INTEGRATED WATER USE IMPACT ASSESSMENT FOR DC URBAN INFRASTRUCTURE

FINAL REPORT

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1. EXECUTIVE SUMMARY

Problem. DCWRRI is currently considering "Research on clean cities and sustainable urban infrastructure that minimizes water use or improves or minimizes impacts to water quality." The research proposed herein addresses tradeoffs with respect to expanding the physical capacity of infrastructure assets (e.g., pipes) against improving sequestration and containment measures (e.g., local stormwater containment or detention) through collaboration with customers.

Objectives and Methodological Contributions. The objectives of this work as originally proposed are as follows:

> *Major Contribution #1—Sustainability Measurement and Evaluation.* **The objective of this research is to identify cost-effective approaches to reduction of the water use footprint of The George Washington University (GWU).** In collaboration with the GWU Office of Sustainability and the DCWRRI, we will integrate life cycle cost analysis and life cycle impact assessment to evaluate GWU infrastructure investments intended to reduce its water use footprint. Potential investments will be identified through multi-criteria decision analysis (MCDA) and subsequently evaluated by a team of GWU students led by a Department of Engineering Management and Systems Engineering (EMSE) Ph.D. student. Dr. Royce Francis, an assistant professor in EMSE, will direct this team.
>
> *Major Contribution #2—Integration of LCIA and LCCA*. In this proposal, we will use the cradle to cradle life cycle of a selected system as the system boundary, units or monetary value of system-relevant purchases as the functional unit of analysis, and employ a synthetic framework for the combination of life-cycle impact assessment (LCIA) and life cycle cost (LCC) and risk assessment (RA) methodologies where the impact of concern is life cycle cost over the life cycle of an infrastructure project. **This proposal will demonstrate the potential for a natural synergy between life-cycle cost analysis and life-cycle impact assessment, while also making methodological contributions to the practice of water footprinting.**

Project Objectives. While the work proposed above underwent some modifications, the first objective was addressed through the first portion of the work, while the second objective was changed to reflect the following:

> *Benefit-Cost Analysis for LID Adoption using LIDRA.* In this project, we use life cycle cost analysis (LCCA) to **evaluate the potential for combined sewer overflow (CSO) reductions through the implementation of low-impact development (LID) in the District of Columbia**.

Outcomes. This research has addressed the DC Water stormwater management problem by developing a methodology that may be used to evaluate infrastructure investments intended to reduce an organization's stormwater loading. This methodology proceeds in two parts. First, decision analysis is undertaken to construct a sustainability definition for interested stakeholders. Second, LCCA is used to evaluate the most important uncertainties remaining in the LID implementation portion of the DC Water long-term control plan (LTCP). The George Washington University was a testbed for part one of this methodology. Efforts to reduce stormwater loading are part of a comprehensive approach to the reduction of water use impacts. As a result, this methodology will be developed through collaboration with The George Washington University's Office of Sustainability efforts to reduce the University's water use impacts. This research has demonstrated the following:

1. This research has developed a **methodology for evaluating the cost effectiveness of stormwater runoff reduction investments**;
2. This research has **described the use of decision analysis to perform sustainability measurement broadly, and we have shown its application in the stormwater management context**.
3. This research has **identified research priorities for system analysis evaluating the use of LID techniques for reducing CSO occurrence in the District of Columbia**.

2. INTRODUCTION

At the time this research was proposed, DCWRRI was considering "Research on clean cities and sustainable urban infrastructure that minimizes water use or improves or minimizes impacts to water quality." The research we proposed intended to address tradeoffs with respect to expanding the physical capacity of infrastructure assets (e.g., pipes) against improving sequestration and containment measures (e.g., local stormwater containment or detention). This goal was in line with DC Water's ongoing attempts to negotiate U.S. EPA support for a LID demonstration project, and more flexibility in implementing its LTCP as stipulated by their Consent Decree.

Initially, we proposed to address the DC Water stormwater management problem by developing a methodology that may be used to evaluate infrastructure investments intended to reduce an organization's stormwater loading, making the following contributions:

1. This research will develop a **water use evaluation methodology** that might be deployed by other large DC Water customers;
2. This research will develop a **methodology for evaluating the cost effectiveness of stormwater runoff reduction investments**;
3. This research will make a methodological contribution to the field of life cycle analysis through **developing an approach to evaluating water use impacts as an impact category in life cycle impact assessment**.

Although some modest changes to the scope of this work were made, the overall goals guided the modification and conduct of this research. **Specifically, the objective of this research was to develop a decision analysis model that could be used to circumscribe the definition of sustainability within The George Washington University (GWU).** This methodology could then be extended to evaluate the definition of sustainability within other organizations or institutions with multiple operational divisions.

In parallel to this decision analysis piece, we set out to understand the potential impact of DC Water stormwater credits or LID installation incentives on its CSO reductions. **To this end, the other objective of this research was to conduct a benefit-cost and uncertainty analysis concerning the reduction of CSO events in the District of Columbia using LCCA**. Our system boundary was defined as the geographic area contained by the CSO drainage area. The methodology we used was low impact development rapid assessment (LIDRA) to evaluate the reduction of impervious surfaces on CSO event occurrence. This research is intended to be a tool for identifying priority future research avenues in order to ensure the effectiveness of DC Water's LID implementation plans.

This report is an exposition of the methodology and results of each of these parallel research approaches. The structure of the report is as follows. In the next chapter, we present the water sustainability definition research corresponding with the first objective listed above. This chapter has been submitted for publication in *Sustainability: Science, Practice, and Policy*, and was co-authored by the PI and one of the graduate research assistants working on the project. The following chapter illustrates the methodology and approach to the uncertainty analysis using LIDRA. This research is very much in progress, so while the results of this section are not complete, some important research objectives are indicated by our current work. We close by discussing some implications of our work and some future research ideas that have been developed as a result of this work funded by the DCWRRI and DC Water.

3. URBAN WATER SUSTAINABILITY DEFINITION: A DECISION-ANALYTIC APPROACH

[The work reported in this section has been submitted for publication as Francis, R.A. and Reyes-Jones, C. (2012) "Urban Water Sustainability Definition: A Decision Analytic Approach," *Sustainability: Science Practice, and Policy* (Under Review)]

3.1 INTRODUCTION

The purpose of this chapter is to describe the development of a decision analysis model that can be used to circumscribe the definition of sustainability within an organization or institution with multiple operational divisions. Ultimately this approach, demonstrated by application to a university's water sustainability strategy, might be used to engage large stakeholders in the decision process for infrastructure owners and planners when developing incentives for green infrastructure development. For example, our case study is contextualized in the idea that such a process might help water utilities more effectively structure incentives for their stakeholders to encourage installation of low-impact development (LID) stormwater control measures by understanding how they incorporate water resource concerns into their overall strategy. The project required this model to be tested in a real world situation; in this case The George Washington University (GW) was used as a case study with the model focusing on water use in the context of the university's sustainability goals.

The objective of this project was to identify the GW definition of sustainability, and discuss how this definition might be operationalized with respect to water use impact and water footprint objectives. This project is compelling because, while many universities have discussed approaches to energy conservation and greenhouse gas reduction goals, GW is among a group of first-moving American universities in discussing approaches to water use footprint reduction goals. Table 1 lists GW market basket and other domestic universities with their water target and water measurement indicator status as of FY 2008 (*1*). From Table 1, we see that while most of these schools have identified water measurement indicators, few of these schools have identified targets for water conservation and consumption reduction goals. While Cockerill and Carp's (*2*) exposition of the role of policy windows in achieving sustainability goals in the multi-stakeholder context is an important example of the growth of academic emphasis on water and water resource sustainability in universities, the focus on water and water resources has grown less robustly than that of energy and waste management. As a result, the definition and methodology developed in this study may be exported to other universities for refinement and further development.

The structure of this chapter is as follows. First, we undertake an overview of the existing GW Water Use impact goals. Second, we present our approach to sustainability definition as a learning process. Third, we provide an overview of our approach to this research, including a high-level overview of decision analysis. Finally, we report the results of our study and discuss its implications for sustainability measurement.

Table 1. Existence of institutional water target, conservation policy, or measurement indicators at GW market basket (italicized) and other domestic universities (normal type) as of FY 2008.

University	Does the university have a water target? (Y/N)	Does the university have a water conservation policy or measurement indicators? (Y/N)
American University	*N*	*Y*
George Mason University	*N*	*Y*
Emory University	*N*	*Y*
Vanderbilt	*N*	*Y*
New York University	*N*	*Y*
USC	*N*	*Y*
Washington University	*N*	*Y*
University of Maryland	*N*	*Y*
BU	*N*	*N*
Duke University	*N*	*Y*
Georgetown University	*N*	*N*
Northwestern University	*N*	*N*
Southern Methodist	*N*	*Y*
Tufts	*N*	*Y*
Tulane	*N*	*N*
University of Miami	*N*	*N*
University of Pennsylvania	*N*	*N*
University of Colorado	Y	Y
University of North Carolina at Chapel Hill		Y
University of California - San Diego	Y	Y
Stanford University	Y	Y
University of Michigan		Y
Arizona State University		Y
Carnegie Mellon University		Y
Harvard University		
University of Georgia		Y
University of Illinois		Y
Washington State University		Y

3.2 GW WATER USE IMPACT GOALS

While the commitment to reduce climate impacts has been widespread (*3*), there have been fewer publicly announced water initiatives at the university level. On 22 April 2011, Earth Day, the GW Office of Sustainability released the GW Water Roadmap (*1*). This roadmap outlines the goals of the University with respect to the sustainability of our water impact in the technical, economic, and environmental impact areas. The GW Water Roadmap is structured into 8 goals:

1. *Reduce water footprint.* The target of this goal is to reduce the overall water consumption of the University by 25% over 10 years from the FY2008 baseline.
2. *Use our campuses as testbeds for new water reclamation technologies to reduce our potable water consumption.* The target for this goal is to reuse all retained stormwater for greywater systems, cooling towers, and irrigation by 2021. GW is anticipating stringent new EPA MS4 regulations that will require high levels of stormwater runoff for new construction.
3. *Capture rainwater that falls on our campuses: zero run-off.* A target for this goal has not been announced.
4. *Use GW campuses as testbeds for permeable space and stormwater runoff quality.* The target for this goal is to achieve a 10% absolute increase in permeable space over 10 years from the FY2011 baseline.
5. *Reduce the amount of contaminants: zero pollution.* No target for this goal has been announced due to a perceived lack of monitoring capacity.
6. *Reduce use of bottled water on campus.* The target for this goal is to achieve 50% reduction in University procurement expenditure on bottled water over five years from the FY2011 baseline.
7. *Use our campuses as test beds for new drinking water technology.* The target for this goal is to achieve 100% incorporation of in-line filters into new construction and major renovations.
8. *Partner with relevant external groups to enhance dialogue on urban water issues; Encourage academic cooperation and dialogue on urban water issues*. No target for this goal has been announced.

The University, through the Office of Sustainability, has committed to further refinement and structuring of the Water Impact strategy by undergoing a formal decision analysis. This is an opportunity to align strategic goals with an active area of research to improve the quality of decisions taken to reduce the water impact by focusing on values and strategic objectives, then using these values to guide development of alternatives.

3.3 DEFINITION OF SUSTAINABILITY DEFINITION AS A [LEARNING] PROCESS

Regardless of the dimension (energy, climate, water, social, etc.), defining sustainability is a controversial and contested endeavor, with over one-hundred definitions currently extant (*4*). On the contrary, defining sustainability from an organizational perspective is a complex undertaking, balancing quantifiable and qualitative strategic objectives. This complexity often makes transparent methods of sustainability measurement for organizations elusive. Moreover, contested definitions of sustainability among organizational stakeholders may make the interpretation of sustainability metrics and subsequent development of policy instruments based on sustainability definitions difficult. For this reason, many researchers assert that sustainability is a place-based concept (e.g., (*5*)).

One of the obstacles to evaluating the effectiveness of sustainability investments is the difficulty in *defining and measuring* sustainability. Work in sustainability measurement has been initiated in the area of infrastructure management (*6-8*), but broader urban sustainability will require more research. This research must emphasize the synthesis of multi-attribute objectives and multiple-actor preferences (*9-11*) into an overall sustainability *definition*. Many researchers and policymakers assume the now canonical Brundtland Commission definition of sustainability: "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (*12*). This is the traditional definition, but this definition is often too conceptual for decision-making and might be difficult to operationalize in specific decision-making contexts. In the university context, recent efforts to augment the Brundtland Commission's framework include an effort to operationalize sustainability along multiple dimensions characterized by quantitative targets (*13*) and an effort to undertake SWOT analysis for the implementation of an environmental management system according to the ISO 14001 standard (*14*). We extend this focus on operationalization and process standardization by arguing that for organizational decision-making and policy formulation, explicit structuring of fundamental sustainability objectives through MCDA and value assessment may increase the transparency of resultant decisions.

Therefore, to increase the transparency of sustainability measurement, we propose that organizations explicitly characterize these goals in their sustainability definitions through value tradeoffs. As a result, *conceptually we define sustainability as a process* facilitating attainment of a system state characterized by multi-criteria value tradeoffs, a fundamental acknowledgment of environmental carrying capacities, site specificity, resilience to hazards and economic shocks, and integration of natural processes. *Operationally, we define sustainability as an objective-value hierarchy with attendant tradeoff weights among sustainability attributes*.

In other words, this case study articulates the GW definition of Water Sustainability through construction of an objective-value hierarchy representing GW's strategic objectives and articulation of strength-of-preference among the attributes in that hierarchy. In decision analysis, the term "objectives" refers to "goals" or "fundamental strategies" while the term value refers to "fundamental strategies" or "basic motivating principles." As such, an objective-value hierarchy is neither objective, nor simply an amalgamation of non-quantitative dimensions of a problem. This definition will serve as a framework for institutional learning with respect to water sustainability as the strategy is being implemented. Of course, our process is flexible and reflects the fact that water sustainability is addressed in a broader systems context including not only financial, operational, academic, and community outreach goals, but also the other environmental and social dimensions of sustainable university systems.

3.4 APPROACH TO RESEARCH

The typical parts of a decision analysis include: i.) Identification of goals and objectives through problem structuring; ii.) Refining goals and objectives by identifying measureable attributes for the fundamental objective hierarchy; iii.) Construction of single attribute value curves for each attribute through direct rating or indifference methods; and, iv.) Construction of multiple attribute value tradeoff weights (*15-17*). If the decision analysis will be used to facilitate comparison of a set of alternatives, the value assessment results will form the basis of the requisite objective function. In addition, sensitivity and consistency analyses may be performed to validate the model's fitness for decision support. Each of these components has varying steps and procedures depending on assumptions about risk attitudes, uncertainty, value versus utility discrimination, attribute ranges and natural scales, and goals of the overall analysis.

One of the more difficult problems addressed in our case study was the aggregation of stakeholder values. This may be done by eliciting values and strength of preferences for each of the stakeholders, then combining through evaluation of each preference structure. Alternatively, we can use a process-based approach assuming that acceptance of the process is an implicit maximization of the utility function for the group. We used what might be described as a hybrid approach. We met with two small groups of stakeholders, such that the project assumed some of the appearance of a group-structuring session, using an instructional presentation to be clear on the goals of decision analysis, and then using an interactive structuring of the value (OV hierarchy) tree and weights [preference] tradeoffs within these small groups.

3.5 GWATER VALUE ASSESSMENT CASE STUDY

Case Study Overview. This research used multi-criteria decision analysis (MCDA) to develop a model for defining sustainability. We have developed much of our study approach on the basis of a case study in which the strategic objectives of British Columbia Hydro were structured so as to guide future decisions (*16*). These methods were augmented by insights provided by informed risk ranking, (*18*) and MCDA to evaluate environmental decisions (*19*). The literature also revealed that few MCDA approaches are specifically designed to incorporate multiple stakeholder perspectives (*20*).

Stakeholder Backgrounds. Our study included four stakeholder participants from the GW community. Our primary interested parties in this study are the GW Division of Operations and GW Office of the President. These interested parties are represented by four individuals familiar with University sustainability strategy, decision making, and operations. They represent the Office of Planning, the Office of Facilities Services, and the Office of Sustainability within our main stakeholders. These four individuals are indicated as "Stakeholder #1, 2, 3, and 4" below. Their brief biosketches are as follows:

- Stakeholder #1 is currently the Director of Facilities Planning and Design Review, responsible for: the creation and maintenance of GW Design Standards; the review of all construction project design documents for compliance with design standards and best practices; the oversight of the LEED certification process for all new construction, targeting LEED Silver or better. Stakeholder #1 is a registered architect and LEED AP and has been with the university for over 14 years serving as Campus Architect, Architecture Manager, and Director of Planning and Environmental Management prior to their current assignment.
- Stakeholder #2 is the Energy and Environmental Manager within Facilities Services, a position they have held for nearly ten years. They are responsible for complying with environmental regulations related to air, water, fuel-oil handling, and recycling; tracking usages and costs of utilities; purchasing electric, gas, and oil; and implementing some energy and water efficiency projects.
- Stakeholder #3 serves as a sustainability facilitator in the GW office of sustainability. In this capacity they help to manage and implement water and ecosystem related projects. They also work on communications, student, faculty and staff engagement.
- Stakeholder #4 is the Director of the University's Office of Sustainability. Stakeholder #4 has over 15 years of experience in advising clients and organizations on how to select sustainability objectives and attain their sustainability goals. In addition to George Washington University, Stakeholder #4 has worked with a variety of industrial organizations in both industrialized and emerging economic contexts.

Constructing the Objective-Value Hierarchy. The first task in the study was to develop an objective value hierarchy. The development of the objective value hierarchy was a multi-phase process beginning with the elicitation of water sustainability objectives from Stakeholders #3 and #4. The second phase involved introducing Stakeholders #1 and #2 and gathering their departmental drivers with respect to water sustainability. The third phase was used to combine all the stakeholder objectives into one objective value hierarchy and allow stakeholders to make revisions and assign attributes.

Phase 1 began with a meeting with GW's Office of Sustainability. This group became the initial stakeholder. The university's GWater plan for mapping the university's water footprint was the initial guide used to begin hierarchy development. After reviewing the 8 goals of the GWater roadmap, the 5 goals that directly or indirectly affected water or stormwater management were used to develop the fundamental objectives of water management at the George Washington University. The initial objective-value hierarchy obtained from this step is shown in Figure 1.

Our original stakeholders (Stakeholders #3 and #4) provided names of important decision makers in the matter of university resource management for the second step in the objective value hierarchy development. Both the Office of Campus Planning and Design, and Facilities Services (both offices are located in the GW Division of Operations) were requested via email to provide insight concerning the following decision dimensions:

1. GW's objectives for managing campus resources
2. LID or green infrastructure technologies GW may be considering, has rejected, or has already implemented (such as the green roof)
3. Obstacles to GW's implementation of LID or green infrastructure
4. Additional GW personnel whom we should involve in this project.

Stakeholders #1 and #2 were identified as a result of this outreach. A meeting was set with these two new stakeholders to conduct a semi-structured interview in which they were informed of the project's research objective, provided an explanation of the planned methodology, and were asked to discuss the questions from the original email. The fundamental objective hierarchy developed for the Office of Sustainability was also reviewed as an example of what would be developed from a Campus Planning and Facilities services perspective.

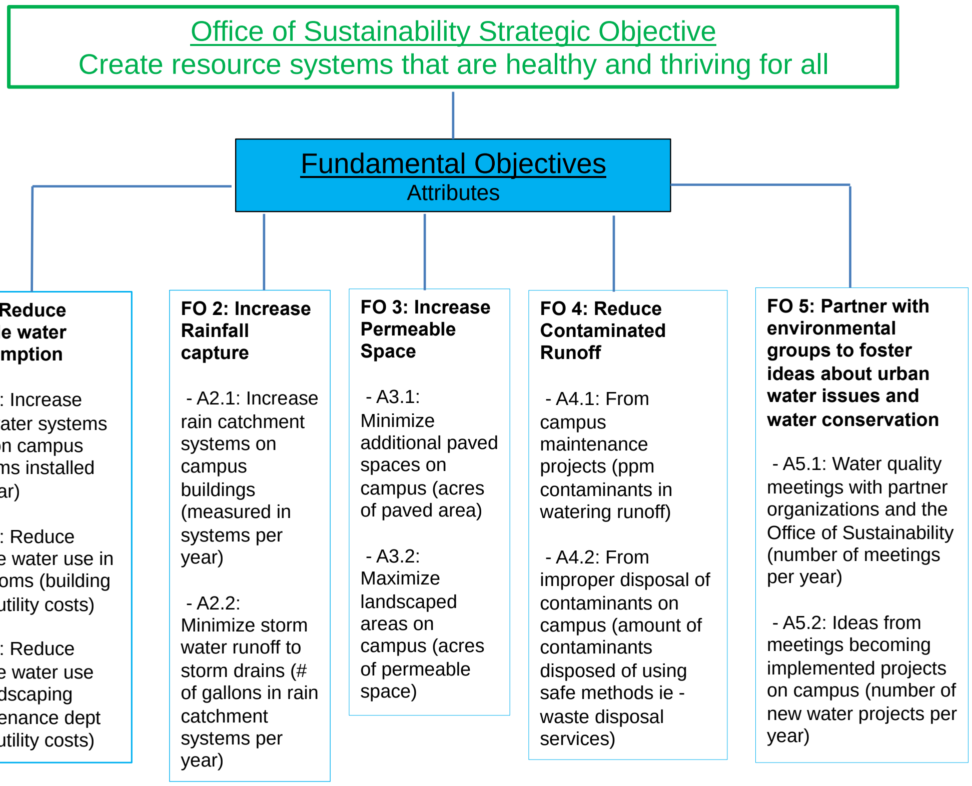

Figure 1. Preliminary objective-value hierarchy obtained from semi-structured interview with Office of Sustainability stakeholders.

After this meeting the authors developed a draft objectives value hierarchy for the GW Division of Operations with input principally from Stakeholders #1 and #2. This objective value hierarchy was based on the objectives and concerns identified by the stakeholders during the two semi-structured interviews. The stakeholders from facilities services provided a list of objectives in a preliminary rank ordering:

1. Comply with Campus Plan
   a. A 20 year plan of campus development and improvement. Plan reflects long-term view of the campus in the context of its surrounding neighborhoods.
2. Implement GWater Strategy
   a. Improvement of GW's water utilization through reduction of potable water waste; increased rainfall capture; increased permeable space; reduced contaminated runoff; and partnering with environmental groups to foster water conservation ideas.
3. Minimize Costs
   a. Minimize financial expenses and work within operations budget. Budget goals met by managing costs associated with new and existing building maintenance; utility costs; and landscaping costs.

4. Achieve Indirect Savings
    a. By choosing projects in the facilities department that would allow for overall maintenance costs.
5. Implement President's Sustainability Initiative
    a. Through "Practice", "Research", and "Outreach". Practice applies to campus implemented sustainability plans; Research applies to utilizing the academic resources of GW to develop new sustainability models and practices; Outreach applies to engaging GW student body to build community relationships with a focus on sustainable education and practice.
6. Comply with building codes
    a. A constraint built in to all aspects of campus development. Complying with city codes is necessary to developing and executing the campus plan. GW's own building goals include LEED certification of all new campus buildings.

The final phase of constructing the objective value hierarchy involved reviewing the fundamental objectives from both stakeholder groups and making edits and additions as needed based on feedback from the stakeholders.

A second meeting with the Stakeholders #3 and #4 was set up as a semi-structured interview. This meeting consisted of discussing the overall hierarchy obtained with input from Stakeholders #1 and #2 from fundamental objectives to attributes. With the input of the Stakeholders #3 and #4 FO2 and FO4 were reconstructed into one Fundamental Objective comprising all of GW's Sustainability Priorities in which the three campus sustainability initiatives fall under, including the GWater Strategy.

An additional fundamental objective was added as Stakeholders #3 and #4 pointed out that they work more closely with GW Capital budgets not necessarily with operating budgets. They develop campus strategies and long-term investment options under these capital budgets. These investments are driven by campus reputation and rankings, projects that have relative risk, and projects that will comply with foreseeable future regulations.

A final meeting was set with Stakeholders #1 and #2 in an informal meeting to review any additional changes they may have had to the Phase 2 hierarchy. This meeting produced final scales for measuring certain constructed attributes and determined which fundamental objectives involved constraints rather than operational attributes. The resulting hierarchy of this phase of semi-structured interviews is shown in Figures 2a and 2b.

Operationalizing the sustainability definition through value assessment. In the value assessment phase of the project, each stakeholder was interviewed in person or by phone to assign weights to the objective value hierarchy. This process required one-hour for each meeting and consisted of two separate parts. During the value assessment process, the stakeholders were allowed to skip assessment of an attribute or objective they didn't feel qualified to score.

<u>Part 1 – Direct rating of levels on individual attributes.</u> After identifying a natural, proxy, or constructed scale (*16*) for each attribute listed in the objective value hierarchy, the first part of the value assessment asked the stakeholder to rate each attribute on a scale of 0-100, with 0 being the worst level of attainment for the attribute and 100 being the best level of attainment. A bi-section method was used to rate the attribute levels, first eliciting the best (100) level of attainment, then the worst (0) then the midpoint level of attainment (50). In some cases, the midpoints between worst and 50 and 50 and 100 were elicited from the stakeholders.

<u>Part 2 – Swing Weighting of Objectives</u>. Swing weighting (*21*) was used to ascertain the strength of preference tradeoffs among the attributes and fundamental objectives at each objective level in the hierarchy. The process started with the lowest levels of the objective hierarchy and worked up to the top level of the hierarchy. Each stakeholder was asked to determine from each group which of the objectives was the most important to reach the best level above all the others (assign this objective 100) and which was the least important (assign a 0). Then the stakeholders were asked to assign weights of importance to the rest of the objectives from worst to

best. The weights were then normalized to determine their scores. After these meetings were conducted, a chart of the best levels of attainment for each attribute was created.

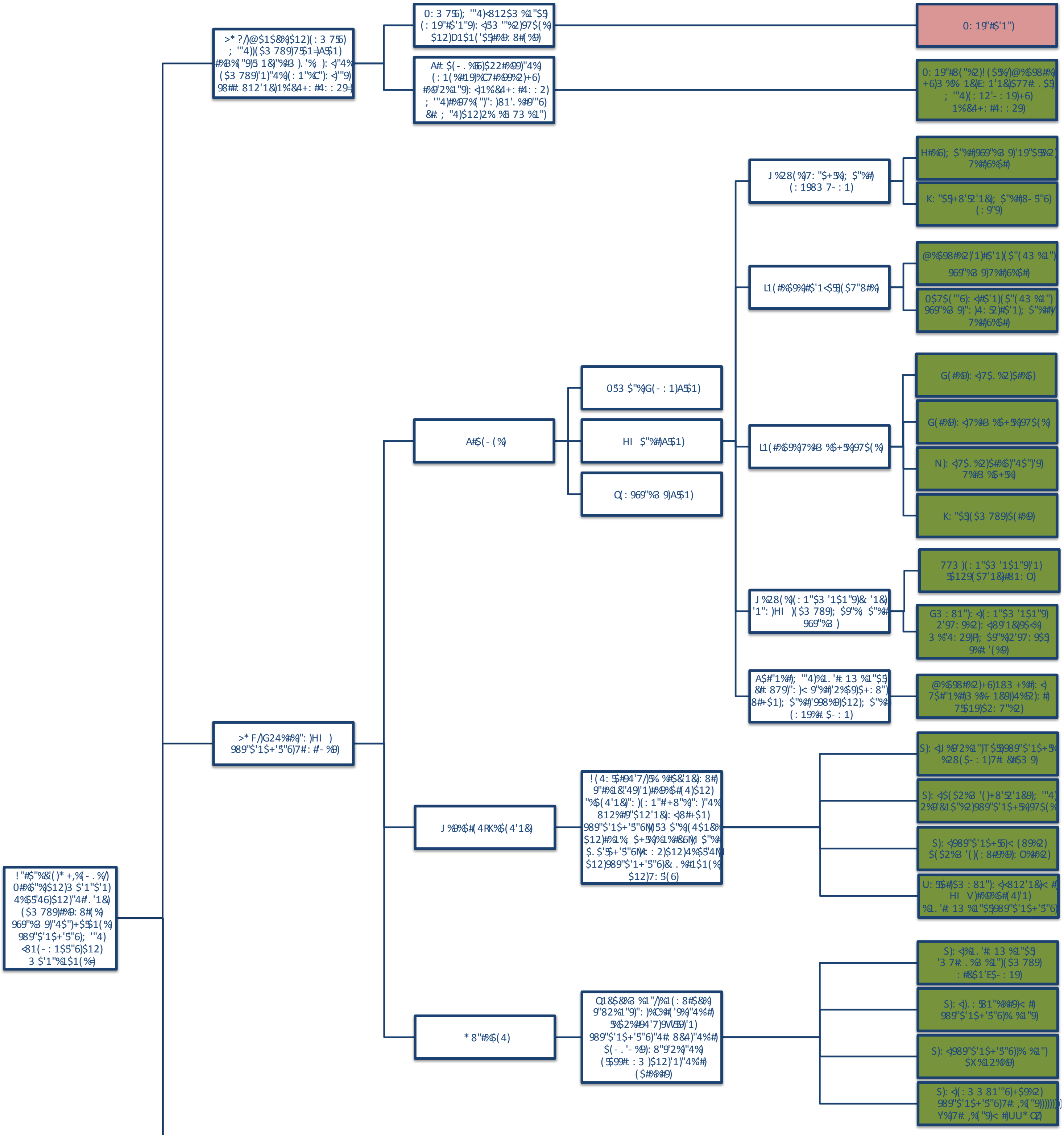

Figure 2a. Fundamental objective hierarchy obtained through value assessment.

After all the stakeholders completed the value assessment all answers were compared and those that were widely varied among the stakeholders were highlighted. Through email the stakeholders were asked to provide feedback about the values that were highly varied and if possible, as to why their answers maybe different from the other stakeholders. They were also offered them one final chance to make changes to their value assessments if they felt it necessary upon reviewing the other stakeholders assessments. The final tradeoff weights obtained from this process are reported in Table 2.

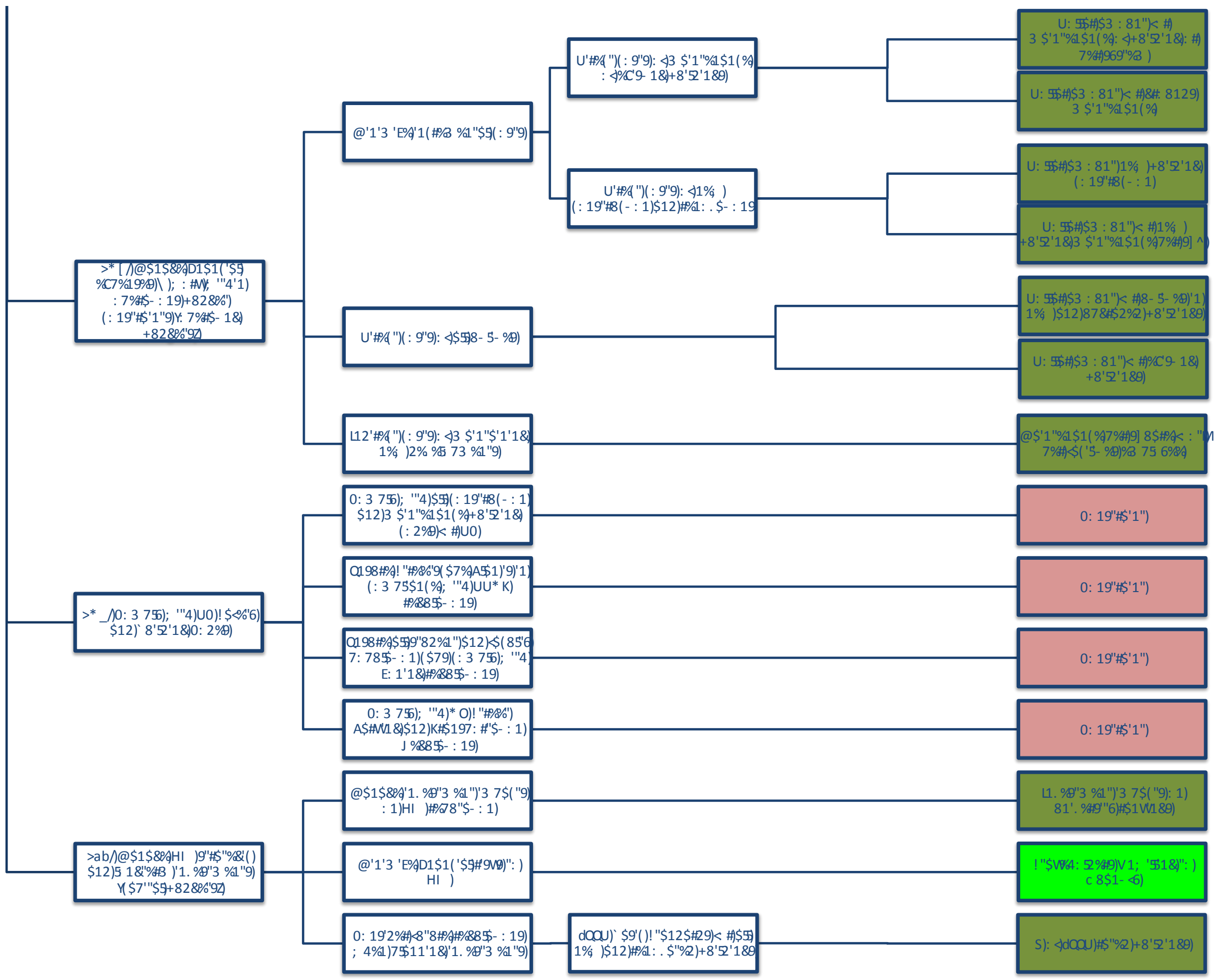

Figure 2b. Fundamental objective hierarchy, continued.

Table 2. Stakeholder weights obtained through value assessment. Levels numbered from highest to lowest.

	Stakeholder #1- Facilties Services	*Stakeholder #2- Campus Planning*	*Stakeholders #3,#4- Office of Sustainability*
	Normalized Swing Weights		
FO1—Manage and Comply with Campus Plan—Level 1			
○ Comply with fundamental constraints of limited space and financial resources	100%	100%	100%
○ Proactively address the concerns expressed by residents of neighborhood with respect to university growth and development	0%	0%	0%
FO2—Adhere to GW Sustainability Priorities—Level 3			
○ Reduce potable water consumption	40%	25%	0%
○ Increase rainfall capture	20%	0%	19%
○ Increase permeable space	24%	28%	24%
○ Reduce contaminant emissions to GW campus wastewater system	16%	0%	48%
○ Partner with environmental groups to foster ideas about urban water issues and water conservation	0%	16%	10%
FO2 - Level 2			
○ Climate Action Plan	57%	57%	30%
○ GWater Plan	43%	43%	37%
○ Ecosystems Plan	0%	0%	33%
FO2 - Level 1			
○ Practice	43%	53%	37%
○ Research/Teaching	57%	47%	30%
○ Outreach	0%	0%	33%
FO3—Manage financial expenses and Operations budget—Level 2			
○ Direct costs of maintenance of existing buildings	100%	100%	59%
○ Direct costs of new construction and renovations	0%	0%	41%
FO3 - Level 1			
○ Minimize incremental costs	43%	0%	32%
○ Direct costs of all utilities	57%	53%	40%
○ Indirect costs of maintaining new	0%	47%	28%

developments			
FO4—Comply with DC Safety and Building Codes—Level 1			
○ Comply with all construction and maintenance building codes for DC	Constraint		
○ Ensure Streetscape Plan is in compliance with DDOT regulations	Constraint		
○ Ensure all student and faculty population caps comply with zoning regulations	Constraint		
○ Comply with Off Street Parking and Transportation Regulations	Constraint		
FO5—Manage GW strategic and long term investments (capital budgets)—Level 1			
○ Manage investment impacts on GW reputation	43%	44%	38%
○ Minimize financial risks to GW	57%	56%	35%
○ Consider future regulations when planning investments	0%	0%	27%
Fundamental Objectives			
○ Manage and comply with campus plan. Plan reflects long-term view of the campus in the context of its surrounding neighborhoods.	24%	26%	Constraint
○ Adhere to GWU sustainability priorities	26%	0%	37%
○ Manage financial expenses & work within operations budget constraints (operating budgets)	29%	25%	30%
○ Comply with DC Safety and Building Codes	0%	22%	Constraint
○ Manage GWU strategic and long-term investments (capital budgets)	21%	27%	33%

3.6 DISCUSSION AND LESSONS LEARNED

The decision analysis model developed here was structured as an objective value hierarchy where stakeholders applied direct rating to the attributes then swing weighted each level of fundamental objectives to define water sustainability. Three findings of note came out of this process.

First, our stakeholders' thinking about their objectives was greatly influenced by the constraints GW faces, especially with respect to Stakeholders' #1 and #2 contributions to the fundamental objective hierarchy. One type of constraint described by our stakeholders was perceived constraints. A perceived constraint is a bound on an attribute at levels the stakeholder believes is realistic, instead of a bound on an attribute at levels the stakeholder thinks are ideal or desirable. Consequently, it was difficult for some of our stakeholders to assign meanings to the value assessment that closely aligned with their experience. For example, when eliciting the value function for the number of rainwater catchment systems installed per year attribute, some stakeholders bounded their value assessments at the minimum they thought GW might install over a 10-year period (assuming that GW will install at least one), whereas other stakeholders assigned the minimum value score to zero. On the other end of the scale, some of our stakeholders bounded the maximum at a number they believed was realistic but not ideal, while other stakeholders ideally thought that installing catchment systems on all buildings that don't currently have them should be the upper bound on the value scale. Another type of constraint encountered in our experience was mandatory obligations on institutional performance implied by contracts or tradition. In other words, the current environment requires that an attribute be attained at a pre-specified level, independent of the values held by the stakeholder. In an ideal decision analysis, these types of constraints might be independently examined as decision opportunities if the stakeholder or decision maker feels the current decision context is unacceptably contained. In this decision situation, however, the stakeholders generally viewed the prevailing constraints (e.g., zoning requirements, conformance to the GW master plan) as non-negotiable and value functions could not be obtained for the relevant attributes. This study illustrates that for some sustainability decisions that encounter prevailing institutional constraints, it may be necessary to evaluate the constraints proactively and discuss the possibility of including their revision in the analysis of the decision context. Some sign that this could be possible was indicated by the fact that although constraints were not given scores in the value assessment portion of this project, some stakeholders did make an attempt to do so. It was unclear how the constraints encountered in this study influenced the elicitation of fundamental objectives, attributes, and value functions, but it was clear that the stakeholders felt bound to include the relevant constraints as fundamental objectives despite an inability to assign a value function over the levels of satisfaction of these constraints.

Second, in considering the tradeoff weights obtained from the swing-weighting portion of the value assessment, it is clear that all stakeholders placed similar emphasis on each of the fundamental objectives. This isn't to say that they valued the objective in the same rank order. Instead, there were few instances where swing weights for attributes supporting the same fundamental objective weren't within 20% of each other. In other words, it was difficult for our stakeholders to discriminate among alternatives in terms of their strength of preference for tradeoffs involved in the attainment of each of the fundamental objectives. In the view of the authors, this is a principal motivation for the underpinning of sustainability definition to be based on MCDA techniques for defining tradeoffs. Although each of the stakeholders could define sustainability conceptually, and even identify the attributes included in this study, the difficulty encountered in articulating tradeoffs among the attributes and objectives renders conceptual definition of sustainability non-operational. On the basis of these swing weights, we recommend that at a minimum, MCDA techniques for value assessment should be undertaken to assist decision makers in structuring their sustainability decision contexts when developing strategies for strengthening the environmental sustainability of an institution or organization. Ideally, actions considered for these purposes should be directly evaluated using tradeoff weights that have been obtained through a transparent process acceptable to all stakeholders involved, in spite of the fact that consensus concerning the weights may be elusive.

This difficulty in reaching consensus in value assessment is widely acknowledged as a practical difficulty in conducting MCDA, while theoretically known as Arrow's impossibility theorem. Indeed, this challenge is indicated by our results as well. Table 2 indicates that different stakeholders put more emphasis on certain objectives or attributes than other stakeholders. This was most likely due to the current roles each stakeholder has at the university. Stakeholders #3 and #4 have a strategic role assisting the Office of the President in identifying areas of competitive advantage GW might engage with respect to sustainability, while Stakeholders #1 and #2 are directly involved with both the operation of the University and implementation of strategic plans with respect to University infrastructure. While we expected differences in strength of preference for attainment on different attributes within the fundamental objective hierarchy, it was unclear *a priori* which objectives might indicate the most discrimination between the roles. These differences may be partially resolved through identification of the primary decision maker(s), but the process through which the value assessment will be achieved must be transparent and accepted by each of the stakeholders.

In summary, we have demonstrated a decision-analytic method for the definition of sustainability using water footprint management as an example. Specifically, the participants were recruited in the context of thinking about low impact development investment structuring in advance of potential stormwater charge increases. The participants articulated their definition of sustainability through the construction of an objective-value hierarchy and elicitation of the attendant value structure through swing weighting. Several challenges were identified during this case study. First, the nature of constraints on colleges and universities, their educational mission, and the decentralized nature of their operation and strategy development make it difficult to describe the form this process might take when generalizing its findings to other types of institutions. However, in future research on sustainability definition, the decentralized decision-making context within colleges and universities make the definition of sustainability processes an attractive case for establishing tradeoffs among sustainability objectives and establishing process legitimacy. Despite these challenges, the stakeholders did agree on the fundamental objective: "Sustainability is creating resource systems that are healthy and thriving for all."

4. BENEFIT-COST ANALYSIS FOR LID ADOPTION USING LIDRA

4.1 INTRODUCTION

Rapid urbanization in our nation's capital has led to an increased pressure on energy and water infrastructure in the district. Over the decades it has become quite challenging to meet the requirements mandated by the Clean Water Act. Due to the scale of the problem and consequences it has had on the environment, local citizen groups filed a suit against the DC Water and Sewer Authority (then known as DC WASA). Consequently, the District of Columbia and DC Water entered into a consent decree with the U.S. Government to resolve the problems related to its combined sewer system (CSS) in the city (*22*). This agreement required DC Water to meet new infrastructural development requirements by 2025 to reduce the number of CSO events.

Conventionally, stormwater is managed using “gray infrastructure” in almost every city in the United States. Gray infrastructure generally consists of building tunnels and pipes, as well as expanding existing sewage and water treatment plants. Gray infrastructure comes with a variety of challenges, ranging from the high costs of developing new infrastructure to funding that continuously goes into the maintenance and operation of existent infrastructure. These problems are only exacerbated with increased development, population and urbanization. As this traditional gray infrastructure is proving inadequate in handling stormwater runoff in cities like Washington DC, more and more cities and communities are advocating green infrastructure as a new environmental strategy to combat the Combined Sewer Overflow (CSO) pollution problem. Green infrastructure, particularly Low Impact Development (LID) infrastructures, are considered to be best management practices (BMP’s) for handling urban stormwater problems and are found to be economically efficient and environmentally effective (*23*).

The EPA defines LID as an approach to land development (or re-development) that works with nature to manage stormwater as close to its source as possible. LID employs principles such as preserving and recreating natural landscape features, minimizing effective imperviousness in order to create functional and appealing site drainage that treats stormwater as a resource rather than as a waste product (*23*). In essence, LID is used as a tool for stormwater management. Various LID options give a city and its developers more wastewater management options and approaches. LID practices include:

i. Bioretention facilities

ii. Rain gardens

iii. Grass swales and channels

iv. Vegetated rooftops

v. Rain barrels and cisterns

vi. Vegetated filter strips

vii. Permeable pavements

All of the above practices perform both runoff volume reduction and pollutant filtering functions for stormwater. As opposed to conventional methods that generally aim to move water off-site and into the storm drains as quickly as possible, LID’s seek to do exactly the opposite. They keep as much water onsite as possible to ensure absorption and infiltration. Instead of large, centralized treatment plants and water storage facilities, LID emphasizes local, decentralized solutions that capitalize on the beneficial services that natural ecosystem functions can provide.

New and effective infrastructure needs to be implemented in the District in time to meet the deadlines imposed by the Consent Decree, between the years 2014 and 2025. This raises a number of questions concerning whether water quality standards could be handled by green infrastructure alone or whether to provide adequate control of CSO’s more gray infrastructure needs to be implemented in the city. Thus, a cost-benefit analysis must be conducted in order to provide a more comprehensive understanding of the costs involved with implementing green infrastructure in the city, as well as the social, economic and environmental costs and benefits of such development. The objective of this study is to demonstrate a rapid assessment model that can be used to support a benefit-cost analysis for evaluating the potential implementation of LID in the LTCP area in place of some grey infrastructure measures.

4.2 LOW-IMPACT DEVELOPMENT RAPID ASSESSMENT (LIDRA)

The primary objective of this study is to identify the impact of customer adoption of LID measures on the occurrence of CSO events. In order to accomplish this objective, we employ the LIDRA method of Montalto et al. (*24*). LIDRA is a rapid analysis method that allows users to cost-effectively evaluate the impacts of implementing LID over impervious surfaces in a stormwater drainage area. This method requires fewer input parameters than other more detailed modeling techniques such as SWMM, while providing a rapid screening based on the application of the rational stormwater runoff modeling method.

The first step in the LIDRA technique is to obtain a record of CSO events for the area under study. In this analysis, we have used the modeled CSO event records used to support the development of the DC Water long-term control plan [LTCP] developed in response to the consent decree referred to earlier (*25*). In the LTCP, DC Water selected 1988-1990 as an average hydrological ensemble, and averaged hydraulic and hydrological model outputs over this period based on this historical data. The predicted number of CSO overflows, average overflow volume in millions of gallons (MG), approximate minimum rainfall depth (in) to cause a CSO event, and the average duration of a CSO event is shown in Table 3 (*25*). This record allows a baseline for assessing the implications of implementing LID in the LTCP stormwater drainage area.

Table 3. Predicted CSO Events under implemented Phase I CSO controls for DC Water based on 1988-1990 average year.

CSO NPDES No.	*Drainage Area Description*	*CSO Drainage Area (acres)*	*No. of Overflows*	*Average Overflow Volume (MG)*	*Approximate Min Rainfall Depth to Cause Overflow (in)*	*Average Overflow Duration (hours)*
Anacostia River CSO's (Cex=0.549, Cp=0.536)						
5	Fort Stanton	65.51	73	0.226575342	0.2	4
6	Fort Stanton	13.56	5	0.022	1	0.5
7	Fort Stanton	188.13	64	0.57765625	0.3	3.7
9	B St./New Jersey Ave	41.27	54	0.311851852	0.3	3.1
10	B St./New Jersey Ave				0.4	2.2
11	B St./New Jersey Ave	732.72	18	13.73388889	no overflows	no overflows
011a	B St./New Jersey Ave				no overflows	no overflows
12	Tiber Creek	1153.83	6	3.623333333	0.7	0.7
13	Canal Street Sewer	20.1	28	0.349285714	0.4	2.5
14	Navy Yard	128.06	49	0.795510204	0.4	3.4
15	Navy Yard	30.82	12	0.06	0.8	0.8
16	Navy Yard	152.58	24	0.554166667	0.5	1.4
17	Navy Yard	259.91	32	0.6265625	0.4	1.6
18	Navy Yard	48.93	35	0.134285714	0.4	1.5
19	Northeast Boundary-Swirl Effluent	4242.39	36	17.93444444	0.1	3.2
19	Northeast Boundary-Swirl Bypass		13	16.09	0.4	1.4
Potomac River CSO's (Cex=0.573, Cp=0.444)						

3	Bolling AFB				no overflows	no overflows
20	Easby Point	573.14	21	2.61	0.5	1.6
21	Potomac Pumping Station	473.78	30	15.281	0.4	2.5
22	I St.-22nd St., NW	125.23	30	1.001333333	0.7	2.2
24	West Rock Creek Diversion Sewer	41.66	17	0.954705882	0.3	3.6
25	31st&K St. NW	9.89	14	0.011428571	0.5	0.9
26	Water St. District (WRC)	13.88			no overflows	no overflows
27	Georgetown	179.38	72	0.729166667	0.1	4.4
28	37th St-Georgetown	21.06	13	0.037692308	0.5	0.7
29	College Pond	300.79	56	0.464285714	0.3	2.8
			Rock Creek CSO's (Cex=0.591, Cex=0.544)			
31	Penn Ave	1.11	9	0.024444444	0.3	1.9
32	26th-M St.	10.38			no overflows	no overflows
33	N St.-25th St.	13.08	6	0.746666667	0.7	1
34	Slash Run Trunk Sewer				no overflows	no overflows
35	Northwest Boundary	546.69			no overflows	no overflows
36	Mass Ave and 24th	69.76	29	0.056551724	0.4	1.8
37	Kalorama Circle West	16.61	3	0.016666667	1.3	0.6
38	Kalorama Circle East	9.54			no overflows	no overflows
39	Belmont Rd	54.25			no overflows	no overflows
40	Biltmore St	24.52	1	0.03	1.3	0.6
41	Ontario Rd.	27.17			no overflows	no overflows
42	Quarry Rd.	36.22			no overflows	no overflows
43	Irving St.	70.31	1	0.15	1.3	0.6
44	Kenyon St.	17.07			no overflows	no overflows
45	Lamont St	17.17	2	0.015	1.3	0.7
46	Park Road	17.38	2	0.005	1.3	0.7
47	Ingleside Terr.	18.16	3	0.083333333	1.3	0.6
48	Oak St-Mt. Pleasant	26.06	2	0.04	1.3	0.7
49	Piney Branch	2433.2	25	1.5892	0.4	1.6
50	M St.-27th St.	36.41			no overflows	no overflows
51	Olive-29th St.	11.87			no overflows	no overflows
52	O St.-31st St.	108.5			no overflows	no overflows
53	Q St.	5.5			no overflows	no overflows
54	West Rock Creek Diversion Sewer	N.A.			no overflows	no overflows
56	Normanstone Dr.	N.A.			no overflows	no overflows
57	Cleveland-28th St. & Conn. Ave	84.5	15	0.155333333	0.5	0.8
58	Connecticut Ave.	5.24			1.7	0.6
60	26th and P St. NW				no overflows	no overflows

Figure 2 shows a map of the LTCP combined sewer shed (CSS) area. The white areas indicate the separate storm/sanitary sewer areas in the District of Columbia. Red dots indicate locations of combined sewer outfall locations permitted under the NPDES discharge permits. While Anacostia and Potomac have not been disaggregated, Rock Creek has been separated into areas that have been used for GIS calculations for demographic and land use data.

The rational method is the most widely used uncalibrated equation for studying rainfall-runoff relationships in watersheds (*26*). The equation relates the peak discharge, Q [ft^3/sec], to a dimensionless runoff coefficient, C, rainfall intensity, i [in/hr], and the study area, A [sq. ft]:

$$Q = CiA \qquad (1.1)$$

The runoff coefficient is a function of land use, land cover, watershed slope, and other factors. A set of recommended runoff coefficients used in this analysis are given in Table 4.

Table 4. Runoff coefficients for the Rational Method from McCuen (2005)

Area Description	*Recommended Runoff Coefficient Value*
Business	
Downtown	0.85
Neighborhood	0.6
Residential	
Single-family	0.4
Multiunits, detached	0.5
Multiunits, attached	0.7
Residential (suburban)	0.35
Apartment	0.6
Industrial	
Light	0.65
Heavy	0.75
Parks, cemeteries	0.2
Playgrounds	0.3
Railroad yard	0.3
Unimproved	0.2
Pavement	0.85
Roofs	0.85
Green Infrastructure	0.35

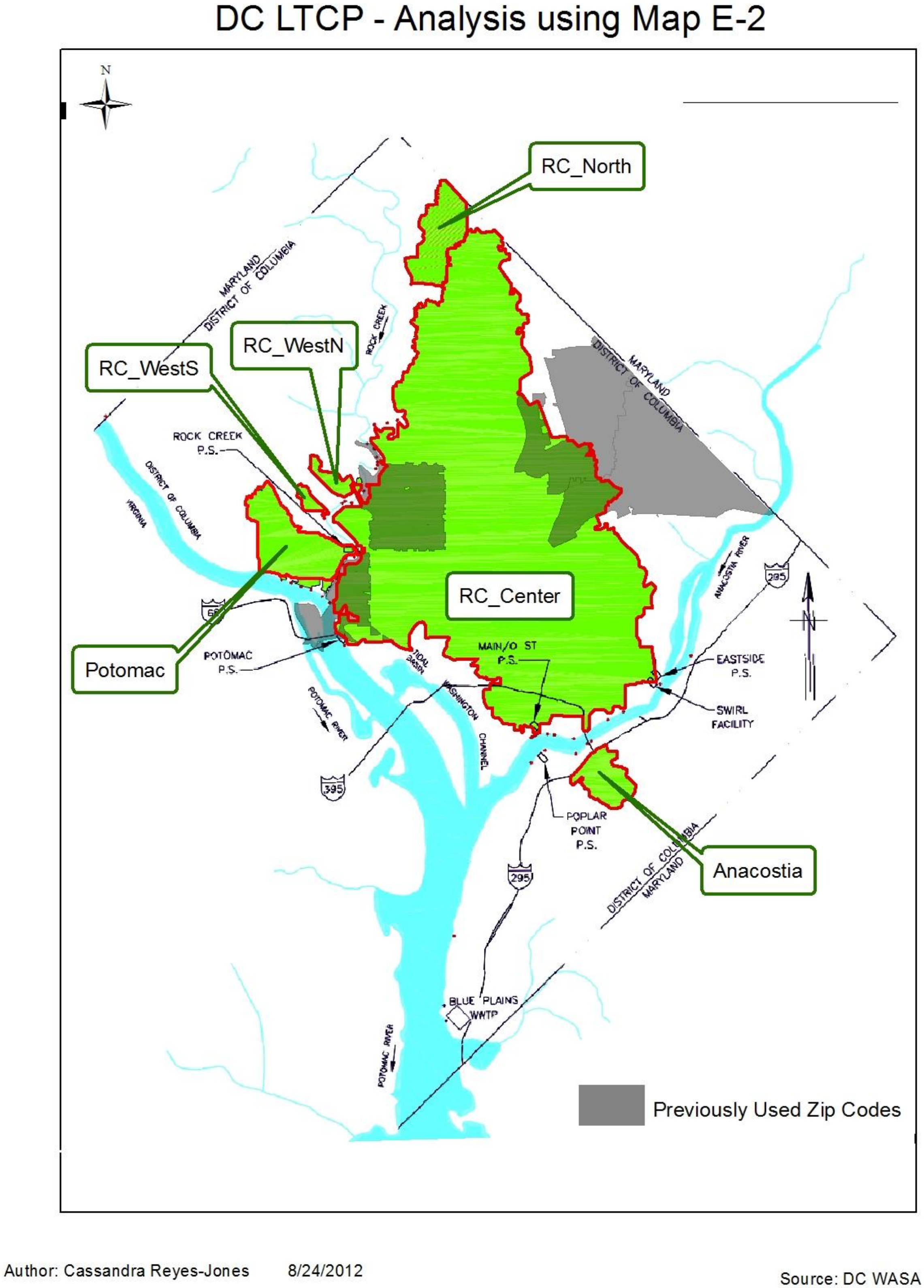

Figure 2. Map showing LTCP areas used in LIDRA analysis. This map was hand-traced from the LTCP combined sewer shed (CSS) map reported by DC Water. Potomac, Anacostia, and Roc Creek runoff areas indicated.

Montalto et al. (*24*, *27*) have developed a rapid assessment technique by modifying the rational method equation as follows:

$$Q_t = C_{ex} \frac{d_{t,C_{ex}}}{t} A$$

where:

Q_t = peak runoff flowrate caused by rainfall of duration, t

C_{ex} = dimensionless runoff coefficient corresponding to existing level of imperviousness (1.2)

t = duration of rainfall preceding CSO event

A = watershed area

$d_{t,C_{ex}}$ = minimum depth of rainfall preceding CSO event under existing conditions

This equation can be used to obtain the effect of LID implementation on the occurrence of CSO events by estimating the new minimum depth of rainfall preceding a CSO event as follows (consult Montalto et al. (*24*) for derivation details):

$$d_{t,C_p} = \frac{C_{ex}}{C_p} d_{t,C_{ex}}$$

where: (1.3)

$d_{t,C_{ex}}$ = minimum depth causing CSO event under existing conditions for duration t

d_{t,C_p} = minimum depth causing CSO event under LID implementation for duration t

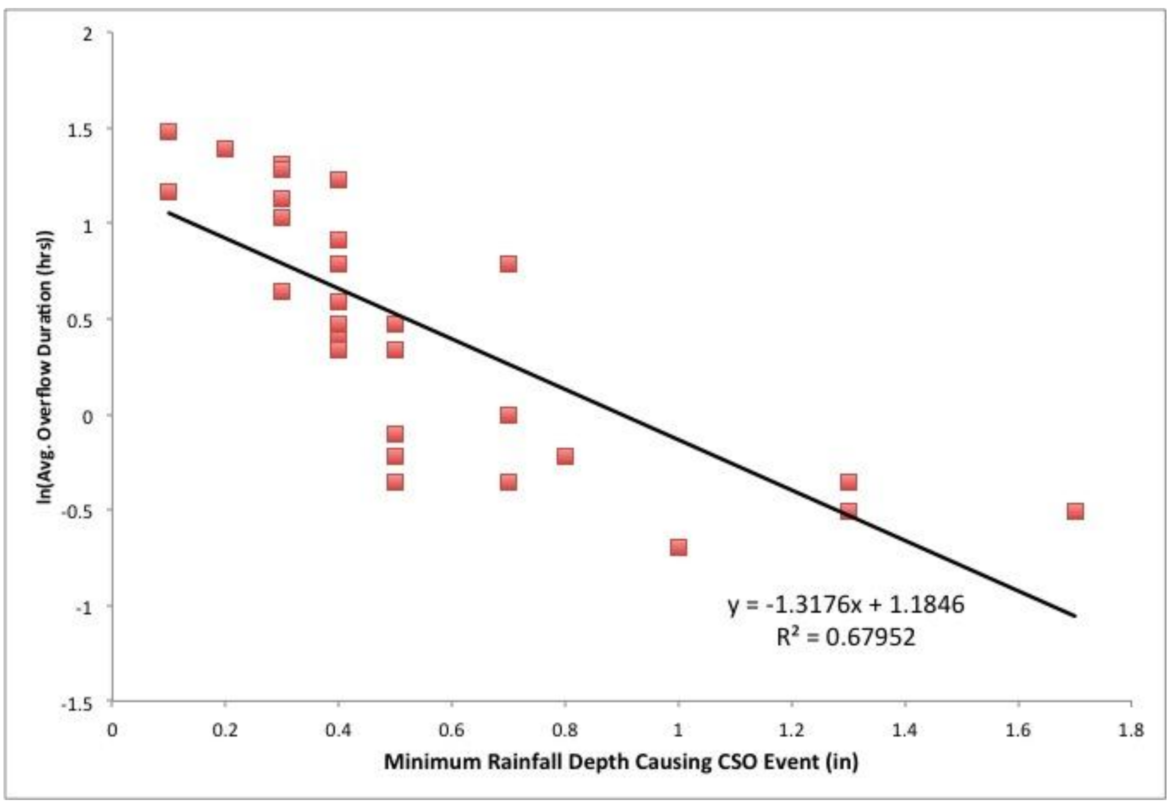

Figure 3. Average overflow duration as a function of minimum rainfall depth causing CSO events in the LTCP area for the 1988-1990 average year.

In using the LIDRA technique, we have made an important assumption that must be mentioned at this point. Montalto et al. (*24*) have applied their technique to cases in which the time of onset of CSO is known. For this case study, we do not know the time of onset of each CSO event in the LTCP average year, only the minimum depth leading to CSO discharge. Consequently, we assume that the minimum depth for the modeled scenarios would be affected only by the changes in imperviousness of the land cover due to LID application. In this sense, we will not be able to disaggregate the effect of rainfall intensity on CSO event occurrence from the influence of imperviousness. As a result, we only report results of our preliminary investigation into the reduction of average CSO duration, and approximate minimum depth of rainfall leading up to a CSO event. We do not have enough information to study the influence of LID intervention on the number or volume of CSO events in this study.

On the other hand, we believe the data reported in the LTCP is adequate for a preliminary investigation into the effect of LID on CSO duration due to the relationship between minimum rainfall depth causing CSO events in the LTCP area and the average duration of these CSO events. This relationship is illustrated in Figure 3. This log-linear relationship appears to fit the data satisfactorily for a screening analysis, with an R^2 of 0.680. Thus, we apply equation 1.3 to estimate the new minimum rainfall depth leading to a CSO, as a function of C_p based on LID application, and then use the new minimum rainfall depth to estimate the expected average duration of a CSO event in the LTCP area.

Table 5. Coefficients for logit model adapted and modified from Ando and Freitas (*28*) rain barrels study to predict LID adoption in LTCP areas.

	Housing Units Occupied	Median Household Income	Percentage ≥5 Unit Building	Percentage ≥Bachelors' Degree	Intercept
Coefficients (Ando and Freitas 2011, Logit Model w/Exclusions)	1.01	0.586	-0.016	-0.019	-3.26

Table 6. Assumed influence of socioeconomic factors on LID adoption in LTCP area based on Ando and Freitas (*28*).

LTCP Area	Percentage ≥Bachelors' Degree	Percentage ≥5 Unit Building	Median Household Income	Housing Units Occupied	Proportion of Customers Adopting LID Measures
Anacostia	8	40	$27,627.50	896	0.178261082
Potomac	82	62	$88,037.00	2106	0.815406131
RC	23	53	$35,102.17	1087	0.207576497

Table 7. Calculated runoff coefficients for LTCP areas based on proportion of customers adopting LID measures assuming 100% of impervious surfaces are targeted

	Runoff Coefficient	Percent LTCP Area	Runoff Coefficient Contribution	Impervious Surface	Impervious Surface Treatment Adoption	LID Runoff Contribution	LID-LTCP Runoff Coefficient Disaggregated
Anacostia	0.549	2%	0.012	47%	18%	0.012	0.536
Potomac	0.573	5%	0.030	55%	82%	0.023	0.444
Rock Creek	0.591	93%	0.547	56%	21%	0.503	0.544
LTCP Runoff Coefficient [Cex]	0.589						
LID Runoff Coefficient [Base Assumption]	0.35						
LID-LTCP Runoff Coefficient [Cp, Assuming adoption rates]	0.538						

In order to compute runoff coefficients for the study area, we have used GIS analysis by census tract in the LTCP to compute a weighted runoff coefficient given the land use characteristics of the area and recommended C values from Table 4. The runoff coefficients used in the analysis are shown in Table 7. The base case LTCP runoff coefficient for existing conditions with no LID applied is assumed to be 0.589. Next, we develop some assumptions for implementation of LID. First, we assume that 100% of the impervious surface area in the LTCP area is targeted for LID implementation. What this means is that we do not assume to size green infrastructure techniques for the capture of a pre-specified amount of stormwater. While this is the approach that was used in the DC Water LTCP, and other municipalities and citizens are using this approach (see the Center for Neighborhood Technology's Green Values Calculator (*29*)), this approach is not consistent with our rapid application of the LIDRA methodology for this case study, and we have not undertaken it as a comparative study here. If this alternative was taken, say, green infrastructure was designed to capture 80% of the surface runoff over 35% of the impervious surface area in the LTCP, then only 35% of the impervious surface area would be modified for the purpose of estimating a modified runoff coefficient, C_p.

After assuming that all impervious surface is available for LID implementation, regardless of capture goals, we then construct a logit model to estimate the probability that an individual customer might adopt LID technologies onsite based on LTCP area demographic characteristics. In order to do this, we have adopted a modified version of the logistic regression model obtained by Ando and Freitas (*28*) used to explain green roof installation in Chicago, IL. While green roofs are only one type of green infrastructure technology, and may have important differences with respect to cost and feasibility of installation, we have assumed for this preliminary analysis that the same proportion of customers adopting rain barrels will also install other LID technologies. In other words, we have assumed that regardless of the LID technology, its application is explained by factors reflected in the socioeconomic data. While this is a bold assumption, it highlights the fact that very few studies are available either evaluating implementation rates of LID technologies in municipal service areas or investigating the effect of customer behavior or characteristics on implementation rates. The coefficients, median demographic characteristics, and probability of adoption used in our analysis are shown in Tables 5-7. If we assume that the LID runoff coefficient is 0.35, the modified runoff coefficient for our study area, C_p, is 0.538.

4.3 RESULTS

Table 8 indicates the results of our analysis in terms of the minimum rainfall depth required to induce CSO events for each LTCP drainage area. While we have shown the base case C_{ex} and C_p for each area, we have also shown the results of pursuing more aggressive LID implementation rates by reducing C_p to 0.45 and 0.35. While the rates of LID implementation expected on the basis of demographic data do not lead us to believe that LID will make a significant impact on the occurrence of CSO events in the LTCP, we see that more aggressive LID implementation rates do, in fact, have important implications for CSO occurrence as greater rainfall depths are required to induce CSO events.

Table 8. Effects of LID Scenarios on Minimum Rainfall Depth to Cause CSO in LTCP Drainage Areas

CSO NPDES No.	*Drainage Area Description*	*Approximate Min Rainfall Depth to Cause Overflow (in)*	*LID Min Rainfall Depth (Cp=0.536)*	*LID Min Rainfall Depth (Cp=0.45)*	*LID Min Rainfall Depth (Cp=0.35)*
		Anacostia River CSO's (Cex=0.549, Cp=0.536)			
5	Fort Stanton	0.2	0.205	0.244	0.3137
6	Fort Stanton	1	1.024	1.22	1.5686
7	Fort Stanton	0.3	0.307	0.366	0.4706
9	B St./New Jersey Ave	0.3	0.307	0.366	0.4706
10	B St./New Jersey Ave	0.4	0.410	0.488	0.6274
11	B St./New Jersey Ave	no overflows	no overflows	no overflows	no overflows

011a	B St./New Jersey Ave	no overflows	no overflows	no overflows	no overflows
12	Tiber Creek	0.7	0.717	0.854	1.0980
13	Canal Street Sewer	0.4	0.410	0.488	0.6274
14	Navy Yard	0.4	0.410	0.488	0.6274
15	Navy Yard	0.8	0.819	0.976	1.2549
16	Navy Yard	0.5	0.512	0.61	0.7843
17	Navy Yard	0.4	0.410	0.488	0.6274
18	Navy Yard	0.4	0.410	0.488	0.6274
19	Northeast Boundary-Swirl Effluent	0.1	0.102	0.122	0.1569
19	Northeast Boundary-Swirl Bypass	0.4	0.410	0.488	0.6274
Potomac River CSO's (Cex=0.573, Cp=0.444)					
3	Bolling AFB	no overflows	no overflows	no overflows	no overflows
20	Easby Point	0.5	0.512	0.61	0.7843
21	Potomac Pumping Station	0.4	0.410	0.488	0.6274
22	I St.-22nd St., NW	0.7	0.717	0.854	1.0980
24	West Rock Creek Diversion Sewer	0.3	0.307	0.366	0.4706
25	31st&K St. NW	0.5	0.512	0.61	0.7843
26	Water St. District (WRC)	no overflows	no overflows	no overflows	no overflows
27	Georgetown	0.1	0.102	0.122	0.1569
28	37th St-Georgetown	0.5	0.512	0.61	0.7843
29	College Pond	0.3	0.307	0.366	0.4706
Rock Creek CSO's (Cex=0.591, Cex=0.544)					
31	**Penn Ave**	0.3	0.307	0.366	0.4706
32	26th-M St.	no overflows	no overflows	no overflows	no overflows
33	N St.-25th St.	0.7	0.717	0.854	1.0980
34	Slash Run Trunk Sewer	no overflows	no overflows	no overflows	no overflows
35	Northwest Boundary	no overflows	no overflows	no overflows	no overflows
36	Mass Ave and 24th	0.4	0.410	0.488	0.6274
37	Kalorama Circle West	1.3	1.332	1.586	2.0391
38	Kalorama Circle East	no overflows	no overflows	no overflows	no overflows
39	Belmont Rd	no overflows	no overflows	no overflows	no overflows
40	Biltmore St	1.3	1.332	1.586	2.0391
41	Ontario Rd.	no overflows	no overflows	no overflows	no overflows
42	Quarry Rd.	no overflows	no overflows	no overflows	no overflows
43	Irving St.	1.3	1.332	1.586	2.0391
44	Kenyon St.	no overflows	no overflows	no overflows	no overflows
45	Lamont St	1.3	1.332	1.586	2.0391
46	Park Road	1.3	1.332	1.586	2.0391

47	Ingleside Terr.	1.3	1.332	1.586	2.0391
48	Oak St-Mt. Pleasant	1.3	1.332	1.586	2.0391
49	Piney Branch	0.4	0.410	0.488	0.6274
50	M St.-27th St.	no overflows	no overflows	no overflows	no overflows
51	Olive-29th St.	no overflows	no overflows	no overflows	no overflows
52	O St.-31st St.	no overflows	no overflows	no overflows	no overflows
53	Q St.	no overflows	no overflows	no overflows	no overflows
54	West Rock Creek Diversion Sewer	no overflows	no overflows	no overflows	no overflows
56	Normanstone Dr.	no overflows	no overflows	no overflows	no overflows
57	Cleveland-28th St. & Conn. Ave	0.5	0.512	0.61	0.7843
58	Connecticut Ave.	1.7	1.741	2.074	2.6666
60	26th and P St. NW	no overflows	no overflows	no overflows	no overflows

This finding is shown more clearly in Table 9. Table 9 shows the corresponding percentage reuctions in CSO overflow duration for different levels of LID implementation. While the differences in minimum rainfall to induce CSO occurrence seem small, the reduction in the average CSO duration, as obtained from the relationship reported in Figure 3, are substantial relative to the expected CSO duration under existing conditions. While even the small changes expected from the LID adoption rates based on demographic data reduce CSO overflow duration by up to 5%, if more aggressive LID implementation rates are undertaken, reductions of up to 70% in some LTCP areas might be achieved.

Table 9. Percentage reductions in average overflow duration for different levels of LID implementation expressed as the runoff coefficient corresponding to treated area.

CSO NPDES No.	***Drainage Area Description***	***Reduction in Average Overflow Duration (Cp=0.536)***	***Reduction in Average Overflow Duration (Cp=0.45)***	***Reduction in Average Overflow Duration (Cp=0.35)***
		Anacostia River CSO's (Cex=0.549, Cp=0.536)		
5	Fort Stanton	1%	6%	14%
6	Fort Stanton	3%	25%	53%
7	Fort Stanton	1%	8%	20%
9	B St./New Jersey Ave	1%	8%	20%
10	B St./New Jersey Ave	1%	11%	26%
11	B St./New Jersey Ave	no overflows	no overflows	no overflows
011a	B St./New Jersey Ave	no overflows	no overflows	no overflows
12	Tiber Creek	2%	18%	41%
13	Canal Street Sewer	1%	11%	26%
14	Navy Yard	1%	11%	26%
15	Navy Yard	3%	21%	45%
16	Navy Yard	2%	13%	31%
17	Navy Yard	1%	11%	26%
18	Navy Yard	1%	11%	26%
19	Northeast Boundary-Swirl Effluent	0%	3%	7%

19	Northeast Boundary-Swirl Bypass	1%	11%	26%
		Potomac River CSO's (Cex=0.573, Cp=0.444)		
3	Bolling AFB	no overflows	no overflows	no overflows
20	Easby Point	2%	13%	31%
21	Potomac Pumping Station	1%	11%	26%
22	I St.-22nd St., NW	2%	18%	41%
24	West Rock Creek Diversion Sewer	1%	8%	20%
25	31st&K St. NW	2%	13%	31%
26	Water St. District (WRC)	no overflows	no overflows	no overflows
27	Georgetown	0%	3%	7%
28	37th St-Georgetown	2%	13%	31%
29	College Pond	1%	8%	20%
		Rock Creek CSO's (Cex=0.591, Cex=0.544)		
31	Penn Ave	1%	8%	20%
32	26th-M St.	no overflows	no overflows	no overflows
33	N St.-25th St.	2%	18%	41%
34	Slash Run Trunk Sewer	no overflows	no overflows	no overflows
35	Northwest Boundary	no overflows	no overflows	no overflows
36	Mass Ave and 24th	1%	11%	26%
37	Kalorama Circle West	4%	31%	62%
38	Kalorama Circle East	no overflows	no overflows	no overflows
39	Belmont Rd	no overflows	no overflows	no overflows
40	Biltmore St	4%	31%	62%
41	Ontario Rd.	no overflows	no overflows	no overflows
42	Quarry Rd.	no overflows	no overflows	no overflows
43	Irving St.	4%	31%	62%
44	Kenyon St.	no overflows	no overflows	no overflows
45	Lamont St	4%	31%	62%
46	Park Road	4%	31%	62%
47	Ingleside Terr.	4%	31%	62%
48	Oak St-Mt. Pleasant	4%	31%	62%
49	Piney Branch	1%	11%	26%
50	M St.-27th St.	no overflows	no overflows	no overflows
51	Olive-29th St.	no overflows	no overflows	no overflows
52	O St.-31st St.	no overflows	no overflows	no overflows
53	Q St.	no overflows	no overflows	no overflows
54	West Rock Creek Diversion Sewer	no overflows	no overflows	no overflows
56	Normanstone Dr.	no overflows	no overflows	no overflows
57	Cleveland-28th St. & Conn. Ave	2%	13%	31%
58	Connecticut Ave.	5%	39%	72%

60	26th and P St. NW	no overflows	no overflows	no overflows

4.4 RECOMMENDATIONS FOR FUTURE RESEARCH

The results of this preliminary screening analysis suggest several conclusions:

1. *LID Implementation Rates and Effectiveness*. Considerably more research is required to understand the influence of LID adoption on the success of LTCP plans developed by municipalities under consent decrees nationwide. If green infrastructure is to be promulgated as a cornerstone of municipal compliance with more stringent requirements of EPA MS4 regulation, then its effectiveness must be guaranteed and more information must be shared about the extent to which LID has been implemented in urban and suburban areas nationwide.
2. *LID Adoption Rates and Consumer Behaviors*. Little is known about the relationship between citizen characteristics and LID adoption. Montalto and colleagues (*27*, *30*, *31*) have investigated this to some extent through the use of agent-based modeling and survey research, but little research in this area has been reported in the literature. In conjunction with LID implementation coverage and effectiveness, it is important to know who will actually implement these technologies. This information is crucial for the effective design of incentive programs and stakeholder engagement materials.
3. *Systems-based Uncertainty Analysis.* More investigation into the important uncertainties is required to prioritize the research recommendations listed above. Most LID studies have incorporated scenario-based evaluation techniques into their investigations, but little sensitivity analysis has clarified the most important assumptions undergirding the increasing appeal of LID as a green infrastructure alternative to other CSO control techniques.

5. RECOMMENDED FUTURE RESEARCH AND CONTINUING RESEARCH

The preliminary results of these analyses suggest a few important findings. We will highlight these in the following bullets. We start with the lessons from sustainability definition for stormwater management:

1. *Future Value of Stormwater Impervious Surface Charge.* First, stormwater control and management may not carry substantial weight for large stakeholder decision making when compared with other items in their decision context. This may be, in part, due to the low stormwater impervious surface charge burden in place currently. DC Water has, however, acknowledged that this charge will increase considerably through 2020, with the potential for further increases if federal funding is not made available for financing improvements to the combined sewer system mandated by the consent decree (*25*). DC Water's stakeholder engagements should focus on the rising costs of stormwater control, and their incentives might incorporate the future costs of stormwater control in their structures.
2. *Visibility and Feasibility of Green Infrastructure Investments*. Second, stakeholders are more likely to commit to energy conservation measures because of the increased financial benefits, the increased visibility, and the higher levels of implementation feasibility they may perceive when compared with green infrastructure implementation. DC Water's stakeholder engagements should focus on this fact, especially since some researchers have shown that pioneers can be important in determining the degree to which green infrastructure measures penetrate the market (*30*).

Concerning the research needs for green infrastructure life cycle analysis and system analysis:

4. *LID Implementation Rates and Effectiveness*. Considerably more research is required to understand the influence of LID adoption on the success of LTCP plans developed by municipalities under consent decrees nationwide. If green infrastructure is to be promulgated as a cornerstone of municipal compliance with more stringent requirements of EPA MS4 regulation, then its effectiveness must be guaranteed and more information must be shared about the extent to which LID has been implemented in urban and suburban areas nationwide.
5. *LID Adoption Rates and Consumer Behaviors*. Little is known about the relationship between citizen characteristics and LID adoption. Montalto and colleagues (*27*, *30*, *31*) have investigated this to some extent through the use of agent-based modeling and survey research, but little research in this area has been reported in the literature. In conjunction with LID implementation coverage and effectiveness, it is important to know who will actually implement these technologies. This information is crucial for the effective design of incentive programs and stakeholder engagement materials.
6. *System*s*-based Uncertainty Analysis.* More investigation into the important uncertainties is required to prioritize the research recommendations listed above. Most LID studies have incorporated scenario-based evaluation techniques into their investigations, but little sensitivity analysis has clarified the most important assumptions undergirding the increasing appeal of LID as a green infrastructure alternative to other CSO control techniques.

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