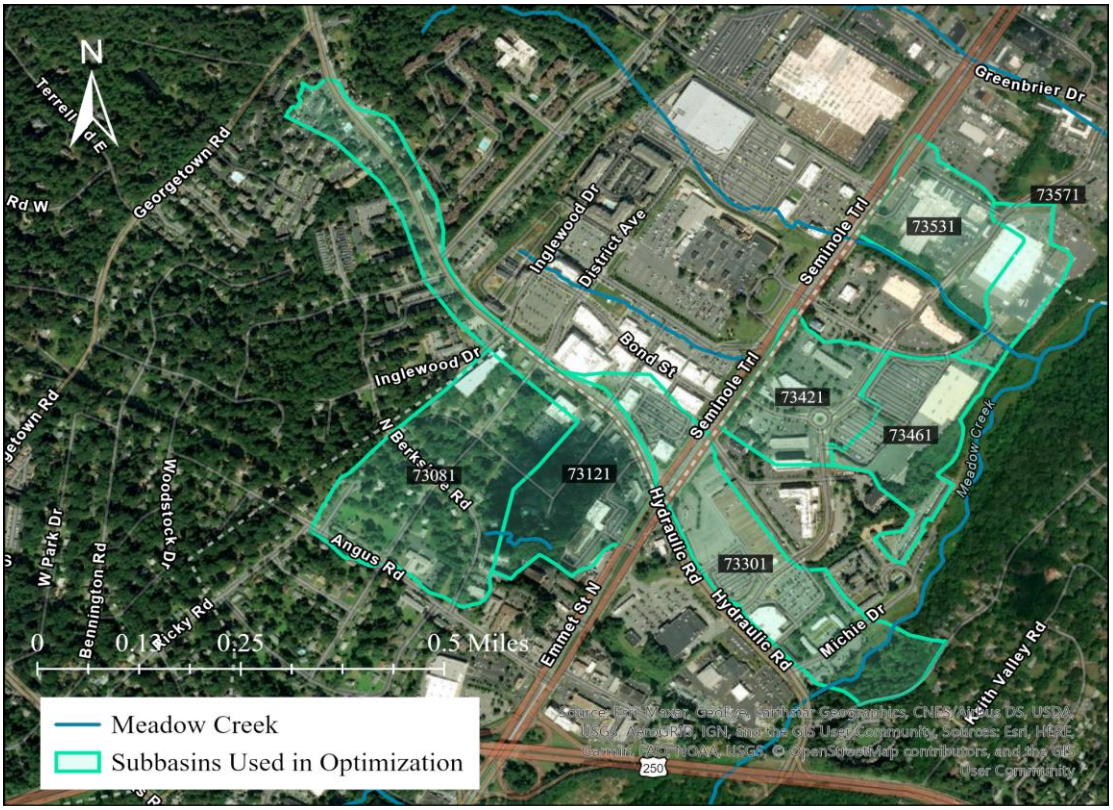


**Figure 13.** Detailed view of subbasins used in the PySWMM optimization.

Using VRRM, subbasins were analyzed in terms of existing conditions to determine the TP reduction required in terms of pounds per year (lb/yr) and in terms of the scenario employed in PySWMM that corresponds to 100% of feasible GI being implemented. The latter scenario allowed for a preliminary estimate of how effective feasible GI would be for meeting the Virginia goal for TP, which is 0.4l lb/yr, as well as an estimated cost for GI. After inputting soil and land use data for the existing conditions of these subbasins, subbasins 73081, 73121, and 73301 were observed to have the highest total TP reduction required, and subbasins 73421, 73461, and 73571 were observed to have the highest TP reduction required per acre. The feasible GI for the 100% implemented scenario of each subbasin was then input into VRRM to determine the amount of TP reduced and the percentage of TP left to address, and the associated cost as predicted by PySWMM was also noted (see Table 6). Subbasins 73081, 73121, and 73571 have the highest TP reduction rates for the 100% scenario and the lowest costs per amount of TP removed. On the other hand, subbasins 73421 and 73301 have the highest costs per amount of TP removed and the lowest TP reduction rates for the 100% scenario.

**Table 6.** VRRM results for scenario where 100% of feasible GI is implemented for six of the subbasins used in the PySWMM optimization. Light blue shading denotes the three subbasins with the highest TP reduction required per area, and teal shading denotes the three subbasins with the highest total TP reduction required.

| Subbasin | Area (ac) | Feasible GI Density | TP Reduction Required (lb/yr) | TP Reduction Required (lb/yr/ac) | TP Reduction for 100% (lb/yr) | % TP Reduction Not Complete | Total Cost for 100% ($) | Cost/TP for 100% ($/lb/yr TP) |
|---|---|---|---|---|---|---|---|---|
| 73421 | 15.45 | 4.16% | 24.24 | 1.57 | 1.35 | 94% | $312,464.82 | $231,455.42 |
| 73461 | 16.26 | 14.53% | 24.03 | 1.48 | 6.95 | 71% | $1,148,510.00 | $165,253.24 |
| 73571 | 8.46 | 20.72% | 12.62 | 1.49 | 9.57 | 24% | $926,703.67 | $96,834.24 |
| 73081 | 35.16 | 3.43% | 24.64 | 0.70 | 11.94 | 52% | $672,192.08 | $56,297.49 |
| 73121 | 34.02 | 3.62% | 34.64 | 1.02 | 19.26 | 44% | $875,467.91 | $45,455.24 |
| 73301 | 31.68 | 2.50% | 40.75 | 1.29 | 1.52 | 96% | $371,047.69 | $244,110.32 |

Using the results of each of these analyses, subbasin 73571 was chosen as the subbasin to develop a site-scale design for. The PySWMM optimization identified this subbasin as the most cost-effective per percent reduction of peak runoff, runoff volume, TN, TP, and mean runoff. Also, this subbasin is more practical to design for due to its small area and high percentage of feasible GI. Although its visibility is not as high as those with more frequently visited businesses, community members visiting Seminole Shopping Center will most likely encounter part of this subbasin as they conduct their business. Further, this subbasin is in close proximity to Meadow Creek and has the shortest direct distance of any of the seven subbasins to the stream. According to the VRRM results, subbasin 73571 also has a high amount of TP reduction required per acre, is the closest of the subbasins to meeting the goal for TP, and has a median cost per TP removed.

### *Subbasin Characterization*

Subbasin 73571 has 1.75 acres of HSG B soil and 6.71 acres of HSG D soil, with surface slopes ranging from 0% to 25%. The breakdown of land use for VRRM prior to BMP implementation is shown in Table 7. The majority of the site is relatively flat, but steeper slopes occur in the northwestern portion and southeastern portion of drainage area A. The water in drainage area A outfalls to the east whereas the water from drainage area B flows more towards the southeast. Also, HSG D dominates the majority of the site; only soils at the northern tip and eastern edge of the site classify as HSG B.

**Table 7.** Pre-BMP land cover for subbasin 73571.

| Land Cover Type | HSG B | HSG D | Total |
|---|---|---|---|
| Forest/Open Space (ac) | 0.01 | 0.02 | 0.04 |
| Managed Turf (ac) | 0.57 | 0.75 | 1.32 |
| Impervious Cover (ac) | 1.17 | 5.93 | 7.10 |
| Total (ac) | 1.75 | 6.71 | 8.46 |

Elevation and slope data were used to determine the flow paths within the subbasin (see Figure 14). Based on these flow paths, the site was divided into two drainage areas, which roughly correspond to two parcels, one owned by Pepsi-Cola (drainage area A) and the other owned by University Tire and Auto Center (drainage area B).

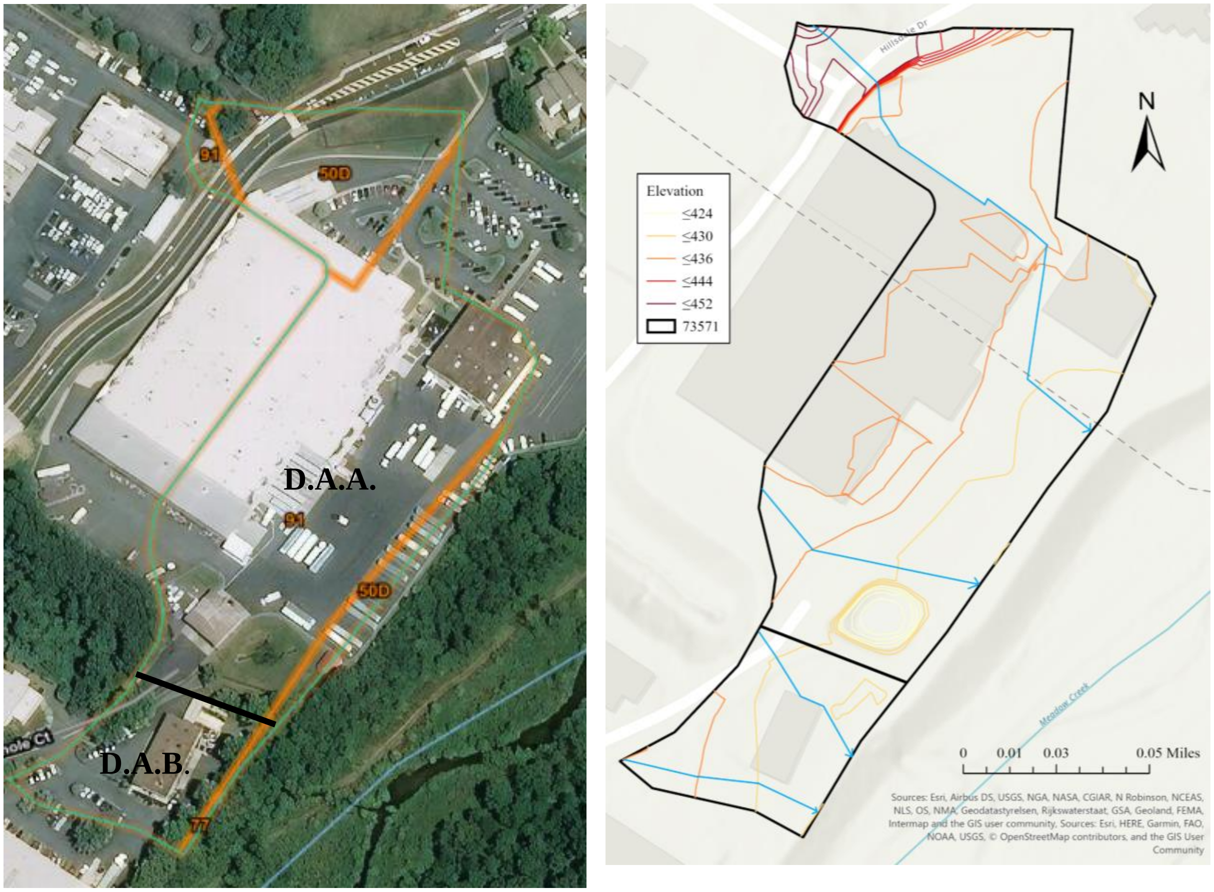


**Figure 14.** Delineation between drainage areas A and B (left) based upon flow paths (right).

To determine runoff characteristics for this site using SWMM, NOAA 1-year, 24-hour and 2-year, 24-hour cumulative design storms were inputted into the SWMM model along with these site characteristics. The cumulative precipitation of 1-year, 24-hour storm and 2-year, 24-hour storm in this subbasin are 3.03 and 3.68 inches, respectively. The resultant pre-BMP hydrographs, which show the peak total outflow, are shown in Figures 15 and 16 below. The peak for the 1-year, 24-hour storm was 11 cfs, and the peak for the 2-year, 24-hour storm was found to be 14 cfs.

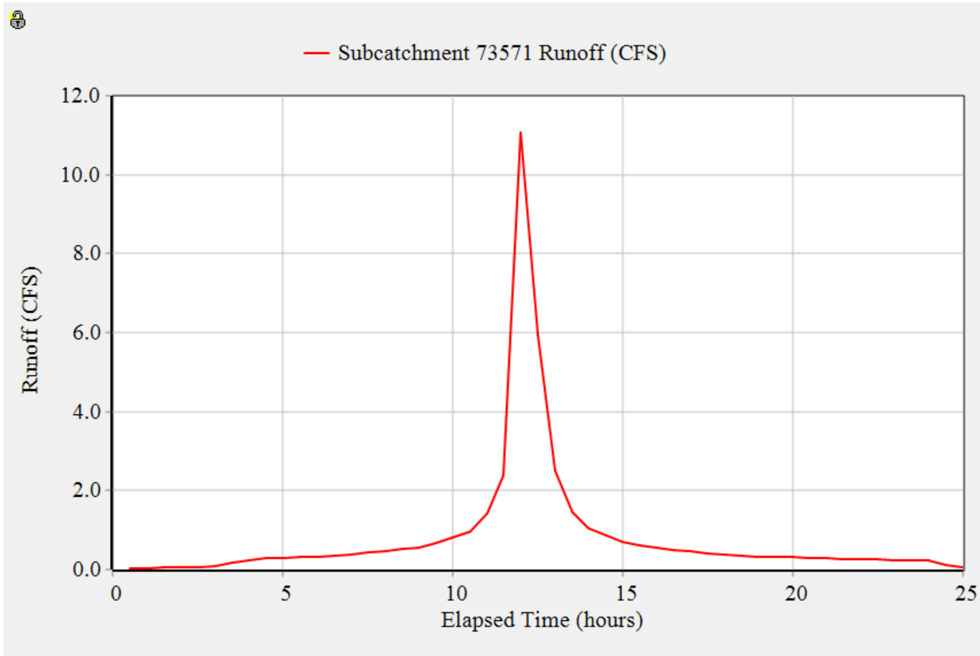


**Figure 15.** 1-year, 24-hour pre-BMP hydrograph for subbasin 73571.

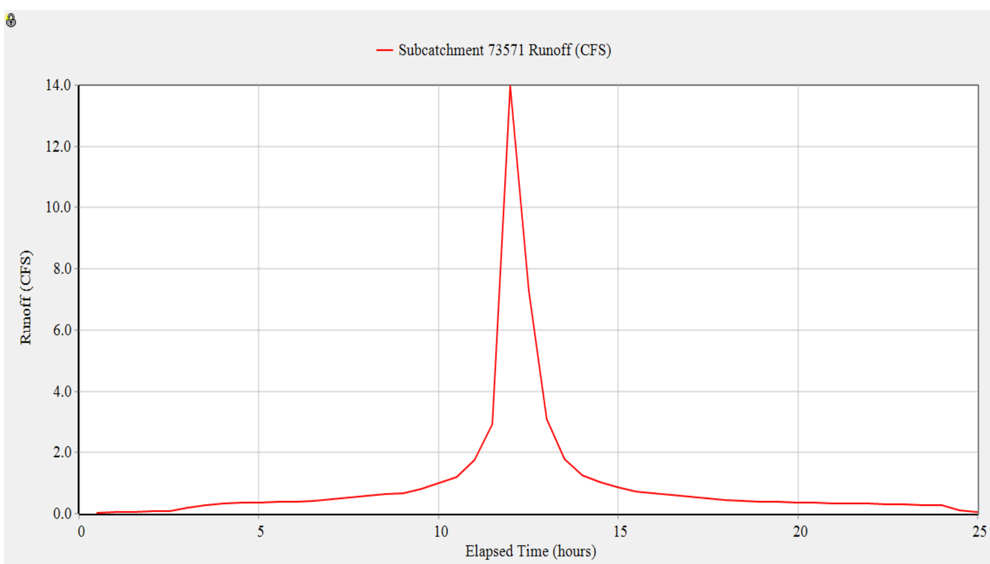


**Figure 16.** 2-year, 24-hour pre-BMP hydrograph for subbasin 73571.

## B. Green Infrastructure Selection

To design for the subbasin, the GI feasibility layers were consulted (see Figure 17). The feasibility layers previously created were for green roofs, bioretention, rain gardens, permeable pavement, and grass swales. Because there was a steep TP reduction goal to achieve, it seemed best to implement each type of BMP from the feasibility layers. It is important to note that an assumption in designing these feasibility layers was that up-gradient building setback distances were used to be conservative. When moving forward with design, the down-gradient building setback distance was used wherever possible.

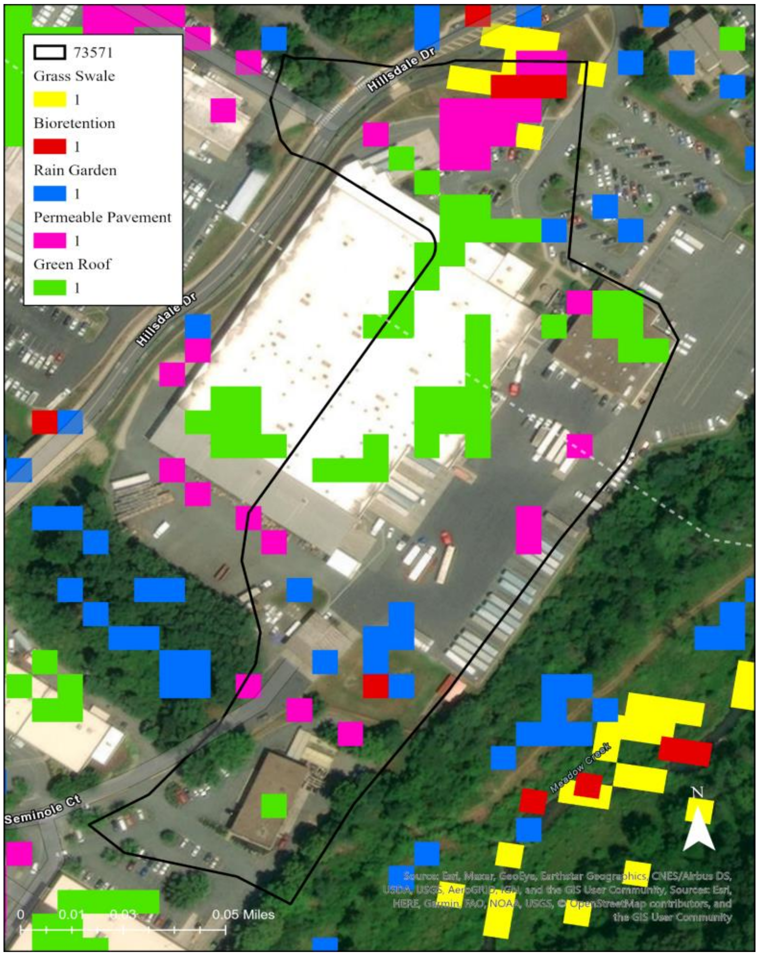


**Figure 17.** GI feasibility layers for subbasin 73571.

## C. Green Infrastructure Design

Rain gardens and bioretention are the most effective BMP types for TP removal, so it was important to implement them wherever feasible. Two level-2 bioretention units were placed on the northern side and two were placed on the southern side of drainage area A. Level-2 rain gardens were placed alongside the northern side of the buildings between the buildings and the parking lot. These rain gardens will likely capture some runoff from the adjacent roof and the water that would have fallen on the existing grassy areas. A rooftop disconnect system was not able to be designed for this area because the majority of the water entering the rain garden would have been from the roof. The specifications for a rooftop-disconnect rain garden notes that the contributing area can only be 25% impervious, which this area exceeds.

Level-2 permeable pavement was placed at numerous locations around the site. The permeable pavement was located in areas designated for parking or storage because that is typically where permeable pavement is implemented to avoid excessive wear and clogging due to consistent traffic. In locations where the existing ground slope is steeper than 1%, it was assumed the pavement would be regraded to accommodate the 0% slope requirement for permeable pavement. This should not contribute to poor drainage, as the permeable pavement allows for water to infiltrate in the areas where it is installed. Because this site is composed primarily of impervious area, it seemed beneficial to replace significant portions of asphalt with permeable pavement to reduce runoff.

Level-2 green roofs were placed on each of the three roofs in the subbasin. To obtain enough surface area to meet the required treatment volume, the team decided to use the whole Pepsi-Cola roof and thus add the additional roof area from subbasin 73531 to the design subbasin. These changes in area are reflected in the post-BMP VRRM worksheet. However, this area was not included in the pre-BMP VRRM because it was assumed that the area of the roof within subbasin 73531 drained within the subbasin. The green roofs were challenging to design due to the number of obstacles on the roofs of each of these buildings, but adequate distance between the vegetation and obstacles, such as HVAC equipment and skylights, was provided.

To further reduce runoff and phosphorus loads, a level-2 grass swale was placed along an existing grass median in drainage area B. This grass swale will capture and treat stormwater along the road. While this area did not appear on the GI feasibility map, the slope along the area where the grass swale will be placed was measured in GIS to be 1% which is desirable for this type of green infrastructure. It is recommended that onsite testing be done to ensure that this is a viable option.

All of the above systems are shown in plan view in context of the site in Figure 18.


**Figure 18**. Plan view of site-scale design for subbasin 73571.

### *Green Roofs*

Figure 19 below shows the section view for the level-2 green roofs. Features such as the leak detection system, thermal insulation, and the lower layer of filter fabric are optional and the owners of the roofs can determine if they want to have these features for their green roof systems.

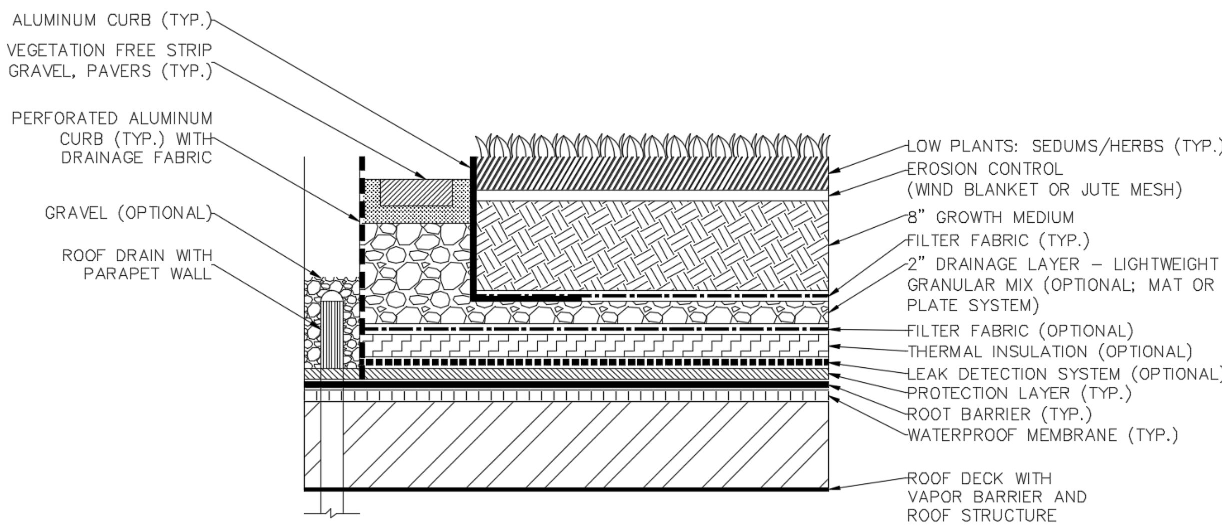


**Figure 19.** Section view of green roof design.

A media depth of eight inches was selected for the green roofs because that is the maximum media depth for an extensive green roof. Extensive green roofs are lighter than intensive roofs, and since the exact capacity for additional weight is unknown, the lighter option was selected. The calculations to determine treatment volume were based on VA BMP Clearinghouse specifications and can be found in Appendix G-4.

**Table 8.** Design specifications for green roofs.

| Design Criteria | Drainage Area A | Drainage Area B |
|---|---|---|
| Contributing Area (sf) | 108,900 | 4,356 |
| Treatment Volume (cf) | 9,483 | 379 |
| Media Depth (in) | 8 | 8 |
| Required Surface Area (sf) | 56,900 | 2,276 |
| Provided Surface Area (sf) | 56,957 | 2,342 |

### *Bioretention & Micro-Bioretention*

The ponding depth was selected at 6 inches, the lowest maximum ponding depth value given by the BMP specifications, to be conservative. The filter media depth was selected as 36 inches to meet the requirement. The mulch layer was selected as 3 inches to provide the maximum benefits of this layer, that is enhancing plant survival, inhibiting weed growth, and pre-treating runoff. These details are displayed in Figure 20 below.

The team was unable to perform soil testing on site. However, the VA BMP Clearinghouse specifications list that HSG B soils typically have an infiltration rate higher than 0.5 inches per hour whereas HSG D groups do not. Therefore, the bioretention units in HSG D soils will have underdrains whereas those located on HSG B soil do not.

The purpose of pretreatment according to the bioretention design specifications is to remove large particles that could clog the filter bed. Additionally, they must evenly spread runoff across the entire width of the bioretention area. According to the VA BMP Clearinghouse specifications, level-2 bioretention units require a pretreatment cell plus one of the following: a grass filter strip, gravel diaphragm, gravel flow spreader, or another approved (manufactured) pre-treatment structure. A gravel diaphragm was selected because it is better for steeper slopes and

Bioretention 4 is located at the bottom of a hole. Level-2 rain gardens are required to have external pretreatment, such as leaf screens or energy dissipators, plus a grass filter strip. A leaf screen and a grass filter strip were selected for this design.

For level-2 bioretention design, a planting plan with turf, herbaceous vegetation, shrubs, and trees is required to achieve surface area coverage of at least 90% within two years. For level-2 rain gardens, a planting plan including two of the four following vegetation types are required: turf, herbaceous vegetation shrubs, or trees. According to the VA BMP Clearinghouse specifications, planting plans should be prepared by a qualified landscape architect who will take into account site-specific conditions.

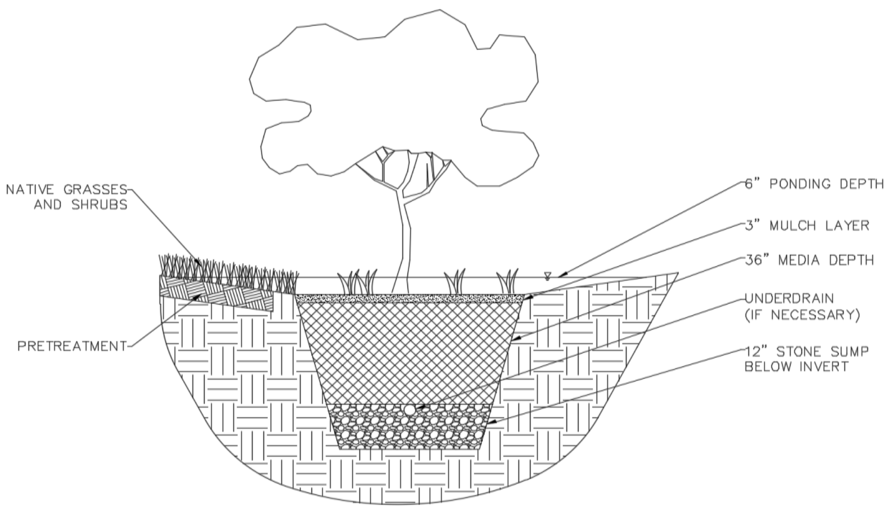


**Figure 20.** Section view of bioretention design.

Details for the sizing of these bioretention and micro-bioretention units are shown in Table 9 below (see Appendix G-4 for calculations). Because Bioretention 3 and Bioretention 4 are located in areas with HSG Type D soils, they will require an underdrain.

**Table 9.** Design specifications for bioretention and micro-bioretention systems.

| Design Criteria | Level 2 Bioretention | Level 2 Microbioretention |
|---|---|---|
| Sizing | $T_{VBMP}$= 13,004 $ft^3$<br>Surface area = 7881.21 sq ft | |
| Design Areas (sf) | Bioretention 1: 2,563<br>Bioretention 2: 1,454<br>Bioretention 3: 1,610<br>Bioretention 4: 1,991 | Rain Garden 1: 661<br>Rain Garden 2: 355<br>Rain Garden 3: 885<br>Rain Garden 4: 578 |
| Total Proposed Area (sf) | 7,618 | 2,479 |
| Contributing Drainage Area (ac) | 4.18 | 0.28 |
| Ponding Depth (in) | 6 | 6 |
| Filter Media Depth total (in) | 36 | 36 |
| Media and surface cover | 3-inch layer of mulch | 3-inch layer of mulch |
| Sub-Soil Testing | 0.05-0.5 inch per hour<br>Underdrain required for<br>Bioretention 3 and Bioretention 4 | 0.5 inch per hour |
| Pre-treatment | Pretreatment cell and gravel diaphragm | Leaf screen and grass filter strip |

***Permeable Pavement***

This subbasin is 83.9% impervious predevelopment, with a significant portion of that area designated for parking. Because of this, this design recommends the implementation of eight permeable pavement units in drainage area A (P1-P8), and one in drainage area B (P9). Specifications for the design of these permeable pavement units are shown within the table below (see Appendix G-4 for calculations).

**Table 10.** Design specifications for permeable pavement.

| Design Criteria | Drainage Area A | Drainage Area B |
|---|---|---|
| Contributing Area (sf) | 66,211<br><br>P1: 5,227<br>P2: 1,307<br>P3: 3,920<br>P4: 6,098<br>P5: 6,534<br>P6: 32,670<br>P7: 4,356<br>P8: 6,098 | 6,970 |
| Treatment Volume ($ft^3$) | 5,242 | 552 |
| Media Depth (ft) | P1: 0.77<br>P2: 0.71<br>P3: 0.74<br>P4: 0.77<br>P5: 0.76<br>P6: 0.76<br>P7: 0.74<br>P8: 0.74 | 0.80 |
| Surface Area (sf) | P1: 2,069<br>P2: 1,307<br>P3: 3,920<br>P4: 6,098<br>P5: 6,534<br>P6: 13,072<br>P7: 1,800<br>P8: 2,515 | 2,600 |

### *Grass Swale*

Because this area has a 1% slope, no check dams are required to manage flow. The side slopes of this grass swale are 4H:1V, with a bottom width of 2 ft and top width of 10 ft. Because this area is characterized as HSG Type D soils, an underdrain will be required. Further design specifications for the grass swale are shown in Table 11 below (see Appendix G-4 for calculations).

**Table 11.** Design specifications for grass swale.

| Design Criteria | Drainage Area B |
|---|---|
| Contributing Area (sq ft) | 18,295 |
| Treatment Volume ($ft^3$) | 1,194 |
| Filter Media Depth total (in) | 36 |
| Infiltration Sump Depth (in) | 12 |
| Storage Depth (ft) | 1.15 |
| Required Surface Area (sf) | 1,142 |
| Provided Surface Area (sf) | 1,740 |
| Sub-Soil Testing | 0.05 inch per hour |
| Pre-treatment | Tree check dams |

## D. SWMM Model

The updated SWMM model for Meadow Creek contains all of the LID controls within the site-scale design for subbasin 73571. These LID controls were added to this subbasin in SWMM according to the SWMM 5.1 user's manual. For the post-BMP analysis, the total area of subbasin 73571 was updated to 10.11 acres to include the total Pepsi-Cola roof area, along with the subsequent increase in percent impervious. This was altered because the design will have the total roof area draining to subbasin 73571. This decrease in roof area for subbasin 73531 was reflected by a decrease in percent impervious in the SWMM model. As shown in Figure 21 below, the peak total outflow of a 1-year, 24-hour storm was reduced to around 6.5 cfs. The peak total outflow of a 2-year, 24-hour storm was 14.9 cfs (see Figure 22). This slight increase in peak outflow between pre- and post-BMP implementation could be attributed to the increase in impervious area from the added section of roof.

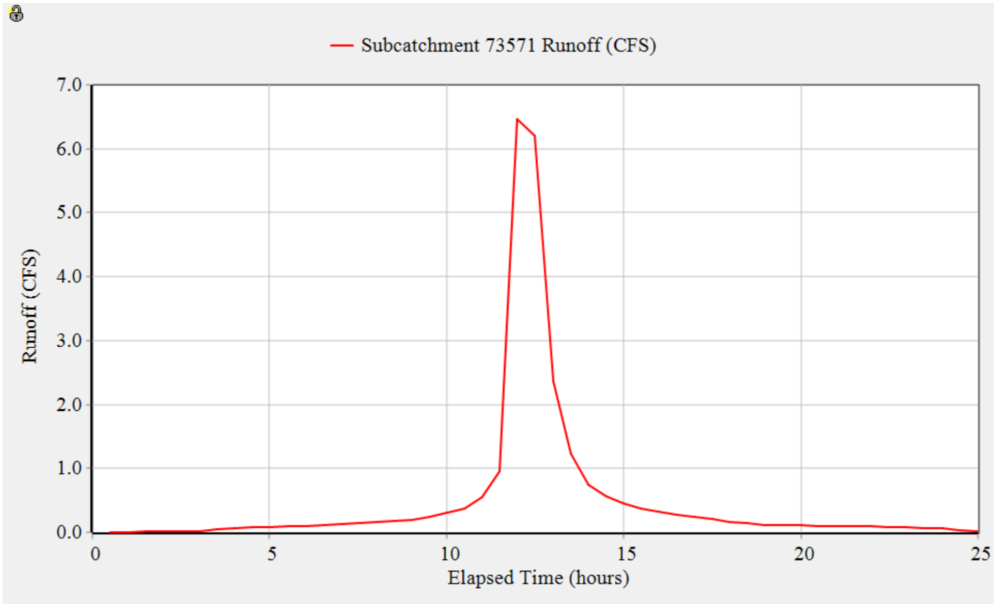


**Figure 21.** 1-year, 24-hour post-BMP hydrograph for subbasin 73571.

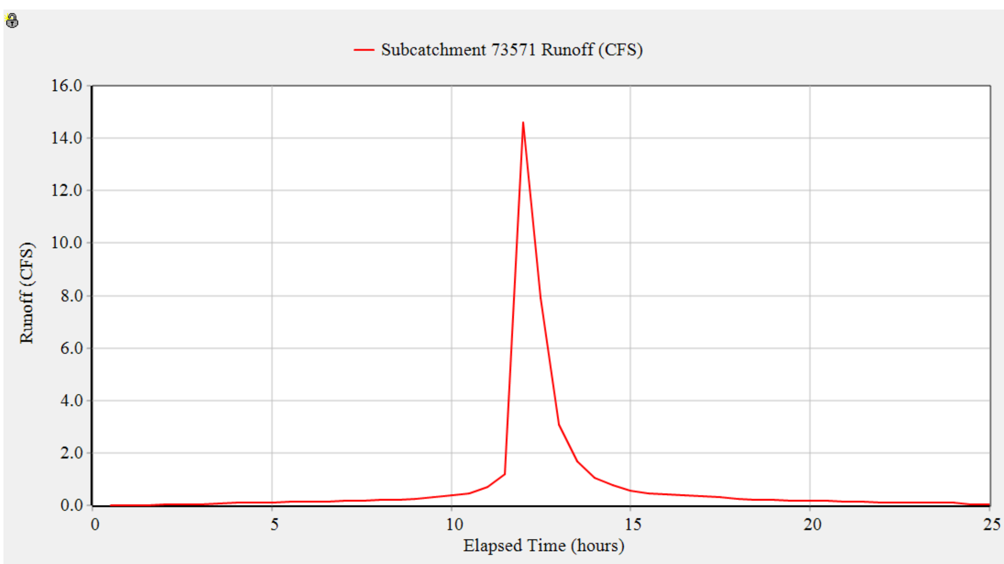


**Figure 22.** 2-year, 24-hour post-BMP hydrograph for subbasin 73571.

While there is still a remaining TP load reduction requirement of 1.12 lb/year post-BMP to achieve the Virginia standard for new development of 0.41 lb/ac/yr TP, the design achieved a 73% reduction in TP and 73.6% reduction in TN. More in-field data collection should be conducted in order to identify any other potential sites for green infrastructure to help meet the TP reduction requirement. Nevertheless, this reduction exceeds that of the redevelopment goal for a given site, which is 10% if the total disturbed acreage is less than 1 acre and 20% if the total disturbed acreage is greater than or equal to 1 acre. Additionally, this BMP site plan resulted in a 60% energy reduction for a 1-year, 24-hour storm and a 21% energy reduction for a 2-year, 24-hour storm (see Tables 12 and 13), thus exceeding the goal of a 20% energy reduction for the subbasin.

**Table 12.** Energy surrogate pre- and post-BMP development for a 1-year, 24-hour storm.

| Scenario | Peak Discharge (cfs) | Runoff Volume (gal) | (Qp*RV) | Reduction (%) |
|---|---|---|---|---|
| Pre-BMP | 11.05 | 560,000 | 827,215.2655 | 60 |
| Post-BMP | 6.50 | 380,000 | 330,190.965 | |

**Table 13.** Energy surrogate pre- and post-BMP development for a 2-year, 24-hour storm.

| Scenario | Peak Discharge (cfs) | Runoff Volume (gal) | (Qp*RV) | Reduction (%) |
|---|---|---|---|---|
| Pre-BMP | 14.00 | 690,000 | 1,291,354.12 | 21 |
| Post-BMP | 14.90 | 510,000 | 1,015,838.492 | |

## 6. Community Outreach

To incorporate the community perspective of GI projects and gather local knowledge, the team developed a community engagement plan that will help inform the recommendation for GI implementation. To initiate the early stages of this plan, the team completed and submitted the project's iProtocol to the UVA IRB-SBS for its pre-review process (see Appendix H). Before contact can be made to potential participants in the study, the IRB-SBS must approve of this human subjects research protocol to ensure that adequate measures are in place to protect the rights and welfare of its subjects. Therefore, one of the primary objectives in developing this protocol was minimizing risk to study subjects. This included addressing any sources of limitations to a subject's ability to consent. Since minors are not able to provide legal consent, the subject pool was restricted to legal adults. The participant pool for this outreach includes adult residents and employees of the region along U.S. 29 bounded by Barracks Road Shopping Center and Seminole Square Shopping Center. The inclusion of employees in local businesses added another possible limitation to consent if employees felt that their job status was contingent on their participation in the study. The team addressed this by including in the Electronic Study Information Page that participation was anonymous and completely voluntary.

The main data source for this study is a Qualtrics survey with questions aimed at receiving feedback from community members on the preferences concerning stormwater development (see Appendix I). One of the study questions requires participants to rank GI based on aesthetic appeal. Feedback on this question will provide the project team with an avenue for quantifying aesthetic value in GI. The survey was verified by ExpertReview automatically to ensure that it was WCAG accessible, mobile compatible, an adequate duration, etc. An informational flyer was created according to IRB requirements as a recruitment tool for the study. The flyer briefly describes the subject of the research, specifies the age requirement (adults 18+), and lists the link to the Qualtrics survey (see Appendix J). Additionally, an electronic study information page followed by an option to consent to the study was created as the consent tool in the iProtocol. Because this study does not include any deception or withholding of information, the project is required to create a document for debriefing.

The iProtocol was approved on April 9, 2021. Responses will continue to be collected until early May and will be attached in Appendix K, which is to be reviewed in conjunction with the results from this report. Local organizations which allowed for the posting of a flyer or communication to associated personnel included Whole Foods Market, Minerals and Mystics, Panera Bread, Pepsi Bottling Company, and Barnes and Noble.

**7. Limitations**

The recommendations provided in this report are meant to serve as a preliminary watershed analysis for future GI planning in Meadow Creek watershed. Each of the four areas of work which were focused upon involved making limiting assumptions.

The data used for the GIS analysis which guided the selection of a target area was ultimately limited by the associated resolution. For the technical analysis, this resolution was defined by the subbasins, and for the social factors analysis, this resolution was defined by the U.S. Census block groups. The inherent assumption of using these forms of data is that the subbasin or block group is homogeneous, which is known to not be accurate in many cases. For block groups, this is especially important because not every block group fits entirely within the watershed, and the portion of the block group within the watershed may not contain the same percentage of a variable that the whole block group does.

Additionally, the stormwater facilities data used to determine untreated acreage was last updated in 2018, so any new facilities were not accounted for. This may especially affect subbasins associated with UVA, as various stormwater projects have and will be built to comply with the requirements of the DEQ for operating a MS4. Moreover, the assumptions made for each of the stormwater facilities do not accurately reflect the contributing drainage area, as the recommended average contributing drainage area was taken to be the area treated. Lastly, the efficiency and conditions of each facility were not investigated, meaning some facilities may be underperforming.

The feasibility of the various GI types used was based primarily upon the specifications listed in the VA BMP Clearinghouse guidelines. However, to be conservative, the upslope maximum setback was used to determine the required building setback distance, and this potentially eliminates or underestimates the feasible site areas for the various GI types (BMPs). Additionally, the various drainage areas will need to be examined individually to verify reported land uses. Similarly, field investigations will need to be conducted at the selected site(s) to verify soil data is accurate by measuring infiltration rate. These feasibility layers cannot be used as a replacement for onsite measurement. Other limitations for the feasibility layers included a lack of publicly available GIS data. Currently, no GIS data is available which documents roof gradients for buildings in the watershed, so the digital elevation model (DEM) data, which documents the gradient of the ground, had to be used instead to provide slopes for feasible area. Also, the permeable pavement feasibility layer had to rely upon the location of parking lots, as there is no available GIS map documenting driveways in this watershed. In conclusion, these maps are meant for screening of feasible areas that likely meet all the requirements for specific types of GI as recommended by the BMP Clearinghouse and not meant to be understood as final design recommendations. Rather, the feasibility layers are meant to aid in targeting areas where future GI could be located.

The broad optimization completed using PySWMM is also affected by the limitations of the feasibility layers generated for various types of GI, as these feasibility layers were employed to determine maximum feasible area for each type of GI within the target area subbasins. Further the costs used in the optimization did not include land costs, which may be required to acquire easements located on private property. Additionally, the optimization is limited by the translation of specifications from the VA BMP Clearinghouse to LID controls used in SWMM to model these systems, as SWMM requires the input of more parameters than the Clearinghouse outlines for standard design. Within SWMM, each of the LID controls that correspond to a feasible type of GI is set to treat a standardized drainage area, which would need to be determined on a case-by-case basis for increased accuracy. For rain gardens, this area is set to 0.5 acres, and for bioretention systems and grass swales, this area is set to 5 acres. Drainage area for permeable pavement systems and green roofs are more accurate, as these systems have explicit drainage areas and are thus more easily modeled. For instance, green roofs can only address the area of the roof they are assigned. As previously mentioned, SWMM models water quality treatment based on infiltration potential and treatment efficiencies, which assume a certain percent of nutrients will be removed by a given LID. However, this is not fully representative of water quality treatment, as other factors must be considered to determine removal efficiencies, such as water residence time and microbiologic community present. Recognizing these assumptions, this method is meant to be a screening tool which allows for subbasins where GI could have the highest hydrological impact to the stream to be identified.

There were many limitations related to the site-scale design. One limitation is that current, detailed topography was not available for this area. The contours used to design the BMPs were downloaded from Charlottesville's Open GIS data website, and the most recent data was from 2018. This contour data was not ideal to design off because it is not very high resolution and contours ran through buildings. This is an issue because the first floor of a building should be flat, so the contour data must not do a great job of modeling the land surrounding buildings. Furthermore, site visits were not possible, so the team was unable to identify where drains are or where obstacles such as utility poles or generators may be. Another limitation is that the amount of additional weight the roofs of these buildings can handle was unknown. Additionally, it was challenging to design the green roofs as there were so many objects on the roofs to avoid. Because only aerial imagery was available, these objects on the roof were unable to be determined as HVAC or skylights definitively. Concerning SWMM, some of the available GI practices in VRRM cannot be employed, as SWMM only supports rain barrels, bioretention systems, grass swales, infiltration practices, green roofs, permeable pavement, and rain gardens. Lastly, this area had such high pollutant loading and percent impervious cover that it was hard to add enough GI practices to treat the stormwater runoff.

## 8. Conclusions & Future Work

In this study, Meadow Creek watershed was assessed in terms of technical need, which was determined by preliminary estimation of the quality and quantity of stormwater runoff using percentage of impervious area and percentage of untreated acreage within each subbasin, and social need, which was determined using context factors, such as race, housing characteristics, and income. Based on a composite ranking of technical and social need, Seminole Square Shopping Center and Barracks Road Shopping Center were identified as having high sociotechnical need, so this region was selected to be the target area for the following optimization using PySWMM. Due to technical setbacks with the PySWMM code, seven of the twenty subbasins were prioritized for analysis based upon PySWMM results for existing conditions of each of the twenty subbasins. From the PySWMM optimization, 73531 and 73571 were found to be the most cost-effective when assessing cost per percent reduction of peak runoff, runoff volume, TN, TP, and mean runoff. Further, these subbasins have small areas and are hence more feasible to design for due to less coordination between property owners and other stakeholders. An important takeaway from the optimization and comparison to the VRRM cost per TP removed is that cost per TP removed does not accurately reflect the reduction benefits provided by GI or any of the other co-benefits which add to the sustainability of GI.

There are many takeaways from this design project that various stakeholders could benefit from. A major takeaway is that the implementation of GI provides many benefits to the community in addition to benefits for stormwater management. These include healthier streams, beautification of the area, the economic benefit from GI as an amenity, and healthier people, since GI promotes spending more time in nature, which improves mental and physical health. Additionally, prominent GI features designed to be amenities help develop community identities. As the City of Charlottesville and Albemarle County continue to develop, they should place more of an emphasis on GI and creating stormwater management features that can be amenities for their communities. However, a main focus from an equity standpoint should be on implementing GI in disadvantaged communities. New development projects will typically implement some form of GI in order to meet the state of Virginia's runoff reduction requirements, but established communities that are home to low-income or disadvantaged populations do not typically see the benefits of these technologies. Therefore, it would be beneficial to focus on elevating the water quality, aesthetic value, and economic savings of these communities.

Future work using the results of this study include altering the design to meet all required goals within Charlottesville and Virginia. Alternatively, the subbasin could be considered suitable for redevelopment, and the GI design suggested in this study could be scaled back to meet minimum reduction requirements for TP. Using either approach to adjust the proposed design, the climate resiliency of the new design could be assessed by using the SWMM Climate Adjustment

Tool (SWMM-CAT), which predicts a future design storm based upon a predicted level of development increase and precipitation based upon existing climate models. This alternative design should also factor in the community perspectives supplied by the survey as much as possible to reflect community values and ensure its acceptance and continued upkeep. Additionally, characterization and optimization of the watershed should be updated as higher resolution versions of existing GIS layers are released, and optimization should include other various types of GI which SWMM can model as LID controls, such as rain barrels and infiltration practices. If working strictly with public agencies, subbasins should be considered based upon availability of public property, such as schools or parks, before being selected for further analysis. Finally, communication with the Pepsi Bottling Company on the benefits of green infrastructure design should be pursued. These benefits include but are not limited to increased visibility through tours with UVA or nearby K-12 schools and economic savings brought on by green infrastructure incentives programs in the city.

This project has allowed for team members to better understand the models and programs used to develop the data and analyses shown within this report, which will aid our future endeavors as environmental and water resource engineers, as many of these programs are used on a daily basis within the industry. The team also gained knowledge of how to conduct fieldwork and operate the instruments involved for discharge measurements and grab samples. Above all, the team gained management and communication skills and a grasp on the time and effort required to conduct a watershed analysis, as well as the obstacles to expect when engaging with new or unfamiliar software and methods. Our hope is that this report aids the broader Charlottesville community by providing results and recommendations to the City of Charlottesville, Albemarle

County, and property owners and by increasing awareness of green infrastructure via our discussions with businesses and posting of the developed community outreach survey.

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## 10. Appendices

Appendices available from Teresa Culver (tbc4e@virginia.edu) upon request.