THESIS

RESILIENCE: A CITY ANALYSIS OF FLOOD AND CSO MITIGATION IN NYC

Submitted by

D. Canon Furth

Department of Civil & Environmental Engineering

In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Summer 2021

Master's Committee:

Advisor: Mazdak Arabi

Sybil Sharvelle

Thomas Bradley

ABSTRACT

RESILIENCE: A CITY ANALYSIS OF FLOOD AND CSO MITIGATION IN NYC

The implementation of green infrastructure (GI) for flood and combined sewer overflow (CSO) mitigation has been increasing in popularity in highly urbanized settings due to overloading of the centralized systems. The utilization of decentralized systems permits dispersed adoption, supplementing the installed grey infrastructure. Large cities, in part due to density and their impervious nature, tend to fall victim to these negative responses.

A resiliency study was performed on New York City, which entailed detailed modeling of five different storm scenarios and four unique intervention scenarios using InfoWorks ICM. Storm Scenario 1 (SC1) is the 1 inch, 1-hour storm, SC5 is the 1.8 inch 1–hour, 5-year storm, SC6 is SC5 with 1.3 ft of surge, SC9 is the 2.6 inch, 3-hour, 5-year storm and SC18 is the 9.1 inch, 24-hour, future 50-year storm with 3.1 ft of sea level rise. Scenario I1 represents constructed and imminent green infrastructure planned for implementation through 2035, I2 evaluates how Long-Term Control Plan (LTCP) grey infrastructure effects flooding in NYC, I3 represents the additional distributed infrastructure throughout the City that would be required by the onsite water management rules for both combined and separate sewers, and I4 evaluates how additional grey infrastructure impacts flooding.

A few key findings include the reduction of CSO volumes at NYC outfalls ranging between 2 to 90 percent, and that green infrastructure systems were most effective in controlling smaller storm scenarios. This study further hones in and examines how the implementation of GI will impact flooding in the City as a whole and per sewershed by exploring the variability in responses and effects under varying precipitation regimes and projected sea level conditions. This study also explores the

complementary and substitutive effects of green and grey infrastructure systems by examining sewershed conditions, precipitation regimes, and management goals.

ACKNOWLEDGEMENTS

I wanted to first off say thank you for this opportunity to learn and grow. I never thought I would get a master's degree. I was always under the impression I didn't like or appreciate academia. This was about until I grew up and finished my undergrad.

For this specific opportunity, I wanted to thank Dr. Mazdak Arabi for making my dream of coming to Colorado State University for my master's degree a reality. I moved to Fort Collins not accepted into the graduate program, and somehow got a job working for Dr. Arabi which shortly thereafter turned into funding. For this belief in me, I extend my deepest gratitude. As well, I wanted to thank the NYC – Department of Design and Construction, NYC Mayors Office of Resiliency, and UWIN by NSF.

Of course, I would not be the man I am today without the people who love me. I am blessed beyond measure to have the parents that I do, the siblings, and friends. My father has been my inspiration; I aspire to be a man like him one day. Thank you dad.

My Fort Collins family, thank you. Everyday Joe's was my safe space and home. Thank you, Darren and Chris, for fostering that atmosphere of consistent love, support, and family for so many students like myself. You will forever have a special place in my heart. To my friends, I could not have survived without you. 66 Degrees you were my confidants and life partners, throughout my ups and downs. I hope to keep you guys around for a long time. To all of the professors who taught courses and believed in me, thank you. Thank you, Dr. Ryan Bailey and Dr. Ben Sharp for your positivity and personable dispositions; they will never be forgotten.

Lastly and most importantly, to God, The Being, The Creator. Whoever He/She is to you, They are real and can provide comfort and support in the most dire of times. I spent many hours just sitting, being. I could

not have accomplished this without this intimate support and love and care. Thank you. Thank you for this opportunity and for seeing me through this to the end.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. Introduction:

The quantity and quality of urban runoff is heavily affected by urbanization (Zhou, 2014), but the implementation of green infrastructure (G.I.) has an overwhelmingly effective influence on mitigation of urban flooding in cities (Liu, 2014). The urbanization of a city is typically synonymous with greater impervious area, less green spaces, and densely populated areas. An increase in impervious area affects the magnitude of peak flows while conjecturally reducing the base flows (Denault, 2007). Not only is there the potential for inland flooding and property damage, but in specific cities this can result in major pollution to the surrounding water bodies. As city municipalities have recently been planning for future climate scenarios and global warming, resilience and sustainability are central points of conversation. As this mindset shift is occurring, the conversation requires greater understanding of the outcomes.

When sewer systems were first installed in the United States, stormwater and sewage utilized the same pipe network to convey the effluent to treatment facilities. This sewage system is commonly referred to as a combined sewer. Some 772 U.S. cities, particularly older ones in the Northeast, Midwest, and Pacific Northwest, have combined sewer systems. After installation, this system was found to have extremely detrimental environmental impacts. Combined sewer overflow ("CSO") events occur when combined sewer pipes, pipes which carry both sewage and stormwater runoff, are overwhelmed during heavy rains, and send untreated sewage into water bodies or residents' basements. CSOs occur when surface runoff exceeds the sewer system's capacity (Montalto, 2007), which also is the leading cause of pollution in rivers, lakes, and estuaries in the United States (USEPA). The traditional approach to urban flood management that has accompanied urban development involved the usage of gray infrastructure (e.g., street gutters, storm pipes, and channels) designed to mitigate flood hazards posed by relatively frequent (e.g., 20 year return period) rainfall events (Schubert, 2017). Grey infrastructure is also commonly referred to as centralized water systems and both terms furthermore will be used synonymously throughout this thesis.

The aging infrastructure in highly urbanized metropolitan areas are increasingly stressed due to climate change and its effects on increased frequency and intensity of heavy rainfall events, storm surge and sea level rise. Current urban drainage can now be classified as vulnerable, due to uncertain urbanization patterns, unpredictable climate change, and anticipated development in the future (Dong, 2017). (Nielson, 2013) suggests that in regions where climate change occurs, a systematic adaptation effort should be undertaken to minimize the impacts on the performance of the drainage systems. Not only is climate change the driver, but the increase in urbanization patterns and changes in drainage boundary conditions can lead to extreme sea surges and fluvial flooding (Pederson, 2012).

Green Infrastructure (GI) is becoming a more popular solution to urban flooding as opposed to traditional grey infrastructure. This is due to many factors, which predominately include the current push for a more sustainable form of urban development. Green infrastructure simultaneously provides natural avenues to assist in urban climate control and water management while providing imperative green spaces in increasingly urbanized areas (Mell, 2009). From an urban water management standpoint, green infrastructure is an intervention type that uses plant or soil systems, permeable pavement or other permeable surfaces or substrates, stormwater harvest and reuse, or landscaping to store, infiltrate, or evapotranspirate stormwater and reduce flows to sewer systems or to surface waters (USEPA). GI is effective at reducing total flow volumes and peak discharge (Schubert, 2017) and also aids in maintaining pre-development runoff volume (Gallo, 2013). Green infrastructure is commonly referred to as decentralized water systems and both terms furthermore will be used synonymously throughout this thesis.

A majority of the studies throughout the literature review have analyzed small scale applications of GI implementation, where a few looked at catchment scale or even citywide effects. In a case study performed in Ohio, 3 years of monitored flow concluded that GI within a small urban catchment can statistically significantly decrease runoff volume (Shuster, 2013). Another study suggests approximately 15, 27, and 38% of the runoff generated from impervious surfaces should be diverted to rain gardens to mitigate flooding from 2-, 5-, and 10-year storm events, respectively (Morsey, 2016). A study in Melbourne, Australia looked at effectiveness of GI on a temporal scale. For storm durations equal to or less than 3 hours, a full implementation of GI would reduce downstream flooded area on average by 91%. On the other hand, for storm durations longer than 3 hours, a full implementation of GI lacks the capacity to retain the resulting rainfall depths and only reduces flooded area by 8% (Schubert, 2017).

At a larger watershed scale, few studies have investigated the effects of stormwater interventions by combining green infrastructure and the underlying grey sewer system. In a study performed by (Ahiablame, 2014), the results indicated that the various levels of rain barrel/cistern and porous pavement implementation resulted in 2-12% runoff reduction for runoff, TP (total phosphorus), and TN (total nitrogen) for the two watersheds. An entire watershed in San Diego was modeled having different levels of residential rainwater harvesting and found the 227-liter barrel to be the most cost-effective storage facility (Walsh, 2014). Another study looked at the effects of distributed and centralized stormwater practices at the watershed scale and found that distributed BMP's (Best Management Practice's) was more effective at restoring pre-development hydrologic response to rainfall events than centralized BMP’s (Loperfido, 2014). At a watershed in Indianapolis, simulation results indicate that a 50% installation level of BMP and LID (Low Impact Development) practices result in a reduced runoff volume of 26.5% (Liu, 2015).

The complimentary usage of grey and green infrastructure has seldom been studied, but the results have been unanimous; merging decentralized and centralized systems allows for the best attributes of each intervention type to be distinguished and enhance their synergy for sustainable design (Zhou, 2014). Despite the effectiveness of green infrastructure mitigating urban flooding, the combination of traditional grey infrastructures with G.I. for urban flood prevention is imperative (Hu, 2019). Green infrastructure alone will never fully eliminate the urban runoff dilemma and it needs to be combined with other runoff reduction measures (Mentens, 2006). Effectiveness of CSO reduction is maximized within the context of integrated watershed planning (Montalto, 2007). Upon performing a life-cycle cost analysis comparing a combination of green (rain gardens) and grey (tunnels) infrastructure combination to a grey-only option to control combined sewer overflow, (Cohen, 2012) discovered that the green/grey combined alternative turned out to be more cost-effective than the grey-only option.

As climate change becomes a harsher global reality, sea level rise is directly correlated as a byproduct. The risk of urban flooding may be intensified as the earth experiences more frequent weather extremes with the global climate change (Foster, 2011). Using green infrastructure to reduce impervious cover could be used to compensate for increased stormwater runoff associated with climate change (Pykea, 2011). Very few studies have attempted to quantify the effects of climate change as it relates to flooding and CSO volume. Results from a study in North Vancouver state that climate change in North Vancouver would not create severe impacts and that stormwater best management practices such as detention ponds and filter strips may find use as mitigation strategies (Denault, 2007). Another simulation study in Asia concluded that the flow quantity and water quality are more sensitive to changes in land use, the degree of urbanization (intensity of land use) and LID measures adopted than to climate change (Wang, 2018).

The goals of this analysis are to study how the implementation of green infrastructure will impact flooding in New York City as a whole and by sewershed, along with examining the complimentary or substitutive effects of Green and Grey Infrastructure. This is achieved by 1) exploring the variability in responses and effects per sewershed under varying precipitation regimes, 2) exploring the variability in responses and effects per sewershed/neighborhood under current and projected future sea level conditions, and 3) exploring the tradeoffs between managing the systems for flood control vs. CSO control. The analysis was undertaken by simulating 5 different storm scenarios while implementing 4 different intervention scenarios and analyzing the outputs. Specifically, the interventions are from New York City's baseline Long Term Control Plan (LTCP), distributed interventions required by prevailing and planned onsite water management rules, and other recommended LTCP interventions are assessed.

2. Methodology:

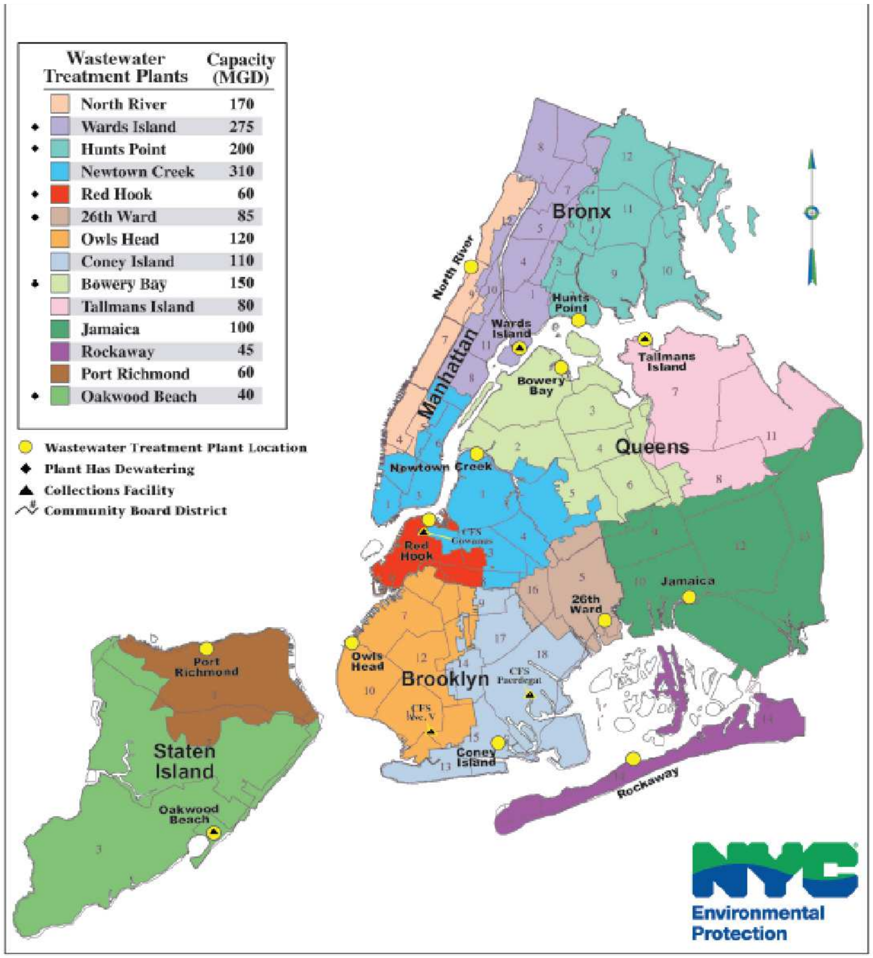
2.1 Study City

New York City was the area of study. The New York City Department of Environmental Protection (DEP) has the responsibility to protect public health and the environment by ensuring supplies of clean drinking water and collecting and treating wastewater for the 8.5 million residents of New York City. Every day, DEP collects and treats 1.3 billion gallons of wastewater through a vast network of pipelines and pump stations that deliver wastewater to 14 treatment plants.

2.1.1 NYC Sewershed System:

New York City is comprised of 14 watersheds. Each watershed houses its own Wastewater Treatment Plant (WWTP) that serves the residents. 13 of the 14 watersheds share a boundary with a waterbody of some kind. Some sewersheds are made up of combined or separate sewer systems. Separate sewer systems are when stormwater and wastewater each have their own conveyance systems.

Figure 1: Outline of the wastewater treatment plant boundaries in the City of New York.



Source: Anthony Fiore, Director of Energy Regulatory Affairs, New York City Mayor's Office of Sustainability, presentation to the American Biogas Study Group: Market Development Summit (May 21, 2015), slide 8.

2.1.2 Current stormwater and combined systems:

Combined sewer systems service approximately 60 percent of the city while the remaining 40 percent is treated with a sanitary sewer system. The current treatment system of NYC wastewater consists of: over 6,000 miles of sewer pipes; 135,000 sewer catch basins; over 495 permitted outfalls for the discharge of Combined Sewer Overflows; 95 wastewater pumping stations that transport it to the 14 wastewater treatment plants located throughout the 5 boroughs. Annually there is an estimated 20 billion gallons of untreated water that flows into the city’s surrounding waterbodies due to CSOs. As of the date of this report, through the NYC Green Infrastructure Program, DEP has constructed over 7,400 green infrastructure assets in the public right-of-way and on public and private properties.

Table 1: The abbreviations of each sewershed, the area in square miles, the volume of maximum effluent treatable, and the percent imperviousness.

Name	WWTP	Area (mi^2)	WWTP Volume (MGD)	Percent Impervious
Bowery Bay	BB	26.48	150	74
Hunts Point	HP	42.38	200	57
Jamaica Bay/26th Ward	JA26	54.16	186	67
Newton Creek	NC	21.99	310	81
North River	NR	8.57	170	71
Oakwood Beach	OB	33.24	40	38
Coney Island/Owl Head	CIOH	42.38	230	73
Port Richmond	PR	21.21	60	47
Red Hook	RH	5.67	60	79
Rockaway	RK	9.81	45	44
Tallman Island	TI	23.27	80	64
Wards Island	WI	18.52	275	66

2.1.3 Pressures on the stormwater and sewer systems:

New York City is one of the most densely populated cities in North America. This water locked area had no choice but to build skyward, developing so people live on top of each other. As the increase in impervious area and decrease in green spaces became synonymous with NYC, NYC experienced more frequent flooding and CSO events. This hazard created many risks for not only the populous, but the environment as well.

While the Wastewater Treatment Plants (WWTPs) are designed to treat twice the permitted dry weather flow, during some rain events the system can become overburdened. When this occurs, a mix of stormwater and untreated wastewater may discharge directly into surrounding waterbodies as CSO to protect the collection system and the treatment process at the WWTP. And as climate change becomes more of a reality, the extremity of the rainfall events will increase alongside with sea level rise. This combination is a recipe for severe events to become even more hazardous. Storm surge and sea level rise play an increasingly important role in CSOs, as outfalls become submerged, not allowing the effluent to exit the system. This causes more inland flooding and ultimately more damage.

With the rapid urbanization of NYC, the need for additional stormwater storage is paramount. Green infrastructure is at the core of this plan. In 2010, the City's goal was to capture the first inch of rainfall on 10% of the impervious areas in combined sewer watersheds through detention or infiltration techniques over the next 20 years. By preventing one inch of precipitation from becoming runoff that surges into the sewers over 10% of each combined sewer watershed's impervious area, DEP estimates that CSOs will be reduced by approximately 1.5 billion gallons per year (bgy). DEP proposes to meet this goal by achieving 1.5% impervious area capture by 2015, an additional 2.5% by 2020, an additional 3% by 2025, and the remaining 3% by 2030 (NYC GI 2010).

2.2 Intervention Scenarios:

Four Intervention Scenarios along with the current baseline scenario were developed and simulated. These intervention scenarios were developed by stakeholder inputs and citywide targets to examine the effects of centralized grey infrastructure, green infrastructure, and combinations thereof. The intervention scenarios include:

- ***IS0***: Baseline conditions
- ***IS1***: Current and planned distributed infrastructure to 2035

- ***IS2***: Baseline Long Term Control Plan (LTCP) infrastructure
- ***IS3***: Planned distributed infrastructure to 2050 and cloudburst systems
- ***IS4:*** Recommended LTCP infrastructure

Each Intervention Scenario had unique available storage. From the Baseline conditions, IS1 added an additional 240 MG of distributed storage, IS2 added an additional 360 MG of centralized storage, IS3 added 511 MG of decentralized storage, and IS4 added 570 MG of decentralized storage. Each intervention scenario adds either decentralized or centralized additional storage volume. Intervention Scenario 1 (IS1) adds the planned decentralized stormwater storage to 2035, as determined by the city. IS2 implements additional centralized (grey) infrastructure per NYC's 2040 Long Term Control Plan (LTCP). IS3 adds distributed infrastructure plan of 2050 along with a cloudburst study. IS4 evaluates how additional centralized infrastructure impacts flooding.

Grey infrastructure systems include conveyance pipes, large, centralized storage basins, pump stations, weirs, and treatment facilities. The typical practice is to collect and convey urban runoff to one or more points of treatment and then release it. In this study, storage tunnels are represented in InfoWorks ICM by modifying existing nodes along the stormwater system to represent the added underground storage capacity. Runoff is then routed to these nodes through the overland topography based on surface slopes or by 1D elements conduits that were previously connected to the modified nodes.

Green Infrastructure, also known as distributed intervention systems, considered in this study include rain gardens, sand filters, green roofs, and permeable pavement. Distributed interventions are represented in the Hydrologic and Hydraulic (H&H) models in two ways. First, if the actual location of the intervention is known, a node with the storage capacity of the infrastructure is added to the 2D model to receive water from the 2D surface. All nodes in InfoWorks ICM must be connected to another node to receive; for this reason, the node is connected to an artificial outfall in order to activate it within the H&H models. The connection is made using a conduit link that was 1 inch in diameter, 1,000 feet long, at a slope of 0.5 percent to significantly restrict flow, creating a near static volume within the node. These were the tested conduit parameters that allowed for the smallest flow rates without causing instability within the H&H models.

A total breakdown of storage volume per sewershed is below in Table 2. Centralized systems versus decentralized systems are noted, as this depicts between grey versus green infrastructure.

Table 2: The volume of decentralized and centralized intervention types per sewershed per intervention scenario. 'Add. Decent.' and 'Add. Centr.' are short for additional decentralized and additional centralized, respectively.

	Storage Volume (MG)						
WPCP	Decentralized IS1 (Total)	Centralized IS2	Total IS2	Add. Decent. IS3	Total IS3	Add. Centr. IS4	Total IS4
BB	23.7	12.6	36.4	12.0	48.4	23.6	72.0
HP	33.3	39.2	72.5	17.8	90.4	0.9	91.3
JA26	49.1	14.7	63.8	21.1	84.9		84.9
NC	20.7		20.7	12.8	33.6	43.2	76.6
NR	7.4		7.4	5.6	12.9		12.9
OB	15.0		15.0	14.8	29.8		29.8
CIOH	33.4	22.7	56.0	18.8	74.9		74.9
PR	15.4		15.4	13.0	28.5		28.5
RH	4.4	8.2	12.6	3.6	16.2		16.2
RK	1.2		1.2	1.1	2.3		2.3
TI	21.7	23.7	45.3	14.0	59.3		59.3
WI	18.3		18.3	12.0	30.4		30.4
Total	243.7	121.1	364.8	146.7	511.5	67.7	579.1

2.3 Storm Scenarios:

Five storm scenarios were modeled, each ranging in duration and intensity, designed to evaluate the effects of various types of interventions on hydrologic responses and flood control under current and future climate scenarios. These include:

- ***SC1 – 1 inch, 1-hour storm***: This scenario is currently used by the NYC Emergency Management (NYCEM) and is one of the least severe storms modeled for the study.

- ***SC5 – 1.8 inch, 1-hour, 5-year storm:*** This scenario represents a short duration and high intensity precipitation event.

- ***SC6 – 1.8 inch, 1-hour, 5-year storm with 1.3 ft surge:*** This scenario is used to examine the effects of storm surge causing outlets of the city sewer system to be submerged.

- ***SC9 – 2.6 inch, 3-hour, 5-year storm:*** This scenario is used to evaluate the DEP site retention standard.

- ***SC18 – 9.1 inch, 24-hour, future 50-year storm with 3.1 ft sea level rise***: This scenario represents a future event that models the current 50-year, future 5-year event with sea level rise (SLR).

2.4 Hydrologic and Hydraulic (H&H) Modeling:

InfoWorks ICM was used to model each of the Intervention Scenarios and the five Storm Scenarios. InfoWorks ICM incorporates 1- and 2-D modeling. The surface layer is a 2-D surface mesh which simulates the rainfall-runoff process and the 1D system is for hydraulic and conveyance simulation.

To add storage per intervention scenario, nodes with a specific storage volume and elevation were placed within the 2D model. The storage volume of each node was computed based on constructed and planned GI data from the NYC DEP. Differences between detention and retention based systems were not accounted for within the model. All areas that accrued less than 4 inches of standing water were not deemed as flooded.

Intervention scenarios examined in this study also include mitigation strategies that are planned for each sewershed or subcatchment, but for which the exact spatial locations are not yet determined. For these situations nodes are added to the H&H models in a distributed fashion adding one node for each 100 ft by 100 ft cell across subcatchment. All nodes within each sewershed or subcatchment is then given a storage volume commensurate with the total planned storage capacity for each sewershed or subcatchment. These nodes are linked with an artificial outlet node via a 1-inch diameter 1,000 ft long pipe to allow the elements to function properly within the H&H models, as discussed above. In the table below, Oakwood Beach has a value of 0 for many of the columns. This is because Oakwood Beach (OB) does not have a combined sewer so there was no information on the storm sewer system. OB was only modeled as 2D mesh.

Table 3: Breakdown of the modeling structures, inlets, outlets, lengths, quantities, and 2D area.

Name	# of Manholes	# of Outfalls	# of Other Nodes	# of Sewerlines	Total Sewerline Length (mi)	# of Pumps	2D Area (acres)
Bowery Bay	749	130	2	721	89.10	5	17409.63
Hunts Point	2786	224	6	892	99.42	5	19425.65
Jamaica Bay/26th Ward	1425	81	6	1544	175.69	6	35484.35
Newton Creek	3447	168	3	3362	113.26	3	19324.36
North River	426	79	2	349	26.70	1	8205.38
Oakwood Beach	0	0	0	0	0.00	0	23072.51
Coney Island/Owl Head	747	188	6	741	108.55	9	28262.02
Port Richmond	462	57	3	409	32.41	4	12421.26
Red Hook	372	58	5	325	23.72	4	4613.98
Rockaway	385	85	1	353	25.50	5	6428.50
Tallman Island	971	120	26	982	97.54	17	19243.43
Wards Island	796	99	11	657	74.52	5	15880.48

2.5 Factors that influence the performance of stormwater interventions under varying storm scenarios:

In order to better understand why some sewersheds performed differently under the same storm scenarios, a regression analysis was performed. This was utilized to identify and quantify the factors that contributed most significantly to flood and CSO mitigation per unique storm scenario. The output data from InfoWorks was classified per sewershed using ArcGIS and datasets were created that represented the characteristics of that specific sewershed. Some sewersheds had higher impervious areas, others had more open space, while others had less overall tree coverage. The response variable, y, is the percent reduction from baseline of that specific storm scenario. Fitting outputs to each storm allowed for comparable results, as the sewersheds responded uniquely to each storm scenario. According to a study performed by (Li, 2019), the assessment results indicated that Normalized Difference Vegetation Index (NDVI), vegetation, and impervious surface were the most important urban surface conditions in the study area for direct runoff generation from 1984 to 2015.

Due to the modeling outputs, the regression equations were fit to nonlinear distributions. Flood volume reduction followed a distribution as follows:

$$y = \exp(a * ({x_1}^{b_1}) * ({x_2}^{b_2}) * ({x_3}^{b_3})) \tag{1}$$

CSO volume followed a distribution as follows:

$$y = a * ({x_1}^{b_1}) * ({x_2}^{b_2}) * ({x_3}^{b_3}) \tag{2}$$

The above nonlinear distributions were fit using the Gauss-Newton method by minimizing the sum of squares. Minimizing the sum of squares follows:

$$\varepsilon(\boldsymbol{a}) = \sum_{i=1}^{N} r_i^2 = \sum_{i=1}^{N} [y_i - f(x_i, a)]^2 = \sum_{i=1}^{N} [y_i - f_i(\boldsymbol{a})]^2 \rightarrow min \tag{3}$$

Where **a** is the optimal parameter vector that minimizes the sum of square error and *N* is a set of data points. The residual error is calculated as follows:

$$r_i = y_i - f(x_i, a) = y_i - f(\boldsymbol{a})(i = 1, \dots, M) \tag{4}$$

where *M* is a set of model parameters. The Gauss-Newton algorithm was used to fit the surrogate model. The Gauss newton algorithm follows:

$$a_{n+1} = a_n + \Delta a = a_n + J^{-}\big(y - f(a_n)\big) = a_n - J^{-}(f(a_n) - y) \tag{5}$$

where J^{-} is the pseudo inverse of *J*, which is the Jacobian matrix with its *ij*th component equal to

$$J_{ij} = \frac{\partial f_i(a)}{\partial a_j}\ (i = 1, \dots, N, j = 1, \dots, M) \tag{6}$$

and

$$y = [y_i, \dots, y_N]^T \tag{7}$$

$$f(a) = [f_i(a), \dots, f_N(a)]^T \tag{8}$$

A 90% confidence interval was used, to allow for uniformity within the model parameters. The confidence interval is obtained by taking twice the margin of error, which is calculated using the equation below:

$$M.E. = \hat{p} \pm z_{\alpha/2}\sqrt{\frac{\hat{p}(1-\hat{p})}{n}} \tag{9}$$

where $\hat{p}$ is the sample proportion of success, n is the sample size and z is the critical value.

The analysis was performed using RStudio. Please see the appendix for the input code.

3. Results:

Results from this study are as follows:

A. Urban water budgets are influenced by the implementation of green infrastructure.

B. As the precipitation intensity increases, infrastructure performance decreases.

C. Green Infrastructure is more effective than grey infrastructure at managing flooding while a combination of both are more effective at managing CSO.

D. Storm surge and future sea level rise have profound effects on the effectiveness of stormwater infrastructure.

E. Mitigating flooding volume is predominately determined by added storage and percent imperviousness.

F. Mitigating CSO volume is predominately determined by added storage and percent of added storage that is grey infrastructure.

G. This study reveals that GI has complimentary (not substitutive) benefits to grey infrastructure

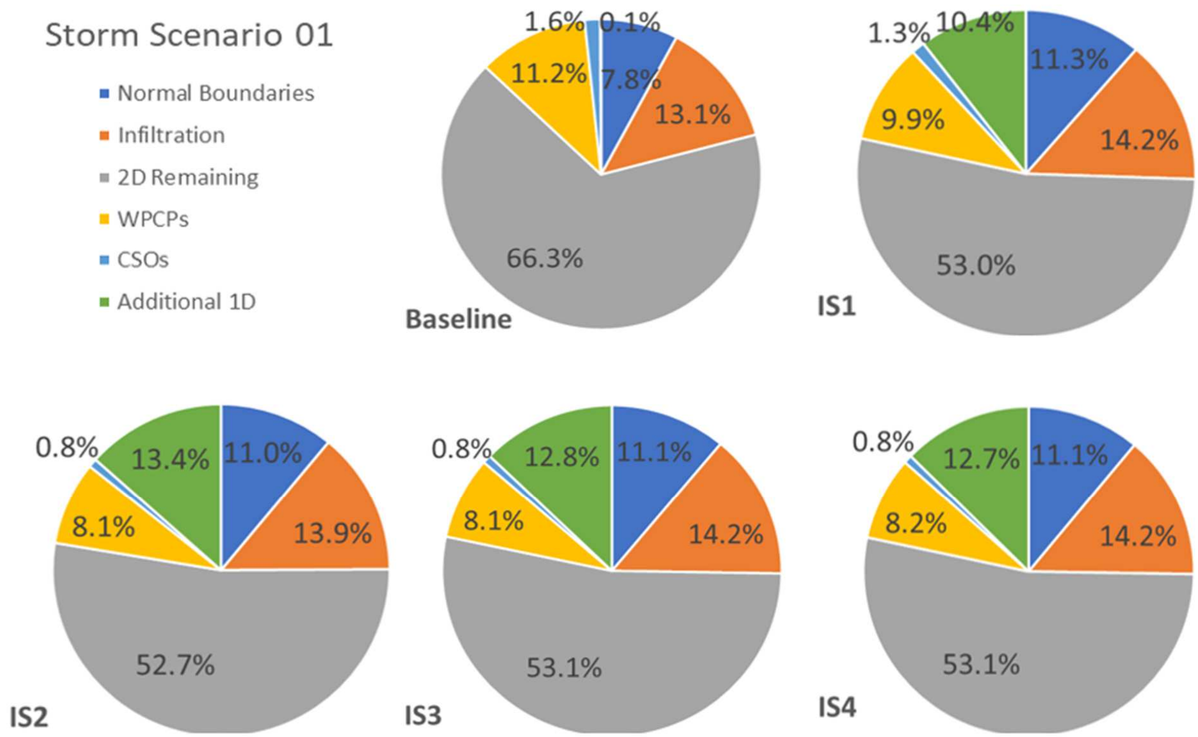
3.1 Changes in water budgets due to the implementation of GI:

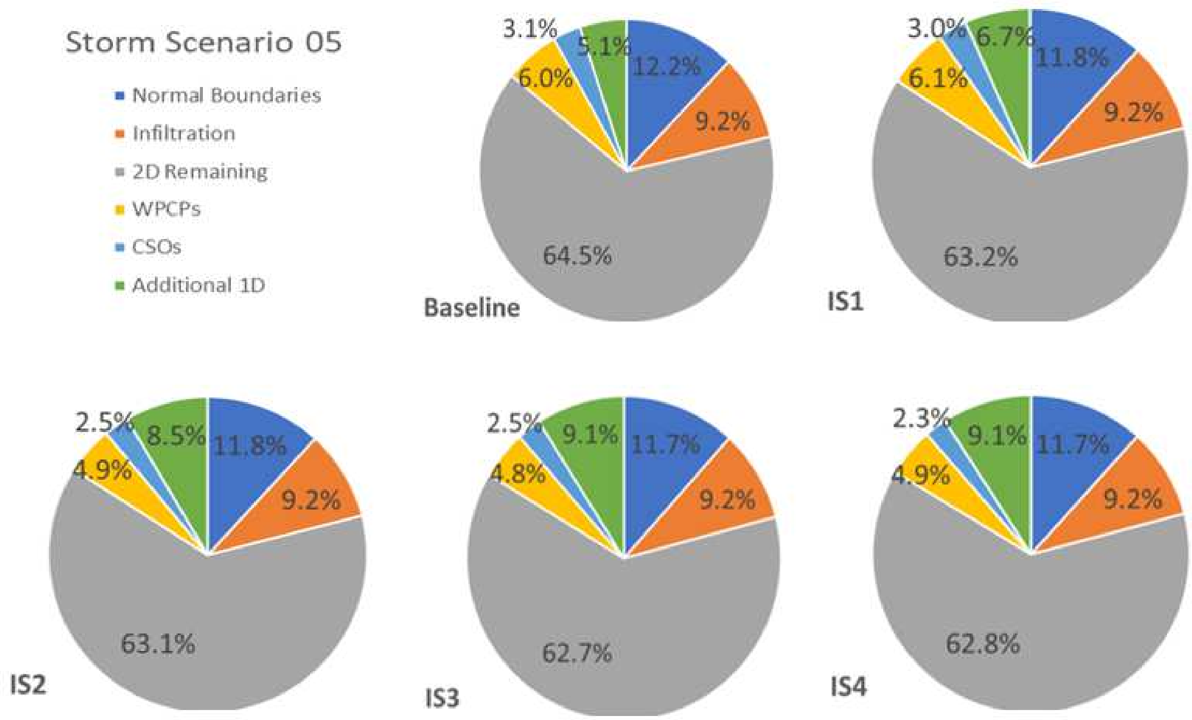
The effects of interventions on water balance in NYC was evaluated for storm scenarios SC01, SC05, and SC09. Urban water fluxes estimated by InfoWorks-ICM were divided into six categories: (1) Normal Boundaries - water outflow from the surface of the 2D mesh; (2) Infiltration - water infiltrated or lost due to interventions; (3) CSOs - water outflow through combined sewer overflows; (4) WRRFs - water treated by the wastewater pollution control plants (WRRF); (5) Additional 1D - water remaining in the 1D system at the end of the model simulation; and (6) 2D Remaining - water remaining on the 2D system at the end of the model simulation. These are depicted in the pie charts below.

Table 4 below is the total volume of inflow for each storm scenario per sewershed. The sewer inflow was calculated using standardized values, modified per storm duration. Again, intervention scenarios 1 and 3 are additional green infrastructure practices while intervention scenarios 2 and 4 implement grey infrastructure.

Table 4: The total volume of inflow for each storm scenario per sewershed in million gallons for storm scenarios 1, 5, and 9.

Total Water Volume Input Per Storm Scenario in Million Gallons (MG)									
Storm Scenario	SC01			SC05			SC09		
Inflow	Rain	Sewer	Total	Rain	Sewer	Total	Rain	Sewer	Total
Bowery Bay	481.2	27.2	508.4	836.9	27.2	864.0	1202.3	39.0	1241.3
Hunts Point	537.0	36.3	573.2	933.8	36.3	970.1	1341.6	51.6	1393.2
Tallman Island	532.0	107.6	639.5	925.1	107.6	1032.6	1329.1	162.4	1491.4
Wards Island	439.0	30.3	469.3	763.4	30.3	793.7	1096.8	85.2	1182.0
Newtown Creek	534.2	49.1	583.2	928.9	49.1	978.0	1334.7	58.6	1398.2
North River	718.6	25.4	744.0	394.4	25.4	419.9	566.7	40.5	607.2
Oakwood Beach	637.8	0.0	637.8	1109.1	0.0	1109.1	1593.4	0.0	1593.4
Port Richmond	343.4	6.9	350.2	597.1	6.9	604.0	857.8	9.6	867.4
Red Hook	127.5	6.5	134.1	221.8	6.5	228.3	318.8	10.5	329.3
Jamaica Bay & 26th Ward	980.9	28.6	1009.5	1705.7	28.6	1734.3	2450.7	44.2	2494.9
Coney Island & Owls Head	778.8	32.3	811.1	1354.3	32.3	1386.7	1945.6	48.5	1994.0
Rockaway Beach	177.7	5.0	182.7	309.0	5.0	314.0	444.0	7.0	451.0
Total	6287.9	355.2	6643.1	10079.5	355.2	10434.7	14481.4	557.2	15043.5


Storm Scenario 01
Normal Boundaries
Infiltration
2D Remaining
WPCPs
CSOs
Additional 1D
Baseline
1.6%
0.1%
11.2%
7.8%
13.1%
66.3%
IS1
1.3%
10.4%
11.3%
9.9%
14.2%
53.0%
IS2
0.8%
13.4%
11.0%
8.1%
13.9%
52.7%
IS3
0.8%
12.8%
11.1%
8.1%
14.2%
53.1%
IS4
0.8%
12.7%
11.1%
8.2%
14.2%
53.1%


Storm Scenario 05
Normal Boundaries
Infiltration
2D Remaining
WPCPs
CSOs
Additional 1D
Baseline
3.1%
5.1%
12.2%
6.0%
9.2%
64.5%
IS1
3.0%
6.7%
11.8%
6.1%
9.2%
63.2%
IS2
2.5%
8.5%
11.8%
4.9%
9.2%
63.1%
IS3
2.5%
9.1%
11.7%
4.8%
9.2%
62.7%
IS4
2.3%
9.1%
11.7%
4.9%
9.2%
62.8%

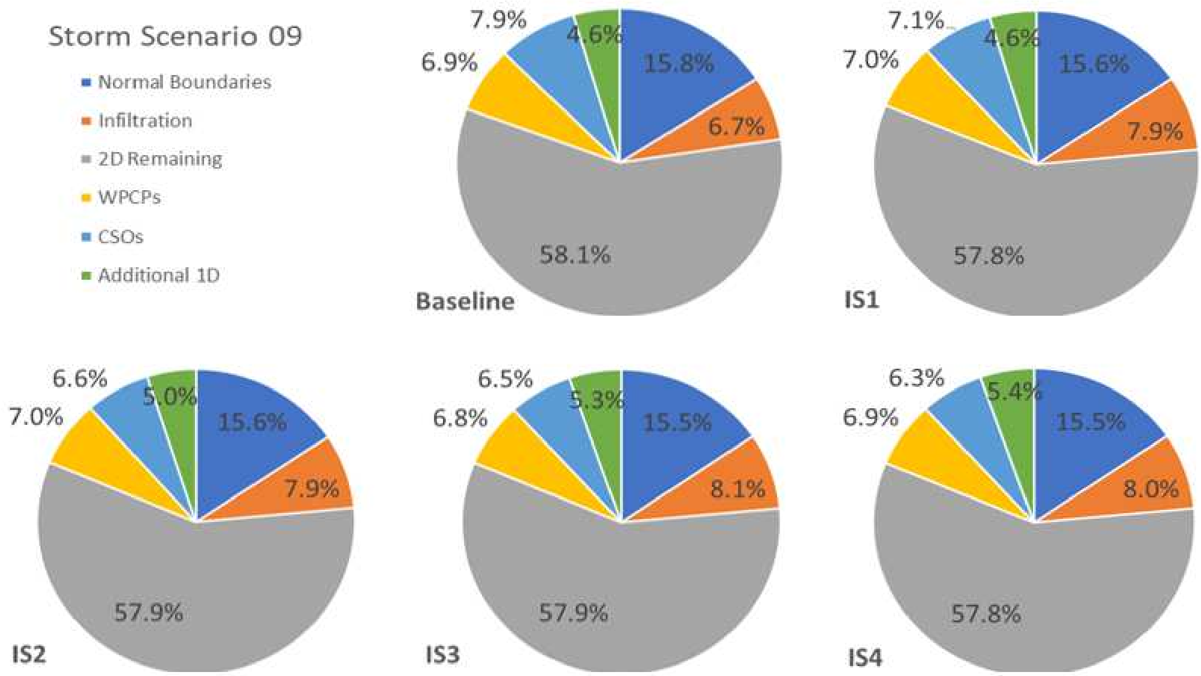


Figure 2: Representation of the water budget for storm scenarios 1, 5, and 9.

The remaining water left on the 2D surface at the end of model simulation was the largest category for each intervention scenario. Model simulations for the storm scenarios were terminated once the maximum flood depth on the 2D mesh and the receding limb of outfall hydrographs were observed. Thus, a significant component of the inflow rainfall remained on the 2D surface. This computationally frugal approach was adopted since it guarantees realization of maximum flood depths for each model grid cell. Longer simulation times may be needed to fully characterize the effects of interventions on inflow/outflow volumes at the outfalls and WRRFs for the storm scenarios. The infiltration category was the most influential in altering the water budgets. This is due to the nature of green infrastructure, as these intervention types are permeable and allow for infiltration into the subsurface. This aspect of the urban water balance proves the effectiveness on green infrastructure.

The analysis of NYC water balance indicated additional potential to retain and detain rainwater provided by stormwater interventions. This is evident in the gradual increases in infiltration and losses from the retention-based practices as well as water remaining in the 1D system from the detention-based practices. Intervention scenario IS1 contained a large number of retention-based practices from the planned citywide green infrastructure, which resulted in a 1 to 1.5% increase in infiltration and evaporative losses compared to the baseline scenario at the NYC level. The increase in infiltration was achieved in conjunction with a 0.5 to 1.5% reduction of CSO volume and intercepting water that would flow overland out of the normal boundaries of the 2D system. Infiltration increased ranging from 1 to 1.5% across the city. Storm scenario 1 experienced a huge increase in 1-D storage of 12%. The less severe storms saw the most decrease in 2-D remaining, which is flooding.

Overall, the urban water balance in NYC was slightly altered by the stormwater interventions investigated in this study. The presence of green infrastructure influenced the natural topography of NYC, retaining more water and permitting infiltration as opposed to allowing the water to remain on the surface. These modest estimated effects seem valid because the magnitude and capacity of added interventions in combination were merely up to 3.5 percent of inflow rainfall and sewage volumes for storm scenario SC9. Storm scenarios 1 and 5 capacity of added interventions were 8.5 percent and 5.5 percent of the total inflow, respectively. Intervention scenarios IS1 and IS3 contain distributed infrastructure and provide approximately 60 percent of the total added capacity. Intervention scenarios IS2 and IS4 encompass centralized systems and make up approximately 40 percent of the total added capacity.

3.2. Citywide flood and CSO response to intervention and storm scenario:

3.2.1 Flood mitigation:

New York City as a whole responded appropriately to the intervention and storm scenarios. Below is a table of all storm scenarios and the percent flood volume reduction from baseline per added intervention scenario.

Table 5: Percent reduction of flood volume from baseline intervention scenario per storm scenario and intervention scenario.

Flood Volume Percent Reduction from Baseline Intervention Scenario						
Intervention Scenario	Added Storage (MG)	SC 01 % Reduction	SC05 % Reduction	SC06 % Reduction	SC09 % Reduction	SC18 % Reduction
IS1	243.75	4.6%	2.6%	1.5%	2.1%	0.8%
IS2	364.87	4.7%	2.7%	1.5%	2.2%	1.0%
IS3	511.61	6.2%	3.7%	2.3%	3.0%	1.2%
IS4	570.49	6.2%	3.7%	2.3%	3.0%	1.2%

The storm that experienced the greatest overall flood reduction was storm scenario 1 while the storm scenario that experienced the least amount was storm scenario 18. An increase in the severity of intervention scenario resulted in decreased efficiency, thus supporting the claim that as the intensity of the storm increases then the effectiveness of the intervention volume decreases. New York City experienced a flood volume decrease of 1% to 6%. This variation in effectiveness is explained by intervention type and location. Some sewersheds experienced greater flood reductions than others even though there was less storage volume capacity. This will be explained in further detail in Section 3.

Again, as the storm intensity increased, the effectiveness of the intervention scenarios decreased. Below are the citywide flood reduction graphs created from the InfoWorks modeling simulation for all 5 storm scenarios. The percentages on the graphs are percent reductions from baseline, only relative to that specific storm scenario.

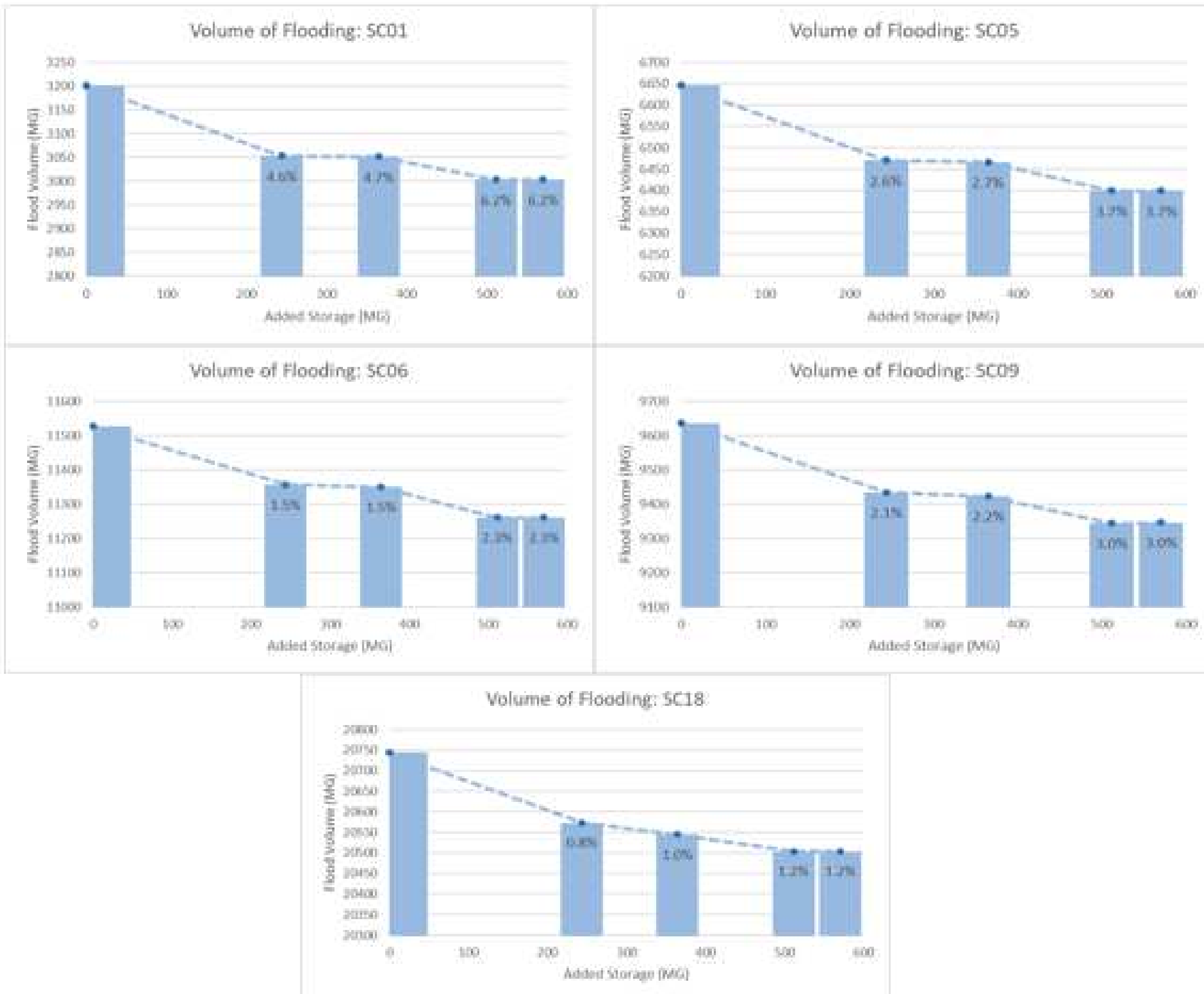


Figure 3: Graphs of flood volume reduction per added storage.

For storm scenario 6 and 18, there is a weaker relationship between reduced flood volume and added storage due to sea level rise and impacts of coastal flooding from storm surge. Sea level rise and costal surge buried the outfalls, thus limiting where the effluent could travel. This increased inland flooding and allowed the sewer system to back up more rapidly. These storm scenarios acted as outliers from the other outputs and, as a result, are kept separate. Storm scenario 18 only saw a decrease in flooding of up to 1.2% with an additional 570 MG of storage installed.

The volume of flooding throughout NYC increased as the storm intensity increased. This is due to the increased amount of rainfall and duration thereof. Firstly, noting the stepwise nature of the above graphs, intervention scenarios 1 and 3 experience the greatest jump in reduction. Recalling that intervention scenarios 1 and 3 were installations of solely green infrastructure, this reiterates that green infrastructure is more effective than grey infrastructure at reducing flooding at a citywide scale. The greatest reductions in flood volume occurred with additional green infrastructure storage capacity. The additional implementation of grey infrastructure only minimally aided in the reduction of flooding.

Secondly, the concavity of the graphs hint at the asymptotic relationship between added storage and flood volume. The city's stormwater infrastructure system is overwhelmed by the intensity and sheer amount of rainfall which is why the initial additional implementation of storage experiences the most amount of flooding reduction. As the system becomes overloaded, there are no additional practices available to store water, thus producing more inland flooding.

3.2.2 Citywide CSO Results:

New York City as a whole responded appropriately to the intervention and storm scenarios. Below is a table of all storm scenarios and the percent CSO flood volume reduction from baseline per added intervention scenario. CSO volume mitigation varied by intervention volume and storm scenario.

Table 6: Percent reduction of combined sewer overflow volume from baseline intervention scenario per storm scenario and intervention scenario.

CSO Volume Percent Reduction from Baseline Intervention Scenario						
Intervention Scenario	Added Storage (MG)	SC01 % Reduction	SC05 % Reduction	SC06 % Reduction	SC09 % Reduction	SC18 % Reduction
IS1	243.75	9.2%	4.8%	1.9%	17.4%	14.7%
IS2	364.87	39.0%	15.6%	1.9%	23.6%	17.0%
IS3	511.61	39.7%	16.4%	2.4%	24.0%	17.2%
IS4	570.49	39.8%	20.8%	3.3%	25.8%	17.7%

Storm scenario 1 saw the greatest reduction in CSO volume while storm scenario 6 experienced the least. NYC experienced a CSO volume reduction of 2% to 40%, depending on storm intensity and duration.

Below are the citywide CSO volume reduction graphs created from the InfoWorks modeling simulation. Only storm scenarios 1, 5, and 9 will be discussed below while 5 and 18 will be discussed later on.

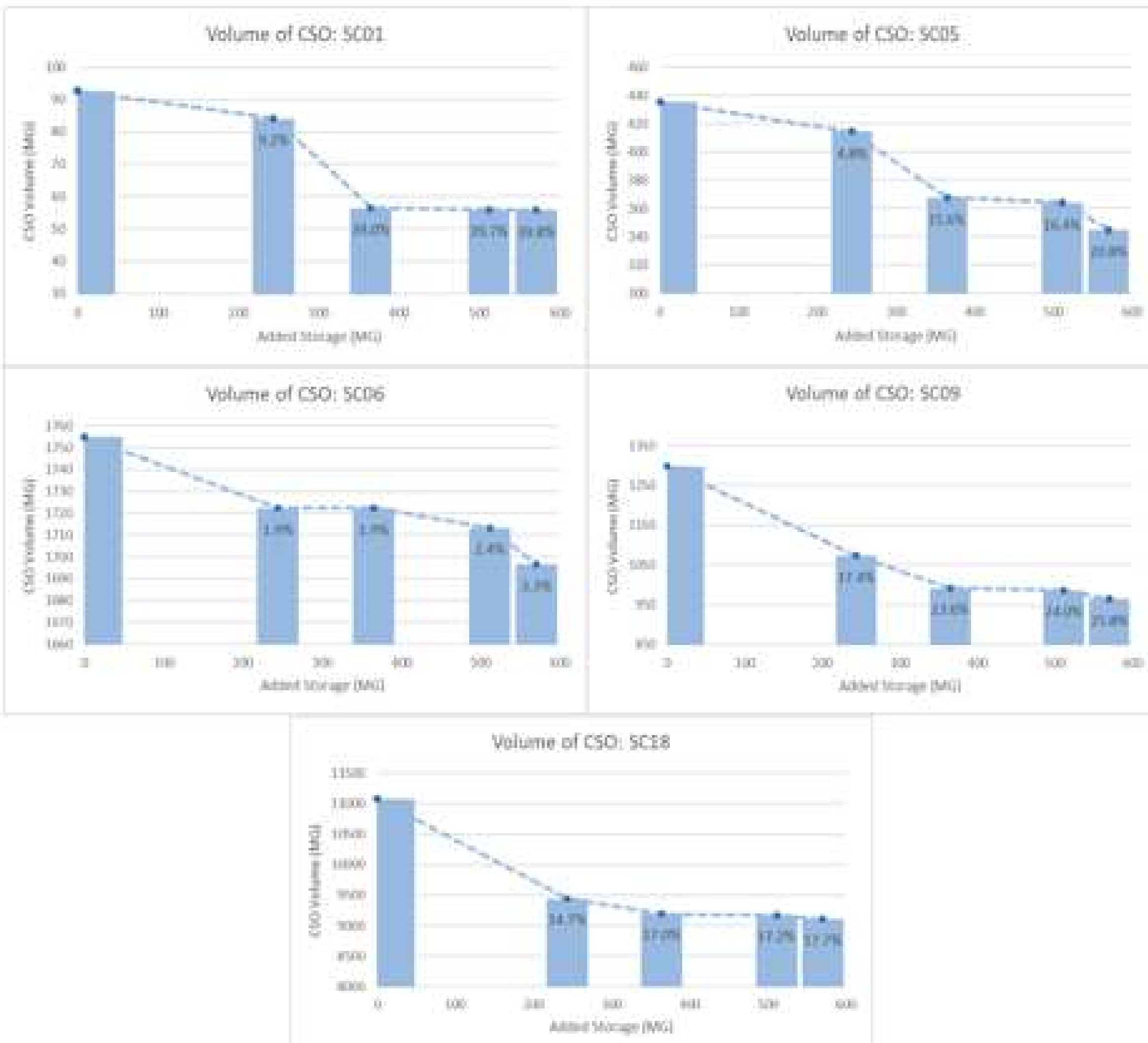


Figure 4: Graphs of combined sewer overflow volume reduction per added storage.

Due to storm surge and sea level rise, the effects of the stormwater intervention systems are greatly reduced. The burying of outfalls during sea level rise and storm surge creates backflows within the system. From storm scenario 6 to 18 there is nearly 10 times as much effluent that flowed into the waterbodies. This vast amount of water in storm scenario 18 allowed for a greater reduction in CSO volume. Storm scenario 6 experienced a maximum CSO volume decrease of 3.3% while storm scenario 18 experienced a maximum CSO volume decrease of 17.7%. Green Infrastructure played a vital role in mitigation due to inland flooding caused by intense rainfall. The short duration of SC06 overwhelmed the system from the start, while the length of simulation for SC18 allowed for retention practices to filter through stormwater.

As noted from the graphs above, the effectiveness of green and grey infrastructure is intermingled. Both green and grey infrastructure play a vital role in mitigating CSO volume. For smaller storms, grey infrastructure plays a larger role in mitigation, while in the larger storms with more precipitation the green infrastructure plays a more major role. This difference is due to the sheer volume of water and the ability of inland GI to collect and locally treat stormwater runoff. Due to these characteristics, a combination of grey and green infrastructure is most effective at mitigating CSO volume. The complimentary effects of grey and green infrastructure in reducing CSO's is more pronounced in larger storms, when both systems are forced to perform together to reduce water volumes.

The asymptotic relationship between added storage and CSO volume reduction is important to note, as more installed infrastructure will not necessarily equate to higher reductions in CSO volume. As seen in storm scenario 9, both green and grey infrastructure play intricate roles in reducing CSO volume. Yet, other factors are at play as well.

3.3 Green versus grey infrastructure as they relate to flood and CSO mitigation:

Looking at the substitutive or complimentary effects between grey and green infrastructure was a main driver into undertaking this research. As green infrastructure is known as the more sustainable solution to stormwater management, grey infrastructure's performance ability is at question, driven by the social and environmental implications.

To analyze this, outputs from the InfoWorks models were graphed as visual aids to fully scrutinize whether grey or green infrastructure was a better choice for future urban stormwater management practices. Below are graphs of percent reduction per incremental added storage. This normalized efficiency metric permits an appropriate comparison between intervention type and volume. Each storm scenario is side by side, with flood reduction on the left and CSO volume reduction on the right. Recall that intervention scenarios 1 and 3 add more green infrastructure while intervention scenarios 2 and 4 add grey infrastructure.

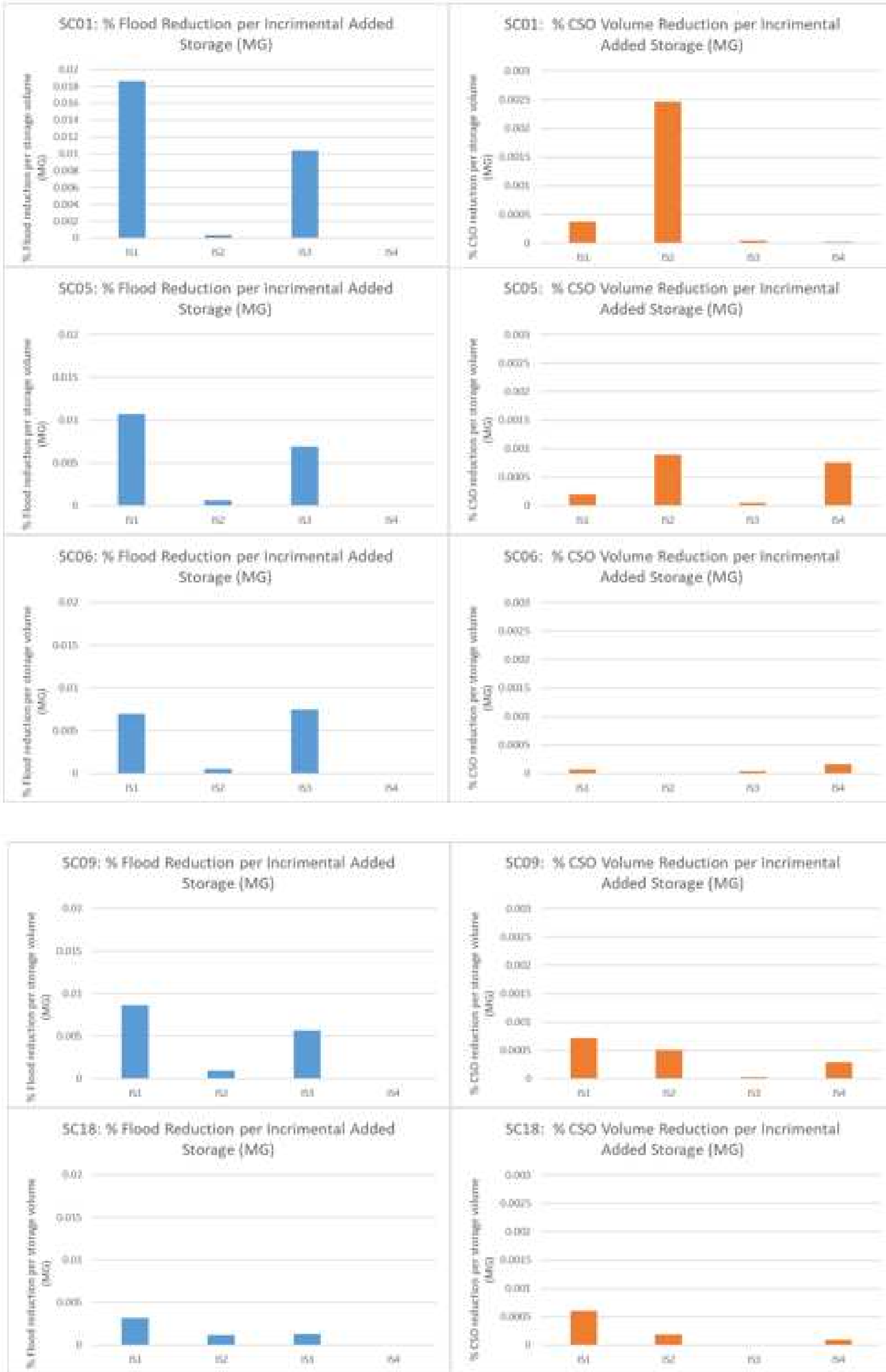


Figure 5: Side by side flood volume reduction/CSO volume reduction per incremental added storage.

From the graphs above, it is clearly seen which infrastructure type better suits the purposed response. Green infrastructure is more efficient and better at flood mitigation, while grey infrastructure is more appropriate for a reduction in CSO volume. This is more apparent for the less severe storm scenarios, as the intervention volumes are not overwhelmed, allowing for proper utilization of the practices.

For CSO reduction, storm scenarios 6, 9, and 18 had less of a definitive forerunner in terms of efficiency. This is due to the sheer amount of water within the system, which overloaded the stormwater practices. Because CSO's are at the very downstream point within a city, all the upstream practices were utilized to capacity due to the rainfall intensity, duration, and volume of water. As each practice got more and more filled as the water traveled downstream towards the outfall point, there were less available practices to collect the access stormwater, thus resulting in more CSO volume. These bottleneck within the system are the last points of contact with NYC, thus allowing any excess water within the system to exit. Storm scenario 6 saw very little reduction in CSO volume due to storm surge and the burying of outfalls.

For flood reduction, only storm scenario 18 did not result as decisively for comparing green and grey infrastructure. Again, this is due to the vast amount of water that fell on the City. Storm scenario 9 experienced green infrastructure making the most efficient impact because of the distributed fashion in which the GI is installed. The surface of NYC as a whole is much larger than a few outfall points, thus allowing the GI to locally treat the stormwater that fell in that specific region and overall reduce the flooding volume.

3.4 Sewershed scale Mitigation Results:

3.4.1 Sewershed scale flood mitigation results:

To analyze the effectiveness of flood mitigation practices per sewershed, graphs below were made and analyzed. The flood volume reduction normalized by unit area and total storage allowed for a comparable baseline throughout area and intervention scenario. These graphs highlight the complimentary benefits of grey and green infrastructure. The sewersheds that experienced the highest overall percent reduction per total storage simply performed more efficiently. This is solely due to factors other than storage volume, hence the necessity to further understand which sewershed characteristics contribute to flood mitigation.

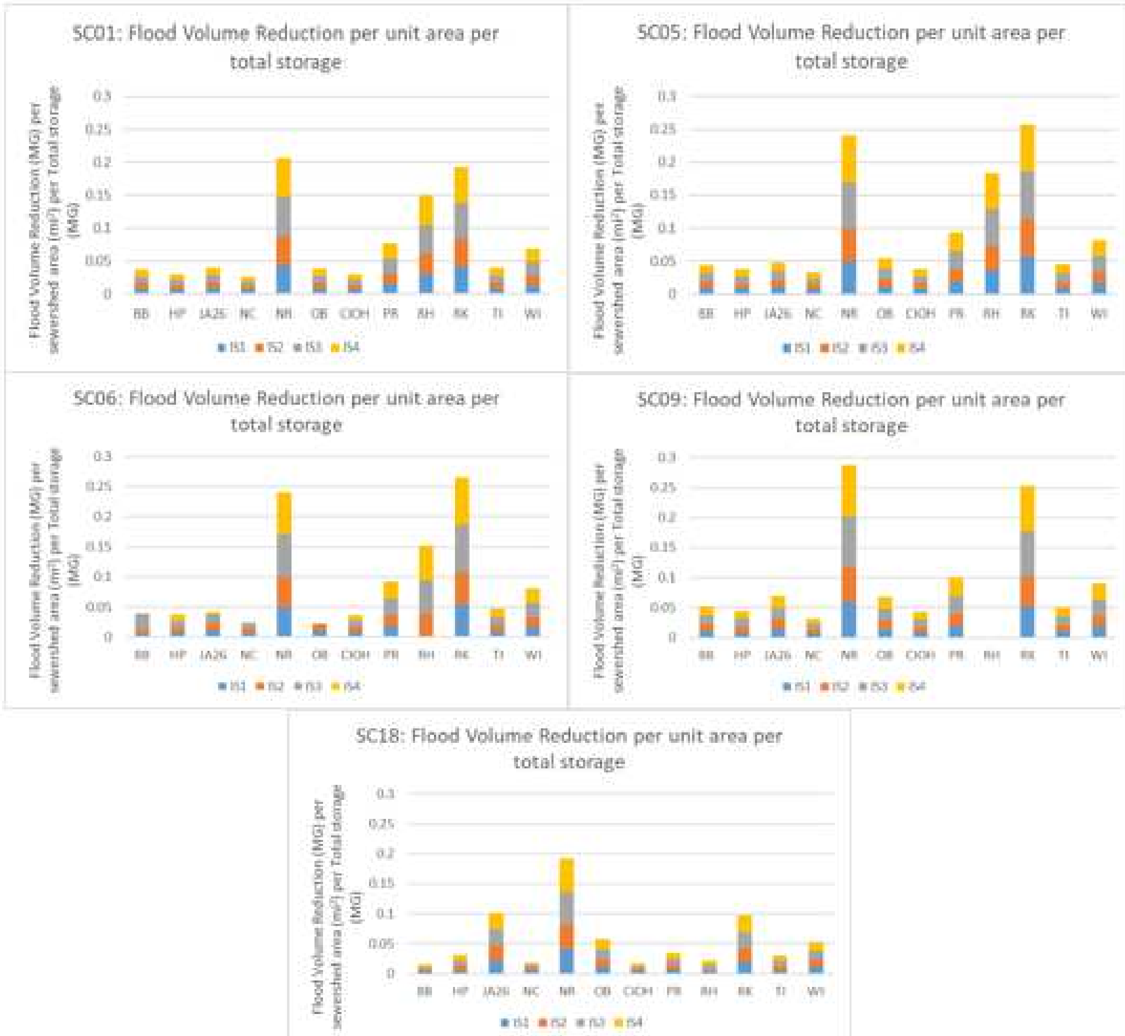


Figure 6: Flood volume reduction per unit area per total storage.

Each of the above graphs have a very similar trend, despite storm intensity and duration. This further highlights the importance of investigating into which sewershed characteristics play a factor in flood mitigation alongside intervention storage volume. Overall, North River (NR) experienced the greatest normalized flood reduction throughout each storm scenario, by a factor of 25 in some cases. The near exact distribution trends highlight the importance of understanding which outside factors other than intervention volume influence flood reduction. Only the results from storm scenario 18 looks different, as the total volume of water, 9.1 inches of water, vastly overwhelmed the stormwater system. This coupled with sea level rise influenced a different response in flood reduction per sewershed. The potential covariates as to why this occurred are explored and quantified in Section 3.5.

On a citywide scale, NYC experienced flood reductions ranging from 1 % to 6.5%. On a sewershed scale, NYC experience flood reductions ranging from 0% to 7.5%. This variance in performance is site specific, as the sewershed characteristics greatly influence the effectiveness of the intervention scenarios. It is also interesting to note the similarities per storm scenario. The uniformity in flood volume reduction per unit area per total added storage remains nearly constant throughout storm intensity and duration. This can be explained by the fact that flood volume reductions ranged only slightly. If more simulations were run, it would be beneficial to include an intervention volume that accounted for a greater percentage of the total inflow. Yet the correlation between added storage and percent reduction is clearly visible.

3.4.2 Sewershed scale CSO results:

To analyze the effectiveness of CSO mitigation practices per sewershed, the graphs below were made. The CSO volume reduction normalized per unit area and total storage allowed for a comparable baseline. Also, these graphs highlight the complimentary benefits of grey and green infrastructure. The sewersheds that experienced the highest overall percent reduction per total storage simply performed more efficiently. This is solely due to factors other than storage volume, hence the necessity to further understand which sewershed characteristics contribute to CSO mitigation.

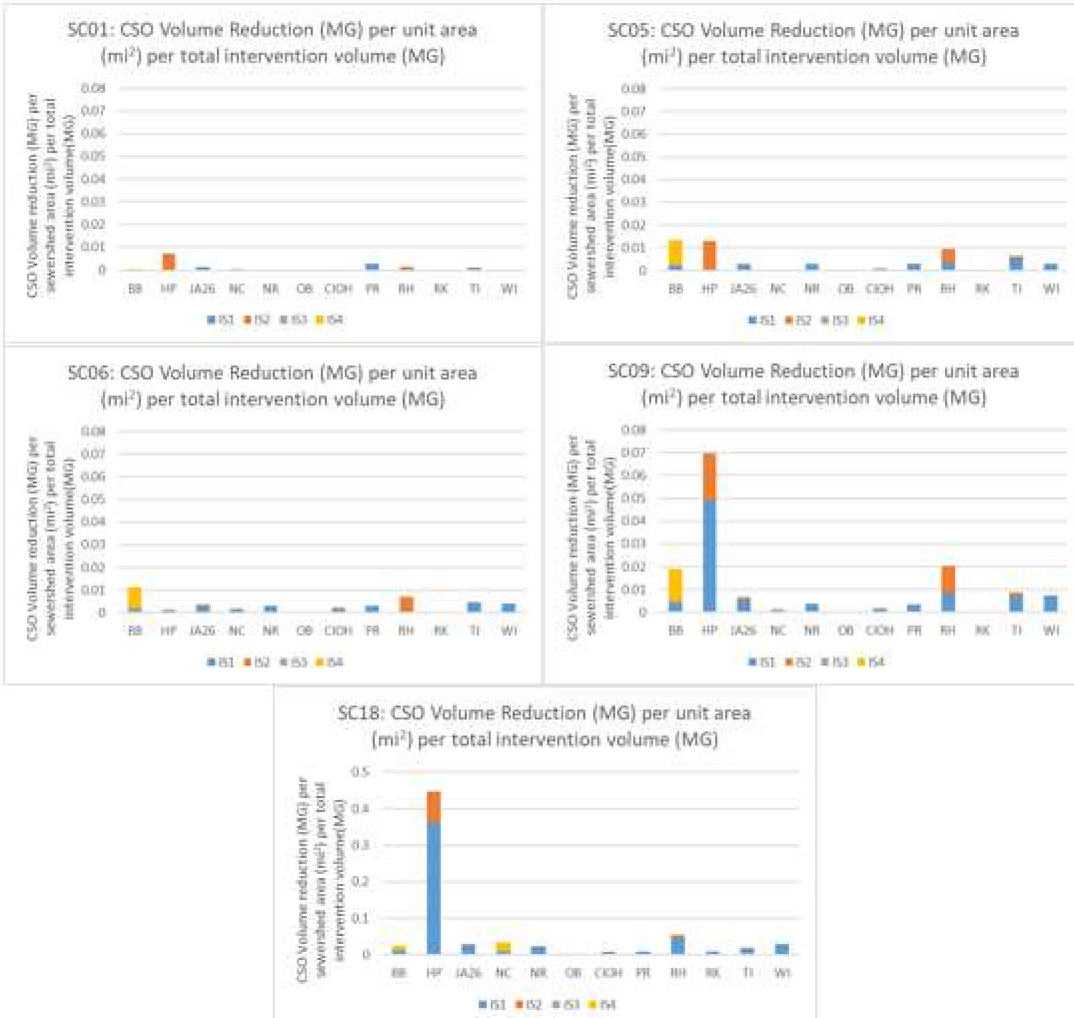


Figure 7: CSO volume reduction per unit area per total storage.

Storm scenarios 9 and 18 were the major outliers in this analysis, as they experienced exponentially more reduction than other storms. Hunts Point saw a very steep increase in CSO reduction for both storm scenarios 9 and 18. HP served as the major outlier in this analysis, as the CSO volume reduction was much higher than any other sewershed. This is due to the amount of water accumulated and that Hunts Point received the most amount of intervention storage volume. Storm scenarios 1-6 have very similar graphical trends.

Again, the graphs do not depict the efficiency per intervention scenario, rather the accumulation and total efficiency of the combined intervention scenarios. On a citywide scale, NYC experienced CSO reductions ranging from 2% to 40%. On a sewershed scale, NYC experienced flood reductions ranging from 1% to 99%. This variance in performance is site specific, as the sewershed characteristics greatly influence the effectiveness of the intervention scenarios.

3.5 Factors that influence the performance of stormwater interventions under varying storm scenarios:

The sewershed and intervention characteristics were compiled. The percentage of green to grey infrastructure was included in the dataset as a possible independent variable to see whether this factor was significant in influencing percent reduction at a sewershed scale. These potential covariates were fit to the appropriate nonlinear equations. The response variable is percent reduction from baseline, i.e., no additional intervention volume. The regression was performed using forwards selection, adding factors that indicated significance. Once 3 of the most frequent factors were found, models were fit using these factors to maintain uniformity. Only storm scenarios 1, 5, and 9 were fit to models. This will be discussed as to why in Section 3.5.3.

3.5.1 Flooding Factors:

Per sewershed, each storm scenario was fit to the equations above and nonlinear models were created. Each nonlinear function is given below in Table 7. Each storm scenario had 3 predictor variables. The 3 covariates include added storage volume, the impervious percentage of that sewershed, and the percentage of open space within that sewershed. The percent impervious has values that range from 38% to 81% and the percent open space ranged from 2 to 13 percent. Again, the nonlinear equation that was fit to this data is as follows:

$$y = \exp(a * (x_1^{b_1}) * (x_2^{b_2}) * (x_3^{b_3})) \tag{3}$$

Table 7: Flood volume nonlinear regression analysis outputs.

Flood Volume Factors and Slope Values								
Storm Scenario	Factors				R-squared	Standard Error	Degrees of Freedom
	Intercept	Intervention Volume	Percent Impervious	Open Space			
SC01	0.04704	0.13116	0.6856	0.1393	0.745	0.2645	44
p-value	*1.97E-01*	*4.72E-05*	*2.32E-04*	*1.19E-02*			
SC05	0.003401	0.20567	1.1249	0.2242	0.722	0.2758	44
p-value	*4.72E-01*	*8.47E-05*	*5.50E-04*	*1.30E-02*			
SC09	0.0002184	0.40906	1.43174	0.48769	0.819	0.3412	40
p-value	*7.04E-01*	*1.20E-04*	*1.21E-02*	*8.86E-03*			

Interpreting the outputs from the regression analysis paints a clearer picture as to why some sewersheds experience more flood reduction than others. A simple sensitivity analysis was performed because of the nonlinear fit of the model. This analysis was utilized to understand the slope values, whether the relationship was positive or negative, i.e., an increase in X caused an increase in Y, or a decrease in X caused an increase in Y, respectively. The OFAT method was used to fit the models, coupled with a forward approach.

From the sensitivity analysis, all 3 factors were found to have a positive correlation. The positive slope value of the percent impervious indicates the higher percent impervious, the greater the impact that storage volume has on flood volume reduction. This makes complete sense, as an area with higher impervious percent will respond more efficiently to additional storage. Open space is a positive driver to flood reduction as well. The positive slope factor clearly shows that areas with higher amounts of open space will experience a greater decrease in flooding than areas with small amounts of open space. In order to graphically represent each regression solution, the expected value of open space is taken and plotted as a constant, contrasting intervention volume and percent impervious. The median value of open space was used. Below are graphs of the fitted nonlinear model depicting the relationship between percent impervious and storage volume. Please see the appendix for code and residual plots. The plots on the left are simulated versus observed values depicting goodness of fit. The other two plots are of the surrogate model.

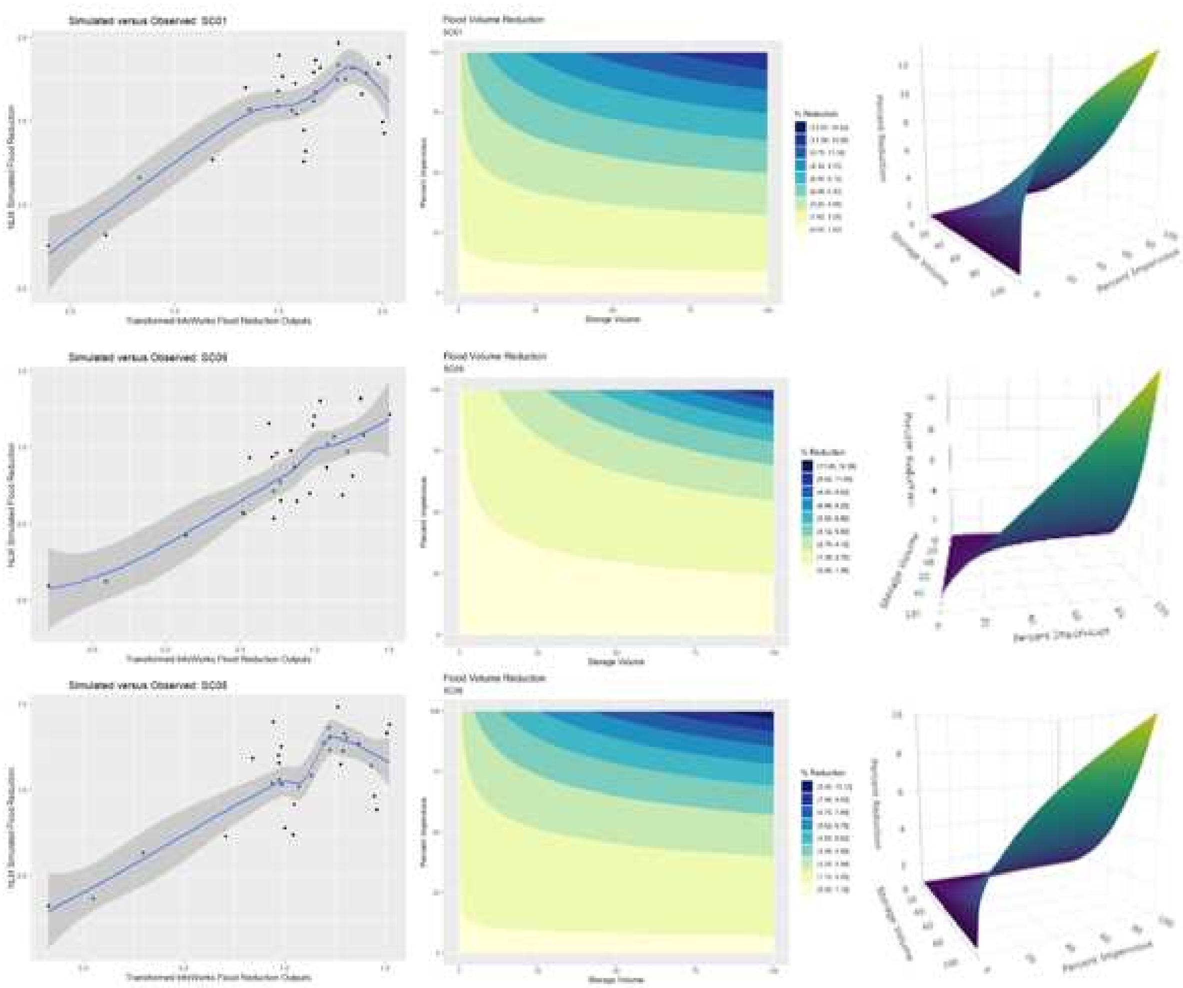


Figure 8: Regression analysis outputs. The first graph is simulated vs. observed. The second and third are the surrogate model.

Looking at the middle graphs, it is evident the immediate effects of shorter, less intense storms. Some magnitude of flood reduction is more likely to occur during less severe storms.

3.5.2 CSO Volume Factors:

Per sewershed, each storm scenario was fit to the equations below and nonlinear models were created. Each nonlinear function is below in Table 8. Each storm scenario had 3 predictor variables. The percent grey has values that range from 38 to 81 percent and the percent open space ranged from 2 to 13 percent. The empty column space indicates that variable was not included in the final nonlinear model. Recall, the nonlinear equation that was fit to this data is as follows:

$$y = a * ({x_1}^{b_1}) * ({x_2}^{b_2}) * ({x_3}^{b_3}) \tag{2}$$

Table 8: CSO volume nonlinear regression analysis outputs.

CSO Flood Volume Factors and Slope Values								
Storm Scenario	Factors				R-squared	Standard Error	Degrees of Freedom
	Intercept	Intervention Volume	Percent Grey	Open Space			
SC01	0.0013	1.219	1.263	0.963	0.949	0.1245	40
p-value	*5.25E-01*	*5.60E-03*	*1.77E-03*	*4.62E-05*			
SC05	$2.09*10^{-7}$	4.346	4.518	-0.249	0.979	0.08835	32
p-value	*7.21E-01*	*5.93E-06*	*5.20E-06*	*0.0834*			
SC09	$6.31*10^{-14}$	8.306	8.668		0.957	0.1332	30
p-value	*2.00E-16*	*6.20E-13*	*0.0022*				

Again, a sensitivity analysis was performed because of the nonlinear fit of the model. This analysis was utilized to understand the slope values, whether the correlation was positive or negative. The OFAT method was used.

From the graphs above, the presence of grey infrastructure was vital in CSO volume mitigation. This was represented within the model taking the form of a percentage; the percentage of added infrastructure that is grey. This regression analysis confirmed the necessity of grey infrastructure to reduce CSO volume, as the positive slope values of percent grey directly correlate to a greater CSO volume reduction. Mitigating CSO volume is also determined by the added intervention storage. These two factors predominately drive the efficiency of CSO volume mitigation within the city of New York. Open space as well plays a factor in CSO reduction. In order to graphically represent the regression surrogates which have 3 covariates, the expected value of open space is taken and plotted as a constant, contrasting intervention volume and percent impervious. The median value of open space was used.

Below are graphs of the fitted nonlinear model depicting the relationship between percent grey and storage volume. Please see the appendix for code and residual plots. The plots on the left are simulated versus observed values depicting goodness of fit. The other two plots are of the surrogate model.

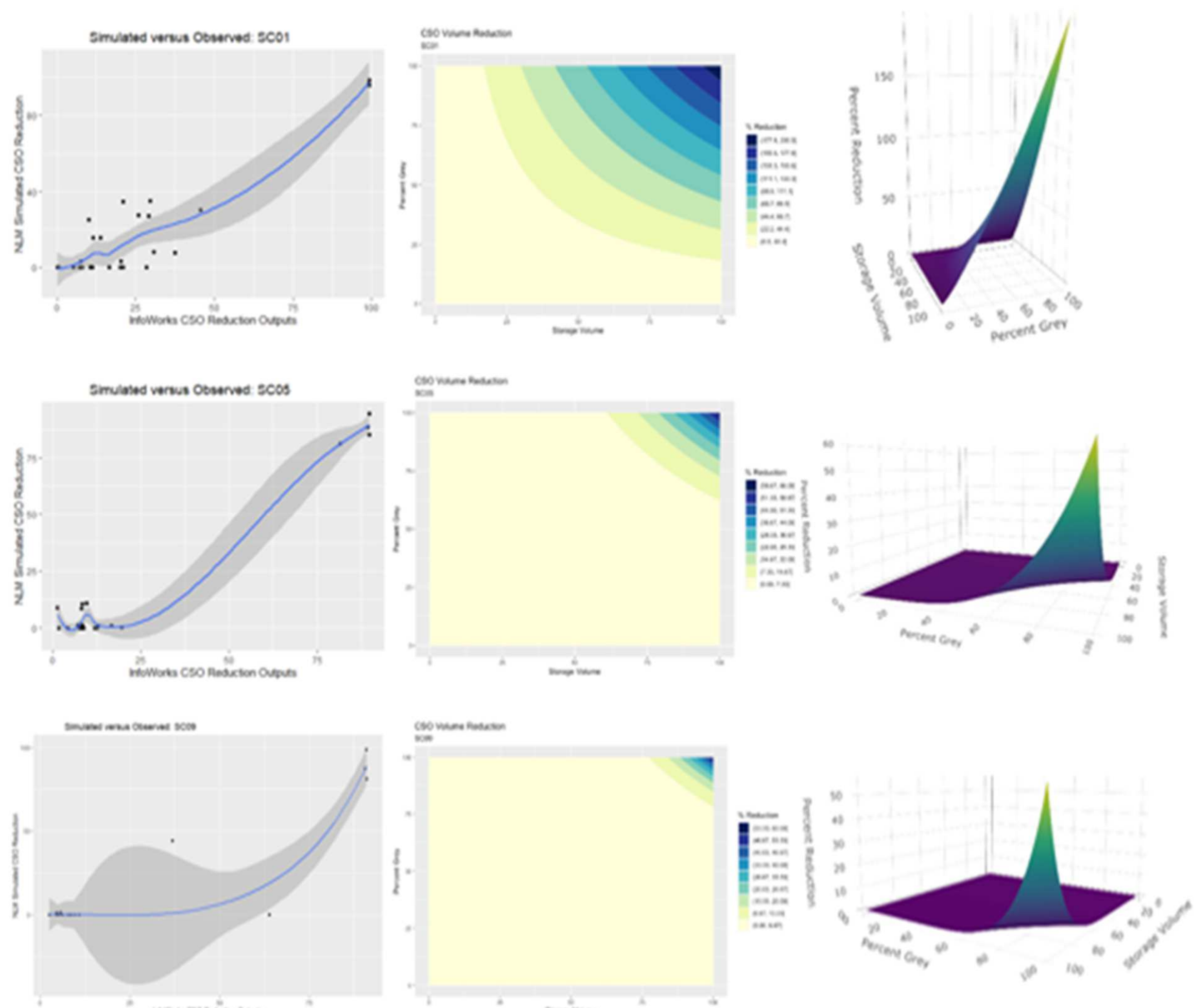


Figure 9: Regression analysis outputs. The first graph is simulated vs. observed. The second and third are the surrogate model.

The model for storm scenario 1 fit well because of the spread of available input data. Storm scenarios 5 and 9 were lacking evenly distributed inputs, therefore not permitting the model to fit well. The large gap in the spread of data is not conducive to proper model fitting.

3.5.3. Storm scenario 6 and 18:

Storm scenarios 6 and 18 were not fit to the models above. The results of the simulations were too unpredictable, and there was not as significant a relationship between volume reduction and intervention volume. This is because the storm surge and sea level rise greatly influenced the outputs of each of model. The vast amount of rainfall for storm scenario 18 overwhelmed the system. The capacity of the intervention was too small for runoff volume because the storm and/or the upgradient contributing area were too large, and thus, the intervention capacity was full before the peak rainfall intensity occurred, limiting the effectiveness of the intervention to mitigate part of the storm that most likely produced the maximum flood depth.

4. Conclusion:

Research suggests that urbanization increases the frequency, magnitude and duration of runoff (Gallo, 2013). This is confirmed in this study of New York City. This study was undertaken to understand the effects of green and grey infrastructure as they relate to flood and CSO mitigation in a highly urbanized area, both at the municipal and sewershed scale. InfoWorks ICM was used to simulate 5 unique storm scenarios with different volumes of intervention storage. IS1 was the addition of 243 MG of distributed infrastructure, IS2 was the addition of 121 MG of centralized infrastructure, IS3 was the addition of 146 MG of distributed, and IS4 was the addition of 59 MG of centralized. Sea level rise, storm surge, and future climate scenarios were also examined, but the results were too varying to quantify. Each intervention scenario was used to assess the effectiveness of the substitutive or complimentary effects of green and grey infrastructure at the municipal and sewershed level.

The complimentary effects of green and grey infrastructure were examined and found to have profound impacts on flood and CSO mitigation in highly urbanized areas. The urban water balance was influenced by the implementation of grey and green infrastructure, resulting with an increase in overall infiltration of up to 1.5%. With the examined intervention scenarios, NYC as a whole experienced flood reduction up to 6.2% while some sewersheds experienced a flood reduction up to 7.5%. On a citywide scale NYC experienced a CSO volume reduction of up to 40% while at a sewershed scale, up to 99%. With the addition of more storage capacity during more severe storms, the overall reduction was less than with more intense storms. This conclusion is consistent with (Zhu, 2017), who found the control ability of LID practices are more effective in flood reduction for shorter duration, lower intensity and smaller peak coefficient rainfall events for shorter duration, lower intensity and smaller peak coefficient rainfall events. As the intensity of the storm increases, the effectiveness of additional infrastructure decreases.

From this study, it was found that on a city-wide scale, green infrastructure is more effective at mitigating flooding while grey infrastructure is vital in CSO volume mitigation. In order to understand the relationships between sewershed characteristics and volume mitigation, a regression analysis was performed. A nonlinear model was fit to the simulation outputs. This surrogate model served as an interpretable approximation to the simulation results. For flood mitigation, the three characteristics included added: storage, percent impervious, and open space. For CSO mitigation, the three constituents included: added storage, percent grey, and open space. In the flood mitigation surrogate model, each variable had a positive correlation to the resulting dependent variable. For example, the higher the percent impervious area, the greater the impact additional storage has on flood mitigation. The CSO mitigation surrogate as well experienced a positive correlation between dependent and independent variables. The effects of sea level rise and storm surge profoundly impact the effectiveness of stormwater management practices, as the significance between volume reduction and storage volume is drastically decreased. According to a study performed by (Pykea, 2011), stormwater runoff is most sensitive to changes in site impervious cover, followed by changes in precipitation volume and event intensity.

The overall takeaway from this study includes the importance of a combination of green and grey infrastructure for urban stormwater management systems. The volume reduction response of the environment is not only contingent upon added storage, but also sewershed characteristics, which include amount of open space and impervious area. According to (Loperfido, 2014), it is important to consider land cover factors as effective stormwater BMP's with respect to urban stream hydrology in addition to the implementation of distributed BMP's.

One aspect of this sewer network that was not analyzed was overall connectedness of infrastructure and sewersheds. Sewersheds that received more runoff due to drainage area of other sewersheds potentially could have skewed the simulation results, contributing to greater flooding or CSO. Another avenue that could have been explored was modeling multiple or at minimum another intervention scenario with a greater ratio of available storage to volume inflow. This study was limited in the analysis due to lack of data point results. More data would have resulted in a stronger, more robust analysis. As well, the feasibility of adding green infrastructure in quantities large enough to majorly reduce flood and CSO volumes is another aspect of the study that was not looked at. In this specific study, finding available impervious spaces on the city ground surface that could be converted into green spaces was a limiting factor for implementation. Other intervention types, say green roofs, would need to be studied in a more rigorous depth to further comprehend the feasibility of installing a large quantity of green infrastructure.

REFERENCES

1. Ahiablame, L.M., Engel, B.A., Chaubey, I. (2013). Effectiveness of low impact development practices in two urbanized watersheds: retrofitting with rain barrel/cistern and porous pavement. J. Environ. Manag. 119, 151e161.
2. Ahiablame, Laurent & Engel, Bernard & Chaubey, Indrajeet. (2012). Effectiveness of Low Impact Development Practices: Literature Review and Suggestions for Future Research. Water, Air, & Soil Pollution. 223. 10.1007/s11270-012-1189-2.
3. Barron, Olga & Barr, Anthony & Donn, Michael. (2013). Effect of urbanisation on the water balance of a catchment with shallow groundwater. Journal of Hydrology. 485. 162–176. 10.1016/j.jhydrol.2012.04.027.
4. Bedan, E.S. and Clausen, J.C. (2009), Stormwater Runoff Quality and Quantity From Traditional and Low Impact Development Watersheds1. JAWRA Journal of the American Water Resources Association, 45: 998-1008. doi:10.1111/j.1752-1688.2009.00342.x
5. Brander, Kent & Owen, Katherine & Potter, Kenneth. (2004). Modeled Impacts of Development Type on Runoff Volume and Infiltration Performance. JAWRA Journal of the American Water Resources Association. 40. 961 - 969. 10.1111/j.1752-1688.2004.tb01059.x.
6. Chang, Ni-Bin & Lu, Jia-Wei & Chui, Ting Fong May & Hartshorn, Nicholas. (2018). Global policy analysis of low impact development for stormwater management in urban regions. Land Use Policy. 70. 368-383. 10.1016/j.landusepol.2017.11.024.
7. Chen, Jingqiu & Theller, Lawrence & Gitau, Margaret & Engel, Bernard & Harbor, Jon. (2016). Urbanization impacts on surface runoff of the contiguous United States. Journal of Environmental Management. 187. 10.1016/j.jenvman.2016.11.017.

8. Cohen, Jeffrey & Field, Richard & Tafuri, Anthony & Ports, Michael. (2012). Cost Comparison of Conventional Gray Combined Sewer Overflow Control Infrastructure versus a Green/Gray Combination. Journal of Irrigation and Drainage Engineering. 138. 534-540. 10.1061/(ASCE)IR.1943-4774.0000432.
9. Dong, Xin & Guo, Hao & Zeng, S. H.. (2017). Enhancing future resilience in urban drainage system: Green versus grey infrastructure. Water Research. 124. 10.1016/j.watres.2017.07.038.
10. Epps, T., & Hathaway, J. (2019). Using spatially-identified effective impervious area to target green infrastructure retrofits: A modeling study in Knoxville, TN. Journal of hydrology, 575, 442-453. doi: 10.1016/j.jhydrol.2019.05.062
11. Foster, J., Lowe, A., Winkelman, S., 2011. The Value of Green Infrastructure for Urban Climate Adaptation. Center for Clean Air Policy, February. Retrieved fromhttp:// ccap.org/assets/The-Value-of-Green-Infrastructure-for-Urban-Climate-Adaptation CCAP-Feb-2011.pdf
12. Gallo, E. & Brooks, Paul & Lohse, Kathleen & Mclain, Jean. (2013). Land cover controls on discharge and runoff solution chemistry of semi-arid urban catchments in the Southwest. Journal of Hydrology. 485. 37–53. 10.1016/j.jhydrol.2012.11.054.
13. Gilroy, Kristin & McCuen, Richard. (2009). Spatio-Temporal Effects of Low Impact Development Practices. Journal of Hydrology - J HYDROL. 367. 228-236. 10.1016/j.jhydrol.2009.01.008.
14. Hou, Jingming & Hao, Han & Qi, Wenchao & Guo, Kaihua & Li, Zhanbin & Hinkelmann, Reinhard. (2019). Experimental Investigation for Impacts of Rain Storms and Terrain Slopes on Low Impact Development Effect in an Idealized Urban Catchment. Journal of Hydrology. 579. 124176. 10.1016/j.jhydrol.2019.124176.
15. Hu, Maochuan & Sayama, Takahiro & Zhang, Xingqi & Tanaka, Kenji & Takara, Kaoru & Yang, Hong. (2017). Evaluation of low impact development approach for mitigating flood inundation at

a watershed scale in China. Journal of Environmental Management. 193. 10.1016/j.jenvman.2017.02.020.

16. Hu, Maochuan & Zhang, Xingqi & Li, Yu & Yang, Hong & Tanka, Kenji. (2019). Flood mitigation performance of low impact development technologies under different storms for retrofitting an urbanized area. Journal of Cleaner Production. 222. 373-380. 10.1016/j.jclepro.2019.03.044.
17. Jiali Qiu, Zhenyao Shen, Guoyong Leng, Hui Xie, Xiaoshu Hou, Guoyuan Wei. (2019). Impacts of climate change on watershed systems and potential adaptation through BMPs in a drinking water source area, Journal of Hydrology. 573. 123-135. 0022-1694, https://doi.org/10.1016/j.jhydrol.2019.03.074.
18. Jung-min Lee, Kyoung-hak Hyun, Jong-soo Choi, Yeo-jin Yoon & Franz Kevin F. Geronimo (2012) Flood reduction analysis on watershed of LID design demonstration district using SWMM5, Desalination and Water Treatment, 38:1-3, 255-261, DOI: 10.1080/19443994.2012.664377
19. Keeley, Melissa & Koburger, Althea & Dolowitz, David & Medearis, Dale & Nickel, Darla & Shuster, William. (2013). Perspectives on the Use of Green Infrastructure for Stormwater Management in Cleveland and Milwaukee. Environmental management. 51. 10.1007/s00267-013-0032-x.
20. Kourtis, Ioannis & Tsihrintzis, Vassilios & Baltas, Evangelos. (2018). Simulation of Low Impact Development (LID) Practices and Comparison with Conventional Drainage Solutions. Proceedings. 2. 640. 10.3390/proceedings2110640.
21. Lee, J.Y. & Moon, Hyoung Jun & Kim, T.I. & Kim, H.W. & Han, Mooyoung. (2013). Quantitative analysis on the urban flood mitigation effect by the extensive green roof system. Environmental pollution (Barking, Essex : 1987). 181C. 257-261. 10.1016/j.envpol.2013.06.039.

22. Li, C.; Liu, M.; Hu, Y.; Zong, M.; Zhao, M.; Todd Walter, M. (2019). Characteristics of impervious surface and its effect on direct runoff: A case study in rapidly urbanized area. Water Supply. 19(7). 1885-1891. https://doi.org/10.2166/ws.2019.064.
23. Line, Daniel & Brown, Robert & III, William & Lord, W.. (2012). Effectiveness of LID for Commercial Development in North Carolina. Journal of Environmental Engineering. 138. 680-688. 10.1061/(ASCE)EE.1943-7870.0000515.
24. Liu, Yaoze & Bralts, Vincent & Engel, Bernard. (2015). Evaluating the effectiveness of management practices on hydrology and water quality at watershed scale with a rainfall-runoff model. Science of The Total Environment. 511. 10.1016/j.scitotenv.2014.12.077.
25. Loperfido, J. & Noe, Gregory & Jarnagin, S. & Hogan, Dianna. (2014). J. V. Loperfido, G. B. Noe, S. T. Jarnagin, and D. M. Hogan. 2014. Effects of distributed and centralized stormwater best management practices and land cover on urban stream hydrology at the catchment scale. Journal of Hydrology: DOI: http://dx.doi.org/10.1016/j.jhydrol.2014.07.007. Journal of Hydrology. 519. 10.1016/j.jhydrol.2014.07.007.
26. Mentens, J., Raes, D., Hermy, M., 2006. Green roofs as a tool for solving the rainwater runoff problem in the urbanized 21st century? Landsc. Urban Plann. 77 (3), 217–226, http://dx.doi.org/10.1016/j.landurbplan.2005.02.010.
27. Montalto, Franco & Behr, Christopher & Alfredo, Katherine & Wolf, Max & Arye, Matvey & Walsh, Mary. (2007). Rapid Assessment of the Cost-Effectiveness of Low Impact Development for CSO Control. Landscape and Urban Planning. 82. 117-131. 10.1016/j.landurbplan.2007.02.004.
28. Morsy, Mohamed & Goodall, Jonathan & Shatnawi, Fadi & Meadows, Michael. (2016). Distributed Stormwater Controls for Flood Mitigation within Urbanized Watersheds: Case Study

of Rocky Branch Watershed in Columbia, South Carolina. Journal of Hydrologic Engineering. 21. 05016025. 10.1061/(ASCE)HE.1943-5584.0001430.

29. Palla, Anna & Gnecco, Ilaria. (2015). Hydrologic modeling of Low Impact Development systems at the urban catchment scale. Journal of Hydrology. 528. 361-368. 10.1016/j.jhydrol.2015.06.050.
30. Pappalardo, Viviana & La Rosa, Daniele & Campisano, Alberto & Greca, Paolo. (2017). The potential of green infrastructure application in urban runoff control for land use planning: A preliminary evaluation from a southern Italy case study. Ecosystem Services. 26PB. 345-354. 10.1016/j.ecoser.2017.04.015.
31. Pedersen, A., Mikkelsen, P. S. & Arnbjerg-Nielsen, K. (2012). Climate change induced impacts on urban flood risk influenced by concurrent hazards. Journal of Flood Risk Management 5 (3), 203–214.
32. Qin, Huapeng & Li, Zhuo-Xi & Fu, Guangtao. (2013). The Effects of Low Impact Development on Urban Flooding Under Different Rainfall Characteristics. Journal of environmental management. 129C. 577-585. 10.1016/j.jenvman.2013.08.026.
33. Shafique, Muhammad & Kim, Reeho. (2015). Low Impact Development Practices: A Review of Current Research and Recommendations for Future Directions. Ecological Chemistry and Engineering S. 22. 10.1515/eces-2015-0032.
34. Shuster, William & Rhea, Lee. (2013). Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). Journal of Hydrology. 485. 177–187. 10.1016/j.jhydrol.2012.10.043.
35. Struck, Scott & Field, Richard & Pitt, Robert & O'Bannon, Deborah & Schmitz, Erich & Ports, Michael & Jacobs, Tom. (2009). Green Infrastructure for CSO Control in Kansas City, Missouri.

Proceedings of the Water Environment Federation. 2009. 3631-3640. 10.2175/193864709793953016.

36. Valinski, N.A. & Chandler, David. (2015). Infiltration performance of engineered surfaces commonly used for distributed stormwater management. Journal of environmental management. 160. 10.1016/j.jenvman.2015.06.032.
37. Walsh, Thomas & Pomeroy, Christine & Burian, Steven. (2014). Hydrologic modeling analysis of a passive, residential rainwater harvesting program in an urbanized, semi-arid watershed. Journal of Hydrology. 508. 240–253. 10.1016/j.jhydrol.2013.10.038.
38. Wissler, Austin & Hunt, William & McLaughlin, Richard. (2019). Hydrologic and water quality performance of two aging and unmaintained dry detention basins receiving highway stormwater runoff. Journal of environmental management. 255. 109853. 10.1016/j.jenvman.2019.109853.
39. Zhu, Z.; Chen, X. Evaluating the Effects of Low Impact Development Practices on Urban Flooding under Different Rainfall Intensities. Water 2017, 9, 548.

APPENDIX

```
library(ggplot2)

library(utils)

library(metR)

## Contour Plot

#generate values incremented by 1 for percentages

X1 <- seq(0,100, 1)

X2 <- seq(0,100, 1)


#matrix of all combinations of percentages

all.combos <- expand.grid(X1,X2)

#all.combos


#make a dataframe from matrix

colnames(all.combos) <- c("X1","X2")

all.combos.dfcso1 <- data.frame(all.combos)

all.combos.dfcso5 <- data.frame(all.combos)

all.combos.dfcso5.2 <- data.frame(all.combos)

all.combos.dfcso9 <- data.frame(all.combos)


#get the equation in there SC01

Y1 = (.0004065*(all.combos.dfcso1$X1^(1.219))*(all.combos.dfcso1$X2^(1.263))*(5.5^.963))

all.combos.dfcso1$Y1=Y1

head(all.combos.dfcso1)


#Plot SC01

ContourPlot <- ggplot(all.combos.dfcso1, aes(X1,X2, z=Y1)) + geom_contour_filled(bins = 9)
```

```
ContourPlot + labs(title = "CSO Volume Reduction", subtitle = "SC01", x = "Storage Volume", y = "Percent Grey") +
  scale_fill_brewer(name = "% Reduction",
                palette="YlGnBu", guide = guide_legend(reverse = TRUE))


ContourPlot1 <- ggplot(all.combos.df, aes(X1,X2, z=Y)) +
  geom_contour_filled(stat = "contour_filled", position = "identity", bins = 8)+
  geom_text_contour()
ContourPlot1 + labs(title = "Percent Reduced Flood Volume", subtitle = "SC09", x = "Storage Volume (MG)", y = "Percent Impervious Surface") +
  scale_fill_brewer(name = "% Reduction",
                palette="YlGnBu", guide = guide_legend(reverse = TRUE))


## Surface Plot
library(plotly)


surface.matrix = matrix(Y1,length(X1),length(X2))


SurfacePlot <- plot_ly(z = ~ surface.matrix)
SurfacePlot <- SurfacePlot %>% add_surface()
SurfacePlot <- SurfacePlot %>% layout(title = "SC01", scene = list(xaxis = list(title = 'Storage Volume'),
                                 yaxis = list(title = 'Percent Grey'),
                                 zaxis = list(title = 'Percent Reduction')))
```