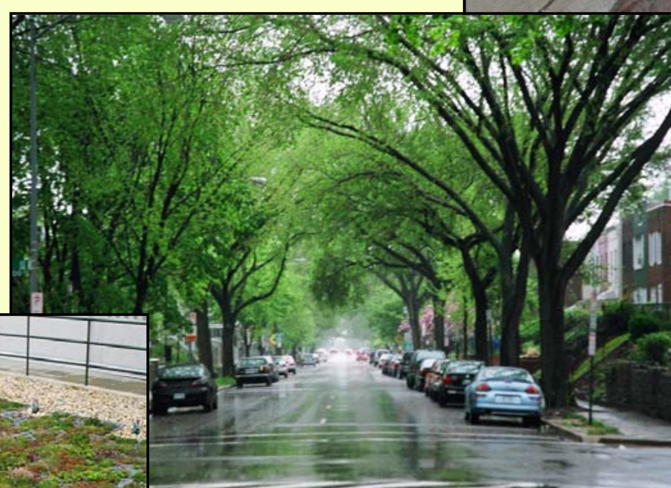
The Green Build-out Model: Quantifying the Stormwater Management Benefits of Trees and Green Roofs in Washington, DC



Casey Trees
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The Green Build-out Model: Quantifying the Stormwater Management Benefits of Trees and Green Roofs in Washington, DC

Prepared by:

Casey Trees

Barbara Deutsch, ASLA, ISA, Senior Director, Principal Investigator

Heather Whitlow, Director, Planning and Design

and

LimnoTech

Michael Sullivan, Vice President
Anouk Savineau, PE
Brian Busiek, PE

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Advisory Team:

- David Jonas Bardin, Esq.; Member, DC Water and Sewer Authority Board of Directors
- Daniel Berry; Revitalization Planner / Urban Design, DC Office of Planning
- Alexi Boado; Urban Watershed Project Officer & LID Coordinator, DC Department of Environment
- Jonathan Essoka, Ph.D.; Environmental Engineer, EPA Office of State and Watershed Partnerships
- Hamid Karimi, Ph.D.; Deputy Director Natural Resources, DC Department of Environment
- Pete Johnson; Anacostia River Initiative, Chesapeake Bay Foundation.
- Chris Kloss; Senior Environmental Scientist, Low Impact Development Center
- Chris Shaheen, ASLA; Revitalization Program Manager, DC Office of Planning
- James L. Sherald, Ph.D.; Chief, Natural Resources & Science, National Park Service National Capital Region, Center for Urban Ecology
- Mohsin Siddique, Ph.D.; Supervisor Environmental Planning, DC Water and Sewer Authority
- Nancy Stoner; Clean Water Project, NRDC
- Neil Weinstein; Executive Director, Low Impact Development Center

Technical Review and Support Team

- Mark Buscaino; Executive Director, Casey Trees
- Dan Smith; Senior Director of Communications, Casey Trees
- Meredith Upchurch, ASLA; Green Infrastructure Designer, Casey Trees
- Maisie Hughes, ASLA; Special Projects Coordinator, Casey Trees,
- David J. Nowak, Ph.D.; Project Leader, Northeastern Research Station USDA Forest Service
- Bob Hoehn; Northeastern Research Station USDA Forest Service
- Jun Wang, Ph.D.; Northeastern Research Station USDA Forest Service
- Steven Peck; Executive Director, Green Roofs for Healthy Cities
- Mindy Lemoine; Environmental Assessment and Innovation Division EPA Region 3
- Phil Rodbell; Urban Forest Specialist, Environmental Assessment and Innovation Division EPA Region 3 (on loan from USDA Forest Service)
- Jennifer Cotting; Program Manager, Environmental Finance Center, University of Maryland

ABSTRACT

The Green Build-out Model is a planning tool that quantifies the cumulative stormwater management benefits of trees and green roofs for different coverage assumptions across the District of Columbia. It calculates potential reductions in stormwater runoff within the municipal separate storm sewer system (MS4) and the combined sewer system (CSS) that contribute to water quality impairment in the Nation's capital.

The Green Build-out Model adds the "green component" to the existing hydrologic and hydraulic model of the District (Mike Urban) used by the DC Water and Sewer Authority to support development of the Long Term Control Plan for the CSS. The MS4 areas were added to the model so that all of the municipal sewer systems were included in one planning tool.

The Green Build-out Model integrates GIS land cover data and hydrologic processes using rainfall storage and coverage areas for trees and green roofs. Interception storage amounts for trees were based on USDA Forest Service research and modeling that relates storage depth to the Leaf Area Index. The storage amounts for green roofs were based on literature values.

Two planning scenarios were evaluated with the Green Build-out Model and compared to existing or baseline conditions. An "intensive greening" scenario or the "Green Build-out" scenario considered putting trees and green roofs wherever it was physically possible. A "moderate greening" scenario looked at putting trees and green roofs where it was more practical and reasonable to do so. A separate tree box scenario was evaluated to estimate the stormwater management benefits associated with increasing the existing tree box dimensions in the downtown area where most sidewalks are at least 20 feet in width.

Scenarios were evaluated with a continuous simulation hydrologic and hydraulic model under average annual rainfall conditions (1990) and for a 6 hour (1 inch) design storm. Reductions in runoff volume and discharge frequency were determined by sewershed for both the CSS and MS4 areas and for the Anacostia, Potomac, and Rock Creek watersheds within the District.

An estimate of pollutant load reductions achieved with green roofs was developed by considering the difference in pollutant loading from a conventional roof and that of a green roof. Finally, annual operational savings for DC WASA from reduced pumping and treatment costs as a result of stormwater flow reductions were estimated at $.01 (one cent) per gallon.

Key findings show:

- Reductions in stormwater runoff volume of up to 7% across the city, with up to 27% reductions in individual sewersheds under the most intensive greening scenario.
- Reductions in untreated discharges in the CSS area are 6% for the moderate greening scenario and over 22% for the intensive greening scenario.
- For an average year, the intensive greening scenario prevents over 1.2 billion gallons of stormwater from entering the sewer systems, resulting in a reduction of over 1 billion gallons in direct untreated discharges to the District's rivers, and a 6.7% reduction in cumulative CSO frequencies (74 individual CSO discharges).
- For an average year, the moderate greening scenario prevents over 311 million gallons of stormwater from entering the sewer systems, resulting in a reduction of 282 million gallons in direct untreated discharges to the District's rivers, and a 1.5% reduction in cumulative CSO frequencies (16 individual CSO discharges).
- With the intensive greening scenario, installing 55 million square feet of green roofs in the CSS area would reduce CSO discharges by 435 million gallons or 19% each year.
- With the intensive greening scenario, an increase in tree canopy across the District from 35 to 57% would reduce stormwater and CSO discharges by 193 million gallons each year.
- Larger tree boxes could reduce stormwater runoff by 23 million gallons each year in the downtown area.
- Green roofs have the potential to keep thousands of pounds of nutrients, metals, and other pollutants out of area waterways.
- WASA could potentially realize between $1.4 and $5.1 million per year in annual operational savings in the CSS area due to reduced pumping and treatment costs.

The Green Build-out model provides an innovative and powerful planning tool for stormwater management in the District of Columbia. The grant findings provide information by sewershed and watershed to target investments in trees, green roofs, and larger tree boxes to yield the greatest return of stormwater benefits city-wide. The research also provides general hydrological relationships and modeling methodologies that are transferable to other municipalities.

These findings show that trees, green roofs, and large tree boxes provide substantial overall reductions in stormwater runoff and untreated discharges in sewer systems District-wide. The greatest opportunity for significant stormwater management benefits from trees, green roofs, and large tree boxes is at the sewershed level in the CSS area where reductions in discharge volume for all sewersheds averaged greater than 22%.

Trees, green roofs, and large tree boxes provide limited reduction in CSO frequencies. However, they do provide significant reductions in stormwater runoff volumes that could have implications for the detailed design of tunnels within the LTCP. Other LID solutions should be considered together when evaluating stormwater management benefits and the capacity to manage large storm events.

Trees and green roofs provide stormwater controls in urban areas where options and space are limited and show particular promise in the MS4 area where subsequent reductions in pollutant loadings could provide the District an option to make progress toward meeting TMDL requirements for its impaired waters.

In addition to stormwater management benefits, implementation of increased tree cover, green roof coverage, and larger tree boxes would also provide improvements in air quality, public health, social capital, and economic development, and reductions in carbon, UV radiation, and the urban heat island effect for the same investment.

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INTRODUCTION

This report presents the research findings from the EPA Water Quality Cooperative Agreement grant entitled “The Green Build-out Model”. It builds upon research presented by Casey Trees and LimnoTech at the Greening Rooftops for Sustainable Communities Conference, in Washington, DC, in 2004[11]. This grant project represents a public-private partnership between Casey Trees and LimnoTech. Casey Trees is a non-profit organization whose mission is to restore, enhance, and protect tree cover in the nation’s capital. LimnoTech is an environmental engineering firm that specializes in water quality assessments, watershed modeling, and NPDES permitting. LimnoTech was part of an engineering team led by Greeley and Hansen Engineers that built the hydrologic and hydraulic Mike Urban model for the DC Water and Sewer Authority (WASA) used in the Long Term Control Plan (LTCP) for the Combined Sewer System (CSS).

The primary goal of the grant was to quantify the contribution that trees and green roofs could make toward reducing stormwater runoff volumes and discharge frequencies in the District of Columbia so that these solutions could be considered in stormwater management strategies. A secondary goal of the grant was to identify policy recommendations to facilitate implementation of trees and green roofs as stormwater controls if the findings were significant.

The Green Build-out Model added the “green component” to the DC WASA Mike Urban Model. Previous research quantified the benefits of trees and/ or green roofs using hydrologic models. The Green Build-out Model is unique because in addition to quantifying the reduction in stormwater runoff volumes, the benefits of trees and green roofs are further quantified by using the hydraulic model to estimate the effects of these reductions in stormwater runoff volumes on the District’s combined and separate storm sewer systems. With this approach, the effects of discharges on receiving waters, pumping stations, and the wastewater treatment plant can be better understood at both a District-wide and sewershed level to target and leverage investments in stormwater infrastructure.

The research considered the stormwater benefits from trees and green roofs, two techniques that have the opportunity to cover large areas of the District and reduce runoff by intercepting rain where it falls. Tree canopy and green roof cover were treated as a land cover change, using the stormwater storage per unit area to incorporate them into the Mike Urban model. Other LID techniques, such as rain gardens, rain barrels, swales and other techniques that are designed to capture and treat runoff already generated, were not evaluated.

Model outputs focused on reductions in stormwater runoff volume and discharge frequencies because the primary sources of pollution in the Anacostia, Potomac, and Rock Creek watersheds are combined sewer overflows and stormwater runoff.

Grant resources were primarily directed at developing the Green Build-out Model. The scope of works also included creating an Advisory Team to participate in all aspects of the grant, and communications tools to transfer the findings to other jurisdictions. As a result of recommendations from the Advisory Team, a simplified analysis of pollutant load reductions from reduced stormwater volumes for green roofs, and an estimate of operational savings from reduced stormwater volumes in the CSS were conducted. A comprehensive cost/benefit analysis was beyond the scope of works for this grant but recommended for future study. Grant deliverables in addition to this report include:

- Advisory Team Policy Recommendations
- Model Results Display Tool to easily find and analyze the model findings
- Green Build-out Mini-model for policy-makers to test different model assumptions

This report is organized to provide background on the combined sewer system (CSS), municipal separate storm sewer system (MS4), and stormwater issues in the District. A discussion of the relationships investigated, the methods and assumptions that governed the research, findings and conclusions are also provided in the main body of the report. Four appendices provide additional information on:

- Appendix A – Detailed Model Findings
- Appendix B – Documentation of Methodology for Green Build-out Model
- Appendix C – Tree Cover Data Inputs
- Appendix D – Advisory Team Policy Recommendations

This report, the Green Build-out Model Results Display Tool, and the Green Build-out Mini-model are available online (after May 1, 2007) at: www.caseytrees.org.

1. BACKGROUND

Water infrastructure is aging in many cities in the United States. Capacity issues due to growth increase the stress on pipes, pumps, and treatment facilities. In addition, the requirements of the Clean Water Act are becoming more stringent. Municipalities and wastewater utilities are increasingly asked to do more with less.

Nearly all of the waters in the District including the Anacostia and Potomac rivers and Rock Creek are listed as impaired by the EPA for a number of reasons. The chief sources of pollution are combined sewer overflows and stormwater discharges. As shown in Figure 1, approximately one-third of the District is served by the CSS and two-thirds by MS4. Both systems operate under permits administered by EPA.

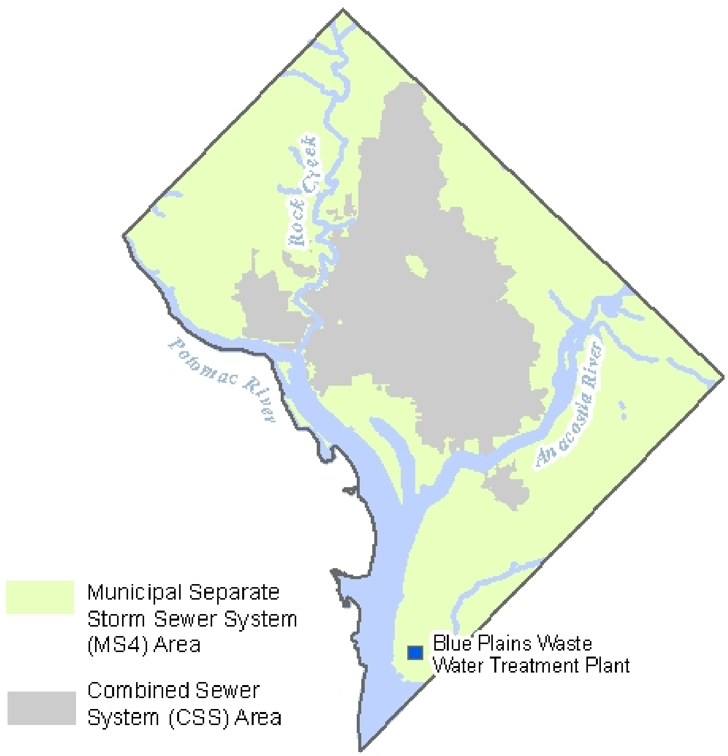

Figure 1: Map of the CSS and MS4 Areas in Washington, DC

In the CSS, WASA developed a comprehensive long-term control plan (LTCP) in 2002 with a projected twenty year implementation schedule[13]. The cost of implementing this plan is currently estimated to be $2.1 billion. During development of the LTCP it was concluded that compliance with the provisions of the Clean Water Act, EPA's CSO Regulations, and the Total Maximum Daily Load (TMDL) allocated to combined sewer overflows (CSOs) would require consistently meeting numerical limits, and that meeting these requirements could only be accomplished with traditional engineering solutions. Consequently, the main CSO control within the LTCP was the proposed construction of three tunnels to intercept combined sewage, and provide necessary storage until it can be treated and discharged to receiving waters.

WASA allocated $3 million to incorporate LID projects at its own facilities under the LTCP. WASA has expressed interest in reexamining the proposed tunnel projects, particularly the Rock Creek Tunnel, during facility planning depending on the extent of LID practices, their performance, and their acceptability to regulatory agencies.

In the MS4 area, the District government is responsible for developing and implementing a stormwater management program designed to prevent harmful pollutants from being washed by stormwater runoff into the storm sewer system (or from being dumped directly into the storm sewer system) and discharged into local waterbodies. The District expects that additional stormwater control will be necessary as EPA develops TMDL requirements to address water quality impairment. The District government is seeking to avoid a similar, if not greater, investment in underground storage tunnels.

In both the CSS and MS4 areas, costs are high for pipes and tunnels and space is limited for traditional stormwater controls such as detention and retention ponds, infiltration controls, grassed swales, and rain gardens. Both green roofs and trees decrease the volume of runoff, reduce peak rates of runoff, and improve water quality. To date, these benefits have not been evaluated nor sufficiently quantified on a cumulative, sewershed and city-wide basis to integrate trees and green roofs into the District's permitting requirements for EPA.

As part of the master planning process, jurisdictions often create a build-out scenario to determine how future development will look if current plans and policies are carried out to the maximum extent. The process is helpful for evaluating various policies and growth scenarios. In a similar manner, the Green Build-out Model for the District quantifies the cumulative contribution that trees and green roofs could potentially make toward reducing stormwater runoff and CSOs under different coverage scenarios. It is a tool to balance gray and green infrastructure, to minimize capital investment and maximize environmental benefits.

Although the Green Build-out Model is customized for the District's existing infrastructure, the assumptions and methods can be applied to model infrastructure in other cities.

2.RELATIONSHIPS INVESTIGATED

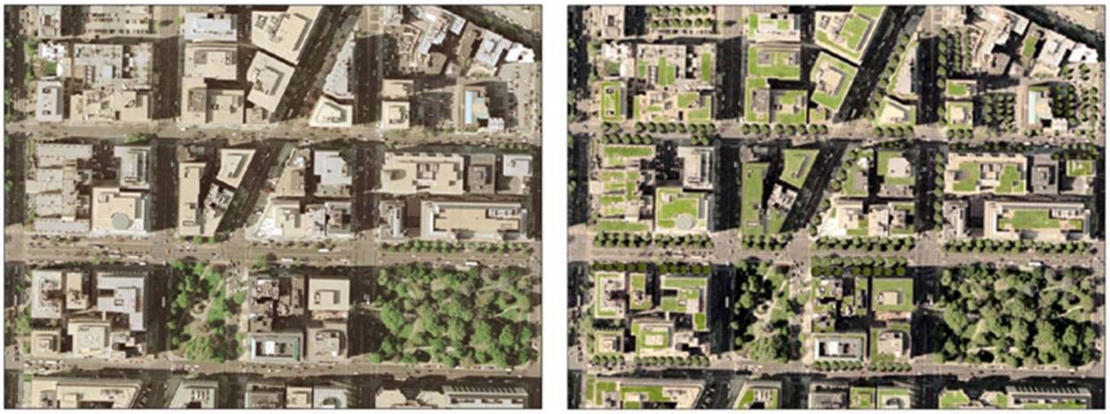

Figure 2: Illustration of a 20 year vision for the District of Columbia if shade trees lined every street and covered all parking lots, and every time a roof needed to be replaced, it would be replaced with a green roof

Stormwater and CSO discharges are frequent in the District of Columbia. Eighty-five percent of all rain events are less than one inch (Figure 3) and it only takes on average on-half inch and often as little as a tenth of an inch of rainfall or less to trigger a discharge in some sewersheds. Research shows that the leaves of trees are like cups and can hold up to one-tenth of an inch of rainwater (see canopy storage in Table 1), and that an extensive green roof with three to four inches of soil media will store one inch of rain on average (Figure 4, Table 2). The research therefore asked the question, "How many green roofs and trees are needed to make a difference to stormwater management in the District?" It investigated the relationships between tree cover, green roof cover, larger tree boxes, and key hydrologic and hydraulic variables including stormwater and CSO volume, flow rate, and frequency. In addition, reductions in pollutant loads as a result of reduced stormwater volumes were estimated, and operational savings from reduced pumping and treatment of stormwater volumes within the CSS were estimated.

It was expected that trees and green roofs on their own would not solve all of the stormwater problems that the District or other municipalities face or replace the need for storage tunnels. However, it was expected that they could make a significant environmental and economic contribution that is not being recognized and therefore not consistently implemented in policy, planning, permitting, and development.

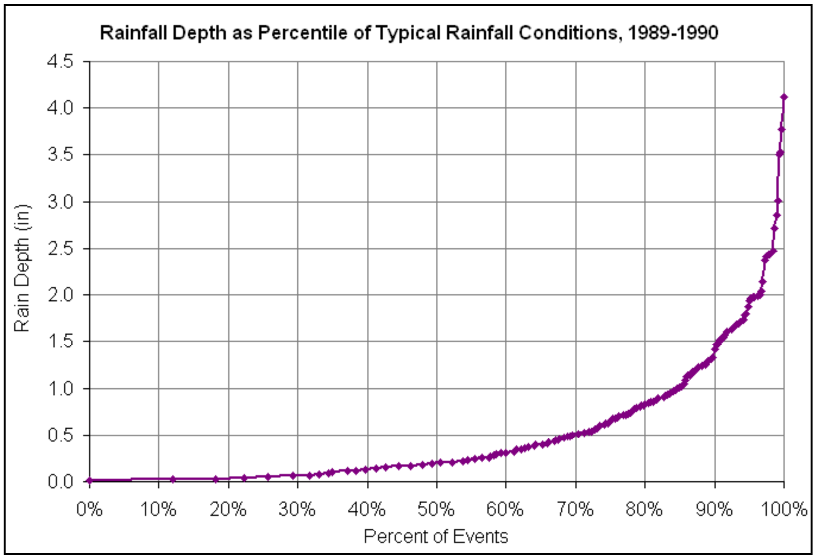

Figure 3: Rainfall depth in Washington, DC for an average year (Data Source: Washington National Airport)

Table 1: Tree Canopy Stormwater Storage

Source	Leaf Storage	Canopy Storage (inches)	Notes
Agricultural Runoff Manual, 1978	Forest cover (light) = 3.5 mm	0.138	Applies factor for seasonality
	Forest cover (heavy) = 5.0 mm	0.197	
Aston, 1979	0.2mm	0.008	E. viminalis
	0.5mm	0.020	E. maculata
	0.3mm	0.012	E. dives
	0.6mm	0.024	Acacia Longifolia
	0.3mm	0.012	E. mannifera subsp. Maculosa
	1.0mm	0.039	Pinus radiata
	0.4mm	0.016	E. cinerea
	0.8mm	0.031	E. pauciflora
Blyth, 2002	0.2mm*LAI	0.027	Assume LAI = 3.49
Crockford and Richardson, 1990	1.7mm (eucalyptus)	0.067	References found in Ramirez, 2000
	2mm (pine)	0.079	
Keim, 2006	(0.10-0.46)*LAI	0.038	Assume LAI = 3.49, mean interception =0.28
Link et al, 2004	3.0-4.1mm	0.140	References found in Keim, 2006
Liu, 1998	0.94mm	0.037	Cypress wetlands
	0.43mm	0.017	Slash pine uplands

Source	Leaf Storage	Canopy Storage (inches)	Notes
Pypker, 2005	1.4mm	0.055	Young Douglas-fir forest
	3.32mm	0.131	Old-growth Douglas-fir forest
Schellekens, 1999	1.15mm	0.045	Used in his model
Wang, 2006	0.2mm*LAI	0.027	Used in UFORE model
Xiao, 2002	9.79mm	0.385	"Public tree" interception, one event
	14.3mm	0.563	Summer interception for one event
	1.19mm	0.047	Winter interception for one event, deciduous sweetgum
Xiao, 2000	2.5-2.9mm	0.106	
Zinke, 1967	0.25-9.14mm (mean = 1.3)	0.051	References found in Ramirez, 2000

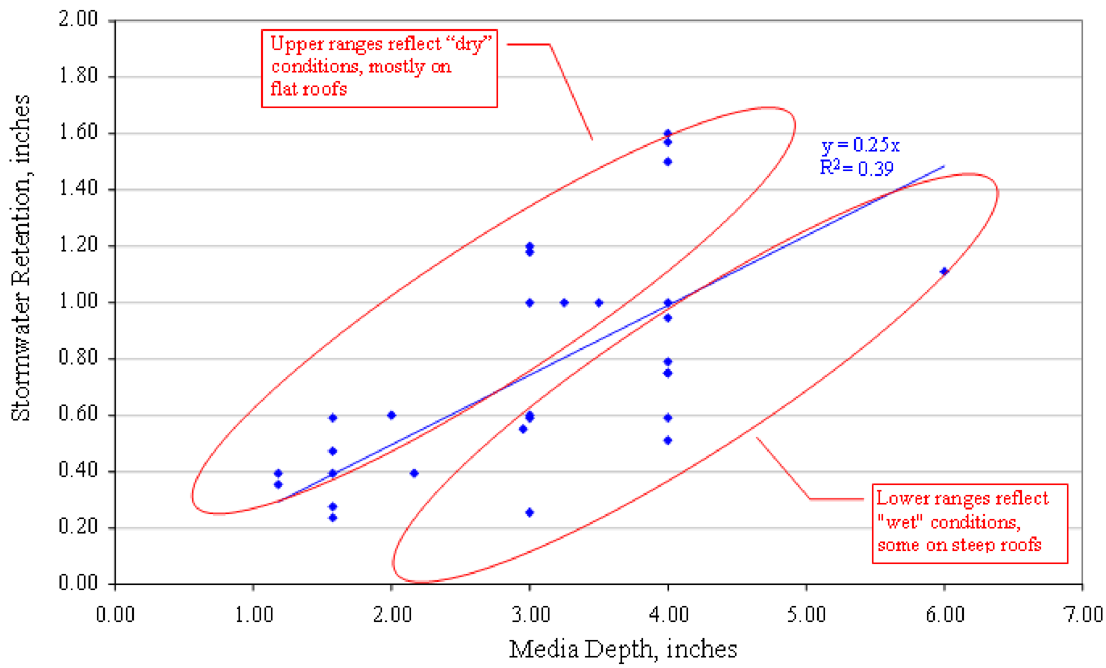

Figure 4: Green Roof Media Depth vs. Storage Amount

Table 2: Green Roof Stormwater Storage

Source	Title	Media Depth (Inches)	Stormwater Storage (Inches)	Notes
Berndtsson 2006	*The Influence of Extensive Vegetated Roofs on Runoff Water Quality*	1.18	0.39	Max capacity
Bengtsson 2005	"Peak Flows from the Sedum-moss Roof" OR "Hydrological Function of a Thin Extensive Green Roof in Southern Sweden"	1.18	0.35	Dry conditions
Berghage, Beattie, et. al. 2004	*Green roof media characteristics: The basics*	3.00	1.20	From Portland green roof conference
Berghage, Beattie, et al	*Stormwater Runoff from Green Roofs*	3.50	1.00	
Biocycle February 2006		4.00	0.79	
		6.00	1.11	
DeNardo, J.C. 2005	*Stormwater Mitigation and Surface Temperature Reduction by Green Roofs*	3.00	0.26	Average wet conditions
		3.00	1.18	Dry conditions
Federal Technology Alert	*Green Roofs* DOE/EE-0298; www.eere.energy.gov/femp	3.00	1.00	
		4.00	1.00	
Green Grid Roofs	Manufacturer's data	4.00	0.95	
Green Roof Blocks	Manufacturer's data	4.00	1.60	Calculated 0.9615 inches retention, using their parameters
Jarrett, Hunt, et. al. 2006	*Annual and Individual Storm Green Roof Stormwater Response Model*	4.00	1.57	
Lipton 2004	*Ecoroofs – A More Sustainable Infrastructure*	4.00	0.75	Average conditions
Liu and Minor 2005	"Performance Evaluation of Extensive Green Roof"	3.00	0.59	Average value for green roof of 3 to 4 inches, from Washington green roof conference
Moran, Hunt, et. al. 2005	"Hydrologic and Water Quality Performance from Greenroofs in Goldsboro and Raleigh, North Carolina"	3.00	0.60	Average conditions, from Washington green roof conference
		4.00	0.75	Sloped roof (7%)
Moran, Hunt, and Jennings 2004	"A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff quality, and Plant Growth"	2.00	0.60	From Portland green roof conference

Source	**Title**	**Media Depth** (Inches)	**Stormwater Storage** (Inches)	**Notes**
Moran 2003	"A North Carolina Field Study to Evaluate Greenroof Runoff Quantity, Runoff quality, and Plant Growth"	4.00	0.51	
		4.00	0.59	
Roofscapes 2002		3.25	1.00	
Van Woert 2005	*Green Roof Stormwater Retension Effects of Roof Surface, Slope, and Media Depth*	1.57	0.28	Theoretical depths
		2.17	0.39	Theoretical depths
		2.95	0.55	Theoretical depths
Villarreal and Bengtsson 2004; Villarreal, Semadeni-Davis, et. al. 2004	"Response of a Sedum Green-roof to Individual Rain Events" and "Inner City Stormwater Control Using a Combination of Best Management Practics"	1.57	0.24	Min of range
		1.57	0.39	Average of range
		1.57	0.47	Max of range
		1.57	0.59	Max, dry conditions

3. METHODS AND ASSUMPTIONS

The methods and assumptions upon which the Green Build-out Model is based are described in this section and accompanied by figures and tables for key findings.

An Advisory Team of key stakeholders from EPA, WASA, the District of Columbia Government, NRDC, and Non-Governmental Organizations was formed to review and comment throughout the research process in a series of four half-day workshops and on-going communications.

3.1 MIKE URBAN MODEL

As background, WASA's Mike Urban hydrologic and hydraulic model served as the platform to integrate GIS information about the sewer systems and green infrastructure. The Mike Urban model has been peer reviewed and successfully applied by WASA in the development of an EPA-approved LTCP for the CSS.

The Mike Urban model builds from the basic run-off equation:

Runoff = Precipitation – potential evapotranspiration – infiltration – storage

Storage amounts for trees and green roofs were added to the model:

*Storage = Interception storage * coverage area*

Interception storage amounts were derived from literature and assumptions for the coverage areas were determined by the research team. Both of these inputs are described further in later sections of this paper.

The Mike Urban model differentiates hydrological processes between pervious and impervious land cover, which was determined using 2005 planimetric data from the District of Columbia Office of the Chief Technology Officer (OCTO)[12] (Figure 5). Coverage areas for trees and green roofs were determined by making assumptions for each land cover type using this planimetric data. Figures 6, 7, and 8 characterize typical rainfall patterns in the District.

The version of Mike Urban that is used to evaluate greening scenarios is referred to as the Green Build-out Model. It was applied for an average rainfall period using hourly precipitation recorded at Reagan National Airport for 1990. Over fifty years of rainfall data were analyzed to select 1990 as an average year. This was the same year used by WASA in development of the LTCP. Potential evapotranspiration rates applicable for the District are published by the Virginia Climatology Office (Figure 8). Infiltration rates apply to pervious areas and were based on soil types found in the District.

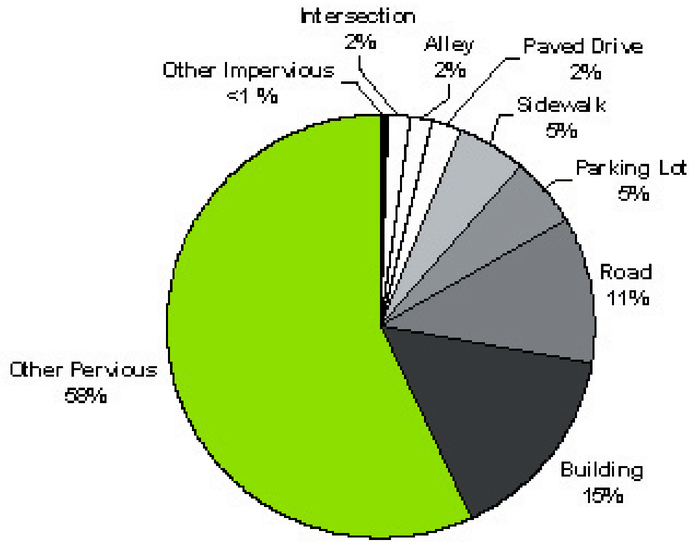

Figure 5: District of Columbia Land Cover Types (Source: 2005 DC GIS)

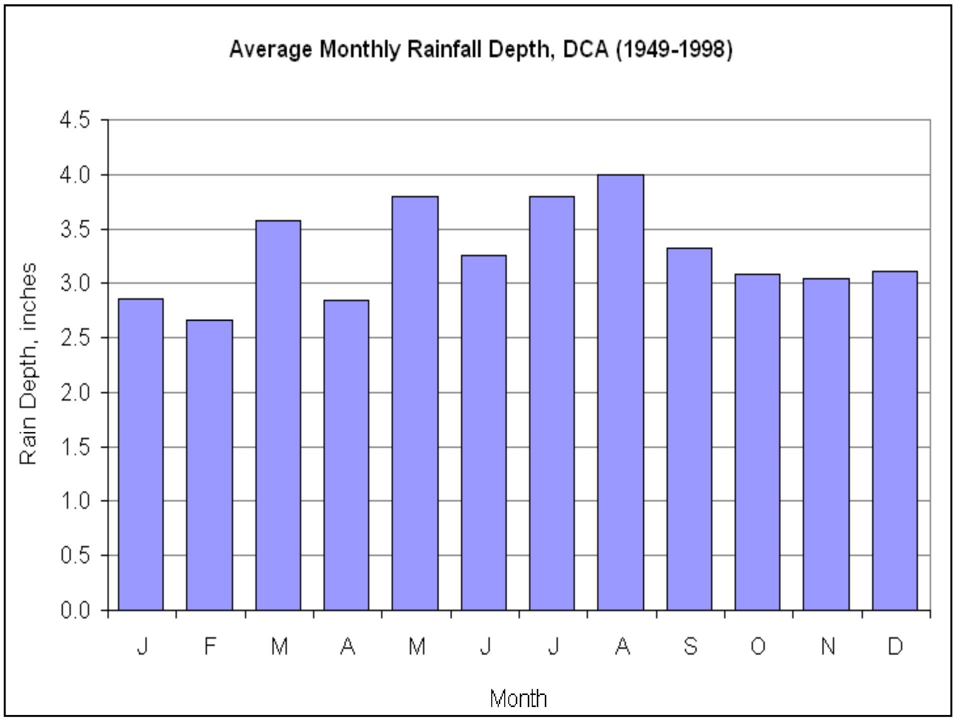

Figure 6: Average monthly rainfall depth in Washington, DC
(Data source: Washington National Airport)

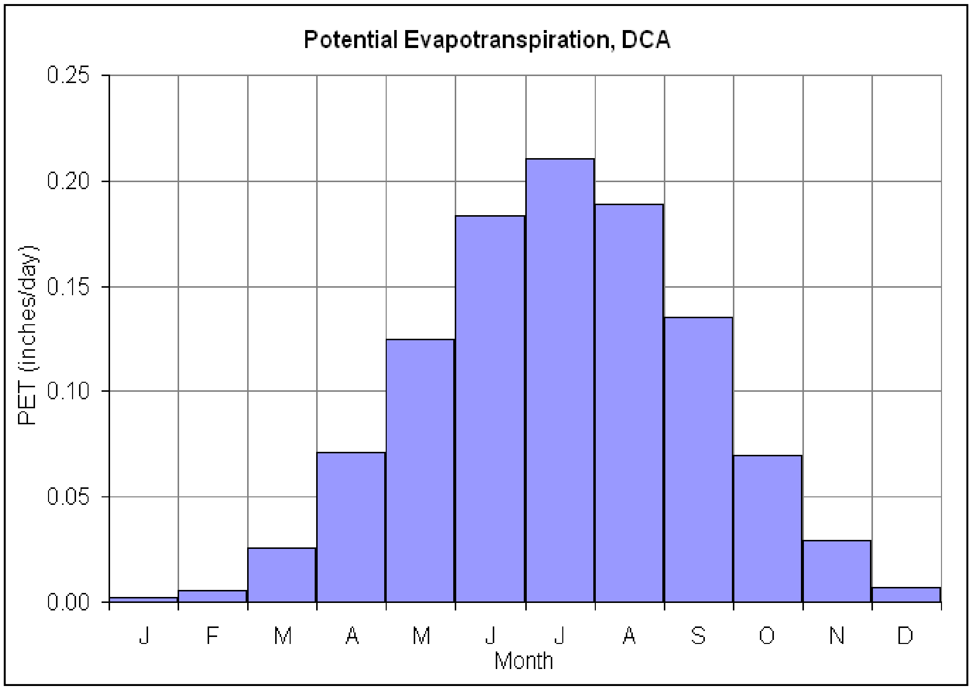

Figure 7: Annual Rainfall Depth in Washington, DC, from 1949-1998 (Data source: Washington National Airport)

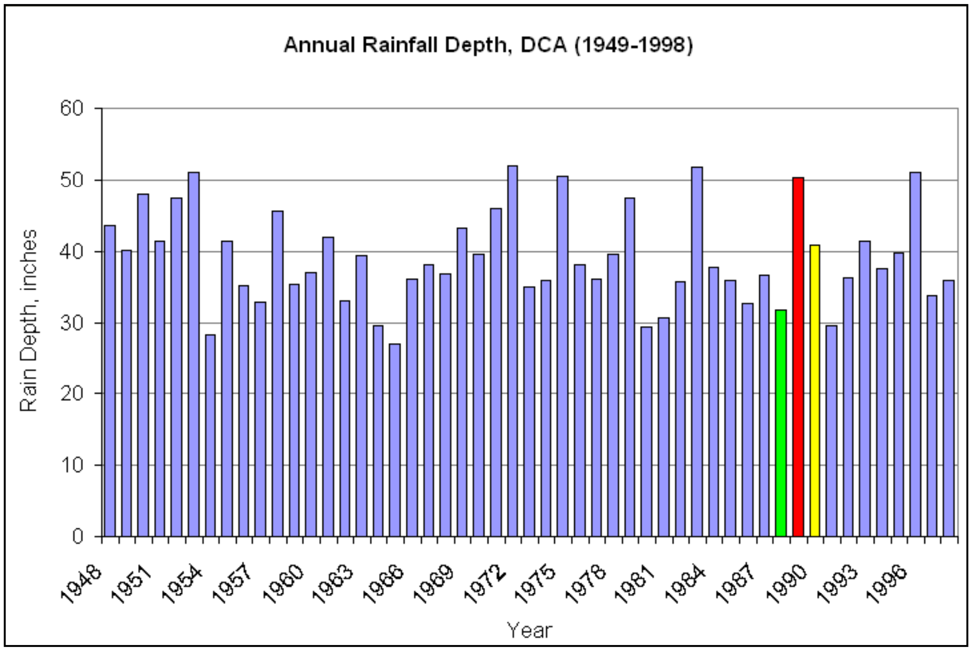

Figure 8: Potential evapotranspiration by month in Washington, DC for an average year (Data source: Virginia Climatology Office)

Additional detail on application of the Green Build-out Model is presented in the following sub-sections. Full documentation on Mike Urban and development of the Green Build-out Model is contained in Appendix B.

3.2 SCENARIO CONCEPTS

Two scenarios were used to determine tree and green roof cover. An “intensive greening scenario” or “Green Build-out scenario” considered putting trees and green roofs wherever it was physically possible. A “moderate greening scenario” looked at putting trees and green roofs where it was practical and reasonable to do so

Existing tree and green roof cover is implicitly part of the current Mike Urban model because the model has been calibrated to actual flow data. Therefore, the stormwater management benefits from trees and green roofs that were added in the Green Build-out Model represent incremental benefits resulting from the difference between the existing tree or green roof coverage and the proposed coverage scenario.

The greening scenarios were evaluated with the Green Build-out Model and compared to existing or baseline conditions. Stormwater and outfall volume/frequency analysis were performed for the CSS and MS4 areas in the Anacostia, Potomac, and Rock Creek watersheds. The results were compared to the existing condition in the District determined from earlier applications of Mike Urban in the LTCP.

3.3 TREE STORAGE

Trees slow and capture rainwater in a number of ways. For the purposes of this research, only interception storage, the amount of rainwater that trees intercept and hold in their leaves, is considered. Stem flow, or the amount of rainwater stored on branches and the trunk, is not considered thereby making the assumptions conservative.

The amount of interception storage provided by trees depends on the storage amount and coverage area. Interception storage was determined using an approach used by the USDA Forest Service in its Urban Forest Effects (UFORE) Hydro Model[41] whereby:

1. *LAI = “Leaf Area Index”, which is a measurement of the one-sided green leaf area per unit ground area in broadleaf canopies and depends on tree species, canopy size, and condition*

2. *LAI = 4.10, which was the average LAI for all live DC Street Trees from the 2002 DC Street Tree Inventory[7].*

3. *Incremental depth = 0.0078 inches, the depth applied across LAI[41]*

4. *Interception Storage = LAI * incremental depth = 0.032 inches*

The UFORE Hydro methodology was selected over other methodologies or interception storage values in the literature for three reasons:

1. Provided interception storage amounts that fit with the Mike Urban Model input units,

2. Could use field data collected in the District of Columbia so it was more accurate than interception storage amounts found in the literature from species in other climate zones with different health, conditions, and species mix, and

3. Used storage amounts that were in range of other literature values and fairly conservative (See Table 1).

In 2002, Casey Trees conducted a detailed GIS-based inventory of the District's 130,000 street trees. In 2004, Casey Trees worked with the USDA Forest Service to survey 200 sample plots to run a UFORE analysis for the District[36]. Both the DC UFORE and DC 2002 Street Tree Inventory found LAIs ranging in value from 0-15 depending on tree species, canopy size, and condition. The average LAI for all District trees found in the DC UFORE Inventory was 3.49. The average LAI for all live trees in the 2002 Street Tree Inventory was 4.10. The LAI in the Street Tree Inventory was chosen as a model input because hypothetical tree cover added for the coverage scenarios in this research would be more like street trees in form, species type, and condition than the weed or woodland trees, which were factored into the DC UFORE Inventory sampling and its LAI determination.

The 2002 Street Tree Inventory found that over 99% of street trees in the District are deciduous. The 2004 DC UFORE Inventory estimated that over 95% of trees in the District are deciduous. It was agreed to assume for the Mike Urban model that all incremental tree cover added to the tree coverage scenarios in this research would be deciduous. The Mike Urban model adjusted for seasonality by considering stormwater management benefits only during the leaf-on season. It was agreed to assume that the leaf-on period in the District was from April 1 through October 31. The model assumptions did not account for interception storage derived from a tree's branches and trunk during the leaf-on or leaf-off season and was therefore a conservative estimate of total interception storage.

3.4 TREE COVER AREA

Existing tree cover was determined by classifying July 2006 IKONOS satellite imagery classified for land cover (1m) including tree canopy[12]. The tree canopy data was overlaid with the District's planimetric data to determine existing tree cover by impervious and pervious land cover types for the Mike Urban model such that:

Tree Cover Area = Proposed Tree Cover – Existing Tree Cover

Assumptions for proposed tree cover for both the moderate greening and intensive greening scenarios were determined for each land cover type by a variety of methods.

These assumptions were agreed upon with the Advisory Group and other District agency representatives. The assumptions are summarized in Table 3.

Table 3: Percentage Tree Cover Assumptions by Land Cover Type

Land Cover Type	Existing Tree Cover	Moderate Tree Cover Scenario	Intensive Tree Cover Scenario
Impervious			
Streetscape (roads, sidewalks, intersections)	22%	25%	35%
Parking lots	7%	30%	50%
Paved drives	23%	50%	80%
Alleys	26%	35%	50%
Median islands, traffic islands, , other	23%	30%	40%
Pervious			
Includes parks, open space, recreational areas, golf courses, soccer fields, cemeteries, front and back yards, school yards, etc	53%	57%	80%
Total Tree Cover	35%	40%	57%

The methods for determining the tree cover assumptions for each land cover type were:

Impervious Land Cover Types (42% total land cover area)

Streetscape (18% land cover area)

- Planimetric data for roads, sidewalks, and intersections were combined to represent the streetscape with tree cover assumed to be provided by street trees. In the District, street trees are generally planted 40 feet apart with the design objective to grow to a 20-foot crown radius so that all canopies are touching.
- If all street tree spaces from the DC 2002 Street Tree Inventory were planted and grown out to be 20 feet in crown radius, tree cover over the streetscape would equal 35%. As the existing tree cover over the streetscape was determined to be 22%, the intensive greening scenario was then chosen to be 35%.
- For the moderate greening scenario, all street tree spaces were filled and all street trees were grown out to be 15 feet in crown radius. A 15 foot crown radius was considered to be a practical and reasonable average given the existing age distribution of the urban forest, the limited size and condition of tree boxes, the high amount of redevelopment in the District, and that one-third of the District's street trees are under wires, which has resulted in planting of smaller species to accommodate overhead utilities. If all street tree spaces were planted and the trees grown out to 15 foot radius, the resultant tree cover over the streetscape would be 25%.

Parking Lots (5% land cover area)

- Several parking lot ordinances from other jurisdictions in the United States require up to 50% tree coverage[37, 42]. These precedents were used to establish the intensive greening scenario.
- To determine the moderate greening scenario assumption, four representative parking lot types were chosen from aerial images of the District[12] and through a design session with the Office of Planning[33], it was determined that it would be reasonable and practical to achieve 40% tree coverage. To be conservative and to account for age distribution and the stressful growing conditions for trees in parking lots, a 30% coverage area was modeled for stormwater management benefits.

Paved Drives (2% land cover area)

- A sampling of aerial images[12] of paved drives from different neighborhoods throughout the District showed that many of the paved drives had approximately 80% tree cover because of their proximity to yards trees and adjacent street trees. This demonstrated the physical possibility and 80% coverage was modeled for the intensive greening scenario.
- For the moderate greening scenario, 50% coverage was chosen and considered reasonable since shade trees could be planted on many properties to overhang driveways.

Alleys (2% land cover area)

- A sampling of aerial images[12] from different neighborhoods throughout the District showed that existing tree cover over alleys resulted from trees growing in back yards and that neighborhood alleys had varying amounts of adjacent open space depending on existing structures, such as driveways or garages. Many alleys had over 50% coverage so this was considered the intensive greening scenario assumption.
- The moderate greening scenario was chosen in between the existing and intensive greening coverages and was determined to be 35%.

Median islands, traffic islands, other (<1% land cover area)

- A sampling of aerial images showed that while many of these spaces were paved and/or unsuitable for planting, many of the islands were not paved and large enough to support trees. Many of the median islands and traffic islands had approximately 40% tree cover so this was chosen for the intensive greening scenario.
- The moderate greening scenario was selected to be between the existing coverage and intensive greening scenario.

Building footprint area (15% land cover area)

- Assume no tree cover on top of buildings

Pervious Land Cover Types (58% total land cover area)

- Existing tree cover over pervious areas was 35%. As GIS data was unavailable to differentiate types of pervious land cover areas, it was assumed that the intensive greening scenario would be 80% of pervious cover rather than 100% of pervious cover to account for golf courses, playing fields, the National Mall and other existing open spaces that would lose their functionality if trees were added.
- The moderate greening scenario was determined after the other land cover assumptions were determined by solving for pervious tree cover to achieve 40%

tree cover overall for the District. This objective was considered reasonable given that American Forests recommends 40 percent tree cover in urban areas and Baltimore, MD and Leesburg, VA have set an urban tree canopy goal of 40%, and Annapolis, MD and Columbia, MD have set urban tree canopy goals of 50%[24].

These tree cover assumptions were then spatially assigned to each corresponding sewershed and land cover type in the Mike Urban model to calculate the storage amount for trees. Full documentation of tree cover data inputs and their use in this analysis is contained in Appendix C.

3.5 GREEN ROOF STORAGE

The amount of storage provided by green roofs depends on the type of green roof, coverage area, and the building size.

Type of green roof

All green roofs were modeled to be extensive green roofs with three to four inches of growth media. Extensive green roofs were assumed District-wide for several reasons:

1. **Literature review:** the most consistent storage amounts in the literature reviewed were for extensive green roofs with media depths of 3-4 inches (See Figure 3).
2. **Purpose as a Stormwater best management practice (BMP):** extensive green roofs with 3-4 inches of growth media, as differentiated from intensive type green roofs, are typically specified when the green roof is primarily used as a stormwater BMP[6, 9, 27, 34].
3. **Design Consistency:** there is less of a range of storage options for a 3-4 inch extensive green roof than an intensive green roof where storage amounts and percent coverage vary greatly depending on the design.
4. **Opportunity:** in general, the greatest opportunity for wide-scale installations of green roofs in the District is for commercial and municipal buildings which can support the weight of extensive green roofs without additional structural investments to the building. For buildings with less load bearing capacity, there is a greater opportunity for retrofitting roofs with 3-4 inch extensive green roofs than for 6 inch or more intensive type green roofs.
5. **Costs:** the greatest opportunity for wide-scale installations of green roofs is for 3-4 inch extensive green roofs because their cost per square foot and maintenance requirements are less than green roofs with greater media depths.
6. **Market trends:** 71% of all green roofs installed in North America in 2004 and 2005, were extensive green roofs[17].
7. **Conservatism:** modeling for 3-4 inch extensive green roofs provides the most conservative assumption for stormwater management benefits.

Storage amounts

Storage amounts found in peer-reviewed literature were summarized in Table 2 and plotted as shown in Figure 3. Storage amounts varied greatly depending on whether the growth media was dry or saturated and whether the roof was flat or sloped. Several studies showed storage amounts of one inch for a green roof with 3-4 inches of soil media[4, 5, 10, 20, 27, 35]. This included the research from Penn State University and Roofscapes whose field studies most approximated the climate in the District. Therefore, storage was assumed to be one inch for three to four inch extensive green roofs.

3.6 GREEN ROOF COVERAGE AREA

Building coverage

It was assumed that the rooftop area was equal to the building footprint area and that 25% of the rooftop area was needed to provide space for HVAC, access, and maintenance. A review of extensive green roof demonstration projects in the District and extensive green roof installations in other cities also showed that in general, the maximum rooftop coverage for extensive green roofs was 75% of the building footprint. Therefore, it was assumed for the Mike Urban model that 75% of the building footprint area would be available for greening. This area was considered the "green roof-ready" area (Figure 9) for model calculations.

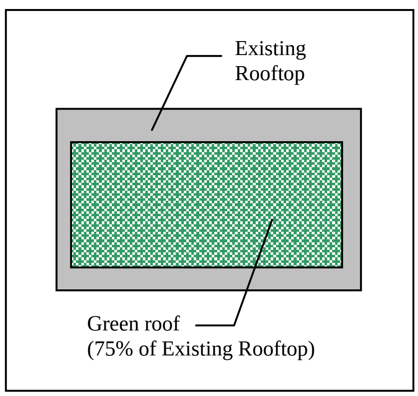

Figure 9: Green Roof-Ready Area

Building sizes

Building sizes were analyzed to assess the opportunity for green roof coverage. As shown in Figure 10, over 60% of the total number of buildings in the District have a footprint less than 1,000 square foot (sf.) and a small percentage of buildings have a footprint greater than 5,000 sf. As the District requires stormwater management controls for projects with site disturbances greater than 5,000 sf., a 5,000 sf. building footprint served as a meaningful point for analysis. Further GIS analysis of building footprint sizes showed that:

- 41% of all building footprint area in the District is greater than 5,000 sf. consisting of commercial, multi-family residential, municipal, or federal land uses

- 59% of all building footprint area in the District is less than 5,000 sf. consisting of residential and small commercial land uses
- 53% of the building footprint area in the CSS area consists of building footprint areas less than 5,000 sf.
- 64% of the building footprint area in the MS4 area consists of building footprint areas less than 5,000 sf.

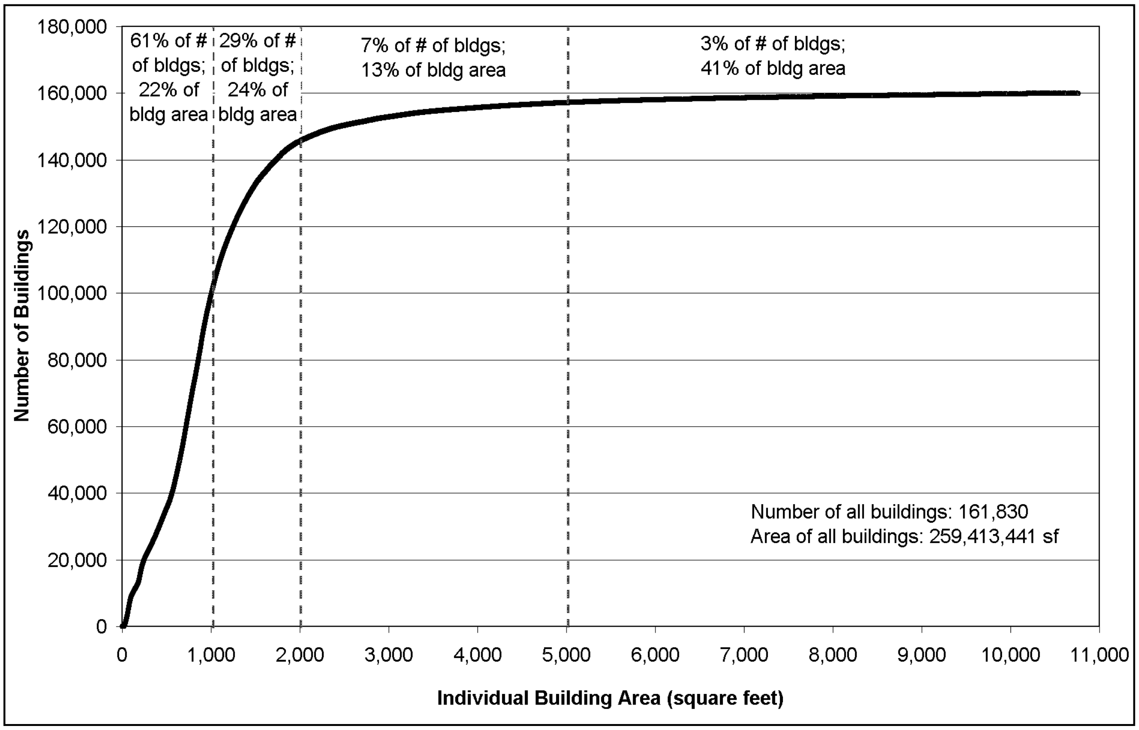

Figure 10: District of Columbia Distribution of Building Footprint Area (Source: D.C. Office of the Chief Technology Officer (OCTO), DC GIS 2005)

Green roof coverage scenarios

Assuming that only 75% of the roof could be covered with a green roof because of HVAC, maintenance, and access requirements, and that there were no structural or historic preservation issues, the most green roof coverage possible in the District would be 75% of the building footprint area or approximately 195 million sf.

Assumptions for the intensive greening and moderate greening coverage scenarios were made for each roof size or building type and attempted to consider structural, historic, or other issues that would impact the opportunity for a green roof. These coverage assumptions are summarized in Table 4.

Table 4: Green Roof Assumptions

Roof Size	Total Roof Area, square feet (sf)	Green Roof-Ready Area (= 75% of roof area)	Number of Buildings	Type of Building	Implementation Considerations	Intensive Greening %	Intensive Greening Green Roof-Ready Area, sf	Moderate Greening % (20% of Intensive Scenario)	Moderate Greening Green Roof Area, sf
<1,000 ft	57,423,950	43,067,963	98,748	Most small rowhomes, garages, sheds	These homes may choose to implement less expensive/ easier LID such as rain barrels. Homes may also be historical and/or less structurally capable of supporting a green roof. Many owners to target.	10%	4,306,796	2%	861,359
1,000ft - 2,000ft	62,224,642	46,666,982	46,126	Larger rowhomes	Generally flat roofs, but potential structural issues. Many owners to target.	30%	14,000,544	6%	2,800,109
2,000ft - 5,000ft	33,295,571	24,971,678	11,447	Single family homes, large rowhomes	Many of these buildings are single family homes, which may have sloped roofs, structural issues.	50%	12,485,839	10%	2,497,168
>5,000ft	106,469,278	79,851,959	5,509	Large commercial, institutional or government buildings	Generally no structural issues. There may be some historical issues and sloped roofs.	90%	71,866,763	18%	14,373,353
Total	**259,413,441**	**194,560,081**	**161,830**	**-**	**-**	**53% of Green roof ready area (or 40% total building area)**	**102,659,943**	**20% of Green roof ready area (or 10.5% of total building area)**	**20,531,989**

For the intensive greening scenario, it was assumed that it would be physically possible to put a 3-4 inch green roof on 90% of all buildings over 5,000 sf. In lieu of GIS data to identify the many historic or protected buildings in the District, a 10% allowance was made for such buildings where it may not be possible to install a green roof in the near future.

Buildings less than 5,000 sf were further categorized by building size. Intensive greening coverage assumptions were estimated for each building size in lieu of GIS data identifying structural capacity, roof slope, and historic preservation status.

The assumptions for the moderate greening scenario were derived by setting an overall coverage objective of 20% or 20 million sf in 20 years for the District. This objective had been determined practical and reasonable in the “Green Roof Vision for Washington, DC” presented at the 2004 Greening Rooftops for Sustainable Communities Conference, and was based on precedents set in Germany and Chicago. Several cities in Germany are estimated to have up to 27% green roof coverage. As of 2006, Chicago is estimated to have over 3 million sf of green roof[18] since its green roof demonstration project was built on City Hall in 2000. The 20% coverage objective for the District of Columbia is still considered practical and feasible today given the accelerated growth and development of the green roof market[17] and increased interest in green roofs as solutions for stormwater management.

Proposed development was not considered in the model as GIS data was not available and most development in the District is typically redevelopment of existing sites and structures.

Existing green roof coverage

The green roof area in the District is estimated to be less than 300,000 sf, based on the 2006 Green Roofs for Healthy Cities industry survey[17]. Given approximately 260 million sf of building footprint area in the District, the existing green roof coverage is less than 0.1%. Therefore, for the purposes of the Mike Urban model the existing green roof coverage was considered zero.

Other

Tree Box scenario

Average tree box size in downtown DC is 4 x 9 ft on streetscapes where sidewalks average twenty feet in width. A Tree Box scenario was evaluated to estimate the stormwater management benefits of increasing existing tree box dimensions to 6 x 20 feet in the downtown core, given District sidewalk widths in that area. Stormwater management benefits were derived from the change in land cover from impervious to pervious. The methodology did not consider the increase in stormwater benefits from improved health, condition, and size of the tree as a result of increased soil volumes.

Pollutant load reductions from stormwater flow reductions

A detailed examination of pollutant load reductions was beyond the scope of this study, but an exploratory literature review was conducted in order to associate pollutant reductions with the stormwater runoff reductions achieved through green roofs.

Studies have shown that properly designed and planted green roofs can be highly effective at filtering pollutants; achieving reductions of up to 95% for metals, 80% for nitrate, and 68% for phosphate[17, 46]. Green roofs also reduce pollutant loads by replacing conventional roofing materials, which have been shown to be substantial contributors of hydrocarbons and metals to roof runoff through leaching[14, 31, 32, 35].

For the purposes of this analysis, an estimate of pollutant load reductions achieved with green roofs was calculated by evaluating the difference in pollutant loading from a conventional roof and that of a green roof. The geometric mean of a range of published concentrations for runoff from a conventional roof was used to establish the baseline pollutant loads. Additional published values of green roof filter efficiency were also used in the analysis. Using these values and runoff volumes calculated with the Green Build-out Model, reductions in pollutant loads were determined for the water stored in the green roof media and the water filtered through it.

Given that this analysis takes into account the reductions from green roofs only, this method represents a conservative estimate of the expected pollutant load reductions from the modeled scenarios. Additional reductions would be expected from the reduced entrainment of surface pollutants and stream channel erosion due to the attenuation of runoff velocities associated with additional tree cover and increased tree box sizes.

Operational savings from stormwater flow reductions

Operational savings for WASA corresponds to reductions in stormwater volumes entering the CSS. Once the tunnels are fully operational, operational savings would be realized by the reduction in stormwater volume that would need to be intercepted by the tunnel system and pumped to Blue Plains Waste Water Treatment Plant for treatment. Utility costs for pumping (electricity) and treatment costs including costs associated with biosolids disposal, treatment chemicals, and supplies were assumed to decrease proportionally for every gallon avoided.

An exploratory evaluation of literature values was undertaken to evaluate operational costs associated with pumping and treatment of wastewater[25, 26]. The majority of costs fell between the range of $0.001 to 0.01 (one cent) per gallon of wastewater. The value of one cent per gallon was used as it appeared to be representative of current costs. Reductions in the volume of stormwater prevented from entering the CSS on an average annual basis were multiplied by this unit cost in order to estimate operational savings.

4. FINDINGS

Two scenarios were used to determine tree and green roof cover. The "intensive greening" or "Green Build-out" scenario considered putting trees and green roofs wherever it was physically possible. The "moderate greening" scenario looked at putting trees and green roofs where it was more practical and reasonable to do so.

Scenarios were evaluated with the Green Build-out Model and compared to existing or baseline conditions. Stormwater and outfall volume and CSO frequency analysis were determined for the CSS and MS4 areas in the Anacostia, Potomac, and Rock Creek watersheds.

All findings are available at www.caseytrees.org in the Build-out Model Results Display Tool. Key findings are presented below. Associated tables and figures not included in the text are located in Appendix A.

4.1 GENERAL HYDROLOGIC RELATIONSHIPS

Hydrologic relationships between tree and green roof cover and stormwater volume reductions were observed and developed as unit area reduction factors. These factors can be used for quick planning calculations for un-modeled scenarios in the Washington, DC area, or for other urban areas with approximately 40 inches of rain per year and similar climate conditions and rainfall distribution patterns. These factors are summarized in Table 5.

Table 5: Unit Area Reduction Factors for General Hydrologic Relationships Between Stormwater Volume Reductions and Tree and Green Roof Cover

Type of Greening	Stormwater runoff volume reduction over an average year MG/Acre	Acres required to achieve a one MG reduction in stormwater over an average year Acres/MG
Green roofs	0.39	2.56
Trees over impervious areas	0.11	9.0
Trees over pervious areas (NRCS Soil Type D)	0.022	45.2
Trees over pervious areas (NRCS Soil Type C)	0.0027	362
Trees over pervious areas (NRCS Soil Type A & B)	0.00008	12,500

Peak shaving is an important goal in urban stormwater management. Peak shaving refers to reducing the magnitude and velocity of peak flow rates. It is well understood that higher peak flows are more erosive and produce more stream channel erosion, and that reducing peak flow rates protects the stream channel and banks from erosion.

Eighty-five percent of all rainfall events in the District of Columbia are less than one inch (Figure 3). The ability of trees and green roofs to reduce peak flow rates associated with a design storm of one inch of rainfall over six hours was tested with the Green Build-out Model. Findings varied from sewershed to sewershed depending on the opportunities for tree planting and green roofs. The results presented in Figure 11 show the reductions in peak flow rate in an individual sewershed with high amounts of impervious surfaces and high opportunity to add trees and green roofs.

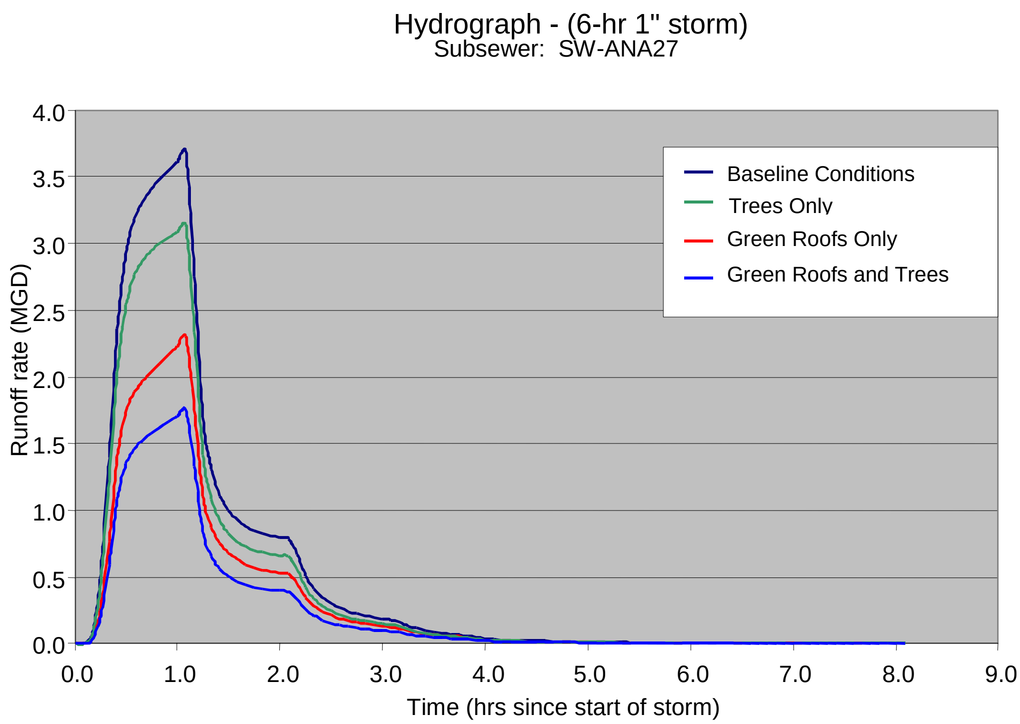

Figure 11: Sample Sewershed Hydrograph (6-hour (1 inch), design storm) (Anacostia Watershed, MS4 area)

4.2 HYDROLOGIC AND HYDRAULIC FINDINGS BY GREEN INFRASTRUCTURE TYPE

Additional relationships among the extent of tree and green roof cover, tree box sizes, and stormwater volume reductions were observed. These observations were made for the combination of all modeled green infrastructure types and for each green infrastructure type individually, District-wide, and for each sewer system. These key findings are presented below.

Trees, Green Roofs, and Tree Boxes Combined

District-wide findings

The District-wide reduction in CSO and stormwater discharges associated with each greening scenario is presented in Figure 12. Other observations are as follows:

- For an average year, the intensive greening scenario prevented over 1.2 billion gallons of stormwater from entering the sewer system resulting in a reduction of 10% or over one billion gallons in untreated discharge to the District's rivers, and a 6.7% reduction in cumulative CSO frequency (74 individual CSO discharges).
- For an average year, the moderate greening scenario prevented over 311 million gallons of stormwater from entering the sewer system resulting in a reduction of 2.6% or 282 million gallons in untreated discharges to the District's rivers, and a 1.5% reduction in cumulative CSO frequency (16 individual CSO discharges).
- For a 1 inch, 6 hour design storm, stormwater and CSO discharges were reduced by 19% District-wide and 32% in the CSS under the intensive greening scenario.
- Sewersheds in the District with the greatest opportunity to add trees and green roofs are concentrated in the downtown core, and Watts Branch and Piney Branch watersheds.

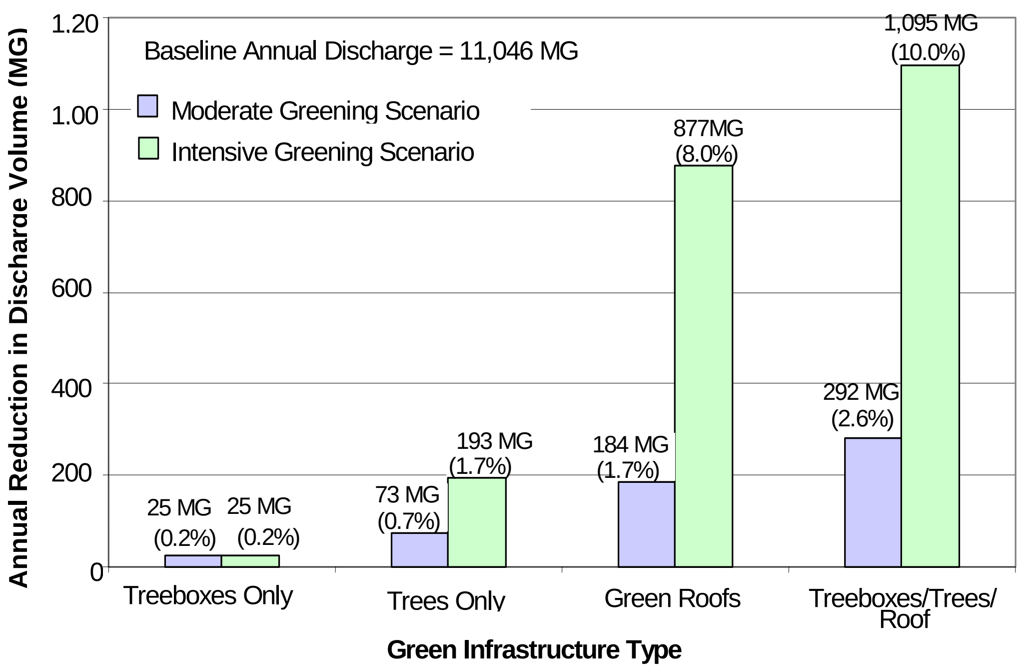

Figure 12: District-wide Reduction in CSO and Stormwater Discharge to All Waterbodies

CSS and MS4 Findings

- The reductions in stormwater discharge from the CSS and MS4 areas associated with the greening scenarios are presented in Figures 13 and 14. Other observations are as follows:
- Reductions in untreated discharges in the CSS area are 6% for the moderate greening scenario and over 22% for the intensive greening scenario.
- 94 of the 751 total (CSS and MS4) sewersheds (12.5%) experience stormwater runoff reductions greater than 10% for the intensive greening scenario, with 8 sewersheds showing reductions between 20% and 27%.
- 60 of 295 sewersheds (20%) in the CSS area experience stormwater runoff reductions greater than 10% for the intensive greening scenario.
- With the moderate greening scenario, installing 11 million square feet of green roofs in the CSS area would reduce CSO discharges by 95 million gallons or 4.2% each year.
- With the intensive greening scenario, installing 55 million square feet of green roofs in the CSS area would reduce CSO discharges by 435 million gallons or 19% each year.

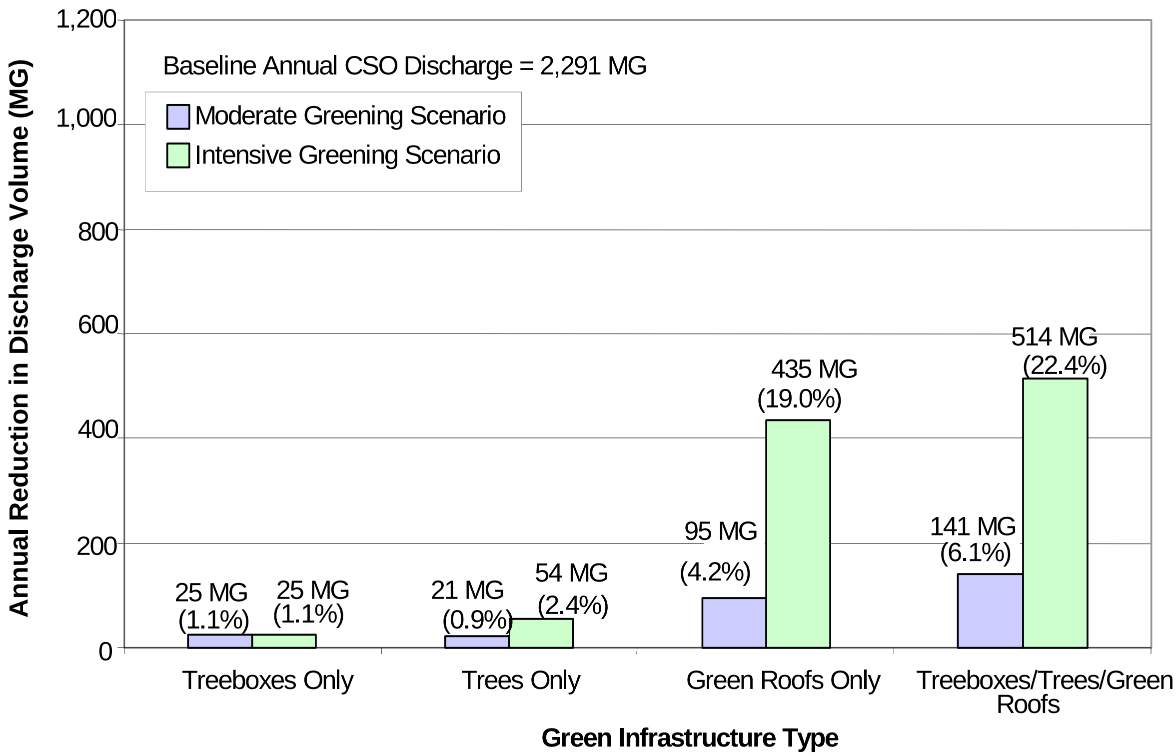

Figure 13: Reduction in CSO Discharge from the CSS

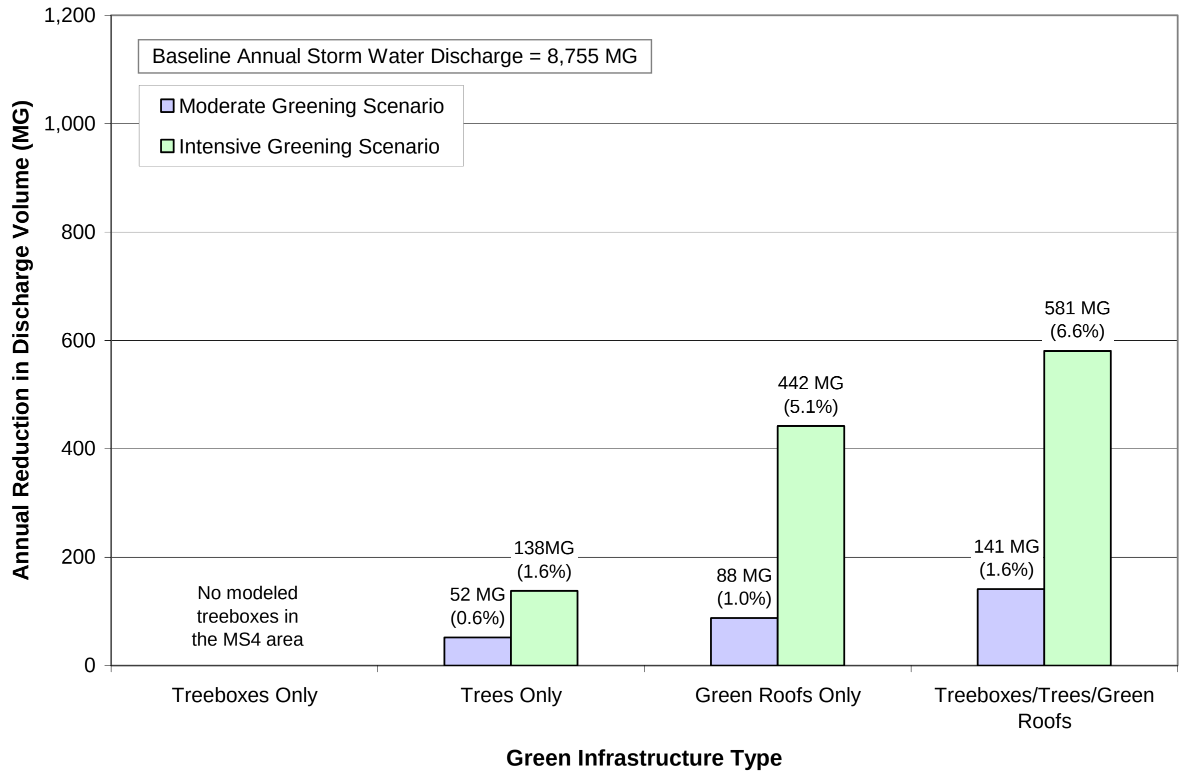

Figure 14: Reduction in Stormwater Discharge from the MS4 Area

Operational Savings from Pumping and Treatment in the CSS

- Using a unit cost of one cent per gallon, it was estimated that WASA would realize between $1.4 and $5.1 million per year in operational savings in the CSS area under the moderate greening and intensive greening scenarios, respectively.

Pollutant Load Reductions from Green Roofs

Green roofs and increased tree cover were estimated to keep thousands of pounds of nutrients, metals, and other pollutants out of area waterways for the intensive greening scenario. Estimated load reductions are summarized in Table 6.

Table 6: Estimation of Pollutant Load Reduction from Green Roofs to Area Receiving Waters

Pollutant	Intensive Greening Scenario	
	Pounds Reduced/Year	*Percent Reduction*
Total Solids	530,000	N/A
Total Suspended Solids	77,000	0.8%
Total Dissolved Solids	210,000	N/A
Biochemical oxygen demand (BOD)	34,000	1.5%
Total phosphorous	340	0.6%
Total phosphates	180	0.9%
Total Kjeldahl nitrogen (TKN)	11,000	4.6%
Ammonia	3,400	4.1%
Phenols	12,000	N/A
Copper	120	2.3%
Lead	180	1.8%
Zinc	3,100	16.1%

Trees Alone

- Stormwater management benefits from incremental tree cover come primarily from trees over impervious surfaces, in particular parking lots and streets. Benefits are fairly evenly distributed across the Anacostia, Rock Creek, and Potomac watersheds (Figure A2).
- For every incremental percentage point increase in tree cover over impervious surfaces in the District, there is a corresponding reduction in stormwater runoff District-wide in an average year of approximately 11 million gallons.
- With the moderate greening scenario, the 1000-acre increase in tree cover in the District (an increase in total canopy cover from 35 to 40%) would reduce stormwater and CSO discharges by 73 million gallons District-wide each year under average year conditions.
- With the intensive greening scenario, the 4,300 acre increase in tree cover in the District (an increase in total canopy cover from 35 to 57%) would reduce stormwater and CSO discharges by 193 million gallons District-wide each year under average year conditions.

Green Roofs Alone

- Stormwater management benefits from additional green roof cover are realized primarily in parts of the city with the greatest building sizes and densities. The highest reductions in untreated discharges are located in the CSS area with overall reductions in untreated discharges of 19%. Within the CSS, the Potomac watershed realizes the greatest reductions in untreated discharges at 24.8%, followed by the Rock Creek at 22.3%, and the Anacostia at 16.6%.

- For every incremental percentage point increase in green roof area in the District, there is a corresponding reduction in stormwater runoff District-wide in an average year of approximately 17 million gallons.
- With the moderate greening scenario, installing 20 million square feet of green roofs would reduce stormwater and CSO discharges by 184 million gallons District-wide each year under average year conditions.
- With the intensive greening scenario, installing 100 million square feet of green roofs would reduce stormwater and CSO discharges by 882 million gallons District-wide each year under average year conditions.

Tree Boxes Alone

- For an average year, increasing the existing size of the tree boxes in the downtown area to 6x20 ft could reduce 23 million gallons of stormwater runoff each year. This results from the replacement of the existing impervious area with pervious area and does not consider the added stormwater benefit that larger tree boxes enable trees to grow larger.
- For a 6 hr. (1 inch) Design Storm, increasing the existing size of the tree boxes in the downtown area to 6 x 20 ft. could reduce 5 million gallons of stormwater runoff each year.

5. CONCLUSIONS

The Green Build-out model provides an innovative and powerful planning tool for stormwater management in the District of Columbia. The research also provides general hydrological relationships and modeling methodologies that are transferable to other municipalities.

The District of Columbia Government, WASA, EPA, NRDC, and key stakeholders agree that the research findings demonstrate the efficacy of tree cover and green roofs as stormwater BMPs on a citywide and sewershed scale for the District, and that trees and green roofs should be a complementary component of any solution to the long-term management of stormwater in the District. The research findings are being used as a basis to evaluate planning, design, regulatory, and incentive policies and practices in the District.

The following conclusions can also be made from the research findings:

- ***Significant Stormwater Management Benefits Provided District-wide***

Trees, green roofs, and large tree boxes provide substantial overall reductions in stormwater runoff and untreated discharges in both sewer systems District-wide. Their cumulative storage capacity manages small rain events which account for the majority of rain events in the District.

- ***Targeted strategies by individual sewershed yield greatest results***

The greatest opportunity for significant stormwater management benefits from trees, green roofs, and large tree boxes is at the sewershed level in the CSS area where reductions for all sewersheds averaged greater than 22%. Some sewersheds have greater potential for stormwater benefits and more opportunities for implementation of green roofs, tree planting, and tree box enlargement than others based on amount of impervious land cover and building size and density. The grant findings provide information by sewershed and watershed to target investments in trees, green roofs, and larger tree boxes to yield the greatest return in stormwater benefits city-wide.

- ***Need for Combined Approaches with other LID solutions***

- In and of themselves, trees, green roofs, and larger tree boxes make significant reductions in stormwater runoff across the District by providing rainfall interception storage. Other LID solutions, such as rain gardens and vegetated swales, provide stormwater reductions with design interventions, and practices, such as street sweeping, provide water quality improvements. All green infrastructure options should be considered together when evaluating stormwater management benefits and the capacity to manage large storm events.

- ***Tunnels still needed in the CSS with only trees, green roofs, and larger tree boxes***

Trees, green roofs, and large tree boxes provide limited reduction in CSO frequencies. Their cumulative storage capacity alone will not replace the need for storage tunnels in the CSS, which are designed to manage infrequent, but large rain events to meet regulatory requirements. However, they do provide significant reductions in stormwater runoff volumes that could have implications for the detailed design of the LTCP. WASA is interested in reexamining proposed tunnel projects, particularly the Rock Creek Tunnel, during facility planning depending on the extent of these practices, their performance, and their acceptability to regulatory agencies.

- ***Extent for wide scale implementation across the District***

Trees and green roofs address different and complementary areas of the urban landscape. At this time, trees are not easily planted on top of buildings and green roofs do not cover streetscapes and parking lots. Between these two solutions, there is the potential to provide effective coverage over all impervious land cover types in the District, demonstrating the opportunity and extent to make large scale changes across the city.

- ***MS4 Opportunities with TMDLs***

Trees and green roofs provide stormwater controls in urban areas where options and space are limited. Such controls through reductions to stormwater peak flow, velocity, and stream bank erosion show particular promise in the MS4 area where subsequent reductions in pollutant loadings could provide the District an option to make progress toward meeting TMDL requirements for its impaired waters.

- ***Operational savings in CSS***

Potential reductions in stormwater runoff within the CSS could lead to substantial annual savings in operational costs associated with storing, pumping and treating combined sewage.

In addition to stormwater management benefits, for the same investment, implementation of increased tree cover, green roof coverage, and larger tree boxes would also provide improvements in air quality, public health, social capital, and economic development, and reductions in carbon, UV radiation, and the urban heat island effect.

5.1 AREAS FOR FURTHER STUDY

Combined sewer overflows and stormwater discharges are the chief sources of pollution in the Anacostia, Potomac, and Rock Creek waters in the District of Columbia. This study conservatively quantifies the potential stormwater benefits of trees, green roofs, and larger tree boxes for the District. The findings of this study are sufficient to advance watershed planning to include trees and green roofs as a significant component of stormwater management. Further areas of study to develop these planning efforts include:

- Application of the Mike Urban model for the LTCP with Green Build-out Model findings and consideration of the results in the detailed design of the tunnels
- Installation of a pilot program to demonstrate the intensive greening scenario in sensitive and targeted sewersheds in both the CSS and MS4 areas, and monitor its results
- Investigation of performance and maintenance standards for trees and green roofs to meet the modeled assumptions
- Development of a GIS database to monitor progress and track installations towards tree and green roof coverage objectives across the District
- Expansion of the Green Build-out Model to include other LID practices, including vegetated solutions and use of pervious or permeable pavement and rain gardens
- Development of implementation tools for site scale design and development review
- Development of comprehensive cost/benefit information to identify implementation options
- Development of incentives to promote trees, green roofs, and other LID practices in targeted areas
- Evaluation of other benefits of trees and green roofs, such as reduction in urban heat island effect, removal of greenhouse gases, energy savings, and air quality improvements, and evaluation of strategies to achieve multiple resource objectives and integrated resource management across municipal and regional functions

5.2 POLICY RECOMMENDATIONS

Policy recommendations resulting from this research were developed by Casey Trees, LimnoTech, and the Advisory Team to facilitate implementation of trees, green roofs, and larger tree boxes as stormwater controls. These recommendations are contained in Appendix D.

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APPENDIX A

DETAILED MODEL FINDINGS

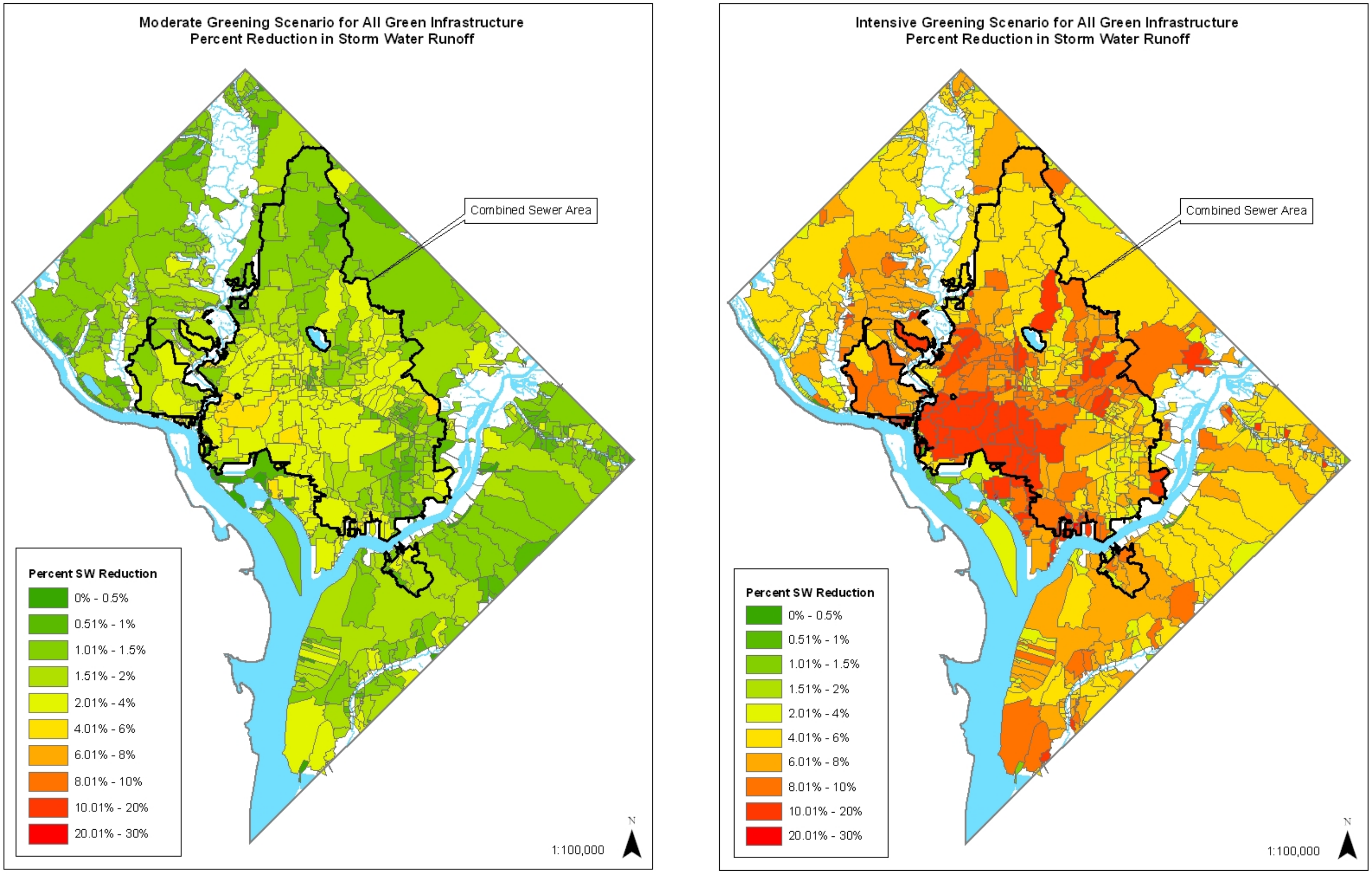


Figure A1: Sewershed comparison of Moderate Greening and Intensive Greening Scenarios for percent reductions in stormwater runoff for all green infrastructure (trees, greenroofs, and tree boxes)

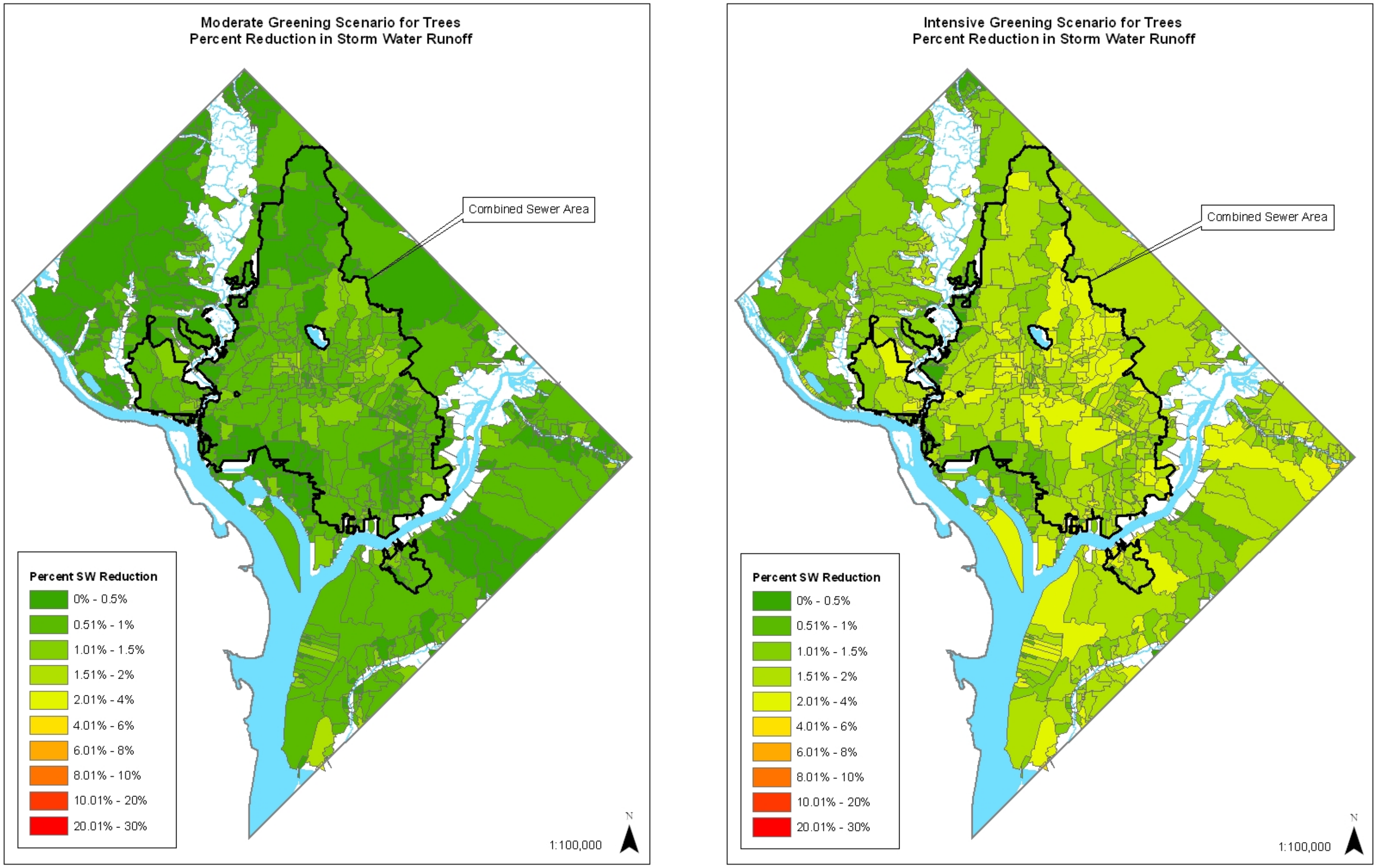
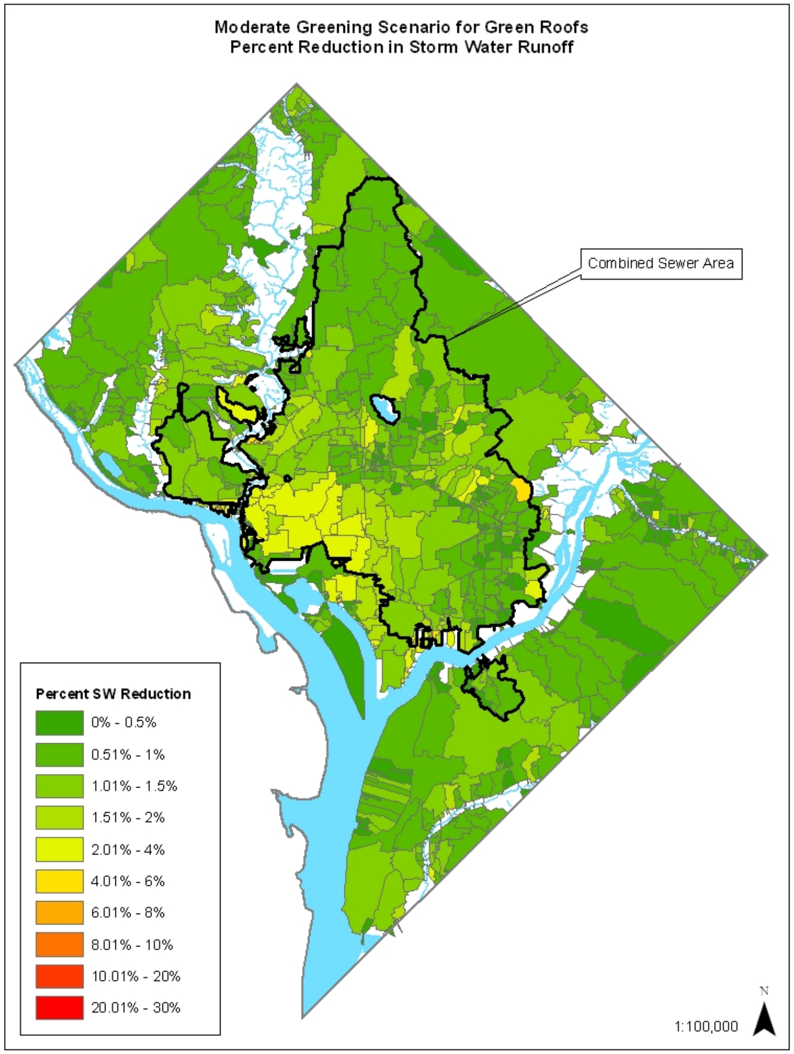


Figure A2: Sewershed comparison of Moderate Greening and Intensive Greening Scenarios for percent reductions in stormwater runoff from tree cover



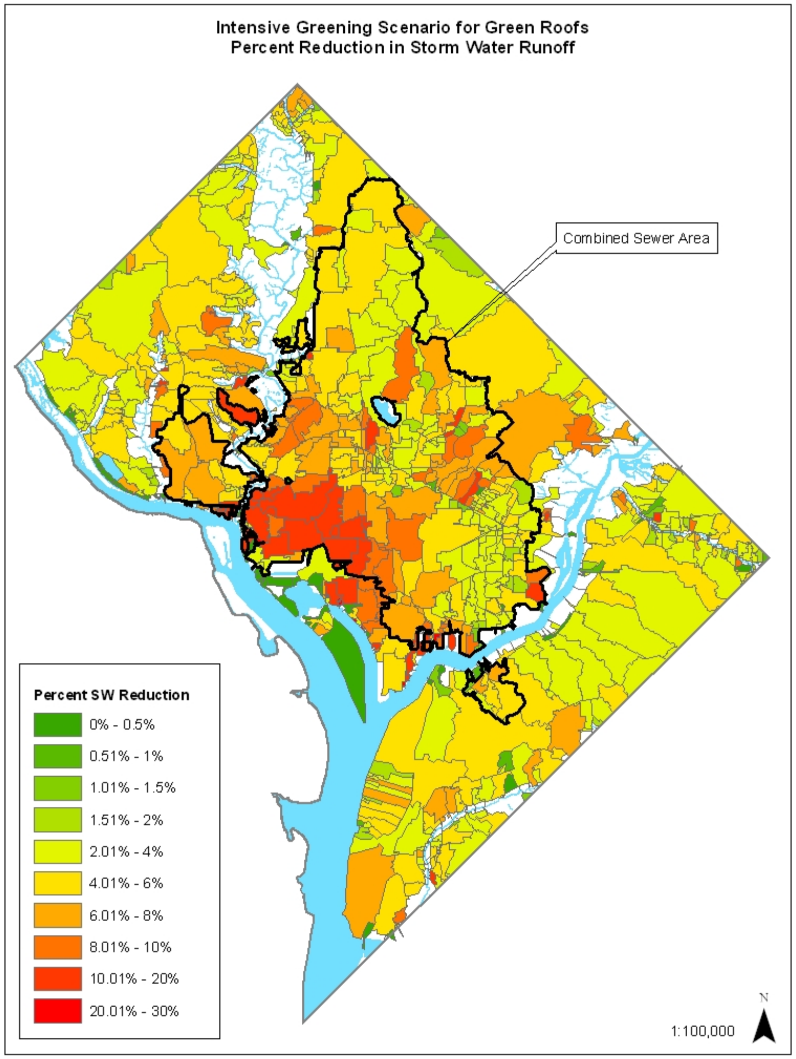


Figure A3: Sewershed comparison of Moderate Greening and Intensive Greening Scenarios for percent reductions in stormwater runoff from greenroof cover

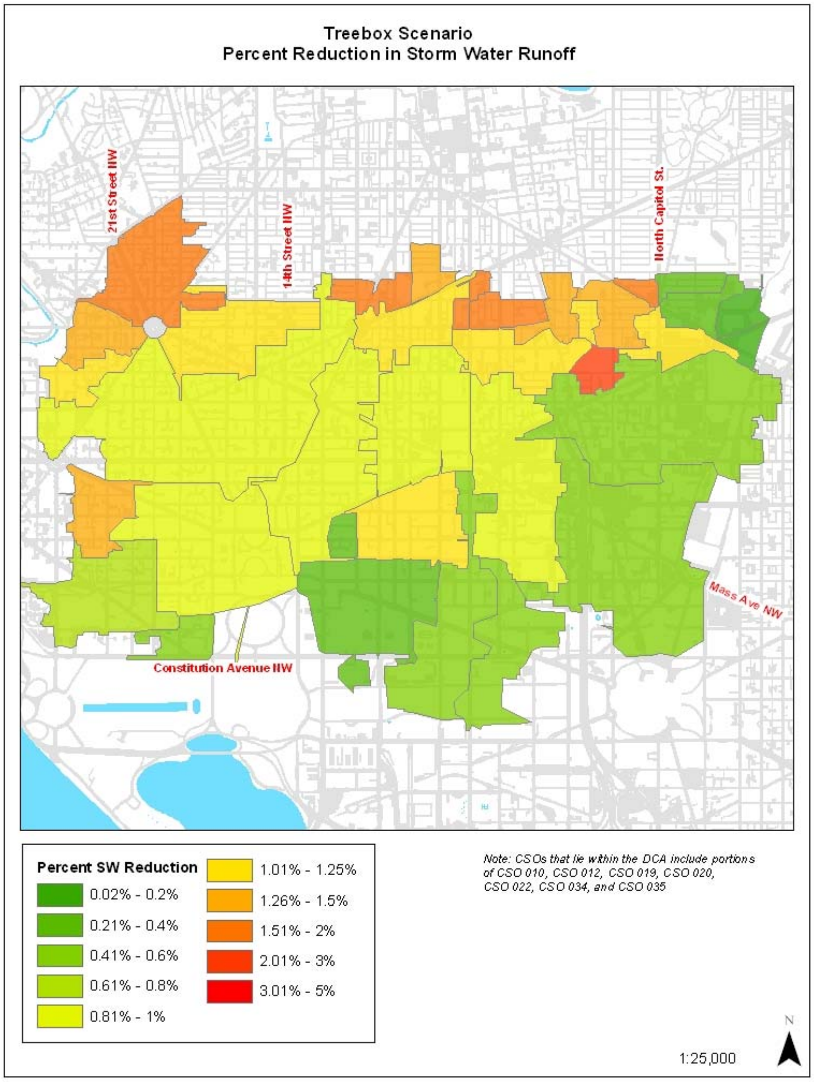


Figure A4: Percent reductions in stormwater runoff in Downtown Character Area for tree box scenario (increasing tree box size from 3 x 5ft to 6 x 20ft)

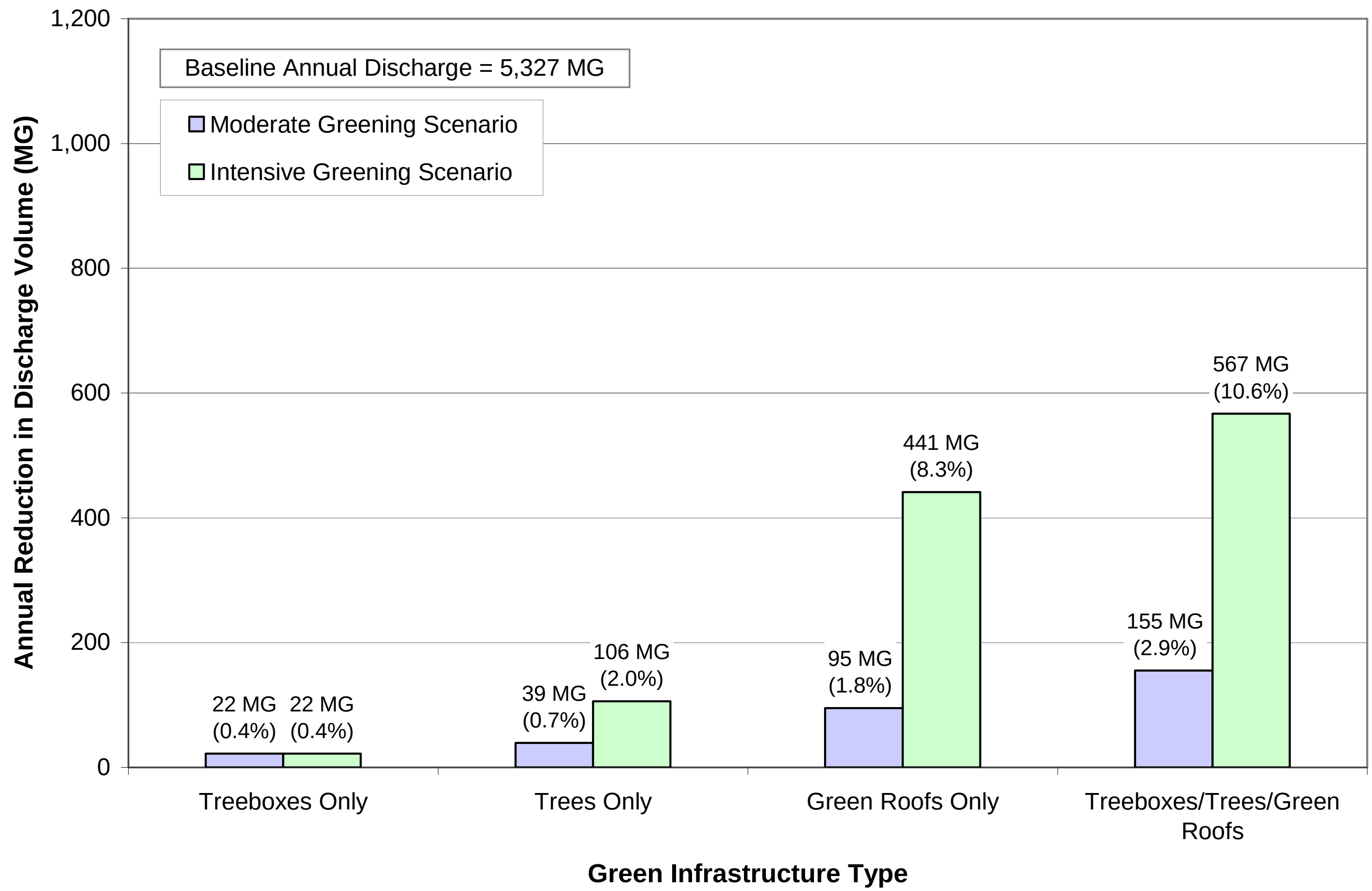


Figure A5: Reduction in CSO and Stormwater Discharge to the Anacostia River

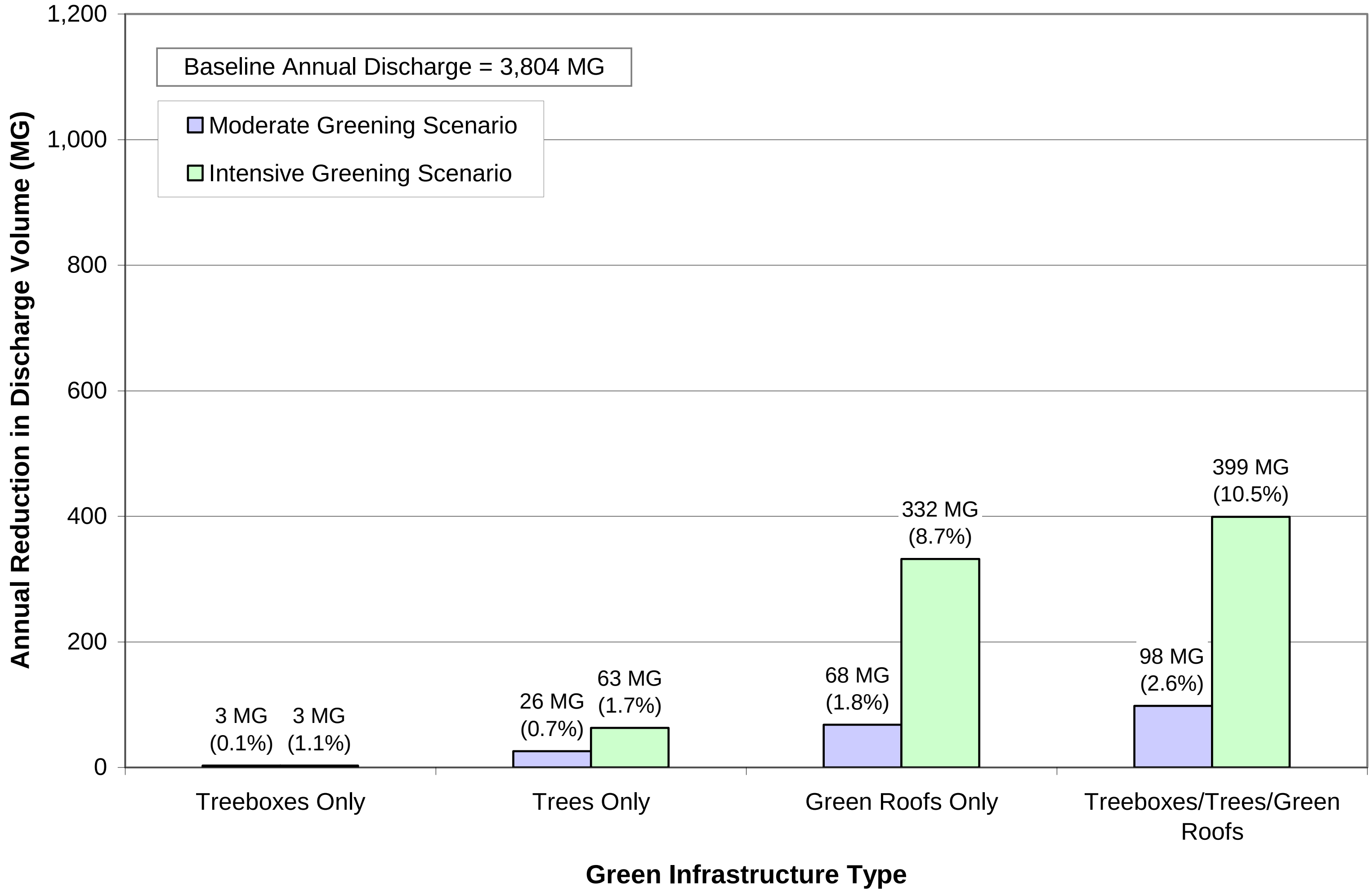


Figure A6: Reduction in CSO and Stormwater Discharge to the Potomac River

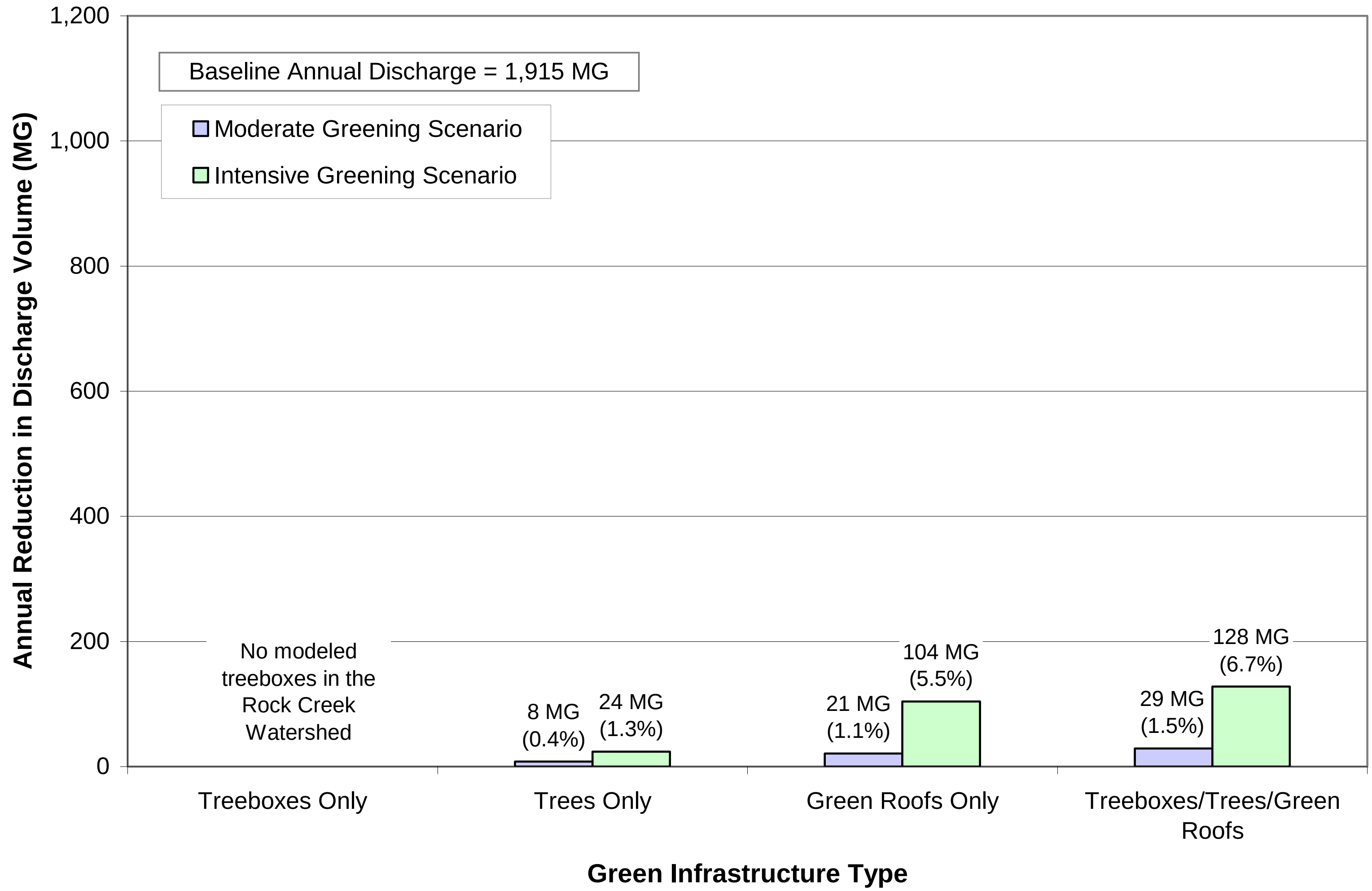


Figure A7: Reduction in CSO and Stormwater Discharge to Rock Creek

Table A1: Summary of Intensive Greening Scenario Results (Average Year)

AVERAGE YEAR WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)	MG (% reduction)	MG (% reduction)
Combined Sewer System					
Anacostia CSOs	1,608	1,586 (1.3% reduction)	1,570 (2.4% reduction)	1,341 (16.6% reduction)	1,282 (20.3% reduction)
Potomac CSOs	628	624 (0.5% reduction)	613 (2.4% reduction)	472 (24.8% reduction)	453 (27.7% reduction)
Rock Creek CSOs	56	56 (0.0% reduction)	55 (1.9% reduction)	43 (22.3% reduction)	42 (24.2% reduction)
Total	2,291	2,266 (1.1% reduction)	2,237 (2.4% reduction)	1,856 (19.0% reduction)	1,777 (22.4% reduction)
Storm Sewer System					
Anacostia Storm	3,719	3,719 (0.0% reduction)	3,652 (1.8% reduction)	3,545 (4.7% reduction)	3,478 (6.5% reduction)
Potomac Storm	3,177	3,177 (0.0% reduction)	3,128 (1.5% reduction)	3,000 (5.6% reduction)	2,952 (7.1% reduction)
Rock Creek Storm	1,860	1,860 (0.0% reduction)	1,836 (1.3% reduction)	1,768 (5.0% reduction)	1,744 (6.2% reduction)
Total	8,755	8,755 (0.0% reduction)	8,617 (1.6% reduction)	8,313 (5.1% reduction)	8,174 (6.6% reduction)
Entire System					
Anacostia	5,327	5,305 (0.4% reduction)	5,221 (2.0% reduction)	4,886 (8.3% reduction)	4,760 (10.6% reduction)
Potomac	3,804	3,801 (0.1% reduction)	3,741 (1.7% reduction)	3,472 (8.7% reduction)	3,405 (10.5% reduction)
Rock Creek	1,915	1,915 (0.0% reduction)	1,891 (1.3% reduction)	1,811 (5.5% reduction)	1,787 (6.7% reduction)
Total	11,046	11,022 (0.2% reduction)	10,853 (1.7% reduction)	10,169 (8.0% reduction)	9,951 (10.0% reduction)

**AVERAGE YEAR WET WEATHER
CUMULATIVE POINT DISCHARGE FREQUENCIES**

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)	No. (% reduction)	No. (% reduction)
Combined Sewer System					
Anacostia CSOs	592	590 (0.3% reduction)	585 (1.2% reduction)	547 (7.6% reduction)	547 (7.6% reduction)
Potomac CSOs	391	391 (0.0% reduction)	388 (0.8% reduction)	368 (5.9% reduction)	368 (5.9% reduction)
Rock Creek CSOs	119	119 (0.0% reduction)	119 (0.0% reduction)	113 (5.0% reduction)	113 (5.0% reduction)
Total	1,102	1,100 (0.2% reduction)	1,092 (0.9% reduction)	1,028 (6.7% reduction)	1,028 (6.7% reduction)

Table A2: Summary of Intensive Greening Scenario Results (Design Storm)

6HR (1") DESIGN STORM WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	6HR (1")	6HR (1")	6HR (1")	6HR (1")	6HR (1")
Model:	C3	C3	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)	MG (% reduction)	MG (% reduction)
Combined Sewer System					
Anacostia CSOs	68	63 (7.5% reduction)	58 (14.5% reduction)	58 (14.2% reduction)	43 (36.3% reduction)
Potomac CSOs	35	35 (0.4% reduction)	34 (0.7% reduction)	26 (24.1% reduction)	26 (25.2% reduction)
Rock Creek CSOs	4	4 (0.0% reduction)	4 (1.8% reduction)	3 (24.9% reduction)	3 (26.7% reduction)
Total	106	101 (4.9% reduction)	96 (9.5% reduction)	87 (17.8% reduction)	72 (32.3% reduction)
Storm Sewer System					
Anacostia Storm	96	96 (0.0% reduction)	96 (0.8% reduction)	86 (11.3% reduction)	85 (12.1% reduction)
Potomac Storm	85	85 (0.0% reduction)	84 (0.8% reduction)	74 (13.1% reduction)	73 (13.9% reduction)
Rock Creek Storm	43	43 (0.0% reduction)	43 (0.6% reduction)	37 (13.6% reduction)	37 (14.3% reduction)
Total	224	224 (0.0% reduction)	222 (0.8% reduction)	196 (12.4% reduction)	194 (13.2% reduction)
Entire System					
Anacostia	164	159 (3.1% reduction)	153 (6.5% reduction)	144 (12.5% reduction)	128 (22.0% reduction)
Potomac	119	119 (0.1% reduction)	118 (0.8% reduction)	100 (16.3% reduction)	99 (17.1% reduction)
Rock Creek	47	47 (0.0% reduction)	46 (0.7% reduction)	40 (14.6% reduction)	40 (15.3% reduction)
Total	330	325 (1.6% reduction)	318 (3.6% reduction)	284 (14.1% reduction)	266 (19.3% reduction)

6HR (1") DESIGN STORM WET WEATHER POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	6HR (1")	6HR (1")	6HR (1")	6HR (1")	6HR (1")
Model:	C3	C3	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)	No. (% reduction)	No. (% reduction)
Combined Sewer System					
Anacostia CSOs	14	14 (0.0% reduction)	14 (0.0% reduction)	14 (0.0% reduction)	14 (0.0% reduction)
Potomac CSOs	8	8 (0.0% reduction)	8 (0.0% reduction)	8 (0.0% reduction)	8 (0.0% reduction)
Rock Creek CSOs	6	6 (0.0% reduction)	6 (0.0% reduction)	4 (33.3% reduction)	4 (33.3% reduction)
Total	28	28 (0.0% reduction)	28 (0.0% reduction)	26 (7.1% reduction)	26 (7.1% reduction)

Table A3: Summary of Moderate Greening Scenario Results (Average Year)

AVERAGE YEAR WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)	MG (% reduction)	MG (% reduction)
Combined Sewer System					
Anacostia CSOs	1,608	1,586 (1.3% reduction)	1,594 (0.8% reduction)	1,548 (3.7% reduction)	1,513 (5.9% reduction)
Potomac CSOs	628	624 (0.5% reduction)	621 (1.1% reduction)	595 (5.2% reduction)	585 (6.8% reduction)
Rock Creek CSOs	56	56 (0.0% reduction)	55 (0.6% reduction)	53 (4.6% reduction)	53 (5.3% reduction)
Total	2,291	2,266 (1.1% reduction)	2,270 (0.9% reduction)	2,196 (4.2% reduction)	2,150 (6.1% reduction)
Storm Sewer System					
Anacostia Storm	3,719	3,719 (0.0% reduction)	3,694 (0.7% reduction)	3,684 (0.9% reduction)	3,659 (1.6% reduction)
Potomac Storm	3,177	3,177 (0.0% reduction)	3,158 (0.6% reduction)	3,141 (1.1% reduction)	3,122 (1.7% reduction)
Rock Creek Storm	1,860	1,860 (0.0% reduction)	1,852 (0.4% reduction)	1,841 (1.0% reduction)	1,833 (1.4% reduction)
Total	8,755	8,755 (0.0% reduction)	8,703 (0.6% reduction)	8,667 (1.0% reduction)	8,614 (1.6% reduction)
Entire System					
Anacostia	5,327	5,305 (0.4% reduction)	5,288 (0.7% reduction)	5,232 (1.8% reduction)	5,172 (2.9% reduction)
Potomac	3,804	3,801 (0.1% reduction)	3,778 (0.7% reduction)	3,736 (1.8% reduction)	3,706 (2.6% reduction)
Rock Creek	1,915	1,915 (0.0% reduction)	1,907 (0.4% reduction)	1,894 (1.1% reduction)	1,886 (1.5% reduction)
Total	11,046	11,022 (0.2% reduction)	10,973 (0.7% reduction)	10,862 (1.7% reduction)	10,764 (2.6% reduction)

AVERAGE YEAR WET WEATHER
CUMULATIVE POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)	No. (% reduction)	No. (% reduction)
Combined Sewer System					
Anacostia CSOs	592	590 (0.3% reduction)	592 (0.0% reduction)	583 (1.5% reduction)	583 (1.5% reduction)
Potomac CSOs	391	391 (0.0% reduction)	389 (0.5% reduction)	385 (1.5% reduction)	385 (1.5% reduction)
Rock Creek CSOs	119	119 (0.0% reduction)	119 (0.0% reduction)	118 (0.8% reduction)	118 (0.8% reduction)
Total	1,102	1,100 (0.2% reduction)	1,100 (0.2% reduction)	1,086 (1.5% reduction)	1,086 (1.5% reduction)

Table A4: Summary of Moderate Greening Scenario Results (Design Storm)

1YR, 6HR (1") DESIGN STORM WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	TREES	GREEN ROOFS	ALL GREEN INFRASTRUCTURE
Year:	6HR (1")	6HR (1")	6HR (1")	6HR (1")	6HR (1")
Model:	C3	C3	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)	MG (% reduction)	MG (% reduction)
Combined Sewer System					
Anacostia CSOs	68	63 (7.5% reduction)	67 (0.4% reduction)	60 (10.6% reduction)	55 (18.5% reduction)
Potomac CSOs	35	35 (0.4% reduction)	35 (0.2% reduction)	33 (5.2% reduction)	33 (5.8% reduction)
Rock Creek CSOs	4	4 (0.0% reduction)	4 (0.5% reduction)	4 (5.1% reduction)	4 (5.6% reduction)
Total	106	101 (4.9% reduction)	106 (0.3% reduction)	97 (8.6% reduction)	92 (13.9% reduction)
Storm Sewer System					
Anacostia Storm	96	96 (0.0% reduction)	96 (0.2% reduction)	94 (2.3% reduction)	94 (2.5% reduction)
Potomac Storm	85	85 (0.0% reduction)	84 (0.2% reduction)	82 (2.6% reduction)	82 (2.9% reduction)
Rock Creek Storm	43	43 (0.0% reduction)	43 (0.2% reduction)	42 (2.7% reduction)	42 (2.9% reduction)
Total	224	224 (0.0% reduction)	223 (0.2% reduction)	218 (2.5% reduction)	218 (2.7% reduction)
Entire System					
Anacostia	164	159 (3.1% reduction)	164 (0.3% reduction)	155 (5.7% reduction)	14 (9.1% reduction)
Potomac	119	119 (0.1% reduction)	119 (0.2% reduction)	115 (3.4% reduction)	115 (3.7% reduction)
Rock Creek	47	47 (0.0% reduction)	47 (0.2% reduction)	45 (2.9% reduction)	45 (3.1% reduction)
Total	330	325 (1.6% reduction)	329 (0.3% reduction)	316 (4.5% reduction)	309 (6.3% reduction)

6HR (1") DESIGN STORM WET WEATHER POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	TREEBOX	TREES	GREENROOFS	ALL GREEN INFRASTRUCTURE
Year:	6HR (1")	6HR (1")	6HR (1")	6HR (1")	6HR (1")
Model:	C3	C3	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)	No. (% reduction)	No. (% reduction)
Combined Sewer System					
Anacostia CSOs	14	14 (0.0% reduction)	14 (0.0% reduction)	14 (0.0% reduction)	14 (0.0% reduction)
Potomac CSOs	8	8 (0.0% reduction)	8 (0.0% reduction)	8 (0.0% reduction)	8 (0.0% reduction)
Rock Creek CSOs	6	6 (0.0% reduction)	6 (0.0% reduction)	5 (16.7% reduction)	5 (16.7% reduction)
Total	28	28 (0.0% reduction)	28 (0.0% reduction)	27 (3.6% reduction)	27 (3.6% reduction)

Table A5: Summary of Moderate and Intensive Greening Scenario Results for Trees (Average Year)

AVERAGE YEAR WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	MODERATE GREENING SCENARIO	INTENSIVE GREENING SCENARIO
Year:	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)
Combined Sewer System			
Anacostia CSOs	1,608	1,594 (0.8% reduction)	1,570 (2.4% reduction)
Potomac CSOs	628	621 (1.1% reduction)	613 (2.4% reduction)
Rock Creek CSOs	56	55 (0.6% reduction)	55 (1.9% reduction)
Total	2,291	2,270 (0.9% reduction)	2,237 (2.4% reduction)
Storm Sewer System			
Anacostia Storm	3,719	3,694 (0.7% reduction)	3,652 (1.8% reduction)
Potomac Storm	3,177	3,158 (0.6% reduction)	3,128 (1.5% reduction)
Rock Creek Storm	1,860	1,852 (0.4% reduction)	1,836 (1.3% reduction)
Total	8,755	8,703 (0.6% reduction)	8,617 (1.6% reduction)
Entire System			
Anacostia	5,327	5,288 (0.7% reduction)	5,221 (2.0% reduction)
Potomac	3,804	3,778 (0.7% reduction)	3,741 (1.7% reduction)
Rock Creek	1,915	1,907 (0.4% reduction)	1,891 (1.3% reduction)
Total	11,046	10,973 (0.7% reduction)	10,853 (1.7% reduction)

AVERAGE YEAR WET WEATHER CUMULATIVE POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	MODERATE GREENING SCENARIO	INTENSIVE GREENING SCENARIO
Year:	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)
Combined Sewer System			
Anacostia CSOs	592	592 (0.0% reduction)	585 (1.2% reduction)
Potomac CSOs	391	389 (0.5% reduction)	388 (0.8% reduction)
Rock Creek CSOs	119	119 (0.0% reduction)	119 (0.0% reduction)
Total	1,102	1,100 (0.2% reduction)	1,092 (0.9% reduction)

Table A6: Summary of Moderate and Intensive Greening Scenario Results for Green Roofs (Average Year)

AVERAGE YEAR WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	MODERATE GREENING SCENARIO	INTENSIVE GREENING SCENARIO
Year:	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3
Units:	MG	MG (% reduction)	MG (% reduction)
Combined Sewer System			
Anacostia CSOs	1,608	1,548 (3.7% reduction)	1,341 (16.6% reduction)
Potomac CSOs	628	595 (5.2% reduction)	472 (24.8% reduction)
Rock Creek CSOs	56	53 (4.6% reduction)	43 (22.3% reduction)
Total	2,291	2,196 (4.2% reduction)	1,856 (19.0% reduction)
Storm Sewer System			
Anacostia Storm	3,719	3,684 (0.9% reduction)	3,545 (4.7% reduction)
Potomac Storm	3,177	3,140 (1.1% reduction)	2,996 (5.7% reduction)
Rock Creek Storm	1,860	1,841 (1.0% reduction)	1,768 (5.0% reduction)
Total	8,755	8,666 (1.0% reduction)	8,308 (5.1% reduction)
Entire System			
Anacostia	5,327	5,232 (1.8% reduction)	4,886 (8.3% reduction)
Potomac	3,804	3,735 (1.8% reduction)	3,467 (8.9% reduction)
Rock Creek	1,915	1,894 (1.1% reduction)	1,811 (5.5% reduction)
Total	11,046	10,862 (1.7% reduction)	10,164 (8.0% reduction)

AVERAGE YEAR WET WEATHER CUMULATIVE POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	MODERATE GREENING SCENARIO	INTENSIVE GREENING SCENARIO
Year:	AVG (1990)	AVG (1990)	AVG (1990)
Model:	C3	C3	C3
Units:	No.	No. (% reduction)	No. (% reduction)
Combined Sewer System			
Anacostia CSOs	592	583 (1.5% reduction)	547 (7.6% reduction)
Potomac CSOs	391	385 (1.5% reduction)	368 (5.9% reduction)
Rock Creek CSOs	119	118 (0.8% reduction)	113 (5.0% reduction)
Total	1,102	1,086 (1.5% reduction)	1,028 (6.7% reduction)

Table A7: Summary of Treebox Scenario Results

AVERAGE YEAR WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	Percent Reduction
Year:	AVG (1990)	AVG (1990)	
Model:	C3	C3	
Units:	MG	MG	
Combined Sewer System			
Anacostia CSOs	1,608	1,586	1.32%
Potomac CSOs	628	624	0.52%
Rock Creek CSOs	56	56	0.02%
Total	2,291	2,266	1.07%
DCA[1]	1,441	1,418	1.57%

AVERAGE YEAR WET WEATHER CUMULATIVE POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	TREEBOX	Percent Reduction
Year:	AVG (1990)	AVG (1990)	
Model:	C3	C3	
Units:	No.	No.	
Combined Sewer System			
Anacostia CSOs	592	590	0.34%
Potomac CSOs	391	391	0.00%
Rock Creek CSOs	119	119	0.00%
Total	1,102	1,100	0.18%
DCA[1]	205	203	0.98%

1YR,6HR (1") DESIGN STORM WET WEATHER POINT UNTREATED DISCHARGES

Scenario:	BASELINE	TREEBOX	Percent Reduction
Year:	1YR,6HR (1")	1YR,6HR (1")	
Model:	C3	C3	
Units:	MG	MG	
Combined Sewer System			
Anacostia CSOs	68	63	7.55%
Potomac CSOs	35	35	0.36%
Rock Creek CSOs	4	4	0.00%
Total	106	101	4.92%
DCA[1]	63	58	8.27%

6HR (1") DESIGN STORM WET WEATHER CUMULATIVE POINT DISCHARGE FREQUENCIES

Scenario:	BASELINE	TREEBOX	Percent Reduction
Year:	1YR,6HR (1")	1YR,6HR (1")	
Model:	C3	C3	
Units:	MG	MG	
Combined Sewer System			
Anacostia CSOs	14	14	0.00%
Potomac CSOs	8	8	0.00%
Rock Creek CSOs	6	6	0.00%
Total	28	28	0.00%
DCA[1]	6	6	0.00%

1. the downtown character area includes CSO 10,12,19,20,22,34, and 35

Table A8: Runoff Volumes for the CSS and MS4 AREA, MG

GREENROOFS - AVERAGE YEAR

Sewershed	Baseline Runoff	Moderate Greening Scenario Runoff (MG)	Moderate Greening Scenario Runoff Volume Reduction (MG)	Moderate Greening Scenario Runoff Reduction (%)	Intensive Greening Scenario Runoff (MG)	Intensive Greening Scenario Runoff Volume Reduction (MG)	Intensive Greening Scenario Runoff Reduction (%)
Total CSS	7,668	7,569	99	1.3%	7,182	486	6.3%
Anacostia CSS	4,219	4,168	51	1.2%	3,971	248	5.9%
Potomac CSS	1,013	994	18	1.8%	922	91	9.0%
Rock Creek CSS	2,437	2,406	30	1.2%	2,289	148	6.1%
Total MS4	8,755	8,667	88	1.0%	8,313	442	5.0%
Anacostia MS4	3,719	3,684	35	0.9%	3,545	174	4.7%
Potomac MS4	3,177	3,141	36	1.1%	3,000	177	5.6%
Rock Creek MS4	1,860	1,841	19	1.0%	1,768	92	4.9%
TOTAL	16,423	16,236	187	1.1%	15,495	928	5.7%

TREES - AVERAGE YEAR

Sewershed	Baseline Runoff	Moderate Greening Scenario Runoff (MG)	Moderate Greening Scenario Runoff Volume Reduction (MG)	Moderate Greening Scenario Runoff Reduction (%)	Intensive Greening Scenario Runoff (MG)	Intensive Greening Scenario Runoff Volume Reduction (MG)	Intensive Greening Scenario Runoff Reduction (%)
Total CSS	7,668	7,613	55	0.7%	7,537	131	1.7%
Anacostia CSS	4,219	4,186	33	0.8%	4,142	76	1.8%
Potomac CSS	1,013	1,006	7	0.7%	997	15	1.5%
Rock Creek CSS	2,437	2,421	16	0.6%	2,397	40	1.6%
Total MS4	8,755	8,703	52	0.6%	8,617	138	1.6%
Anacostia MS4	3,719	3,694	25	0.7%	3,652	67	1.8%
Potomac MS4	3,177	3,158	19	0.6%	3,128	49	1.5%
Rock Creek MS4	1,860	1,852	8	0.4%	1,836	24	1.3%
TOTAL	16,423	16,316	107	0.7%	16,154	269	1.6%

ALL Green Infrastructure(including tree boxes) - AVERAGE YEAR

Sewershed	Baseline Runoff	Moderate Greening Scenario Runoff (MG)	Moderate Greening Scenario Runoff Volume Reduction (MG)	Moderate Greening Scenario Runoff Reduction (%)	Intensive Greening Scenario Runoff (MG)	Intensive Greening Scenario Runoff Volume Reduction (MG)	Intensive Greening Scenario Runoff Reduction (%)
Total CSS	7,668	7,498	170	2.2%	7,034	634	8.3%
Anacostia CSS	4,219	4,129	90	2.1%	3,888	330	7.8%
Potomac CSS	1,013	983	30	3.0%	902	111	11.0%
Rock Creek CSS	2,437	2,386	51	2.1%	2,244	193	7.9%
Total MS4	8,755	8,615	140	1.6%	8,174	581	6.6%
Anacostia MS4	3,719	3,659	60	1.6%	3,478	241	6.5%
Potomac MS4	3,177	3,122	54	1.7%	2,951	225	7.1%
Rock Creek MS4	1,860	1,833	26	1.4%	1,744	115	6.2%
TOTAL	16,423	16,112	311	1.9%	15,208	1,216	7.4%

APPENDIX B

DOCUMENTATION OF METHODOLOGY FOR GREEN BUILD-OUT MODEL

1. INTRODUCTION

This Appendix documents the modeling methodology for the EPA Water Quality Cooperative Agreement grant entitled "The Green Build-out Model." The Green Build-out Model is used to quantify the cumulative stormwater management benefits related to increases in "green infrastructure" in Washington, DC (the District), namely tree cover and green roofs. This research represents a public-private partnership between Casey Trees, a non-profit organization whose mission is to restore, enhance, and protect tree cover in our nation's capital, and LimnoTech, an environmental engineering firm that built the hydrologic and hydraulic sewer model for the District of Columbia Water and Sewer Authority (WASA) and applied it for development of the Long-Term Control Plan (LTCP) for WASA's Combined Sewer System (CSS).

In addition to documenting modeling methodology, a secondary goal of this Appendix is to demonstrate to interested parties how to set up a similar green infrastructure model for their own communities. While the model inputs described in this report are specific to the District, the modeling approach, assumptions, and methods are universal and can be used to model infrastructure in other cities. This Appendix also describes the development of the Mini-model, a simplified version of the Green Build-out Model, that uses simplified unit-area stormwater reduction values to assess the value of adding trees and green roofs in the District. Again, the Mini-model is also specific to the District, but its methodology can be extended for application in other cities or municipalities.

2. MODEL BACKGROUND

Since the inception of the District's sewer system in the late 1800s, it has repeatedly been the subject of study, design, and construction to expand service to a growing, spreading population and to improve public health and water quality for the metropolitan Washington area. To assist with the development of the LTCP in the late 1990s, WASA developed a complex hydrologic and hydraulic model of the CSS. This model is in use today and continues to be refined as more and better data on the system become available.

The sewer system model has undergone two sets of calibration rounds, once for the development of the LTCP in 2000, and once in 2005-2006 after more metering data became available. A third round of calibration is expected to occur in 2007, which will include new metered data along the Anacostia River as well as improved geographic information system (GIS) layers to define the surface hydrology.

The sewer system model has not only been used for the development of the LTCP, but also for numerous other projects such as investigation of localized flooding problems, Intermunicipal Agreement negotiations, evaluation of improvements at pump stations and at the Blue Plains Wastewater Treatment Plant, and for examination of emergency operations. The hydrologic and hydraulic (H&H) modeling conducted for the Green Build-out Model builds upon the existing sewer system model for the District. The model scenario that represents the existing sewer system (Scenario C3) assumes that upgrades have been made at the major pump stations and control structures, but that the storage tunnels and other elements of the LTCP are not yet in place.

The sewer system model is an application of Mike Urban, a proprietary modeling platform supported by the Danish Hydraulic Institute (DHI). This software package uses DHI's MOUSE software for the hydrologic and hydraulic modeling, and integrates it with a GIS platform for improved visual functionality. Mike Urban has been peer reviewed and successfully applied by WASA in the development of the EPA-approved LTCP for the CSS. The Mike Urban software was chosen because it accommodates a high degree of detail in characterizing the sewer system, including:

1. Real-time control features, which enable characterization of the network's dynamically-controlled inflatable dams and pump stations
2. Dry weather flow time series at each sewershed in the combined sewer system
3. Wet weather simulation of each sewershed in the combined sewer system using detailed hydrologic inputs that are unique to each sewershed
4. Boundary time series for flow entering the District from other jurisdictions, with wet-weather adjustment factors
5. Sanitary sewershed wastewater inputs, reflecting demographic and user-specific data, with wet-weather infiltration and inflow inputs
6. Tide-level time series at system outfalls

The modeling of the green infrastructure is a two-step process. First, the storm runoff is determined based on the local hydrology. Second, the calculated storm runoff is routed through the sewer system to determine the impact of the green infrastructure on CSO overflows. Both these processes are described below.

3. RUNOFF MODEL INPUTS

The surface runoff computations are calculated in Mike Urban using the kinematic wave equation, a commonly used method for simulation of urban hydrology. This method assumes that runoff behaves like flow in an open channel. The sewershed inputs (Figure B1) for the kinematic wave equation include:

- Area
- Slope
- Length
- Surface type
  - Impervious Steep
  - Impervious Flat
  - Pervious Small
  - Pervious Medium
  - Pervious Large
- Storage
- Infiltration (Horton parameters)
- Roughness (Manning coefficient)
- Evapotranspiration
- Rainfall

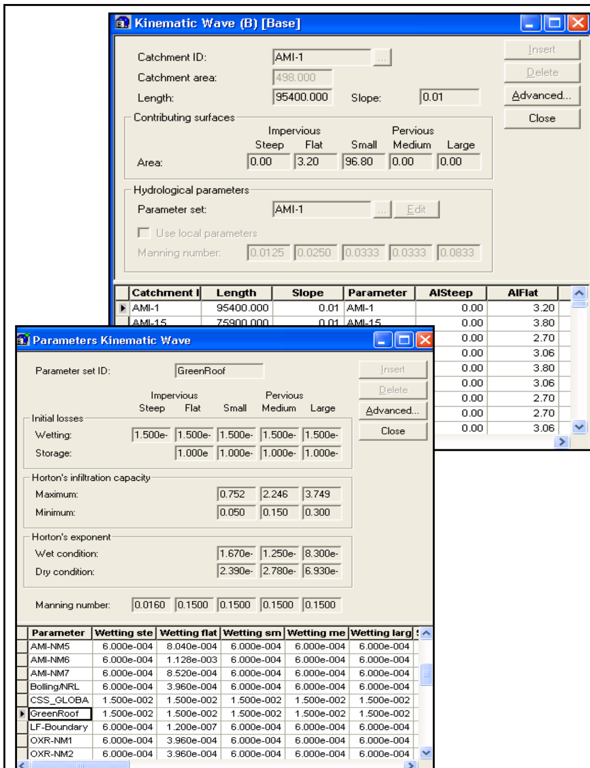


Figure B1: Screenshots of the Mike Urban Runoff Input Files

Each of these inputs is described in the following sections.

The runoff volume is controlled by the amount of precipitation, the size and characteristics of the sewershed, and various hydrological loss mechanisms. Calculation of runoff is represented by the following equation:

Runoff = Precipitation – Evapotranspiration – Infiltration – Storage

The shape of the runoff hydrograph is controlled by the length, slope and roughness of the sewershed surface.

3.1 AREA

The area of each sewershed is a critical factor in determining the runoff volume. For the purpose of this study, there are two defined areas that convey runoff: the existing sewershed area and the green infrastructure area (*i.e.*, the area covered by new green roofs and trees).

3.1.1 Existing Sewershed Area

The sewer service area within the District covers 33,720 acres, of which 12,470 acres are in the CSS area and 21,250 acres are in the municipal separate storm sewer system (MS4) area. The CSS generally serves the central, older portion of the District. Approximately 66% of this area drains to the lower Anacostia River, with the remainder draining to Rock Creek and the Potomac River. There are 60 outfalls listed in WASA's National Pollutant Discharge Elimination System (NPDES) permit, including 17 along the Anacostia River, 14 along the Potomac River, and 29 along Rock Creek. The MS4 area serves the newer, outlying portions of the District and is characterized by a separate sewer system for the sanitary and storm flows. There are 619 storm sewer outfalls in the MS4 area, including 234 along the Anacostia River, 195 along the Potomac River, and 190 along Rock Creek.

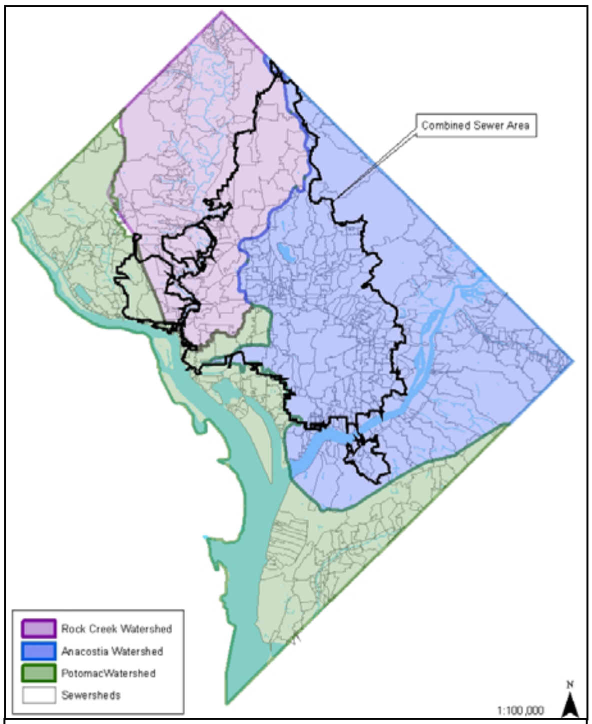


Figure B2: Depiction of all Sewersheds

Because the sewered area in the District is so large, it was divided into sewersheds, small entities with specific drainage area and flow characteristics. Areas with complex hydrology and hydraulics have more detailed sewershed delineations than areas that are hydrologically homogenous and hydraulically simple. This allows for a comprehensive representation of the sewer system, without unnecessarily slowing down the hydrologic and hydraulic computations in Mike Urban with too

much detail. There are 295 sewersheds in the CSS area, with a median area of 22 acres. The MS4 area was divided into 456 sewersheds, with a median area of 11 acres.
All of the sewersheds that were modeled in Mike Urban are presented in Figure B2. The contributing area of each was determined using GIS. These sewersheds were calibrated against flow meter data during the development of the sewer system model for the LTCP.

3.1.2 Green Infrastructure Area

The area of the green infrastructure varies depending on the scenario that was evaluated (intensive vs. moderate greening). Note that the Green Build-out Model calculates stormwater management benefits related to *incremental increases* in green infrastructure. It does not explicitly calculate the benefits of existing green infrastructure. The existing tree and green roof cover is implicitly part of the current Mike Urban model because the model has been calibrated to existing land use conditions. Therefore, the stormwater management benefits associated with the tree and green roof areas added to the model as part of this research were the incremental benefits resulting from the difference between the existing tree or green roof coverage and the proposed coverage scenario. The amount of area that is assigned to the added green infrastructure is explained in more detail in Section 3.6 of the main report.

3.2 SLOPE

The slope of a sewershed affects the shape of the hydrograph and the peak flow rate, and it is determined using United States Geologic Survey topographic maps. The topography of the city varies from the very flat and low areas around the tidal basin and the National Mall, to the very steep and hilly terrain along the upper reaches of Rock Creek Park and Oxon Run. A map of the topography within the District is presented in Figure B3.

The slope of each sewershed was calculated as follows:

$$slope = \frac{highest\ elevation - lowest\ elevation}{average\ length\ of\ \ sewershed}$$

The existing slopes range from over 40% in the hilly portions of the northwest MS4 area to less than 0.1% in the very flat areas of the Northeast Boundary (NEB) CSS area. The median slope is slightly more than 3%. To simulate the green infrastructure, it was assumed that all green roofs would have an essentially flat roof (slope = 1%) and that areas with trees were assumed to have the same slope as the local topography.

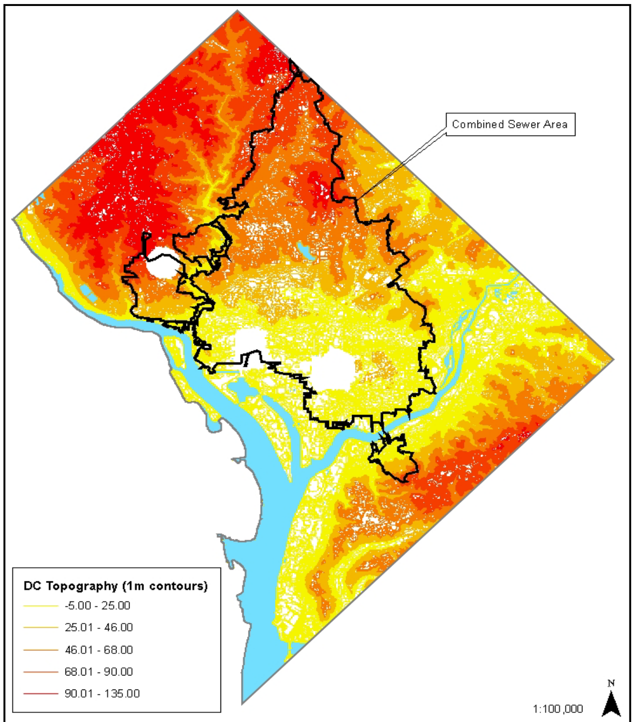


Figure B3: Topography of Washington, DC

3.3 SEWERSHED LENGTH

Sewershed length also affects the shape and timing of the hydrograph and the peak flow rate. The length of each sewershed was measured in GIS by tracing the average overland flow path. It varies from less than 60 feet long to over 11,000 feet long. This is a calibration parameter and the lengths were adjusted as appropriate to obtain the best possible matches with the meter flow data.

3.4 SURFACE TYPE

The Mike Urban model differentiates hydrological processes between pervious and impervious land cover. Land cover in the District varies from the very impervious commercial and institutional "downtown" area, to the moderately pervious residential areas on the fringes of the city. This type of data is readily available from the 2005 planimetric data released by the District's Office of the Chief Technology Officer (OCTO). A graph of the different pervious and impervious areas in the city is presented in Figure B4.

Mike Urban allows five different surface type categories for each sewershed, including flat impervious, steep impervious, small pervious, medium pervious, and high pervious. These different surface type subcategories allow the user to provide specific details that are unique to each sewershed. It is up to the user to decide how to correlate land cover to the five surface type categories. For the existing conditions, the impervious area was calculated by summing the building, sidewalk and road area. The distinction between the flat and steep impervious areas was made individually for each sewershed as shown in Table B1. Note that most building rooftops in the District are flat, which is why a large percentage of impervious roof cover is assigned to the flat impervious category.

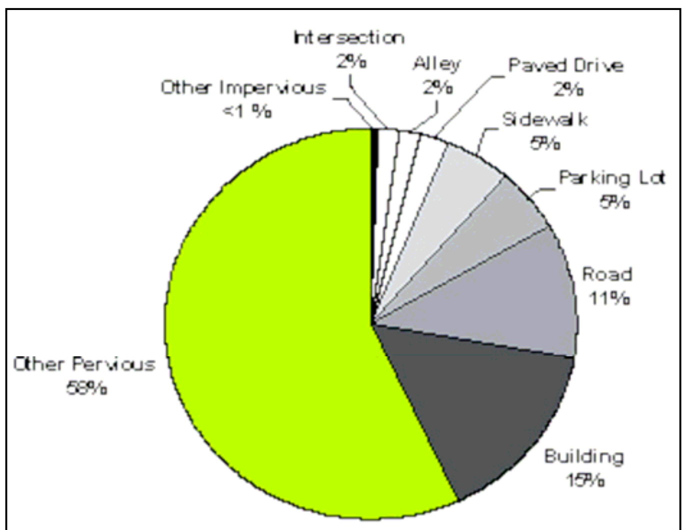


Figure B4: DC Land Cover

Table B1: Determination of Flat and Steep Impervious Area

Condition	Steep Impervious Area	Flat Impervious Area
If sewershed slope > 8%	100% of all roads + sidewalks 25% of all buildings	0% of all roads + sidewalks 75% of all buildings
If sewershed slope < 8%	0% of all roads + sidewalks 25% of all buildings	100% of all roads + sidewalks 75% of all buildings

The distinction between small, medium, and large pervious areas was made individually for each sewershed based on the four major hydrologic soil groups (HSG) as defined by the Natural Resource Conservation Service.

In addition to specifying the area within a sewershed, the user also specifies different storage and infiltration values for each of the five surface type categories. The storage and infiltration values are explained in further detail in Sections 3.5 and 3.6 respectively.

Trees are assigned to each of the five surface types categories depending on the location of the tree (*i.e.*, a street tree will be assigned to the impervious category, whereas a parkland tree will be assigned to the pervious category). Green roofs always fall into the flat impervious category because we are assuming that only flat roofs will have green roofs.

3.5 STORAGE

Storage defines the rain depth necessary before runoff begins. This parameter is determined through the calibration process. There are two types of storage parameters in Mike Urban: wetting losses and storage losses. The wetting loss is typically the smaller value and refers to the depth of rain necessary to wet the surface of a catchment. Mike Urban allows a wetting value for all five surface types. The storage loss is typically the larger value and accounts for the losses associated with the depressions typically found on the surface of impervious and pervious catchments. Mike Urban allows storage losses for all surface types except steep impervious, where it is assumed that the slope of the surface is too high for any significant accumulation to occur. For the purposes of this study, there are three types of storages:

1. Average catchment storage
2. Tree storage
3. Green roof storage

3.5.1 Average Catchment Storage

Calibration of the sewer system model for the District showed that, on average, flat impervious areas store approximately 0.085 inches of rain and pervious areas store 0.115 inches of rain (Table B2). This storage accounts for the depressions typically found on the surface of impervious and pervious catchments.

Table B2: Wetting and Storage Values Used in Mike Urban

	Steep Impervious	Flat Impervious	Small Pervious	Medium Pervious	Large Pervious
Wetting, Inches	0.015	0.015	0.015	0.015	0.015
Storage, Inches	-	0.070	0.100	0.100	0.100

3.5.2 Tree Storage

The amount of interception storage provided by trees was determined using the same methodology used by the USDA Forest Service in its Urban Forest Effects (UFORE) Hydro Model whereby:

$$Storage = LAI * 0.0078 \text{ inches} = 0.032 \text{ inches}$$

The “Leaf Area Index” or LAI is a measurement of the one-sided green leaf area per unit ground area in broadleaf canopies and depends on tree species, canopy size, and condition. The average LAI found by the Casey Trees 2002 Street Tree Inventory was 4.10. The reasons for choosing the UFORE Hydro methodology is explained in the main body of the report. The Mike Urban model accounted for the effects of seasonality by considering storage benefits only during the leaf-on season (April 1 through October 31). The model also assumes that storage is provided from leaves only, and does not account for interception storage derived from a tree’s branches and trunk.

3.5.3 Green Roof Storage

The amount of storage provided by green roofs depends on the depth of the green roof media. The model assumes that all green roofs are extensive with three to four inches of growth media. The reasons for assuming extensive green roofs District-wide are listed in the main body of the report.

Storage amounts found in peer reviewed literature varied greatly depending on whether the growth media was dry or saturated and whether the roof was flat or sloped (see Figure 4 and Table 2 in the main report). Several studies found storage amounts of one inch for a green roof with 3-4 inches of soil media. This included the research from Penn State University and Roofscapes whose field studies most closely approximated the climate in the District. Therefore, for the purposes of this study, storage was assumed to be one inch for an extensive green roof.

3.6 INFILTRATION

Infiltration plays a significant role in absorbing rainfall over pervious areas and in mitigating runoff volumes. The infiltration rates depend on the type of soil present. Because of the heavy urbanization of the city, many of the soils are very compacted and consist of fill that are not native to the area. These soils typically have little infiltration capacity. In contrast, parts of the city that consist of peaty and aerated soils such as those often find in forested parkland have a high infiltration capacity. A map of the hydrologic soil groups found in the District is shown in Figure B5. HSG A is a soil type with a high infiltration rate, whereas HSG D soils have a very low infiltration rate. The hydrologic soil groups were related to the three pervious categories that are allowed in Mike Urban, as follows:

- Small pervious (low permeability) = 100% HSG D + 30% of undefined soils
- Medium pervious (medium permeability) = 100% HSG C + 70% of undefined soils
- Large pervious (high permeability) = 100% of HSG A and 100% of HSG B

Infiltration losses are calculated using Horton's equation, a standard process that defines infiltration according to the saturation of the soils. Horton's equation uses four parameters to calculate the infiltration capacity of a certain area:

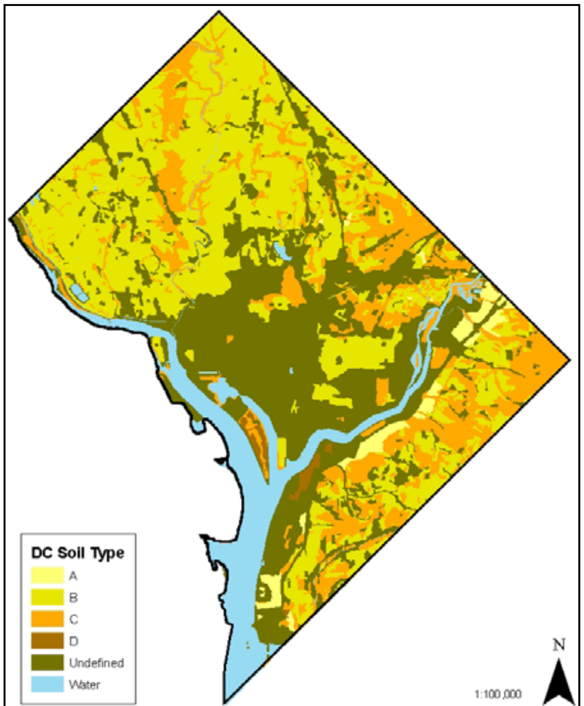


Figure B5: Hydrologic Soil Groups in Washington, DC

1. Start Infiltration (in/hr): the fastest rate of infiltration, which occurs when the soils are unsaturated.
2. End Infiltration (in/hr): the slowest rate of infiltration, which occurs when the soils are saturated.
3. Horton's Exponent (1/sec): determines how quickly the infiltration rate decreases when the soils move from an unsaturated to a saturated condition during wet weather conditions.
4. Inverse Horton Exponent (1/sec): determines how quickly the infiltration rate recovers after rainfall stops (*i.e.* the drying period), when the soils move from a saturated to an unsaturated condition.

The infiltration parameter values for the existing conditions were determined during the model calibration process and are shown in Table B3 below.

Table B3: Infiltration Parameters Used in Mike Urban

	Small Pervious	Medium Pervious	Large Pervious
Maximum Infiltration (in/hr)	0.752	2.246	3.749
Minimum Infiltration (in/hr)	0.050	0.150	0.300
Horton's Exponent (1/sec)	1.67×10^{-3}	1.25×10^{-3}	8.30×10^{-4}
Inverse Horton's Exponent (1/sec)	3.29×10^{-5}	2.78×10^{-5}	6.93×10^{-5}

The infiltration rates do not affect the parameterization of green infrastructure; infiltration rates remain the same regardless of whether or not a tree or green roof is present. While it could be argued that trees improve the infiltration of the underlying soils by providing aeration through its roots, such a complex phenomena would be difficult to model and was not included in this study. It was also assumed that green roofs do not have infiltration rates, since the growth media is contained by an impervious membrane and therefore acts more like a storage container than typical pervious areas. This also means that the rate of precipitation is never constrained by the theoretical infiltration rate of the green roof media.

3.7 ROUGHNESS

The roughness of a catchment is a function of the land cover and is also a calibration parameter. It is used in the hydraulic routing of the runoff, using Manning's formula:

$$Q = \frac{1.486}{n} R_h^{\frac{2}{3}} S^{\frac{1}{2}} A, \text{ where}$$

Q = Flow (cfs)
n = Manning roughness coefficient)
R_h = hydraulic radius (ft)
S = slope (ft/ft)
A = area (ft^2)

The Manning roughness coefficient impacts peak flow rates, and care must be taken to choose an appropriate value. Mike Urban allows a different roughness value for each of the five surface type categories, but only two were used. One represents the impervious cover while the other represents the pervious cover. The impervious Manning coefficient affects the peaking of flow from the impervious areas in a catchment. The pervious Manning coefficient affects the peaking of flow from the pervious areas in a catchment.

The calibration efforts resulted in the selection of an impervious roughness value of 0.016 and a pervious roughness value of 0.15. These fall within the range of published values for impervious and pervious cover. Roughness values for the green infrastructure areas are very similar. Trees over impervious cover have a roughness of 0.016 and trees over pervious cover have a roughness of 0.15. Green roofs always have a roughness value of 0.15.

3.8 EVAPOTRANSPIRATION

Evapotranspiration is a very important hydrologic element that is distinctly seasonal in the District. Evapotranspiration refers to water losses to the atmosphere from the combined effect of evaporation and plant transpiration. Evapotranspiration replenishes the wetting and storage capacity of the catchment after the end of a rainfall event. Evapotranspiration rates applicable for the District as shown in Figure B6 are published by the Virginia Climatology Office.

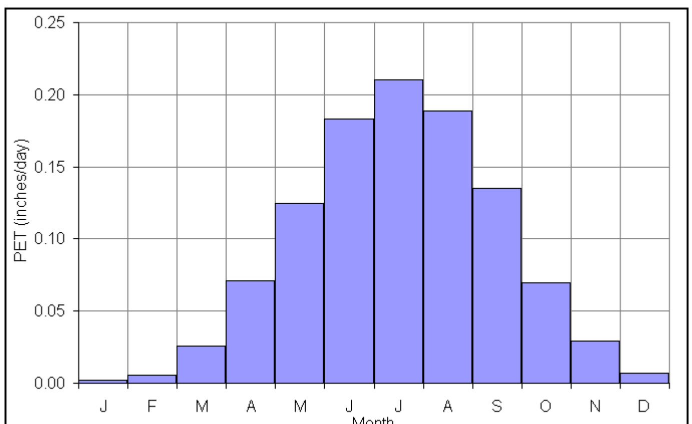


Figure B6: Evapotranspiration Rates for Washington, DC

3.9 RAINFALL

Rainfall data is critical to simulate the runoff response of each sewershed and the green infrastructure. Official rainfall and other meteorological records for the District are observed at Reagan National Airport (National Airport) by the National Weather Service, and recorded by the National Climate Data Center. National Airport is located on the Virginia (western) bank of the Potomac River, approximately 3 miles south of the White House, and adjacent to the confluence of the Potomac and Anacostia Rivers. Continuous records of hourly and daily rainfall amounts extend back from the present to 1949. Based on this period of record, the year 1990 was selected as the year that best represents system-wide annual average rainfall conditions in the District. This was the same year used by WASA in the LTCP. The statistics for 1990 are presented in Table B4. The average year rainfall data was used as input to Mike Urban as hourly inputs.

Table 4: Rainfall Statistics for Washington, DC

Statistic	1990	Long-Term Average[1]
Annual Rainfall (inches)	40.84	38.95
No. Events > 0.05 inches[2]	74	74
Average Storm Duration (hours)	9.6	9.9
Average Maximum Intensity (in/hr)	0.15	0.15
Maximum intensity (in/hr)	1.25	1.30

Notes:
1. Ronald Reagan National Airport hourly data, 1949-1998
2. Individual events separated by a minimum of 6 hours with no rain. A threshold of 0.05" was selected since rainfall less than this produces minimal, if any, runoff.

It is interesting to note that 85% of the rain events during the average year are less than 1-inch in depth (Figure B7). This is of particular importance because a basic extensive green roof can typically store 1-inch of precipitation.

In a separate analysis, the runoff response of the sewersheds to a 1-year, 6-hour design storm was also modeled. This design storm corresponds to 1 inch of rain. Design storms are theoretical storms with a given duration, frequency, distribution, and rainfall depth that are typical for the area of interest. The design storm rainfall distribution, also known as a design hyetograph, is obtained from intensity-duration- frequency (IDF) curves for the location of interest. IDF curves are typically provided by municipal, state or federal government agencies, but are usually only applicable for areas smaller than the District. Therefore, the design hyetograph for this study was calculated from an analysis of historical rainfall records for the District. More information on the development of this design storm can be found in WASA's LTCP. The distribution of this rain event is shown in Figure B8.

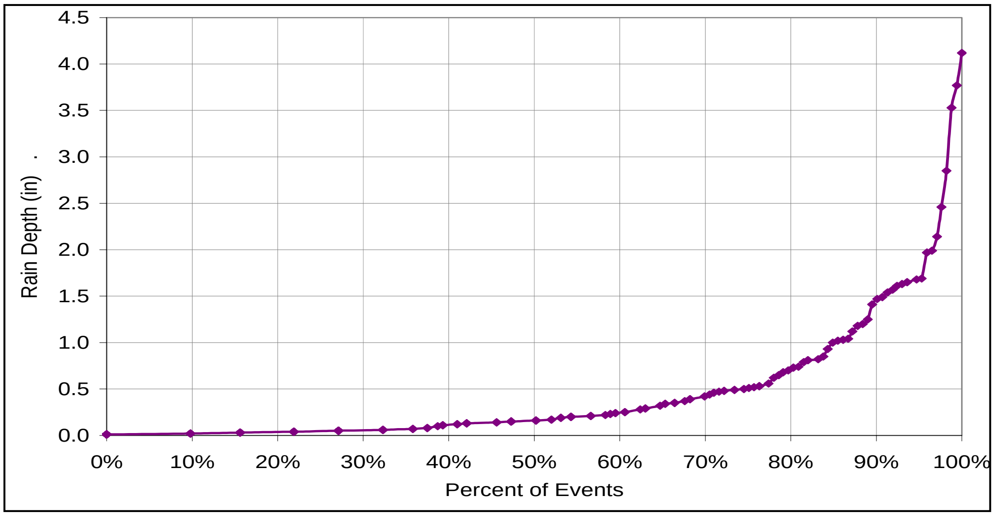


Figure B7: Rainfall Depth as Percentile of Average Rainfall

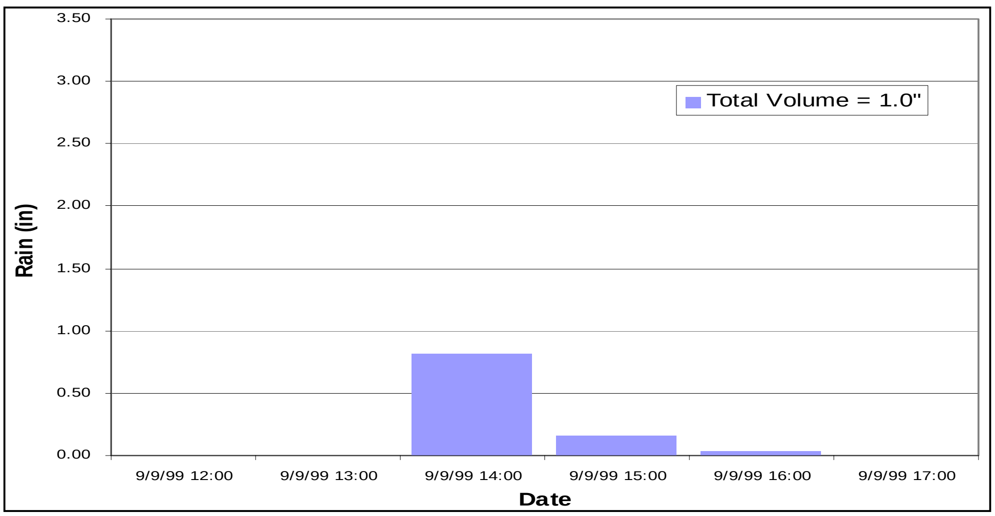


Figure B8: 1-year, 6-hour Design Storm for DC

4. HYDRAULIC MODEL INPUTS

The results of the runoff model are routed through the sewer system described in Mike Urban in a process called hydraulic routing. Each sewershed is connected to the sewer system through a node (*i.e.* a manhole or catch basin) at its nearest location (Figure B9). Once the modeled runoff has entered the sewer system, it combines with the dry weather flow inputs (entered as a time series for each sewershed), and travels downstream to the nearest storm outfall (in the MS4 area) or to a CSO outfall or the Blue Plains Waste Water Treatment Plant (in the CSS area). Flow in the CSS area passes through and over various flow control structures, pump stations, and inflatable dams. There are more than 100 such diversion or regulator structures in the CSS area. This system of diversion structures provides storage capacity for some of the wet weather contribution and diverts excess flow into one or more of the 60 NPDES-permitted CSO outfalls in the District. While not every single pipe of the sewer system is included in Mike Urban, all key items such as the interceptors, large trunk sewers, flow structures, outfalls, pump stations, and treatment facility are included. The representation allows for sufficient detail to accurately represent the sewer system, without unnecessarily slowing down model computation time with excess detail. The model inputs for each of these structures include information such as the length, slope, material, geometry, and other important hydraulic information. Refer to WASA's CSS LTCP and its technical appendices for more detailed information on the sewer system.

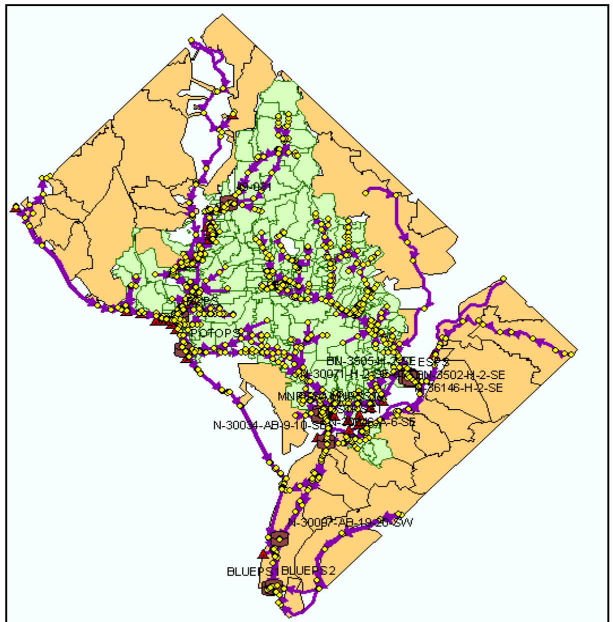


Figure B9: The Hydraulic Network in Mike Urban

5. MODEL SCENARIOS

Model scenarios were developed to analyze the stormwater management benefits of green infrastructure. These scenarios were compared against the "Baseline" condition, which represents the calibrated, existing conditions for the city. Two green infrastructure scenarios were analyzed in this study with the Green Build-out Model. The first is referred to as the moderate greening scenario. The second is the intensive greening scenario. The moderate greening scenario looked at putting trees and green roofs where it was practical and reasonable to do so. The intensive greening scenario considered putting trees and green roofs wherever it was physically possible. As discussed in Section 3.1.2 only the incremental increase in green infrastructure was modeled. Scenarios were run for an average year (1990) wet weather continuous simulation, and a 1-year, 6-hour (1") design storm. The tree and green roof area cover was determined by applying a standard methodology across the city, explained in the following sections.

5.1 TREE COVER ASSUMPTIONS

Existing tree cover was determined by classifying July 2006 IKONOS satellite imagery classified for land cover (1m) including tree canopy. The tree canopy data was overlaid with the District's planimetric data to determine existing tree cover by impervious and pervious land cover types for the Mike Urban model. Assumptions for proposed increases in tree cover for both the moderate greening and intensive greening scenarios were determined for each land cover type by a variety of methods, which are described below. These assumptions were discussed at length with the Advisory Team and other District government agency representatives.

The methods for determining the tree cover assumptions listed in Table B5 are explained in the main body of the report. The tree cover assumptions were spatially assigned to either the pervious or impervious land cover type in the Mike Urban model, and assigned the runoff parameters for trees.

Table B5: Percentage Tree Cover Assumptions by Land Cover Type

Land Cover Type	**Existing Coverage**	**Moderate Greening Scenario**	**Intensive Greening Scenario**
Impervious Tree Cover			
Roads, sidewalks, intersections	22%	25%	35%
Parking lots	7%	30%	50%
Paved drives	23%	50%	80%
Alleys	26%	35%	50%
Median islands, traffic islands, hidden medians, other	23%	30%	40%
Pervious Tree Cover			
Includes parks, open space, cemeteries, yards, etc	53%	57%	80%
Total Tree Cover	***35%***	***40%***	***57%***

5.2 GREEN ROOF COVER ASSUMPTIONS

Based on a Green Roofs for Healthy Cities survey, the area of existing green roofs in the District is less than 300,000 square feet, which is less than 0.1% of the total building footprint in the city. Therefore, for the purposes of the Mike Urban model the existing green roof coverage was considered to be zero. An analysis of building sizes was completed to determine the opportunity for green roof coverage, using GIS data that is readily available from OCTO. Details on this analysis can be found in the main body of the report.

It was assumed that the rooftop area was equal to the building footprint area and that 25% of the rooftop area was needed to provide space for HVAC, access, and maintenance. Therefore, it was assumed for the Mike Urban model that 75% of the building footprint area would be available for the application of green roofs. This area was considered the "green roof-ready" area (Figure B10) for model calculations.

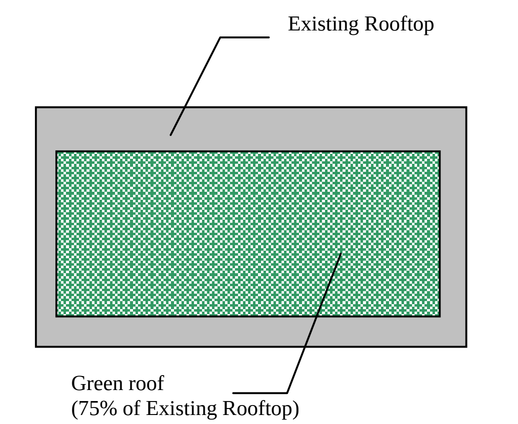


Figure B10: Green roof-Ready Area

Assumptions for the moderate greening and intensive greening scenarios were made for each roof size or building type while considering structural, historic, and other issues that would impact the opportunity for a green roof. These coverage assumptions are summarized in Table B6. More details on the rationale behind these assumptions can be found in the main body of the report. Proposed development was not considered in the model as GIS data was not available and most new development in the District is typically redevelopment of existing structures.

Table B6: Green roof Cover Assumptions

Roof Type	Total Roof Area (square feet)	Moderate Greening Scenario Green roof Area	Intensive Greening Scenario Green roof Area
< 1,000sf	57,423,950	20% of build-out area or 2% x 75% of roofs (861,359 sf)	10% x 75% of roofs (4,306,796 sf)
1,000sf – 2,000sf	62,224,642	20% of build-out area or 6% x 75% of roofs (2,800,109 sf)	30% x 75% of roofs (14,000,544 sf)
2,000sf – 5,000sf	33,295,571	20% of build-out area or 10% x 75% of roofs (2,497,168 sf)	50% x 75% of roofs (12,485,839 sf)
> 5,000sf	106,469,278	20% of build-out area or 18% x 75% of roofs (14,373,353 sf)	90% x 75% of roofs (71,866,763 sf)
TOTAL	**259,413,441**	**~20% of build-out area or 10.5% x 75% of roofs (20,531,989 sf)**	**53% x 75% of roofs (102,659,943 sf)**

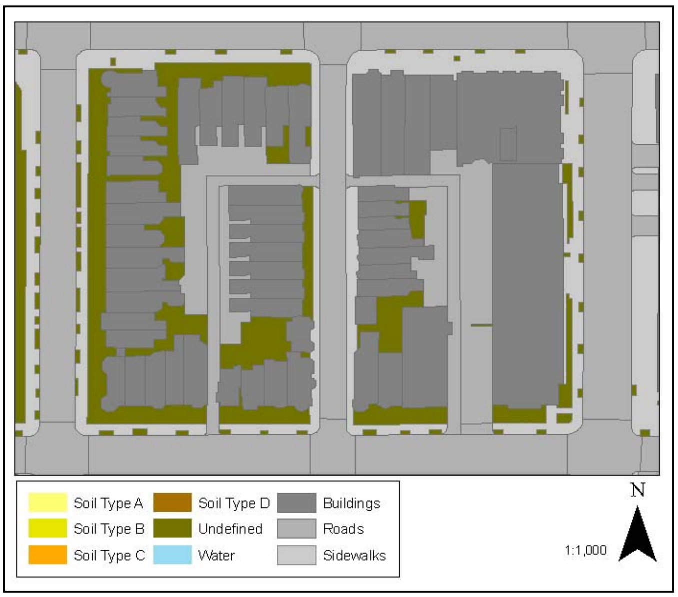
5.3 TREE BOX ASSUMPTIONS

A Tree Box scenario was also calculated to estimate the stormwater management benefits of increasing the minimum tree box dimensions from 3 x 5 feet to 6 x 20 feet in the downtown core where sidewalks average 20 feet in width. The Casey Trees Advisory Group agreed that a 6 x 20 foot tree box was reasonable in the downtown core, given District sidewalk widths on most streets there. Stormwater management benefits were derived from the change in land cover from impervious to pervious. The methodology did not consider the improved health, condition, and size of the tree as a result of increased soil volumes.

6. INTEGRATION OF GREEN INFRASTRUCTURE IN MIKE URBAN

This section explains how the inputs for the green infrastructure were handled in Mike Urban. A schematic of an example sewershed prior to adding any green infrastructure is shown in Figure B11. This sewershed has runoff parameters associated with the baseline conditions.

To add green infrastructure to the model, the green infrastructure area is separated from the baseline sewershed area since each area is governed by a different set of parameter values. This is accomplished in Mike Urban by splitting the sewershed into two "subsheds." Using green roofs as an example, this is illustrated in Figure B12. The green roofs, outlined in blue, is represented in the first "subshed" with the area and hydrologic parameters of green roofs, while the second subshed has the area and hydrologic parameters of the existing sewershed without the footprint occupied by the green roofs. After running the model, the calculated runoff from these two subsheds is summed to get the total runoff from this sewershed with the green infrastructure.



Hydrologic Parameters	
Name	Area 1
Area	100 acres
Slope	5%
Length	1000 ft
Imp. Flat	60%
Imp. Steep	10%
Per. Small	10%
Per. Medium	10%
Per. Large	10%
Imp. Wetting	0.015
Imp. Storage	0.070
Per. Wetting	0.015
Per. Storage	0.100
Infiltration	Std values
Imp. Roughness	0.016
Per. Roughness	0.15
Evapotranspiration	Std values

Figure B11: Example "Baseline" Sewershed with its Hydrologic Parameters

Hydrologic Parameters		
Name	Area 1, no green roofs	Green roofs
Area	90 acres	10 acres
Slope	5%	1%
Length	1000 ft	1000 ft
Imp. Flat	55.6%	100%
Imp. Steep	11.1%	N/A
Per. Small	11.1%	N/A
Per. Medium	11.1%	N/A
Per. Large	11.1%	N/A
Imp. Wetting	0.015 inch	0.015 inch
Imp. Storage	0.070 inch	1.0 inch
Per. Wetting	0.015 inch	N/A
Per. Storage	0.100 inch	N/A
Infiltration	Std values	N/A
Imp. Roughness	0.016	0.15
Per. Roughness	0.15	N/A

Figure B12: Example Sewershed with Green Roofs Added

The runoff from the two subsheds is routed through the same node in the hydraulic system, to determine the effect of the green infrastructure on the combined sewer and storm outfalls. Even though the example shown in Figure B12 is for green roofs, the same approach applies for adding trees as well.

The approach for modeling increases in tree box size is slightly different. That analysis assumes that a portion of the impervious cover (sidewalk) will be converted to pervious cover (soil) by increasing the size of the tree box. As a result, a portion of the impervious cover reassigned to the pervious cover, and the total area remains the same. All other hydrologic inputs stay the same.

7. RESULTS

As mentioned earlier, the modeling of the green infrastructure is a two-step process. First, the storm runoff is determined based on the local hydrology. Second, the calculated storm runoff is routed through the sewer system to determine the impact of the green infrastructure on CSO overflows. The hydrologic computations to determine the storm runoff are run using a 5-minute time step, which allows for good resolution of the flow hydrographs. The hydraulic computations to determine the sewer system response is run using a 5-second time step, which is necessary in order for the model to run without computational errors. The hydraulic results are averaged on an hourly basis in order to keep the results file within a reasonable size limit.

The results of the Green Build-out Model scenarios are explained in detail in the main body of the report and in Appendix A – Detailed Model Findings. The results are presented both in terms of runoff volume and the CSO outfall volumes and frequencies. The runoff results were used to create the Mini-model, as explained in the next section.

8. THE MINI-MODEL

While the Green Build-out Model in Mike Urban is extremely capable in terms of modeling runoff and sewer responses to green infrastructure, it is also very complex and time-consuming to set up and run various scenarios (typically one week to set up, run, and extract results). The Advisory Group requested that the modeling team create a user-friendly modeling tool that would be quicker to use and apply. The user-friendly tool, nicknamed the Mini-model, allows the user to make changes to the green infrastructure coverage and immediately determine the impacts on the stormwater volume. The intended use of the Mini-model is for planning purposes. It provides a screneing tool for city planners and others to assess the relative impact of adding green infrastructure in specific areas of the District. The Mini-model is not intended to replace the Green Build-out Model.

The Mini-model uses unit-area reduction factors to determine the reduction in runoff from implementing green infrastructure. A hypothetical 100-acre area sewershed that consisted entirely of flat impervious land cover was used to develop the unit-area reduction factors (UARFs) for green roofs. This hypothetical area had all of the hydrological parameters assigned for flat impervious land cover (the baseline condition). Using the Green Build-out Model, it was tested and runoff volume was calculated under average rainfall year conditions. The next step was to assume that this same 100-acre area was converted into green roofs, with all of the same assumptions and hydrological parameters that are assigned to green roofs in the Green Build-out Model. This area was also tested under the average rainfall year conditions and the runoff volume calculated. The UARF is subsequently calculated as follows:

$$UARF_{greenroof}\,(MG/YR/acre) = \frac{Baseline\ Runoff\ \ (MG/YR) - Green\ Infrastructure\ Runoff\ \ (MG/YR)}{100\ (acres)}$$

This same methodology is applied for trees over impervious and small/medium/large pervious cover. The UARFs were then tested in each sewershed for each scenario, compared with the Green Build-out Model results, and adjusted as necessary to obtain the best possible match between the Green Build-out Model and the Mini-model. The median difference between the results generated by the models on a sewershed level is less than 0.002 million gallon per year (MGY). However, note that in some sewersheds, the difference between the Green Build-out Model and the Mini-model can be as much as 1.4 MGY. Because there is a certain degree of variability in the results produced by the Mini-model, users are forewarned that results from the Mini-model are appropriate for screening scenarios at the planing level. It is not meant to replace the detailed model results that are provided by the Green Build-out Model.

The final UARFs that are used in the Mini-model are shown in Table B7.

Table B7: Unit Area Reduction Factors Used with the Mini-Model

Type of Greening	**UARF (MG/YR/Acre)**
Green roofs	0.39400
Trees over impervious cover	0.11117
Trees over small pervious cover	0.02210
Trees over medium pervious cover	0.00276
Trees over large pervious cover	0.00008

DRAFT APPENDIX C

TREE COVER DATA INPUTS

NOTE: This appendix is a draft. A final version of this appendix will be available online after May 1, 2007 at: www.caseytrees.org.

1. INTRODUCTION

The Green Build-out Model adds the 'green component' to the rainfall storage amounts for trees and green roofs to the Mike Urban model according to the following relationship..

Storage = Interception storage * Coverage area

This appendix documents the analysis process for determining the tree canopy data inputs for the "Green Build Out Model" and considers two coverage scenarios. The methods are based on available data for the District of Columbia and transferable to other municipalities interested in understanding existing canopy conditions and opportunities to add tree cover.

2. BACKGROUND

Three related analyses needed to be performed to generate the inputs for the tree cover model assumptions: precise spatial representation of the existing canopy by land cover type and sewershed; and the two opportunity scenarios for the moderate and intensive greening assumptions. The data generated for the existing tree cover canopy of the District is the key base data. Joined with the land cover type and sewershed data, these data sets complete the baseline and the assumption scenarios.

For this type of large area land cover and vegetation analysis the most reliable and practical data source is satellite imagery. To generate the tree cover data set we were able to obtain high resolution IKONOS satellite imagery taken for the DC area in July 2006 through GeoEye. The scenes were then classified for land cover particularly tree canopy at a one-meter resolution.

The District of Columbia's Office of the Chief Technology Officer, DCGIS, has an extensive publicly available data set digitized 'leaf off' from aerial photos (April, 2005). This data is FGDC compliant and readily available on the District of Columbia's website. This data was used to establish the boundaries needed to divide the city into the specific areas of interest for the existing canopy analysis and the opportunity scenarios. The sewershed layer was compiled by the Water and Sewer Authority (WASA) of DC. The layers extracted for these methods are: impervious surface, buildings and sewershed boundaries.

The DCGIS layers provide a reliable data set for establishing the assumptions for a majority of the land cover (impervious surface) types. However, for the streetscape opportunity scenarios we were able to use the Casey Trees street tree space inventory data layer (2002). This data set spatially represents 130,000 street tree spaces in DC including the size and condition of the tree in the box. This layer created a more detailed measurement for the street scape (roads, sidewalk and intersection) assumptions.

3. METHODS

The methods use geographic information system analysis to generate the data sets needed as inputs to the Green Build out/Mike Urban model. The fundamental data set in this analysis is the *existing tree canopy* layer for the District. This layer is analyzed to generate existing tree cover by land cover type (impervious surface) and by sewershed. The assumptions (Table C1) for proposed increases in tree cover for both the moderate greening and intensive greening scenarios were also determined by each land cover type and sewershed.

A relationship is made between existing canopy and the outfall percentage from each sewershed demonstrating the impact of 'greening'. The assumptions are made for interception rates by drawing a comparison from *existing* canopy and *increasing* canopy. The methodology for calculating existing and increasing tree cover to build these assumptions is primarily described in this section. The methods for generating the road, sidewalk and intersections assumptions are described here where the assumptions for the other land cover types are described in the body of the paper.

Table 1: Percentage Tree Cover Assumptions by Land Cover Type

Land Cover Type	**Existing Coverage**	**Moderate Greening Scenario**	**Intensive Greening Scenario**
Impervious Tree Cover			
Roads, sidewalks, intersections	**22%**	25%	35%
Parking lots	**7%**	30%	50%
Paved drives	**23%**	50%	80%
Alleys	**26%**	35%	50%
Median islands, traffic islands, hidden medians, other	**23%**	30%	40%
Pervious Tree Cover			
Includes parks, open space, cemeteries, yards, etc.	**53%**	57%	80%
Total Tree Cover	***35%***	***40%***	***57%***

3.1 DATA SOURCES AND DATA PREPARATION

Data sets needed for existing canopy and opportunity analysis:

- Existing tree canopy
- Boundaries for surface land cover type and sewersheds

Data sets needed for assumption analysis:

- Existing tree canopy

- Boundaries for surface land cover type and street tree spaces

3.1.1 Land Cover/Tree Canopy Base Data

IKONOS satellite imagery taken of the District of Columbia in July 2006 was used to classify the land cover in one meter resolution by the Spatial Analysis Lab at the University of Vermont/US Forest Service. Figure C1 illustrates the classification process: the satellite image on the top half and the bottom showing the color bands depicting the vegetation vs. the impervious areas. Land cover is classified as ‘canopy’ to the edge of the tree crown’s dripline meaning from a ‘bird’s eye’ view some pervious and/or impervious surface will be classified as ‘canopy’. “Canopy” was extracted and used as the ‘existing canopy’ data set. ‘No Data’ was also extracted to identify where an alternative method was needed for determining existing canopy.

The land cover was classified into five (5) class types (Table C2):

- **Open Land:** Scattered small vegetation, grass, bare earth
- **Canopy:** Existing tree canopy
- **Impervious Surface:** (i.e.) Buildings, Sidewalks, Roads, Artificial turf
- Water
- **No Data:** Cloud Cover*

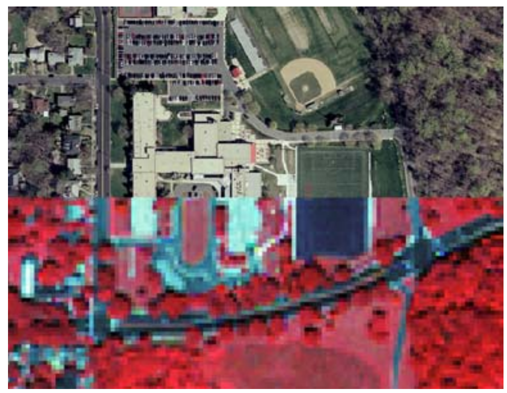


Figure C1: Image taken by IKONOS Satellite, Washington, DC

Table C2: IKONOS Land Cover Classes Citywide

CODE	Existing Land Cover 2006	Square Meters Total
1000	Open Land	27,807,457
2000	Canopy (~34%)	55,807,105
3000	Impervious	70,336,770
4000	Water	15,342,741
5000	No Data (Cloud) (~4.5%)	7,239,821
	TOTAL	**176,533,894**

3.1.2 Existing Canopy Cover where satellite imagery was unavailable

Clouds covered 4.5% of the District in the IKONOS images inhibiting the use this imagery for existing tree canopy. In this instance to show the existing canopy cover we used the Casey Trees 2002 street tree inventory. The street tree inventory is an inventory of street tree *spaces* with an attribute of existing trees or empty box as well as size of the tree crown. The crown radius field was used to determine the existing canopy of the street tree in these areas. The layer was converted to the same projection as the IKONOS and DCGIS base layers.

3.1.3 Land Surface Cover Type (i.e. Impervious Surface) and Sewershed Base Data

DCGIS impervious surface and boundary data sets (2005) were used to define the surface boundaries for the impervious or pervious base layer analysis. Using ESRI ArcGIS Spatial Analyst software, this vector data set was converted to raster in the same projection and one meter cell size as the IKONOS imagery to ensure a precise overlay. Each impervious field of interest was reclassified and given a unique CODE. Table C3 displays the results.

Table C3: DCGIS-OCTO Land Cover Surface Type Data Classes

CODE	Impervious Surface ReClassified (Grouped)	Square Meters Total
10000	Road and Hidden Road	17,455,450
20000	Sidewalk and Hidden Sidewalk	8,509,836
30000	Median and Traffic Island and Hidden Median	603,874
40000	Paved Drive	3,267,858
50000	Parking Lot	8,545,049
60000	Building and Parking Garage	24,221,620
70000	Alley	2,952,640
80000	Intersection	2,648,948
	TOTAL	**68,205,275**

3.2 DETERMINE THE DISTRICT'S EXISTING TREE CANOPY FOR LAND COVER TYPE AND SEWERSHED

Using the 'canopy' data set extracted for the district illustrated in Table 3.1, further analysis was performed to generate:

- the area (m^2) of existing canopy in each land cover type (i.e Roads, sidewalks Table 3.2)
- the area (m^2) of existing canopy in each land cover type by sewershed.

3.2.1 Determine Area of Existing Canopy in each Impervious Surface Class

- The key analysis was performed using ESRI ArcGIS Spatial Analyst cell statistics and raster calculator functions. With each raster cell size equal to one square meter the sum of the *canopy* CODE (Table C2) and the *Impervious Surface* CODE (Table C3) produced a formula for the area in square meters that canopy extended over that surface (Table C4).

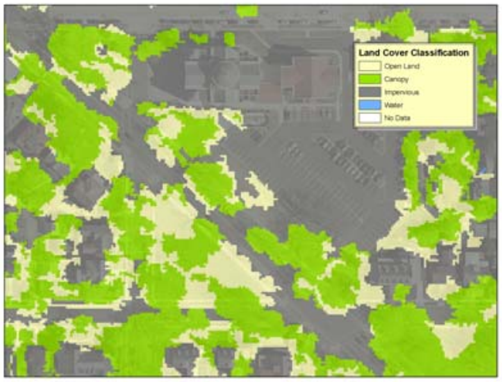


Figure C2: IKONOS Land Cover

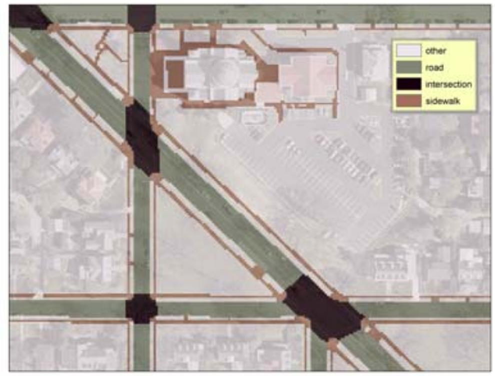


Figure C3: Rasterized Street Scape

3.2.2 Determine Area of Existing Canopy over each Impervious Surface Category by sewershed (CSO and CSS)

The existing canopy was determined for each sewershed. A relationship between existing tree canopy can be made from the data available on outfall to each sewershed. Over 700 sewersheds are in the District stormwater system. Each CSS (456) and CSO (316) were also given a unique three digit CODE. Using the same methods of the 1^2m cell size, the SUM of each CODE results in tree canopy and surface (m^2) in each sewershed (Table C4). See example below:

Table C4: Example Canopy Calculations

CODE	Square Meters
12032	1673.0
12033	2495.0
12034	430.0
12326	1991.0
12327	561.0
52188	168.0
52189	7.0
52190	585.0
82190	270.0

Example

CODE 12032 inferred from chart at left: Roads (10000) with overhanging canopy (2000) in CSO 032 equals 1673 square meters

CODE 52186: Parking Lots (50000) with overhanging canopy (2000) in CSS 188 totaled 168 square meters

CODE 82190: Intersections (80000) with overhanging canopy (2000) in CSO 190 total 270 square meters

The final CODE(s) was the formula used as inputs to the Mike Urban Model for existing tree canopy over each land cover type in each CSO and CSS in the District.

3.3 DETERMINE STREET TREE CANOPY OPPORTUNITY FOR LAND COVER TYPES FOR THE TWO ASSUMPTION SCENARIOS: MODERATE AND INTENSIVE

Assumptions for the ‘moderate’ and ‘intensive’ greening scenarios for tree canopy were generated for each impervious surface cover class (Table 1). The extensive street tree data available of 130,000 street trees spaces provided a more accurate representation of the street scape for opportunity over roads, sidewalks and intersections therefore these three land cover surface types were analyzed using a different methodology than the other land cover surface types. The methods for the assumptions scenarios for roads, sidewalks and intersections are described here. The other land cover types are described in the body of the report.

The assumptions scenarios are based on the percentage of available land cover area not currently occupied by existing tree canopy or the tree canopy ‘opportunity’. The easiest way to find the opportunity is to create a layer with maximum tree canopy coverage and then subtract the existing canopy. The existing tree canopy has already been determined for the first stage analysis described above.

Determine maximum street tree canopy

With the knowledge that the District plants street trees an average distance of 40 feet apart, the maximum ideal tree canopy would have a 20ft radius where the dripline’s are touching. To generate this layer of maximum street tree canopy, we used a 20 foot buffer on the Casey Trees street tree point file creating the polygon layer used for analysis (Figure 4). The polygon layer was converted to raster and given a CODE and calculated for square meter area (Figure 5).

Methods for ‘moderate’ and ‘intensive’ scenario assumptions

The maximum street tree canopy numbers were totaled individually for roads, sidewalks and intersections (Table C4) and then within each sewershed. Using the same ArcGIS Spatial Analysis tools the existing canopy generated in previous analysis (Section 3.2) was subtracted from the maximum canopy. The result was the ‘intensive’ opportunity assumption.

The ‘moderate’ case scenario used the same methodology using a 15ft crown radius. An ideal canopy would have a graduated age class of trees where not all of the trees were at a maximum (20ft radius) or minimum at the same time. An illustration of the overlay for the ‘moderate’ case scenario analysis in ArcGIS is in Figure C4.

Figure C4: ‘Moderate’ streetscape scenario

Table C4: The Maximum street tree canopy opportunity by land cover type

CODE	Build Out Scenario	Square Meters Total
6000	Build Out over Pervious	5,715,465
7000	Build Out over Road	5,764,744
8000	Build Out over Intersection	2,422,222
9000	Build Out over Sidewalk	2,877,128
150000	BuildOut 15 Ft Scenario + above codes	
Xxx	The last three numbers are the unique CODE for sewershed.	

Street tree canopy data point file with a 20ft buffer (Figure C5) is overlaid onto the streetscape layer (Figure C6) to create the maximum opportunity for tree cover over the roads, sidewalks and intersection land cover types (Figure C7).

Figure 5: Street Tree Build Out

Figure 6: Impervious Surface Overlay

Figure 7: Build Out of Land Cover Type (see Table C4)

4. DISCUSSION

The tree canopy analysis for this report is an innovative method to understanding the extent of tree canopy in Washington, DC. It is easily applied to this model for environmental management highlighting the District's storm water issues. Tree canopy is a vital and dynamic component to each city and should be considered in every environmental and economic agenda. This appendix provides a simple methodology to do that.

APPENDIX D

POLICY RECOMMENDATIONS

An Advisory Team of key stakeholders from EPA, WASA, the District of Columbia Government, and Non-Governmental Organizations was formed to review and comment throughout the research and development of the Green Build-out Model and grant process. Based on the findings of the research, the Advisory Team recommended the following policy recommendations:

Overall

- Establish stormwater and sewer fees that are related to the runoff generated by a site. In conjunction with these fees, develop and implement a credit or other incentive program for sites using tree cover, green roofs, and other onsite stormwater management designs and technologies.
- Explore programs to calculate the effective perviousness of a site and establish effective perviousness minimums for development and redevelopment
- Create a GIS database system and protocols to monitor and measure performance toward increasing green roof and tree cover
- Provide leadership for implementation of intensive greening strategies on District government properties, facilities, and streetscapes
- Restructure public space permit process to emphasize reduction of impervious surfaces and continuous street tree canopy.

Green Roofs

- Determine and adopt District-wide green roof coverage objectives, develop a strategy to achieve those objectives with both the public and private sector, and provide incentives to build green roofs. Establish an office in the City charged and resourced with implementing the strategy and monitoring performance.
- Establish performance minimums for green roofs subject to incentives that would set requirements for stormwater retention and pollutant removal

Trees

- Determine and adopt District-wide urban tree canopy goals, and develop and implement an urban forestry management plan as specified in the Comprehensive Plan to attain these tree canopy goals.
- Establish, adopt, and enforce tree canopy requirements for parking lots, site development, and site redevelopment
- Increase the minimum tree box size in downtown DC and along streets with wide sidewalks
- Attain and maintain full street tree stocking (130,000 trees) through a rigorous program of monitoring, maintenance and replanting. Use large canopy trees in street tree locations whenever possible