RE-GREENING WASHINGTON, DC:

A Green Roof Vision
Based on Quantifying
Storm Water and Air Quality Benefits

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Introduction

This paper presents a quantitative assessment of the storm water and air quality benefits provided by green roofs at different coverage scenarios in Washington, DC. Quantifying these benefits allows the contribution of green roofs to be included in developing solutions to air and water quality problems in the District of Columbia, improving public health, optimizing capital investment in municipal infrastructure, and guiding future growth as the city redevelops.

The District of Columbia is a 61.4 square mile area, home to 572,000 residents, and the capital of the United States. In the last 30 years, the City:

Lost 200,000 residents to the surrounding metropolitan area [1]
Lost 64% of its areas with heavy tree cover[2]
Increased storm water runoff by 34%[3]

At this time, District of Columbia residents pay some of the highest taxes in the United States, yet the District:

Does not meet federal water quality standards for the Anacostia, Potomac, and Rock Creek Rivers
Must invest in a Long Term Control Plan (LTCP) to manage its combined sewer overflows (CSOs). Current cost is $1.9 billion for three large underground storm water storage tunnels.
Is not meeting federal air quality standards for ground-level ozone and particulate matter [4]
Is in jeopardy of losing approximately $120 million/ year in Federal Highway Funds for not meeting federal air quality standards
Has one of the highest asthma rates in the country: 6.5% of children[5] and 5% of adults[6]

Mayor Anthony Williams is committed to increasing the District's population by 100,000 residents by 2010 to revitalize the city and provide the tax base necessary to support city services. The mayor is also committed to ensuring that there is an overall benefit to the environment from this increased infill and redevelopment. His vision to clean up the Anacostia River and revitalize its neighborhoods led to a unique partnership between District and Federal Government and the establishment of the Anacostia Waterfront Initiative (AWI) in 2000. His legacy will also include the revision of the City's Comprehensive Plan, last updated in 1984, and the development and implementation of an Environmental Agenda to clean the City's air and water.

Approximately 15% of District land is covered with buildings and approximately 14 million square feet (sf) of additional building footprint area is proposed in the next 20 years[7], primarily in the downtown business area, near transportation corridors and metro stations, and in the Anacostia Waterfront Initiative area. By many indicators, Washington is currently considered to be one of the hottest real estate markets in the country.

While the design, construction, and operation of buildings account for significant economic opportunity in DC and 20% of all economic activity in the United States[8], buildings also account for 40% of raw material consumption, 35% of total energy use, 65% of electricity use, 12% of fresh water supplies, 88% of potable water supplies, and 30% of greenhouse gas emissions[9]. Therefore, green building and green infrastructure strategies are critical to minimizing the environmental impacts of development.

Green roofs provide significant opportunities to minimize building impacts and provide multiple environmental and economic benefits. In addition to reducing heat island effect, energy usage, and raw material consumption by typically doubling the life of the roof[10], green roofs provide air and water quality benefits.

Green roofs store rain and consequently reduce storm water runoff volumes and the rate of runoff. The District of Columbia is served by both combined and separate storm sewer systems. In a municipal separate storm sewer system (MS4), reducing runoff lowers the amount of untreated polluted storm water that discharges directly to receiving waters. By reducing the rate of runoff, green roofs help to control erosion around storm water inlet and outlet points. In a combined sewer system (CSS), where storm water and wastewater share the same pipes, green roofs improve water quality in receiving streams by reducing the number of combined sewer overflow discharges that occur when the system's capacity is exceeded by increased storm water volumes.

Green roofs, like all vegetation, provide air quality benefits. They remove ozone, particulate matter, and other pollutants from the air through physical and biological processes. Green roofs also reduce temperatures, which can preclude the chemical reaction that produces ground-level ozone.

Research Goals

The goals of this research are to:

1. Quantify the contribution green roofs can make toward improving air and water quality in the District of Columbia at different green roof coverage scenarios
2. Assess benefits at different coverage scenarios and propose a green roof coverage objective to form the basis of a Green Roof Vision for DC
3. Identify next steps and areas for further study

Methodology

General Approach

This research determines and assesses the water and air quality benefits at different green roof coverage scenarios for existing buildings and proposed development throughout the District. The storm water benefits were estimated using a model created by LimnoTech, Inc, which developed the modeling for the DC Water and Sewer Authority's (WASA) Long Term Control Plan for combined sewer overflows. The air quality benefits were estimated using the Urban Forest Effects model (UFORE), developed by the United States Department of Agriculture (USDA) Forest Service. A green roof coverage objective was proposed based on the estimated water and air benefits, the mix of existing and proposed development, and projected and actual green roof coverage in other cities.

Green Roof Opportunity Area

The opportunity area for green roof coverage in the District of Columbia was determined by considering all existing and proposed buildings with footprints greater than 10,000 square feet. This size building is typically a commercial, industrial, government, or large residential building and was selected for the relative ease of widespread green roof implementation.

Existing building footprints were obtained from the DC Office of the Chief Technology Officer (OCTO) and reflect conditions as of 2002. For these buildings, the rooftop area was assumed to equal the building footprint area. The proposed development area was obtained from the DC Office of Planning and includes both planned and proposed projects that will come online in the next 2-15 years. Based on discussions with the Office of Planning, the rooftop area for proposed development was assumed to cover 80 percent of the lot.

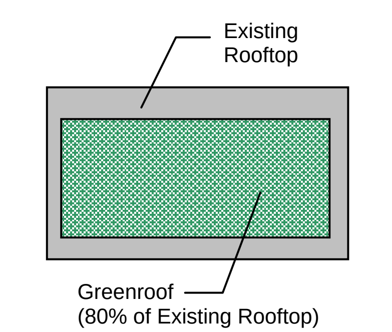


Figure 1: Green roof-ready area

The amount of rooftop area available for green roof coverage was identified as the "green roof ready-area". It was assumed that green roof vegetation would cover 80% of the area of each roof to account for standard rooftop features such as the HVAC system and roof access (Figure 1).

Buildings comprise approximately 15 percent of the District's total land area. Using 80% of the footprint of buildings greater than 10,000 square feet, Washington DC currently has approximately 75 million square feet of rooftop area available for green roof projects, or 29 percent of the total building area. Table 1 summarizes the building areas for the entire city. Figure 2 shows the spatial distribution of the "green roof-ready" buildings in the District.

Table 1: Summary of land and building areas in Washington, DC

Land/Building Description	Area (sq ft)	Percentage
Total land area in DC	**1,711,500,000**	
Total building footprint in DC	**262,043,000**	**15% of total land area**
Existing	247,781,000	95% of total building footprint area
Proposed (new)	14,262,000	5% of total building footprint area
Total building footprint >10,000sf	**93,713,000**	**36% of total building footprint area**
Existing	79,740,000	85% of bldg>10,000sf area
Proposed (new)	13,973,000	15% of bldg>10,000sf area
Total "green roof-ready" area (80% of footprint)	**74,970,000**	**29% of total building footprint area**
Existing	63,792,000	85% of "green roof-ready" area
Proposed (new)	11,178,000	15% of "green roof-ready" area

Coverage Scenarios

Six scenarios were used to explore benefits of green roof coverages ranging from 0% to 100% coverage. Coverages were calculated as a percentage of the green roof-ready area. For example, 100% green roof coverage is in effect 80% of the rooftop area for buildings over 10,000 sf; 20% green roof coverage is in effect 16% of the rooftop area for buildings over 10,000 sf (Table 2).

Table 2: Summary of building areas used in green roof benefit calculations

Scenario (% Green roof Coverage)	Total Green Roof Ready Area (sf)	% of Roof Space on Buildings > 10,000 sf	% of Total Building Footprint Area in DC
Case 1 (0%)	0	0%	0%
Case 2 (20%)	14,994,000	16%	6%
Case 3 (40%)	29,988,000	32%	11%
Case 4 (60%)	44,982,000	48%	17%
Case 5 (80%)	59,976,000	64%	23%
Case 6 (100%)	74,970,000	80%	29%

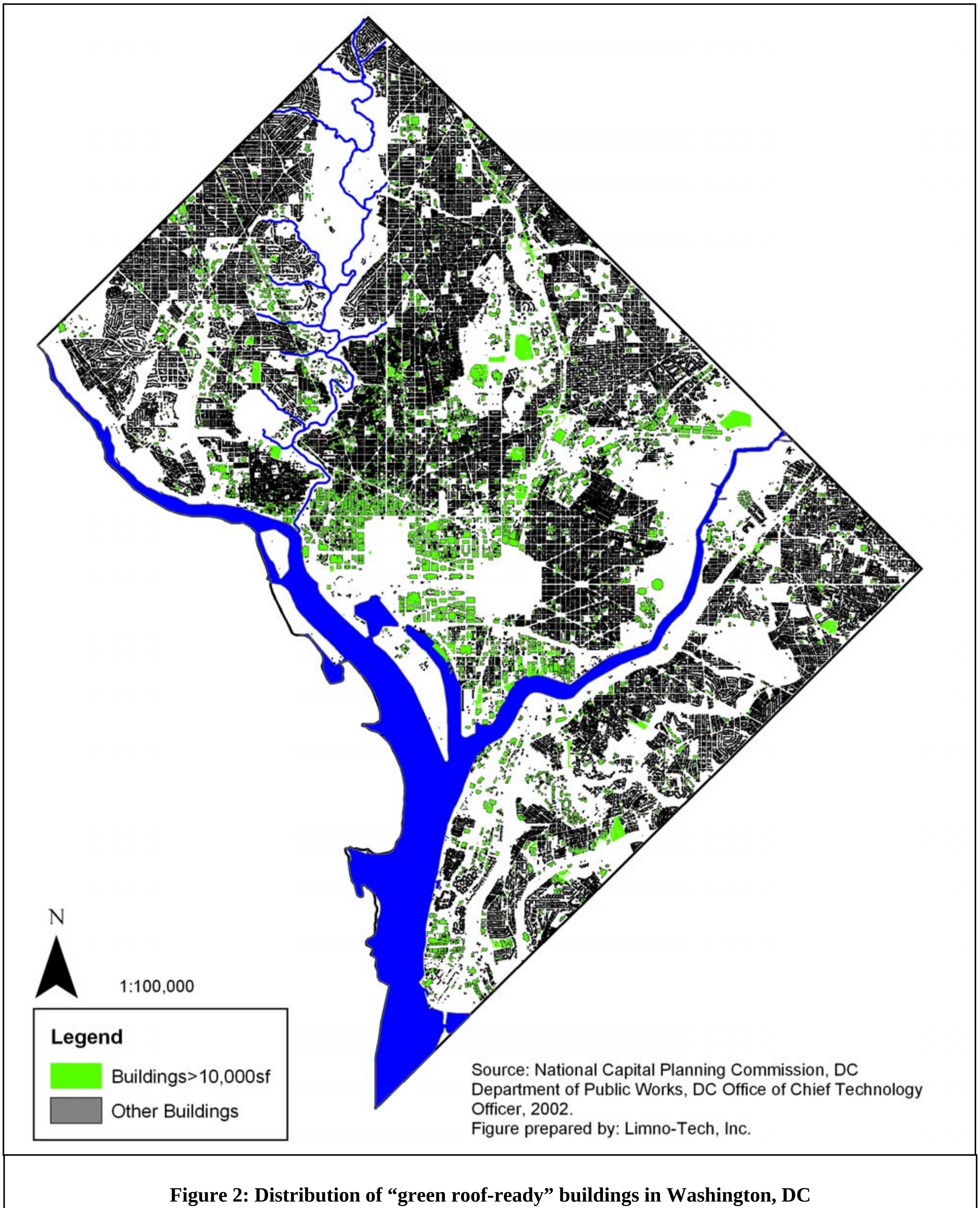


Figure 2: Distribution of “green roof-ready” buildings in Washington, DC

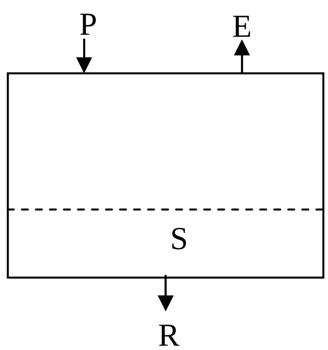
Types of Green Roofs

Extensive green roofs utilize soil depths of 2-6 inches, require minimal maintenance, and typically can be built with no additional structural support to the building thereby offering greater opportunity for widespread application. Intensive green roofs utilize more than 6 inches of soil, can support greater plant mass such as shrubs and trees, require greater maintenance for plants, and typically involve additional structural support to bear the added weight of the green roof. For each of the six scenarios, it was assumed that 80% of green roofs would be extensive green roofs and 20% would be intensive.

Storm Water Model

The storm water model was built by Limno-Tech to quantify the cumulative contribution green roofs make toward reducing storm water runoff and combined sewer overflow events in the District of Columbia. The model was designed specifically for the District of Columbia's sewer system, where approximately one-third of land is served by a CSS and two-thirds by an MS4. Storm water benefits were determined for the District as a whole and within the three watersheds of the District: the Anacostia River, the Potomac River, and Rock Creek (Figure 4).

A simple mass balance was used to estimate roof runoff, as illustrated in Figure 3.



$$\mathbf{R} = \mathbf{P} - \mathbf{E} - \mathbf{S}$$

(roof runoff) (precipitation) (evapotranspiration) (storage)

Figure 3: Mass balance used to calculate roof runoff

The storm water benefits were calculated based on "average year" conditions. A review of 50 years of rainfall data at Ronald Reagan National Airport showed that the year 1990 is most representative of an average year. The hourly precipitation record for 1990 was obtained from the National Weather Service. The mass balance assumes green roof storage is regenerated through evapotranspiration. Evapotranspiration rates were obtained from the Virginia State Climatology Office. Based on these rates, it was estimated that storage would completely regenerate if more than four days elapse between rain events. The model assumes 2 inches of rainwater storage for extensive green roofs and 4 inches for intensive.[11] Conventional roofs store approximately 0.04 inches of rain, as determined by using the Natural Resources Conservation Service (NRCS) curve number methodology.

The reduction in CSOs was calculated by comparing the storage capacity provided by green roofs to the overflow volume discharged at each combined sewer outfall for each rain event. If the green roof storage capacity is greater than the overflow volume, then no overflow event occurs. If the storage capacity is less than the overflow volume, an overflow event will occur. CSO discharge volumes for each rain event in 1990 were obtained from the Long Term Control Plan.

DC WASA and the District of Columbia Department of Health, Watershed Protection Division reviewed the findings to assess their significance.

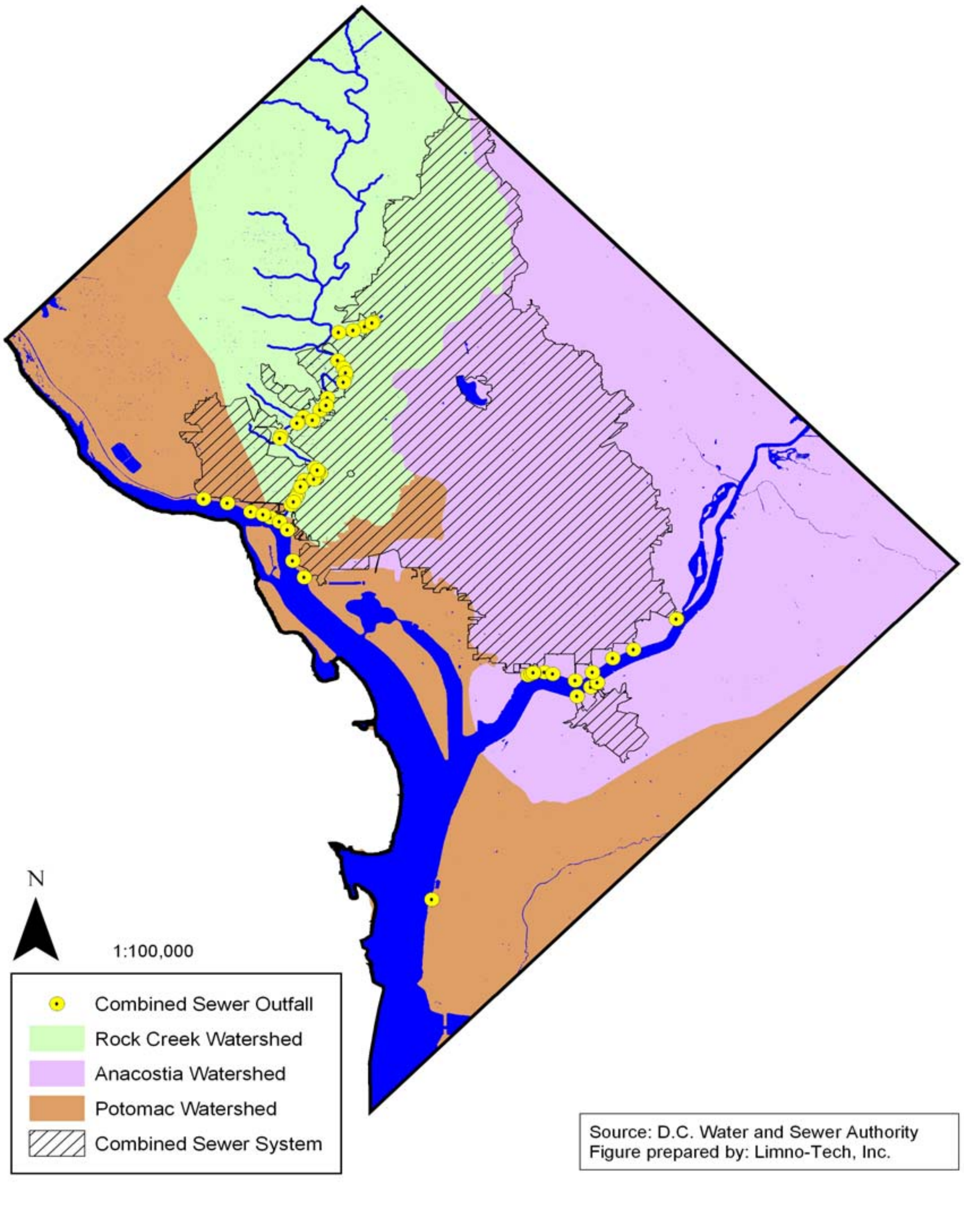


Figure 4: Location of watersheds, sewer systems, and CSO outfalls in the District

Air Quality Model

The USDA Forest Service's Urban Forest Effects (UFORE) model was used to determine the air quality benefits provided by green roofs. This model, developed by Dave Nowak at the Syracuse Research Station, uses local hourly pollution concentrations, meteorological data, and plant-specific air pollution removal rates to quantify the benefits provided by urban forests. Air pollutants include: ground-level ozone, particulate matter, sulfur dioxide, nitrogen dioxide, and carbon monoxide.

The UFORE model air pollutant removal depends on the type of vegetation. The UFORE model has been developed for trees, shrubs, and grasses, however no removal rate data exists for sedums, which are the typical vegetation type for extensive green roofs in the Washington area. A 50:50 mix of grasses and evergreen shrubs was used by researchers at the University of Toronto's Environment Canada and recommended by the USDA Forest Service to estimate typical green roof composition. It was assumed that this combination will approximate the DC-wide mix of evergreen and deciduous vegetation used in intensive and extensive green roofs, both in terms of seasonal foliage change and the size and shape of the leaves.

The air quality benefits from green roofs were then compared to the air quality benefits obtained from street trees for the District of Columbia as determined in the Casey Trees 2002 Street Tree Inventory[12].

Target Green Roof Coverage

The determination of the target green roof coverage was based on:

- Significance of the benefits provided at the different green roof coverage scenarios
- Green roof coverage in other cities
- Ease of implementation in Washington, DC

The storm water and air quality benefits were then determined for this target green roof coverage.

Findings

Storm Water Model Findings

On a per roof basis, the storm water mass balance model predicted that an extensive green roof can reduce roof runoff volumes by approximately 65 percent, while an intensive roof can reduce runoff by 85 percent. Using a combination of 80% extensive and 20% intensive ratio across all green roof-ready buildings in the District, roof runoff volume would decrease by as much as 69% as compared to conventional rooftops (Figure 5).

On a cumulative basis, the findings of the storm water runoff model for all six cases over an average year of precipitation are shown in Table 3. As Case 2 shows, at the minimum coverage scenario of 20% of all "green roof-ready" buildings, 23 million gallons would be added to the city's storage capacity. This is the equivalent of approximately 80 Olympic sized swimming pools. Over the course of an average year, this translates into 297 million gallons of precipitation that would be captured by the green roof instead of entering the combined or storm sewer system. At 100% coverage, if all of the buildings over 10,000 square feet were green roofed, almost 1,500 million gallons could be stored throughout the course of a year.

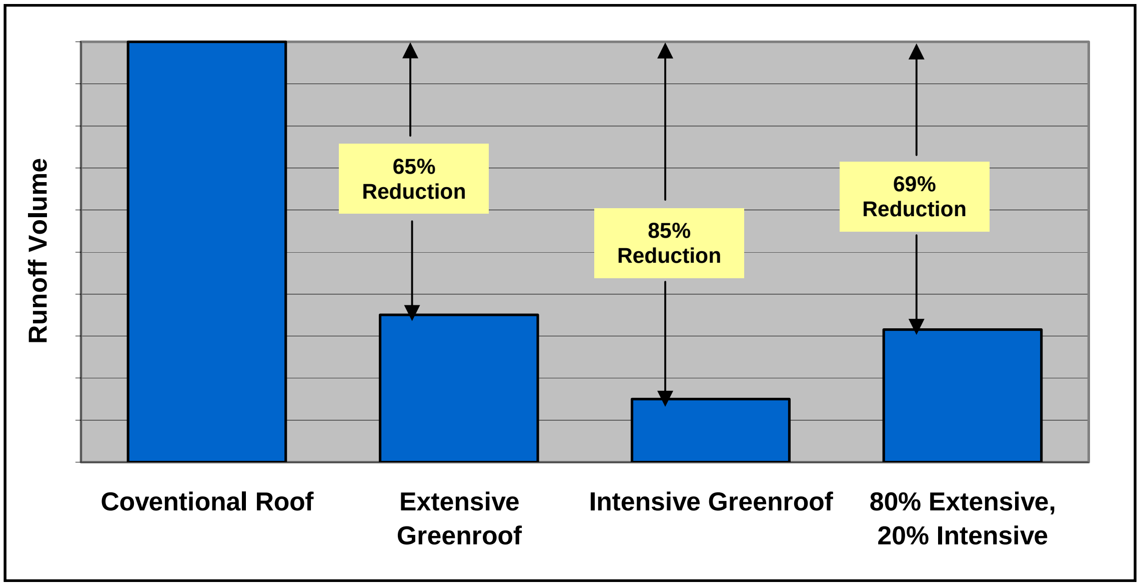


Figure 5: Comparison of roof runoff for conventional roofs and green roofs

The reduction in city-wide storm water runoff volume that green roofs would provide in an average year is shown in the final column of Table 3. While the absolute values of storm water volume retention are considerable, they comprise a small percentage of the total runoff generated by the entire city. The magnitude of the impact of green roofs is diluted when analyzed at the city-wide level because buildings covering 10,000 square feet or more make up just 6% of the total city area. Yet, in areas of high-density development dominated by impervious land covers, such as the downtown commercial core, green roofs would provide significant reductions in storm water volume.

Table 3: Impact of green roofs on storm water runoff volume

Scenario (% Green roof Coverage)	Total Green roof Area (Square feet)	Total Available Roof Storage (Million gal)	Annual Storage Provided by Green roofs (Million gal)	Annual Citywide Runoff Volume (Million gal)	Reduction in Annual Citywide Runoff
Case 1 (0%)	0	2	0	25,550	0%
Case 2 (20%)	14,994,000	23	297	25,250	1.2%
Case 3 (40%)	29,988,000	45	594	24,950	2.3%
Case 4 (60%)	44,982,000	68	891	24,660	3.5%
Case 5 (80%)	59,976,000	90	1,188	24,360	4.6%
Case 6 (100%)	74,970,000	113	1,485	24,060	5.8%

Because green roofs prevent and delay roof runoff, they also impact the number of combined sewer overflow events in the District. For the different green roof scenarios, Table 4 shows the number of rainfall events that trigger CSOs in an average year in each of the District's three watersheds. It also shows how the number of overflow events would decrease under each of the six green roof scenarios. While increasing the number of green roofs would have no effect on the number of rain events that cause overflows in the Potomac River watershed, even 20% green roof coverage would significantly lower the number of rain events leading to overflows into Rock Creek. Rain events leading to overflows in the

Anacostia watershed would be moderately reduced with increasing green roof coverage. It is important to note that even one such rain event has adverse effects on water quality, since the receiving streams for the discharges experience high bacteria levels, depletion of dissolved oxygen, and accelerated erosion of stream banks.

Table 4: Number of annual rain events that trigger combined sewer overflows

Scenario	Anacostia River	Potomac River	Rock Creek
Case 1 (0%)	73	72	28
Case 2 (20%)	71	72	18
Case 3 (40%)	70	72	18
Case 4 (60%)	67	72	14
Case 5 (80%)	67	72	12
Case 6 (100%)	66	72	12

When the capacity of the combined sewer is exceeded during a rain event, the excess flow is discharged directly to the Anacostia River, the Potomac River, or Rock Creek through a CSO outfall. There are 60 CSO outfall points in the District, 17 in the Anacostia River, 14 in the Potomac River, and 29 in Rock Creek (Figure 3). A single rain event could trigger anywhere from zero to 60 discharges depending on its intensity and duration. There are 73 rain events in an average year that can trigger discharges at any of the 60 outfalls, resulting in many discharges of unprocessed sewage to the District's river system. Table 5 shows the reduction in the total number of CSO discharges triggered by rain events in an average year for the different green roof scenarios.

Table 5: Reduction in the number and volume of CSO discharges triggered by annual rain events

	Anacostia River		Potomac River		Rock Creek		Total	
# of CSO Outfalls	17		14		29		60	
	Number	*Volume*	*Number*	*Volume*	*Number*	*Volume*	*Number*	*Volume*
Case 1 (0%)	0%	0 MG	0%	0 MG	0%	0 MG	0%	0 MG
Case 2 (20%)	7%	52 MG	13%	15 MG	38%	8 MG	13%	75 MG
Case 3 (40%)	9%	104 MG	24%	33 MG	46%	13 MG	19%	150 MG
Case 4 (60%)	13%	155 MG	26%	38 MG	56%	17 MG	23%	210 MG
Case 5 (80%)	15%	206 MG	28%	48 MG	61%	20 MG	25%	273 MG
Case 6 (100%)	17%	254 MG	32%	56 MG	62%	23 MG	28%	334 MG

When Table 5 is analyzed alongside Table 4, it becomes apparent that although green roofs have only a moderate impact in reducing the annual number of rain events that lead to discharges, they significantly lower the number of discharges that occur for each rain event. Implementing green roofs on just 20% of green roof-ready buildings would prevent 13% of the discharges that occur every year, thereby keeping approximately 75 million gallons of raw sewage from entering the District's river systems.

In addition to CSO benefits, green roofs will also impact the volume of storm water that enters DC's separate sewer system. The separate storm sewer flows are discharged directly to the receiving waters without treatment, and carry many pollutants such as oils, nutrients, bacteria, and metals.

WASA has stated that these storm water benefits are significant for both the CSO and MS4 areas with respect to meeting DC water quality objectives, and that they could potentially provide significant savings in capital investment in the LTCP. The District Department of Health agrees and has stated that the findings of this analysis will serve as the basis for creating additional incentives and regulations to support wide-scale implementation of green roofs.

Air Quality Model Findings

For the UFORE model, a 50-50 grass/evergreen shrub mix was used to approximate the average composition of green roofs. Figure 6 displays the proportions of the various pollutants removed by this type of green roof vegetation mix. As the figure shows, the highest pollutant removal is for ozone (O_3), followed by particulate matter less than 10 microns in diameter (PM10). High concentrations of these two pollutants are responsible for the federal air quality standard violations in the Washington Metropolitan area. Green roofs also remove substantial amounts of sulfur dioxide (SO_2), nitrogen dioxide (NO_2), and carbon monoxide (CO).

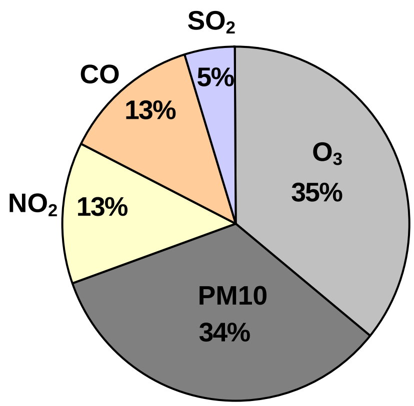


Figure 6: Proportions of air pollutants removed by green roofs

Because an average vegetation mix was used in the UFORE model, the pollution removal at different coverage scenarios depends only on the green roof area. Table 6 shows the total metric tons of these air pollutants that would be removed annually under the different green roof coverage scenarios.

In order to assess the significance of the air quality benefits provided by green roofs, the air pollutant removal values were compared to those provided by street trees. The UFORE model had previously been run for the 105,900 street trees in the District[13], taking into account the species mix, size, and condition of those trees. Using the total pollution removed by all of the street trees in the District, the removal rate of an "average" street tree was calculated for each pollutant.

Table 6 lists the number of street trees that would remove an equivalent amount of pollution as the green roofs under each coverage scenario.

Table 6: Green roof air pollutant removal and street tree equivalence

Scenario (% Green roof Coverage)	Total Annual Pollutant Removal (Metric Tons)	Equivalent # of DC Street Trees				
		O3	PM10	SO2	NO2	CO
Case 1 (0%)	0	0	0	0	0	0
Case 2 (20%)	11.6	17,300	23,000	19,100	18,700	19,300
Case 3 (40%)	23.2	34,500	46,000	38,300	37,400	38,500
Case 4 (60%)	34.8	51,800	68,900	57,400	56,100	57,800
Case 5 (80%)	46.4	69,000	91,900	76,500	74,800	77,000
Case 6 (100%)	58.0	86,300	114,900	95,700	93,500	96,300

Target Green Roof Coverage

The determination of the target green roof coverage was based on:

Significance of the benefits provided at the different green roof coverage scenarios
Green roof coverage in other cities
Ease of implementation in Washington, DC

Findings show storm water and air quality benefits to be significant at the lowest green roof coverage scenario of 20%. A 20% green roof coverage would prevent, on average, 13% of CSO discharges, thereby keeping 75 million gallons of raw sewage from entering the District's river systems. This coverage would also provide the same air quality benefits as approximately 19,500 trees. Based on efforts in other municipalities, a 20% green roof coverage appears to be a reasonable and feasible target for the District of Columbia.

At this time Germany is estimated to have anywhere from 14 - 27% green roof coverage depending on considerations regarding existing flat roofs, new construction, all buildings, certain cities, or the country at large. The city of Chicago has implemented policies and incentives that encourage the installation of green roofs on new construction and major renovations, which has resulted in over 120 projects totaling over 1.6 million square feet of green roof in various stages of contracted development. The city of Portland Oregon has developed policies and incentives to facilitate wide-scale implementation of green roofs. Once the City's Clean River Incentive and Discount Program is running, green roof coverage is expected to quickly and significantly increase.

A number of initiatives underway in DC provide an opportunity to facilitate similar wide-scale implementation of green roofs in the District. These include the establishment of the new DC Department of the Environment, the update of the Comprehensive Plan, and the Water and Sewer Authority's Long Term Control Plan to manage Combined Sewer Overflows.

Based on these factors, a starting target green roof coverage for DC was assumed to be 20%. A scenario for achieving 20% coverage was then developed by prioritizing coverage on proposed development in order to facilitate implementation. In this case, if 80% of the proposed green roof-ready building areas and 20% of the existing green roof-ready building areas had green roofs, there would be 21.7 million square feet of green roof area in DC. This is the approximate equivalent of 20% of the total roof area on all buildings greater than 10,000 square feet.

Water and Air Quality Benefits for the Target Green Roof Coverage

The storm water and air quality benefits were calculated for the target green roof coverage. Tables 7 and 8 below show the findings of the storm water model assuming that 20% of existing and 80% of new development have green roofs. The same assumptions used in the original six scenarios apply. The green roofs would add 33 million gallons to the city's storm water storage capacity. The cumulative storage over the course of an average year would exceed 430 million gallons. The number of CSO discharges would decrease by 15%.

Table 7: Storm water runoff reduction for target green roof coverage scenario

Target Green Roof Coverage	Total Green roof Area (Square Feet)	Total Available Roof Storage (Million Gal)	Annual Storage Provided by Green roofs (Million Gal)	Reduction in Annual Citywide Runoff
Existing Dev (20% Green roofs)	12,758,000	19	253	1.0%
Proposed Dev (80% Green roofs)	8,943,000	13	177	0.8%
Total	21,701,000	33	430	1.7%

Table 8: Reduction in the number and volume of CSO discharges for target green roof coverage

	Anacostia River		Potomac River		Rock Creek		Total	
# of CSO Outfalls	17		14		29		60	
	#	*Volume*	*#*	*Volume*	*#*	*Volume*	*#*	*Volume*
Existing Dev (20% Green roofs)	5%	43 MG	13%	14 MG	37%	8 MG	12%	65 MG
Proposed Dev (80% Green roofs)	6%	36 MG	3%	3 MG	2%	2 MG	4%	41 MG
Total	9%	79 MG	14%	16 MG	39%	9 MG	15%	104 MG

Air pollution removal from green roofs at the target coverage is shown in Figure 7. On average, the air quality benefits are equivalent to those that 28,000 street trees would provide.

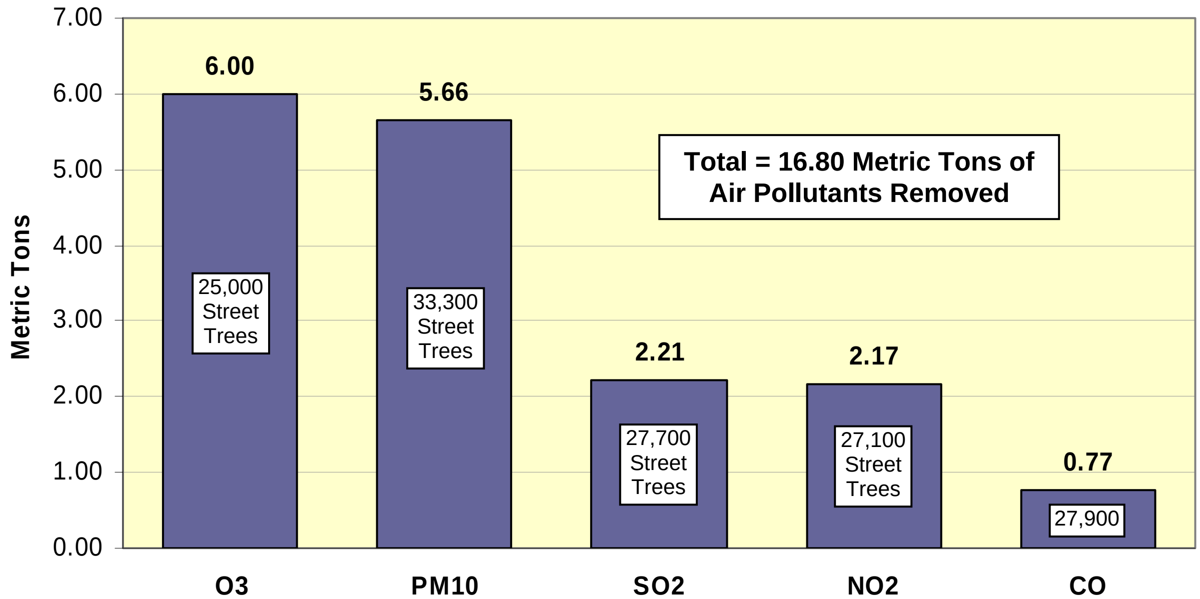


Figure 7: Air pollutant removal for target green roof scenario

Summary Findings at Target Green Roof Coverage

If 80% of all proposed and 20% of all existing green roof-ready buildings had green roofs, the resulting 21,700,000 square feet of green roofs would provide the following storm water and air quality benefits:

Storm Water Management

30 million gallon increase in the city's storm water storage capacity
(Proposed Long-Term Control Plan tunnels could store 194 million gallons)

430 million gallons of rainwater stored over the course of an average year
(The equivalent of 1700 Olympic-sized swimming pools)

1.7% reduction in citywide runoff

15% reduction in the total number of CSO discharges per year
- 9% reduction in discharges to the Anacostia River
- 14% reduction in discharges to the Potomac River
- 39% reduction in discharges to Rock Creek

The DC Water and Sewer Authority (WASA) has stated that these storm water benefits are significant with respect to meeting DC water quality and storm water objectives, and that they could potentially provide significant savings in capital investment in the LTCP. The District Department of Health agrees the findings of this analysis will serve as the basis for creating additional incentives and regulations that support more wide-scale implementation of green roofs.

Air Quality

Annual removal of 16.8 tons of air pollutants (O_3, SO_2, CO, NO_2, and particles)
(The equivalent of approximately 28,000 street trees)

Annual removal of 6.0 tons of ground-level ozone from the air
(The equivalent of approximately 25,000 street trees)

Annual removal of 5.7 tons of particles from the air
(The equivalent of approximately 33,000 street trees)

The air quality benefits are approximately 25% of the contribution of DC's 105,900 street trees, suggesting that green roofs would make a significant contribution to air quality improvements. Further work is required to determine additional significance of these findings for air quality planning in the District.

Recommendations

Based on the findings at the target green roof coverage, the recommended green roof coverage objective is:

20 years/ 20% coverage/ 20 million sf

To meet the "20-20-20" objective would require leadership from both the DC and Federal Government to direct that all new buildings in the District have a green roof, and that every existing roof be replaced with a green roof when it needs to be replaced. Given that roofs in the Washington area typically last 10-20 years, significant environmental improvements would be achieved in less than one generation.

Next Steps

The next steps are to communicate the findings of this study, achieve support for the proposed "20-20-20" Vision, finalize objectives, and develop an implementation strategy in partnership with city and federal agencies and stakeholders. Implementation of the Green Roof Vision for DC will require coordination and integrated resource management amongst the outstanding planning initiatives underway in the District:

Establishment of the new DC Department of the Environment
Mayor's Environmental Agenda
Mayor's Anacostia Waterfront Initiative
Update of DC Comprehensive Plan
Water and Sewer Authority's Long Term Control Plan (LTCP) to manage CSOs
Metropolitan Washington Council of Government's State Implementation Plan to meet air quality targets

Areas for Further Study

Potential areas for further study to support District-wide implementation include:

Hydrologic Modeling of Storm Water Benefits

The storm water modeling presented in this paper provides a general understanding of the impacts of green roofs on storm water quantity and combined sewer overflows. More detailed and robust modeling is necessary to understand how green roofs can be used to minimize combined sewer overflows and influence the detailed design of the proposed storage tunnels as described in the WASA's LTCP.

Future modeling efforts would include building a detailed hydrologic and hydraulic (H&H) model using software such as the Danish Hydraulic Institute MOUSE program. This model was already used for the development of the city's LTCP, and could be built upon to determine the effects of green roofs on storm water quantity and quality. The advantage of using a robust H&H model is the ability to calibrate and validate to real time conditions, and predicting the frequency, volume and duration of CSOs relative to long term rainfall records and the state or condition of the combined sewer system (such as existing conditions or future condition with various CSO controls).

Green Build-out Model for DC

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, creating a green build-out model for Washington DC, will quantify the benefits of trees and green roofs under different coverage scenarios. This data can then be used to guide the form of future development and optimize capital investment in municipal infrastructure.

Heat Island Modeling

Heat island modeling depends on an area's climate, topography, and pattern of development. Because heat island simulations involve the creation of a mesoscale atmospheric simulation model, their use in estimating the impacts of green roofs on ambient air temperature has been limited. The few green roof heat island studies that have been completed have yielded promising results. Findings from an Environment Canada study of Toronto in 2002, indicate that relatively minimal green roof implementation, approximately 6% of the total available roof space, would reduce summer air temperatures in the city by 1-2^{o}C (1.8-3.6 ^{o}F). Creating a heat island model for Washington DC would allow a prediction of the overall reduction in temperature, as well as the air quality benefits and energy savings resulting from decreased demand for air conditioning.

Economic Cost/Benefit Analysis

With green roof cover objectives and associated benefits quantified, cost estimates, cost benefit analyses, and implementation strategies for city-wide implementation can be developed. In addition to storm water and air quality benefits, other benefits of green roof cover can be quantified and considered for implementation to reflect the value of the multiple benefits provided.

Final Thoughts

There is an unprecedented convergence of planning initiatives and opportunities to develop and retrofit the District of Columbia with green infrastructure.

This research quantifies the contribution made by green roofs to improve the City's air and water, and is a first step to determining the optimal balance of green and gray infrastructure to reduce capital investment, provide other public and private benefits, and create a legacy for the capital of the United States as a Model Green City.

Storm water and air quality benefits are only two of the many benefits green roofs and green infrastructure provide. The value of green roofs should be evaluated in context with the other multiple benefits.

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