# Assessment of the Effectiveness of Impervious Area Reduction and Green Infrastructure at Improving Water Quality and Reducing Flooding at the Watershed-Scale

FINAL TECHNICAL REPORT

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**Summary**: This project builds on work that resulted from 2014-15 funding from the New York State Water Resources Institute examining the relationship between landscape characteristics and water quality and quantity using field monitoring and geospatial datasets from the Kromma Kill Watershed in Albany County, NY. Simple statistical analyses were used to examine the correlational relationships between watershed characteristics, such as drainage density and percent impervious, and water quality and quantity. For this project, hypotheses were developed from these correlation analyses about causal relationships between landscape characteristics and water quantity and quality. These hypotheses were then tested using a rainfall-runoff model, EPA SWMM. For the second part of this project, a Siena undergraduate student used the model to examine the impact of green roofs versus constructed wetlands on water quality and quantity in the Kromma Kill Watershed. Both projects highlight the complexity of urban landscapes and the processes that control water quality and quantity in watersheds. Results suggest that watershed plans that rely only on reducing the percentage of effective imperviousness are not a "one size fits all" solution. Simply reducing the percentage of effective imperviousness through green infrastructure (GI) may not be the most effective solution for every management objective. Special attention must be paid to the type of GI utilized. For example, retention based GI (wetlands) is best utilized when centralized and reducing peak flow or selected pollutants is the main management objective. However, detention based GI (green roofs) is best utilized when it is decentralized and reducing surface runoff, runoff ratios, and all pollutants entering a system is the main objective.

## 1 Introduction

The processes that control runoff quality and quantity in urban watersheds are complex and not well understood. While impervious surface coverage has traditionally been used to examine altered hydrologic response in urban watersheds, several studies suggest that other elements of the urban landscape, particularly those associated with urban infrastructure and the drainage system, play an equally important role. Research from the Kromma Kill, an urban watershed located in Albany County, NY, suggests that while percent impervious coverage can be used to predict general water quality, other elements of the urban landscape, particularly those associated with subwatershed slope and drainage network structures, have a greater impact on the magnitude of flood response and specific water quality parameters than percent imperviousness. Thus watershed plans that rely only on reducing the percentage of effective imperviousness of the watershed may not serve as the most effective solution for every management objective. The objective of this project is to assess the effectiveness in improving water quality and reducing flooding of green infrastructure (GI) and other stormwater management strategies that aim to reduce the percentage of effective imperviousness versus those that target the drainage network system. These issues will be examined in the subwatersheds of the Kromma Kill using monitoring data collected in 2013 and 2014, a 3d hydraulic river channel model, and a rainfall-runoff model.

### 1.1 Study Area

The setting for this project is the Kromma Kill watershed (20 km$^2$), located in the Town of Colonie and Village of Menands, Albany County, New York (Fig. 1). The Kromma Kill is 18% impervious (with its gaged subwatersheds ranging in imperviousness from 8 to 31%). The predominant land use type is residential with large tracts of developed open space comprising its middle reaches and commercial land uses in its lower reaches, which is the floodplain of the Hudson River. Community priorities within the watershed include several historic sites of national and regional importance, including a U.S. Presidential Gravesite (Chester Alan Arthur) and one of the first Hudson River trading post sites (Schuyler Flats National Historic Landmark).

At present the Kromma Kill watershed is prone to flooding and other water quality issues. Flooding events are most severe in the downstream Village of Menands and in nearby Albany Rural Cemetery, where stream bank erosion has necessitated gravesite relocation and recently caused a road collapse. Adding to water quality issues within the watershed is a brownfield site, the inactive and largely abandoned Al Tech Steel facility (NYS Department of Environmental Conservation site record, Al Tech Specialty Steel, Site Code 401003). A 2004 Town of Colonie Stormwater Management Report indicates that PCBs have been detected in sediment downstream of the brownfield site, and hazardous waste is known to be present in at least three portions of the total property of almost 100 acres. Site-wide monitoring activities continue from concern over heavy metals, fuel oil, and PCB contamination from former production and waste disposal operations at the site. Furthermore, excessive nutrients generated through turf maintenance on a golf course, sprawling housing development, and Siena College may serve as additional potential sources of stormwater pollution. Water quality and quantity issues have landed the Kromma Kill watershed on the New York State 303d Waterbody Inventory/Priority Waterbodies list, making it a priority watershed for Albany County and the focus of targeted work related to implementing Municipal Separate Storm Sewer System (MS4) Permit requirements.

For this project, special attention is paid on a 213 acre subwatershed of the Kromma Kill, designated the "New Hall" or NH subwatershed due to the Siena College New Hall dormitory located near the subwatershed outlet (Fig. 2). The study area is 22.8% impervious and contains 5 stormwater wetlands a 1 detention pond with a filtration basin. The 5.4 total mile drainage network is comprised of 95% pipes and 5% surface channels. The average slope is 7.6% and the predominant soil type is loamy sand. Of the 48.7 acres of impervious surfaces in the study area, 11.5% are buildings. There are a total of 7 drainage points in the study area, the largest with a drainage area of 109 acres.

## 1.2 Previous Work

As part of a 2014-15 NYS WRI-funded study rainfall, runoff, and water quality parameters were measured in the field in 5 Kromma Kill subwatersheds. Landsurface and drainage network characteristics were computed for these same subwatersheds. Strong and significant correlations were identified between the field data and landscape characteristics. Michelle Golden (formally of Siena College, now with the NYS Department of Environmental Conservation) contributed to the geospatial analyses. Dr. Kevin Rhoads (Siena College Department of Chemistry and Biochemistry) and Dr. Mary Beth Kolozsvary and Nick McCloskey (Siena College Department of Environmental Studies and Sciences) collected and analyzed the water quality data. For methodology of the geospatial analyses and field data collection, please refer to the 2015 NYS WRI Final Report.

Results of the correlation analyses suggest the following:

- Rather than percent imperviousness, the strongest predictor of runoff ratio in the Kromma Kill subwatersheds is the area ratio. Strong and significant relationships also exist between runoff ratio and subbasin slope and slope ratio.

- However, percent imperviousness (TIA and DCIA) is the strongest predictor of water quality in the Kromma Kill subwatersheds as quantified through both the biotic index and EPT index.

- The strongest predictors of nitrate and total nitrogen concentration are distance-weighted imperviousness, outfall density, and stormwater density. Distance-weighted imperviousness is the strongest predictor of total dissolved solids, but strong and significant correlations exist between outfall density and stormwater density.

From these correlation analyses, several hypotheses were developed and tested using the EPA SWMM model in Project 1 (described below).

## 2 Project 1: The Role of Drainage Network and Landsurface Characteristics in Controlling Water Quality and Quantity in a Small Urban Watershed

### 2.1 Abstract

The processes that control runoff quantity and quality in urban watersheds are complex and not well understood. While impervious surface coverage has traditionally been used to examine altered hydrologic response in urban watersheds, several studies suggest that other elements of the urban landscape, particularly those associated with urban infrastructure and the drainage system play an equally important role. The relative importance of impervious surfaces, stormwater ponds, expansion of the drainage network, and drainage network structures in controlling hydrologic response is examined in the subwatersheds of the Kromma Kill, an urban watershed located in Albany County, NY. In this study, Geographic Information Systems (GIS) is used to compute geospatial landsurface and drainage network properties of 5 Kromma Kill subwatersheds. In these same subwatersheds, water quantity (rainfall and runoff) and quality (macroinvertebrates, nitrate ($NO_3$), total nitrogen (TN), dissolved oxygen (DO), total dissolved solids (TDS), and non-purgable organic carbon (NPOC)) parameters were measured. Strong and significant correlations between geospatial characteristics and field observations are identified from which hypotheses about causal relationships are developed. These hypotheses are tested using the EPA SWMM stormwater model. Statistical correlational and modeling analyses suggest that percent imperviousness is the primary predictor of flooding and water quality, but subbasin slope, drainage density, and pond density are also important. Unexpectedly, correlational analyses show that the runoff ratio, $NO_3$, TN, and TDS all increase with increasing stormwater management density. However, modeling analyses suggest that this is most likely the result of increases impervious surface coverage and drainage density, which also increased as stormwater management density increases. Results have important implications for stormwater management plans, especially those aimed at reducing the effective impervious surface coverage of urban watersheds. Reducing the percentage of effective imperviousness in a watershed is not a “one size fits all” solution.

### 2.2 Literature Review

Traditionally, the percent impervious of a watershed has been the focus of examining altered hydrologic response due to urbanization (Leopold [1968], Schueler [1994], Arnold & Gibbons [1996], Paul & Meyer [2001], Schueler [2003], Schueler et al. [2009]). Recently, efforts have focused on the impact of the connectivity of impervious surfaces (Booth & Jackson [1997], Shuster et al. [2005], Roy & Shuster [2009], Barron et al. [2009]) and the location and pattern of the impervious surfaces within a drainage system (Mejía & Moglen [2009], Mejía & Moglen [2010]).

While these studies suggest that the percent coverage, connectivity, and distribution of impervious surfaces within a watershed impact hydrologic response, a growing body of literature suggests that other elements of the urban environment, particularly those associated with the drainage network also play a role in altered hydrologic response in urban watersheds. These include alteration and extension of the drainage network (Graf [1977], Smith et al. [2002]), the distribution of stormwater detention ponds (McCuen [1979], Emerson et al. [2005], Goff & Gentry [2006], Smith et al. [2013], Smith et al. [2015]), and drainage efficiency (Aronica & Lanza [2005]).

The structure of the drainage network itself may also impact hydrologic response in urban watersheds. Similarities such as Horton's laws of stream numbers, stream lengths, and basin area can be observed in the drainage networks of all natural river basins (Rodriguez-Iturbe & Rinaldo [1997]) and geomorphic properties of natural basins can be used to predict hydrologic response (Rodriguez-Iturbe & Valdes [1979], Rinaldo et al. [1995]). Research focused on urban drainage systems (Smith et al. [2002], Beighley & He [2009], Meierdiercks et al. [2010a], Ogden et al. [2011]) suggests that geomorphic properties of urban drainage networks such as drainage density and the expansion of the drainage network (the width function) can impact hydrologic response. Furthermore, the relative importance of impervious cover versus drainage network characteristics in predicating flood response in an urban watershed may be scale-dependent (Javier et al. [2007]).

This literature on the processes that control hydrologic response in urban watersheds is far from conclusive. A review in Ogden et al. [2011] highlights the inconsistencies: "the literature contains contradictory conclusions regarding the relative effects of urbanization on peak flood flows due to increase in impervious area, drainage density and width function, and the addition of subsurface storm drains." Several of these studies (Javier et al. [2007], Meierdiercks et al. [2010a], Ogden et al. [2011]) have occurred in a single watershed. It is unclear how the results translate to other urban watersheds given the heterogeneity of hydrologic response in small urban watersheds (Meierdiercks et al. [2010b]) especially at varying spatial scales and storm magnitudes. Though rainfall is a principal determinant of hydrologic response in any watershed, the heterogeneity of land surface composition and infrastructure in urban watersheds can combine with rainfall variability in space and time (Ogden & Julien [1993], Ogden et al. [2000], Mejía & Moglen [2010], Ogden et al. [2011]) to create major challenges for hydrologic analyses.

The literature on the impacts of impervious surfaces and other elements of the urban landscape on water quality are also inclusive. Impervious surface coverage is often used to predict runoff quality in urban watersheds (Schueler [2003]), however several studies have also focused on the role of drainage network properties (such as those examined for this project) in controlling urban runoff quality, specifically imperviousness connectivity (Hatt et al. [2004], Carle et al. [2005], Christopher J. Walsh [2005]), overland flow paths (Walsh & Kunapo [2009]), and drainage characteristics such as road and pond density (Walters et al. [2009], Sun et al. [2013])).

Major elements of the urban landscape that are built specifically to control flooding and improve water quality are stormwater detention ponds and constructed wetlands. Though designed to reduce flood peaks, at the watershed-scale, their effectiveness at the watershed-scale seems to vary by watershed (McCuen [1979], Emerson et al. [2005], Meierdiercks et al. [2010b], Smith et al. [2013]) and may be scale-dependent (Smith et al. [2015]). In terms of water quality, removal efficiencies can vary substantially not only by site, but but type of contaminant (Center for Watershed Protection (CWP) [2007], Koch et al. [2014], Leisenring et al. [2014]).

The inconsistencies in the existing literature point to the need to further examine imperviousness, stormwater management controls, and other aspects of urban landscape and the impact on water quality and quantity. In this study, these issues are examined through both field data analyses and modeling studies in the urban/suburban subwatersheds of the Kromma Kill (20 km$^2$) located in Albany County, NY (Fig. 1). In the Kromma Kill Watershed, land surface and drainage network properties are characterized using geospatial datasets and geographic information systems (GIS) software. Runoff quantity is examined through observations of rainfall and runoff and water quality is characterized through biomonitoring (macroinvertebrate), nitrate ($NO_3$), total nitrogen (TN), dissolved oxygen (DO), total dissolved solids (TDS), total organic carbon (TOC), and non-purgable organic carbon (NPOC) observations. Strong and significant correlations are identied between landsurface and drainage network properties and field observations, from which hypotheses about causal relationships are developed. These hypotheses are tested using the EPA SWMM stormwater model.

## 2.3 Methods

Modeling analyses were performed using the Environmental Protection Agency's Stormwater Management Model (EPA SWMM). SWMM is a rainfall-runoff and hydraulic routing model that uses rainfall as input and routes runoff (rainfall minus infiltration) over the land surface, through stormwater pipes, wetlands and detention ponds, and the surface channel network. GIS and field datasets are used to construct and parameterize the model. Field data are used as forcing, calibration, and validation. A model of the NH subwatershed, the most urbanized of the subwatershed, was developed to examine the impact of imperviousness, drainage structure, slope and other landscape characteristics on water quality and quantity. While correlational analyses were performed with water quality parameter collected during low-flow conditions, model analyses examine water quality during storm events.

For this study, a 60 minute 1 year design storm (0.88 inches in 60 minutes, from Northeast Regional Climate Center,`http://precip.eas.cornell.edu/`) is used as input, the Green-Ampt equation is used to compute infiltration, runoff is routed over the land surface assuming the impervious and pervious portions of each subcatchment are directly connected to a stormwater catchbasin. Once entering a catchbasin, runoff is routed through stormwater detention ponds and wetlands, stormwater pipes, and the surface channel network. The model was calibrated using rainfall and runoff data from five storms close in magnitude and duration to the design storm. The saturated hydraulic conductivity and the mannings roughness of the pervious and impervious portions of the study area were adjusted to match the timing and volume of the observed discharge hydrographs (calibrated values are Ksat = 0.1875; n-perv = 0.3; n-imperv = 0.02). For water quality, total dissolved solids, nitrate, total nitrogen and total phosphorus were added to the system and the EMC function was used to compute pollutant washoff during rain events. The model was calibrated to match concentrations of total dissolved solids and nitrate measured in the field during a storm event during the summer of 2014 close in magnitude to the design storm. For total phosphorus and total nitrogen, the model was calibrated to match values typical of urban runoff (James et al. [2010]). See the Appendix for a table of the source for all model parameters and James et al. [2005] for a full description of the mathematical equations used by SWMM.

The SWMM model represents the "business as usual" or existing conditions within the NH subwatershed. Several alternative design scenarios were created to test the impact of imperviousness, drainage density, stormwater management density, and surface slope on water quality and quantity. In each alternative model scenario, one landscape characteristic was modified to represent the upper or lower limit of that landscape characteristic for all five subwatersheds. For example, the NH watershed is 23.8% imperviousness. In the first alternative design scenario, the imperviousness of the NH subwatershed was by 33% to represent the imperviousness of the AS subwatershed (which is 7.9% imperviousness). In the second and third scenarios, the total percentage of imperviousness of the NH subwatershed was unchanged, but all imperviousness was concentrated near and far from the outlet, respectively. In the fourth design scenario, the model was modified to simulating decreasing the drainage density by 23% (to simulate a conversion from the maximum drainage density (pipe and surface channels) of the NH subwatershed of 20.37 ft/mi to the density of the AN subwatershed, 4.78 ft/mi). The fifth and sixth design scenarios involve increasing the slope of each subcatchment by 10% and decreasing the slope by 53% respectively to represent the least steep (AS) and most steep (LI) subcatchments. The seventh and last alternative design scenario involves removing the two stormwater management ponds to best match the minimum management density within the Kromma Kill Watershed (the AS subwatershed at 0.9 ponds/$mi^2$).

## 2.4 Results

From these correlation analyses, the following hypotheses were developed and tested using the EPA SWMM model:

- Impervious surfaces will impact flooding, but subbasin slope, drainage density, and pond density are also important. These latter landscape characteristics may help to explain some of the variation in the plot of imperviousness versus runoff ratio.
- We see an increase in water contaminants with increasing stormwater management density not because the ponds are adding contaminants to the system but because stormwater management ponds are a consequence of increased urban infrastructure density.

Although the results of the correlation analyses suggest that the strongest predictors of the runoff ratio in the Kromma Kill subwatershed is the area ratio, subbasin slope, and slope ratio, model results suggest that imperviousness has a greater impact on water quantity, as represented by both the runoff ratio and peak discharge, than slope. When the percent imperviousness of the NH subwatershed is reduced by 33% to match that of the least impervious subwatershed (AS), the runoff ratio decreases by 34.0% and peak discharge decreases by 24.4% (Table 1). This is compared to a percent reduction of -19.0% and -1.5% for reducing drainage density by 23% and and overall change of 5.6% and 4.2% for converting from the minimum to maximum slope. The location of imperviousness has a greater impact on peak discharges compared to decreasing the overall percent imperviousness. With all imperviousness concentrated near the outlet, most of which is downstream of the two stormwater management ponds in the subwatershed, peak discharge at the outlet increased by 57.1%. When the stormwater management ponds were removed completely, peak discharges increases by 358%.

In terms of water quality, the model scenario that results in the most improved removal efficiency for all four pollutants is to decrease the slope by 53% (Table 2). Consequently, the worst removal efficiency for TDS and TN is to increase slope. According to correlation analyses, while subbasin slope was an important predictor of DO and EPT, is was not the most significant predictor of TDS, TN and $NO_3$. The worst removal efficiency for $NO_3$ and TP, was the model scenario in which stormwater management ponds are removed. While removing the stormwater management ponds results in poorer removal efficiency for all four pollutants, this scenario was even worse for $NO_3$ and TP.

Stormwater management ponds are typically designed to mitigate flooding by reducing runoff peak flows and volumes. Increasingly, stormwater management ponds are also designed to improve runoff quality. Thus an unexpected result of the correlation analyses is that as stormwater management density is positively correlated with runoff ratio and several water quality variables; several of these variables (TDS, $NO_3$, and TN) are both positively and significantly correlated with stormwater management density. There are two possible explanations for this unexpected result. One possibility is that stormwater pond density is simply a consequence of increased urban infrastructure density and imperviousness. As cited above, both imperviousness and urban infrastructure have been shown to be associated with flooding and poor water quality. Furthermore, according to correlation analyses of geospatial watershed characteristics, stormwater management density is both positively correlated with imperviousness (r=0.77) and density (stream/pipe r= 0.98 , pipe r= 0.98, and outfall r = 0.99). A second explanation is that while the stormwater wetlands remove some contaminants from the watershed by reducing runoff quantity, they can also produce excess TN and TDS (Center for Watershed Protection (CWP) [2007], Koch et al. [2014], Leisenring et al. [2014]).

To test whether the increase in water contaminants with increasing stormwater management density is the result of stormwater ponds adding contaminants to the system or a consequence of increased urban infrastructure density, the SWMM model is used. As stated above, removing stormwater management ponds from the NH subwatershed model resulted in a reduction of the pollutant removal efficiency of the subwatershed supporting the hypothesis that the unexpected result from the correlation analyses is not the result of wetlands adding contaminants to the system. Thus, the increase in water contaminants with increasing stormwater management density is likely a consequence of increased urban infrastructure density.

## 2.5 Discussion

Results highlight the complexity of urban landscapes and the processes that control runoff quantity and quality in small urban watersheds. The percent imperviousness of a watershed is typically used to characterize urban landscapes and predict the increase in flooding and decrease in water quality as a result of urban development. Yet, studies examining the role of drainage structure in predicting flooding and water quality suggest that these element of the urban landscape may also be important. The results presented here through field data analysis, geospatial analyses, and modeling studies, suggest that impervious surfaces can be used to predict flooding and water quality, but subbasin slope, drainage density, and stormwater pond density are also important. Thus incorporating some of these latter elements into our stormwater models, may help to improve their predictive capabilities.

These results also have important implications for stormwater managers and watershed practitioners. Developing and implementing watershed management plans is costly. While post-implementation monitoring is essential for assessing the success of these plans (National Research Council [2009]), the overall cost of watershed management plans could be reduced if management strategies were limited to those that were known to target the dominant controls on hydrologic response. Green stormwater infrastructure (GI), such as green roofs and porous pavement, has been promoted as a way to reduce the effective imperviousness of urban watersheds. Results of this study suggest that watershed plans that rely only on reducing the percentage of effective imperviousness are not a “one size fits all” solution. Reducing the percentage of effective imperviousness can help to meet some management objectives, but may not serve as the most effective, and therefore economical, solution for every management objective.

## 2.6 Conclusion

The conclusions of this study are summarized as follows:

1. Modeling results suggest that impervious surfaces will impact flooding, but subbasin slope, drainage density, and pond density are also important. These latter landscape characteristics may help to explain some of the variation in the plot of imperviousness versus runoff ratio.

2. An unexpected result of the correlation analyses is that the runoff ratio increases with increasing stormwater management pond density and TDS, $NO_3$, and TN concentrations are all positively and significantly correlated with stormwater management density. Though some studies suggest that detention pond and stormwater wetlands can add certain types of contaminants to urban runoff, model analyses suggest that its not the case in the NH subwatershed. Rather, it is likely that increasing stormwater management density is a consequence of increasing imperviousness and urban infrastructure density. These results suggest that stormwater management strategies, such as constructed wetlands, do not fully mitigate the negative impacts of urban development.

3. In examining the impacts on flooding and water quality of impervious surfaces versus other elements of the urban landing including urban infrastructure, both correlational analyses of field data and stormwater modeling suggest that impervious surfaces do impact flooding and water quality, but subbasin slope, drainage density, and stormwater management density are also important. Results have important implications for sustainable urban drainage systems and stormwater management strategies, especially those aimed at reducing the effective impervious surface coverage of urban watersheds. Drainage network properties or properties that are computed from characterizations of both hillslope and drainage network properties are strongly and significantly correlated with the runoff ratio, total nitrogen, nitrate, and total dissolved solids. Watershed plans that rely only on reducing the percentage of effective imperviousness are not a ”one size fits all” solution. Reducing the percentage

of effective imperviousness can help to meet some management objectives, but may not serve as the most effective, and therefore economical, solution for every management objective.

## 3 Project 2: The Impact of Centralized versus Decentralized Green Infrastructure (GI) on Water Quality and Quantity at the Watershed Scale

The majority of this project and report was prepared by Nick McCloskey, a junior undergraduate student in the Siena College Department of Environmental Studies and Sciences. Nick helped with field data collection the during the 2014 summer season and during the summer of 2015 and the 2015-16 academic year, Nick used his knowledge of the Kromma Kill Watershed and interest in GI to develop a number of hypotheses about the impact of GI on water quality and quantity in a subwatershed of the Kromma Kill. As a result of this work, Nick presented his research at the Environmental Consortium of Colleges and Universities conference last fall and is first author on a manuscript in preparation. A first draft of this manuscript is provided below.

### 3.1 Abstract

Green infrastructure (GI) is a stormwater management strategy that promotes local capture and infiltration of rainfall runoff to protect, restore, or mimic the natural water cycle. This research focuses on assessing the impact of GI on water quality and quantity on a watershed scale by examining the impact of the location and type to effectively treat water. To do this, the EPA SWMM model is utilized to replicate Siena College's subwatershed and run simulations of various design scenarios. Based on these simulations, we discovered that both the original purpose and natural functions of the green infrastructure type make certain locations more suitable for treating various water quality and quantity parameters. For example, retention based GI (wetlands) is best utilized when centralized (large drainage areas) and reducing peak flow or selected pollutants is the main management objective. However, detention based GI (green roofs) is best utilized when it is decentralized (small drainage areas) and reducing surface runoff, runoff ratios, and all pollutants entering a system is the main objective.This knowledge can be used in the future to help water resource managers as well as city planners and private institutions when they are contemplating adding new green infrastructure into their watersheds.

### 3.2 Literature Review

Local human environmental impacts have become popular topics of study and discussion around the world. These impacts are an even larger concern in highly urbanized areas. More and more local businesses, home owners, and institutions are trying to do their part to attempt to mitigate environmental damages and reduce their overall footprint. For many years this was a difficult thing to do, but recently new technologies have allowed these groups and individuals to make more significant and efficient impacts on the world around them. Green infrastructure (GI) is one of these new technologies. Green infrastructure can come in many different forms and each has its own impacts on the environment around it. GI is defined by the EPA as being "any infrastructure that uses natural hydrologic features to manage water and provide environmental and community benefits" (EPA). From basic, easy to install, do it yourself projects to large federally-funded ones, GI is expanding and being utilized more and more. Due to this fact, many researchers have begun to study these projects to learn more about them. This new and expanding technology has opened up a new field of research to the scientific community.

One of the biggest issues faced by researchers looking at green infrastructure is attempting to answer the question of what is the best way to use this new technology to improve water quality and control water quantity. In other words, can GI be optimized to improve specific water quality and quantity parameters?

Literature shows researchers have attempted to determine how we can best use green infrastructure to our advantage in many different ways. Some studies have looked at the various types of GI (Lee et al. [2012]) while others focused more on one type but looked to optimize the size, shape, cost or location of these projects (Thurston et al. [2003], Zhen et al. [2004]). Each of these articles have made large contributions to the current field of literature but yet there is still no consensus on which of these is best or even how to go about studying green infrastructure. Meaning, for this field of research, there are very few hard and fast rules where X + Y equals a desired outcome for your watershed. Because of this further research is needed to discover some of these trends and rules for GI so they may be utilized to their fullest potential.

Many researchers have examined the effectiveness of individual GI structures through field monitoring projects. A few studies have attempted to synthesize the results of these numerous projects to summarize the effectiveness of different types of GI at reducing flooding and improving water quality (Center for Watershed Protection (CWP) [2007], Koch et al. [2014], Leisenring et al. [2014]). These synthesis studies have found that the effectiveness of GI depends on the type of GI, specific site conditions, and pollutants measured. Furthermore, literature reviews have highlighted the many uncertainties associated with GI. Ahiablame et al. [2012] points to the need to further monitor individual GI structures over different spatial and temporal scales as well as evaluate the performance of GI practices at the watershed and regional scales.

Several studies have attempted to assess GI at the watershed-scale through field monitoring (Deitz [2007], Dietz & Clausen [2008], Hood et al. [2007]). Stormwater modeling is another strategy that is used to examine the effectiveness of GI across large spatial scales. Modeling provides the flexibility to examine a variety of different management strategies including those that may not be economically feasible. Like the site-scale evaluations of GI, results of GI performance at the watershed-scale depend on the type of GI, specific site conditions, and pollutants measured, but are also scale-dependent and rain-dependent (volume and temporal variability) (Qin et al. [2013], Ahiablame et al. [2013], Liu et al. [2014], Liu et al. [2015], Guan et al. [2015], Rosa et al. [2015]). In general, results do indicate that GI reduces runoff and pollutant loads.

However, as GI is a relatively new technology, Lee et al. [2012] highlights the uncertainties associated with the way models represent different types of GI. One model that has been shown to successfully model traditional stormwater infrastructure, in addition to GI, is the Environmental Protection Agency's Stormwater Management Model (EPA SWMM). In particular, SWMM has been used to assess the effectiveness of green roofs (Burszta-Adamiak & Mrowiec [2013]). Green roofs have many complex parts that can be changed and altered. This makes them incredibly versatile but also more complex and difficult to study. These are just some of the many reasons that more researchers are focusing specifically on green roofs (Burszta-Adamiak & Mrowiec [2013], Berndtsson [2010], Kadas [2006], MacIvor et al. [2011], Alfredo et al. [2009], Abi Aad et al. [2009]).

One strength in the field of GI is the management of the size and placement of various GI projects throughout a watershed to accomplish a specific task. A recent study performed using a cost-optimization model showed that it was more cost effective to install many, small, decentralized water retention ponds instead of completing one single large pond that is more centrally located. They also state that, "this paper focuses basically on cost, the upstream ecological benefit of the dispersed investment approach is an important factor to consider in evaluating and comparing these two approaches", centralized versus decentralized (Thurston et al. [2003]). This project uses the SWMM model to examine the ecological benefits of centralized and decentralized GI to determine what the impacts on water quality and quantity may be.

The objectives of the project are summarized as follows:

- Utilize SWMM to build a working calibrated model of Siena College's campus subwatershed.
- Use this model to analyze the differences in water quality and quantity between centralized and decentralized GI in the form of an existing centralized wetland, simulated decentralized wetlands, and simulated centralized and decentralized green roofs.

- Assess the normalized results to determine if drainage area, location, or GI type has a larger impact on water quality and quantity.

Results suggest that both the original purpose and natural functions of the green infrastructure type make certain locations more suitable for treating various water quality and quantity parameters. For example, retention based GI (wetlands) is best utilized when centralized (large drainage area) and reducing peak flow or selected pollutants is the main management objective. However, detention based GI (green roofs) is best utilized when it is decentralized (small drainage) and reducing surface runoff, runoff ratios, and all pollutants entering a system is the main objective.This knowledge can be used in the future to help water resource managers as well as city planners and private institutions when they are contemplating adding new green infrastructure into their watersheds.

## 3.3 Methods

For this study, a stormwater model of the Siena College campus was generated from field observations and GIS datasets. Field observations of rainfall are used as model forcing and streamflow and water quality measurements are used to calibrate and validate the model. The model was then modified to represent several design scenarios to examine the impact of each scenario on stormwater runoff quantity and quality.

*Field Data Collection*

Observations of rainfall and runoff are made in the subwatershed using a rain and stream gaging stations. The rain gage station consists of a tipping bucket rain gage to capture rainfall timing (at 5 minute intervals) while two Tru-Check rain gages are used to verify storm total depth. The stream gaging station consists of a water level logger that records water depth at 5 minute intervals. By making direct discharge measurements using a wading rod and current meter, a rating curve is developed to convert continuously measured water level into estimates of streamflow. Temperature, conductivity, dissolved oxygen (DO), nitrate, salinity, and total dissolved solids (TDS) were measured in the field using a YSI Professional Plus meter once per week June through August 2014 during baseflow conditions. Surface water grab samples were be collected in 0.25 L polyethylene bottles. Water is collected by dipping the clean bottle below the surface (wearing gloves), uncapping the bottle under water, allowing it to fill and recapping the bottle to avoid surface scum entering the bottle. Grab samples were analyzed for total nitrogen (TN) and non-purgable organic carbon (NPOC).

*Model Development*

Modeling analyses were performed using the Environmental Protection Agency's Stormwater Management Model (EPA SWMM). SWMM is a rainfall-runoff and hydraulic routing model that uses rainfall as input and routes runoff (rainfall minus infiltration) over the land surface, through stormwater pipes, wetlands and detention ponds, and the surface channel network. GIS and field datasets are used to construct and parameterize the model. Field data are used as forcing, calibration, and validation. For this study, a 60 minute 1 year design storm (0.88 inches in 60 minutes, from Northeast Regional Climate Center, `http://precip.eas.cornell.edu/`) is used as input, the Green-Ampt equation is used to compute infiltration, runoff is routed over the land surface assuming the impervious and pervious portions of each subcatchment are directly connected to a stormwater catchbasin. Once entering a catchbasin, runoff is routed through stormwater detention ponds and wetlands, stormwater pipes, and the surface channel network. The model was calibrated using rainfall and runoff data from five storms close in magnitude and duration to the design storm. The saturated hydraulic conductivity and the manning's roughness of the pervious and impervious portions of the study area were adjusted to match the timing and volume of the observed discharge hydrographs (calibrated values are Ksat = 0.1875; n-perv = 0.3; n-imperv = 0.02). For water quality, total dissolved solids, nitrate, total nitrogen and total phosphorus were added to the system and the EMC function was used to compute pollutant washoff during rain events. The model was calibrated to match concentrations of total dissolved solids and nitrate measured in the field during a storm event during the summer of 2014 close in magnitude to the design storm. For total phosphorus and total nitrogen, the model was calibrated to match values typical of urban runoff (James et al. [2010]). See the Appendix for a table of the source for all model parameters and James et al. [2005] for a full description of the mathematical equations used by SWMM.

*Experimental Design*

In order to begin to test our hypothesis various design scenarios were created in SWMM to address the research objectives set up for the study. Each scenario and the following data are based on the same one year design storm on the same time interval. The first scenario is called the "business as usual scenario". This scenario was created to replicate the current conditions seen throughout the Siena College subwatershed. This will be used as our control scenario to compare how the changes we make will affect the current real life conditions. This natural green infrastructure will act as our model for centralized GI in a watershed. Constructed wetlands and retention ponds are very popular types of green infrastructure due to the low cost and maintenance.

The second scenario is very similar to the first except for the omission of the wetland. The wetland was removed by rerouting the flow through this area as if it was a conduit instead of a storage area. This allows us to use this scenario as a control to assess the impacts of having no green infrastructure at all. This is important because it will allow us to determine the baseline water quality and quantity of the system without any GI. This, in turn, allows for a better assessment of the impacts of the added green infrastructure in the other scenarios.

The third scenario also omits the centralized wetland but instead adds decentralized green infrastructure in the form of green roofs. For this type of GI an elevated roof surface is needed for them to be implemented. Due to this the overall area of the green roofs are restricted to the available area of roof surfaces on campus. Because of this we decided to simulate all available roof area on campus being converted to green roofs. To do this, GIS was used to determine the percent area of the watershed that was roof surface. This number was determined to be 11.5% of the overall area (and about half the impervious area). Because we wanted to create an extreme decentralization case all subcatchments had to be even in the amount of GI treatment they received. This was done by individually adding a green roof to each subcatchment that would equal 11.5% of that specific subcatchments area. This then resulted in the watershed having a total of 11.5% of its total area covered in green roofs.

These three scenarios are all realistic management scenarios, meaning they could be easily implemented into the existing infrastructure that is found on Siena Colleges campus and utilized as a management technique. Although these three scenarios are the most realistic from a management perspective these do not provide enough information to accurately compare and quantify the impact of each on water quality and quantity. Two more scenarios are needed in order to determine if the differences seen between the scenarios are due to the location (centralized versus decentralized) or the GI type (wetland versus green roof). These scenarios will also be used to normalize the results for drainage area so we can determine if the amount of impact a system is having is due to the volume of pollutants it is treating or the actual efficiency of the system. These two scenarios are not as realistic from a management standpoint but they are a necessary thought experiment in order to properly interpret the results and compare the individual stormwater management techniques.

The first of these two scenarios is the decentralized wetland scenario. In this scenario the centralized wetland was again removed and then 9 smaller wetlands were created and placed throughout the subwatershed in 9 different subcatchments. These subcatchments were chosen based on the amount of open space available along with their individual drainage characteristics. The drainage area of these wetlands were made equivalent to the drainage area of the decentralized green roofs. By normalizing the results for drainage area in this way it will allow for a more accurate comparison of the decentralized scenarios and therefore the GI types. This scenario is not as realistic due to the fact that creating many small wetlands is not as feasible due to the need for large amounts of open uninterrupted space, which on campus there is not an abundance of.

The last scenario created was the centralized green roof scenario. This was done by, again removing the centralized wetland, and then converting all impervious surface in the 3 centermost subcatchments that surrounded the wetland to green roofs. Also again to normalize the results the green roofs were given the same drainage area as the centralized wetland. This scenario is also not very realistic due to the need for green roofs to be on a roof. If you do not have a large centralized building within your watershed it would be difficult to create this scenario.

### 3.4 Results and Discussion

In order to efficiently analyze and discuss the differences between each of these design scenarios we first had to be sure that each scenario was receiving the same treatment. As mentioned before each simulation is based on a 1 year design storm. This allows the same amount of water to enter the system in each scenario over the same time period.

*Water Quantity*

In urban environments a water quantity characteristic that is often analyzed is peak flow, the maximum volumetric flow rate in a drainage system. For example a very high and fast peak flow indicates that the water is running off the land surface rapidly and not percolating through the soil. This is often the case in urban areas and this can have many negative impacts on streams as well as downstream communities. In more rural areas peak flow is usually a longer and more gradual process and the peaks are not as high. This is because with more permeable surfaces more water is entering the soils and groundwater supply. For these reasons, we began our analysis by creating a hydrograph for each scenario in order to compare the peak flow at the watershed's outlet for this storm event. The hydrograph of each design scenario is shown in Fig. 3. The smallest peak was produced by centralized wetland scenario at 12.7 cfs. This is because a wetland is a retention based storage area that will capture surface runoff during a storm event and release it slowly, which decreases the peak, as well as extends the period of time that the peak flow occurs. By removing this we see a dramatic increase in the peak flow from 12.7 cfs to 50.5 cfs in the no wetland control scenario. Because the centralized wetland scenario did so well at reducing peak flow it would be easily assumed that the decentralized wetland would also reduce peak flow in a significant way. However, the decentralized wetland scenario was the second worst design scenario with a peak flow of 43.7 cfs. The centralized green roofs reduced peak flow to 29.8 cfs, which is better than the control but not as good as the centralized wetland. Although both of these centralized scenarios were more efficient than their decentralized counterparts with the same GI type.

A second quantification of water quantity is the runoff ratio, the fraction of rainfall that becomes runoff during a given time period. The no wetland and centralized wetland scenarios were almost identical at 0.29 and 0.27 respectively but the centralized green roof scenario was 0.18; this 38% difference from the control is a significant one and the largest of all the scenarios. Changing the wetlands to a decentralized position had no impact on the runoff ratio. However, when the green roofs were changed to a decentralized position it increased the runoff ratio to 0.21 which is not as good as the centralized green roof scenario but was still more efficient than either of the wetland scenarios.This is due to the functions green roofs provide. Green roofs actually use water and allow it to re-enter the water cycle very quickly instead of holding on to it like wetlands. They also convert impervious surface to pervious, which is more dramatic of a change than pervious to temporary storage.

*Water Quality*

When the amount of surface runoff is reduced, less pollutants are swept off of the impervious land surfaces and into surface water bodies. This idea of less runoff equals less pollution entering the system led us to believe that we would see the same dramatic reductions in pollutant volume and concentration that we saw in the runoff ratio. The four pollutants analyzed were chosen based on the field data collected and the availability of historical data. The summary of these pollutants can be seen in Fig. 4 along with the percent removed and percent difference for each pollutant in each scenario.

As expected, the control scenario had the lowest percent removal for all pollutants (Fig. 4). With no green infrastructure helping to mitigate the pollutants in the runoff this is all able to enter the surface water.

When examining both wetland scenarios an odd trend can be seen. Both the decentralized and centralized wetland scenarios removed nitrates and total phosphorus well but they did not remove TN or TDS nearly as well. For the centralized wetlands the percent removal of nitrates and phosphorus was 55 and 37% respectively while the total nitrogen and total dissolved solids were not much higher than the control scenario at 4.3 and 6.3%. This is because wetlands actually add to TDS and nitrogen while eliminating total phosphorus and nitrates (Leisenring et al. [2014]).

When the green roof scenarios were analyzed for water quality it was discovered they were also limited by another outside force. This force was size and drainage area. As the drainage area or size of an individual green roof increased its ability to remove pollutants decreased. This can be seen when comparing the centralized versus decentralized green roof scenarios. The decentralized green roofs, which are smaller and handle a smaller volume of water per site when compared to the large centralized green roof, was much more efficient at removing pollutants. All pollutants for this scenario were reduced by 38-40% (Fig. 4). On average, when compared to all other scenarios, this was the most efficient in terms of water quality and pollutant removal. The centralized green roof however, did not remove pollutants very efficiently at all and was not much better than the control scenario. This scenario only reduced pollutants by 5-10% (Fig.4) and was the worst test scenario other than the control. This is because green roofs can only handle a certain amount of water at a given time. By centralizing the green roof and increasing the amount of water entering the system you make it much less efficient.

When comparing both wetland scenarios against the green roof scenarios, the green roofs had less deviations between pollutants meaning that they impacted all pollutants evenly while wetlands only impacted selected pollutants. These selected pollutants however were removed more efficiently than the green roofs. This same trend was seen when using volume of pollutants entering the system as well.

### 3.5 Conclusion

The original purpose and natural functions of a GI type may make certain locations be more suitable for treating various water quality and quantity parameters. These factors need to be applied on a case by case basis in order to make effective management decisions. However, some basic trends can be identified that will help provide insight into this decision making process. Retention based GI, such as wetlands, are best utilized when centralized and having a large drainage area and when reducing peak flow or selected pollutants (TP, $NO_3$) is the main objective. Detention based GI, such as green roofs, are best utilized when decentralized or having a small drainage area and when reducing surface runoff, runoff ratios, and all pollutants entering a system is the main objective. The conclusions of this study are summarized as follows:

1. When assessing water quantity impacts for the viable management scenarios, it was seen that wetlands reduced peak flow more effectively than green roofs, but green roofs more effectively reduced the runoff ratio even though the green roofs treat a smaller drainage area. This is caused by the difference in how each of these actually goes about treating water (retention versus detention).

2. When comparing the centralized scenarios, the wetland reduced peak flows better than the centralized green roofs. However, the centralized green roofs reduce the runoff ratio. The decentralized green roofs also reduced peak flows and the runoff ratio better than decentralized wetlands. This supports the suggestion that the differences observed were due to fundamental differences between the types of GI. It also shows that decentralized GI only works if it is based in detention rather than retention due to the volume of water that needs to be accommodated.

3. When water quality is assessed for the viable management scenarios, decentralized green roofs removed all pollutants equally well, while the wetland removed some more efficiently (TP, $NO_3$) but other less efficiently (TN, TDS) due to natural wetland functions and their ability to remediate selected pollutants. However, on average, the best scenario for removing pollutants was the decentralized green roofs.

4. When the centralized scenarios are compared, both scenarios were limited by some factor that made them less efficient. The centralized green roofs again treated all pollutants evenly, however they did this very poorly. This was because the green roofs work in detention and are not meant to contain large volumes of water like a retention based system, so they were limited by their ability to treat large amounts of water in a short period of time. The wetlands, as we have seen previously, are limited by their natural functions and inability to effectively remediate total nitrogen and total dissolved solids. Overall, the centralized wetlands are better at improving downstream water quality but are limited by natural processes, while centralized green roofs are limited by the way that green roofs treat water.

5. When the decentralized scenarios are compared for water quality, the decentralized green roofs severely out-competed the decentralized wetlands in pollutant removal. This goes to show that, again, decentralized GI works more efficiently if it is based on detention.

## 4 Future Work

Though a SWMM model has been built for the full Kromma Kill Watershed, Nick decided to focus his modeling analyses on the New Hall Watershed because at the time he began his project, it was better characterized and therefore he had more confidence in the results. Future work will focus on testing his hypotheses in larger subwatersheds with varying landscape characteristics (ex. drainage structures and imperviousness) and exploring the impacts of different types of GI and stormwater management structures (such as detention ponds) on water quantity and quality.

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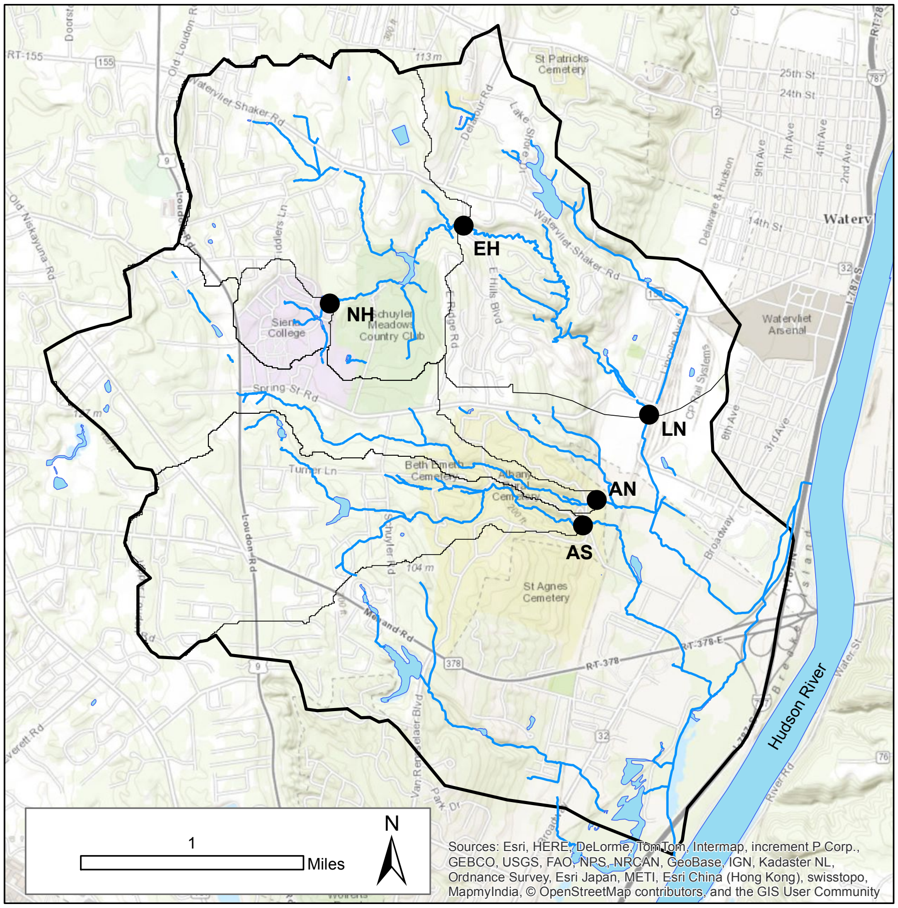
## 6 Tables and Figures

Table 1: Results of SWMM water quantity modeling

| Model Scenario | Runoff Ratio | % Change | Peak Discharge (cfs) | % Change |
|---|---|---|---|---|
| Business as Usual | 0.40 | – | 12.7 | – |
| Decrease Imp by 33% | 0.26 | −34.0% | 9.6 | −24.4% |
| Downstream Imperviousness | 0.42 | 5.2% | 19.9 | 57.1% |
| Upstream Imperviousness | 0.37 | −7.7% | 11.2 | −11.6% |
| Decrease Drainage Density by 23% | 0.32 | −19.0% | 12.5 | −1.5% |
| Increase Slope by 10% | 0.40 | 0.7% | 12.7 | 0.6% |
| Decrease Slope by 53% | 0.38 | −4.9% | 12.2 | −3.6% |
| Remove SWM Ponds | 0.44 | 9.6% | 58.0 | 357.6% |

Table 2: Results of SWMM water quality modeling

| | % Removed (Concentration) | | | | Percent Difference | | | |
|---|---|---|---|---|---|---|---|---|
| Model Scenario | TN | TDS | $NO_3$ | TP | TN | TDS | $NO_3$ | TP |
| Business as Usual | 7.6% | 10.2% | 73.4% | 49.4% | - | - | - | - |
| Decrease Imp by 33% | 9.3% | 13.0% | 73.1% | 51.1% | 21.9% | 28.1% | -0.4% | 3.3% |
| Downstream Imperviousness | 6.3% | 9.7% | 68.4% | 48.7% | -17.1% | -4.7% | -6.8% | -1.5% |
| Upstream Imperviousness | 7.8% | 10.1% | 70.8% | 45.1% | 2.5% | -0.3% | -3.4% | -8.8% |
| Decrease Drainage Density by 23% | 7.5% | 9.8% | 76.1% | 53.0% | -2.0% | -3.8% | 3.7% | 7.2% |
| Increase Slope by 10% | 2.1% | 2.8% | 20.7% | 13.9% | -72.5% | -72.3% | -71.8% | -71.9% |
| Decrease Slope by 53% | 15.6% | 18.0% | 76.3% | 54.6% | 104.5% | 77.0% | 4.0% | 10.5% |
| Remove SWM Ponds | 6.6% | 6.6% | 6.6% | 6.6% | -13.5% | -35.0% | -91.0% | -86.7% |



Sources: Esri, HERE, DeLorme, TomTom, Intermap, increment P Corp., GEBCO, USGS, FAO, NPS, NRCAN, GeoBase, IGN, Kadaster NL, Ordnance Survey, Esri Japan, METI, Esri China (Hong Kong), swisstopo, MapmyIndia, © OpenStreetMap contributors, and the GIS User Community

Figure 1: The Kromma Kill watershed (20 km$^2$) with subwatersheds (NH, EH, LN, AN, AS) delineated.

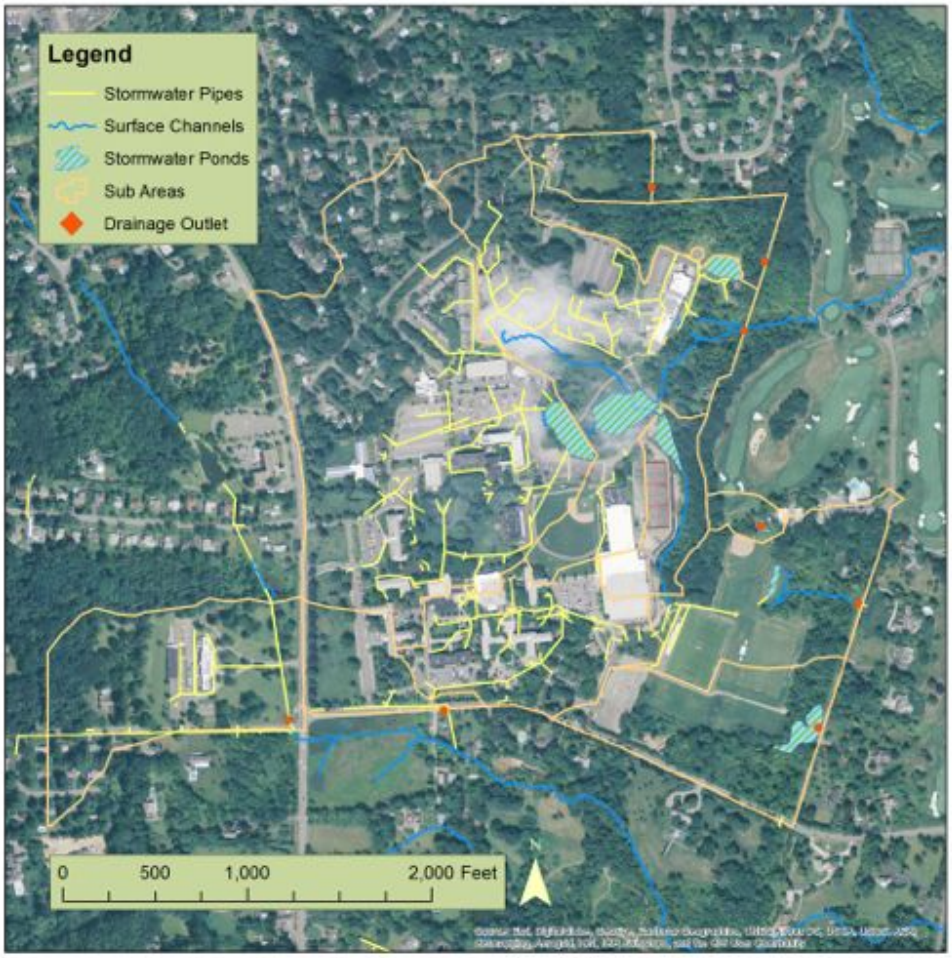


Figure 2: The “New Hall” subwatershed encompasses most of the Siena College campus.

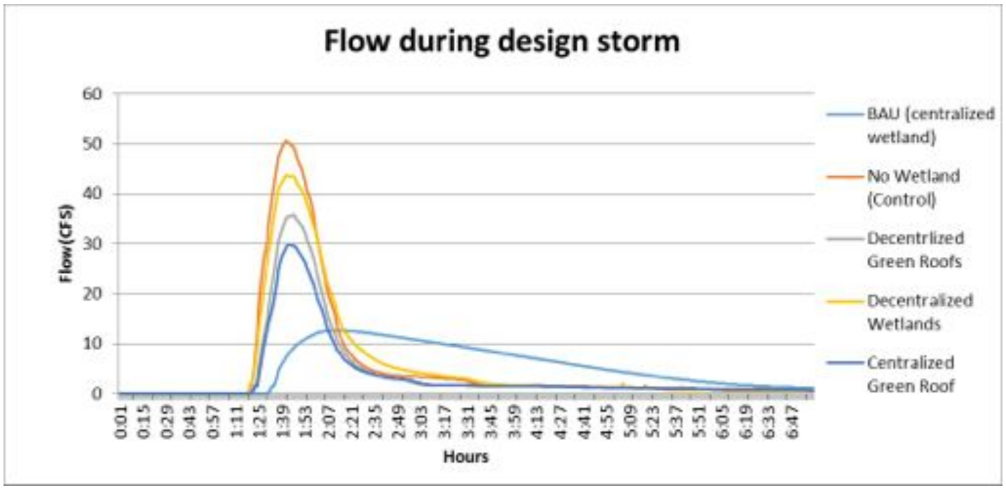


Figure 3: Hydrograph for each design scenario.

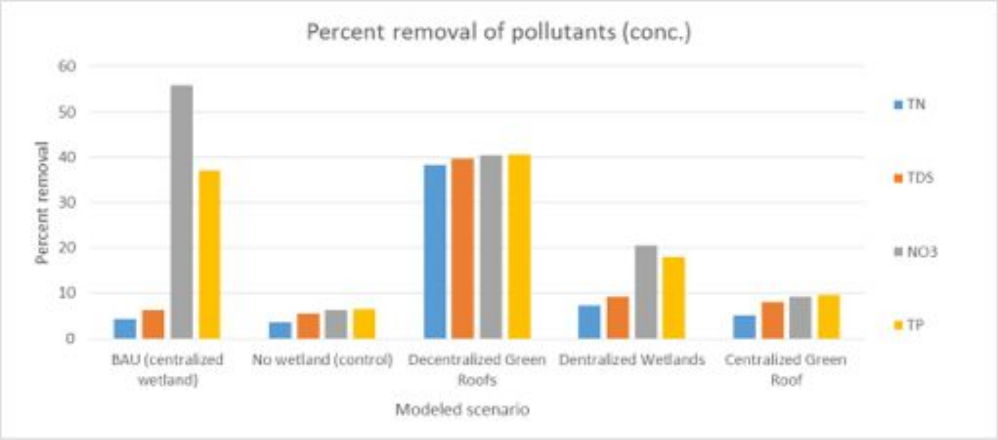
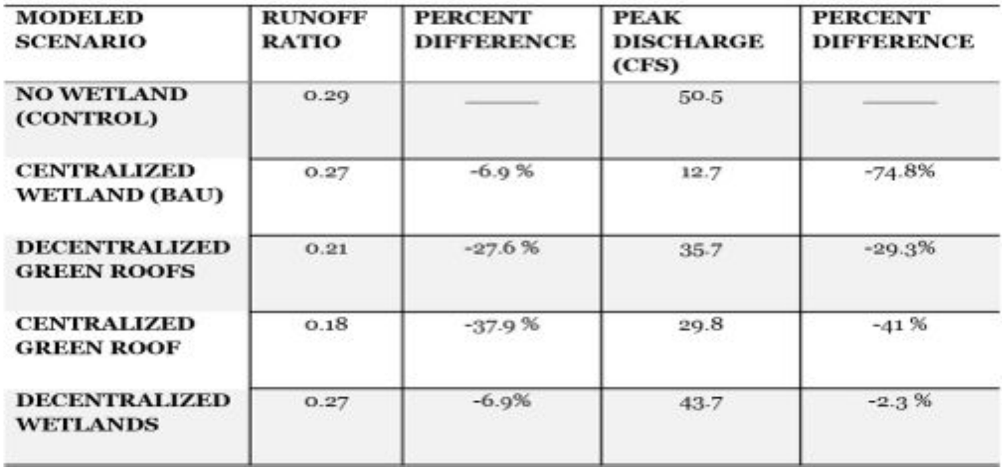


Figure 4: Percent removal of contaminants for each design scenario.



| MODELED SCENARIO | RUNOFF RATIO | PERCENT DIFFERENCE | PEAK DISCHARGE (CFS) | PERCENT DIFFERENCE |
|---|---|---|---|---|
| NO WETLAND (CONTROL) | 0.29 | ——— | 50.5 | ——— |
| CENTRALIZED WETLAND (BAU) | 0.27 | -6.9 % | 12.7 | -74.8% |
| DECENTRALIZED GREEN ROOFS | 0.21 | -27.6 % | 35.7 | -29.3% |
| CENTRALIZED GREEN ROOF | 0.18 | -37.9 % | 29.8 | -41 % |
| DECENTRALIZED WETLANDS | 0.27 | -6.9% | 43.7 | -2.3 % |

Figure 5: Design scenario water quantity results.

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