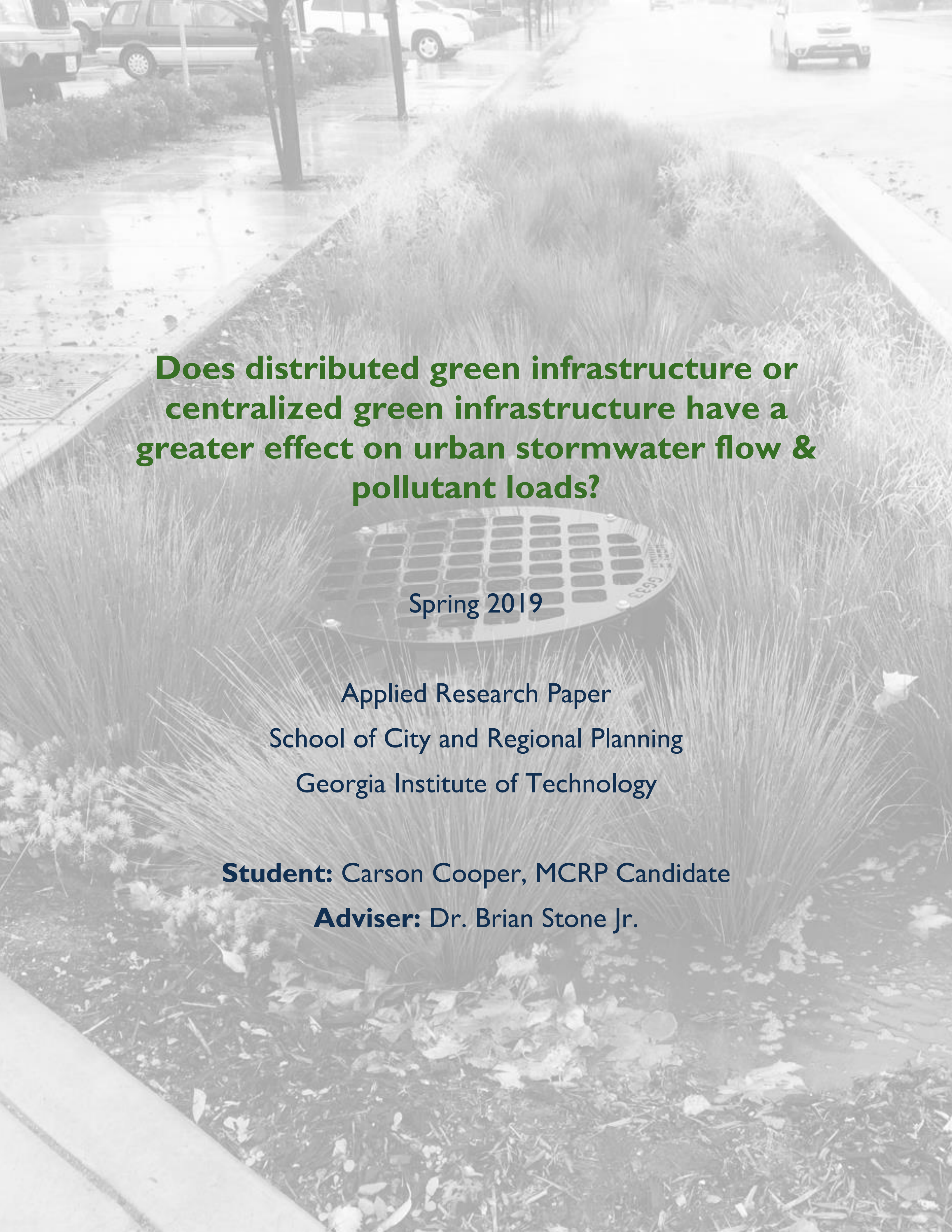

Does distributed green infrastructure or centralized green infrastructure have a greater effect on urban stormwater flow & pollutant loads?

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Introduction

Urban flooding during and after large storm events is an issue that current infrastructure cannot accommodate. Increases in urbanization and development, and therefore impervious surfaces, have led to significant increases in stormwater runoff. An urban area with 75-100% impervious cover has, on average, 45% more stormwater runoff than natural ground cover (U.S. EPA, 2003). This increase is predominantly attributed to reduced absorption and infiltration that results from a lack of vegetation and natural ground cover but can also be attributed to altered hydrologic flow patterns (Walsh et al., 2012). Current infrastructure techniques are constructed to fit the hydrologic flow to the built environment, but the altered flow pattern contributes to increased velocity and quantity of runoff. The increased velocity has subsequent consequences on the water body that collects runoff at outflow, including erosion, vegetation damage, and habitat disruption (Desert Water Harvesting Initiative, 2013).

Urbanization has also had adverse effects on stormwater quality, as urban materials and pollution are washed away from impervious surfaces. An estimated 10 trillion gallons of untreated stormwater runoff from paved surfaces run into waterways each year in America, due to overflow of infrastructure systems (Garrison et al., 2011). The increase in pollutant concentration increases the amount of time and cost to treat stormwater or, conversely, runoff overflows and exits the system untreated, which has adverse effects on the environment and leads to unsafe water that is used for drinking, recreation, and wildlife habitats (U.S. EPA, 2003). In 1997, the U.S. Environmental Protection Agency (EPA) estimated the total cost from illness and loss of economic output due to urban stormwater pollution to be millions of dollars each year (U.S. EPA, 1998). This estimate does not even include the cost of infrastructure maintenance, treatment, as well as fees that must be paid by cities when water quality standards set in national regulations are not met. Global climate change has also contributed to an increase in runoff, as storm events have increased in both intensity and frequency (U.S. EPA, 2016). The continued densification of cities and loss of greenspace will exacerbate these stormwater issues unless cities adapt to accommodate more quantity and pollutants (Haaland et al., 2015).

Traditional stormwater management has sought to maximize catchment capacitance, which is "the extent to which rainwater, snowmelt, and runoff onto and in transport from impervious surfaces to pervious areas can be infiltrated, stored, and released as catchment baseflow or evapotranspiration (Miles and Band, 2015). However, traditional management techniques, also known as grey infrastructure, include engineered solutions such as retention and detention facilities that catch water, but do little to slow runoff or absorb water as it is in transport to the facility. In contrast, green infrastructure, which emerged in the 1990s and is the current set of best management practices to improve runoff absorption and

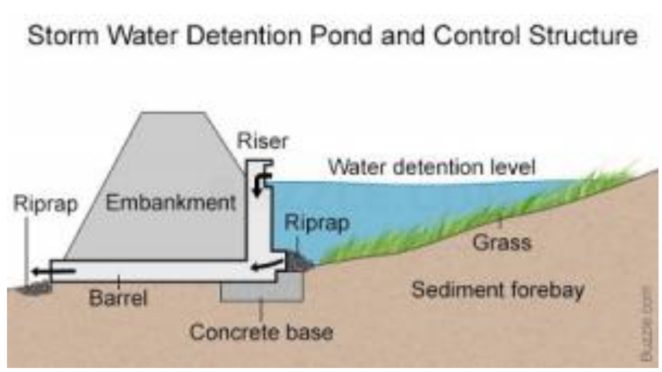


Diagram of Typical Stormwater Detention Pond (Hughes, 2016) filtration, can both reduce runoff volumes and improve water quality (Berndtsson, 2010; Golden and Hoghooghi, 2018). Green infrastructure differs from traditional infrastructure in that it utilizes a systems approach to purposeful placement of vegetative features, both engineered and natural, to mimic pre-development hydrologic patterns (U.S. EPA, 2003).

There has been significant research on the benefits of implementing green infrastructure and how it compares to traditional stormwater management, however, little research has explored the exact placement of green infrastructure. The proven benefits of green infrastructure make a case for its implementation but the question of which type of infrastructure should be implemented and where remains: **How can we best strategically place and design green infrastructure to aid in stormwater reduction and filtration for all types of storms?**

As cities increasingly implement policies and regulations for stormwater management, as well as climate change adaptation more generally, research should address the placement and configuration of green infrastructure designed for these purposes. This paper intends to explore this question by comparing two approaches: distributed green infrastructure versus centralized green infrastructure. The proven benefits of green infrastructure have been attributed to its more distributed approach when compared to its grey infrastructure counterpart, a more centralized approach. However, green infrastructure itself can be laid out in a centralized and concentrated design, such as a large park, or in a more distributed manner, such as street trees lining a corridor. It is expected that distributed greenspace and green infrastructure will have a greater reduction in total runoff and pollutant volumes, and more closely mimic the pre-development hydrology flow for lower intensity storms. However, it is also expected that centralized greenspace will have a greater effect on reducing total runoff and pollutant volumes for higher intensity storm events, such as a 1-in-100-year storm.

The following section of the paper will review current stormwater management techniques, green infrastructure research, a collection of stormwater models used to predict runoff volume and quality, as well as a brief review of location-based and design of green infrastructure research. The remainder of the paper will provide an analysis, based on the climate conditions and regulations of the City of Atlanta, Georgia, using the BMP SELECT model to compare the two design approaches, centralized and distributed, and provide policy recommendations to improve management based on the results. City planners, engineers, and landscape designers alike will benefit from an increased understanding of how to prioritize areas on a site for green infrastructure and design them with specific treatments and locations.

Literature Review

The existing literature around green infrastructure and stormwater modeling is extensive. There are many techniques to manage, model, and design for stormwater, which has led to an extensive base of research on these various methods. This section discusses relevant research in order to provide a brief summary of these management, modeling, and design techniques, and how the research can continue to be expanded.

Green vs. Grey Infrastructure

Green infrastructure, also known as low-impact development, uses "plants, soils, and landscape design to control nonpoint sources of water and materials in the built environment" (Golden and Hoghooghi, 2018). Nonpoint sources refer to nonpoint source pollution, meaning that it comes from multiple sources rather than a single, traceable source (U.S. EPA, 2018). Green infrastructure not only includes plants and soils in and of themselves, but also engineered devices such as bioswales and green roofs, that are designed with specific soils, layers, and their own infiltration basins on-site (Golden and Hoghooghi, 2018).

In contrast, traditional stormwater management, also known as grey infrastructure, focuses on structural means to control stormwater runoff (Fry and Maxwell, 2016). Grey infrastructure techniques focus on conveyance, or the movement of stormwater, and detention and retention, but have little to no impact on erosion, local flooding, and water quality filtration (Fry and Maxwell, 2016). Aside from their differences in construction, impacts, and effectiveness, these two techniques also significantly differ in how the infrastructure is managed. When compared to grey infrastructure, green infrastructure is much more affordable. One study found through a cost-benefit analysis that the total costs to maintain green infrastructure over a 25-year period amounted to $2.4 billion, compared to $8 billion for grey infrastructure for the City of Philadelphia (Walshe, 2013). The costs of maintenance are so much lower because green infrastructure involves above-ground, vegetative solutions, whereas grey infrastructure requires the construction of man-made ponds, pumps, and underground pipe system. Green infrastructure can also be implemented in a retrofitting context or implemented retroactively once a city is built; in contrast, grey infrastructure typically needs to be constructed in conjunction with development.

Current Green Infrastructure Techniques

Currently, green infrastructure techniques are widely considered to be BMPs (best management practices), because of their numerous benefits in regard to stormwater quantity and

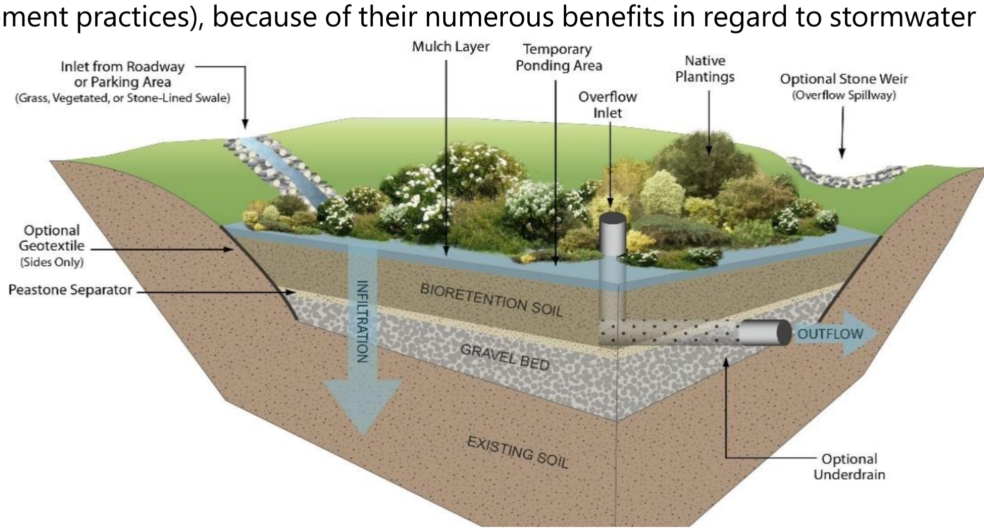


Diagram of Typical Bioretention Pond
(Massachusetts DEP, n.d.)

quality. One technique, bioretention systems, are similar to constructed retention ponds and utilize soil and native plants to slow runoff and remove pollutants (U.S. EPA, 1999). Bioretention ponds are designed with several components including vegetative buffers, a soil or sand bed, a shallow ponding area or infiltration basin, and organic layer (U.S. EPA, 1999; New Jersey Stormwater BMP Manual, 2009). The sand or soil bed slows the runoff and allows it to be collected in the shallow ponding area before infiltrating through organic material and into the subsoil (U.S. EPA, 1999). The vegetation and organic matter in the soil allows for proper filtration and pollutant removal before the runoff reaches groundwater. The permeability rate and pollutant removal rates vary with organic material thickness and the plants chosen for the buffer, but have shown proven success in removing pollutants, including sediments and solids (New Jersey Stormwater BMP Manual, 2009). One study found that bioretention was able to remove 77-79% of phosphorus on-site, compared to grey infrastructure which requires a costly pipe system and stormwater treatment facility (Davis, 2007).

Diagram of a Green Roof
(Insulation Corporation of America, n.d.)

Green roofs, another technique, are a more costly approach to green infrastructure management. They have very specific site design and engineering requirements, such as a thick soil layer, infiltration basin, and complex gutter system, because they pose more risk to the building on which they sit (Berndtsson, 2010). However, when constructed successfully, green roofs minimize rapid runoff and peak flow off of buildings, retaining 20-100% of rainfall inputs (Golden and Hoghooghi, 2018).

Example of a Rain Garden
(U.S. EPA, n.d.)

Rain gardens, a type of bioretention, differ slightly in that they are typically less designed than bioretention systems (Marritz, 2013). While both utilize vegetative materials, organic matter, and soil layers to slow and treat stormwater, rain gardens are not as specifically designed for hydrologic flow and are implemented more as an absorption mechanism and attractive landscape feature (Marritz, 2013). Nevertheless, even while rain gardens are not held to as high of an engineering standard as bioretention, they are still an effective green infrastructure technique as one study found they were able to reduce runoff by 62-98% (Vineyard et al., 2015).

Bioswales, another type of bioretention, are specifically designed to be linear bioretention facilities and are more engineered than rain gardens and sometimes more engineered than

Example of a Bioswale (Gibb, 2015)

bioretention ponds (Golden and Hoghooghi, 2018). Bioswales often include "engineered soil" which amends the existing soil to include materials that improve infiltration, such as gravel, and are typically implemented in more urban settings such as streetscapes, medians, and parking lots (Xiao and McPherson, 2011). Engineered soil is often required in these settings where soil is more likely to be compacted, and amended soil also improves aeration for the vegetation planted in the swale (Xiao and McPherson, 2011). One study found that a bioswale with engineered soil reduced runoff by 88.8% and pollutant removal amounted to 95.4% (Xiao and McPherson, 2011).

Finally, another common green infrastructure technique is permeable pavement, which includes gravel or brick-paved parking lots and surfaces that would traditionally be paved with asphalt (Golden and Hoghooghi, 2018). Permeable pavements, while a less vegetative infrastructure treatment, can have great impact on areas that would otherwise be completely impervious, and can reduce average runoff volume by 50-93%, as well as reduce the transport of motor oil and other pollutants from automobiles (Golden and Hoghooghi, 2018). All of these green infrastructure techniques have proven to have greater reductions in runoff volume, as well as greater success in pollutant removal than traditional grey infrastructure techniques.

Example of Permeable Pavement (NACTO, n.d.)

The form of grey and green infrastructure also differ greatly, in that grey infrastructure is implemented in a centralized manner in which the engineered ponds are connected to a centralized treatment facility through a network of pipes. In contrast, green infrastructure is a more distributed approach that focuses on "disconnecting impervious surfaces and treat[ing] runoff at the source" (Zhang et al., n.d.). This distributed approach has proven to be better at managing peak flow and total runoff, especially for smaller storm events, improving regional water quality by treating it at the source, and better for groundwater recharge and erosion management (Loperfido et al., 2014).

Location and Configuration of Infrastructure

Numerous studies have compared the configuration or location of grey infrastructure and how that impacts its effectiveness, with fewer focused on the different configurations and layouts of green infrastructure treatments. As green infrastructure is meant to be implemented to mimic the natural hydrology of the area, it is important to understand exactly where it should be implemented and how.

One study in Beijing compared several scenarios, including both green and grey techniques, to find which design and treatment was the optimal solution to reduce flooding (Liu et al., 2014). The study compared five scenarios: expanding greenspace, converting greenspace to be concave, constructing retention ponds, converting pavements to permeable pavements, or combining and integrating all four treatments together. The results showed that the combined integrated approach reduced total runoff by 85-100% and peak flow by 92.8-100% (Liu et al., 2014). However, the results also showed that the second-best performing single treatment was the retention pond, a grey infrastructure technique, suggesting that the success of the combined approach can be predominantly attributed to the pond's ability to store large amounts of water.

Another study in Boston compared two different grey and green infrastructure techniques on different land uses to see which treatment in which location would achieve optimal water quality, specifically phosphorus reductions, for the catchment basin the Charles River (Hurley and Forman, 2011). The study compared implementing 1-40 retention ponds per site that covered 5-15% of the drainage area to biofilters on each site that covered 5-10% of the drainage area (Hurley and Forman, 2011). The study modeled treatments in three configurations across the watershed: consolidated, a single, central detention pond, dispersed biofilters, equally distributed, and highly dispersed biofilters, which was a smaller-scale equal distribution. The results found that they only met the government's proposed phosphorus level, 65% reduction, when treating 100% of urban land with either a pond or biofilter, and that the land uses performed similarly (Hurley and Forman, 2011). The detention pond, a grey infrastructure technique, was found to perform better than both configurations of biofilters. The larger biofilters, the equally distributed scenario, performed better than the highly dispersed, smaller-scale equally distributed, biofilters. However, this shows how the density of green infrastructure affects quality rather than the configuration, as they were both equally distributed. While this study did not find answers as to how green infrastructure should specifically be configured, they did find that configuration was a more significant factor than total treatment area and were able to achieve 75% phosphorus reduction when the designs were configured in a combined consolidated and dispersed approach (Hurley and Forman, 2011).

A study in Denver has extensively researched the configuration of green infrastructure treatments, bioretention and rain gardens, in order to see how the treatment performed at reducing total runoff and flood depths, and how different configurations affected the level of reduction (Fry and Maxwell, 2016). The study looked at different "configurations" of greenspace in which they replaced 15-50% of existing, underutilized pervious area with green infrastructure in four different areas: street sides, front yards, backyards, and open field space (Fry and Maxwell, 2016). They found that a marginal increase in treatment area reduced BMP effectiveness, and that placement or location was a more significant factor than simply increasing BMP area (Fry and

Maxwell, 2016). When considering storm intensity, the treatments were more effective at reducing flood depths, increasing surface storage, and increasing infiltration volume during larger storms, and more effective at reducing peak flows and total runoff volume during smaller storms (Fry and Maxwell, 2016). When testing the configurations, treatments implemented along the street side performed the best at reducing runoff, but within the local context of this watershed (Fry and Maxwell, 2016). This study offers a comprehensive approach to green infrastructure configuration research, however, it includes assumptions that could be improved, as it used a conceptual approach to represent green infrastructure by adjusting soil type in the model, and neglects important factors, such as evapotranspiration.

Current Stormwater Modeling Methods and Scale

There are numerous stormwater models that are widely-used in research, each with different parameters, complexities, and assumptions, as well as many that are created for specific research studies. One of the most reputable and accurate, as well as most complex, stormwater models is the U.S Environmental Protection Agency (EPA)'s Storm Water Management Model (SWMM). The SWMM model is suitable for a wide range of uses but is known to be very complicated to use, especially to those unfamiliar with modeling techniques (Elliott and Trowsdale, 2007). Nonetheless, the SWMM model offers the most comprehensive set of simulation capabilities, including the ability to represent several green infrastructure techniques including infiltration (bioretention and bioswales), rain gardens, permeable paving, and green roofs (Elliott and Trowsdale, 2007).

For the purposes of this study, however, the BMP SELECT (Best Management Practices System Effectiveness and Life-cycle Evaluation of Costs Tool) model developed by the Water Environment Research Foundation (WERF) will be used (WERF, 2013). While the SWMM model is regarded as a more specific design tool, BMP SELECT allows for similar high-level modeling, green infrastructure design, and is more-user friendly, known as a "facilitating mechanism for BMP alternatives analysis" (WERF, 2013). The model developers also conducted a case study of a constructed wetland and its stormwater reduction effects for a watershed in Philadelphia by using both the SWMM version 5 model and BMP SELECT model Reynolds et al., 2012). The study found that the BMP SELECT model produced comparable results to SWMM5 for water volume, water quality, and cost of infrastructure (Reynolds et al., 2012). Similar to SWMM, BMP SELECT can be used to test location-based and configuration research, as it divides catchments and sub-catchment areas into pervious and impervious components, identified by the modeler (Elliot and Trowsdale, 2007; WERF, 2013). Additionally, both SWMM and BMP SELECT account for evapotranspiration, a factor that was neglected in the aforementioned Denver study. Cost is also an important factor when considering green infrastructure and stormwater management techniques, and BMP SELECT conducts a life-span and cost analysis of each treatment to allow for comparison. The BMP SELECT model will be discussed more in detail and how it relates to this study within the Methods section.

There are a number of other models that can be reviewed, including: MOUSE, MUSIC, SLAMM, P8, RUNQUAL, StormTac, UVQ, WBM LTHIA-LID, RECARGA, RHESSys, VELMA, HEC-HMS, GSSHA, and HSPF, each that focuses on a certain purpose for modeling, such as SLAMM being the most widely used and comprehensive model for modeling water quality specifically (Elliot and Trowsdale, 2007). GSSHA (Gridded Surface Subsurface Hydrologic Analysis) was the model used in the Denver study, as it is the most location-based stormwater model, but it is more focused on subsurface geology, and does not include green infrastructure treatments in its parameters. All of these models contain slightly different equations and assumptions, ultimately leading to varying results, and must be regarded for what they are: estimations.

As much modeling as there is, there are flaws in what they yet cannot measure including baseflow components, surface-subsurface interactions, contaminant transport channels, links to ecological systems, and varying levels of scale (Golden and Hoghooghi, 2018). Typically, stormwater models are used at a fine scale, such as a specific site, sub-catchment, or defined area, and aggregated to represent the local watershed level (Golden and Hoghooghi, 2018). However, there is a lack of research conducted at the regional or catchment scale, making it more difficult to make larger conclusions about the stormwater system and long-term effects of interventions. Conversely, it is also difficult to make high-resolution, finite-scale conclusions about the impacts of individual green infrastructure treatments, as well as the impacts of their configuration and location.

The uncertainty in models and scale is due to the fact that stormwater management is a site-specific, contextually-based system, and translating concepts of various ecological factors and processes into mathematical descriptions is difficult. The fact of the matter is that an appropriate level of uncertainty must be accepted, and the assumptions of the model must be noted. The assumptions and limitations of the model used in this study, BMP SELECT, are further discussed in the Methods section. Additionally, one must realize the conclusions that the scale represents and avoid committing an ecological fallacy. Smaller-scale results are *aggregated* to reach conclusions about a larger-scale; they are not simply scaled up.

Expanding Current Research

This paper intends to expand and improve the current literature by providing specific design technique information at the site level, incorporating evapotranspiration, and conducting a density and design storm comparison.

The Denver study simply represented bioretention through soil type changes, as they were limited by the GSSHA model. By using the BMP SELECT model, it is more user-friendly, and more green infrastructure techniques can be represented using more traditional methods. Additionally, their study did not account for evapotranspiration as they saw it as a negligible factor when in fact, evapotranspiration can account for 15-20% of all inflow water on an annual basis (Sharkey, 2006). Other studies have found that evapotranspiration and infiltration together can account for the fate of 50-90% of inflow depending on the soil type, media depth, and drainage configuration (Heasom et al., 2006; Hunt et al., 2006). Therefore, it is necessary to account for evapotranspiration when conducting an analysis of infiltration and green infrastructure treatments. By utilizing the

BMP SELECT model, evapotranspiration will be accounted for through local evaporation rates and produce results that account for this factor.

The Boston study looked at different configurations of green infrastructure and found that it was a significant factor in reducing phosphorus loads; however, the study did not analyze how these configurations affected runoff and other pollutants. The BMP SELECT model allows the user to look at all common pollutant loads including nitrogen, suspended solids, fecal coliform, zinc, and copper, in addition to outflow and runoff. This paper will also better inform spatial analysis of GI configuration by comparing different design configurations against one another, rather than just finding that GI location is a significant factor in addition to treatment area.

Finally, the Denver model conducted their analysis in a neighborhood watershed based on its current suburban form. Several models and studies have compared various urban forms, such as suburban to urban, or land uses, such as institutional and industrial, to see how implementing green infrastructure can be affected by the environment in which its implemented. The urban form and/or land use plays an important part in determining how the buildings are configured, an uncontrollable impervious surface, and would affect the effectiveness and possibly cost of maintenance and lifetime of the green infrastructure treatment. This paper will model treatments on an existing industrial site with 94% impervious cover that is ripe for redevelopment, which offers a unique opportunity to analyze the site in a preliminary design phase and model different configurations and coverage areas to find the optimal scenario.

By conducting a comprehensive study from a design perspective, this paper will improve current research and provide a configuration analysis that informs optimal green infrastructure placement and design at the site level.

Methods

The methods section describes the rationale and process behind the study conducted in this paper. The section describes the BMP SELECT model in detail, the study area used to ground the scenarios, and the methods used to create different green infrastructure scenarios and parameters.

Model Background: Development and Uses

The BMP SELECT Model Version 2.0 was developed in 2013 by the Water Environment Research Foundation (WERF), with expertise from the U.S. EPA, professors at the University of Utah and Colorado State University, and stormwater professionals. It is intended to serve as a planning-stage tool, in which the analyst can make informed decisions on the best practices for the site based on preliminary data on the watershed and design parameters (WERF, 2013). BMP SELECT requires hourly rainfall data from the local climate, while other parameters either assume a default value or can be customized by the analyst. The model was coded into an Excel spreadsheet interface with guided buttons for ease of accessibility and usability, as well as a full user guide and supplementary tutorial. BMP SELECT outputs include annual pollutant load estimates, runoff volume, flow and pollutant load exceedance curves, and whole life cost estimates of BMP treatments (capital, operations, and maintenance costs).

BMP SELECT is intended for modeling at the "watershed" level, which can be interpreted as an entire river watershed, a sub-watershed basin, or even a site-level catchment. For example, a Philadelphia case study modeled runoff from 174 acres of upstream development within the Wissahickon River watershed in order to see the benefits of implementing a single wetland (Reynolds et al., 2012). In contrast, a supplementary tutorial shows the use of the SELECT model for several treatments within several sub-catchments of a 29-acre residential development (WERF, n.d.). This variation in scale allows the user to make large-scale river basin plans or evaluate scenarios at the project level for new developments or retrofitting of existing developments.

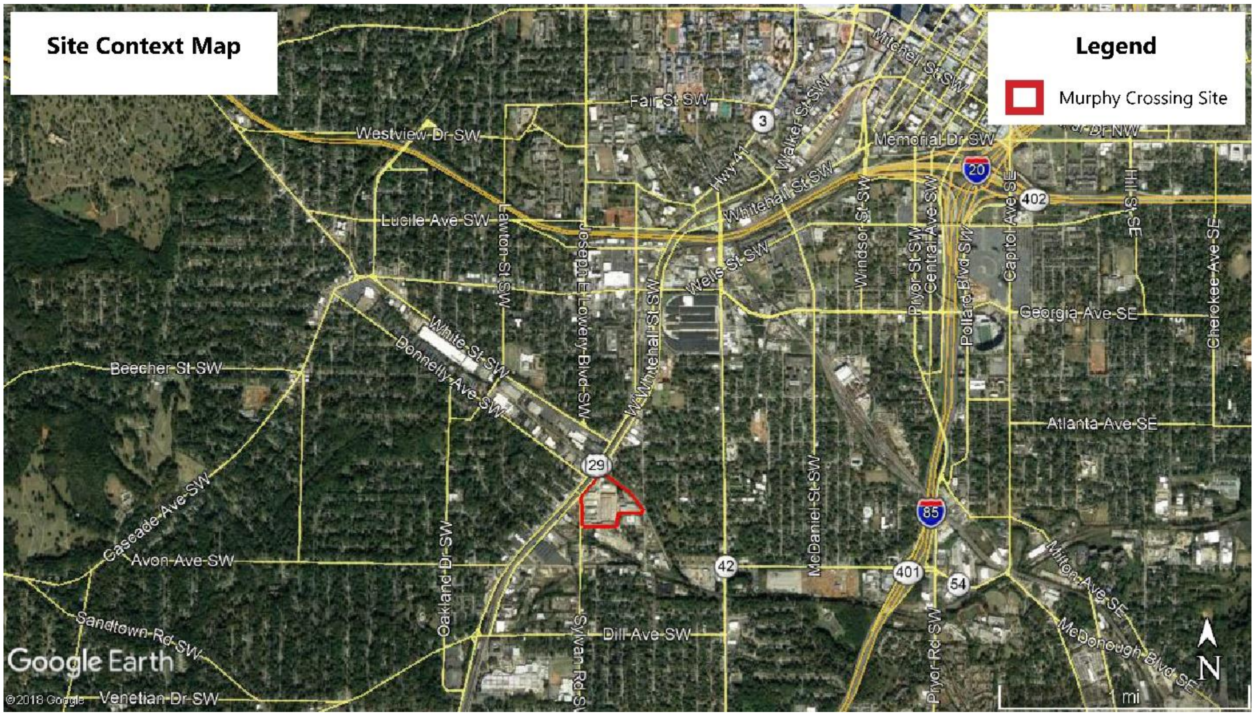
BMP SELECT developers state that the user is more likely an urban planner of a municipality, regulatory agency, or consultant, with some background knowledge rather than a designer or engineer that has advanced expertise and technical knowledge. The model is able to provide outputs quickly, aiding the decision-making process in the preliminary stage. It can be used for evaluating BMP alternatives including BMP placement, layout, type, and cost, and approximating the potential impacts of alternative scenarios.

Limitations and Assumptions

While the Philadelphia case study conducted by the model developers showed similar results between the BMP SELECT and SWMM5 models, it should be noted that SELECT uses much simpler equations and utilizes less parameters than SWMM and other more complex models. SELECT is limited in that the user is unable to put in specific soil data and the actual location of the site and watershed; however, these factors are indirectly accounted for through the runoff coefficient associated with each land use, user-input maximum depression storage, and percentage of impervious cover of the area. Additionally, while the user can define and manipulate values to create another type of BMP, the model itself only simulates the following treatments: extended detention, bioretention, wetland basin, swale, permeable pavement, or filter. Therefore, the user must put in more values and research in order to define a treatment not programmed within SELECT.

Description of Study Area

Figure 1, Site Context Map



The site being used for this study is located in Southwest Atlanta off of Murphy Ave SW along the planned Westside Beltline trail, as shown in Figures 1 and 2.

Figure 2, Murphy's Crossing Site Map

Figure 3, Contour Lines Map (Contour Data Source: Fulton County)

Previously housing the Archives and History Warehouse and Georgia State Farmers Market, the site now sits as an abandoned, light-industrial warehouse covered by impervious surfaces. Atlanta Beltline Incorporated (ABI) purchased the site and conducted a market study and

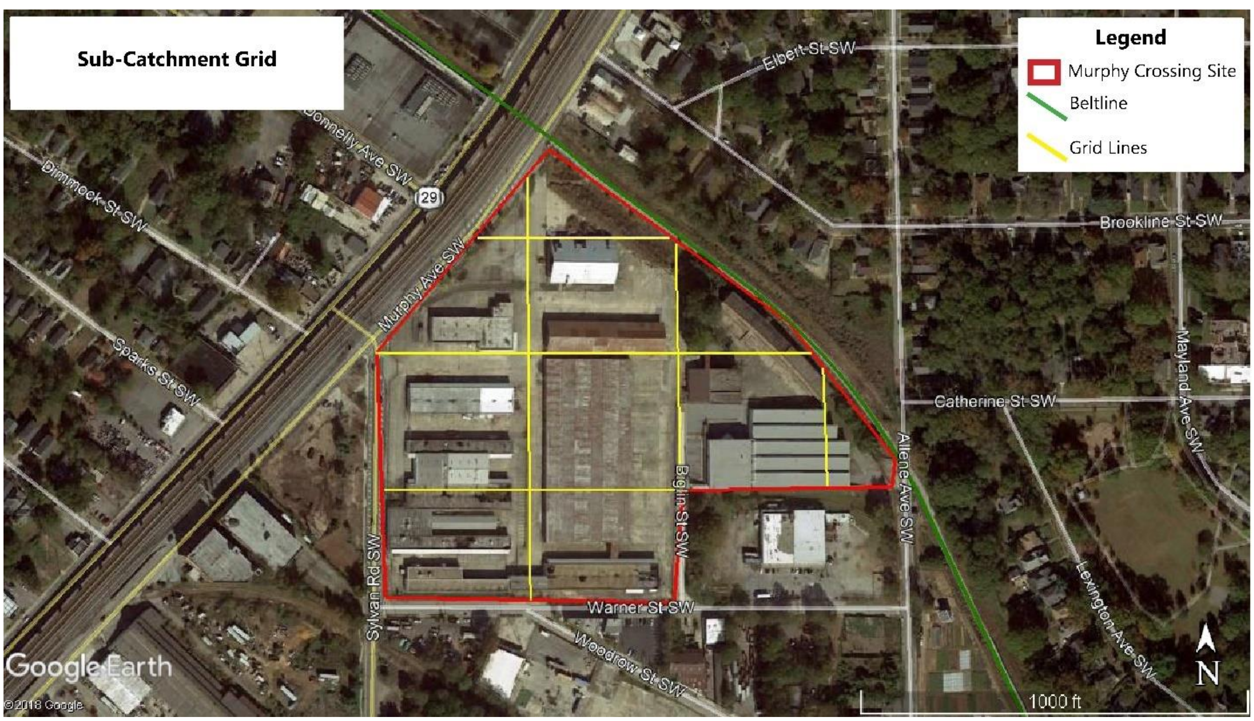


Figure 4, Sub-Catchment Grid Map

community engagement process in 2016 in hopes to determine best uses and create a redevelopment strategy (Keenan 2018; ABI, 2018). Known as "Murphy's Crossing," the approximately 21-acre site is considered to be a key catalyst property along the Westside Trail with significant potential to provide economic development to the surrounding neighborhoods (Keenan 2018).

Murphy's Crossing was chosen as the study area for this paper as it presents an opportunity to remedy the extensive pervious surfaces that currently dominate the site. Currently only 1.31 acres of the 21-acre site is pervious, about 6.24% of the total area. As the site becomes available for redevelopment, it is important to incorporate green infrastructure into its design in order to reduce stormwater runoff and improve the current water quality. The Beltline's Westside Trail, a future public amenity, currently sits in the watershed of Murphy's Crossing, as shown by the contour lines in Figure 3, with the lighter lines representing higher elevation. The contours show a rapid decrease in elevation from the eastern boundary of Murphy's Crossing to the Beltline, so the runoff flows directly to this future public amenity. By improving the quantity and quality of stormwater runoff coming from Murphy's Crossing, the quantity and quality of runoff affecting and flowing from the Westside Trail will also improve.

Green Infrastructure Scenarios

The site was divided into about seven equal grid cells, each representing an approximate area of three acres, as shown in Figure 4. The site's irregular shape made it difficult to create equal sub-catchments; however, dividing the site into approximately seven grid cells made the area of each cell approximately equal to three acres, as the total area is approximately 21 acres. These grid cells were used in order to quantify different amounts of green infrastructure treatments in two different configurations—centrally distributed green infrastructure and equally distributed green infrastructure. A central distribution, or centralized design approach, of green infrastructure indicates that all the treatment area is in the center of the site, whereas, an equal distribution, or more distributed design approach, indicates that the treatment area is divided equally into each of the seven sub-catchments. The 5% and 50% scenarios are visually represented in Figures 5-8 to show how these parameters represent the layout of the site.

Ten scenarios were modeled: 5%-50% area treated with BMP in 5% increments. Similar to the Denver study, BMPs were modeled up to 50% of the total site area as it may not be financially feasible or publicly accepted (Fry and Maxwell, 2017). Being a small site that is ripe for redevelopment in an up and coming area along the Beltline, 50% treatment area was chosen as a realistic upper bound for when the site is completely redeveloped. It is likely that this site will house commercial or residential uses and parking, and therefore it can only be expected that up to 50%, or 10.9 acres, could be devoted to green infrastructure, not including green roofs atop buildings which cannot be modeled within BMP SELECT. For each scenario, a percentage of the total site was determined, and the two design configuration scenarios were quantified as portions of the total percentage. The different scenarios are shown in Table 1.

Table 1: Green Infrastructure Scenarios

Amount of Total Area (21.8 acres) treated with GI		Scenario 1: Equally Distributed		Scenario 2: Centrally Distributed	
Percent of Total Area	Acres	# of cells treated	# of acres treated per cell	# of cells treated	# of acres treated per cell
5%	1.09	7	0.16	1	1.09
10%	2.18	7	0.31	1	2.18
15%	3.27	7	0.47	2	1.64
20%	4.36	7	0.62	2	2.18
25%	5.45	7	0.78	2	2.73
30%	6.54	7	0.93	3	2.18
35%	7.63	7	1.09	3	2.54
40%	8.72	7	1.25	3	2.91
45%	9.81	7	1.40	4	2.45
50%	10.9	7	1.56	4	2.73

Figure 5, Centrally Distributed GI for 5% of Site

Figure 6, Equally Distributed GI for 5% of Site

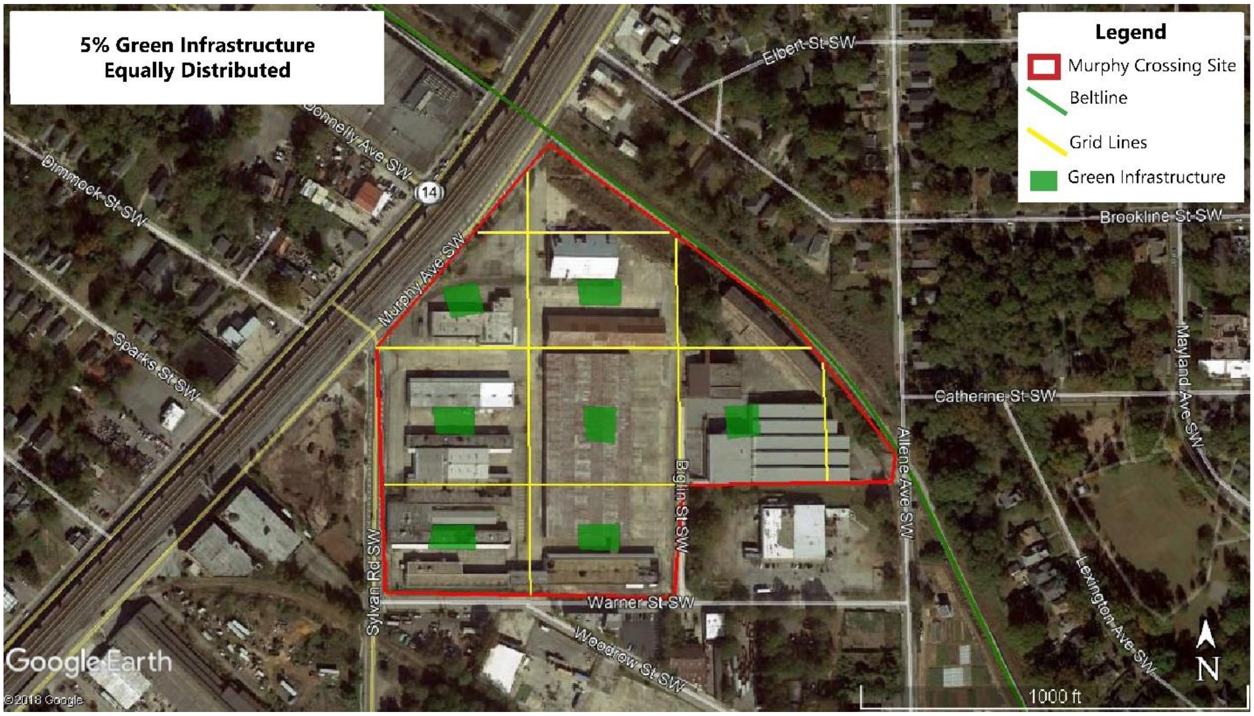


Figure 7, Centrally Distributed GI for 50% of Site

Figure 8, Equally Distributed GI for 50% of Site

Model Parameters

BMP SELECT has a set of meteorological parameters, separate from the BMP and scenario parameters. The metrological and climate inputs are the only part of the model that represent the specific site. In order to calculate design storms, Atlanta's IDF (Intensity-Duration-Frequency) curves for precipitation were obtained from NOAA. The frequency and intensity are represented by a "#-year" storm, meaning the chance of that storm's intensity occurring. For example, a very intense storm would be considered a "100-year" storm, as it is only likely to occur once every 100 years.

Stormwater modeling and management literature typically models 1-year to 100-year storms for 2-hour to 48-hour events, or continuous rainfall depending on the model used (Fry and Maxwell, 2017; Hurley and Forman, 2011; Liu et al., 2014). Therefore, various design storm intensities were modeled in this study for a 24-hour event, and the associated values for each design storm are shown in Table 2. In order to model these events, hourly rainfall data was obtained from NOAA's National Center for Environmental Information (NCEI) hourly precipitation dataset (NCEI, 2013). These values are collected from NOAA rain gauges, typically located at airports, to provide long-term, historical precipitation data. Atlanta's data is collected at Hartsfield-Jackson Airport and data for the years 2009-2018 were downloaded. Days were chosen from the historic rainfall data based on having the closest amount to the respective design storm to represent 24-hour events, as shown in Table 2.

Monthly evaporation data for Atlanta was obtained from a 1982 NOAA Technical Report, the most recent and comprehensive assessment on pan evaporation data available in the U.S. (NOAA, 1982).

Table 2: Atlanta Design Storm and Event Values for 24-hour Event

Design Storm		Actual Event	
Frequency	Rainfall (in)	Date	Rainfall (in)
2-year	3.7	4/28/2013	3.7
10-year	5.03	3/3/2012	5.03
25-year	5.95	4/23/2018	5.97
50-year	6.71	9/11/2017	6.84
100-year	7.5	9/21/2009	7.23

BMP SELECT requires the user to input the land use of the catchment site, as well as the land use of each sub-catchment. The model has pre-set land uses for commercial, residential, and undeveloped land; however, it also allows the user to add a new land use and input its corresponding percentage of impervious surface, runoff coefficient, maximum depression storage, and pollutant loads. Murphy's Crossing and each sub-catchment fall under a light industrial land use, which has a runoff coefficient of 0.79 (calculated by the model) and percent impervious land cover of 94%. The depression storage, 0.05 inches, and pollutant load values for the commercial land use, which is represented with 83% impervious cover, were used for the light industrial land use.

For the different scenarios, the model has options to "Add a New Scenario" and the treatment conditions and sub-catchment conditions can be changed per scenario. The inputs for the BMP's require the following parameters:

- Contributing area (percentage of the sub-catchment treated with BMP/GI)
- Type of BMP treatment (bioretention, permeable pavement, etc.)
- WQCV (water quality capture volume)
- Drawdown time
- Percent losses, which accounts for infiltration and evapotranspiration
- Holding capacities (storage volume)

Each of these values is set to a default within the model, but the user has the option to adjust each parameter if necessary. For example, the model assumes a drawdown time of 12 hours; however, the Georgia Stormwater Management Manual suggest a drawdown time of 24 hours for green infrastructure (Atlanta Regional Commission, 2016).

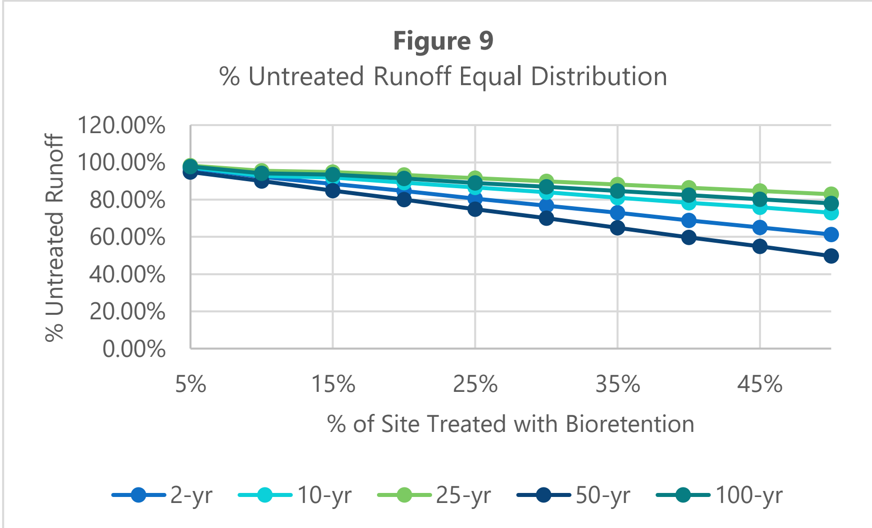
For the sake of this paper, bioretention was the only treatment modeled and the only factors that were adjusted were the contributing area per each scenario and sub-catchment, the design storm event (rainfall), and the drawdown time. Bioretention was the only treatment used because this paper is more concerned with the configuration and coverage of the BMP rather than the type of BMP, therefore the BMP was kept constant. This study could be expanded in the future to show the differences between configuration and BMP treatment to test if the optimal performance of one configuration for a reduction in outflow and pollutant volumes is consistent across treatment type.

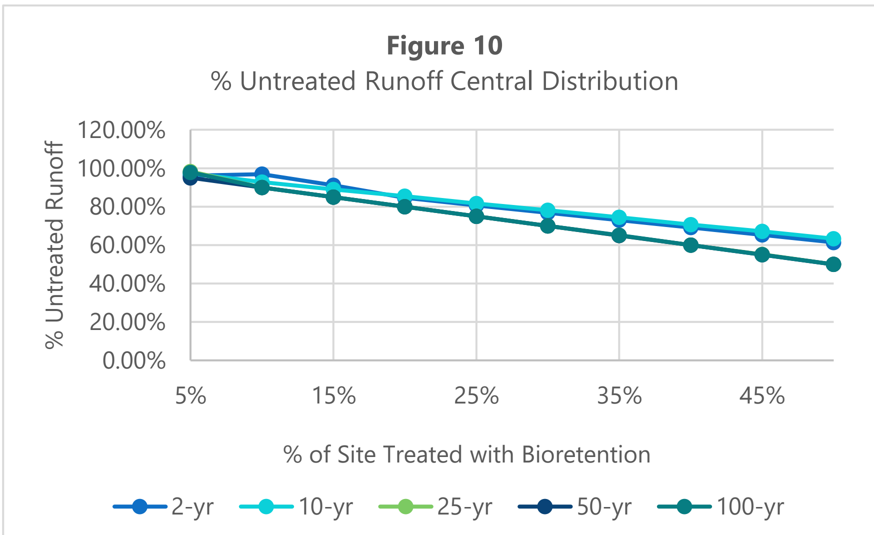
Additionally, a bioretention basin showed the most potential for the Murphy's Crossing based on the BMP selection guide located in the Georgia Stormwater Management Manual (p. 139, Atlanta Regional Commission, 2016). Compared to the other options that BMP SELECT allows the user to choose, bioretention is proven to reduce runoff, reduce pollutant loads on average by 80%, and is considered medium in cost-level. Bioretention is often implemented in very pervious areas, such as parking lots, and could easily be included into the Murphy's Crossing redevelopment design.

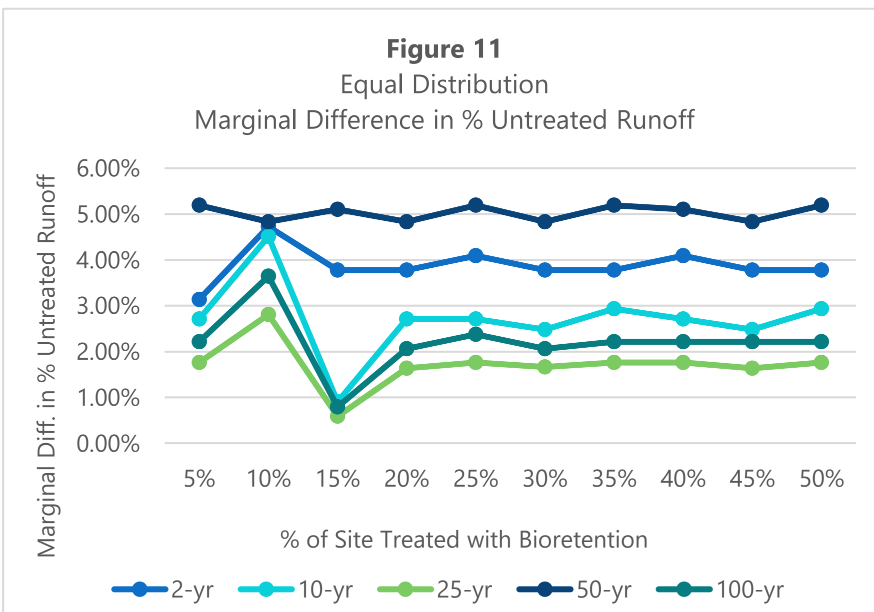
Results

Each design storm event showed a reduction in percent untreated runoff from the site as treatment area increased for both configurations, as shown in Figures 9 and 10. The equally distributed scenario showed a greater difference between each of the design storms than the centralized scenario; however, the centralized scenario showed consistent and greater reductions, especially in the larger storm events—the 25-year, 50-year, and 100-year storms. This is consistent with the hypothesis and literature, which state that GI treatments are less effective with larger storms.

Figures 11 and 12 show the differences in percent untreated runoff per 5% increase in treatment area, or the marginal difference. Similar to the Denver study's findings, the "BMP effectiveness" for the equal distribution, or the marginal reduction in runoff per increase in treatment area, increased at first then suddenly dropped at 15% coverage for three out of five of the







design storms; the Denver study found a significant drop in effectiveness between 15% and 25% treatment area (Fry and Maxwell, 2016). Following the drop at 15%, the BMP effectiveness increased again at 20% and stayed relatively the same as coverage area increased. The 2-year and 50-year storms were less affected by these trends, perhaps because a 2-year storm is less intense and more frequent, and a 50-year storm is moderately high-intensity.

Most of the storms showed a similar trend for the centralized approach, again with the exception of the 2-year and 50-year storms. The 10-year, 25-year, and 100-year storms showed a large marginal increase at 10% treatment, followed by a significant drop at 15% coverage, then relatively stagnant curves. In contrast, the 2-year curve showed a decrease in effectiveness at 10%, large increase at 15%-20%, and dropped and plateaued at 25% treated area. This curve does not follow the literature, as the Denver study found decreased marginal returns for BMP effectiveness as treatment

Figure 12
Central Distribution
Marginal Difference in % Untreated Runoff

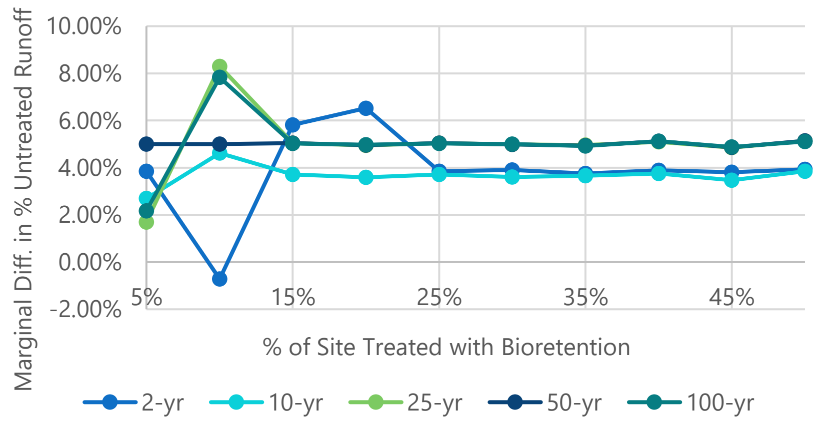


Figure 13
2-yr Storm
Total BMP Outflow cu. Ft. (Treated Water)

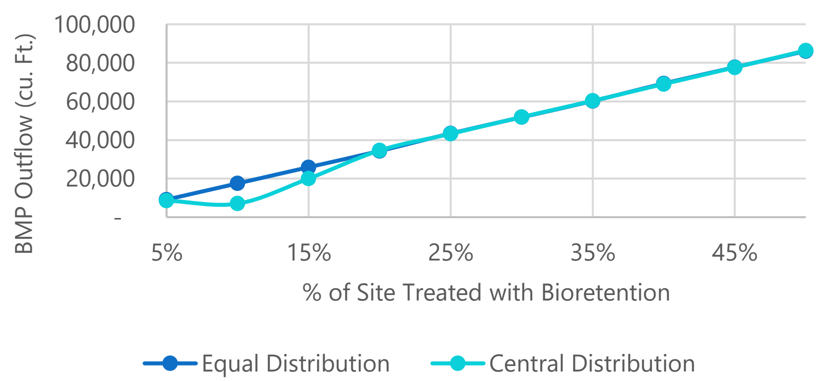
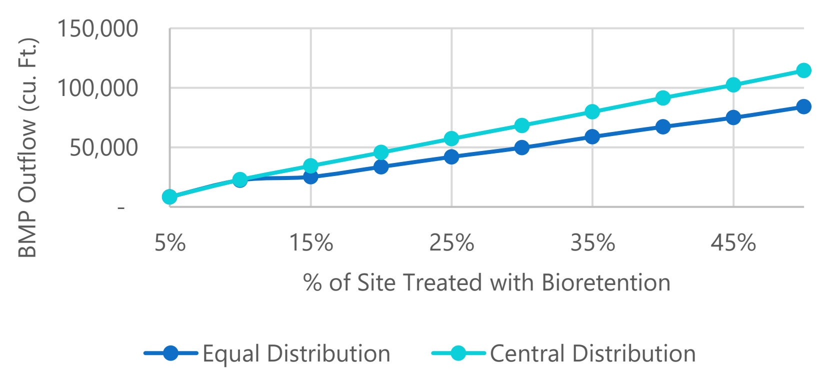


Figure 14
10-yr Storm
Total BMP Outflow cu. ft. (Treated Water)



area increased for smaller storms (Fry and Maxwell, 2016). The 50-year storm showed a flat curve for the centralized approach, consistently showing approximately the same BMP effectiveness regardless of treatment area. This is also inconsistent with the Denver study, as they found increases and decreases, but no stagnant trends.

Figure 15
25-yr Storm
Total BMP Outflow cu. Ft. (Treated Water)

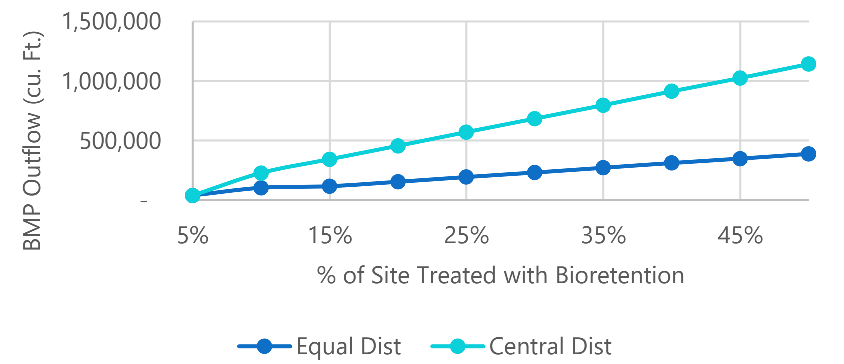


Figure 16
50-yr Storm
Total BMP Outflow cu. Ft. (Treated Water)

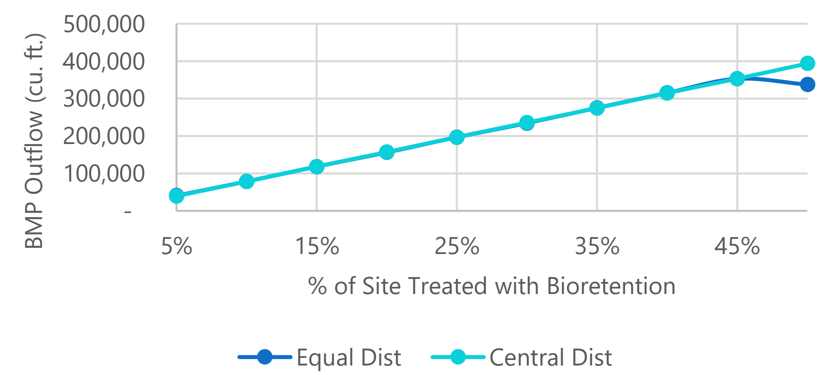
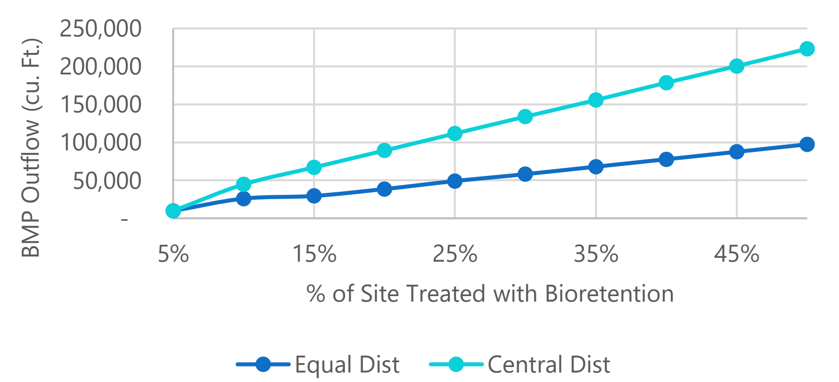


Figure 17
100-yr Storm
Total BMP Outflow cu. ft. (Treated Water)



Each design storm event showed an increase in outflow, or treated water, from the bioretention as the percentage of treatment area increased, regardless of the design configuration, as shown in Figures 13-17. This is equivalent to a reduction in total runoff from the site due to the increasing coverage of bioretention area, increasing the site's ability to absorb and filter stormwater. The 2-year and 50-year storms showed the greatest similarity between the two configurations, equally distributed and centrally distributed, while the other three design storms showed a greater split between the two configurations, with the central distribution out-performing the equal distribution. This is half consistent with the proposed hypothesis, which expected that the decentralized, or equally distributed, approach to green infrastructure would out-perform a more centralized, or centrally distributed, design during lower-intensity storms, but that a centralized approach would be able to absorb and treat more water during a higher-intensity storm. The results show, however, that the centralized approach offset runoff by a greater or similar amount for all storms. The results are consistent with the literature which suggests that spatial location of GI is a larger determining factor of GI effectiveness in less-intense storms, whereas density of GI is a larger determining factor of effectiveness in high-intensity storms (Fry and Maxwell, 2016; Palla and Gnecco, 2015; Qin et al., 2013).

There was not a great enough variation between the two configurations' and design storms' average pollutant concentration to show graphically; however, some of these variations were found to be significant when the p-values of the differences were compared, as shown in Table 3.

Figure 18 shows the percent difference between the two design configurations with respect to percent untreated runoff, calculated by subtracting the central distribution from the equal, and dividing by the equal. The 25-year and 100-year storms showed the greatest positive

Figure 18

% Difference in % Untreated Runoff Between Two Configurations

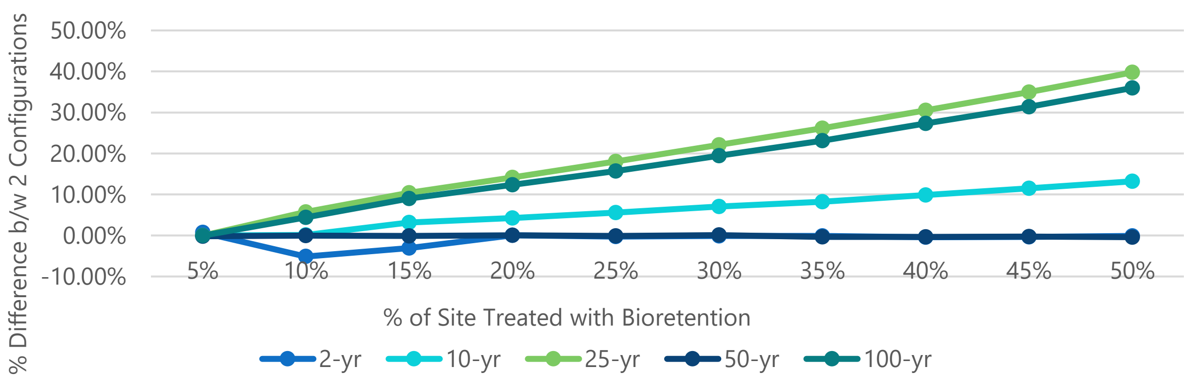
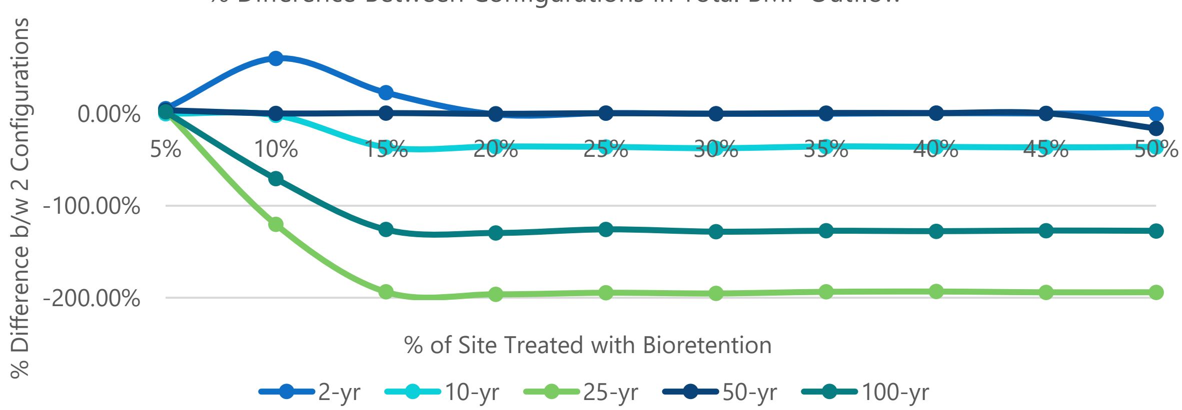
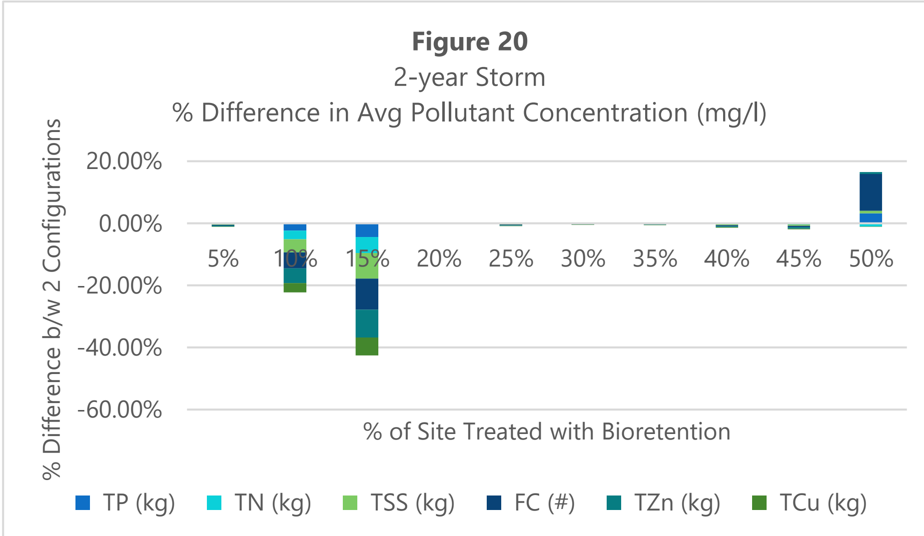


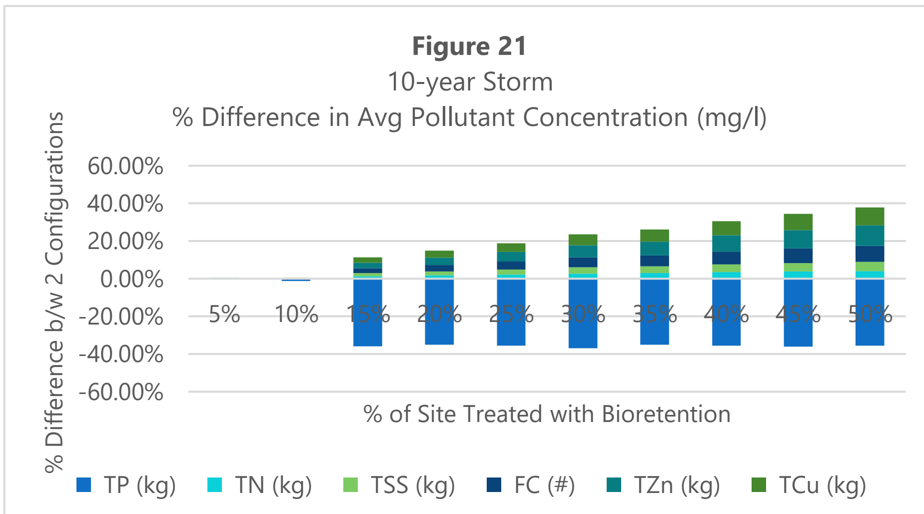
Figure 19

% Difference Between Configurations in Total BMP Outflow



percent difference, meaning the centralized design out-performed the equal distribution for these two storms, as a smaller number is desired. The 10-year storm showed a much smaller negative difference and the 50-year storm showed almost no difference. The 2-year storm showed the equal distribution performed slightly better up until 20% coverage, then there was little to no difference in runoff between the two configurations.





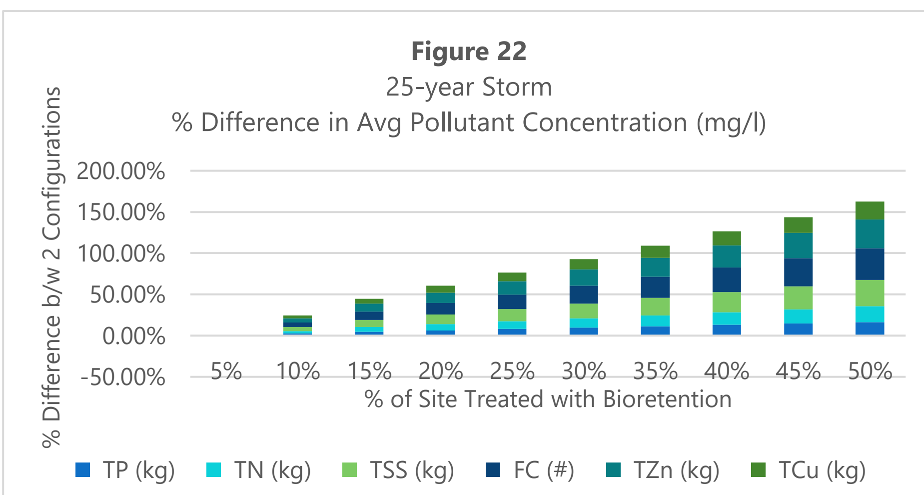
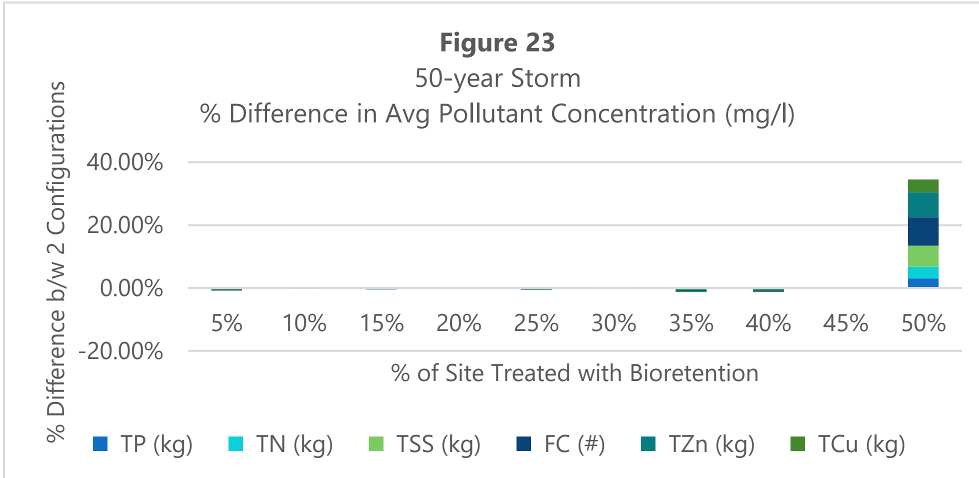
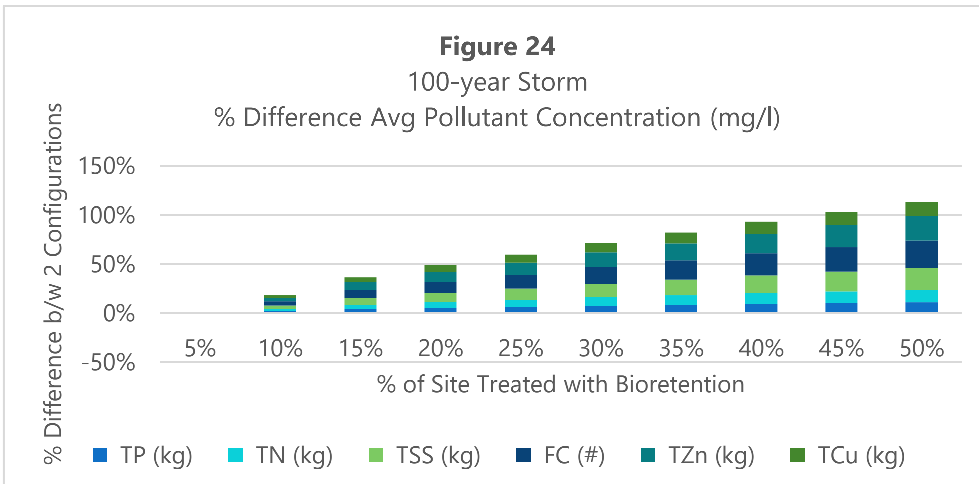


Figure 19 shows the percent difference between the two design configurations with respect to outflow, treated water, calculated the same way as Figure 18 but with the desire for a larger number. The 2-year storm had the smallest percent difference when ignoring the outlier at 10% treatment. The 2-year storm was also the only design storm with consistently positive values, meaning the equal distribution out-performed the central distribution. However, the rest of the design storms showed negative percentages, meaning the central distribution out-performed the equal distribution. These results are also consistent with the hypothesis and literature, as the centralized design performed better at reducing total runoff in higher-intensity storms. The curve of difference of each storm shows a different trend, with the exception of the 25-year and 100-year storms. The significance of these differences is shown in Table 3.





Figures 20-24 show the percent difference between the two design configurations with respect to average pollutant concentration. Almost every design storm, except for the 2-year storm, showed a positive difference in each pollutant's concentration, meaning the equally distributed bioretention system out-performed the centrally distributed system. Most of these differences showed high significance, as shown in Table 3. These results support similar literature, such as the Boston case study, which found that distributed biofilters covering 5% of the area achieved the same 75% reduction in phosphorus as a few centralized ponds covering 15% of the area (Hurley and Forman, 2011). In that case, configuration was significantly more effective than treatment area regarding pollutant removal.

Uniquely, the 10-year storm showed a positive percent difference for every pollutant except for Total Phosphorus (TP), which indicates that the central bioretention system performed better at removing TP loads, but not other pollutants, and this difference was found to be 99% significant. This is somewhat surprising, as phosphorus and nitrogen typically pollute together from fertilizer sources, and zinc, suspended solids, and copper are more commonly found in suburban, urban, and industrial sites (MPCA, 2018; StormwateRx, n.d.). However, phosphorus attaches to soil particles more than other pollutants, allowing it to be carried along more easily into water bodies with runoff (USGS, 2018). Atlanta has had a history of poor nutrient load management downstream, as the Chattahoochee River, located just west of Murphy's Crossing, has shown high levels of phosphorus in the past (USGS, 2018; Thornton, 2015). Perhaps, for the amount of rainfall in a 10-year storm, a more centralized system was better at capturing phosphorus and the soil particles it attaches to because it has a large, single capture area within the site which more closely mimics a water body. The 50-year storm had the smallest percent difference when ignoring the outlier at 50% treatment. Once again, each design storm showed a different trend except for the 25-year and 100-year storms.

The significance of these differences is shown in Table 3. The 2-year storm showed no significance for all variables, while the other design storms showed 99% significance for every variable, except for the 50-year storm. The 50-year storm showed 99% significance for differences in percent untreated runoff but was not found to be significant for any other variable.

Table 3, Significance of Differences in Outflow and Pollutant Concentration between Two Configurations

	% Untreated Runoff	Total BMP Outflow	TP (kg)	TN (kg)	TSS (kg)	FC (#)	TZn (kg)	TCu (kg)
2-year Storm								
P-value:	0.17774279	0.178311688	0.452659	0.114508	0.17233	0.603037	0.165076	0.147384
Significance:	Not	Not	Not	Not	Not	Not	Not	Not
10-year Storm								
P-value:	0.001058	0.001038	0.000622	0.000622	0.000622	0.000622	0.000621	0.000618
Significance:	99%	99%	99%	99%	99%	99%	99%	99%
25-year Storm								
P-value:	0.000547	0.000545	0.002213	0.002213	0.002213	0.002213	0.002213	0.002215
Significance:	99%	99%	99%	99%	99%	99%	99%	99%
50-year Storm								
P-value:	0.01017	0.336676	0.422664	0.422567	0.422567	0.422568	0.422189	0.42121
Significance:	99%	Not	Not	Not	Not	Not	Not	Not
100-year Storm								
P-value:	0.000588	0.00058425	0.000251	0.000251	0.000251	0.000251	0.000251	0.000249
Significance:	99%	99%	99%	99%	99%	99%	99%	99%

Summary of Results

- *Percent Untreated Runoff*
  - Centralized performed similarly to decentralized for smaller storm events, and better than decentralized for larger storm events
- *Total BMP Outflow (Treated Water)*
  - Centralized performed similarly to decentralized for smaller storm events, and better than decentralized for larger storm events
- *Pollutant Concentration*
  - Decentralized performed better than centralized for all storm events
- *Significance of Differences in Performance Between 2 Configurations*
  - 2-year storm showed little to no significance for all variables
  - 50-year storm showed no significance for any variable except % untreated runoff
  - 10-year, 25-year, and 100-year storms showed significance for all variables

Policy Recommendations

Based on the results of this paper, professionals can better understand site-level stormwater management using green infrastructure and how it fits into the larger regional context of the watershed. State and regional governmental entities often create large-scale stormwater management plans that incorporate design guidelines for green infrastructure, similar to the 2016 Georgia Stormwater Management Model referenced in this paper. Cities, however, have the ability to create and enforce guidelines at the site-level for each development.

This section will describe how specific policies in Atlanta and Georgia can be improved or changed as an example of how stormwater management policies can be informed by the quantitative results and modeled scenarios of this study. After analyzing the current regulations and guidelines, policy recommendations will be formed with the new understanding of site-level green infrastructure configurations found in this study.

Current Regulations & Guidelines in Atlanta

The City of Atlanta's Department of Watershed Management, in partnership with other water-conscious organizations, has created a GI Taskforce that manages the City's new Post-Development Stormwater Ordinance, revised in 2013, and GI Strategic Action Plan, published in 2018. The Ordinance now includes much more stringent requirements to include GI for new developments and redevelopments, which would apply to Murphy's Crossing, as listed below (City of Atlanta Department of Watershed Management, 2013):

- Projects must treat the first 1.0″ of stormwater runoff with green infrastructure
- Requires new single-family residences to manage the first 1.0″ of stormwater runoff on their site
- Prior to issuing a permit, applicants are required to meet with City professionals for a stormwater consultation meeting and ensure that GI was incorporated into the design

While these requirements are more aggressive in requiring GI than traditional stormwater management regulations, they do not include specific site-level requirements regarding the location, size, type, or storage volume of the GI treatment. Additionally, only requiring GI to treat the first 1.0″ of runoff does not accommodate larger storms with greater volumes of rainfall. This Ordinance is supplemented by design guidelines for different types of projects, such as single-family residences or small commercial sites, as well as the State's extensive design guidelines, but guidelines do not ensure that proper management is occurring. For example, the City's guidelines for Small Commercial sites includes a table that outlines treatments, recommended areas, and surface types where it can be implemented, as shown in Figure 25. However, these are just recommendations and do not require or incentivize developments to go beyond minimum requirements. By using the results presented in this paper, cities can better determine the optimal design for each project to manage on-site stormwater for a variety of design storms.

Figure 25, Appropriate GI Practice Selection by Contributing Drainage Area (City of Atlanta Dept. of Watershed Management, 2014)

GI Practice	Surface Type of Contributing Area					Design Incorporates Pre-Treatment	Practice Requires Pre-Treatment	Recommended Size of GI Practice Based on Contributing Area *
	Pavement	Roof	Grass / Stabilized Landscape	Dumpster Pad	Loose Gravel or Exposed Soil (High Sediment Potential)**			
Bioretention	✓	✓	✓	✓		✓		5% to 10% of Contributing Area
Infiltration Trenches	✓	✓	✓	✓			✓	5% of Contributing Area
Bioswales	✓	✓	✓	✓		✓		5% of Contributing Area
Permeable Pavement	✓	✓				✓		25% of Contributing Area
Stormwater Planter	✓	✓	✓			✓		5% of Contributing Area
Subsurface Infiltration	✓	✓	✓				✓	5% to 10% of Contributing Area
Rainwater Harvesting	✓	✓	✓				✓	No Restriction
Green Roof		✓				✓		100% of Contributing Area

* *Recommended size assumes suitable soil conditions (Type C Soils or better) and typical design soil and gravel cross section depths for each GI Practice. With appropriate conditions, practices can be sized to handle greater contributing areas, or a combination of practices can be employed to address larger contributing areas.*

** *All loose gravel or exposed soil contributing areas require appropriate pre-treatment practices.*

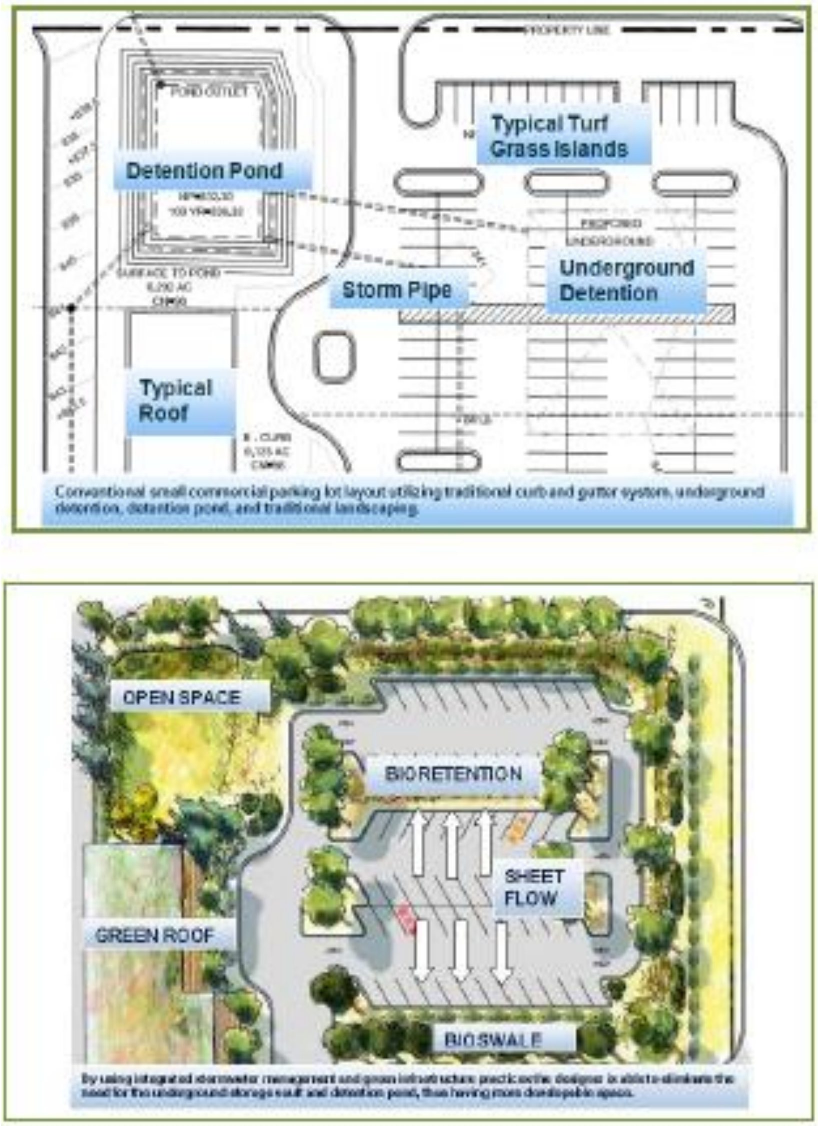


Figure 26, Traditional vs. GI Practices (City of Atlanta Dept. of Watershed Management, 2014)

Recommendation 1: Improve Atlanta's Current Green Infrastructure Policies

Prepare for Larger Storms Using Green Infrastructure

By only requiring a site to manage the first inch of runoff using green infrastructure, more reliance is placed on traditional grey infrastructure systems during large storms with larger amounts of runoff. The results of this study, however, show how to best use GI to manage larger storms through a centralized design approach and aggressive treatment area (>15% of the site). Atlanta's guidelines for Small Commercial Sites includes a figure of an idealistic green infrastructure scenario, in which all traditional grey infrastructure and open space contains a GI treatment, as shown in Figure 26, covering approximately 50-60% of the site. The table shown in Figure 25, however, only recommends 5-10% treatment area for most treatments, with the exception of a green roof, a very costly GI practice.

The marginal results shown in Figures 11 and 12 indicate that GI is very effective when increasing the treatment area from 5% to 10%, decreases at 15%, and increases again and stays relatively constant with higher coverage areas. These marginal differences in GI effectiveness may have been what determined Atlanta's policy that recommends 5-10% GI size, consistent with previous studies; however, with higher percentages of GI on-site, more runoff can be absorbed and treated even if effectiveness does not increase with increasing coverage. The City of Atlanta should recommend, if not require, higher percentages of GI coverage that more closely reflect the image in Figure 26.

Improvements could be made by amending the current policies to require sites to manage more than the first inch of runoff with GI, recommending higher percentages of GI coverage, and adjusting the language in the consultation meeting requirement. Currently, projects are required to meet with stormwater professionals "to ensure GI was incorporated into the design," but this could be improved by stating "to ensure GI was incorporated into the design *as much as possible*." By adding *'as much as possible'* to the requirement, city officials will be able to advise the design process more and help projects think creatively to design the site around achieving more aggressive coverage of GI, such as Figure 26.

Figure 27, How the green infrastructure approach works at different scales (Allen, 2012)

The key question of this paper around how to approach GI design should also be incorporated into the design consultation meetings on a site-by-site basis. If the proposed project site is upstream of important water bodies or sites, more attention should be paid to water treatment, and therefore a more distributed and decentralized approach to green infrastructure should be used. However, if the proposed project site is within a floodplain or experiences periodic inundation during large storms, the green infrastructure treatments should be more centralized within the site to help reduce runoff.

<u>Incentivize & Fund the Use of Green Infrastructure</u>

Many cities have created incentives to encourage the use of green infrastructure, especially within residential neighborhoods. While the City of Atlanta has a requirement for newly constructed sites and homes, there are only guidelines and recommendations on the benefits of green infrastructure for existing residences. By creating an incentive program, engaging the public and professionals, and hosting design workshops, the City can encourage GI for both existing and newly constructed sites.

Atlanta's last Green Infrastructure Strategic Action Plan under Mayor Reed, published in 2016, actually included recommendations for incentives that have yet to be implemented, including dedicating a portion of sewer bill revenue to funding green infrastructure incentive grants and streamlining permits and fees for developers if they include open space and GI (City of Atlanta Department of Watershed Management, 2016). The most recent Strategic Action Plan published in 2018 under Mayor Bottoms, however, has more general action items in how to fund GI and make it more affordable, simply stating: "Evaluate public-private partnership funding models" and "Evaluate grant funding to promote GI implementation on private property, focusing on low-income communities of color" (City of Atlanta Department of Watershed Management, 2018).

While the more recent plan includes more equity initiatives, it is not as specific when it comes to funding mechanisms, which weakens the action item. The EPA has published a municipal handbook containing incentive mechanisms for encouraging green infrastructure including implementation strategies and case examples (U.S. EPA, 2009). The recommended mechanisms include: stormwater fee discounts, development incentives, grants, rebates and installation financing, and awards and recognition programs that may include prize money (U.S. EPA, 2009). As the City of Atlanta "evaluates" financing mechanisms listed in the 2018 Strategic Action Plan, the EPA's municipal handbook should be referenced.

Cross-Jurisdictional Planning for All Scales

The state-wide manual and design guidelines, in combination with the City's guidelines and regulations, creates a lot of different materials to reference when designing both sites and large-scale, multi-parcel developments. These materials should be coordinated with each other as well as other city and state-wide plans to streamline stormwater practices and green infrastructure design. One paper suggests strategies to plan for green infrastructure from the site to regional to landscape scale in both urban and rural contexts, summarized in a diagram shown in Figure 27 (Allen, 2012).

Green infrastructure and stormwater management goals can be coordinated and incorporated into larger conservation and preservation plans and strategies in order to achieve even greater benefits from GI and better watershed coordination between sites and regions. Allen recommends a "seamless quilt of planning" that embraces the interconnections between biodiversity, conservation science, urban forestry, smart growth, and low-impact development to strengthen the planning and implementation framework of green infrastructure more holistically (Allen, 2012). The City of Atlanta should create and coordinate partnerships with environmental, conservation-minded, and stormwater management organizations in all sectors and scales to strengthen GI design, runoff reduction, and water quality at a larger scale.

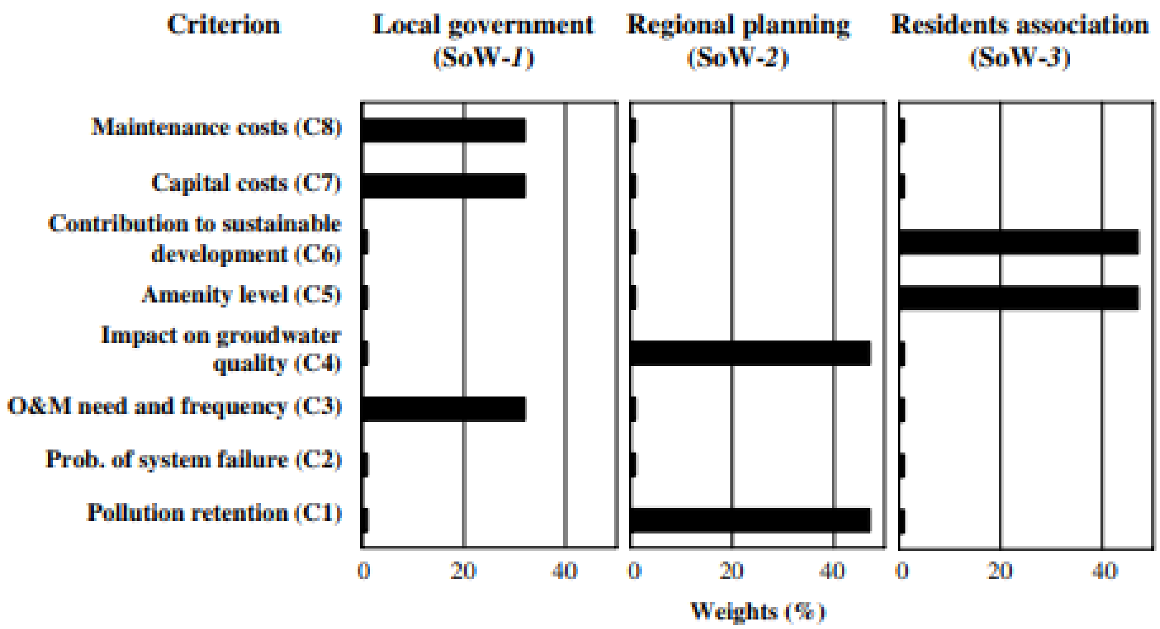


Figure 28, Different Criterion Weights for Each Stakeholder Group (Martin et al., 2006)

Recommendation 2: Improve Site-Analysis Criteria

Decision-Making Criteria

The current state stormwater management model contains a BMP or GI Selection Guide, as referenced before, that contains the following parameters as decision-making factors:

- Runoff reduction
- Pollutant load reductions
- Site applicability factors
  - LID/GI Drainage Area (ac)
  - Space Required (% of Impervious Drainage Area)
  - Max Site Slope
  - Minimum Head (Elevation Difference)
  - Depth to Water Table
- Construction costs and maintenance burden

There are other factors that have been developed in the literature to improve site-analysis criteria through this multicriteria approach. A national survey conducted in France included the above factors, as well as additional parameters, and found which factors were the most important to local governments, regional governments, and residents, shown in Figure 28 (Martin et al., 2006). The additional parameters not listed in the Georgia guide included (Martin et al., 2006):

1. Hydraulic efficiency, which affects overall system performance regarding hydraulic control and pollution control
2. Environmental impact, including impacts on receiving waters, pollution, and ecological diversity
3. Social and sustainable urban living, such as GI as an aesthetic amenity or serving multiple functions, contributing to an overall sustainable development and social inclusion

By understanding the desires of each stakeholder group, each level of government can better create standards, guidelines, and policies that meet these desires. Georgia and Atlanta should similarly conduct surveys about GI concerns, obstacles, desires, and most important decision-making factors to involve the public, coordinate cross-jurisdictional planning, and achieve stormwater management and green infrastructure goals.

The Murphy's Crossing site modeled in this paper, which is owned by the Atlanta Regional Commission and likely to become a public hotspot along the Beltline, must consider both the government's and public's desires for stormwater management. A centralized approach proved to be more conducive to reducing runoff, however, it may not meet stakeholders' desires for a public amenity, low impact development, or pollutant control. All of these factors need to be considered when determining the best design of green infrastructure for a site.

Land Suitability Analysis

An additional analysis integrated with conservation principles—land suitability analysis—can be conducted to further develop the low-environmental impact, or sustainable development, criterion. A case study utilized this approach in Ohio to analyze pre-development and post-development strategies and their environmental impacts (Wang et al., 2010). The land suitability analysis factors included in the study were slope, hydrologic soil group, and soil drainage classification, in order to determine areas that would accommodate development with the smallest increase in runoff from the watershed (Wang et al., 2010). Based on this analysis, they created GI design scenarios on the most suitable areas and determined optimal design configurations of impervious and pervious surfaces (Wang et al., 2010.

Land suitability analysis is typically conducted in order to minimize development costs on a site by building where the least amount of pre-development grading needs to be done. By incorporating stormwater and GI principles as a phase within this analysis, low-impact designs will be able to minimize costs of cut-and-fill practices as well as stormwater management through green infrastructure. This analysis could have been conducted before the scenarios in this study in order to create more complex GI configurations than equally distributed or centralized and find the most optimal design for Murphy's Crossing.

Conclusion

This study informed a small piece of the complexities of stormwater management and green infrastructure design. As global climate change is expected to increase the frequency and intensity of weather events and raise temperatures, especially in cities, infrastructure must be built to accommodate runoff of more intense design storms, such as a 100-year or even 200-year storm. The existing literature shows the numerous benefits of green infrastructure not only in improving water quality and reducing runoff quantity, but also ecosystem services that help to mitigate heat, clean air, and store carbon emissions. Therefore, green infrastructure should be aggressively incorporated into stormwater systems to accommodate large storms and other changing climatic factors. The results of this paper show how two different approaches to GI design, equally distributed or centralized, had different optimizing benefits on an industrial site, with a decentralized approach performing better at reducing pollutant loads and a centralized approach performing better at reducing runoff.

This study should be expanded to include more GI design factors and scenarios in order to quantify even more design approaches and apply to more types of sites. These GI scenarios may perform differently on different land uses or with different types of GI and different storage volume depths. Due to the varying types of green infrastructure, as well as their varying layers, engineered soil types, and media depths, it is important to consider the potential amount of infiltration that can result from different treatment designs. Additionally, as climate change increases the likelihood of more intense storms, these scenarios should be run with 200-year or greater design storms to help designs prepare for the worst. This study could also include more complex design approaches than the two presented scenarios, such as a combined decentralized and centralized approach, randomly distributed approach, or one that aligns with biophilic design principles and the existing natural landscape. This paper analyzed the site level in order to inform specific site design policies and guidelines, however, the recommendations also encourage larger-scale coordination and design. Therefore, this question of decentralized vs. centralized should be analyzed from the site to landscape level and analyze a site's context within contributing watershed treatments. Finally, GI design is not only determined by technical factors such as runoff reduction and pollutant loads. Designs and policies relating to stormwater management are also influenced by political and governance structures, economic constraints, and social and communal desires, and all of these factors can inform optimal, sustainable green infrastructure design and implementation that meets stormwater management goals and regulations.

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