INTEGRATED WATER MANAGEMENT AND GREEN INFRASTRUCTURE RETROFITS IN URBAN AREAS: PERSPECTIVES ON ENERGY SAVINGS, WATER QUALITY IMPROVEMENTS AND ECONOMIC INCENTIVES

by

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A dissertation submitted to the faculty of
The University of North Carolina at Charlotte
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy in
Infrastructure and Environmental Systems

Charlotte

2017

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ABSTRACT

PATRICIA ANNE BAJAK MALINOWSKI. Integrated water management and green infrastructure retrofits in urban areas: perspectives on energy savings, water quality improvements and economic incentives. (Under the direction of DR. JY S. WU)

This research investigates various aspects of implementing integrated water management (IWM) measures in urban areas, with a specific focus on green infrastructure (GI) retrofits. Three major perspectives are examined in relation to water resources policy and management: energy savings benefits of IWM measures that reduce demand on potable water supplies and centralized wastewater treatment facilities; use of impervious area reduction as the key metric in determining the extent of GI retrofits possible relative to water quality goals in existing urban watersheds with aquatic life and biological impairments due to stormwater runoff and prioritization for GI retrofit experimentation at the catchment scale; and, efficacy of stormwater fee credits as an economic incentive for private commercial property owners to implement GI retrofits. The results of these investigations answer questions addressing knowledge gaps from these three perspectives and provide guidance for policy and management decisions regarding GI's role in achieving sustainable urban water infrastructure goals.

The first area of this research is based on the knowledge that water supply and wastewater treatment systems are energy intensive processes. Consequently, IWM measures that reduce potable water consumption and/or wastewater generation can potentially translate into significant energy savings. From this perspective, the energy savings associated with IWM measures of rainwater harvesting and gray water reuse are estimated both at national and local utility scales using published data. The results indicate that aggregate energy savings due to reduction in water and wastewater demand from widespread implementation of rainwater harvesting and gray water reuse can be large for water utilities. Although disaggregated savings at the household scale are small, the knowledge of potential energy and cost savings to individual consumers is important for water utilities and policy makers when considering how to promote and incentivize the sustainable use of water.

Building on the concepts that stream health is related to extent of watershed impervious area and GI measures that remove runoff volume effectively reduce impervious area, the second area of this research identifies both the extent of impervious area reduction that GI retrofits can provide at the watershed scale and the relative contribution by property type. The extent of potential reduction in directly connected impervious area (DCIA) by GI retrofits is quantified within two impaired case study watersheds with different development characteristics in Mecklenburg County, North Carolina: Upper Little Sugar Creek (ULSC) which is dominated by commercial development and Six Mile Creek which is dominated by single-family residential development. The results indicate that GI retrofits are needed on all property types, public or private, to significantly impact aggregate DCIA reduction within the case study watersheds. Private commercial property plays a significant role in this regard providing almost 45% of the total DCIA reduction capability in ULSC and 35% in Six Mile Creek. Public property alone has the potential to provide approximately 35% of total DCIA reduction in both watersheds; however, the majority of this is from roadways and sidewalks with a small portion attributed to public owned commercial type development. The percentages of DCIA remaining in each watershed under maximum or moderate GI

retrofit coverage scenarios do not appear to be particularly promising relative to a stream health threshold of 10% impervious area. However, in an adaptive management approach, actual measured improvements to water quality as a result of DCIA reduction will have greater meaning than magnitude of reduction or remaining DCIA percentage.

The use of distributed stormwater controls is still mostly an unproven technology for urban stream restoration due to the limited number of watershed or catchment scale experiments of GI retrofits. A screening and prioritization scheme to select potential catchments for GI retrofit experimentation is developed using a multi-criteria decision analysis (MCDA) approach with a focus on DCIA reduction potential and applied to the two case study watersheds. Addition criteria are also considered and the overall prioritization goal is to identify catchments that will provide a manageable number and extent of GI retrofits such that measureable improvements in water quality can be potentially attained in a reasonable time horizon. The MCDA approach provides a framework to identify the best or few best catchment options within a priority watershed of interest to consider for further evaluation. The results provide decision makers and other stakeholders with information regarding the tradeoffs between different catchment options. Final catchment selection requires quantitative field evaluation and judgement calls as there are compromises to be made even when a few best catchment options are identified.

Low participation rates in stormwater fee credit programs indicate that the benefits attributed to the credits are not being realized, most notably, the benefit of providing an incentive for private property owners to control stormwater on their sites. This is a problem if fee credits are to be used as an incentive to achieve the level of

private property participation in GI retrofitting needed to impact stream quality improvements in impaired watersheds. In this third area of research an assessment is made of the economic value of various U.S. stormwater utility fee and credit structures, including the city of Charlotte's existing and proposed programs, relative to GI investment value for both private commercial property owners and stormwater utilities. The results indicate that a stormwater fee and credit combination based on the cost of capital and fee credits to the stormwater utility and fee credits equal to the cost of annual maintenance to property owners can provide equitable incentives to both groups to invest in GI retrofits. These results are useful in addressing policy questions regarding the characteristics and role of equitable utility fee and credit programs in sustainable urban stormwater management.

DEDICATION

To Keith and Matthew

In memory of

Anne L. Mattingly Bajak, M.S.Ed.

Joseph A. Bajak, J.D.

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LIST OF ACRONYMS AND ABBREVIATIONS

ac	Acre
AHP	Analytical Hierarchy Process
BOD	Biochemical oxygen demand
BMP	Best management practice
CAMA	Computer aided mass appraisal
CII	Commercial, institutional, industrial
CIP	Capital investment plan
CMSWS	Charlotte-Mecklenburg Stormwater Services
CMUD	Charlotte-Mecklenburg Utilities Department (Charlotte Water)
CN	Curve number
CS	Catchment score
CSO	Combined sewer overflow
CW	Charlotte Water (formerly CMUD)
CWA	Clean Water Act
DO	Dissolved oxygen
DCIA	Directly connected impervious area
EIA	Effective impervious area
EOP	Edge of pavement
ERU	Equivalent residential unit
ESU	Equivalent service unit
FC	Fecal coliform
ft^2	Square feet

FY	Fiscal year
GA	Gross area
GI	Green infrastructure
GIS	Geographic information system
Gpcd	Gallons per capita per day
GWR	Gray water reuse
ha	Hectare
HSG	Hydrologic soil group
IA	Impervious area
IC	Impervious cover
ICM	Impervious Cover Method
IRR	Internal rate of return
IWM	Integrated water management
km^2	Square kilometers
kWh	Kilowatt-hour
kWh/yr	Kilowatt-hours/year
LCA	Life-cycle analysis
LID	Low impact development
LL Res	Large lot residential
LUSI	Lake Use Support Index
M	Million
MCDA	Multi-criteria decision analysis
MF Res	Multi-family residential

MG	Million gallons
MGD	Million gallons per day
mi^2	Square miles
n	Number of criteria under consideration
N	Number of catchment options
NCDENR	North Carolina Department of Environment and Natural Resources
NCDEQ	North Carolina Department of Environmental Quality
NPV	Net present value
NPS	Non-point source
NGO	Non-government official
NPDES	National Pollutant Discharge Elimination System
NPV	Net present value
NRCS	Natural Resources Conservation Service (formerly SCS)
PCO	Post-construction ordinance
PP	Permeable pavement
PV	Performance value
Q1	Quartile 1 (25%)
Q2	Quartile 2 (50%)
Q3	Quartile 3 (75%)
r	Pearson product moment coefficient
r^2	Pearson coefficient of determination
Res	Residential
RWH	Rainwater harvesting

SCS	Soil Conservation Service (Natural Resources Conservation Service)
SF	Single-family
SFEU	Single-family equivalent unit
SF Res	Single-family residential
SMC	Six Mile Creek
SUSI	Stream Use Support Index
TAR	Treatment area ratio
TIA	Total impervious area
TMDL	Total daily maximum load
TN	Total nitrogen
TP	Total phosphorus
TPV	Transformed performance value
TSS	Total suspended solids
ULSC	Upper Little Sugar Creek
USCB	United States Census Bureau
USDA	United State Department of Agriculture
USDOE	United States Department of Energy
USEPA	United States Environmental Protection Agency
WT	Weight

CHAPTER 1: INTRODUCTION

1.1 Background

1.1.1 Integrated Water Management (IWM)

Integrated water management (IWM) refers to the coordinated and efficient management of stormwater, potable water, and wastewater infrastructure systems within the urban water cycle. Historically, these systems have been developed using a supply-side approach and for the most part have been managed separately (Wilkinson 2012). IWM measures that focus on demand-side techniques are intended to promote reductions in potable water demand, centralized wastewater treatment, and stormwater runoff quantity, which can be implemented either by water infrastructure suppliers or their customers (Wilkinson 2012). Specific measures that can be used to integrate management between connected elements of the urban water use cycle are low-impact development (LID) techniques including green infrastructure (GI), grey-water reuse, wastewater recycling, decentralized wastewater treatment, and repair and replacement of leaking water and sewer pipes (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; University of California Berkeley (UCB) and University of California Los Angeles (UCLA) 2011) as illustrated in Figure 1.1.

1.1.2 Green Infrastructure (GI)

The National Pollutant Discharge Elimination System (NPDES) Stormwater Program has been in existence for over 25 years. However, stream water quality in the majority of U.S. urban areas has not improved as anticipated, and the U.S. Environmental

Protection Agency (USEPA) and the National Research Council (NRC) identify stormwater runoff in urban areas as a major contributor to urban stream pollution (NRC 2008; USEPA 2009b; USEPA 2015c). The approach to urban stormwater management has evolved over this same time period. In the early years of the NPDES Stormwater Program the preferred structural method for stormwater quality control was large regional detention facilities designed to capture pollutants in urban runoff in addition to controlling increased peak flows and runoff volume from new and re-development. Recently, there has been a shift in the fundamental philosophy for water quality control and a preference for managing stormwater closer to its source via the use of smaller distributed infrastructure measure has emerged (Garrison et al. 2009; Reese 2009; USEPA 2010, 2014f and 2015c). These distributed measures are referred to as green infrastructure.

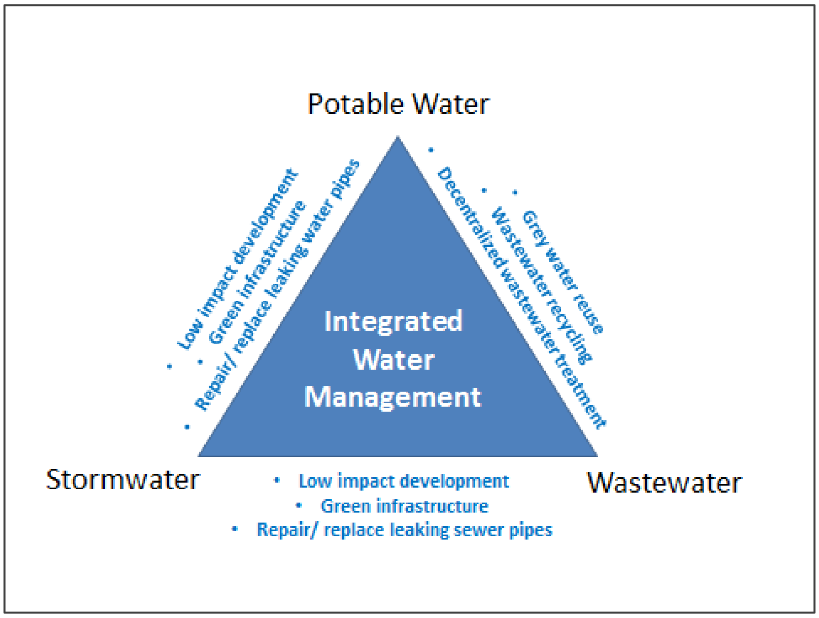

Figure 1.1: Integrated Water Management and the Urban Water Cycle

1.1.3 Watershed Impervious Cover, Stream Water Quality and GI

The urbanization of land results in the alteration of permeable land surfaces to impervious surfaces. This increase in impervious area results in increased stormwater flows, channel erosion and pollutant loadings causing degradation of receiving stream water quality and ecosystem habitat. Impervious area has been identified as a major indicator of stream health and watersheds with as low as 10% impervious cover have shown signs of stream impairment (Klein 1979; Booth and Jackson 1997; Schueler et al. 2009; USEPA 2014c). When GI type measures such as permeable pavement, infiltration basins, bioretention basins, green roofs, and rainwater harvestings systems are distributed throughout a catchment, the volume and quality of stormwater runoff from impervious surfaces are essentially managed at the source via reuse, infiltration and evaporation processes. These measures are increasingly seen as effective means of managing urban stormwater quality because of their ability to reduce the effective impervious extent by reducing the transport of pollutants and the volume of runoff to receiving streams (Walsh et al. 2005a; Bitting and Kloss 2008; Kloss 2008; USEPA 2014d and 2014e). Traditional peak flow and volume control measures do not reduce runoff volume and are, therefore, not considered to reduce effective impervious area (USEPA 2014c).

1.1.4 GI Benefits and Issues Rated to Urban Retrofitting

In addition to urban stormwater water quality protection and improvement, GI measures also provide many other benefits within an urban area including achieving the IWM objectives of reducing potable water demand, wastewater treatment volume, and stormwater runoff volume; groundwater recharge; delayed or deferred infrastructure investment costs; reduction in infrastructure size; ecosystem enhancement; urban environment enhancement; and, matching of water quality with appropriate use (Garrison et al. 2009; Spivey-Weber 2012; USEPA 2012; Steffen et al. 2013; Vieira et al. 2014). Further, because the amount of energy used to source, distribute and treat water is great (Allen et al. 2010; GAO 2011; USEPA 2013a; USEPA 2013b) GI measures that reduce demand on potable water supplies and wastewater treatment volume also have the potential to save a significant amount of energy (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; American Rivers et al. 2012). There are also many non-water related benefits of GI including reduced heat island effect, an increase in property values and improvements in air quality (Jaffe 2010; Pugh et al. 2012; Flynn and Traver 2013; Thomas 2014). Although these various benefits of GI measures are widely acknowledged, there are numerous difficulties in retrofitting the existing built environment.

Current major GI retrofit programs in the U.S. are mainly a result of regulatory actions in combined sewer areas (judicial consent decrees) and in severely impaired watersheds such as the Chesapeake Bay watershed (total maximum daily load (TMDL) and NPDES permit requirements). There is also increasing regulatory pressure for GI retrofit programs in municipal separate storm sewer (MS4) areas with receiving stream impairments as evidenced by impervious area reduction requirements being introduced by USEPA in stormwater TMDLs and NPDES permits outside the Chesapeake Bay area (PETE and ME-DEP 2006; CT-DEP 2007; ME-DEP 2012; UCONN 2015; USEPA 2014c, 2015d and 2015e).

Municipalities are implementing GI in three ways: land development policies for new and redevelopment projects; retrofits on public and institutional land; and, incentive programs for voluntary retrofits on already developed private property (USEPA 2010, 2014f). GI retrofit policies that rely on redevelopment projects alone will not significantly reduce effective impervious area in a reasonable time horizon (Bitting and Kloss 2008; USEPA 2009a) and retrofit programs not related to new and redevelopment face many difficulties including public funding limitations, land availability, and unwilling participation of private property owners (Cotting 2013; Copeland 2014). Physical constraints can also impact the type and extent of GI retrofits possible on existing property (Ellis et al. 2013). Further, although driven by regulatory actions, retrofit requirements are the responsibility of the municipality, and because of legal issues pertaining to property rights (Parikh et al. 2005; Ellis et al. 2013) owners of existing development in most cases cannot be required to retrofit their properties.

The result of these obstacles has been for municipalities to focus GI retrofits largely on public and institutional land (Bitting and Kloss 2008). Although there are several benefits to starting a retrofit program on public property the areal extent is limited except for public road right-of-ways where construction can be more costly due to utility conflicts and logistics related to road closures (Valderrama et al. 2015). Therefore, retrofits are needed on privately owned commercial property in order to meet regulatory requirements and in some urban and suburban areas and municipal stormwater managers are turning to market based and other types of incentive based strategies to overcome the related property rights issues (Parikh et al. 2005; Bitting and Kloss 2008; USEPA 2010; Ando and Netusil 2013).

1.1.5 Stormwater Utility Fee and Credit Programs

Presently, the most widely used market based method to finance urban stormwater management programs in the U.S. is a price based user fee paid to stormwater utilities (Reese 2009; SESWA 2013; Black & Veatch 2014; Campbell et al. 2014). Campbell et al. (2014) identify over 1,500 stormwater utilities in the U.S. with user fee based funding systems. The user fees are essentially impact fees based on the demand a property places on the stormwater system and the majority are based in some manner on the amount of impervious area on a parcel, either estimated or measured. The rate structures are simple or complex and many utilities offer credits or adjustments to fees based on property or user classification and actions taken by property owners that reduce demand on the stormwater systems (Reese 1996; Doll et al. 1999; Ellard 2011; Berahzer and Hughes 2014).

Stormwater fee credits can provide an ongoing reduction to a property's stormwater fee due to practices that reduce demand on the stormwater system or reduce the public costs of the service. Fee credits are widely acknowledged as important incentives for private property owners to participate in stormwater control activities including installation of stormwater control facilities on their properties, because of the benefit to stormwater management systems in urban areas. In addition, fee credits also have been useful in justifying the fee as a user or impact fee as opposed to a tax, due to the ability of a ratepayer to pay the fee or reduce it by controlling a portion of stormwater runoff from their property (Doll et al. 1999; Reese 1999; Berahzer and Hughes 2014).

However, the available data from the most recent stormwater utility surveys indicate that fee credits are not being widely used, with reported user rates of between

2.15% (Mason 2015) and 4% (Black & Veatch 2014). The most common reason attributed to low fee credit usage is the low price of the fee (Doll et al. 1999; Thurston 2006; Ando and Netusil 2013; Berahzer 2014; Nickel et al. 2014; Ruhlman et al. 2014), however, both the magnitude of the fee and the value of the fee credit together will influence the success of this type of incentive (Doll et al. 1999).

This low participation rate indicates that the benefits attributed to fee credits are not being realized, most notably, the benefit of providing an incentive for private property owners to control stormwater on their sites. This is especially true in relation to controls that improve water quality. Current fee credits offered by municipalities are commonly based on peak and volume control for convenience and emergency storm events (Doll et al. 1999; van der Tak 2015) and are not geared toward incentivizing measures for control of smaller storm events that improve stormwater quality such as GI and stream stabilization. Black & Veatch (2014) reports that 44% of the utilities surveyed offer fee credits and only half of these provide credit for water quality control. Further, less than 40% provide fee credits specifically for GI type measures. These are indicators of the difficulty municipalities will have in using fee credits as an incentive to achieve required levels of private property participation in GI retrofit programs.

1.2 Research Objectives, Research Questions and Significance of Research

The overall purpose of this research is to investigate various aspects of implementing integrated water management (IWM) measures in urban areas, with a specific emphasis on green infrastructure (GI) retrofits. Three major perspectives are examined in relation to water resources policy and management: energy savings benefits of IWM measures that reduce demand on potable water supplies and centralized wastewater treatment facilities; extent of GI retrofits possible and necessary to achieve water quality goals in existing urban watersheds with aquatic life and biological impairments due mainly to stormwater runoff, and prioritization for GI retrofit experimentation at the catchment scale to prove the technology using impervious area reduction as the key metric; and, efficacy of stormwater fee credits as an economic incentive for private commercial property owners to implement GI retrofits. The overarching objective of these three separate but connected analyses is to answer important questions that will guide policy and management decisions to further the understanding of GI's role in achieving sustainable urban water infrastructure management goals. It is intended that this GI retrofit strategy based on impervious area reduction will be a part of an overall water quality standards based adaptive management approach to watershed restoration that includes stream scale and riparian zone improvements as well as non-structural measures and will aid in expediting evaluation of GI performance in this context.

1.2.1 Perspectives on IWM Measures and Energy Savings

1.2.1.1 Research Objectives and Research Questions

Water supply and wastewater treatment are energy-intensive processes and are one of the largest consumers of energy in a municipality (Allen et al. 2010; USEPA 2015a); therefore, reducing potable water use for landscape irrigation and other uses with IWM measures can potentially save a significant amount of energy (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; American Rivers et al. 2012). The overall objective of this portion of research is to quantify the magnitude of energy savings in widespread implementation of certain IWM measures in an urban area. The main question to be answered is: Can sufficient energy savings be realized from the implementation of rainwater harvesting and gray water reuse systems to provide economic incentives that might encourage retrofits by water utilities and their customers?

1.2.1.2 Significance of Research

a) Knowledge Gap

Although energy savings are frequently mentioned as a benefit of IWM and GI measures, only a few sources provide aggregated estimates of these potential savings and the associated costs savings at the regional or municipal scales. Also, none of these studies quantifies the savings potential at the consumer level nor do they discuss the effect consumer scale savings might have on decisions regarding implementation of these measures within existing urban areas.

b) Justification

Managing energy and water resources in a sustainable manner and developing an understanding of the connection between them is becoming more critical as the demand for both increases in the United States in conjunction with competing uses between public water supply and electricity generation (Cohen et al. 2004; Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; NCSL 2009; Sovacool and Sovacool 2009; AWE and ACEEE 2011; Scott et al. 2011; Stillwell et al. 2011a, 2011b; WERF 2011; Wilkinson 2012; EnerNOC, Inc. and Washington University 2013). Sustainable and efficient water-infrastructure management is becoming increasingly necessary due to growing municipal demand in urban areas, competition with other water uses such as for energy production and agricultural use, stricter treatment standards, and aging infrastructure (WERF 2011; Wilkinson 2012). IWM measures can be used to meet this water management challenge.

Therefore, there is a need to quantify the magnitude of energy savings afforded by IWM measures at various scales: national, regional or municipal, and individual consumer, not only to support system management decisions but also to understand the implications of these savings for water infrastructure providers and consumers in urban areas and to aid in the development and coordination of appropriate economic incentives that will encourage and optimize IWM implementation by both groups (USEPA 2013a).

1.2.2 Perspectives on GI Retrofits and Water Quality Improvements

1.2.2.1 Research Objectives and Research Questions

Municipalities tend to focus GI retrofits on public property due to the many obstacles to retrofitting private property (Bitting and Kloss 2008), but the extent of suitable public land is limited. The problem for stormwater managers is how to use limited public funds to focus implementation of GI retrofits on the most suitable properties within a catchment, whether public or private.

Building on the concept that stream health and restoration are related to the extent of watershed impervious area, the main objectives of this portion of the research are: to identify both the extent to which GI retrofits can be used to reduce imperious area within a watershed and the relative contribution by property type and public or private ownership in achieving stream restoration goals; and, to develop a catchment prioritization scheme with a focus on impervious area reduction capacity and additional features that will provide a manageable number and extent of GI retrofits such that measureable improvements in water quality can potentially be attained in a reasonable time horizon. The focus is on catchments in small urban watersheds with aquatic life and biological impairments due mainly to stormwater runoff. It is intended that this catchment scale GI retrofit planning strategy based on reduction of effective impervious cover will be a part of an overall water quality standards based adaptive management approach to watershed restoration that includes stream scale and riparian zone improvements as well as non-structural measures and will aid in expediting evaluation of GI performance in this context. The results will support the development of long term experimental pilot studies to further validate the restoration strategy of watershed wide distributed stormwater management measures to all potential stakeholders, public or private.

The main questions to be answered by this research are: 1) What is the extent of GI retrofits needed and potentially achievable within high priority, stormwater impaired urban watersheds with different land use characteristics to reduce the level of effective impervious area to achieve stream health goals; 2) What is the potential contribution to impervious area reduction from different property types (public, private, commercial, single-family, roadway); 3) To what extent is contribution from private commercial property necessary in this regard; 4) What criteria are important in identifying the most suitable catchments for GI retrofit experimentation that will provide a manageable number and extent of GI retrofits such that measureable improvements in water quality can potentially be attained in a reasonable time frame; and, 5) Are these criteria different for watersheds with different development characteristics?

1.2.2.2 Significance of Research

a) Knowledge Gap

There are many studies that develop and apply decision support tools to demonstrate the ability to optimize selection of GI measures at the site scale (Viavattene et al. 2010; Young et al. 2010; Jia et al. 2013). At the catchment and watershed scale there are several case study applications of decision support and modeling tools of varying complexity to select cost effective GI retrofits and to simulate their impact on pollutant removal and stormwater volume and peak flow reduction (Sullivan et al. 2008; DeBusk et al. 2010; McGarity 2012; Lee and Riverson 2013; Chen et al. 2014; Gagrani et al. 2014). None of these modeling studies determines the hypothetical potential of restoration within each watershed or the extent of GI retrofits needed to achieve various levels of potential restoration based on removal of effective impervious area. Additionally, although the need for GI retrofits on both public and private properties to achieve restoration goals is widely acknowledged (USEPA 2010, 2014f, 2015c; Valderrama and Davis 2015), no studies identify the extent necessary or possible relative to restoration potential.

The limited numbers of GI retrofit research programs that have been implemented to collect performance monitoring data conclude the need for denser implementation of retrofits within a catchment in order to obtain measurable levels of restoration (Roy et al. 2014) or have not yet produced enough data to reach conclusions (Walsh et al. 2015). Therefore, examples of significant impervious area reduction or the optimal configuration or density of GI implementation for demonstrating program effectiveness at the catchment level does not exist. Observed achievement of performance goals of catchment scale distributed stormwater management is essential in helping to advance this approach for urban stream restoration from theory to proven technology (Schueler et al. 2009).

b) Justification

A simple screening process is needed to define the extent and configuration of public and private GI retrofits within a watershed that will result in the level of impervious area reduction necessary to achieve target water quality improvement goals and to prioritize implementation at the catchment level. Stormwater infrastructure managers need guidance on strategies that can focus limited funds and maximize improvement of urban water quality. Initial GI retrofit implementation programs should allow local stormwater managers to develop useful data that will strengthen or challenge the applicability of distributed watershed management in their unique watersheds.

Currently, there are a limited number of watershed or catchment scale experiments of GI retrofits and little information is available regarding the potential impact of GI retrofit implementation across a watershed (Jaffe et al. 2010). Therefore, this is still mostly an unproven technology for urban stream restoration and more experiments are needed (Schueler et al. 2009). Due to the long term nature of the strategy, the primary obstacles to implementing catchment scale retrofit programs are locating and funding a sufficient number and extent of retrofits to demonstrate performance effectiveness (Ellis 2013; Walsh et al. 2015). A catchment scale plan that defines the amount of retrofit required to meet water quality goals (Schiff et al. 2014) and the magnitude of impervious area that is technically feasible to disconnect (Owen 2011; Ellis 2013; Schiff et al. 2014) will help advance this strategy (Ellis 2013). Selecting the most suitable catchments to conduct these experiments in terms of cost efficiency and potential to provide results within a reasonable time period is important to prove the technology (Walsh et al. 2015). As the strategy is advanced and the benefits of GI are further quantified, the case for all types of private property participation can be strengthened.

The level of ecological restoration of an urban stream realistically possible or achievable needs to be defined at the watershed scale and worked towards over a long period of time. A strategy for GI retrofit planning is needed that goes beyond individual site suitability and considers catchment level site relationships of restoration potential with a watershed system perspective.

1.2.3 Perspectives on GI Retrofits and Economic Incentives

1.2.3.1 Research Objectives and Research Questions

The low participation rate in stormwater fee credit programs indicates that the benefits attributed to them are not being realized, most notably, the benefit of providing an incentive for private property owners to control stormwater on their sites. This is a problem if fee credits are to be used as an incentive to achieve the level of participation in GI retrofitting needed to impact stream water quality improvements in impaired watersheds. The overall objective of this research is to determine the characteristics of an equitable stormwater fee and credit program that will provide effective incentives to private commercial property owners to invest in GI retrofits. The intention is to provide insight into economic and policy issues needed to create an equitable and favorable incentive approach for both stormwater utilities and owners that will promote GI retrofits on commercial property in existing urban areas and guide overall stormwater management efforts for both water quality and water quantity.

The main research questions are: 1) What are the ownership characteristics and regulatory drivers of stormwater BMPs within CMSWS's service area that currently receive fee credits and does this information provide insight into reasons for non-participation in the program; 2) What is the value of GI to private commercial property owners and do the current stormwater fee and credit structures of CMSWS and other U.S. stormwater utilities provide an equitable incentive to invest in GI retrofits; 3) What are the characteristics of an equitable GI retrofit program for CMSWS?

1.2.3.2 Significance of Research

a) Knowledge Gap

The available data from the most recent stormwater utility surveys and (SESWA 2013; Black & Veatch 2014) indicate that fee credits are not being widely used, with a reported maximum user rate of 4% and the reasons for low participation in fee credit programs have not been verified. This low participation rate indicates that the fee credit benefits related to stormwater control are not being realized. This is especially true in relation to controls to improve water quality. Current fee credits offered by municipalities are commonly based on peak and volume control for convenience and emergency storm events (Doll et al. 1999; van der Tak 2015). As such, most existing fee credit programs are not geared toward incentivizing measures that improve stormwater quality such as green infrastructure and stream stabilization.

In addition, due to growing regulatory pressure to implement GI retrofits in existing urban areas with severe stream impairments, the limited number of sites suitable for retrofit and the need for voluntary participation by private commercial property owners in these areas, there is the need to understand owners' attitudes toward and willingness to participate in retrofit incentive programs. Several studies exist regarding attitudes toward and willingness to implement GI for residential property owners, stormwater managers and construction professionals (Giacalone et al. 2010; Green et al. 2012; Olorunkiya et al. 2012; Cadavid and Ando 2013; Keeley et al. 2013; Carlson et al. 2014; Larson et al. 2014; Baptiste et al. 2015; Carlet 2015). However, there are none that investigate the attitudes and willingness to participate for private commercial property owners.

b) Justification

Identification of the specific barriers for private commercial property owner participation existing fee credit programs is needed if fee credits are to be used as an incentive GI retrofits on private property. In addition, there is a need to make stormwater user fees and fee credit structures equitable such they provide incentives to both the utility and to private property owners to implement water quality and water quantity improvements to the system. Doll et al. (1999) concluded that research is needed to assess the efficacy and economic equity issues relative to stormwater utility fees and credits. There are no such studies in the literature at this time.

Research is needed to examine why participation in fee credit programs is so low and to determine if there is a relationship between this current low rate and the potential for incentivizing private commercial property owners to implement GI retrofits on existing development. It is intended to provide insight into economic and data issues that are needed to establish an equitable and favorable incentive approach that will work with current stormwater utility fee and credit structures to promote GI retrofits on existing private commercial property. The results will also be useful in addressing associated policy questions regarding equitable utility fee and fee credit programs to guide overall stormwater management efforts for both water quality and water quantity within a municipal service area.

1.3 Dissertation Organization

This dissertation consists of six chapters. Background information for various topics important to the three research areas: energy savings, water quality and economic incentives, and the research objectives and research questions for each are provided in Chapter 1. The significance of the proposed research in each area in terms of the knowledge gap and justification for the research are also provided. Chapter 2 provides an extensive literature review conducted to inform the development and design of the research areas.

This research utilizes published data, GIS data and software, multi-criteria decision analysis and financial analysis to meet the established objectives and to answer the identified research questions. Chapters 3, 4 and 5 present the data, analysis methodology and results obtained for each research area including discussion and conclusions. The conclusions from all three sections are summarized in Chapter 6 and a connection between all three research areas is made by addressing the implications of this research for sustainable water infrastructure management in urban area areas. References are then provided.

CHAPTER 2: LITERATURE REVIEW

2.1 Perspectives on IWM Measures and Energy Savings

The existing literature is reviewed for several topics including: documented benefits of IWM; specific issues related to energy savings and IWM; IWM and life-cycle assessments; and, the role of end-use heating in water related energy savings. A summary of existing literature on each topic is presented along with how the knowledge is going to be used to meet the objectives of this research. The results of the literature are then used to identify the knowledge gap, formulate the research questions and provide justification for the methodology and analytical procedures utilized in this portion of the research effort.

2.1.1 Energy Savings due to Reduction in Potable Water Demand

Energy savings due to a reduction in potable water demand are also frequently mentioned as a benefit of IWM. Numerous technical reports and research studies by government and non-government organizations indicate the amount of energy used to source, distribute and treat water is great (Allen et al. 2010; GAO 2011; USEPA 2013a, 2013b); that water and wastewater utilities are one of the largest consumers of energy in a municipality, often accounting for up to 30-40% of total energy consumed (USEPA 2015a); and, that reducing potable water use for landscape irrigation and other uses via low impact development (LID) and green infrastructure (GI) practices can save a significant amount of energy (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; American Rivers et al. 2012). American Rivers et al. (2012) estimate that groundwater recharge from green infrastructure could save the City of Los Angeles over $23 million in energy costs each year, and Garrison et al. (2009) estimate that potable water reductions due to LID in the urbanized areas of southern California and portions of the San Francisco Bay area alone could save up to approximately 1.2 billion kWh of electricity per year.

2.1.2 Life Cycle Assessment

Life cycle assessment (LCA) of the economic and/ or environmental impacts of various IWM type water conservation strategies at the individual site level are also found in the literature. These studies acknowledge the many benefits but also caution that there may be adverse impacts related to high energy requirements of such measures. Vieira et al. (2014) evaluate the energy intensity of rainwater harvesting systems and conclude that characteristics of energy intensity of central water supply, local climate characteristics and rainwater catchment system design have the greatest impact on overall economic and environmental performance. Anand and Apul (2011) perform an LCA to compare cost, energy requirements and carbon emissions for various combinations of potable and rainwater sources with standard and high efficiency sanitation devices (toilets). The results indicate that high efficiency devices with a rainwater source have the best economic result, the lowest embedded energy, and the lowest carbon emissions. However, the high efficiency device with a potable water supply outperformed the standard device supplied with rainwater in all evaluation categories due to the high cost and manufacturing energy input of the rainwater apparatus compared to centrally supplied water.

Racoviceanu and Karney (2010) provide an LCA comparison of operational energy use and greenhouse gas (GHG) emissions between a base case and two residential water conservation strategies. In the first strategy, potable water demand is reduced using water efficient devices and in the second strategy, a rainwater harvesting system is added to further reduce potable water demand. Although reductions in energy use and GHG emissions is realized as a direct result of the significant water savings in both strategies, the greatest reductions are realized as a result of the decrease in heated water demand. When heated water is omitted from the analysis, the water efficient strategy resulted in the lowest impacts. Although the rainwater harvesting strategy resulted in the greatest water savings, the embedded energy in the manufacture of the cistern makes it the least efficient strategy. This strategy would have been further weakened had the energy requirements for an on-site pump been taken into account. These LCA results highlight the energy, cost and environmental related issues of various water conservation strategies and the impact that defined analysis boundaries have on overall results.

2.1.3 End Use Heating

End use water heating has an important impact on the relationship between energy and water demands. A total of 13% of all power consumed in the U.S. each year is for water related uses. Over two-thirds of that amount or 9% of total power consumption is for end use water heating and the remaining 4% is for water supply and treatment (NCSL 2009). It follows then, as indicated by the results of Racoviceanu and Karney (2010), that energy requirements of end use water heating have a large influence on energy impacts of conserving water for indoor uses. Further, Abdallah and Rosenberg’s (2014) analysis of the link between household energy and indoor heated water use highlights the importance of collaborative energy and indoor water conservation measures.

2.2 Perspectives on GI Retrofits and Water Quality Improvements

The existing literature is reviewed on several topics including: the relationship between level of watershed imperviousness and stream health; classification and measurement of impervious area; GI and the ability to reduce runoff volume and effective impervious area and how this is concept is currently being used by stormwater managers and regulators; issues related to stream restoration goals, methods and scale; decision support tools for GI site selection and catchment scale performance effectiveness; and, existing catchment scale experimentation studies. Imperviousness is referred to using various terms throughout the literature: impervious area (IA), impervious cover (IC), total impervious area (TIA), effective impervious area (EIA), and directly connected impervious area (DCIA). DCIA and EIA are equivalent and DCIA is less than or equal to TIA. This literature review retains original reference terminology but attempts to relate all terms to either TIA or DCIA when possible. The results of the literature review are used to identify the knowledge gap, formulate the research questions and provide guidance and justification for the methodology and analytical procedures utilized in this portion of the research effort.

2.2.1 The Relationship between Impervious Area and Stream Water Quality

Klein (1979) is one of the earliest studies to indicate a relationship between the extent of watershed urbanization and stream water quality. Klein compared biological sampling data with degree of watershed urbanization as defined by percent impervious area calculated using methods based on land use cover. The paper concludes from analysis of data from watersheds and streams through the piedmont area of Maryland indicate that stream quality impairment can first be seen when watershed imperviousness reaches 12% and becomes severe after reaching 30% imperviousness.

To further the concept of a relationship between total impervious area (TIA) and stream health, the impervious cover model (ICM) was first introduced by Schueler in 1994 as a tool to help water managers predict future stream conditions based on the TIA of future land development. The initial model was developed by analyzing the results of several research studies relating stream quality and imperviousness including Klein (1979). It consisted of a straight line relationship between TIA and four categories of stream quality: sensitive, impacted, non-supporting and urban drainage. Numerical boundaries of TIA associated with each category are identified as $\leq$ 10%, 10-25%, 25-60% and $\geq$ 60%, respectively (Schueler 2000).

CWP (2003) furthered the work done to develop the initial ICM by analyzing the results from over 250 additional studies relating watershed imperviousness to various stream health indicators. Most recently, Schueler et al. (2009) analyze the results of several additional studies completed since 2003 to further demonstrate and confirm the application of the ICM to predict the average behavior of stream hydrologic, physical, chemical and biological responses on the basis of percent TIA in the contributing drainage catchment. This latest investigation also provides an improved ICM that expresses the range of TIA disturbance thresholds as a cone of variation rather than a straight line relationship. This reformulated ICM, shown in Figure 2.1, indicates the range of stream quality variability is greatest for low TIA (< 10%) converging to a small range of stream quality variability for large amount of TIA (> 60%) with a continuous increase in stream degradation as TIA increases.

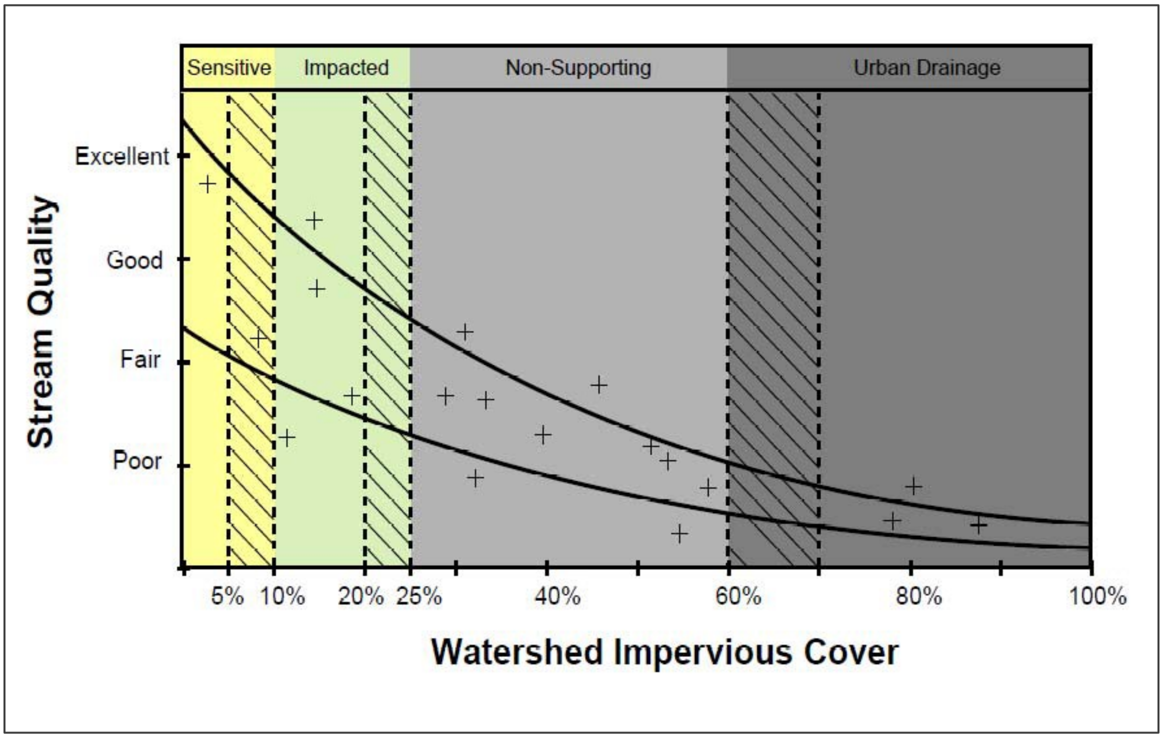

Figure 2.1: Impervious Cover Method (Schueler et al. 2009)

The ICM is offered as a tool for watershed managers to manage stream response to urbanization by measuring and managing TIA in response to future land use. It is used by some municipalities as a planning tool to control growth and to set stormwater management policy. For this research the IWM is used as a frame of reference to support the concept of quantification of impervious area to develop restoration goals and as a guide for determining the potential to meet GI retrofit goals within existing impaired streams.

There are several qualifiers for use of the ICM as a planning tool: the relationship between watershed imperviousness and stream health is based on TIA which should be accurately measured; TIA should not be the only metric used to predict stream quality at low TIA%; streams with low TIA% should not automatically be assumed to be of good to excellent quality; stream quality classifications should be based on actual monitoring data and water quality criteria; and, applicable watersheds are 1^{st}, 2^{nd} and 3^{rd} order alluvial streams (stream beds made up of alluvium materials such as clay, silt and sand that change with flow conditions) with drainage areas ranging from 0.2 to 20 mi^2, in similar physiographic regions to those used in development of the model along the Atlantic coast, in the Piedmont and Pacific Northwest areas of the U.S., and, with homogeneous slopes (CWP 2003; Schueler et al. 2009).

2.2.2 Classifying and Quantifying Watershed Impervious Area

Extent of impervious area is widely used as a measure for various watershed planning and management purposes including setting rates for stormwater utility fees (Arnold and Gibbons 1996; Parikh et al. 2005; SESWA 2013; Black & Veatch 2014; Campbell et al. 2014) and off-site mitigation (Parikh et al. 2005) and is increasingly being used as a surrogate to measure level of stream impairment and to track compliance with water quality regulations (USEPA 2014c). Although impervious area is measurable and may be simpler to work with than models that incorporate several complex variables to estimate the quantity and quality of stormwater runoff (Arnold and Gibbons 1996), there are differences in how it is measured which affects its magnitude and use in application.

2.2.2.1 TIA vs. DCIA

Watershed impervious area consists of surfaces that do not allow rainwater to infiltrate into the underlying soils and generate runoff such as roads, roofs, parking lots, sidewalks, and driveways. Directly connected impervious area (DCIA), also referred to as effective impervious area (EIA), is that portion of TIA that is directly connected to a receiving waterbody via a continuous hydraulic connection of other impervious surfaces, pipes and conveyance facilities that do not reduce the volume of runoff. Disconnected impervious area is that portion of TIA where stormwater flows naturally across adjacent pervious areas or is routed to stormwater management facilities that reduce the volume of runoff reaching the stream.

This distinction between TIA and DCIA is important because runoff from DCIA is considered to be the main contributor to stream impairment (Brabec 2009). A reduction in DCIA, either through conversion to pervious area (e.g., routing runoff from DCIA through a bioretention basin or infiltration trench) or complete removal of impervious area (rainwater harvesting system or permeable pavement), is believed to contribute to improving stream health (USEPA 2010, 2011, 2014f, 2015d, 2015e).

There are also two different types of pervious surfaces, natural pervious surfaces such as forest land and meadows and nominally pervious surfaces such as lawns or turf that have been disturbed and compacted thereby lowering the natural infiltration capacity (Booth and Jackson 1997). CWP (2003) indicates that the fraction of watershed area that is turf within low-density residential development could play a significant role in impacted streams in the 10-25% TIA range in terms of both runoff quality and quantity. The runoff characteristics of these pervious surfaces are much different than natural condition pervious areas and are not included in TIA but should be taken into consideration in any study of runoff potential. Hirschman et al. (2008) also discuss the importance of accounting for pervious areas with compacted urban soils and managed turf areas to accurately account for the potential of urban runoff volume from impervious, turf and natural areas especially when nutrients are an issue.

2.2.2.2 TIA and DCIA Measurement Techniques

Typical techniques currently used to measure TIA include: land use interpretation from USGS National Land Cover Database (NLCD) Landsat satellite imagery data (Roy and Shuster 2009; Homer et al. 2015); digital measurements of parcel scale impervious surfaces from aerial photographs (Booth and Jackson 1997; Brabec 2009; Roy and Shuster 2009) or assigning characteristic values of TIA to different land use classifications (CWP 2003). Estimates of DCIA can then be determined from TIA by using empirical models that relate DCIA as a function of TIA or by conducting field assessments to identify drains, downspouts, connections, disconnections, slopes and direction for driveways and yards.

Characteristic values of TIA and DCIA associated with different land use types are available from various sources. The most commonly used set of values are those defined for TIA in TR-55, Urban Hydrology for Small Watersheds (NRCS 1986). Other regional and local values have been developed such as those for suburban areas within the Chesapeake Bay watershed presented by CWP (2003) and developed by Cappiella and Brown, values from the USEPA's Rouge River, Michigan and used by USEPA in Region 1 small MS4 permits (USEPA 2011); and characteristic values for both TIA and DCIA as proposed by Dinicola for use in western Washington State used by Booth and

Jackson (1997), which are based on a combination of empirical relationships from three prior studies by Alley and Veenhuis, Laenen, and Prysch and Ebbert. If land use classes are used to estimate TIA, local data should be developed using a large number of land use classes and should be field checked (Brabec 2009; CWP 2003). These various characteristic values for land use impervious area are summarized in Table 2.1.

Roy and Schuster (2009) develop an empirical relationship between DCIA and TIA based on GIS data and field assessments for suburban Cincinnati, OH residential parcels and compare their results with estimates made from two published empirical relationships (see Table 2.2). They conclude that accurate estimates of TIA can be determined from digitizing aerial photos at the parcel scale, however, the connectivity of TIA, or DCIA, can only be accurately determined through further field assessment due to the high variability in DCIA versus TIA at the parcel scale. They further conclude that when calculating average DCIA for several parcels (> 60 acres) estimates of DCIA based on TIA may be sufficient, depending on their intended use. Lee and Heaney (2003) also conclude that field assessment is critical to accurately estimating DCIA.

Sutherland (2000) presents an empirical equation for estimating DCIA from TIA based on data developed by the U.S. Geological Survey (USGS) from several watersheds in the Portland and Salem, Oregon areas that appears to be valid for watersheds with TIA between 10% and 50%. But because TIA can exceed 50% and go as high as 90% in some smaller watersheds, the USGS data are further used to develop several empirical equations relating TIA and DCIA for watershed with different levels of development and assumed connectedness. The USGS equation and the Sutherland equations are provided in Table 2.2.

2.2.3 The Relationship between Runoff Volume Control and Impervious Area Reduction

The approach to urban stormwater quality management has evolved since the early 1990s when the USEPA Stormwater Rule was first promulgated. In the early years of the NPDES Stormwater Program the preferred structural method for stormwater quality control was large regional detention facilities designed to capture pollutants in urban runoff in addition to controlling increased peak flows from new and re-development. However, stream water quality in the majority of U.S. urban areas has not improved as anticipated and the USEPA (2009b, 2015c) and the National Research Council (NRC 2008) identify stormwater runoff in urban areas as a major contributor to urban stream pollution.

Booth and Jackson (1997) were the first to show that the pollutant removal performance effectiveness of stormwater detention ponds is not as significant as assumed. Hirschman et al. (2008) point to recent BMP performance research focused on runoff volume reduction of GI measures and pollutant removal efficiency which indicates that runoff reduction not only reduces pollutant loads but also does a better job of mimicking pre-development hydrology. This in turn can reduce overbank flooding and channel erosion, and recharge groundwater.

Reese (2009) provides a detailed discussion of volume based hydrology and demonstrates that volume control is the basic control factor of stormwater management at every level from water scarcity, pollution reduction and channel erosion impacts associated with high frequency low rainfall events to flood control and floodplain management issues associated with low frequency large rainfall events. The conclusion is that control or removal of volume is much more important than treatment of volume.

Jaffe et al. (2010) reviewed BMP performance data from over 50 peer-reviewed journal articles and concluded that GI measures are on average as effective at TSS and TN removal as traditionally designed detention basins and are also effective in reducing peak flows. Unlike the traditional BMPs, GI-type BMPs are also capable of reducing runoff volume and improving water quality which traditional detention BMPs do not do.

Viavattene et al. (2010) reference both Reese (2009) and Hirschman et al. (2008) in arguing that achieving runoff reduction is the first factor to address in sustainable urban stormwater management. The authors develop a GIS-based BMP selection and performance assessment tool with total runoff reduction as a key performance standard for water quality compliance.

2.2.4 Impervious Area Reduction Capability of GI Measures

GI measures such as permeable pavement, infiltration basins, bioretention basins, green roofs, rainwater harvestings systems and tree plantings (including pits and planters) reduce the volume of stormwater runoff from impervious surfaces via canopy interception; soil, engineered and extended infiltration; reuse; evaporation; and, evapotranspiration processes (CSN 2009). Retention of 100% of volume from small frequent rainfall events can be achieved (Ellis 2013). GI measures are increasingly seen as effective means of managing urban stormwater because of their ability to reduce DCIA by reducing the transport of pollutants and the volume of runoff to receiving streams (Walsh et al. 2005a; Bitting and Kloss 2008; Kloss 2008; USEPA 2014c, 2014d, 2014e).

Traditional peak flow control measures do not reduce runoff volume and are, therefore, not considered to reduce effective impervious area (USEPA 2014c). Novatny (2008) explains that although regional BMPs are good at providing peak flow reduction and flood mitigation benefits at the watershed scale, they are not as effective at improving water quality because there is space between where pollutants are generated and washed off and where they are treated and most are designed for flow peak control and few reduce volume and effective impervious area.

Roy and Shuster (2009) conclude that it may be appropriate to use parcel scale DCIA estimates to predict the impact on receiving stream effects due to DCIA disconnection using GI retrofits. USEPA Region 1 is in the process of finalizing requirements for small MS4 permittees to estimate and track TIA and DCIA that have been added or removed each year due to development and GI retrofits (USEPA 2011, 2014c). USEPA (2014c) and CSN (2009) have compiled the most comprehensive data on the runoff reduction capabilities of GI practices. These values are presented in Table 2.3.

2.2.5 GI Retrofit Policy Drivers

2.2.5.1 Clean Water Act Regulatory Mechanisms and Management Strategies for GI Retrofit Programs

The U.S. Clean Water Act (CWA) focuses on control of point sources of water pollution and the use of end of pipe controls to achieve improvements in water quality with discharge regulations administered through the NPDES Program. In 1990, the USEPA began regulating point source stormwater discharges under the NPDES Stormwater Program which requires the use of best management practices (BMPs) to control stormwater quality. BMPs are used in place of numeric limitations and standards when those are infeasible or in conjunction with numeric, non-numeric and water-quality based effluent limitations (USEPA 2016a, 2016b). GI measures are a subset of the wider range of BMP control measures available to meet CWA and NPDES stormwater discharge requirements. But unlike traditional BMPs that are considered end-of-pipe measures and are utilized in relatively large contributing drainage areas, GI measures are implemented at the source with smaller contributing areas. Distributed throughout a watershed, GI measures are more of a land use based control instrument which is typically the purview of state and local land development regulations (Owen 2011). However, there are several urban areas where the USEPA is using CWA based regulatory mechanisms including judicial actions to require municipalities to specifically install GI type retrofits including:

a) Enforcement actions via judicial consent decrees or other enforcement mechanisms that are a result of specific CWA violations due to sanitary sewer overflows (SSOs) and/ or combined sewer overflows (CSOs) such as in Philadelphia, PA, Chicago, IL and New York City (ELI 2015; USEPA 2015b);

b) NPDES MS4 permitting violations in severely impaired watersheds where municipalities' permits include specific LID and GI retrofit goals tied to total maximum daily load (TMDL) allocations such as those in several municipalities within the Chesapeake Bay watershed in USEPA Region 3 (USEPA 2014a);

c) GI retrofit requirements through reduction in directly connected impervious area (DCIA) tied to TMDL load allocations such as those within Barberry Creek Watershed, ME (USEPA 2008b), several additional impaired Maine streams within USEPA Region 1 (ME-DEP 2012), and in the Eagleville Brook Watershed, CT (CT-DEP 2007; UCONN 2015); and,

d) DCIA reduction goals and accounting procedures in NPDES permits in New Hampshire and Massachusetts (USEPA 2011, 2014c, 2015d, 2015e).

These GI retrofit requirements most often take the form of GI plan development, authorization to use GI in place of traditional gray infrastructure in order to reduce SSO and CSO discharges, the specification of a specific dollar amount to be used toward implementation of GI measures, goals for control or disconnection of a certain quantity of impervious area (USEPA 2008b; ME-DEP 2012); and requirements to inventory and prioritize municipal and other public properties that have the potential for GI retrofit (USEPA 2015d, 2015e) .

2.2.5.2 GI Retrofit and Impervious Area Reduction Requirements for Stormwater Related Water Quality Impairments

Stream impairments due to urban stormwater runoff sources are most commonly attributed to sediment, pathogens, nutrients and metals. Biological and aquatic life impairments are sometimes identified alone or in combination with one or more of these pollutants. In some cases aquatic life impairments can be caused solely as a result of physical damage caused by the increased volume and duration of stormwater flows as well as the reduction in baseflow. USEPA Region 1 is applying the ICM as an innovative approach in developing loading allocations for stormwater source pollutants for TMDLs where urban stormwater is causing aquatic life and biological impairments. The reduction of impervious cover (IC) is used as a surrogate for pollutant reduction because there are no data that identify the specific combination of pollutant loadings that are contributing to the aquatic life impairment (ME-DEP 2012).

The ICM strategy is believed to work well within an adaptive management approach to environmental restoration (ENSR 2005). Performance monitoring and aquatic life assessments are key components in the adaptive management approach of the

IC reduction strategy where GI measures are implemented in a phased manner until water quality standards are attained. Outcomes are evaluated as implementation progresses and future GI measures are selected based on lessons learned and achieved performance effectiveness. The IC targets suggested by the ICM are not intended to be numerical compliance goals; rather they are intended as a guide with compliance determined by monitoring and achieving state water quality standards (ENSR 2005; PETE and ME-DEP 2006). Success is determined based on achieving water quality standards, not on reaching the IC% target. If water quality standards are achieved before the IC% target is met, then compliance is satisfied. However, if the alternate is true, if IC% is reached before water quality standards are met, then the IC% goal needs to be revised (ME-DEP 2012).

2.2.5.3 Implementation of Impervious Cover TMDLs

TMDLs for streams impaired by urban stormwater are implemented via the NPDES stormwater permitting program, and account for both existing and future pollutant loads. There is growing regulatory pressure for GI retrofits in existing urban areas as indicated by the impervious area reduction requirements being introduced in stormwater TMDL allocations. GI retrofits can reduce stormwater runoff flow and erosive effects and help meet the pollutant loading allocations for non-point stormwater sources.

The Barberry Creek watershed in Maine, a Class C designated stream, has an existing IC of 23% and a TMDL target of 12% IC. The Barberry Creek TMDL is being implemented under Maine’s NPDES Program (PETE and ME-DEP 2006). In addition, the Maine Impervious Cover TMDL (ME-DEP 2012) includes IC reduction amounts for 30 impaired stream segments based on stream class. Current watershed ICs range from

7% to 50% and target ICs range between 5% and 16%. The Maine TMDL sets the IC target goal for fresh water streams based on four classification as follows: Class AA and A: $\leq$ 5% IC; Class B: $\leq$ 9% IC; and Class C: $\leq$ 16% IC. These IC targets are being used as goals by regulatory programs such as Maine's NPDES MS4 Permit Program.

In Connecticut, Eagleville Brook, a Class B/A designated stream, has three segments with existing IC coverages of 5%, 14% and 27% and a TMDL IC target of 12% for all segments (CT-DEP 2007) to meet Class A designated uses. Progress is to be measured by amount of IC disconnected and the amount of runoff volume reduced. Runoff volume reduced will be monitored, estimated from empirical formulas and modeled using USEPA's Stormwater Management Model (SWMM) to determine volume impact of implemented and planned BMPs (UCONN 2015).

USEPA Region 3 has several new Phase 1 and Phase 2 MS4 permits with GI and conventional BMP retrofit requirements based on TN, TP and TSS treatment effectiveness as a result of the 2010 Chesapeake Bay TMDL (MDE 2011; USEPA 2014a). The State of Maryland requires MS4s to determine impervious area using local land use maps and impervious coefficients or more detailed aerial photography and GIS applications when available and then delineate the portions of impervious area that are either already treated, partially treated or available for retrofit. There is a current requirement for total restoration of 20% of impervious area within all Phase I MS4 permit areas (MDE 2011). For example, Prince Georges County is required to reduce 2,000 acres of impervious area over 3 years and 15,000 acres by 2025 (ASCE 2015). Washington DC's Phase 1 permit requires retrofits to reduce or disconnect 413 acres of impervious area over the permit term (typically 5 years). This amount will reduce the

District's existing impervious cover of 16,997 acres (43.4% of total area of 39,203 acres) by approximately 2.5% (DDE 2014). Disconnection of impervious area is done through implementation of GI measures that reduce the volume of runoff such as disconnection to pervious surfaces, infiltration or rainwater harvesting.

USEPA Region 1 is currently responding to public comments on Draft Small MS4 Permits for the states of New Hampshire and Massachusetts. The 2013 Draft New Hampshire (USEPA 2015d) and 2014 Draft Massachusetts (USEPA 2015e) Small MS4 Permits (will) require regulated communities to estimate and track TIA and DCIA that have been added or removed each year due to development and GI retrofits. Both draft permits also include requirements for screening and prioritizing municipal owned property and other public open spaces for potential reduction of DCIA using GI practices.

The baseline TIA proposed for the New Hampshire Small MS4 permit is based on impervious area coefficients for land use types from the Rouge River, MI study (USEPA 2011) and the Massachusetts permit baseline TIA is derived from 1-meter orthoimagery (USEPA 2014d). The Sutherland (2000) equations (see Table 2.2) are used to derive DCIA from TIA for both permits. The reduction in DCIA due to various volume reducing GI measures is calculated using the equation:

$$\text{Reduced DCIA}_{\text{BMP}} = \text{DCIA}_{\text{BMP}} * (1 - \text{BMP}_{\text{Mult}}) \qquad \text{(Eq. 2.1)}$$

Where,

DCIA = Directly connected impervious area;

Reduced DCIA_{BMP} = Amount of DCIA reduced by a BMP;

DCIA_{BMP} = DCIA draining to the BMP

BMP_{MULT} = BMP disconnection multiplier (= 1-% runoff volume reduction/100) (varies)

DCIA reduced due to GI retrofits will be determined from disconnection multipliers based on percent runoff reduction volume reported in CSN (2009) and USEPA (2014c). For infiltration trenches and basins, runoff volume reduction percent depends on soil infiltration rate and runoff depth captured derived from Tetra Tech Inc. (2010) and reported in USEPA (2014c).

DCIA is always going to be less than or equal to TIA. Therefore the boundaries suggested by the ICM which is based on TIA, are upper limits. Also, the exact value of TIA or DCIA is only a guide and the adaptive management prescribed by TMDLs is that monitoring of water quality impairments will dictate the exact endpoint of retrofit required. If water quality impairments are resolved before an impervious cover threshold goal is met, then compliance is attained. This also says something about water quality attainment and restoration goals for a particular stream and setting them and designated uses realistically for the specific watershed.

2.2.6 Stream Restoration Goals and Scale of Restoration Efforts

2.2.6.1 Stream Restoration Goals

Urban stream management typically involves efforts in three main areas: flood control and floodplain management; erosion protection; and restoring or maintaining functional ecosystems (Vietz et al. 2016). The functional level of stream ecological systems depends upon the various physical, chemical and biological characteristics within and adjacent to the stream including channel shape, soil type, sediment dynamics, velocity, depth and duration of flow, water temperature, concentration of dissolved oxygen and other chemical constituents, and riparian and aquatic habitat. Restoration efforts must clearly identify the existing level of ecological function within the stream and then define the level of ecological function to be attained (NRCS 2007).

Decisions regarding goals for level of ecological function are unique to the specific stream, watershed and community in question and depend on the nature and extent of physical, chemical and biological processes that have been lost or disrupted and to what extent; and the causes of these losses, disruptions and degradation at both reach-scale and watershed scale (NRCS 2007). The overall restoration objective should be based on local conditions and realistic in terms of what might actually be attainable within the catchment (Walsh et al. 2005b). Urban streams cannot be expected to function as those in an undeveloped forest; therefore, complete restoration to natural channels cannot be expected (Hirschman et al. 2008; Owen 2011; McMillan and Vidon 2014).

There are many challenging issues to consider when developing restoration goals. They include: existing regulatory requirements; defining the value of the stream within the community (e.g., property, aesthetic, recreation, water supply value) and the associated benefits of restoration; cost of various restoration techniques; available funding for restoration; and, over what period of time restoration efforts will be accomplished (NRCS 2007). The degradation of urban streams and loss of ecological function occurs as the watershed is developed over a long period of time (Owen 2011) and the goals for restoration should consider past, current and future land uses within the watershed that contribute to the impairment (McMillan and Vidon 2014). Restoration to most levels of ecological function cannot take place overnight and will require substantial funding (Owen 2011). Once the issues have been considered, short-term and long-term restoration goals should be developed that provide a reasonable matching of benefits and costs and that meet the objectives of all stakeholders. The NRC (2008) favors an adaptive management approach to water quality restoration wherein goals are continuously reassessed as restoration efforts are implemented.

2.2.6.2 Scale of Restoration Efforts

Once restoration goals are identified, the various techniques available and/or required to restore the ecologic functions that have been lost or degraded must be considered at both reach-scale and catchment/watershed scale. There are several reach scale techniques that can be accomplished over a short period of time such as channel reconfiguration and bank stabilization; riparian zone management; in-stream habitat improvement; land acquisition; and flood plain reconnection. Other restoration techniques that are implemented at the catchment or watershed scales and require a longer period of time to design and implement include implementation of development policy and standards revisions; and, stormwater management techniques including retrofitting of existing water infrastructure and uncontrolled impervious area.

Channel reconfiguration and stabilization techniques are implemented to enhance in-stream habitat, prevent further streambank erosion and improve water quality. This type of stream restoration is low cost with immediate and local recovery results (Booth 2005; PETE and ME-DEP 2006). However, a growing body of literature supports the view that reach scale restoration techniques may not match the scales of cause and effect, that is, they may be beneficial only for local improvements within the reach.

Booth and Jackson (1997) postulate that both upland and riparian areas must be considered to mitigate stream impacts of urbanization. Walsh et al. (2005b) in a review of research concerning ecological degradation of urban streams conclude that it is likely that short term local restoration measures alone will not be able to improve aquatic life impairments and that the impacts of urbanization will require catchment scale solutions. Roy et al. (2008) discuss what they believe to be the barriers and potential solutions to urban stormwater management and conclude that watershed wide solutions are a prerequisite for sustaining ecosystem health.

Selvakumar et al. (2010) present monitoring results from an 800 linear foot (LF) stream restoration project in the North Fork Accotink Creek in Fairfax City, VA where the goals were to stabilize the channel, and to reduce streambank erosion and sediment load in the stream. Monitoring data collected for one year prior to and for two years after restoration showed small improvements in biological quality post-restoration with a slight increase in macroinvertebrate populations. However, populations were still below impairment level indicating poor water quality conditions. Further, no statistically significant differences in chemical or biological constituents were recorded between pre- and post-restoration. The authors conclude that stream restoration alone had little effect on improvement of in-stream water quality and biological habitat but did reduce stream bank erosion. The authors posit that volume control of runoff from impervious surfaces in the watershed might help improve water quality conditions in the restored stream reach of their study.

Ellis et al. (2013) state that retrofits of existing separate storm sewer areas with GI type facilities are currently done slowly as a result of infill and redevelopment and mostly focus on peak flow control. The authors support a catchment based planning approach using strategic spatial planning and goal setting and state that it is important to determine what amount of impervious area is it technically feasible to disconnect within an urban area.

Gagrani et al. (2014) refer to the 2008 NRC Report as favoring a watershed scale approach to stormwater management and cite several studies that recommend basin-wide assessment of existing and retrofit GI and conventional stormwater BMPs in impaired watersheds with existing stormwater management facilities.

McMillan and Vidon (2014), in a review and commentary of stream restoration practices, indicate that although physical stability of restored streams can be achieved in a relatively short period of time (~ 5 years), ecological function most likely will require a much longer period for recovery (~ 10 to 100 years). The authors suggest that the effectiveness of local scale measures in improving ecological function is limited because watershed scale urban land use processes are not considered and recommend an approach that considers mitigation measures throughout the watershed.

Vietz et al. (2016) cite several studies which provide growing evidence that stream restoration goals need to address the causal reasons for channel degradation at the catchment scale. The authors focus on the physical impacts due to urbanization, as opposed to biological and chemical impacts, and conclude that catchment scale stressors responsible for urban stream degradation must be addressed in order for a stream to function properly with appropriate rates of sediment supply, deposition and erosion. They also conclude that short term stream scale restoration approaches may not provide the intended ecological benefits in urban streams and recommend the inclusion of long-term catchment scale restoration strategies to achieve chemical and biological as well as physical restoration goals.

The current literature supports the notion that a watershed wide restoration strategy requires the implementation of techniques at various scales such as stream scale channel reconfiguration and riparian zone restoration, mitigation of land use through the use of distributed onsite stormwater management facilities that reduce volume and pollutants of interest; and larger regional BMPs that provide flood control and some water quality benefits. McGarity (2012) concludes that stormwater management for restoration of impaired watersheds is a complex multi-objective problem that needs to be addressed at multiple scales- from site scale to watershed scale.

2.2.7 Existing Decision Support and Modeling Tools for BMP and GI Implementation

The USEPA maintains a website with information and links to various site and watershed scale GI modeling tools that support planning and design decisions based on runoff volume, runoff rate, pollutant loading and cost (USEPA 2015f). Watershed scale models and tools explicitly included on the website are: USEPA's System for Urban Stormwater Treatment and Analysis Integration (SUSTAIN) Model, Hydrological Simulation Program – FORTRAN (HSPF), and Stormwater Management Model (SWMM) with LID Controls; and, Water Environment Research Foundation's (WERF) BMP SELECT Model.

The SUSTAIN Model is a decision support and optimization tool that can be used to site and evaluate BMPs based on cost and pollutant removal effectiveness at various scales in urban watersheds (Shoemaker et al. 2011). The model has the ability to evaluate the cost effectiveness of various configurations of BMPs and the aggregate effect of a large number of BMPs to achieve a target pollutant removal or flow reduction goal (Lai et al. 2010). HSPF incorporates USEPA's Agricultural Runoff Management (ARM) and

Nonpoint Source Runoff (NPS) models to allow simulation of watershed hydrology and water quality including fate and transport of conventional and toxic pollutants through integration of land and soil contaminant runoff processes with in-stream hydraulic and sediment-chemical interactions. The USEPA SWMM Model with LID Controls is an urban hydrology and hydraulics model that simulates urban hydrology, pollutant loading and BMP treatment processes and pollutant transport and can be linked to the SUSTAIN Model for optimizing the selection and placement of GI and conventional BMPs. The WERF BMP SELECT Model allows modeling of runoff volume, pollutant loads and costs of several GI and conventional BMPs at both the site and watershed scales using the WERF Whole Life Cost Model for cost calculations.

In addition to these tools that are explicitly supported by USEPA, Shoemaker et al. (2009) identify several additional public-domain watershed and BMP simulation models that that can be integrated into or adapted for use with SUSTAIN. Further, several additional decision support and modeling tools for both GI-type and traditional BMP planning and analysis at both site and watershed scales are described in the literature. There are various approaches for decision analysis with several levels of complexity. Tools exist that are widely accepted and used and those that have been developed and applied for a specific research study. A number of case studies reported in the literature make use of various combinations of these tools. Several case studies reported in the literature are summarized in Table 2.4 and are briefly described in the following paragraphs. Site scale case studies are included in this review in addition to watershed scale case studies to show how decision support tools are applied at both scales.

Wu et al. (2006) develop a coupled watershed and receiving water modeling system to determine BMP placement at the watershed scale. Instream water quality response to BMP performance using a Monte Carlo simulation identifies multiple feasible placement alternatives for traditional BMPs. The authors prepare a case study on Swift Creek, a 63.7 mi^2 (165 km^2) watershed in Chesterfield Co., VA with eutrophication impairments due to non-point source pollution. The goal of the modeling effort is BMP efficiency for pollution reduction. HSPF is used to model watershed hydrology and CE-QUAL-W2, a two-dimensional, laterally averaged, hydrodynamic and water quality model, is used to model instream water quality. Land use based data are used to develop pollutant loadings for NH4, NO3, PO4 and TSS and BMP performance data is taken from the International Stormwater BMP Database for TP, P (solution), TN, NOx, NH4 and TSS. Traditional BMPs that reduce the targeted pollutants rather than runoff reducing GI-type BMPs are considered: stormwater wet ponds and stormwater wetlands. Parcel scale site suitability is not considered. Water quality response based on BMP performance at catchment outlets (average drainage area = 5 mi^2) is modeled. Water quality response to GI-type BMP performance could be simulated at the catchment scale using this model formulation once parcel scale suitability is determined. This is a complex model simulation, not a screening tool.

Sullivan et al. (2008) describe the Enhanced Green Build-Out Model for Washington D.C. which quantifies cumulative stormwater runoff reductions as a result of GI measures. The model integrates GI runoff reduction into an existing hydrologic and hydraulic model of the combined sewer and separate sewer areas of Washington D.C.

(MIKE Urban). The runoff reduction capability of GI measures is mimicked by assigning an interception storage depth for each GI-type BMP.

Randhir and Shriver (2009) develop a conceptual watershed restoration prioritization model based on attributes related to economic and environmental goals of three policy objectives: water quality impairments (TSS), habitat impairments (percent core and priority habitats) and level of urbanization (effective impervious area). Incentive policies for restoration are evaluated individually for each policy objective and then for a multi-objective policy considering restoration in all three impairment areas. A case study is performed on the 722 mi^2 (1871 km^2) Chicopee River Watershed in central Massachusetts. The results indicate that tradeoffs between economic and environmental goals are necessary to achieve the optimal restoration strategy and that a watershed scale, multi-attribute assessment approach that considers multi- policy objectives is needed to develop cost efficient, stakeholder supported restoration practices.

A GIS based site scale modeling tool is developed by Viavattene et al. (2010) to identify appropriate GI measures and their locations to control urban runoff and reduce pollutants loads to receiving water. The authors perform a case study on an 11.1 acre (4.5 ha) section of a 420 acre (170 ha) development site to model the effectiveness of green roofs and porous pavement in reducing pollutant loads and runoff volume during an extreme runoff event. One of the conclusions of this study is that storage treatment of urban runoff in regional facilities is less effective and generally more costly than runoff control at a source.

Young et al. (2010) use the Analytical Hierarchy Approach (AHP) in combination with GIS data as a decision tool for selecting stormwater management BMPs. The AHP is a mathematically based multi-criteria decision making tool and the authors apply it to evaluate the most common factors that impact BMP selection (e.g., cost, pollutant removal, contributing drainage area, etc.). Selection criteria are defined by the user and the relative importance of each criterion is also defined by the user which can be determined in consultation with stakeholders. A case study is performed and the AHP driven BMP Selector model used to rank BMP options for a 13 acre (5.26 ha) new development site in Blacksburg, VA. USEPA SWMM is then used to model the peak flow and pollutant (TN and TSS) reduction effects of recommended BMPs. The authors conclude that physical site constraints should be given the highest priority for BMP selection and that multi-criteria decision making tools should be just one component of the decision making process.

DeBusk et al. (2010) develop a watershed model of a 465 acre (188 ha) catchment within New Hope Creek, North Carolina which is impaired for fecal coliform bacteria, turbidity, low dissolved oxygen and biological integrity in order to identify cost-effective retrofit opportunities that could be implemented to reduce pollutant loadings entering New Hope Creek and, ultimately, Jordan Lake, a water supply reservoir. Current annual loadings of TP and TN as well as reductions in loadings that could be achieved by implementing GI retrofits are estimated. The SCS Curve Number (CN) method and land use based pollutant loadings from various literature sources for TN, and TP are used. Retrofit GI measures are appropriately sized and constructed to treat the 1-inch water quality volume. Land use within watershed is roads (25%), CII (25%), residential (19%) and institutional (29%). Pollutant reduction capabilities for several GI measures in terms of % mass reduction, % concentration reduction and mean effluent concentration are determined from the literature. A major conclusion is that GI efficiency results are greatly affected by which of these quantifiers is used. Also, the authors found that retrofits on existing property, in addition to requiring LID and GI type implementation on new development, must be considered within a watershed in order to meet water quality goals. Hydrologic benefits are not studied in this research. The quantity and type of retrofit opportunities based on land use are identified and conclusions relating land use and most appropriate retrofits are made.

McGarity (2012) describes the formulation of StormWISE (stormwater investment strategy evaluator); a multi-objective optimization model that can be used to develop and evaluate strategies to maximize water quality benefits of GI retrofits at the watershed scale. It is screening model with water quality goals based on cost-effectiveness. The model uses aggregate land use characteristics with SCS CNs to estimate TN, TP and TSS export coefficients and event mean concentrations within two watershed drainage zones, headwaters and lowland. Non-point buildup and wash off are simulated using exponential accumulation and wash off functions. Pollutant reduction efficiencies are input for various GI measures and RUNQUAL is used to simulate hydrology. The paper presents a case study of the StormWISE Model for Little Crum Creek which encompasses a 3.2 mi^2 (8.3 km^2) area of the Crum Creek watershed in suburban Philadelphia, PA, with impairments due to stormwater runoff from the MS4 and unfiltered riparian zones.

Various combinations of gray and GI retrofits to reduce CSO overflow volume are analyzed for cost-effectiveness by Lee and Riverson (2013). The SUSTAIN Model with XP-SWMM are used to select and model GI measures for a 100-acre case study watershed and demonstration project in Kansas City, MO.

Jia et al. (2013) develop a screening level multi-criteria index ranking system for BMP and GI selection for an urban site based on key criteria of site suitability, runoff control benefits and cost. Indicator criteria for runoff control effectiveness relative to quantity control (volume reduction, peak flow delay and peak flow reduction), quality control (removal capabilities for various pollutants) and other benefits such as reuse potential, ecological benefits and aesthetics are assigned based on extensive review of the literature. These criteria are normalized and integrated for BMP and GI selection. A case study is performed by applying the ranking system to a 74 acre (30 ha) college campus in Foshan City, China. In consideration of the site's physical characteristics and building layout, with cost as the primary concern, the ranking system indicated that wet ponds, bioretention cells, and green roofs are the most preferred stormwater control measures for the site, while porous pavements, infiltration trenches, and rainwater barrels are the least preferred. This tool ranks BMP and GI measures based on site suitability and the indicator criteria can be weighted based on level of importance. This ranking tool is applicable for BMP and GI selection at the site scale but could be applied as a screening tool to rank control measures on a watershed scale.

The hydrologic and water quality benefits of existing structural stormwater BMPs and retrofit GI measures to reduce runoff volume, peak flow, TSS, TP and TN are analyzed by Gagrani et al. (2014) in a case study of a 0.74 mi^2 (1.92 km^2) subwatershed of the Beaverdam Creek watershed, NC using the Model of Urban Stormwater Improvement Conceptualization (MUSIC) Model. Three scenarios are evaluated:

increase in runoff volume, peak flow and TSS, TN and TP loading from undeveloped condition to post-development with no stormwater control; ability of existing BMPs to reduce increase of runoff volume, peak flow and TSS, TN and TP loadings post-development; and additional reduction in TP, TSS and TP due in post-development with backyard raingardens. Results show that residential rooftops contribute a small areal extent to the stormwater BMPs (9%) and suburban lawns contribute the majority of TP, TN and TSS runoff. A main conclusion is that bioretention basins should be used to capture lawn runoff in residential areas to capture TP and TN.

2.2.8 GI Placement and Screening Criteria

There are many criteria to consider when selecting sites for GI measures as well as for selecting the type of GI measure to place on a particular site. The primary objective for selecting type and placement is to maximize the runoff, peak flow and/or pollutant reduction benefits at minimum cost. The focus of this research is on runoff volume reduction expressed as a function of impervious area reduction capability of BMPs as identified in Table 2.3. In addition to the functional capabilities of GI measures there are additional community and environmental criteria that need to be considered when selecting BMPs including: installation and maintenance costs, safety risks, aesthetic and ecosystem benefits, and habitat value (Young et al. 2010; CWP 2013). These criteria, defined in terms of high, medium and low for runoff reducing GI measures, are summarized in Table 2.5. Finally, detailed site and building characteristics are important for GI measure selection. Site placement criteria fall into three general categories: site suitability, location within the watershed and connectivity. The most common considerations and limitations are described in the following sections and are summarized along with impervious area/ runoff volume reduction capabilities in Table 2.3.

2.2.8.1 Site Suitability

Site criteria for BMP suitability include physical, land use and building characteristics at the parcel scale. Important physical characteristics used to evaluate potential benefits of installing BMPs on each parcel are soil type, slope, impervious area, pervious area, contributing drainage area, soil compaction of pervious area (disturbed or undisturbed), depth to groundwater, depth to bedrock, and presence of contaminated runoff (Lai et al. 2010; Young et al. 2010; CWP 2013). Land use (commercial, institutional, industrial, single-family residential, multi-family residential or roadway) and ownership (public or private) are also important considerations in determining which type of GI measure would be suitable for a particular parcel. Ellis et al. (2013) state that Walsh identifies streets and highways as contributing the most significant flow and pollutant sources within urban areas and conclude that retrofitting streets with roadside vegetation within the public right-of-way minimizes costs if done during roadway improvement projects. Finally, certain building characteristics are also important to GI suitability for a particular site including available treatment footprint area for GI (e.g., ratio of parcel area to building area).

2.2.8.2 Location within Watershed

GI placement within a watershed is related to the location of impervious area within a watershed because GI practices are used to disconnect impervious areas that are hydraulically connected to streams. Brabec (2009) investigated this question from a land planning perspective and states that research on the impacts of impervious area location at the watershed scale is scarce. The author further states that although the literature concludes that location of impervious area within the watershed is important to stream health, few studies have quantified this relationship. Further, Brabec (2009) states that many researchers have concluded that the distance between impervious area and stream channel is most important in areas not hydraulically connected to the stream.

2.2.8.3 Connectivity of Retrofit

Novatny (2008) explains that while regional BMPs reduce peak flow due to urbanization and provide flood mitigation benefits at the watershed scale, they are fragmented and this discontinuity results in untreated reaches between where pollutants are generated and where they are treated. Also, regional BMPs are not as effective at improving water quality because they are generally not designed to reduce runoff volume. GI measures that are distributed through a watershed not only reduce runoff volume due to urbanization they also reduce pollutants loads before they get into the stream system. The connectivity of distributed measures is also important and this connectivity must be considered at the watershed scale and include flood plain and wetland systems in order to preserve the ecological function Novatny (2008). CWP (2003) cites several studies that indicate that aquatic insect and fish diversity are associated with high levels of riparian continuity.

The case for connectivity GI retrofit parcels is supported further by conclusions borrowed from landscape planners. Benedict and McMahon (2001) indicate that a connected network of green space that functions as a whole helps to maintain the processes and services necessary for a healthy ecosystem and biodiversity of wildlife biodiversity. The necessity of green space connectivity to maximize habitat benefits is also confirmed and supported by Tzoulas et al. (2007) and USEPA (2014f). Li et al. (2005) cite Wu and Hobbs who indicate that a connected network of green corridors and parcels and help preserve linkage between diverse ecosystems.

2.2.9 Catchment Scale GI Retrofit Experimentation

Watershed-wide reduction of effective impervious area via the implementation of GI retrofits to reduce runoff volume and pollutant loading is an emerging approach for reducing the impacts of existing urbanization (Hoenicke et al. 2010; Walsh et al. 2015). Catchment scale GI experimentation is just beginning to be studied. Therefore, performance assessment data is scarce and comprehensive knowledge of the benefits and cost effectiveness of the overall strategy are not known (Walsh et al. 2015). There is therefore a need for well-designed watershed scale GI retrofit pilot or experimentation programs to measure performance, demonstrate benefits and determine cost effectiveness (Walsh et al. 2005a; Hoenicke et al. 2010; Vietz et al. 2016).

Walsh et al. (2005b) argue that well designed retrofit research studies together with an adaptive management approach are needed to assess the restoration potential of urban streams. Extensive monitoring before, during and after retrofits are implemented is required to obtain the data needed to determine performance and effectiveness (Bitting and Kloss 2008). An adaptive management approach will allow for adjustments to be made based on lessons learned for future implementation and to build stakeholder and community support. There are a few existing watershed scale experimentation studies described in the literature. These are summarized below along with the lessons learned for future experimentation studies.

A catchment scale monitoring study of the effect of LID and GI-type measures on runoff quantity and quality conducted by Dietz and Clausen (2007) shows that the techniques used can greatly reduce the impacts of development on receiving waters. The study compares runoff monitoring data collected downstream from a 4.2 acre (1.7 ha) residential development with LID and GI-type measures (rain gardens, permeable pavement, grass swales and cluster layout) with that collected downstream from a 5 acre (2 ha) development with traditional curb and gutter stormwater management facilities. TP, TN and runoff volume vs. total imperviousness are measured as development progressed. Annual runoff and pollutant export from traditional development increased while those from LID/GI development did not.

Various papers provide analysis of a widely published GI retrofit and monitoring study conducted on Shepherd Creek in suburban Cincinnati, OH (Shuster and Rhea 2013; Roy et al. 2014). The researchers conducted a long term pilot study on Shepherd Creek to determine the effect of reducing DCIA on aquatic system health. A total of 83 rain gardens and 170 rain barrels are distributed on 30% of the parcels in four subcatchment areas. Stream discharge quantity and quality and precipitation are monitored for three years prior to GI retrofit implementation and three years post retrofit. The ratio of area treated to total area is small and the results are minor effects on stream flow volume and water quality with no changes in biotic health. The greatest reduction in DCIA (11.6% to 10.4%) results from the rain barrels in the most impaired sub-catchment. The rain gardens did not reduce DCIA. The researchers conclude that impacts of additional retrofits in the catchment could be increased by placing additional retrofits to control impervious surfaces from parking lots and multi-family housing and especially from road surfaces which account for a large proportion of connected impervious area in urban areas. Also, further research is needed to "define the minimum effect threshold and restoration trajectories for retrofitting catchments to improve the health of stream ecosystems". Roy et al. (2014) indicate that there is little research on the effectiveness of decentralized parcel scale stormwater management practices on improving downstream aquatic health in suburban catchments. The little research that is available focuses on new development catchments such as those described above by Dietz and Clausen (2007) but no catchment scale studies of retrofits in existing development other than the Shepherd Creek study and one being conducted in Australia as described below (Walsh et al. 2015). Roy et al. (2014) argue that there is a need to define a "minimum threshold and restoration trajectory" for catchment retrofit to see this improvement.

Walsh et al. (2015) describe a catchment scale experiment of 289 distributed rainwater tanks, rain gardens and infiltration systems currently being conducted in Little Stringybark Creek, a small urban stream catchment in Australia. The main objective is to determine if these stormwater volume control and reduction measures can sufficiently modify the quantity and quality of runoff to impact instream ecological conditions. The researchers selected a catchment with impairments due to urban stormwater runoff and with a small enough area of connected impervious area to feasibly implement the number and extent of BMP retrofits required to theoretically achieve ecological response. Assessment monitoring is conducted before and during and is continuing after BMP implementation to compare ecological patterns in the study stream with those in a similarly degraded stream with no GI-type BMPs and to a reference stream not affected by urban runoff. The researchers state that although some improvements in water quality are being measured, the “rate and trajectory of ecological recovery” will most likely take years to know. The researchers provide two important lessons in terms of experiment design and implementation. First, design variations for the BMPs implemented were necessary due to site constraints, property owner requirements and efforts to minimize maintenance requirements. Also, the impact of new development within the catchment must be accounted for or controlled in order to prevent undermining the monitoring results.

2.3 Perspectives on GI Retrofits and Economic Incentives

The existing literature is reviewed on several topics including: general economic considerations of pollution control policies; incentive based strategies for implementing GI retrofits on existing development; municipal stormwater fees and fee credit programs in the U.S., studies of attitudes toward and willingness to participate in GI retrofit and implementation; the value of GI measures including benefits and life cycle costs; stormwater fee magnitude (price) considerations; and, issues related to acquiring and maintaining fee credits. The results of the literature review are used to identify the knowledge gap, formulate the research questions and provide guidance and justification for the methodology and analytical procedures utilized in this portion of the research effort.

2.3.1 Economic Policy Considerations of Pollution Control and GI Retrofits

Command and control (CAC) approaches to pollution abatement, including water pollution control, set uniform standards for all sources. There are three main methods of CAC: technology standards that require a particular technology to reduce emissions; performance standards that limit the amount of emissions a polluter can discharge but allow flexibility in how the goal is achieved; and, technology based performance standards that require individual polluters to limit effluents using the best available technology. Incentive based (IB) approaches to pollution control do not dictate performance or technology requirements for pollution abatement; rather, they use principles of the free market to achieve desired levels of pollution output at the lowest possible cost. The two main IB approaches to pollution abatement are priced based emissions taxes or fees, which either require polluters to pay a certain amount of money per unit of pollution emitted or subsidies where the polluters are paid a certain amount of money per unit of pollution abated; and allowance trading that sets the total allowable amount of pollution and allowances are then traded between polluters. IB approaches are intended to allocate total abatement costs to those with relatively lower abatement costs. (Parikh et al. 2005; Keohane and Olmstead 2007; USEPA 2014b)

There are advantages and disadvantages of each approach depending on the type, source and amount of pollution. IB approaches are preferred when the costs for reducing pollution vary widely for dischargers because incentives achieve an abatement goal at the total minimum cost for each polluter by allowing the discharger the flexibility to decide whether to pay for emissions, trade allowances or pollute. However, when there are a large number of discharges with similar costs for abatement, CAC approaches are more appropriate because IB approaches are very costly to monitor and enforce. A CAC approach is also preferable when the potential damage or harm of pollution is great such as with highly toxic materials. (Keohane and Olmstead 2007; USEPA 2014b)

The federal CWA focuses on control of point sources of water pollution and the use of end of pipe controls to achieve improvements in water quality. Land use based controls in the form of land development regulations that mandate the use of GI measures (Owen 2011) are implemented at the state and municipal level and usually apply to new development or re-development activities only and do not include provisions for GI retrofits of existing development. Land use based controls are also a CAC approach because GI measures are typically required to meet uniform design standards for the control of the first 1 to 1.5 inches of stormwater runoff or a specific frequent event such as the 1- to 2-year return period storm, with the main purposes of runoff volume and pollution control. When these uniform design standards are applied to individual properties within a watershed or service area, the costs to achieve compliance vary based on the unique physical characteristics of each site such as soil type, slope, depth to groundwater or depth to bedrock. This means that different properties will have different costs to meet the same uniform control requirements even though there is flexibility in GI selection.

For separate storm sewer areas, the most common CAC approaches for water quality control have been the use of traditional site and regional stormwater BMPs such as detention or retention basins to control excess runoff from large infrequent events (e.g., 10- to 25-year return period storms). Their main purpose is peak flow reduction and flood mitigation with the presumed additional benefit of pollution reduction achieved through detention and infiltration of a specified water quality volume. In combined sewer areas, other CAC approaches to reduce stormwater runoff volume and pollution include the separation of storm and sanitary sewers as done in Minneapolis, MN; Portland, OR; and Columbus, OH (USEPA 1999a) or the construction of large underground overflow storage tunnels and retention basins to capture wet weather flows and hold the water until it can be treated at a wastewater treatment plant (WWTP) as done in San Francisco, CA and Milwaukee, WI (USEPA 1999b) and in several other municipalities. However, GI measures which are distributed throughout the watershed are increasingly seen as a more cost effective means of managing urban stormwater runoff quality in both combined and separate storm sewer areas with many additional benefits (USEPA 2009a, 2010, 2015c; Jaffe 2010; Ando and Netusil 2013; Cadavid and Ando 2013, Valderrama et al. 2013; Valderrama and Davis 2015).

2.3.2 Strategies for Implementing GI Retrofits in Urban Areas

The objective of stormwater management policies is to provide cost effective strategies for managing risks associated with the damaging effects of increased stormwater runoff and pollutant loads caused by urbanization (Thurston et al. 2003; Bitting and Kloss 2008). Policies for retrofitting existing urban areas with GI require unique approaches due to the many obstacles that must be addressed. While economists advocate IB measures over CAC methods for managing these types of risks, retrofitting existing urban areas with GI requires a combination of these two approaches. Municipalities can require GI as CAC performance and technology standards to regulate new and redevelopment but will most likely need an IB approach for implementation to assure that the measures being constructed are cost-effective. However, IB strategies are essentially the only option for GI retrofits on existing development because regulatory controls cannot be used to require retrofits due to legal issues related to property rights (Parikh et al. 2005; Thurston et al. 2010). As stated earlier, the two main IB approaches are price based emissions taxes, and allowance trading. For retrofits on existing development, emissions fees in the form of stormwater user fees and fee credits are appropriate because of the property rights issue while allowance trading can be effective for new and redevelopment (Parikh et al. 2005).

A stormwater user fee is a price based emissions fee (Pigouvian tax) that charges property owners to discharge the excess runoff generated by their property (the difference between the runoff generated under natural or existing conditions and that generated under developed conditions) (Parikh et al. 2005; USEPA 2014b). In theory, the size of the fee is based on the total cost to control excess runoff in the watershed in order to provide flood mitigation, pollution control and protection of aquatic habitat. Stormwater fees are commonly based on the type of property (commercial or residential) and the amount of impervious area on that property. A stormwater fee in conjunction with a fee credit is an IB approach that is intended to provide an incentive to stormwater dischargers (property owners) to reduce the amount of runoff from their site by providing some level of control. In theory, property owners with larger costs to control runoff will pay the fee, while those with lower costs for control will install runoff control measures to reduce their costs by receiving the credit (Ando and Netusil 2013). Fee credits can apply to both GI measures and traditional BMPs.

A stormwater retention credit trading system allows regulated projects to retain up to a specified amount of required GI stormwater volume off-site and then uses a private market to pay dividends to property owners who install GI retrofits on their own property. This policy works well in highly urbanized city centers where the cost and availability of land add a significant financial burden to normal retrofit costs and in areas with economic development problems (CWP 2013). An allowance market is set up by setting a cap for runoff from the watershed and then dividing the allowable runoff (allowances) among parcel owners. The allowances grant permission to discharge a certain amount of runoff and are traded between property owners who can reduce runoff using GI measures at a lower cost and those where control would be more costly. Typically, water quality trading programs such as those set up for Cherry Creek, CO and the Neuse River Basin, NC are based on a loading cap for a particular pollutant as specified by a TMDL or a watershed-based limit (Morgan and Wolverton 2005). In Washington, DC, a retention credit trading program has been developed in response to requirements of the city's new NPDES stormwater permit (Johnston 2013). Retention credits are basically a "fee-in-lieu of" program. Voluntary offsets can be used to meet allowances in a regulatory situation but since they need to be funded through user fees, Parikh et al. (2005) argue that this approach essentially reverts to a price control.

Several documents provide detailed case study examples of GI implementation and retrofit programs (Bitting and Kloss 2008; USEPA 2010). In many cases, demonstration projects and pilot projects on public property are being implemented by municipal agencies to promote the feasibility and multiple benefits of GI, to showcase and gain support for the technology, to educate the public and establish community support and to streamline the process by working out design, construction and maintenance issues before engaging private property owners (USEPA 2008b, 2009a, 2010; CWP 2013). In many cases, municipalities have taken advantage of public funding opportunities by incorporating GI retrofits into transportation, capital building and water infrastructure improvement projects (USEPA 2010; Ellis 2013).

2.3.3 Incentive Strategies for GI Retrofits on Existing Development

The focus of this research is on incentive strategies that can be used for retrofitting existing development rather than on those that can be used for new and redevelopment. Incentives that reduce or completely offset the capital cost of retrofits are particularly important because retrofits on already developed land are voluntary (Valderrama and Davis 2015). There are many direct and indirect financial tools that municipalities can use to help property owners with the upfront capital costs of installing specific GI retrofits on their sites including grants, subsidies, cost-sharing, voluntary offsets or reverse auctions, and installation financing (USEPA 2010). Rebates and tax credits can be used to offset the capital cost of installation of GI measures once installation is complete. In addition, the following strategies can be used in conjunction with capital cost relief to encourage and support GI retrofits on private property:

a) Stormwater fee and fee credits: A stormwater user fee is used to charge property owners to discharge the excess runoff generated by their property (Parikh et al. 2005, USEPA 2014b) and typically based on the type of property and the amount of impervious area on that property. A stormwater fee is used with a fee credit to provide an incentive to property owners to reduce the amount of runoff from their site by providing some level of control. Current fee and fee credit programs in the U.S. are discussed in detail in Section 2.3.4.

b) Public-private partnerships: In order to meet its NPDES permit requirements for impervious area reduction through GI retrofits, Prince Georges County (PGC), MD has entered into a 30 –year public-private partnership (P3) with a private firm that will oversee the design, construction and permitting of impervious area retrofits within the county (Landers 2015). Although the projects have not been identified yet, PGC is using the P3 to take advantage of the private sector's ability to complete projects quickly and cost effectively. PGC is funding the projects but there are additional financial incentives for the private firm for generating local business and reaching budget and schedule targets.

c) Competitive grants and project aggregation: In Philadelphia, the Greened Acre Retrofit Program (GARP) encourages contractors and design-build firms to compete for public grant money to finance the capital costs of GI retrofit projects (Valderrama and Davis 2015). The firms compete for the funds by proposing the lowest-cost retrofit opportunities on private land and are encouraged to aggregate projects to lower transaction costs and to increase profit margins. The competition for limited funds ensures that the firms seek out the most-cost effective properties and keep construction costs competitive thereby keeping capital costs low. Fee credits of up to 90% of annual stormwater fees are used to ensure long term maintenance and performance of GI. This is in essence a voluntary offset where both the capital subsidy and the fee credit reimbursement equal the costs of capital and ongoing maintenance.

d) Award and recognition programs – Award and recognition programs for GI retrofit projects can provide publicity and marketing opportunities to property owners for participating in community projects or projects on their own sites. Design competitions that offer monetary compensation or awards can also be used to encourage local property owners to become involved with innovative and model demonstration projects (USEPA 2009a).

e) Public education and outreach programs – Public awareness, education and outreach programs can all provide effective incentives to obtain public support and participation in GI retrofit programs.

f) Maintenance agreements and easement reimbursement – A major barrier to GI retrofits after the capital financing for GI retrofit project is the cost of ongoing maintenance and access to private property. Municipalities can provide maintenance for a specified amount of time and easement reimbursement to the property owner in exchange for access to the property as an incentive to overcome this obstacle (USEPA 2010).

Nickel et al. (2014) present lessons learned from the German experience of incentivizing the use of GI where problems similar to U.S. cities exist related to flooding, CSOs and stormwater quality. Innovative policy approaches being used in the Emscher and Berlin regions are described and the results used to extract important lessons for effective GI implementation in other urban areas. The authors conclude that the primary ingredients for successful GI implementation include: a long term, quantifiable goal; flexible policies that include a variety of incentives; and public leadership with strong stakeholder involvement.

Incentive programs for GI retrofits in existing areas should be flexible, include various mechanisms and approaches, take advantage of multiple benefits, and target specific problem areas. The most successful strategies have significant stakeholder involvement and cooperation. The policies must also be tailored to meet the unique development patterns, environmental and climate characteristics, institutional and legal structures, and social values of each municipality and watershed (USEPA 2010).

Crisostomo et al. (2015) suggest several possibilities for public agencies regarding GI retrofit programs including: define long term goal and target and prioritize suitable retrofit locations; fund the installation of publicly owned GI retrofits on private properties within entire neighborhoods where property owner provides ROW easements to allow installation and access for public maintenance and inspection; fund installation and pay property owner to maintain; and, provide different incentives for different scales of projects.

The WEF report on user fee funded stormwater programs concludes that stormwater managers should focus incentives on commercial properties because of their size and greater potential for savings with fee credits, commercial property owners are generally financially more stable and have access to greater funding than residential property owners; have larger areas to install retrofits and can control area from the public right-of-way; and, are more easily and cost effectively monitored and enforced (WEF 2013).

2.3.4 Municipal Stormwater Utility Fees and Fee Credit Programs in the U.S.

2.3.4.1 Stormwater Utilities and Fees

User fee funded stormwater utilities are widely used in the U.S. for financing stormwater management activities in urban areas (Reese 1996; SESWA 2013; Black & Veatch 2014; Campbell et al. 2014). The 2014 Western Kentucky University (WKU) Stormwater Utility Survey identifies close to 1,500 stormwater utilities in the U.S. (Campbell et al. 2014). The survey data indicate that revenue generation is typically through user fees, where use is equated to the demand a property places on the stormwater system and for the services needed to construct and maintain the system. In addition, the majority of stormwater user fees are based in some way on the amount of impervious area of a property, whether residential, commercial or institutional. Over half of the utilities included in the survey set the fee based on the impervious area expressed in terms of equivalent residential unit which is the average impervious area for a residential parcel within the municipality. Other methods for setting fees include those based on the Natural Resources Conservation Service (NCRS) method of calculating runoff, flat fees, amount of water used (determined from water meter), number of parking spaces, zoning based fees or other metrics (Campbell et al. 2014).

2.3.4.2 Stormwater Fee Credits

Stormwater fee credits provide an ongoing reduction to a property's stormwater fee due to practices that reduce demand on the stormwater system or reduce the cost of service. Stormwater fee credits are widely acknowledged as important incentives for private property participation in stormwater control activities, including GI retrofits, which benefit stormwater management systems in urban areas (Doll et al. 1999; Reese 1999; Berahzer and Hughes 2014). The main benefits attributed to fee credits are that they: 1) address legal concerns of stormwater utility user fees and justify the fee as a user or impact fee as opposed to a tax by allowing rate payers the choice of paying the fee or managing site stormwater runoff; 2) encourage private property owners to control stormwater on their property thereby providing water quantity and water quality improvements to the system; and, 3) reduce public expenditures for stormwater management because of the actions taken by private property owners (Berahzer and Hughes 2014).

Fee credits are offered by 44% of the 78 utilities located in 25 states across the U.S. included in Black & Veatch’s 2014 Stormwater Utility Survey (Black & Veatch 2014) for such practices as: volume reduction, peak flow reduction, water quality control, direct discharge to a surface water body, good housekeeping practices, education, and NPDES permit compliance. However, the number of eligible properties that seek credit is low at only 4% and less than 40% of the utilities that offer fee credits do so for GI measures. The 2015 SESWA Stormwater Utility Survey (Mason 2015) indicates that for the 76 survey participants located in 7 states in the southeastern U.S., the average number of property owners that seek credit is also low at 2.15% with an average credit reduction of 24.5%. The 2013 SESWA Stormwater Utility Survey (SESWA 2013) reported that for the 75 participants in that years’ survey, the average credit reduction is 25.6%. The WKU Survey (Campbell et al. 2014) provides fee data for most of the 1,500 stormwater utilities across the U.S. and Canada included in the survey but does not provide information regarding fee credit value or mechanisms.

The most common reason attributed to low fee credit usage is the low price of the fee (Doll et al. 1999; Thurston 2006; Ando and Netusil 2013; Berahzer 2014; Nickel et al. 2014; Ruhlman et al. 2014), however, both the magnitude of the fee and the value of the fee credit together will influence the success of this type of incentive (Doll et al. 1999). Crisostomo et al. (2015) cite examples of additional barriers to participation in credit incentive programs including high administrative costs and technical requirements that involve the use of outside consultants making the cost to acquire the credit greater than the benefit; long term contracts, and permanent easement requirements; risks related to duration and credit renewal policies; and lack of knowledge of stormwater issues in general and the credit program specifically.

Doll et al. (1999) and van der Tak (2015) provide detailed information on fee credit programs for 11 and 13 U.S. stormwater utilities, respectively. For this research, current detailed information is obtained for 9 fee and fee credit programs of cities included in one or both of the Black & Veatch (2014) and the SWSWA (2013) surveys: Charlotte, NC; DeKalb County, GA; Greenville County, SC; Gwinnett County, GA; Montgomery County, MD; Philadelphia, PA; Prince Georges County, MD; Raleigh, NC; and Seattle, WA. These fee credit programs are selected based on similarity in size, revenue, and population served in comparison to the case study city for this research, Charlotte, NC; or, the innovative credit programs that have been developed. Fees per impervious area and credit requirements for these utilities are summarized in Table 2.6.

Nickel et al. (2014) conclude that with a low fee price, credits are most effective when paired with other incentives, especially for existing development, based on their study of such programs in Germany where fees twice as high as the highest in the U.S. In Germany, stormwater fees are based on individual parcel assessments and impervious surface determined from aerial photography and satellite data, similar to the U.S. The average annual stormwater fee is $4,008 per impervious acre with the highest fee in Berlin of $8,534 per impervious acre. Fee reduction of up to 50% is granted for onsite GI or LID measures that increase evaporation or infiltration. Although these fees are high in comparison to stormwater fees in the U.S. as indicated in Table 2.6, even in Berlin, the fees are not high enough to adequately incentivize GI.

2.3.4.3 Price Elasticity of Stormwater Fees

Price elasticity refers to the relationship between price and demand of a consumable good. It is the mathematical measure of demand response of users to changes in price. In the water supply market, there is an inverse relationship between the price of water and the quantity of water demand, that is, as the price increases; the demand is reduced (Tiger and Hughes 2014). Demand for a particular good can be described as elastic if a 1% increase in price leads to a greater than 1% decrease in demand; or inelastic if a 1% increase in price leads to less than a 1% decrease in demand. The price elasticity of water demand (except cooling water) varies by price structure, geographic region, water end use (indoor or outdoor), customer class, demographics and weather and is generally considered to be inelastic – that is the demand for water does not change much with changes in prices (Espey et al. 1997; Tiger et al. 2014). Price elasticity demand for essential water uses may be inelastic; however, non-essential demand tends to be elastic which explains why utilities can use water rates to encourage water conservation for uses such as landscape irrigation and other outdoor uses. Agricultural water demand is also considered to be elastic as demand can approach zero if costs go too high (Howe 2005; Olmstead and Stavins 2007).

In theory, the concept of elasticity of demand should be applicable to stormwater fee prices and parallels to elasticity of demand for water supply prices should be possible. However, in practice this is not so straightforward. Stormwater fees and associated fee credits in the U.S. are generally not high enough (Doll et al. 1999; Thurston 2006; Ando and Netusil 2013; Berahzer 2014; Ruhlman et al. 2014) relative to the cost of reducing demand to induce behavioral or structural responses from stormwater utility users.

Behavior responses for reducing water demand include practices such as reducing the length of showers and landscape irrigation volume. An analogous behavior response for stormwater demand would be disconnection of building downspouts. Installation of low flow shower heads or drought resistant landscapes are structural responses that reduce water demand. Analogous responses for stormwater demand would be construction of stormwater management BMPs or GI measures. Actual stormwater demand responses are typically induced exclusively by regulation during the development process or an offering of a financial incentive although there does appears not to be a demand response related to fee credit availability.

2.3.5 Studies of Attitudes toward and Willingness to Participate in GI Implementation

There are many important factors to consider when identifying potential properties for GI retrofit including ownership and physical properties such as soil type, depth to groundwater and slope. In addition to knowledge of property ownership it is also important to know the willingness of property owners to retrofit (McGarity 2013). The literature includes several studies of attitudes toward and willingness to participate in GI retrofits of residential property owners, municipal and government officials and design and construction professionals. Various techniques to describe or predict behavior, attitude and potential for adoption are used including surveys, interviews, an agent based model, a voluntary offset program, and a demographic and spatial analysis of actual GI adopters. These studies are summarized in Table 2.7.

Familiarity with GI and environmental knowledge appear to be major factors influencing willingness to implement GI by municipal and professional stakeholders and residential property owners pointing to the necessity of public education and awareness for a successful retrofit program (Ando and Freitas 2011; Olorunkiya et al. 2012; Keeley et al. 2013; Montalto et al. 2013; Carlson et al. 2014; Baptiste et al. 2015; Carlet 2015). Community demonstration projects are also noted as an effective tool to demonstrate the technology and gain stakeholder acceptance (Olorunkiya et al. 2012; Carlson et al. 2014; Carlet 2015).

It appears that reduction of flooding is less of a motivator than the potential environmental benefits of implementing GI measures (Ando and Freitas 2011; Cadavid and Ando 2013) and aesthetics are more important than cost or health factors (Larson et al. 2014; Baptiste et al. 2015). Social capital and knowledge of positive actions taken by local community members have a large influence on willingness to participate in GI and stormwater management (Giacalone et al. 2010; Green et al. 2012) even more so than negative reports of local water pollution (Giacalone et al. 2010).

2.3.6 Value of Green Infrastructure

The concept of total economic value (TEV) is used to describe the full value of a natural resource and can be extended to include environmental infrastructure such as GI (Vandermeulen et al. 2011). There are three major components of TEV: value related to use including direct use, indirect use and option values; value related to non-use; and, investment value. Value elements of GI identified in the literature within each of these categories are summarized in Table 2.8 (Wise et al. 2010; American Rivers et al. 2012; Clements et al. 2013; Valderrama et al. 2013).

The value of GI is dependent upon the objectives of a specific project and the perspective of the owner or investor (Vandermeulen et al. 2011). For this research, the value of GI retrofits is assessed from two perspectives: stormwater utilities and private property owners. Only the values that readily inform these perspectives and are reflected in market transactions associated with GI retrofits (direct use and investment values) are considered (Vandermeulen et al. 2011). Intangible value is not considered. The result is an assessment of the benefits and costs of GI retrofits in terms of stormwater fees and fee credits (direct use benefits) which can be directly equated to the investment value (costs) of GI retrofits including capital and annual maintenance costs.

Other direct use benefits of GI that could accrue to individual property owners and have market based value such as tax credits, development incentives, savings in building energy costs and increase in property values are beyond the scope of this research. The direct use benefit of cost savings resulting from a reduction in potable water demand due to rainwater harvesting is not considered in this research; however, for properties with large irrigation demand, this benefit could be substantial. The direct use value of GI retrofits related to reduction in pollutant loads and gray infrastructure requirements that accrue to the stormwater utility and flow through to the community are also not considered.

Attempts have been made to quantify many indirect use benefits of ecosystem services such as improvements to wildlife habitat, air quality and neighborhood aesthetics; ground water recharge and mitigation of urban heat island, although, these as well as option values related to biodiversity and climate change resiliency and the non-use values of existence, legacy and altruism are hard to measure and monetize and in many cases are location specific (Wise et al. 2010; Clements et al. 2013). Quantifying the indirect value of GI retrofits is also outside the scope of this research.

Table 2.1: Characteristic Values of TIA and DCIA for Different Land Use Types

Land Use Category	NRCS (1986)[a]	CWP (2003)[b]	USEPA (2011)[c]	Booth and Jackson (1997)[d]	
	% TIA	% TIA	% DCIA	% TIA	% DCIA
Commercial and business	85	72.2	76	90	86
Industrial	72	53.4 (light)	56		
Institutional		34.4	34[2]		
Municipals		35.4			
Schools		30.4			
Churches		39.9			
Residential: Multi-family		44.4	51	60	48
Residential: Townhome		40.9			
Residential: 1/8 acre	65	32.6			
Residential: 1/4 acre	38	27.8	38	35	24
Residential: 1/3 acre	30				
Residential: 1/2 acre	25	21.2			
Residential: 1 acre	20	14.3	19	20	10
Residential: 2 acres	12	10.6		10	4
Parks		12.5			
Cemeteries		8.3			
Golf		5			
Open Urban Land		8.6	11		
Agriculture		1.9	2		
Forest			1.9		

Notes: TIA = total impervious area; DCIA = directly connected impervious area

[a] Urban Hydrology for Small Watersheds, TR-55

[b] As proposed by Cappiella and Brown for use in suburban Chesapeake Bay watersheds.

[c] For New Hampshire Small MS4 Permits, from USEPA Rouge River, Michigan study.

[d] As proposed by Dinicola for use in western Washington State.

Table 2.2: Empirical Equations for DCIA versus TIA

Source: Roy and Shuster (2009)

Developed by:	Applicable Geographic Region	Equation
Alley and Veenhuis	Denver, CO	$DCIA = 0.15 * TIA^{1.41}$
Wenger et al.	Etowah River Basin, GA	$DCIA = (1.046 * TIA) - 6.23\%$
Roy and Shuster	Shepherd Cr., Cincinnati, OH (suburban res.)	$DCIA = (0.627 * TIA) - 1.86\%$

Source: Sutherland (2000)

Developed by:	Applicable Geographic Regions	Equation
Laenen et al. (USGS)	Portland and Salem, OR (10% < TIA < 50%)	$DCIA = 3.6 + 0.43(TIA)$

Source: Sutherland (2000)

Watershed Selection Criteria:	Assumed Land Use	Equation
• Totally Connected: 100% storm sewered, all impervious area connected	• Not applicable	$DCIA = TIA$
• Highly Connected: Mostly storm sewered with curb and gutter, no dry wells or infiltration, residential roof tops directly connected	• High density residential	$DCIA = 0.4(TIA)^{1.2}$
• Average: Mostly storm sewered with curb and gutter, no dry wells or infiltration, residential roof tops not directly connected	• Commercial, industrial, institutional, open land and medium density residential	$DCIA = 0.1(TIA)^{1.5}$
• Somewhat Connected: 50% not storm sewered but with open section roads, grassy swales, residential rooftops not connected, some infiltration	• Low density residential	$DCIA = 0.04(TIA)^{1.7}$
• Mostly Disconnected: Small % urban area is storm sewered or 70% or more infiltrated/disconnected	• Agricultural, Forest land	$DCIA = 0.01(TIA)^{2}$

Notes: DCIA = Directly connected impervious area; TIA = Total impervious are

Table 2.3: Runoff Reduction Potential and Screening Criteria for GI Measures

	Runoff Reduction Potential		Land Uses: Res.	Land Uses: CII	Land Uses: Road/ Hwy	Contrib. Drainage Area	Slope
GI Measure	(USEPA 2014c)	(CSN 2009)	(CWP 2013)	(CWP 2013)	(CWP 2013)	(CWP 2013)	(CWP 2013)
Green roof	n/a	45-60%		X		Green roof SA +25%	Bldg. roof < 2%
Rainwater harvesting	n/a	40%	X	X		n/a	n/a
Disconnection to pervious area	50%	50% (HSG A) 50% (HSG B) 20% (HSG C)	X	X		1,000 ft^2 per roof DS	< 5%
Permeable paving:	75%	n/a				2-5 x PP area	< 5%
• No underdrain	n/a	75% (HSG A, B)	X	X			
• With underdrain	n/a	45% (HSG C, D)		X			
Bioretention/ rain garden	85%	n/a				Res: < 1 ac CII: < 2.5 ac	< 1%
• No underdrain	n/a	80% (HSG A, B)	X	X	X		
• With underdrain	n/a	40% (HSG C, D)		X	X		
Extended detention	n/a	*Lined:* 0% *Unlined:* 15%		X		10-25 ac	< 1%
Infiltration trench	100% (HSG A) 96% (HSG B) 85% (HSG C)	50-90%		X		< 2 ac	< 1%

Table 2.3 (continued)

Infiltration basin	100% (HSG A) 96% (HSG B) 82% (HSG C)	50-90%		X		< 5 ac	< 1%
Grassed channel	75%	20% (HSG A, B) 10% (HSG C, D)	X	X	X	< 2.5 ac	< 4%
Dry swale	75%	n/a	X	X	X	< 2.5 ac	< 4%
• No underdrain	n/a	60% (HSG A, B)					
• With underdrain	n/a	40% (HSG C, D)					
Tree pits	n/a	15%	X	X	X	< 1 ac	< 1%
Stormwater planters	n/a	15%	X	X		< 1 ac	< 1%
Tree planting	n/a	15%	X	X	X	n/a	n/a

Notes: ac = Acre; CII = Commercial, industrial, institutional; DS = Downspout; ft^2 = Square feet; GI = Green infrastructure; HSG = Hydrologic soil group; Hwy = Highway; n/a = Not applicable; PP = Permeable pavement; Res. = Residential; SA = Surface area

Table 2.4: Case Studies: Decision Support and Modeling Tools for GI and BMP Implementation

Study	Scale/ Area	Location	Models	Objectives/ Goals
Wu et al. (2006)	Watershed scale 63.7 mi^2 (165 km^2)	Swift Creek, VA	Watershed simulation using HSPF (hydrology) and CE-QUAL-W2 (hydrodynamic and water quality)	Optimization of traditional BMP placement for TP and TN removal effectiveness
Sullivan et al. (2008)	Watershed scale	Washington D.C.	Green Build Out Model (GI performance) and MIKE Urban model (urban hydrology and hydraulics)	Runoff reduction capability of GI
Randhir and Shriver (2009)	Watershed scale 722 mi^2 (1,871 km^2)	Chicopee River, MA	Multi-objective optimization and prioritization	Cost effective environmental control of impairments (TSS, habitat, EIA)
Viavattene et al. (2010)	Site scale 11 ac (4.5 ha)	Birmingham, England	GIS based GI BMP selection and performance model linked to hydraulic simulation using STORM	Performance effectiveness of GI pollution reduction and runoff volume reduction.
Young et al. (2010)	Site scale 13 ac (5.26 ha)	Blacksburg, VA	AHP for GI BMP selection considering pollutant removal and runoff reduction potential and SWMM for hydrology simulation of BMP runoff volume reduction	GI selection and modeling for effectiveness of site scale runoff control effectiveness

Table 2.4 (continued)

DeBusk et al. (2010)	Catchment scale 465 ac (188 ha)	New Hope Creek, NC	GI BMPs selected by site suitability. Land use based SCS CN and pollutant loadings and literature values for GI reduction capabilities and costs	Cost effective reduction in TP and TN using GI
McGarity (2012)	Watershed scale 3.2 mi^2 (8.3 km^2)	Little Crum Creek, PA	StormWISE for multi-objective BMP optimization and RUNQUAL (SCS CN based) for hydrologic and water quality simulation	Cost effective water quality control
Jia et al. (2013)	Site scale 74 ac (30 ha)	Foshan City, China	Screening level site suitability multi-criteria BMP selection and ranking tool	Cost effective water quantity and quality control
Lee and Riverson (2013)	Catchment scale 100 ac (pilot) (40 ha)	Kansas City, MO	SUSTAIN and XP-SWMM to compare various alternatives of gray and GI retrofits	CSO volume reduction with GI
Gagrani et al. (2014)	Catchment scale 474 ac (190 ha)	Beaverdam Creek, NC	MUSIC to model reduction in pollutants, runoff volume and peak from user specified GI (rain barrels)	Cost effective reduction in TP, TN, TSS, volume and peak using GI (rain barrels)
Chen et al. (2014)	Watershed scale 34 mi^2 (88 km^2)	Yuanshanyan Watershed, Taoyuan County, Taiwan	SUSTAIN to model LID BMP placement for water quality management (SS reduction) in a water supply watershed	Assess effectiveness of LID practices in pollutant reduction (TP, TN, SS, BOD)

Notes: ac = Acre; BMP = Best management practice; CSO = Combined sewer overflow; EIA = Effective impervious area; GI = Green infrastructure; ha= Hectare; km^2 = square kilometers; mi^2 = square miles; SCS CN = Soil conservation service curve number; SS= Suspended solids; TN = Total nitrogen; TP = Total phosphorus; TSS = Total suspended solids

Table 2.5: Community and Environmental Factors for GI Measure Screening

GI Measure	Maint. Burden	Cost	Safety Risk	Space Req.	Environ. Benefits	Habitat Value	Score
Green roof	L (3)	H (1)	L (3)	L (3)	H (3)	L (1)	14
Rainwater harvesting	L (3)	M (2)	L (3)	L (3)	H (3)	L (1)	15
Disconnection to pervious area	L (3)	L (3)	L (3)	M (2)	M (2)	L (1)	14
Permeable paving	H (1)	H (1)	L (3)	L (3)	M (2)	L (1)	11
Bioretention							
• No underdrain	M (2)	L (3)	L (3)	M (2)	H (3)	M (2)	15
• With underdrain	H (1)	M (2)	L (3)	M (2)	H (3)	M (2)	13
Raingarden	L (3)	L (3)	L (3)	L (3)	H (3)	M (2)	17
Extended detention	H (1)	L (3)	M (2)	H (1)	M (2)	H (3)	12
Infiltration trench	L (3)	M (2)	L (3)	M (2)	L (1)	L (1)	12
Infiltration basin	L (3)	M (2)	L (3)	M (2)	L (1)	L (1)	12
Grass channel	M (2)	L (3)	L (3)	M (2)	M (2)	L (1)	13
Dry swale	H (1)	M (2)	L (3)	M (2)	M (2)	L (1)	11
Tree pits	M (2)	H (1)	L (3)	L (3)	H (3)	M (2)	14
Stormwater planters	L (3)	M (2)	L (3)	L (3)	H (3)	L (1)	15
Tree planting	n/a	n/a	n/a	n/a	n/a	n/a	n/a

Notes: L = Low; M = Medium; H = High; GI = Green infrastructure; n /a = Not applicable
Source: Adapted from CWP (2013)

Table 2.6: Summary of Selected Municipal Stormwater Utility Fee and Fee Credit Programs

Municipality /Population /Physical Area Served /Annual Revenue	Fee Basis	Annual Stormwater Fee	Stormwater Fee Credit and Eligibility
Charlotte, NC [a, b] /696,000 /194,300 ac. /$51M	SFR: Tier 1: IA <2,000 ft^2 (median = 1,673 ft^2, 20% of accounts) Tier 2: 2,000 $\le$ IA < 3,000 ft^2 (median = 2,467 ft^2, 40.5% of accounts) Tier 3: 3,000 $\le$ IA < 5,000 ft^2 (median = 3,648 ft^2, 29.3% of accounts) Tier 4: IA $\ge$ 5,000 ft^2 (median = 6,034 ft^2, 10.2% of accounts) All other: per impervious acre	SFR: Tier 1: $85.68 Tier 2: $122.16 Tier 3: $175.44 Tier 4: $285.64 All other: $1,975/ imp. acre	Existing: 100% Maximum (all properties eligible except SFR) • 40% - (Control peak 10-yr, 6-hr) • 60% - (Control volume 2-yr, 6-hr) Proposed: 71% Maximum (*all properties eligible*): • 4% - Pollutant removal (control 1-in.) • 14% - Stream stability (control 1-yr.) • 22% - Routine flooding (control 10-yr.) • 16% - Moderate flooding (control 25-yr.) • 15% - Extreme flooding (control 100-yr.)
DeKalb County, GA [a, c] /700,000 /171,520 ac. /$16.9M	SFR: 1 ERU MFR: 0.5 ERU x no. units All other: 1 ERU/3,000 ft^2 IA (1 ERU = 3,000 ft^{2}IA)	SFR: $48 MFR: $24 x no. units All other: $48/ERU = $697/ imp. acre	40% Maximum (*all eligible*): • 10 % - Water Quality (treat runoff from 1.2 in. precipitation depth from effective IA for annual 80% TSS reduction) • 10% - Channel Protection (24-hr. extended detention of 1-yr., 24-hr. volume) • 10% - Overbank Flood (control peak 25-yr. to < 90% undeveloped condition) • 10% - Extreme Flood (control 100-yr. peak to undeveloped condition, downstream to point of 10 x IA

Table 2.6 (continued)

Greenville County, SC [a, d] /461,000 /500,000 /$8.2M	Class 1a (developed residential & agricultural < 1,000 ft^2 heated 1st floor) Class 1b (developed residential & agricultural > 1,000 ft^2 heated 1st floor) Class 2 (developed non-residential) Class 3 (undeveloped residential & agricultural) Class 4 (undeveloped non-residential) (1 ERU = 2,477 SF)	Class 1a: $22.80 Class 1b: $25.65 Class 2: $27/ERU = $475/ imp. acre Class 3: $22.80 Class 4: $22.80	Maximum 25% (*developed non-residential eligible*) • 25% - Water quantity max o Tree preservation, 10% max. o Upgrade retention/detention to current regulations, 15% max. o Over detention/ retention, 25% max o Discharge elimination, 25% max. • 25% - Water quality max (based on impervious area controlled and pollutant removal capability of BMP): o New development BMPs, 10% max. o Retrofit BMPs, 25% max. o Off-site control, 25% max.
Gwinnett County, GA [a, e] /667,455 /212,430 ac. /$31.4M	Per 100 ft^2 impervious area	$2.46/100 SF (=$1,072/ imp. acre)	40% Maximum (*all eligible*): • 5% - 30% - Watershed Stewardship (various activities such as rain barrels, sprinkler sensors, stormwater training, easement donation, streambank stabilization (150 ft^2 streambank = 100 ft^2 IA) • 10% - Water Quality (control/capture runoff from 1.2 in. storm using green roofs, porous pavement, rain gardens, cisterns, up to 10% credit) • 10% - Channel Protection (24-hr. extended detention of 1-yr., 24-hr. volume) • 10% - Peak Flow (control peak to predeveloped 2-yr. and 25-yr., 24-hr. events)

Table 2.6 (continued)

Montgomery County, MD [f, g] /972,000 /324,480 ac. /$17M	SFR: Tiers 1-7: < 1,000 ft^2 to > 6,215 ft^2 1 ERU = 2,406 ft^2	SFR: Tiers 1-7: $29.17-$265.20/ SF Non-res (with special provisions for non-profit and agricultural properties): 1 ERU = $88.40 (=$1,600.46/ imp. acre)	80% Maximum (*all properties eligible*): • SFR (3-yr. term) • Non-Res (3-yr. term. County will fill out application for 50% of credit value).
Philadelphia, PA [h]	Per parcel fee: Gross area (GA) + Impervious area (IA) + Billing fee	Residential: $149.88 + 26.64 (billing) Non-res: $58.94/500 ft^2 IA + $7.58/500 ft^2 GA + $34.56 billing (= $5,135/imp. acre + $660/gross acre + $34.68 billing)	90% Maximum of IA and 90% Maximum GA (*Non-res. and condo*) and 97% Maximum for industrial properties with NPDES permit: • Manage first 1-in. runoff from IA
Prince George's County, MD [i]	SFR: Tier 1: Admin fee + 0.6 ESU Tier 2: Admin fee + 1.0 ESU Tier 3: Admin fee +2.0 ESU All other: Admin fee + 1 ESU/ 2,465 ft^2 1 ESU = 2,465 ft^2	SFR: Tier 1: $33.12 Tier 2: $41.48 Tier 3: $62.38 All other: $20.58 + $20.90/2,465 ft^2 (=$20.58 + $369.33/ imp. acre) Admin fee = $20.58/account 1 ESU = $20.90	100% Maximum (*all properties eligible*): • Approved runoff facilities

Table 2.6 (continued)

Raleigh, NC [a, j] /403,892 /143,865 ac. /$15.5M	SFR: Tier 1: 400 – 1,000 ft^2 Tier 2: 1,001 – 3,870 ft^2 Tier 3: 3,871 – 6,620 ft^2 Tier 4: 6,621 – 9,500 ft^2 Tier 5: > 9,500 ft^2 (= commercial rate) Commercial rate: per SFEU 1 SFEU = 2,260 ft^2	SFR: Tier1: $19.20 Tier 2: $48.00 Tier 3: $81.60 Tier 4: $139.20 Commercial rate: $48/SFEU= $925/ imp. acre	85% Maximum (*all properties, except SFR, eligible*): • 20% - On-site Control (exceed 2-yr. and 10-yr., 24-hr. design criteria, up to 20% credit) • 30% - Off-site Control (control up to 100 acres offsite runoff for 25-yr., 24-hr. or larger design storm, up to 30% credit) • 35% - Site NPDES Permit (up to 35% credit)
Seattle, WA [k]	Small res. parcel tiers: 1: < 2,000 ft^2 2: 2,000 – 2,999 ft^2 3: 3,000 – 4,999 SF 4: 5,000 – 6,999 SF 5: 7,000 – 9,999 SF All other: per 1,000 SF	Small res., per parcel: 1: $123.81 2: $206.93 3: $286.63 4: $390.03 5: $491.40 All other: per 1,000 SF: Undev. (0-15% IA): *Regular: $31.24 (= $1,361/ imp. acre)* *LI:$18.57 (= $809/imp. acre)* Light (16-35% IA): *Regular: $48.52 (= $2,114/ imp. acre)* *LI: $38.31 (= $1,669/ imp. acre)* Medium (36-65% IA): *Regular: $70.67 (= $3,078/ imp. acre)* *LI: $57.21 (=$2,492/ imp. acre)* Heavy (66-85% IA): $93.56 (= $4,075/ imp. acre) Very Heavy (>85% IA): $112.38 (=$4,895/ imp. acre)	50% Maximum (*all eligible*): Pre-2009 design: • 24-48% - WQ (6-month, 24-hr.) • 13-46% - Flow Control 1 (2- and 25-yr. peak) • 10-46% - Flow Control 2 (2-, 25- and 100-yr. peak control) • 10% - RWH, reuse (commercial only) Post-2009 design: • 24-47% - (WQ design storm volume or flow rate) • 5-50% - Flow Control 1 (91% infiltration or reduction, 1-yr. flow) • 19-50% - Flow Control 3: Pre-Developed Forest (match half 2-yr. to 50-yr. flow duration to forest conditions) • 17-50% - Flow Control 4: Pre-Developed Pasture (match half 2-yr. to 25-yr. flow duration to pasture conditions) • 21-50% - Flow Control 5: Peak Flow Control (2- and 25-yr.)

Table 2.6 (continued)

Notes: ERU = equivalent residential unit; ESU = equivalent service unit; ft^2= square feet; GA = gross area; hr. = hour; IA = impervious area; imp. acre = impervious acre; in. = inch; LI = low impact; M = million; MFR = multi-family residential; NPDES = National Pollutant Discharge Elimination System; RWH = rainwater harvesting SFEU = single-family equivalent unit; SFR = single-family residential; TSS = total suspended solids; WQ = water quality; yr. = year.

[a] Population, physical area served and annual revenue data from SESWA (2013)
[b] Fee and credit information from CMSWS (2008b, 2012, 2015c and 2016a)
[c] Fee rates from DeKalb County (2016) and fee credit information from DeKalb County (2011)
[d] Fee rates from Greenville County (2007) and fee credit information from Greenville County (2008)
[e] Fee rates from Gwinnett County (2005); fee credit information from Gwinnett County (2011) and Gwinnett County (2014)
[f] Montgomery County population and annual revenue data from van der Tak (2015)
[g] Fee rate and fee credit information from Montgomery County (2016)
[h] Fee rate and fee credit information from PWD (2016), effective July 1, 2017 and thereafter.
[i] Fee rates from PGC (2013), PGC (2015) and PGC (2016a) and fee credit information from PGC (2016b).
[j] Fee rates from Raleigh (2016) and fee credit information from Raleigh (2014)
[k] Fee rates from SPU (2016a) and fee credit information from SPU (2016b)

Table 2.7: Summary: Studies of Attitude toward and Willingness to Implement Stormwater Improvements and GI

Study	Main Objective	Data Collection Instrument	Type of Respondent	Number of Respondents	Results/ Main Conclusions
Ando and Freitas 2011	To determine what factors influence households to purchase rain barrels in Chicago's subsidized rain barrel program.	Demographic and spatial data analysis of GI adopters (rain barrel purchasers)	Residential	3,000 (number of rain barrels purchased)	• Distance from distribution point affects adoption rates • Public education efforts increased purchases • Greater rain barrel purchases in: ○ High income neighborhoods ○ Green Party voters ○ Single-family; multi-family (<10 units) ○ Owner occupied • No correlation between purchasers location and reports of flooding
Baptiste et al. 2015	To understand the factors that influence willingness to implement GI on private residential property in Syracuse, NY (combined sewer area).	Door-to-door survey	Residential	229	• Demographics have little correlation to environmental knowledge • Aesthetics play a more important role than cost or health factors in GI implementation • In hypothetical scenarios, aesthetics, cost, gender (females more willing) and environmental knowledge are the most important factors influencing willingness to implement GI.
Cadavid and Ando 2013	To determine residents' willingness to pay for several elements of stormwater management outcomes in an urbanizing area of Champaign-Urbana, IL	Choice experiment survey	Single-family residential	131	• Higher value is placed on reduction of basement flooding than on street or yard flooding and willingness to pay depends on how much flooding is currently experienced • A large value is placed on environmental and water quality benefits to a stream • Policies and infrastructure projects that reduce flooding for only a limited number of residences but worsen aquatic habitat may have questionable net benefits for the community

Table 2.7 (continued)

Carlet 2015	To determine attitudes of municipal staff toward GI in order to understand environmental innovation adoptions by local government.	On-line survey	Municipal officials	292	• Attitudes toward GI are influenced by perceived usefulness but ease of use is not a significant factor (probably because of familiarity of respondents) • Unfamiliarity with an innovation increases the magnitude of risk and uncertainty which reduces rate of adoption and implementation • To improve awareness and adoption, need to increase understanding of GI through implementation of high profile projects that demonstrate the technology
Carlson et al. 2014	To determine knowledge, attitudes, perspectives and willingness to participate in implementing LID for flooding reduction in a combined sewer area discharging to the Mystic River in Somerset, MA.	In-person interviews	Residential, local, state and federal government representatives; non-government organization (NGO) representatives	41 (20 residents; 9 NGOs; 6 local and state government; 6 federal government)	• The majority feel positively toward LID • Residents, city employees more hesitant towards GI; NGOs, state and federal reps. more open to acceptance • Community projects can be used to demonstrate suitability of LID, useful to check design assumptions and efficiency • Need education of residents to explain LID at household level and change perspective of stormwater from nuisance to valuable resource
Giacalone et al. 2010	To determine public perception, knowledge, behaviors and willingness to participate stormwater improvements in order to guide development of targeted stormwater education program.	Telephone survey	Residential	1,599	• Residents are willing to assist in efforts to improve the quality of local waterways • There is a greater likelihood of participation in response to positive local media coverage of positive actions taken by residents to improve water quality (social equity) • Participation is less likely in response to media coverage of water pollution problems

Table 2.7 (continued)

Green et al. 2012	To determine residents' willingness to implement rain barrels and rain gardens in the Shepherd Creek, Ohio watershed.	Reverse auction (voluntary off-sets)	Residential	≈120	• Social capital played a significant role in adjacent properties willingness to participate in program. • Social capital may be as important a factor as education, physical suitability of site and financial capital to obtain widespread acceptance and investment in GI • Economic incentives can encourage local environmental management through citizen engagement
Kaplowitz and Lupi 2012	To determine stakeholder preference for stormwater BMPs	Choice experiment survey	Residential	767	• Strong preference for streambank naturalization as a BMP over other choices of dry pond, wet pond, wetland, filter strip, and rip rap
Keeley et al. 2013	To understand approaches and challenges of integrating green and gray infrastructure in Milwaukee and Cleveland (combined sewer areas).	In-depth interviews	Regional sewer district employees; local government officials; community development organizers	8	Financial • Only small portion of stormwater fees go to GI • Fee acceptance/ lack of public understanding of issues • Limitations on use of funds Administrative & Political • Fragmentation of responsibility and scale of management • Need multi-jurisdictional approach • Need to engage and educate stakeholders and public • Focus on stormwater and community amenity as major benefits of GI • Challenges in capturing other non-water benefits Technical • Outdated infrastructure and regulations • Concerns regarding access to technical expertise • Scale and maintenance of GI

Table 2.7 (continued)

Larson et al. 2014	To determine barriers that prevent residents from installing rain gardens, cisterns, or permeable pavers; estimate potential participation with financial incentive, Howard Co., MD.	In-person and e-mail survey	Residential	110 (66 in-person; 44 e-mail)	• Older residents are less interested in environmental concerns than younger residents • High perceived installation and maintenance for GI • Aesthetics, rain gardens are positive, rain barrels are negative • Lack of knowledge of costs and benefits of GI • Survey conducted prior to implementation of stormwater fee, so willingness to participate not affected by potential decrease in an existing fee
Montalto et al. 2013	To estimate GI property owner adoption rates in Philadelphia neighborhood for two scenarios: 1) will adopt based on technical feasibility, economic self-interest alone; 2) will adopt based on additional elements of experience, knowledge, social networks, interaction with local environment.	Agent based model	Residential	n/a	• Stakeholder outreach and participation is important for effective of watershed-scale GI programs. • In order to develop sustainable GI programs, need to consider physical and social attributes of the target neighborhood. • Stakeholder perspectives and motivations affect the success of decentralized approaches to urban stormwater management using GI.
Olorunkiya et al. 2012	To explore the risks and concern of contractual liabilities as a barrier to LID and GI design and construction in Auckland, New Zealand.	Semi-structured interview and survey	Design and construction professionals	183 (15 interview; 168 survey)	• Rate of LID infrastructure implementation is affected by perception of risk, uncertainty due to low level awareness of new technology • Stormwater managers must promote LID through public awareness and education to ensure community wide learning for sufficient amount of LID implementation • Design and construction professionals can act as "champions" to promote acceptance of LID

Notes: BMP = Best management practice; GI = Green infrastructure; LID = Low impact development; NGO = Non-government organization

Table 2.8: Total Economic Value of GI

Value [a]	Description		
Use Values (Benefits and Reduced Costs)			
Direct Use Value	Stormwater Utility: • Reduce stormwater runoff peak flow and volume/ reduction in flood damages/ reduction in gray infrastructure costs (pipe size) • Reduce pollutant loads/ improvements to stormwater runoff quality • Reduce potable water/ treatment demand • Reduce wastewater treatment demand • Reduce energy demand for water/wastewater treatment		Property Owner: • Tax credits • Stormwater utility fee credits and rebates • Development incentives • Decrease potable water supply and wastewater costs • Decrease building energy costs
Indirect Use Value	Watershed environment: • Minimize erosion • Improve wildlife habitat • Increase groundwater recharge • Mitigate urban heat island effect • Improve air quality • Reduce noise pollution • Reduce atmospheric CO_2	Community/Social: • Increase recreation opportunity • Improve neighborhood aesthetics • Public education opportunities • Increase community cohesion • Provide space for urban agriculture • Improve health and job satisfaction • Reduce crime	Property Owner: • Increase property values • Increase rental rates • Increase retail sales
Option Value	Value related to the ability to benefit from GI in the future; the option to use in the future		

Table 2.8 (continued)

Non-Use Values: (Intangible Benefits)	
Existence Value	Value in knowing that the GI measure exists
Legacy or Bequest Value	Value based in knowing that future generations will benefit from GI
Altruistic Value	Value in knowing that others can benefit from the GI measure
Investment Value (Costs and Generated Benefits)	
Cost Value	Property Owner: • Opportunity cost/ land cost • Capital cost (design and construction) • Operations and maintenance cost
Generated Value	Income generated for third party investors (design firms, construction firms, maintenance contractors)

[a] Sources: Wise et al. (2010), Vandermeulen et al. (2011), American Rivers et al. (2012), Clements et al. (2013), Valderrama et al. (2013).

CHAPTER 3: PERSPECTIVES ON IWM MEASURES AND ENERGY SAVINGS

3.1 Introduction

Water supply and wastewater treatment are energy-intensive processes and are two of the largest consumers of energy in a municipality (Allen et al. 2010; USEPA 2015a); therefore, reducing potable water use for landscape irrigation and other uses with IWM measures can potentially save a significant amount of energy (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; American Rivers et al. 2012). The overall objective of this portion of research is to quantify the magnitude of energy savings in widespread implementation of certain IWM measures. This section describes the data, methodology and analyses conducted to meet this objective and to answer the research question related to IWM implementation and energy savings identified in Section 1.2.1.

3.2 Data

3.2.1 National Data

3.2.1.1 National Energy Intensity of Water Supply and Wastewater Treatment

In order to estimate the potential energy savings that could be achieved from reductions in water supply and wastewater treatment demand, an estimate of average energy intensity of these systems on a national basis is needed. There are relatively few published estimates of embedded energy of individual public water supply systems in the U.S., and of those available, there is a wide range of energy intensities reported due to variations in regional water sources and quality, topography, distribution system characteristics, and climate. The majority of data available are from studies done in the western U.S., specifically in California (Navigant Consulting 2006), Arizona (Hoover 2012) and Utah (Larsen and Burien 2012), although a few nationwide and other local studies exist or have been compiled by the U.S. Department of Energy (USDOE 2012) and others (Sanders and Webber 2012). The most recent and comprehensive national compilation and analysis of public water supply energy intensity data is published by the Electric Power Research Institute (EPRI) in 2013 (EnerNOC, Inc. and Washington University 2013) and updates work previously published by EPRI in 2002 (ICF Consulting 2002) and 1996 (Burton and EPRI 1996).

EnerNOC, Inc. and Washington University (2013) developed separate national energy intensity values for surface water, groundwater and desalination water supply systems of 1,600, 2,100 and 12,000 kWh/MG, respectively, based on extensive data collection from government organizations, private research groups and other sources as well as an exhaustive literature review, including many of the studies cited in Chapter 2. These values are used with approximations of total population served by each type of public water system in the U.S., also provided by EnerNOC, Inc. and Washington University (2013), to calculate a weighted average of energy intensity of water supply of 2,070 kWh/MG for use in the national assessment calculations.

Unlike the large variations in energy intensities for water supply systems in different regions of the U.S., energy intensities for wastewater treatment depend mainly on the treatment processes utilized and plant capacity which are more similar throughout the country. The more sophisticated treatment processes require more energy while larger capacity treatment plants have economies of scale (USEPA 2008a, Larsen and Burien 2012, Sanders 2012, EnerNOC Inc. and Washington University 2013). As with values for the energy intensity of water supply, EnerNOC, Inc. and Washington University (2013) present the most recent and comprehensive national compilation and analysis of public wastewater treatment energy intensity data and updates previous work published by EPRI in 1996 (Burton and EPRI 1996). The 2013 report provides estimates of energy intensity for typical wastewater treatment unit processes as a function of flow rate and then groups the results into four treatment categories: less than secondary, secondary, greater than secondary, and no discharge. A weighted average (by volume treated for each category) is calculated for energy intensity of wastewater treatment of 2,430 kWh/MG from these data for use in the national assessment (EnerNOC, Inc. and Washington University 2013).

3.2.1.2 Potable Water Demand and End Uses in the U.S.

The United States Geological Survey (USGS) estimates that total U.S. water withdrawal in 2005 was 410,000 million gallons per day (MGD) and that approximately 44,200 MGD or just less than 11% was for public water supply for an estimated 258 million people. Further, 58% of the public supply volume or 25,600 MGD was for residential uses which equates to approximately 100 gallons per capita per day (Gpcd); 28% or 12,400 MGD was for commercial, industrial and institutional (CII) uses; and 14% or 6,200 MGD was for public use and system losses (Kenny et al. 2009, USEPA 2013a). The USEPA estimates that 30% (USEPA 2013b) of residential demand, 7,700 MGD or 30 Gpcd, is used outdoors for lawn and garden irrigation or for other outdoor uses; and between 5% and 30% of CII demand (USEPA 2012b), or 620 to 3,700 MGD is used for landscape irrigation. Table 3.1 provides a summary of the national public water demand values for both residential and CII sectors as well as total per capita demand and allocation percentages between indoor and outdoor use.

3.2.1.3 Potential Demand Reductions

Data and information from various sources are used to develop estimates of the potential reduction in potable water demand for outdoor uses due to implementation of the IWM measures of rainwater harvesting and gray water reuse. The actual amount of rainwater available to meet the demand for landscape irrigation and other outdoor uses in any given location will be dependent on local climate, rainfall characteristics, and system design (USEPA 2013c). Steffen et al. (2013) quantify the water-saving efficiency performance (percent reduction in potable water demand) of urban residential rainwater harvesting systems for outdoor water supply for 23 cities within seven climatic regions of the U.S. Their results indicate that outdoor use water-saving efficiencies for the seven climate regions of the U.S. range between a low of 2% in the Southwest to a high of 40% in the Southeast with required cistern sizes of 760 gallons and 5,700 gallons, respectively. If just a single 50 gallon rain barrel is used, the low and high outdoor water savings efficiency values range again between the low in the Southwest at 2% and the high in the Southeast at 10%. These results are used to estimate ranges of potential reduction in potable water demand due to rainwater harvesting at both the national and local scales.

A gap exists in the literature regarding the ability of rainwater harvesting systems to meet the irrigation and outdoor use demand of the CII sector. It is reasonable to assume, however, that the performance of rainwater harvesting systems for CII buildings would be higher than that for residential buildings because the irrigation demand of the CII sector is typically less (Mayer et al. 1999; Dziegielewski et al. 2000; USEPA 2012b, 2013b) and CII sector building roofs should generally be able to capture and store a larger volume of water than residential buildings. In addition, policy mechanisms can affect rainwater harvesting goals for the CII sector, such as the City of Tucson (Arizona) requirement that 50% of commercial property irrigation water be supplied from rainwater (Kloss 2008). Therefore, it is assumed that on a nationwide basis, up to 50% of CII sector irrigation demands can be met by rainwater harvesting systems.

Gray water generated in the residential sector generally refers to water that is discharged from showers, baths, and clothes washers, and accounts for an estimated 40% of residential indoor use (Mayer et al. 1999). Gray water could likely be used as a supplement to rainwater harvesting in many areas to further reduce the potable water demand for landscape irrigation in the residential sector. Gray water generated in the CII sector is from restroom faucets and laundry use, and accounts for only about 6% of CII indoor use (Gleick et al. 2003). Therefore, it is assumed that there is insufficient gray water produced in the CII sector to substantially supplement rainwater harvesting in the reduction of irrigation water demand.

3.2.2 Charlotte, North Carolina Data

3.2.2.1 Charlotte Energy Intensity Data

To determine energy savings as a result of reducing wastewater treatment demand due to the use of gray water for outdoor irrigation, a flow weighted average of energy intensities for Charlotte-Mecklenburg Utility Department’s (CMUD) five wastewater treatment plants (William Rice, personal communication, August 8, 2013) of 3,200 kWh/MG is used. Similar data regarding energy intensity of CMUD’s three water treatment plants and associated water supply distribution system are unavailable. In the absence of site-specific data, the national average value of energy intensity for surface water source, treatment, and distribution of 1,600 kWh/MG is used (EnerNOC, Inc. and Washington University 2013) for the case study analysis because 100% of CMUD water supply is sourced from surface water.

3.2.2.3 CMUD Potable Water Demand and End Uses

Local water supply planning data are available for CMUD from the North Carolina Department of Environment and Natural Resources (NCDENR) Local Water Supply Planning (LWSP) website (NCDENR 2014a). Metered connection and average daily metered use data for the most recent year (2012) are used to determine total annual demand volume for residential, CII sectors, unaccounted, and system process uses. The 2012 values are 55% residential, 28% CII, 13% unaccounted, and 4% system process uses, compared to national values of 58%, 28% and 14% (combined total system process and unaccounted uses). CMUD's residential use of 55% of the public supply volume or 55.3 MGD for a population of 796,209 equates to approximately 70 Gpcd.

Latham (2008) cites estimates of outdoor water use as a percentage of total use for various municipalities in North Carolina. Single-family residential outdoor water use is reported to vary between 20% and 22% in the cities of Raleigh and Wilmington, respectively, and up to 50% in the Town of Cary. When multi-family and commercial connections are included, the outdoor use estimate for Cary falls to about 35%. There are no outdoor water use data available for the CMUD service area; therefore, the range of 20% to 35% is reasonable for use in the case study assessment because the national average value of 30% (USEPA 2013b) falls within this range. The national low and high outdoor water use estimates for CII connections of 5% to 30% of total water demand are used for the CMUD case study due to the lack of detailed local data. Table 3.1 provides a summary of the water demand values for CMUD including total per capita demand as well as the allocation percentages between indoor and outdoor use and the corresponding per capita demand for both high and low outdoor use scenarios.

3.2.2.4 CMUD Potential Demand Reductions

Steffen et al. (2013) indicate that water-saving efficiencies for the residential sector in the southeast region of the U.S. range between a high of 40% with a required cistern size of 5,700 gallons to a low of 10% if just a single 50 gallon rain barrel is used. In both scenarios, gray water is estimated at 40% of indoor demand (Mayer et al. 1999) and can replace the remaining outdoor demand in both the high and low outdoor water use scenarios for combined maximum reductions of 100%. As discussed previously for the national assessment, it is assumed that an average of 50% of CII sector irrigation demands can be met by rainwater harvesting systems in the CMUD service area. Table 3.2 provides a summary of the potential outdoor water demand reduction percentages used in the CMUD case study.

3.2.2.5 CMUD Rate Structure, Fee and Budget Data

Historically, in the U.S., the majority of municipal water suppliers have set their price for water to only pay for the cost of operating and maintaining the system, and energy costs are typically a significant portion of these ongoing operations costs. However, charging consumers for only the operational cost of supplying water does not provide the revenue needed to reinvest in infrastructure upgrades and replacement, contributing to the challenge of aging water infrastructure. Full cost pricing refers to the full financial costs to supply and treat water and includes both ongoing operations and maintenance as well as capital replacement costs. When full-cost pricing is used, the energy portion of the consumer cost is a smaller portion of the total cost of water supply, due to the magnitude of the capital replacement costs relative to the cost of ongoing operations and maintenance.

North Carolina Session Law (SL) 2008-143 requires local governments and large community water systems to base their water fees on full-cost pricing principles in order to be eligible for state water infrastructure funds (Cotting 2013). As such, CMUD's water rates include a fixed administrative charge, increasing volumetric block rates where the price of water increases as the amount of water increases, and a sewer fee based on the volume of water supplied, as well as a fixed administrative charge and an availability fee.

CMUD's annual budget data for FY 2012 (City of Charlotte 2012) are provided in Table 3.3. CMUD reports that its annual electricity costs are 4% of its total annual expenditures (CMUD 2014). This analysis includes a comparison of the calculated annual energy cost savings to the annual budget data in order to gauge the impact these potential savings would have on CMUD's budget.

3.3 Methodology

The energy requirements for water supply and wastewater treatment reported in existing literature are used to estimate the corresponding potential energy savings via reductions in demand volumes associated with certain IWM practices. Specifically, the potential energy savings due to the reduction in potable water demand and wastewater treatment volume as a result of rainwater harvesting and gray water reuse for landscape irrigation and other outdoor uses is quantified. Captured rainwater and gray water from indoor uses can reduce energy consumption when used for landscape irrigation and other outdoor uses by residential and commercial, industrial, and institutional (CII) consumers in place of more energy- intensive water supply sources, especially in areas with high water supply energy intensities (Garrison et al. 2009; Griffiths-Sattenspiel and Wilson 2009; UCB and UCLA 2011). Using various data sources, potential demand reductions, energy savings and cost savings on a national basis and at the local municipal water utility level are estimated using CMUD as a case study. Both national and municipal assessments are conducted in order to determine if there is a relationship between the results on a per household basis at both scales.

3.3.1 Methodology for National Assessment

Estimates of the potential annual energy savings due to the reduction in U.S. public water supply and wastewater treatment demand from implementing rainwater harvesting and gray water reuse systems to replace landscape irrigation and outdoor water use in the residential and CII sectors are determined. This analysis considers two outdoor water use scenarios: 1) high outdoor water use representing 30% of total demand for the residential sector and 30% for the CII sector, and 2) low outdoor water use representing 30% and 5% of total demand for the residential and CII sectors, respectively. This analysis evaluates the potential for reduction in outdoor water demand for each development sector (residential and CII) for both outdoor water use scenarios using a range of demand reduction values that represent the use of rainwater harvesting only and rainwater harvesting in combination with gray water reuse. In the residential sector, both high and low outdoor use scenarios are identical; and rainwater harvesting is able to reduce nationwide demand on average by between 2% and 40%. In both scenarios, gray water is estimated at 40% of indoor demand (Mayer et al. 1999) and can replace the remaining outdoor demand for a combined maximum reduction of 100%. In the CII sector, rainwater harvesting can reduce the outdoor demand in both high and low outdoor use scenarios by 50%.

The estimates for national energy intensity of water supply and wastewater treatment of 2,070 kWh/MG and 2,430 kWh/MG, respectively, are used with the demand values identified in Table 3.1, to calculate the annual national energy savings in kilowatt-hours per year (kWh/yr) for 2%, 20%, 40% and 100% reductions in public water demand for both the high and low outdoor use scenarios. In all scenarios, the reduction in CII outdoor water demand due to rainwater harvesting is 50%. Also, the additional energy savings due to the reduction of wastewater treatment demand resulting from gray water reuse in the residential sector are also calculated and added to the energy savings resulting from the reduction in potable water demand. Table 3.2 provides a detailed summary of the various scenarios analyzed, labeled H1-H4 and L1-L4 for high and low outdoor water use scenarios, respectively.

Energy savings are calculated in kWh/yr as the product of average daily demand reduction in MGD over a 365 day period and the estimated U.S. average energy intensity of potable water supply or wastewater treatment. The associated annual electricity cost savings are calculated using the rolling U.S. 12-month average retail price of electricity to industrial customers ending in March 2014 of $0.0693/kWh (EIA 2014). Estimates of annual energy and energy cost savings are also developed on a U.S. per capita basis using the U.S. population estimate for water supply in 2005 of 258 million (Kenny et al. 2009) and on a household basis using the U.S. Census Bureau (USCB) report of 2.6 persons per household (average of 2000 and 2010 values, USCB 2012).

3.3.2 Methodology for Charlotte, North Carolina Assessment

A similar analysis to the nationwide estimate of energy and associated cost savings due to rainwater harvesting and gray water reuse measures to replace demand for irrigation water and other outdoor uses is performed for the CMUD service area available using local data. The calculated energy and costs savings are then related to CMUD's Fiscal Year (FY) 2012 total, operating and electricity expenditures.

Using the two outdoor water use scenarios described previously, the potential annual energy savings for CMUD due to the reduction in potable water demand as a result of implementing rainwater harvesting and gray water reuse systems to replace landscape irrigation and outdoor water use in the residential and CII sectors is estimated. The potential for reduction in outdoor water demand for each development sector for both scenarios using rainwater harvesting only and rainwater harvesting supplemented by gray water reuse is evaluated for the CMUD service area using a range of reduction values similar to that done for the nationwide assessment, with a few exceptions. In the residential sector, for both high and low outdoor use scenarios, rainwater harvesting is able to reduce demand on average by between 10% and 40%, as opposed to 2% and 40% in the nationwide estimate. Table 3.2 provides details for the various scenarios analyzed.

Energy savings in kWh/yr are calculated as the product of average daily demand reduction in MGD over a 365 day period and the estimated U.S. weighted average energy intensity of potable surface water supply of 1,600 kWh/MG (EnerNOC, Inc. and Washington University 2013) or the CMUD flow weighted average energy intensity of wastewater treatment of 3,230 kWh/MG (CMUD 2013). The annual electricity cost savings of these reductions in energy demand are then calculated using CMUD's peak price paid for electricity of $0.06/ kWh (CMUD 2013).

Estimates of annual energy and energy cost savings for the residential sector are also developed on a per capita basis using the CMUD service area population estimate for 2012 of 796,209 (NCDENR 2014a); on a per household basis for energy savings from the residential sector only using the 2012 population estimate and 2.5 persons per household (NCDENR 2014a); and, on a per CII metered connection basis from the CII sector only using the numbered of metered CII connections in 2012 of 1,406.

3.4 Results and Discussion

3.4.1 Energy and Cost Savings at the National, Utility and per Household Levels

It is estimated that on a nationwide basis the potential for total energy savings of reduced potable water demand for the high outdoor water use scenarios ranges between 1.6 and 3.8 billion kWh/yr using rainwater harvesting alone to replace outdoor irrigation water demand and up to 14 billion kWh/yr when both potable water and wastewater treatment demand are reduced using combined rainwater harvesting and gray water reuse measures. Total associated annual electricity cost savings range between $110 million and $270 million for the rainwater harvesting only cases and up to $950 million for the combined rainwater harvesting and gray water use case.

Nationwide energy savings for the low outdoor water use scenarios range between <1 and 2.6 billion kWh/yr for potable water demand reduction due to rainwater harvesting alone with electricity cost savings between $25 million and $180 million and up to 13 billion kWh/yr and $870 million in savings for the combined rainwater harvesting and gray water reuse case.

While the aggregate energy and cost savings possible from IWM measures of rainwater harvesting and gray water reuse are significant, these values should also be considered at a distributed scale. On a per household basis, the maximum total energy and associated cost savings from any demand reduction case for the high and low use scenarios is approximately 120 kWh/yr and $8.60/yr. A summary of key results for the national assessment is given in Table 3.4 while detailed results for all high and low outdoor water use scenarios are provided in Table 3.5.

It is estimated that CMUD could save between 1.0 to 6.9 million kWh/yr of electricity due to a reduction in potable water demand through customer implementation of rainwater harvesting measures to replace outdoor irrigation water and up to 31 million kWh/yr if both potable water and wastewater treatment demand are reduced via the implementation of combined rainwater harvesting and gray water reuse measures. At the current stated cost of $0.06/kWh, the associated electricity cost savings range between $63,000 and $410,000 per year with rainwater harvesting measures only, and up to $1.8 million/yr if gray water reuse measures are implemented as well. Table 3.4 summarizes key results for the CMUD case study while detailed results for all high and low outdoor water use scenarios and all reduction percentage cases, as well as the per capita, per metered connection and per household results are in Table 3.6.

This analysis indicates that significant energy and associated cost savings are possible at water utilities nationwide as a result of the reduction in potable water demand through implementation of rainwater harvesting and gray water reuse measures to replace landscape irrigation and other outdoor water uses. The greatest savings are realized in the high outdoor demand scenario where potential savings of up to 3.8 billion kWh and $270 million per year from rainwater harvesting alone could be achieved nationwide, and up to 14 billion kWh and $950 million per year when combined with gray water reuse.

The estimated nationwide energy savings of 14 billion kWh/yr for 100% reduction of outdoor water use is similar to the result obtained in a more general analysis by Young (2014); which estimates a savings of 14.8 billion kWh/yr due to a reduction in cold potable water uses. The more detailed data and literature values presented in this study provide an estimate of the potential extent and range of energy and cost savings for individual IWM measures. An understanding of these details is important for policy considerations especially at the municipal level where variations in climate and irrigation demand characteristics will affect the benefit-cost potential of specific practices and ultimately local consumers' willingness to adopt them.

At the municipal level, the results for the CMUD case study also look promising with savings potential for the regional water utility in Charlotte of up to 6.9 million kWh and $410,000 per year through rainwater harvesting, or 31 million kWh and $1.8 million per year when supplemented with gray water reuse. Although these savings amount to less than 1% of CMUD's FY 2012 total expenditures and just under 2% of the same year's total operating expenditures, they could reduce CMUD's annual electricity cost of $11.55 million by about 16%. Table 3.7 summarizes the relationships between CMUD's estimated potential energy cost savings and the utility's FY 2012 total expenditures, operating expenditures, and estimated electricity expenditures.

These results appear favorable for CMUD and other utilities in the U.S. based on the aggregate nationwide and municipal assessments. However, because the cost of energy is not decoupled from the cost of water, unless a utility can pass along the savings to the individual consumers there will be no economic incentive for the consumer to implement these types of measures in order to simply save energy. Therefore, an important question is: Are there enough energy cost savings on a per household basis such that water utilities can share these savings with their customers as an economic incentive to implement these types of measures?

To answer this question, national and municipal results are assessed at a distributed scale by determining the energy and cost savings on a per-household level. Annual energy savings per household for the nationwide and municipal case study assessments are similarly low, ranging between 1 and 120 kWh/yr for all scenarios and cases examined with associated cost savings of less than $10.

3.4.2 Economic Incentives and Disincentives of IWM for Water Suppliers and Consumers

The potential energy savings of IWM measures can add to the incremental economic benefits of IWM, which can provide significant financial incentives to water utilities to promote their use, including delaying capital investments, augmenting existing water supplies, and eliminating the need to develop new water sources. However, utilities also face challenges with widespread implementation of IWM measures. First, both rainwater harvesting and gray water reuse may encounter policy barriers, as many areas restrict such IWM measures within current state water rights or municipal code. Gray water reuse has additional impediments due mainly to health and safety concerns (USEPA 2012a). Also, while energy and the associated costs savings are realized by water utilities, rainwater harvesting and gray water reuse systems are implemented by the consumer, leading to a mismatch between the scales of operation and accounting of savings. Finally, any reduction in demand will result in a reduction in revenue for the utility. Vieira et al. (2014) demonstrate that the implementation of water efficient devices and rainwater harvesting can significantly reduce the potable water demand of a community. The financial incentives to promote the use of IWM measures at the consumer level need to be carefully coordinated with potential reductions in revenue. The key to optimizing implementation of these measures is to develop policies and incentives that balance the economic benefits between suppliers and consumers.

The energy costs of centrally supplied water are not decoupled from the price of water charged to consumers. Therefore, there is little to no consideration of energy savings in consumers' decisions regarding water use or implementing IWM type water conservation methods. Even if energy costs of central supplied water are separated from the price of water, they appear to be small at the individual household level. Therefore, the use of incentives for consumers to install rainwater harvesting or gray water reuse systems will likely require additional policy actions beyond the message of energy savings. Existing economic incentives for consumers to implement rainwater harvesting systems do exist in the U.S. and include full or partial rebate and credit programs offered by water utilities, reduced prices on equipment, and the direct cost savings associated with lower water consumption (USEPA 2013c).

Although LCA results for energy and environmental impacts are important when considering community water management strategies, individual consumers will most likely base their decisions regarding implementation of rainwater harvesting and gray water reuse measures on a comparison of capital costs and their potential savings from reduced water use. The potential savings will depend mainly on the local price of water;

local rainfall patterns; system design characteristics (gravity fed or pump); and individual property demand requirements. Benefit-cost analysis is beyond the scope of this paper; however, there are many resources available to aid in determining costs and benefits of rainwater harvesting and gray water reuse systems (Memon et al. 2005; WERF 2009; USEPA 2013c; Yu et al. 2013; Yu et al. 2014).

3.4.3 Importance of Assessing Energy Savings at Multiple Scales

When the energy and cost savings cited as a result of reduced potable water consumption for areas in California (Garrison et al. 2009; American Rivers et al. 2012) are distributed among the populations involved, the annual savings per household are similar to this study's results. This paper clarifies this unstated result that differs with preconceived notions implied by the reported magnitude of aggregate savings. Low per household savings is an important perspective with significant policy implications that are not acknowledged by other studies of IWM implementation.

Although the disaggregated savings are small, the knowledge of potential energy and cost savings at all scales is important for water utilities and policy makers when considering how to promote and incentivize consumers in the sustainable use of water. USEPA (2015a) estimates that approximately 100 million kWh of electricity can be saved annually if one out of every 100 American homes is retrofitted with water-efficient fixtures. Using the same rationale, the results of this analysis indicate that if 1% of American households harvested their rainwater for landscape irrigation, 240 million kWh of electricity would be saved, almost 2.5 times the energy savings compared to water efficient fixtures. This perspective demonstrates that there is value in every increment of water efficiency because each can lead to great aggregate savings.

3.5 Conclusions

It is posited that reducing demand on the energy intensive urban water infrastructure systems of water source, distribution and treatment through the widespread use of rainwater harvesting and graywater reuse will result in large energy savings at the national scale, the local municipal scale and the individual consumer scale. Quantifying the energy savings associated with IWM measures better explains the potential benefits from their implementation. This analysis indicates that while significant energy and associated cost savings are possible at water utilities nationwide as a result of the reduction in potable water demand through implementation of these measures to replace landscape irrigation and other outdoor water uses, these savings appear to be low when disaggregated at the household scale. Therefore, the answer to the question “Can sufficient energy savings be realized from IWM measures of rainwater harvesting and gray water reuse to provide economic incentives that might encourage implementation by water utilities and their customers?” appears to be “yes” for water utilities and “no” for consumers. Aggregate energy savings can be large for water utilities and although the disaggregated savings are small, the knowledge of potential energy and cost savings at this scale is important for water utilities and policy makers when considering how to promote and incentivize consumers in the sustainable use of water.

These results raise additional questions regarding the role of energy savings in IWM implementation: How can a utility’s potential aggregate energy savings be incorporated into the water conservation message to consumers? What benefits can utilities provide to consumers so they can realize the energy savings associated with saving water while simultaneously offsetting the reduction in revenue from the reduced demand? How do utility energy savings compare as motivators for conservation with other intangible benefits of water conservation to the consumer? Because water demand for irrigation and other outdoor uses occurs mainly during the hot summer months when energy use for air conditioning is also at its peak, can water pricing based on energy demand provide water utilities an effective means of offering economic incentives for implementing IWM measures that reduce outdoor use?

Further research is needed to address these uncertainties including: reliable utility energy data; LCAs that include the complete energy, economic and environmental impacts of community wide rainwater harvesting and gray water reuse scenarios, keeping in mind that the defined analysis boundary will have a great impact on the results; assessment of the potential impact of local climate on supply and demand characteristics; and, information regarding customers' willingness to participate in retrofit programs. The development of local incentive policies for IWM measures will depend on reliable measured data and detailed analyses.

With appropriate analyses, the energy savings benefits of rainwater harvesting and gray water reuse, as well as other IWM measures, can be adequately accounted for when evaluating the benefits and costs of alternative water management scenarios within a community or watershed and communicated to consumers to promote sustainable water use. This assessment at various scales and for specific IWM measures, the analysis of the relationship between results at different scales, and this discussion of economic incentives and policy implications, go beyond broad aggregate estimates of energy savings due to reductions in potable water use and provide a framework that can help motivate these necessary future research efforts.

Table 3.1: National and Charlotte, NC Potable Water Demand Values

Scenario	Total Demand	Outdoor Demand	Indoor Demand	Gray Water Available for Reuse [e]
	Gpcd	% total, Gpcd	% total, Gpcd	% indoor, Gpcd
U.S. National Residential [a]				
High Outdoor	100	30%, 30	70%, 70	40%, 28
Low Outdoor	100	30%, 30	70%, 70	40%, 28
U.S. National CII [b]				
High Outdoor	n/a	30%	70%	n/a
Low Outdoor	n/a	5%	95%	n/a
Charlotte, NC Residential [c]				
High Outdoor	70	35%, 24	65%, 46	40%, 18
Low Outdoor	70	20%, 14	80%, 56	40%, 22
Charlotte, North Carolina CII [d]				
High Outdoor	n/a	30%	70%	n/a
Low Outdoor	n/a	5%	95%	n/a

Notes: CII = Commercial, industrial, institutional sectors; Gpcd = Gallons per capita per day.

[a] U.S. national residential water demand: per capita (Kenny et al. 2009 and USEPA 2013b); indoor/outdoor (USEPA 2013b).
[b] U.S. national CII water demand: total (Kenny et al. 2009); indoor/ outdoor (USEPA 2012b).
[c] Charlotte, North Carolina residential water demand: per capita (NCDENR 2014a); indoor/outdoor (Latham 2008).
[d] Charlotte, North Carolina CII demand: total (NCDENR 2014a); indoor/ outdoor (USEPA 2012b).
[e] Gray water is approximately 40% of residential indoor use (Mayer et al. 1999).

Table 3.2: Percent Reduction in Outdoor Water Demand due to Rainwater Harvesting and Gray Water Reuse

IWM Measure(s)	Rainwater Harvesting Only (H1 and L1)	Rainwater Harvesting Only (H2 and L2)	Rainwater Harvesting Only (H3 and L3)	Rainwater Harvesting and/or Gray Water Reuse (H4 and L4)
High and Low Outdoor Water Use Scenarios [a]				
Residential [b, c]	2% (National) 10% (Charlotte)	20%	40%	100%
CII [d]	50%	50%	50%	50%

Notes: CII = Commercial, industrial, institutional sectors

[a] See Table 3.1 for a summary of potable water demand values; H1 – H4 = high outdoor water demand scenarios; L1 – L4 = low outdoor water demand values.

[b] Steffan et al. 2013.

[c] Gray water is approximately 40% of residential indoor use (Mayer et al. 1999) and is assumed to replace 93% of outdoor water demand at the national scale and 75% and 100% of high and low outdoor water use demand scenarios, respectively, for the Charlotte, North Carolina Case Study.

[d] Kloss 2008.

Table 3.3: CMUD FY 2012 Budget Data

Total Expenditures [a]	$288,560,220
Total Operating Expenditures [a]	$111,555,112
Debt Service/ Capital Investment Plan Support [a]	$177,005,108
Annual Electricity Cost [b]	$11,550,000
Annual Electricity Cost as % of Total Budget [b]	4%
Annual Electricity Cost as % of Annual Operating Budget [a, b]	10.4%

Notes: CMUD = Charlotte-Mecklenburg Utility Department; FY = Fiscal Year.

[a] Source: City of Charlotte (2012).

[b] Annual electricity cost calculated as 4% of total annual budget (CMUD 2014).

Table 3.4: U.S. National and CMUD Potential Annual Energy Savings (and Associated Cost Savings) from Rainwater Harvesting and Gray Water Reuse

Scenarios [a]	Rainwater Harvesting Only: Scenarios L1 – L3 and H1 – H3	Rainwater Harvesting + Gray Water Reuse: L4 and H4
U.S. National [b]		
Total	0.39 B – 3.8 B kWh ($25M – $270M)	13 B – 14 B kWh ($870M - $950M)
Per-Household [c]	1 - 24 kWh ($0.08 - $1.70)	120 kWh ($8.60)
CMUD [d]		
Total	1.0 M – 6.9 M kWh ($63K – $410K)	20 M – 31 M kWh ($1.2M – $1.8M)
Per-Household [c]	2 – 14 kWh ($0.12 - $0.85)	85 – 90 kWh ($3.70 – $5.30)

Notes: B = Billion; CMUD = Charlotte-Mecklenburg Utility Department; K = Thousand; kWh = kilowatt-hours; M = Million.

[a] See Table 3.1 and Table 3.2 for scenario details.
[b] See Table 3.5 for detailed National results.
[c] Per household results are based on residential values only.
[d] See Table 3.6 for detailed CMUD results.

Table 3.5: Potential U.S. Annual Energy and Cost Savings

High Outdoor Water Use Scenarios [a]				
Scenario	H1	H2	H3	H4
	Annual Energy Savings of Reduced Demand (kWh/yr)			
Residential water supply [b]	0.12 B	1.2 B	2.4 B	6.0 B
CII water supply [b]	1.4 B	1.4 B	1.4 B	1.4 B
Residential wastewater treatment [c]	0	0	0	6.4 B
Total	1.6 B	2.6 B	3.8 B	14 B
Total per capita, res. only [d]	0.5	4.6	9.2	48
Per household, res. only [e]	1.2	12	24	120
	Annual Electricity Cost Savings ($/yr)			
Total [f]	$110 M	$180 M	$270 M	$950 M
Total per capita, res. only [d]	$0.03	$0.32	$0.64	$3.30
Per household, res. only [e]	$0.08	$0.83	$1.70	$8.60
Low Outdoor Water Use Scenarios [a]				
	L1	L2	L3	L4
	Annual Energy Savings of Reduced Demand (kWh/yr)			
Residential water supply [b]	0.12 B	1.2 B	2.4 B	6.0 B
CII water supply [b]	0.24 B	0.24 B	0.24 B	0.24 B
Residential wastewater treatment [c]	0	0	0	6.4 B
Total	0.39 B	1.4 B	2.6 B	13 B
Total per capita, res. only [d]	0.46	4.6	9.2	48
Per household, res. only [e]	1.2	12	24	120
	Annual Electricity Cost Savings ($/yr)			
Total [f]	$25 M	$99 M	$180 M	$870 M
Total per capita, res. only [d]	$0.03	$0.32	$0.64	$3.30
Per household, res. only [e]	$0.08	$0.83	$1.70	$8.60

Notes: B = Billion; CII = Commercial, industrial, institutional sectors; GWR = Gray water reuse; kWh/yr = kilowatt-hours per year; M = Million; RWH = Rainwater harvesting; Res. = Residential; $/yr = U.S. dollars per year.

[a] See Table 3.1 and Table 3.2 for scenario details.
[b] U.S. weighted average energy intensity (by source volume and population served) of water supply for all sources = 2,070 kilowatt-hours per million gallons (EnerNOC, Inc. and Washington University 2013, p. 4-17).
[c] U.S. weighted average energy intensity (by treatment type and volume treated) of wastewater treatment = 2,430 kilowatt-hours per million gallons (EnerNOC, Inc. and Washington University 2013, p. 5-16).
[d] U.S. population estimate for public water supply in 2005 = 258 million (Kenney et al. 2009).
[e] U.S. total households based on 2.60 persons per household (average of 2000 and 2010, USCB 2012).
[f] Average retail price of electricity to industrial customers, rolling 12-month average, March 2014 = $0.0693 (EIA 2014).

Table 3.6: Detailed Results – Potential CMUD Annual Energy and Cost Savings

High Outdoor Water Use Scenarios [a]				
Scenario	H1	H2	H3	H4
	Annual Energy Savings of Reduced Demand (kWh/yr)			
Residential water supply [b]	1.1 M	2.3 M	4.5 M	11 M
CII water supply [b]	2.4 M	2.4 M	2.4 M	2.4 M
Residential wastewater treatment [c]	0	0	0	17 M
Total	3.5 M	4.6 M	6.9 M	31 M
Total per capita, res. only [d]	1.4	2.8	5.7	36
Per household, res. only [e]	3.6	7.1	14	90
Per CII connection, CII only [f]	170	170	170	170
	Annual Electricity Cost Savings ($/yr)			
Total [g]	$210,000	$280,000	$410,000	$1.8 M
Total per capita, res. only [d]	$0.09	$0.17	$0.34	$2.10
Per household, res. only [e]	$0.21	$0.43	$0.85	$5.30
Per CII connection, CII only [f]	$10	$10	$10	$10
Low Outdoor Water Use Scenarios [a]				
Scenario	L1	L2	L3	L4
	Annual Energy Savings of Reduced Demand (kWh/yr)			
Residential water supply [b]	0.65 M	1.3 M	2.6 M	6.5 M
CII water supply [b]	0.40 M	0.40 M	0.40 M	0.40 M
Residential wastewater treatment [c]	0	0	0	13 M
Total	1.0 M	1.7 M	3.0 M	20 M
Total per capita, res. only [d]	1.2	1.6	3.2	25
Per household, res. only [e]	2.0	4.1	8.1	61
Per CII connection, CII only [f]	28	28	28	28
	Annual Electricity Cost Savings ($/yr)			
Total [g]	$63,000	$101,000	$180,000	$1.2 M
Total per capita, res. only [d]	$0.05	$0.10	$0.19	$1.50
Per household, res. only [e]	$0.12	$0.24	$0.49	$3.70
Per CII connection, CII only [f]	$1.70	$1.70	$1.70	$1.70

Notes: CII = Commercial, industrial and institutional sectors; CMUD = Charlotte-Mecklenburg Utility Department; GWR = Gray water reuse; kWh/yr = kilowatt-hours per year; M = Million; Res. = Residential; RWH = Rainwater harvesting; RES = Residential sector; $/yr = U.S. dollars per year.

[a] See Table 3.1 and Table 3.2 for scenario details.

[b] National weighted average energy intensity of water supply for surface water sources = 1,600 kilowatt-hours per million gallons (EnerNOC, Inc. and Washington University 2013).

[c] CMUD flow weighted average energy intensity of five wastewater treatment plants = 3,230 kilowatt-hours per million gallons (CMUD 2013).

[d] CMUD service area population in 2012 = 796,209 (NCDENR 2014a).

[e] CMUD service area, no. households = 2012 service area population/2.5 persons per household (NCDENR 2014a).

[f] CMUD service area, number of metered CII connections in 2012 = 14,006 (NCDENR 2014a).

[g] CMUD price for electricity = $0.060/kWh (CMUD 2013).

Table 3.7: Detailed Results – Comparison of CMUD Potential Annual Energy Cost Savings to CMUD FY 2012 Budget Metrics

High Outdoor Water Use Scenarios [a]				
	H1	H2	H3	H4
Total Electricity Cost of Reduced Demand = Savings Potential ($/yr)	$210,000	$280,000	$410,000	$1.9 M
Cost savings as % of total annual budget [b]	0.07%	0.10%	0.14%	0.64%
Cost savings as % of annual operating budget [b]	0.19%	0.25%	0.37%	1.7%
Cost savings as % of annual electricity cost [b]	1.8%	2.4%	3.6%	16 %
Low Outdoor Water Use Scenario [a]				
	L1	L2	L3	L4
Total Electricity Cost of Reduced Demand = Savings Potential ($/yr)	$63,000	$101,000	$180,000	$1.2 M
Cost savings as % of total annual budget [b]	0.02%	0.04%	0.06%	0.41%
Cost savings as % of annual operating budget [b]	0.06%	0.09%	0.16%	1.1%
Cost savings as % of annual electricity cost [b]	0.54%	0.88%	1.6%	10%

Notes: CII = Commercial, industrial, institutional sectors; CIP = Capital improvement program; CMUD = Charlotte-Mecklenburg Utility Department; FY = Fiscal Year; GWR = Gray water reuse; M = Million; RWH = Rainwater harvesting; RES = Residential sector; $/yr = U.S. dollars per year.

[a] See Table 3.1 and Table 3.2 for scenario details.

[b] See Table 3.3 for CMUD FY 2012 Budget Data.

CHAPTER 4: PERSPECTIVES ON GI RETROFITS AND WATER QUALITY IMPROVEMENTS

4.1 Introduction

Municipalities tend to focus GI retrofits on public property due to the many obstacles to retrofitting private property (Bitting and Kloss 2008), but the extent of suitable public land is limited. The problem for stormwater managers is how to use limited public funds to focus implementation of GI retrofits on the most suitable properties within a catchment, whether public or private.

Building on the concept that stream health and restoration are related to the extent of watershed impervious area, the main objectives of this portion of the research are: to identify both the extent to which GI retrofits can be used to reduce imperious area within a watershed and the relative contribution by property type and public or private ownership in achieving stream restoration goals; and, to develop a catchment prioritization scheme with a focus on impervious area reduction capacity and additional features that have the potential to provide a manageable number and extent of GI retrofits such that measureable and significant performance data can be attained in a reasonable time horizon. This section describes the data, methodology and analyses conducted to meet these objectives and to answer the research questions related to GI retrofits and water quality improvements identified in Section 1.2.2.

4.2 Data

The majority of data used in this portion of the research are GIS data from the Mecklenburg County and the City of Charlotte Open Mapping websites, (Mecklenburg County 2016, City of Charlotte 2016). The GIS data layers used are listed in Table 4.1. Additional data and parameter estimates from the literature are used as indicated in the specific methodology descriptions.

4.3 Methodology

The primary methodology for this portion of research utilizes a case study approach where two impaired urban watersheds in the City of Charlotte, Mecklenburg County, North Carolina are analyzed to answer the research questions identified relative to GI retrofits and water quality improvements. Land use characteristics of the case study watersheds are intentionally different; commercial development dominates one watershed and residential development dominates the other. The individual elements of analysis within the broader case study methodology are based on the body of literature that concludes the extent of watershed impervious cover is a gauge of stream quality health in combination with the literature that supports the concept that GI measures that reduce runoff volume have the ability to reduce effective impervious area, thereby improving stream health. The functional approach for this portion of research consists of three main segments: 1) selection of suitable case study watersheds within the City of Charlotte-Mecklenburg County; 2) identification of suitable parcels and the corresponding extent of GI retrofit and impervious area reduction possible within the two case studies watersheds; and, 3) development of a catchment scale ranking and prioritization scheme for a GI retrofit experimentation program. The detailed methodologies used for these water quality related research components are described in detail in the following sections and are summarized in Table 4.2. ArcMAP/ArcGIS 10.1 (ESRI 2012) software is used to perform the GIS analyses for this research. MS-Excel (Microsoft 2010) is used to perform all additional analyses.

4.3.1 Selection of Case Study Watersheds

The Charlotte-Mecklenburg Storm Water Services (CMSWS) current watershed scale prioritization ranking scheme (CMSWS 2015c) is used along with stream designated use support ratings, TMDL status and watershed impervious area characteristics to identify suitable case study watersheds for this analysis. CMSWS ranks watersheds in two areas: management conditions related to environmental planning and regulatory controls and existing environmental and land use conditions. A composite ranking is also identified. It is appropriate to begin a GI retrofit experimentation program in one of the high priority watersheds identified by CMSWS for water quality improvements. CMSWS water quality program watershed rankings are indicated in Table 4.3. This research is focused on the relationship between impervious cover and stream health; consequently detailed impervious cover data within each watershed are the main criteria of interest and are used in combination with CMSWS's overall rankings of individual streams and information on stream health (use support and TMDL status) to select case study watersheds.

CMSWS identifies both a Stream Supporting Use Index (SUSI) for twenty-four (24) surface water streams and a Lake Supporting Use Index (LUSI) for three (3) lakes within Mecklenburg County. Theses indices rate the surface waters as impaired, partially supporting, supporting or highly supporting. SUSI scores are calculated quarterly using bacteriological, metals, nutrients, physical and biological data that are collected 12 times a year from 24 monitoring sites. Bacteriological, metals, nutrient and physical data collected 6 times a year from 28 monitoring locations within the three lakes are used to calculate bi-monthly LUSI scores. As of the first quarter of 2016, all 24 stream segments within the County are either impaired or partially-supporting their designated uses and as of September 2016 all areas within the 3 lakes are partially to highly supporting their designated uses (CMSWS 2016b). Table 4.3 provides snapshot SUSI and LUSI ratings for Mecklenburg County streams and lakes. The current stream use support status for all streams within Mecklenburg County is shown on Figure 4.1.

In addition to CMSWS designated use ratings, States are required to report stream assessment data to the USEPA under section 303(d) of the Clean Water Act (CWA) every two years. The 303(d) impaired waters list identifies waters that have exceeded water quality standards for a particular parameter that require a TMDL or alternative plan to improve water quality. Once a TMDL or TMDL Alternative is approved, the stream segment is removed from the 303(d) list. Table 4.3 also summarizes current 303(d) listing (NCDEQ 2016) and TMDL status information (CMSWS 2008a, 2015a) for Mecklenburg County streams.

The total amount of impervious cover in each stormwater watershed within Mecklenburg County is determined by overlaying the three impervious layers, Commercial Impervious, Other Impervious (road edge of pavement – EOP and sidewalk), and Residential (single-family) Impervious, onto the Stormwater Watershed layer using the ArcGIS Identity tool. Attribute selection criteria are used within the resulting layers to tabulate the quantity of impervious area within each impervious layer type within each of thirty-three (33) watersheds identified in the stormwater watershed layer within Mecklenburg County. Table 4.4 summarizes these impervious area quantities and the total impervious area for each stormwater watershed.

Two case study watersheds are selected from 17 priority watersheds that are ranked within the top ten of the existing conditions, management conditions or composite categories of the CMSWS watershed priority ranking process, have an existing TMDL and/or are currently listed on the 303(d) list and have high amounts of impervious area but with different land use characteristics – one where commercial impervious area dominates and one where residential impervious area dominates. The two watersheds selected for case study are Upper Little Sugar Creek (ULSC) and Six Mile Creek. The ULSC watershed has the greatest amount of total impervious area within Mecklenburg County at 40.13% and is ranked at No. 2 and No. 4 in the CMSWS Water Quality Program Ranking for existing conditions and composite categories, respectively. The watershed is dominated by commercial impervious surfaces at 21.43%, with 7.39% single-family residential impervious area, and 11.35% roadway/sidewalk impervious area. Like all other streams within the Charlotte-Mecklenburg urban area, ULSC is a class “C” stream with designated uses that include secondary recreation, fishing, wildlife, fish consumption, aquatic life including propagation, survival and maintenance of biological integrity (NCDENR 2014 b). ULSC is impaired due to copper and mercury concentrations and has total maximum daily loads (TMDLs) for dissolved oxygen, fecal coliform and fecal coliform (CMSWS 2015a).

The Six Mile Creek watershed has the eleventh greatest amount of total impervious area within Mecklenburg County at 22.23% and is ranked No. 8 in the management condition category in the CMSWS Water Quality Program. The watershed is dominated by single-family residential impervious surfaces at 9.09%, with 6.37% commercial impervious area, and 6.77% roadway/sidewalk impervious area. Six Mile Creek is also a class “C” stream, is currently rated as partially supporting by CMSWS (2016b) and is currently on the 303(d) List (NCDEQ 2016) for impairment due to ‘poor fish community’. Six Mile Creek does not currently have a TMDL.

4.3.2 Watershed Scale Evaluation of Impervious Area Reduction Potential

Available GIS data (impervious area and other spatial data) and non-spatial characteristics are used to assess extent of suitable public and private property within the case study watersheds available for GI retrofits. This assessment is combined with literature values of volume reduction capability of various GI measures to estimate the extent to which these measures can reasonably be placed in order to reduce directly connected impervious area (DCIA). Table 4.2 summarizes the GIS analysis methodology procedures conducted for the watershed scale evaluations including GIS data layers used and created and the specific ArcGIS analysis tools used.

4.3.2.1 Estimation of DCIA

It is necessary to determine whether Mecklenburg County’s impervious area data are representative of total impervious area (TIA) or directly connected impervious area (DCIA). The distinction between TIA and DCIA is important because runoff from DCIA is believed to be the main contributor to stream impairment (Brabec 2009). A reduction in DCIA, either through conversion (e.g., routing runoff from DCIA through a bioretention basin or an infiltration trench or over a pervious surface) or removal (rainwater harvesting system or permeable pavement), is believed to contribute to improvements in stream health (USEPA 2010, 2011, 2014f, 2015d, 2015e).

The impervious area data for the two case study watersheds, ULSC and Six Mile Creek, are combined with City of Charlotte existing land use data to estimate impervious area percentages for different land use categories. The existing land use layer for each case study watershed is overlaid onto the three impervious area layers (‘Commercial’, ‘Residential’ (single-family) and ‘Other’ (roadway EOP/sidewalk)) using the ArcGIS intersect tool. Table 4.5 and Table 4.6 summarize the impervious area quantities within each City of Charlotte existing land use category for the ULSC and Six Mile Creek watersheds, respectively. The total amount of impervious area within each land use type is then added together to get a percent impervious for that land use type. The resulting areas are then grouped to align with the 20 land use categories identified by the Center for Watershed Protection (CWP) (CWP 2003, attributed to Cappiella and Brown 2001) and weighted averages based on land area within each category are computed for each watershed. These land use impervious area percentages derived for the two case study watersheds are then compared to various published values and estimates of TIA and DCIA from empirical relationships for different land use types to determine if the Charlotte data are more characteristic of TIA or DCIA. This comparison is provided in Table 4.7.

The published values and estimates from empirical relationship estimates of DCIA and TIA are grouped into nine land use categories and the data plotted using a box and whisker plot, shown in Figure 4.2. The Charlotte impervious area values are added to the plot for comparison to determine if the impervious area data needs to be adjusted from TIA to DCIA using published empirical relationships or if the available data can be assumed to be representative of DCIA. This analysis indicates that, with the exception of impervious area estimates for civic/institutional and open space/ recreation land uses within Six Mile Creek, the Charlotte data are more representative of DCIA than TIA. It is not unreasonable that the amount of impervious surface area within civic/institutional and open space/recreational type land uses would vary widely. Using the impervious area data as DCIA will allow these values to be reduced through future field assessments as necessary – any level of disconnection found can be subtracted from baseline DCIA.

4.3.2.2 Physical Suitability: Soil, Slope, Bedrock and Groundwater Characteristics

Physical characteristics that govern the type of GI measures that are suitable for a particular property include hydrologic soil group (HSG), slope, depth to groundwater, and depth to bedrock. Planning level values for all of these characteristics are identified through soil classifications provided in the Soil Survey for Mecklenburg County (USDA 1980). Table 4.8 lists the physical data used in the parcel suitability analyses for the soil types that exist within the case study watersheds. The GIS soil data layer identifies the spatial extent of each soil type. HSG is a main determinant of the type of GI measure that is appropriate for use on a site.

The soil types are grouped according to HSG and attribute selection expressions are created to enable selection of specific characteristics related to HSG (A, B, C, D or Urban), slope (less than 8% or greater than 8%), and groundwater depth (less than or greater than 2 ft. below the surface). Depth to bedrock for all soils is suitable for GI placement. The expressions are used with property type and ownership attributes identified in the parcel data layer to determine suitable areal extent of impervious area reduction for individual BMPs. Composite soil and impervious area layers are created for each impervious area type, ‘SoilComImp’, ‘SoilSFImp’ and ‘SoilOtherImp’, for each watershed using the ArcGIS intersect tool for parcel suitability analysis.

4.3.2.3 Parcel Suitability: Property Type and Ownership

The ArcGIS spatial join tool is first used to combine the Cadastral – Tax Parcel Boundaries layer (‘ParcelNoData’) with the Cadastral – Tax Parcel with CAMA Data layer (‘ParcelTax’) to create a layer (‘ParcelNoDataTaxJoin’) that combines all of the individual property ownership tax data within a single parcel polygon, preserving the total parcel area (‘shape_area’ and ‘st_area_sh’). Next the ArcGIS intersect tool is used to join the ‘ParcelNoDataTaxJoin’ layer to the composite soil type and impervious layers, ‘SoilComImpInt’ and ‘SoilSFImpInt’ to create two new composite layers called ‘ParcelTaxSoilComImp’ and ‘ParcelTaxSoilSFImp’, preserving the total area. The ‘Other’ impervious layer is not parcel based so there is no parcel layer to join to the ‘SoilOtherImpInt’ ‘layer. (Property ownership of roads and sidewalk is distinguished by attributes as discussed later.) This process is done for both the ULSC and Six Mile Creek watersheds.

Values populating the ‘descproper’ and ‘accounttyp’ attributes within the composite layer with commercial impervious area, ‘ParcelTaxSoilComImp’ are used to create layers with further refinement to distinguish between government/ public owned property, privately owned institutional property, general commercial property such as retail, office and warehouse property and multi-family residential property. Table 4.9 lists the attribute values apportioned to each of these four commercial property types. As stated earlier “Other” impervious area layer is not parcel based, however, property ownership is determined by attributes for City EOP, State EOP, unmaintained (private) EOP, and public or private sidewalks. Single-family parcels are considered to be privately owned.

4.3.2.4 Selection of GI Measures and GIS Layer Development

The final step of the GIS analysis methodology involves determination of which GI measures are most suitable for which parcels based on property type, impervious area subtheme (building, paved, driveway, etc.), and physical characteristics (HSG soil type, slope, and depth to groundwater). Attribute selection is performed on the composite parcel-soil type-impervious layers according to the type of GI that is most appropriate for the specific property type, ownership, physical characteristics (using expressions created as described above) and impervious area subtheme characteristics and new layers are created. The GI measures considered in this research are those that have the ability to reduce runoff volume: bioretention basins/ raingardens, permeable pavement, grassed channel, green roof, rainwater harvesting, disconnection of impervious area, and tree pits/trees.

Soils within the ULSC and Six Mile Creek watersheds are considered suitable for a particular GI measure depending on HSG, slope and high water table. Depth to bedrock of all soils within both watersheds is suitable for all GI measures. Characteristic slopes do not preclude GI use except in the case of grassed channels, permeable pavement and disconnection of impervious area which are only used on slopes of less than 8%. Soils with high water table < 2 ft. (occurs in some HSG C and all HSG D soils in Six Mile Creek watershed) are only suitable for grassed channels because they do not require underdrains.

Neither ULSC nor Six Mile Creek have HSG A soils; both have a large extent of HSG B and a lesser amount of HSG C soils; ULSC has a large extent of ‘Urban’ soils; and, Six Mile Creek has a large amount of HSG D soils. Soils are labeled ‘Urban’ due to the extensive amount of disturbance to the native soil as a result of land development and construction. Because there is also a large amount of soil classified as HSG B or HSG C in ULSC, assumptions regarding the type of GI appropriate for Urban soils are made assuming B or C soils are present with special adjustments made regarding treatment area ratios and coverage ratios for GI measures on ‘Urban’ soil.

Bioretention basins are assumed to be suitable to accept runoff from all building, paved or other areas on commercial properties and roadways with HSG B, HSG C or Urban soils, on any slope. Raingardens are suitable to accept runoff from building areas in single-family areas with HSG B and HSG C soils with slopes greater than 8%. The high water table for any bioretention basin or raingarden must be greater than 2 feet below the ground surface.

It is assumed that single-family properties on HSG B and HSG C soils with land with slopes less than 8% can simply disconnect building and other impervious areas to existing pervious surfaces instead of using more costly raingardens. The high water table for impervious area disconnection must also be greater than 2 feet below the ground surface.

Permeable pavement is considered suitable for ‘other’ impervious surfaces on commercial properties on HSG B and HSG C soils and single-family driveway surfaces on HSG B soils, with slopes of less than 8% and high water table greater than 2 feet below ground surface. Permeable pavement is not considered on single-family parcels with HSG C soils because of the costs related to underdrain requirements.

Grassed channels are suitable to accept runoff from ‘building’, ‘paved’, ‘other’ and driveways impervious surfaces in HSG C and HSG D soil areas where the seasonal high water table is not amenable to other types of GI measures (less than 2 feet below ground surface) and slopes are less than 8%.

Green roofs and/or rainwater harvesting systems are assumed to be suitable for commercial building impervious areas on ‘Urban’ soils. Slope and ground water table are not a consideration in this case and a distinction between green roof and rainwater harvesting is not specified because both have the same volume reduction multiplier. Although Ando and Freitas (2011) indicate that fewer rain barrels are bought by renters and multi-family property owners in their Chicago study area most likely because they have less control over landscape decisions, rain water harvesting is used as a viable GI measure for this research for multi-family dwellings because it is assumed that roof top collections systems and/or green roofs would be the only GI measures feasible in this type of high density area with ‘Urban’ soil.

Tree pits/trees are assumed to be suitable on all state and city maintained roadway and sidewalk impervious areas on ‘Urban’ soil areas and for unmaintained roadways and sidewalk areas in HSG B, HSG C or ‘Urban’ soils, all with high water table greater than 2 feet below ground surface.

Table 4.10 and Table 4.11 list the GIS layers created using these GI selection criteria to determine extent of GI retrofit and DCIA reduction possible in the ULSC and Six Mile Creek watersheds, respectively. These tables identify the individual layers created for impervious area property ownership type, and corresponding parcel subthemes and physical characteristics that are used to determine suitable GI measure and potential DCIA reduction.

4.3.2.5 Putting it All Together: Extent of DCIA Reduction Potential

The reduction in DCIA due to the various GI measures is calculated using the data from the GIS analyses and the BMP disconnection multipliers provided in Table 2.3 of this document (USEPA 2014c) in an MS-Excel spreadsheet (Microsoft 2010). Using the GIS impervious area data as the DCIA baseline, the extent of DCIA reduction as a result of GI retrofit implementation within the case study watersheds is calculated using DCIA values for the various attribute defined analysis layers created using a spreadsheet as is the contribution to the reduction from different parcel types: commercial (government/public, institutional/ private, office/warehouse, multi-family residential); single-family residential; and, other (roadway/sidewalk).

A treatment area ratio (TAR) is defined for this research as the proportion of suitable impervious area that is treatable vs. amount of pervious area available for the GI footprint and generally accounts for that portion of the impervious area that cannot be treated due to site constraints and therefore, remains impervious. The TAR is assumed to be 1.0 for all suitable impervious areas except when certain GI measures are used and/or on ‘Urban’ soils. For these cases, the ratio is 0.75 for green roofs and rainwater harvesting systems due to building equipment space requirements and 0.83 for bioretention and tree pits where building footprint to parcel area may not provide adequate space for a bioretention footprint.

Two scenarios for DCIA reduction are evaluated in terms of potential GI implementation after the TAR is applied: maximum coverage and moderate coverage. The maximum coverage ratio is the theoretically total possible impervious area reduction based on suitable site characteristics and GI reduction capability. The maximum coverage ratio is assumed to be 1.0 and the moderate coverage ratio is 0.50 for all BMPs except tree pits/trees, green roofs, and grassed channels. Tree pits/tree coverage ratios are from Deutsch et al. (2007) and based on median and traffic island values for city and state roadway EOP and on streetscape values for unmaintained EOP and sidewalks. All commercial building green roof coverage assumptions are based on either rowhome or commercial building values in Deutsch et al. (2007). Grassed channels are assumed to be reasonably appropriate for large lot single-family residential (LL Res) areas only. From the Existing Land Use GIS layer, LL Res accounts for approximately 2% of all single-family land use area in the ULSC watershed and 4% in the Six Mile Creek watershed. These values are used as the maximum coverage ratio for grassed channel and are cut in half for the moderate coverage scenario. All other areas where grassed channels are specified (all other areas where high water table is less than 2 feet below surface) are assigned maximum and moderate coverage ratios of 0. The volume reduction multiplier, treatment area ratio and maximum and moderate coverage ratios for each analysis layer are also listed in Table 4.10 and Table 4.11 for the case study watersheds.

4.3.3 Multi-Criteria Decision Analysis: Prioritizing Catchments for GI Retrofit Experimentation

A catchment scale prioritization strategy is developed to determine the best catchments for possible GI retrofit experimentation within the case study watersheds using the methodology developed for the watershed scale DCIA reduction evaluation, and a multi-criteria decision analysis (MCDA) approach (Hajkowicz et al. 2000; Hyde et al. 2005; Hajkowicz and Collins 2007). An MCDA approach is appropriate because there are multiple evaluation criteria, measured in different units, necessary to guide the prioritization process. The MCDA approach consists of several steps:

1. Identify the decision options to be scored and ranked;
2. Select the set of evaluation criteria for the decision options relevant to the prioritization objective:
    a. Identify criteria of importance;
    b. Obtain performance values for each criterion for each decision option;
    c. Check for redundancy;
3. Transform performance values to a commensurate scale;
4. Assign priority ranks to evaluation criteria;
5. Weight the transformed scores based on the priority rank and weight function;
6. Sum and rank the weighted option scores using a weighted summation value function;
7. Perform a sensitivity analysis of resultant decision option ranks by systematic variation of criterion priority rank and/or weight function; and,
8. Make a decision.

The MCDA decision options in this research are catchments and the evaluation criteria are parameters related to the amount of DCIA, DCIA reduction capability and other non-redundant physical features of the catchment options relevant to the overall prioritization objective.

4.3.3.1 Identification of Decision Options: Catchment Delineation

The decision options for the prioritization strategy are catchment areas within the two case study watersheds, ULSC and Six Mile Creek. Each watershed is divided into several catchment areas defined using GIS watershed model sub-basins (Engineering models – watershed sub-basin drainage boundary layer). Individual sub-basins are hand selected using the ArcGIS interactive selection tool ("select features" arrow icon) to create several individual catchment boundary layers for each watershed. Each defined catchment is made up of first-, second-, and third order streams and total catchment drainage area is similar in order of magnitude to that of two GI retrofit experimentation watersheds, Shepherd Creek (Shuster and Rhea 2013; Roy et al. 2014) and Little Stringybark Creek (Walsh et al. 2015) which are both approximately 500 acres. Each defined catchment boundary layer is named using the sub-basin nomenclature and identification of the most downstream sub-basin.

An attribute field with the catchment name is added to each catchment layer and the sub-basin boundaries are dissolved using the ArcGIS dissolve tool. All defined catchment boundary layers within each case study watershed are then merged to form a single catchment boundary layer called "Catchments_FirstOrder" which is a single layer of catchment boundaries for each watershed. These catchment boundary layers are used in conjunction with the ArcGIS data layers and methodology developed for parcel suitability at the watershed scale in order to develop evaluation criteria for catchment prioritization.

4.3.3.2 Selection of Non-Redundant Evaluation Criteria

a. Identification of Evaluation Criteria

The primary objectives for GI retrofit experimentation are to maximize water quality impact while minimizing cost and construction issues, with potential completion over a reasonable time horizon. Although the primary criterion for catchment prioritization in this research is the reduction of DCIA, there are additional criteria that are important for economic and expediency purposes as well as criteria of importance for experimentation studies as indicated in the literature (Shuster and Rhea 2013; Walsh et al. 2015). Therefore, criteria to be evaluated in this research are focused on DCIA reduction potential in general and on public owned property; DCIA density; likelihood of new development; connectivity of green space; and cost considerations.

With these objectives in mind, maximizing DCIA reduction potential in conjunction with minimizing total area of DCIA to retrofit are the two most important criteria. Several additional criteria related to imperviousness are also considered since DCIA reduction is the main metric on which this entire methodology is based. Higher magnitudes of DCIA reduction potential on public owned commercial property is desirable; however, public roadway DCIA reduction potential is not a priority. Connectivity of potential retrofit sites is evaluated through DCIA density of catchment, and the presence of existing GI or conventional BMPs, park property, greenways and wetlands. Another important factor is that the catchment be relatively stable in terms of development with minimal vacant land. An experimentation study should not be undertaken in a rapidly developing watershed or with a significant amount of developable or vacant property unless controls are required to offset the effects of development

(Walsh et al. 2015). Also, a smaller number of parcels within a catchment is desirable to minimize the number of property owners needed for retrofit participation. Finally, total capital cost for retrofits within each catchment is also considered. Table 4.13 lists the 30 criteria selected for evaluation.

b. Performance Value Development and Data Adjustment

The catchment boundary layer for each case study watershed is joined using the ArcGIS intersect tool to the composite soil-impervious-parcel tax layers created for the watershed scale analyses described in Chapter 4.4.2 as well as several additional watershed scale layers in order to develop performance values for the selected evaluation criteria identified in Table 4.12. Some GIS data layers have spatial overlaps and adjustments are made so that these areas are not accounted for in performance values for more than one criterion. Overlap occurs between the following layers and/or spatial attributes: some wetland areas are included in both the Lakes_ponds and Wetlands layers; and, and some park property included in the Park Property layer, is also area that is defined as vacant in the parcel data that is used to create a Vacant Area layer. The ArcGIS union tool is used to join each of these sets of layers within each watershed to identify the overlap area and remove it from one of the layers so that they are not double counted and duplication of information in the scoring process is avoided. For example, wetland area that is included in both the Lakes_ponds layer as well as the Wetlands layer is removed from the Lakes_ponds layer and only counted as wetland area. Similarly, park area that is included in both the Park Property layer and is identified as vacant area layer is removed from the created Vacant Area layer and counted only as Park Property. In this case it is assumed that designated Park Property is not available for development in the future which the Vacant Area layer is used to identify. Although there is also spatial overlap between the Park Property and Government/public impervious area layers, the park area is not removed from the Government/public impervious area because it is important to account for this in both cases. However, when independence is checked between these layers, if a significant relationship exists, only one of the layers is selected as a non-redundant criterion.

c. Criteria Independence

GIS data values for 30 prioritization criteria of interest, listed in Table 4.12, are collected and/ or derived for each defined catchment within each case study watershed. It is important that the criteria selected be non-redundant (independent of one another) to prevent exaggerating the effect of a particular catchment feature in the prioritization process. Criteria independence is evaluated using critical values of the Pearson product moment correlation coefficient, r, which indicates the strength of the relationship between two criteria. The critical Pearson r used to determine if a relationship exists between criteria (and are therefore not independent), is based on degrees of freedom, df = N – 2 (where N = number of pairs of criterion values or number of catchment options, in this case) and a 0.01 level of significance for a two-tailed test (Havlicek and Crain 1988).

The independence tests are done for three sets of data or cases: catchment criteria pairs for each case study watershed individually, ULSC and Six Mile Creek, and then for criteria pairs from all catchments from both watersheds combined to increase the sample size, N, of the universe of catchments. As the number of criterion pairs (in this case – the number of catchments) to evaluate increases, the critical r value decreases, increasing the likelihood of correlation between criteria and resulting in fewer independent variables.

Further analysis of the relationships between criteria is conducted. Prairie (1996) shows that the predictive power of linear regression models with the Pearson coefficient of determination, r, less than 0.81 ($r^2 \leq 0.65$) is low and almost constant but increases rapidly for r values greater than 0.81. The Pearson r is a measure of the proportion of variance that is common between two variables – that is – what proportion of the criteria being measured by one variable is also being measured by the other variable. Although analysis of Pearson r values in this research is performed to avoid selecting redundant criteria for prioritization (criteria that are measuring the same catchment features) rather than for identifying predictive quality, this threshold value of r is also considered when selecting final criteria for prioritization. In addition, bivariate scatter plots are used to visualize the relationship between final criteria selected to further validate independence. An effort is made to merge criterion sets or remove data sets where possible and the final set of non-redundant criteria includes the fewest number that represent the overall research objectives (Hajkowicz et al. 2000).

4.3.3.3 Transformation of Criterion Performance Values

Multi-criteria value functions (or quantitative ranking algorithms) require that the criteria performance values under consideration be standardized into commensurate units. A linear utility scoring function is used to adjust criteria performance values (PV) based on their distance from the minimum or maximum value of each criterion set. For each set of non-redundant criteria for all catchments under consideration; PVs are transformed using a utility function that assigns a score between 1 and 0 to indicate best to worst performance among all catchments being considered for the two cases:

$$\mathrm{TPV}_{ij} = \frac{\mathrm{PVij - MinPVi}}{\mathrm{MaxPVi - MinPVi}}\text{, when a higher PV is better} \qquad \text{(Eq. 4.1)}$$

$$\mathrm{TPV}_{ij} = \frac{\mathrm{MaxPVi - PVij}}{\mathrm{MaxPVi - MinPVi}}\text{, when a lower PV is better} \qquad \text{(Eq. 4.2)}$$

Where, TPVij = Transformed performance value of the i^{th} criterion for the j^{th} catchment, on a scale of 0 to 1 where 1 indicates best performance;

PVij = Performance value of the i^{th} criterion for the j^{th} catchment;

MinPVi = Minimum performance value of the i^{th} criterion; and,

MaxPVi = Maximum performance value of the i^{th} criterion.

4.3.3.4 Criterion Priority Rank Order

Once the final set of criteria is selected for evaluation, where n = the number of non-redundant criteria, each criterion is assigned a rank order of importance from 1 to n, with 1 = most important criterion, 2 = second most important, and so on. The criterion priority rank order is a preference decision made by appropriate decisions makers (in this case, the researcher). The criterion priority rank order is very important because it significantly impacts the weight assigned to each standardized criterion PV score which affects the final results. Priority rank order is not a factor when equal weight is assumed or when criterion weight is assigned, but for other criteria weight functions, the priority rank position (order of importance) of each criterion determines its weight in the value function.

4.3.3.5 Criterion Weight Functions

Transformed criterion PV scores are weighted using five alternative criterion weight functions: equal weight, rank sum, rank reciprocal, rank centroid and assigned weight (Malczewski 1999). The criterion weights are determined using the formulas (Barron and Barrett 2001):

Equal Weight: $\mathrm{WT}_i = \frac{1}{n}$ (Eq. 4.3)

Rank Sum Weight: $\mathrm{WT}_i = \frac{n-i+1}{\sum_{j=1}^{n} j}$ (Eq. 4.4)

Rank Reciprocal Weight: $\mathrm{WT}_i = \frac{\frac{1}{i}}{\sum_{j=1}^{n}(\frac{1}{j})}$ (Eq. 4.5)

Rank Centroid Weight: $\mathrm{WT}_i = (\frac{1}{n}) \sum_{j=i}^{n}(\frac{1}{j})$ (Eq. 4.6)

Where, WT_i = Weight of i^{th} criterion;

i = Rank position of i^{th} criterion; and,

n = Number of non-redundant criteria.

The sum of all WT_i = 1.0 for all weight functions. The priority rank order is not a factor when equal weight is assumed but the preference decision is that all criteria are of equal importance. Preference decisions are also used when assigned weights are assumed although there is no formula to calculate the relative differences of the weights. An additional weighting method, the analytical hierarchy process (AHP) (Saaty 1987; Flitter et al. 2013), uses pairwise comparison and a relative ratio scale between selected criteria to determine their relative importance. The AHP is not used in this research, however, application of AHP could be useful in an actual experimentation project where stakeholders would provide preference input to the pairwise comparisons to obtain consensus on the relative importance and resulting weight of each criterion.

4.3.3.6 Multi-Criteria Value Function

A weighted summation value function is used to weight, sum and rank the transformed PV scores for each criterion to obtain a total score for each catchment according to equation:

$$\mathrm{CS}_j = \sum_{i=1}^{n} \mathrm{TPV}_{i,j}\mathrm{WT}_i \qquad \text{(Eq. 4.7)}$$

Where, CS_j = catchment score for j^{th} catchment, j = 1,…., N

n = Number of non-redundant criteria,

N = Number of catchment options

$\mathrm{TPV}_{i,j}$ = Transformed performance value for the i^{th} criterion for j^{th} catchment, on a scale of 0 to 1 where 1 indicates best performance; and,

WT_i = Weight for i^{th} criterion (non-negative and sum to 1).

The summed catchment score is then ordered from 1 to N, where N is the number of catchments, to determine catchment priority, i.e., the relative suitability of each catchment for GI retrofit experimentation, with 1 = the highest catchment score (most suitable) and N = lowest catchment score (least suitable).

4.3.3.7 Sensitivity Analysis

The weight assigned to each non-redundant evaluation criterion is very important to the final decision outcome when using a MCDA approach (Hyde et al. 2005). When a weighted summation value function is used to calculate decision option scores, the weight applied to each PV is dependent on both the weight function selected and the priority rank order assigned to each criterion. A sensitivity analysis involves the systematic variation of the criterion priority ranks and/or the weight function to determine the effect on the resulting decision option value scores. The number of rank order combinations in a MCDA with 5 criteria is 120 (= 5!) and the number with 6 criteria is 720 (= 6!). If three weight functions are applied to each of these combinations there are 360 and 2,160 possible scenarios, respectively. Complex sensitivity analysis approaches for MCDA (Triantaphyllou and Sanchez 1997; Hajkowicz et al. 2000; Hyde et al. 2005; Chen et al. 2010) can be used to identify the magnitude of change in criterion weighting that will result in a significant alteration of the final decision option value scores. When the final results are minimally affected by these variations, the results are assumed to be reliable and robust (Hajkowicz et al. 2000).

For this research only one order of criterion priority ranks is used. The priority rank order is assigned using the overarching objectives of expediency and economic efficiency coupled with critical lessons learned from GI experimentation studies reported in the literature. A sensitivity analysis is performed by varying the weights applied to the TPVs using the various specified weighting methods. The criteria are either given equal weights, weighted using the rank sum, rank reciprocal or rank centroid functions, or assigned a weight according to the preference of the decision maker (in this case – the researcher). The same relative preference order used in the weight functions is also used in the assigned weight scenario.

4.3.3.8 Making a Final Decision

For each weighting method, the six catchments with the highest CS are identified for the three test cases (ULSC, Six Mile Creek and combined ULSC and Six Mile Creek). In addition, the CSs are summed across all five weighting methods to obtain an overall CS value for each catchment. The catchments are ranked accordingly for each test case.

These two methods of evaluating CS values are used to determine the highest priority catchments within each case study watershed to consider for experimentation.

4.4 Results and Discussion

The results are presented and discussed in two sections and align with the questions established for this portion this research. First, the impervious characteristics of the two selected case study watersheds are described. Watershed scale quantification of DCIA relative to property type and ownership are presented and discussed and observations relative to GI retrofit potential and potential for DCIA reduction in each category are made. The results of the watershed scale evaluation of DCIA reduction potential are then provided and interpretations of differences due to watershed development type are offered. Finally, results of the MCDA strategy for prioritizing catchments scale for GI retrofit experimentation are detailed and discussed.

4.4.1 Results of Watershed Scale Analyses

4.4.1.1 Impervious Area Characteristics of Case Study Watersheds

The selection of ULSC and Six Mile Creek as case study watersheds for this research is based in part on the differences in their overall impervious area characteristics. Although both have total impervious area in excess of 20% of watershed area, ULSC is dominated by commercial impervious area and Six Mile Creek is dominated by residential impervious area. The reason for selecting watersheds with different development type impervious area is to examine the effect these differences might have on potential for GI retrofit and associated DCIA reduction and catchment prioritization for GI retrofit experimentation.

ULSC has a total of 40.1% impervious area comprised of 21.4% commercial, 7.4% single-family and 11.3% other (roadway EOP and sidewalk). By contrast, Six Mile Creek has a total of 22.2% impervious area with 6.4% commercial, 9.1% single-family and 6.8% roadway EOP and sidewalk. The geographic extent of the different types of impervious areas within the two watersheds is shown in Figures 4.3 and 4.4. Detailed characteristics of the impervious area within the two watersheds are tabulated in Table 4.13. These impervious area percentages are dissimilar when viewed as proportion of the total watershed area, but the differences and similarities in impervious area characteristics relative to total watershed impervious area are more salient. Commercial impervious area accounts for just over 50% of all impervious area in ULSC while it accounts for just about 30% in Six Mile Creek. Single –family impervious area accounts for just less than 20% for ULSC and approximately 40% of all impervious area within Six Mile Creek. Interestingly, in both watersheds, road EOP and sidewalk impervious area accounts for about 30% of all impervious area. This holds true for all stormwater watersheds within the CMSWS service area.

Table 4.13 also includes a tabulation of impervious area based on property ownership providing distinction between public and private owned impervious area as well as parcel subtheme quantities (e.g., building, paved, driveway, etc.). The most notable figures in this table are those that tabulate total public and total private impervious area percentages. In both case study watersheds, public owned impervious area accounts for approximately 35% of total impervious area while private owned account for 65%. The public impervious area is dominated by road surfaces and sidewalks in both watersheds with much smaller proportions on public owned commercial development. Figures 4.5 and Figure 4.6 provide graphic representation of each watershed's impervious area property ownership distribution.

4.4.1.2 Watershed Scale DCIA Reduction Potential

a) Extent of DCIA Reduction Possible

As indicated in Section 4.3.2.1, the Mecklenburg County impervious area GIS data (Mecklenburg County 2016) are representative of DCIA for the ULSC and Six Mile Creek watersheds. The GIS analysis procedures and tools summarized in Table 4.2 are used with the specified GIS data to estimate extent of potential DCIA reduction in the two selected case study watersheds.

Watershed level results for DCIA reduction according to property ownership type are presented for maximum and moderate scenarios of DCIA reduction potential in ULSC and Six Mile Creek watersheds in Table 4.14 and Table 4.15, respectively. Total watershed DCIA in the ULSC watershed can be reduced from 40.1% to 22.1% in the maximum GI retrofit coverage scenario and to 31.4% in the moderate coverage scenario. This corresponds to reductions of 44.9% and 21.6% of existing DCIA. In Six Mile Creek, total watershed DCIA can be reduced from 22.2% to either 15.7% in the maximum coverage scenario or 19.0% in the moderate coverage scenario with corresponding reductions of 29.2% and 14.1% of existing DCIA, respectively. These results are shown in terms of potential improvement to stream quality in Figure 4.7. The potential stream quality corresponding to each of the remaining watershed DCIA percentages of 22.1% or 31.4% in ULSC and 15.7% or 19.0% in Six Mile Creek is shown as a range within the limits of the ICM because it is not possible to predict the actual level of stream quality resulting from these levels of DCIA removal.

Potential DCIA reduction is less than the quantity of DCIA treated. The amount of DCIA treated in the moderate coverage scenarios in this research of 34.5% in ULSC and 25.9% in Six Mile Creek are within the range of impervious area treatment targets for existing regulatory based retrofit programs. As a result of the 2010 Chesapeake Bay TMDL (USEPA 2014a) the State of Maryland requires restoration of a total of 20% of impervious area within all Phase I MS4 permit areas (MDE 2011). In Philadelphia, the goal is to retrofit 33% of the impervious area within the combined sewer area over 25 years (Valderrama et al. 2013) and in New York City, the goal is to control 10% of impervious area over 20 years (ELI 2015).

DCIA reduction to treatment ratios are 62.6% (=21.6%/34.5%) for USLC and 55.6% (14.4%/25.9%) for Six Mile Creek. This ratio is essentially a weighted average of the volume reduction multiplier applied over the watershed and is a function of the types of GI measures that can reasonably be placed according to land use and physical characteristics (soil, slope and depth to groundwater).

b) DCIA Reduction by Property Type

Due to the obstacles in retrofitting private property existing urban areas, many municipalities are focusing GI retrofit efforts on public owned property. An examination of DCIA reduction by property type is conducted to understand which property type provides the greatest potential contribution to DCIA reduction and to determine of public property can provide a sufficient amount relative to potential water quality improvement targets.

The relationship between proportion of total watershed DCIA and contribution to DCIA reduction for different property ownership categories in the moderate coverage scenario for the case study watersheds is illustrated in Figure 4.8 and Figure 4.9. The results presented in Figure 4.8 for ULSC indicate that private owned general commercial property (commercial, office, warehouse) contributes the greatest amount to total DCIA but does not provide a proportionally commensurate amount to total DCIA reduction. Commercial properties in the institutional and multi-family residential categories as well as single-family residential property contribute more to total DCIA reduction relative to their proportion of DCIA within the watershed.

In the Six Mile Creek watershed, the greatest proportion of DCIA is attributed to single-family residential property which does not contribute a commensurate proportion of DCIA reduction; while government and multi-family commercial property and to a lesser extent general commercial properties (commercial, office and warehouse) contribute a greater proportion to DCIA reduction than their proportion of total DCIA. These results are shown in Figure 4.9. In both watersheds, multi-family residential property is the greatest contributor to DCIA reduction relative to its proportion in the watershed as indicated in the figures and may point to a focus on multi-family residential property owners for GI retrofit opportunities.

Public owned roadway EOP/sidewalks provide the greatest amount of DCIA reduction of any individual property type in both total reduction (about 30% of total DCIA in both watersheds) and in relative contribution, where the percent of total DCIA reduced is slightly greater than or equal to the contribution to total DCIA. However, if DCIA reduction from all types of private owned commercial property provide the greatest amount of reduction at just over 44% of the total in ULSC and just over 34% in Six Mile Creek.

Figure 4.10 and Figure 4.10 show the proportion of public and private property reduced DCIA in the case study watersheds for the moderate coverage scenario. Public property is divided between commercial and roadway/sidewalk and private property is divided between commercial and single-family residential. In ULSC, private commercial property provides the greatest amount of DCIA reduction at 44.4% which is greater than the DCIA reduction potential of all public property where public commercial provides 5.2% and roadway/sidewalk 29.1%. Although DCIA reduction potential of private commercial property in Six Mile Creek also provides the greatest amount at 34.2%, total public property provides more with roadway/sidewalk contributing 31.4% and commercial 7.0%.

4.4.2 Prioritization of Catchments for GI Retrofit Experimentation

The strategy to prioritize catchments for GI retrofit experimentation is based on the methodology developed for evaluation of watershed scale DCIA reduction and a multi-decision criteria analysis (MCDA) as described in the methodology. The various components of this strategy and the results at each stage are presented.

4.4.2.1 Catchment Area Options

A total of 21 catchment areas ranging in size from 118 to 868 acres are delineated for the ULSC watershed. Similarly, the Six Mile Creek watershed has 16 defined catchments with areas between 106 and 787 acres in size. The average catchment size is 378 acres in ULSC and 346 acres in Six Mile Creek. Catchment sub-basin and total areas for ULSC and Six Mile Creek are identified in Table 4.16 and Table 4.17, respectively. These catchments are the decision options in the MCDA process. The total area within the defined catchments do not add up to the total watershed areas because there are sub-basins within each watershed that are not included in any catchment, such as adjacent to the main stream and in sub-basins that span the main stream. Catchment area maps are provided in Figure 4.12 and Figure 4.13 for ULSC and Six Mile Creek watersheds, respectively.

4.4.2.2 Non-Redundant Evaluation Criteria

Catchment scale evaluation data or performance values (PV) are collected for primary criteria (impervious area data obtained directly from the GIS database) using the catchment boundary layers developed for the ULSC and Six Mile Creek watersheds and the procedures and data layers developed for watershed scale evaluation. DCIA reduction potential within each catchment is also calculated in the same manner as for the watershed scale evaluations. Additional primary catchment criteria PV data are also developed for park property, vacant area, and pond and wetland area, vacant area, number of parcels and number of existing BMPs. Some of these data layers required adjustments to account for spatial overlaps as discussed in Section 4.3.3.2.b. Evaluation data for secondary criteria are derived from primary data (e.g. density data).

MS-Excel (Microsoft 2010) is used to calculate the Pearson product moment coefficient, r, between the 30 sets of catchment scale PVs for each of the three scenarios, ULSC, Six Mile Creek and combined ULSC and Six Mile Creek. Of the 30 defined criteria, 5 non-redundant criteria are selected for evaluation for the 21 catchments within the ULSC data set; 6 are selected for the 16 catchments of Six Mile Creek data set; and 5 criteria are selected for the 37 catchments in the combined ULSC and Six Mile Creek data set. These results are summarized in Table 4.18 where correlation of redundant data sets for each case is presented and the non-redundant criteria are identified. The non-redundant criteria include Total DCIA, Potential Government/Public Property DCIA reduction, Total Potential DCIA Reduction as Percent of Total DCIA, and Vacant Area Density for all three data sets; Park + Pond and Wetland Area is also included for ULSC; Six Mile Creek and the Combined case both also include DCIA Density; and Pond and Wetland is also included in the Six Mile Creek case.

In general, correlation between most criteria pairs for both watersheds are similar in magnitude with expected minor differences and a few notable exceptions. For example, 'Total DCIA' is better correlated to 'Commercial DCIA' in ULSC than in Six Mile Creek ($r = 0.91$ vs. 0.82) and is better correlated to 'Single-Family Residential DCIA' in Six Mile Creek than in ULSC ($r = 0.77$ vs. 0.65). 'DCIA Density' correlates negatively with 'Total Potential DCIA Reduction as % of Total DCIA' for ULSC but does not correlate for Six Mile Creek or the combined case. The most variable correlations from watershed to watershed are for 'Park Area' and 'Pond and Wetland Area'. Pearson 'r' values range from 0.76 and 0.55 for 'Park Area' and 'Government Area DCIA Reduction' for Six Mile Creek and combined ULSC and Six Mile Creek, respectively, to no correlation between these criteria in ULSC. The correlation for the combined set is clearly lowered from that of Six Mile Creek alone due to the non-existence of a relationship between park area and government area in the ULSC watershed. There is a moderate negative correlation between 'Pond and Wetland Area' and 'DCIA Density' in the Combined ULSC and Six Mile data set but no correlation between Pond and Wetland Area and any other criterion in the either the ULSC or Six Mile Creek data sets. Other than these minor differences in criteria correlation, overall the relationships between criteria pairs based mainly on impervious area are similar between the two watersheds while relationships involving open areas such as park, pond and wetlands are specific to each watershed and highly dependent on watershed development characteristics. These characteristics have a significant impact on criteria independence when the data from sets from these two watersheds with very different development characteristics are combined.

Catchment area maps are created with overlays to allow visualization of the spatial extent of the various criteria selected for the prioritization process. Figure 4.14 and Figure 4.15 show the catchment area options and the extent of DCIA property ownership; Figure 4.16 and Figure 4.17 show catchment area and extent of the various HSGs; and, Figure 4.18 and Figure 4.19 show catchment area and extent of additional non-redundant criteria (park; ponds and wetlands; and vacant area).

4.4.2.3 Transformation Utility Functions for Non-Redundant Evaluation Criteria

The PV for non-redundant criteria under consideration for each case, ULSC, Six Mile Creek and the combined ULSC and Six Mile Creek are standardized into commensurate units using the utility transformation functions described in Section 4.3.3.3 of this document. One of two linear utility scoring functions is used to transform the PVs performance values (PV) based on their distance from the minimum or maximum value of each criterion set by assigning a score between 1 and 0 to indicate best to worst. The majority of transformation functions are based on distance to the maximum PV (Eq. 4.1) where a score of 1.0 is assigned to the maximum PV. The only criteria that are based on the distance to the minimum PV (Eq. 4.2) where the minimum PV is assigned a score of 1.0 are ‘Total DCIA’ and ‘Vacant Area Density’. The objective is to minimize the PV for these two criteria. The objectives for all criteria considered are indicated in Table 4.12.

PV data sets are evaluated for extreme data outliers that could have a significant impact on the transformed criteria scores. A high outlier value for ‘Vacant Area Density’ of 60.9% in the SixMile-9 catchment of Six Mile Creek watershed is eliminated from the transformation utility functions for both the Six Mile Creek and combined ULSC and Six Mile Creek analyses. Final PV transformation functions for ULSC, Six Mile Creek and combined ULSC and Six Mile Creek, are shown in Figure 4.20, Figure 4.21 and Figure 4.22, respectively.

4.4.2.4 Criterion Priority Rank and Weights

Preference decisions regarding priority rank order of the non-redundant criteria are made. The priority rank of a criterion is important because it impacts the weight assigned to each when utilizing the rank sum (Eq. 4.4), rank reciprocal (Eq. 4.5) or the rank Centroid (Eq. 4.6) weight functions. Priority preferences are inherent when using the equal weight (Eq. 4.3) or assigned weight functions.

Maximizing the ratio of the amount of DCIA that can be reduced to total DCIA in a catchment (‘Potential DCIA Reduction as % of Total DCIA’) is believed to be the most important criterion in GI retrofit experimentation in order to maximize the potential to observe significant improvements to water quality in a reasonable time frame. It is not known yet what the critical density of GI retrofits is that will produce measurable improvements to stream water quality and most likely this threshold will be different for each watershed but it is reasonable to assume that denser retrofits will provide a greater likelihood of measureable results. The second most important criterion is to minimize the total amount of DCIA to be reduced in order to minimize the total cost of the program. Next, it is very important that major changes in the development characteristics of the catchment be kept at a minimum as indicated by Walsh et al. (2015) in the Little Stringybark Creek experimentation study currently underway in Australia. Ideally, as indicated in application of the assigned weight function for the Six Mile Creek and combined watershed cases, all three of these criteria are considered to be equally important and therefore are assigned equal weight. The remaining criteria are ordered in the following priority order: 'Potential GovtPublic DCIA Reduction'; 'DCIA Density' and then 'Pond and Wetland' or 'Park + Pond and Wetland'. Criterion weights for n= 5 and n=6, the number of non-redundant criteria in the three watershed test cases, are given in Table 4.19. The weight functions are shown graphically in Figure 4.23 and Figure 4.24 for n=5 and n=6, respectively.

4.4.2.5 Priority Catchments for Experimentation Study

The catchments with the highest six catchment scores (CS) calculated using the weighted summation value function (Eq. 4.7) with the transformed performance values (TPV) and each of the five weight functions are identified for each case study set of catchments, ULSC, Six Mile Creek and combined ULSC and Six Mile Creek along with the resultant CSs in Figure 4.25, Figure 4.27 and Figure 4.29. Figure 4.25 shows that the top catchment options to be considered for GI retrofit experimentation in the ULSC watershed are ULSC-8, ULSC-9, ULSC-11 and ULSC-17. These catchments rank in the top six for all of the weighting options considered. Four catchments in the Six Mile Creek watershed also rank in the top six for all of the weighting options: Six Mile-1, Six Mile-2, Six Mile-4 and FlatBr-7 as indicated in Figure 4.27. When the MCDA process is applied to the set of combined ULSC and Six Mile Creek catchments, the catchments in the ULSC watershed dominate the results with four ULSC catchments ranking in the top six for all weighting options: ULSC-9, ULSC-10, ULSC-11, and ULSC-17. Only two Six Mile Creek catchment ranks in the top six any of the weighting methods, Six Mile-2 and FlatBr-7. Catchments in ULSC clearly dominate the results of the decision process as indicated in Figure 4.29.

An additional analysis is done by summing the CSs for all catchments across all five weighted value functions for the three cases and the results are shown in Figure 4.26, Figure 4.28 and Figure 4.30. These graphs show the cumulative CS weight for all catchments considered either within the context of a single watershed or the two watersheds combined. Recall, the ULSC watershed is dominated by commercial development and the Six Mile Creek watershed is dominated by single-family development. Comparing average PVs of the criteria used for evaluation of the combined watershed catchments shows that the ULSC values outperform the Six Mile Creek values for all criteria except that of 'Total DCIA'. In that case, the average 'Total DCIA' of Six Mile Creek catchments is lower than that of ULSC which is the desired objective for that criterion. Table 4.20 summarizes the comparison of average criteria values. Figure 4.30 illustrates the cumulative sum of all weighted CS values of the two watersheds in the combined analysis and it is clear how the ULSC catchments dominate the results.

Table 4.21 provides a summary of PVs for the non-redundant criteria of the top six ranked catchments in all three cases. The final decision regarding catchment selection for an experimentation study will involve collecting additional data and information regarding the top catchments in both watersheds including: field investigations to locate actual potential retrofit sites; locating existing GI facilities and existing monitoring sites; collecting information on individual property owners' willingness to participate in a retrofit project; obtaining stakeholder input and identifying additional stakeholder issues and preferences; and, identifying suitable monitoring locations. These further data collection efforts will allow discussion of tradeoffs in criteria PVs, using the results to look more in depth at the top ranked catchments in both watersheds.

4.5 Conclusions

It is posited that if an extensive amount of DCIA reduction is needed in an existing urbanized watershed in order to meet water quality goals, then GI retrofits on a substantial number of privately owned properties will be needed in addition to retrofits on public properties. The quantification of the extent of potential DCIA reduction by property type within the two case study watersheds in Mecklenburg County, North Carolina, provides answers to the research questions asked relative to GI retrofits and water quality improvements.

The results of maximum and moderate potential DCIA reduction scenarios for the case study watersheds answer the question "What extent of GI retrofits is needed and potentially achievable to reduce DCIA to levels that might meet stream health goals?" In USLC, maximum DCIA reduction is estimated at approximately 45% of existing DCIA or a more realistic moderate value of about 22% of existing DCIA. The remaining watershed DCIA percentages are 22.1% or 31.4%. In Six Mile Creek a potential maximum reduction of 29% of existing DCIA or a more realistic moderate reduction of about 14% bring the remaining DCIA percentage to 15.7% or 19.0%. The percentages of DCIA remaining in each watershed under either coverage scenario do not appear to be particularly promising relative to a stream health threshold of 10% TIA. However, in an adaptive management approach, actual measured improvements to water quality as a result of DCIA reduction will have greater meaning than magnitude of DCIA reduction or remaining DCIA percentage.

The results indicate that GI retrofits are needed on all property types, public or private, to significantly impact aggregate DCIA reduction in either maximum or moderate coverage scenarios within the case study watersheds. Private commercial properties play a significant role in this regard providing almost 45% of the total DCIA reduction capability in ULSC and 35% in Six Mile Creek. GI retrofits on private single-family properties can also substantially contribute to DCIA reduction in both watersheds providing just over 21% of the total in ULSC and 27% in Six Mile Creek.

Public property alone has the potential to provide approximately 35% of total DCIA reduction in both watersheds which if accomplished could make a substantial contribution to improvements in stream health; however, the majority of public DCIA reduction is from roadways and sidewalks with a small portion from public owned commercial type development. There is strong support for focusing GI retrofits on roadways not only because they are public owned, but also because they contribute a large portion of the stormwater pollutant load in urban areas. However, retrofitting roadways with GI is typically more costly than on other types of properties because of construction logistics related to traffic and underground utilities (Valderrama et al. 2015). Valderrama et al. (2015) indicate that public money may be best spent subsidizing lower cost retrofits on private property. GI retrofits on roadways can be more efficiently accomplished as part of scheduled road construction projects and should be a long term management strategy within a watershed and incorporated into land development and redevelopment policies.

The results of this research answer the questions regarding the hypothetical potential of restoration within the case study watersheds based on removal of effective impervious area and support the suggestion that a significant amount of retrofit is needed on private commercial properties in addition to public property to potentially achieve stream health goals. Targeting the most cost effective retrofits with the greatest capacity for DCIA reduction will be a key strategy in any retrofit program.

Values for several key independent criteria are determined for catchments within the two case study watersheds and are prioritized within a MCDA framework in order to answer the questions related to catchment prioritization. The question "What criteria are important in identifying the most suitable catchments for GI retrofit experimentation that will provide a manageable number and extent of GI retrofits such that measureable improvements in water quality can potentially be attained in a reasonable time frame?" is answered in part by study design. Several criteria are identified as important and purposely selected for evaluation with DCIA reduction as the key criterion. The selection of additional significant criteria is informed from the literature review such as government owned property and connectivity of GI with existing green space (parks, ponds, wetlands) and criteria suggested by lessons learned in existing experimentation studies regarding amount of DCIA to be treated, density of retrofit and effects of new development on performance results. This question is further answered by the evaluation of relationships between criteria pairs for catchments within each case study watershed and the combined case. This check of criteria independence also answers the question regarding whether important criteria are different for watersheds with different development characteristics.

In general, correlation between most criteria pairs based on impervious area for both watersheds are similar in magnitude with expected minor differences and a few notable exceptions while relationships involving open areas such as park, pond and wetlands are specific to each watershed and highly dependent on watershed development characteristics. These characteristics have a significant impact on criteria independence when the data sets from these two watersheds with very different development characteristics are combined. In addition, criteria independence is affected as the number of criteria pairs increases because the critical Pearson r for level of significance decreases. The result of these differences is four criteria (Total DCIA, Potential Government DCIA Reduction, Total Potential DCIA Reduction as % of Total DCIA and Vacant Area Density) are important for priority analysis in all three cases ULSC, Six Mile Creek and combined ULSC and Six Mile Creek; Park + Pond Wetland is important in ULSC; DCIA Density is important in both Six Mile Creek and the combined case; and Pond/Wetland is important in Six Mile Creek.

The results of this research call in to question the benefit of combining data from two watersheds with very different development characteristics simply to increase the sample size when searching for a catchment for potential experimentation because the criteria values from the more densely developed watershed dominate the priority MCDA results. This is a result of the specific criteria selected for this MCDA process. Comparing average PVs of the criteria used for priority analysis of the combined watershed catchments shows that the ULSC catchment values outperform the Six Mile

Creek values for all criteria except that of ‘Total DCIA’. In that case, the average ‘Total DCIA’ of Six Mile Creek catchments is lower than that of ULSC which is the desired objective for that criterion. The higher density impervious area catchments dominated the results.

This does not necessarily mean that selecting a catchment in Six Mile Creek is a poor choice for GI retrofit experimentation, but it appears that from the watershed scale perspective, a watershed that is dominated by single-family residential development may not provide the optimal DCIA density or potential DCIA reduction in comparison to catchments from a more densely developed watershed. Catchment selection by targeted MCDA for individual watersheds may be more appropriate in this regard.

A significant conclusion in the Shepherd Creek GI retrofit experimentation study (Roy et al. 2014) is that the extent of retrofits in the watershed did not result in significant improvements to the biotic health of the stream. The authors conclude that a significant amount of additional impervious area within the watershed, especially from parking lots and roadways, would need to be treated in order to achieve that result. This supports the conclusions of this study that indicate GI retrofits are needed on all property types within a watershed to achieve the extent of DCIA reduction required to see improvements to stream health.

Roy et al. (2014) also conclude that further research is needed to determine the “minimum effect threshold and restoration trajectories for retrofitting catchments” needed to see improvements in stream health. Selection of a catchment using the prioritization process developed by this research could be a first step in achieving that goal. Few catchments in the two case study watersheds approach the 10% ICM impervious area threshold as a result of DCIA reduction, but the criteria used in the prioritization process focus the decision outcome on the greatest proportion of potential DCIA reduction relative to the existing condition, so that quantifiable stream improvements could be expected. The goal is not to reach 10% DCIA but to retrofit enough DCIA to produce measurable results.

The results provide a framework to identify the best or few best catchment options within a priority watershed of interest to consider for further evaluation for experimentation study. Preferences by actual decision makers and other stakeholders, systematic variation of the priority ranks of the selected evaluation criteria, inclusion of performance values for additional decision options (catchments) will affect the prioritization results. The MCDA approach can provide decision makers with information regarding the tradeoffs between different decision options. The final decision will involve judgement calls as there are tradeoffs to be made even when a few best options are identified; every criterion value is typically not optimal in any option scenario. Field evaluation of the top catchment options and stakeholder involvement will be required to finalize the selection.

Public owned DCIA is a good place to start retrofits whether as part of a general retrofit program or an experimentation program if in a choice catchment. However, DCIA reduction via GI retrofits on all property types is needed in order to achieve measurable results.

Table 4.1: Summary of GIS Data Used in GI Retrofit Analyses

Source [a]	Category	Layer
Mecklenburg County	Cadastral	Tax Parcel Boundaries
Mecklenburg County	Cadastral	Tax Parcel with CAMA Data
Mecklenburg County	Environmental	Creeks and Streams
Mecklenburg County	Environmental	Lakes and Ponds
Mecklenburg County	Environmental	Soils
Mecklenburg County	Environmental	Stormwater Watersheds
Mecklenburg County	Environmental	Water Quality Buffers
Mecklenburg County	Environmental	Wetlands
Mecklenburg County	Flood Mitigation	Engineering Models (watershed sub-basin drainage boundaries)
Mecklenburg County	Impervious	Commercial
Mecklenburg County	Impervious	Other (roadway EOP, sidewalks)
Mecklenburg County	Impervious	Residential (single-family)
Mecklenburg County	Parks and Recreation	Greenways
Mecklenburg County	Parks and Recreation	Park Property
Mecklenburg County	Political	Mecklenburg County Boundary
City of Charlotte	Stormwater Inventory	Pipes
City of Charlotte	Stormwater Inventory	Open Drainage
City of Charlotte	n/a	BMP Database
City of Charlotte	n/a	Existing Land Use
City of Charlotte	n/a	Ponds

Notes: BMP = Best management practice; CAMA = Computer aided mass appraisal; EOP = Edge of pavement; n/a = Not applicable.

[a] Sources: Mecklenburg County (2016), City of Charlotte (2016).

Table 4.2: Summary of GIS Analyses for Water Quality Perspectives: Data, ArcGIS Tools, and Procedures

Analysis	Objective	GIS Data/ Layer	ArcGIS Data Analysis Tool/ Procedure	Analysis Review/ Comments
County Scale				
Characterize impervious area (IA) in Charlotte-Mecklenburg Stormwater Watersheds	Selection of case study watersheds	• Stormwater watershed (SWW) • Commercial impervious (ComImp) • Residential impervious (single-family)(SFResImp) • Other impervious (road EOP/sidewalk) (OthImp)	• Use Identity tool to join SWW layer to IA layers • Attribute selection of joined layers to tabulate amount of IA within each SWW	• Match sums of 'shape_area' with 'imp_area' in ComImp and SFResImp • Match sums of 'shape-area' and 'st_area_sh' in OtherImp
Watershed Scale				
Determine IA % of existing land use types in case study watersheds	Determine whether GIS IA data layers represent TIA or DCIA	• ULSC SWW • SMC SWW • Existing land use (LU) • ComImp • SFResImp • OthImp	• Use Intersect tool to join ULSC and SMC SWWs with LU, ComImp, SFResImp, OthImp layers • Sum IA quantities within each LU category	• 'Shape_area' preserved in composite layers created with LU, ComImp and SFResImp but not OthImp • OthImp not fully accounted for in LU layer • Major road EOP outside LU polygons
Physical Suitability: Identify watershed physical characteristics: hydrologic soil group (HSG), slope, depth to groundwater (GW)	Create composite layers of IA type and physical characteristics	• ULSC SWW • SMC SWW • Environment – Soils • ComImp • SFResImp • OthImp	• Use Interest tool to join ULSC, SMC SWWs with Soils and ComImp, SFResImp, OthImp layers • Create attribute selection expressions based on HSG, slope and depth to GW	• IA preserved in composite layer intersect

Table 4.2 (continued)

Parcel Suitability: Identify property type and ownership characteristics	Create composite layers for matching GI with parcel type, ownership type, and composite layers of IA type and physical characteristics	• ULSC SWW • SMC SWW • ParcelNoData • ParcelTaxData • SoilComImp • SoilSFResImp • SoilOthImp	• Use Spatial Join tool to overlay ParcelNoData and ParcelTaxData • Use Intersect tool to join parcel layer to SoilComImp and SoiSFResImp • Use attribute selection expressions for physical characteristics (see Table 4.8), property type (see Table 4.9 for commercial) to create GI layers for DCIA reduction calculations (see Tables 4.10, 4.11)	• ParcelTaxData layer contains several tax data entries for each parcel • Joined ParcelNoData/Tax Data layer preserves total parcel area of ParcelNoData • SoilOthImp is not parcel based
Catchment Scale *(all analyses performed for both ULSC and Six Mile Creek watersheds)*				
Catchment option identification and delineation	Create boundary layer for catchment options to use in MCDA	• ULSC SWW • SMC SWW • Flood Mitigation Engineering Models (hydrology watershed sub-basin drainage boundaries)	• Use interactive selection tool to select sub-basins for catchments • Add attribute field with catchment name to each catchment layer • Dissolve sub-basin boundaries within each catchment layer • Merge catchment layers to form a single catchment boundary layer	

Table 4.2 (continued)

Catchment performance value (PV) development	Develop PV data for catchments to use in MCDA	• Catchment boundary layer (Catch_FirstOrder) • Data layers created in watershed scale analyses (see above and Tables 4.10, 4.11)	• Use Intersect tool to join Catch_FirstOrder layer with other composite and individual layers • Use attribute selection to obtain PV data values for each Catchment	
PV data adjustment	Adjust data for GIS layers with spatial overlap	• Wetlands • Lakes_ponds • Park_property • ParcelTaxData (Vacant area)	• Use Union tool to join sets of layers to • Identify overlap area and remove from one of the layers	• Park and vacant parcel overlap: ULSC = 12.8%; SMC = 11.5%

Notes: DCIA = Directly connected impervious area; EOP = Edge of pavement; GI = Green infrastructure; GIS = Geographic information system; GW = Groundwater; HSG = Hydrologic soil group; IA = Impervious area; MCDA = Multi-criteria decision analysis; PV = Performance value; SMC = Six Mile Creek; SWW = Stormwater watershed; TIA = Total impervious area; ULSC = Upper Little Sugar Creek

Table 4.3: Mecklenburg County Surface Water Quality Indices and Program Ranking

Stream or Lake [a]	Surface Water Quality Indices			Water Quality Program Ranking [d]		
	SUSI/ LUSI Rating [a]	303(d) List [b]	Approved TMDL [c]	Existing	Mgmt.	Overall
Upper Little Sugar	Impaired	Copper	DO, FC, Turbidity	2		4
Lower Little Sugar	Impaired	Copper	DO, FC, Turbidity	3		7
Briar	Impaired			5		8
Irwin	Partially Supporting	Copper	DO, FC, Turbidity	1 (Upper), 8 (Stewart)		6 (Upper)
McMullen	Partially Supporting	Poor Benthos				
Sugar	Impaired	Benthos, Copper	FC, Turbidity	9		
Clem						
McAlpine (Upper)	Partially Supporting	Fair Benthos and Fish Community	DO, FC, Turbidity	6		9
McAlpine (Lower)	Partially Supporting	Fair Benthos and Fish Community	DO, FC, Turbidity	7		10
Steele	Partially Supporting		FC		9	
Twelve Mile		Fair Fish Community				
Six Mile	Partially Supporting	Poor Fish Community			8	
Mallard	Partially Supporting	Copper				
Four Mile	Partially Supporting			10		
Lower Clarke		Poor Fish Community				
Back	Partially Supporting	Fair Benthos				
Long	Partially Supporting	Copper	Turbidity			
McDowell	Partially Supporting		TMDL Alternative – Watershed Management Plan [e]		3	1
Paw	Partially Supporting					

Table 4.3 (continued)

Crooked		Poor and Fair Benthos, Fair Fish Community			10	
Mtn. Island Lake	Prt to High Support	PCB Fish Cons Advisory				
McKee	Partially Supporting	Fair Benthos	FC			
Reedy	Partially Supporting	Fair Benthos				
Lake Norman	Highly Supporting	PCB Fish Cons Advisory				
Catawba		Fair Benthos and Fish Community				
Lake Wylie	Prt to High Support	PCB Fish Cons Advisory	Chlorophyll-a			
Goose	Partially Supporting				1	2
Rocky Creek						
Beaverdam		DO				
Clarke		Poor Fish Community			7	
Clear	Partially Supporting	Turbidity				
Caldwell		Fair Benthos				
Gar	Partially Supporting				4	
West Rocky River	Partially Supporting				6	
Clarks Creek	Partially Supporting					
Coffey	Partially Supporting					
Torrence –McDowell [f]					2	3
Irvins – McAlpine [f]				4	5	5

Notes: Cons = Consumption; DO = Dissolved oxygen; FC = Fecal coliform; LUSI = Lake Use Support Index; Prt to High Support = Partially to Highly Supporting; PCB = Polychlorinated biphenyl; SUSI = Stream Use Support Index; TMDL = Total Daily Maximum Load

[a] Source: CMSWS (2016b)
[b] Source: NCDEQ (2016)
[c] Source: CMSWS (2015a)
[d] Source: CMSWS (2015c)
[e] Source: CMSWS (2008a)
[f] Torrence and Irvins Creeks are identified specifically in CMSWS (2015c) but not in CMSWS (2016b)

Table 4.4: Total Impervious Area in Mecklenburg County Stormwater Watersheds

Watershed	Watershed Area [a]	Commercial Impervious Area [b]		Single-family Impervious Area [c]		Other Impervious Area [d]		Total Impervious Area	
	(ft^2)	(ft^2)	%	(ft^2)	%	(ft^2)	%	(ft^2)	%
Upper Little Sugar	538,174,904	115,317,619	21.4%	39,573,572	7.4%	61,058,644	11.4%	215,949,835	40.1%
Lower Little Sugar	278,983,176	51,405,705	18.4%	20,160,047	7.2%	20,690,512	7.4%	92,256,264	33.1%
Briar	602,220,538	81,188,902	13.5%	59,981,085	10.0%	52,801,430	8.8%	193,971,417	32.2%
Irwin	835,810,692	133,454,675	16.0%	38,607,244	4.6%	79,742,865	9.5%	251,804,784	30.1%
McMullen	424,012,338	49,397,338	11.7%	45,112,180	10.6%	31,878,066	7.5%	126,387,584	29.8%
Sugar	1,042,469,510	211,379,492	20.3%	17,653,048	1.7%	60,007,379	5.8%	289,039,919	27.7%
Clem	75,749,502	7,510,465	9.9%	7,253,040	9.6%	5,834,233	7.7%	20,597,738	27.2%
McAlpine	1,650,072,452	164,227,489	10.0%	140,380,182	8.5%	107,570,186	6.5%	412,177,857	25.0%
Steele	433,215,061	61,030,690	14.1%	21,903,449	5.1%	21,688,446	5.0%	104,622,585	24.1%
Twelve Mile	23,192,116	394,142	1.7%	3,060,854	13.2%	1,903,140	8.2%	5,358,136	23.1%
Six Mile	358,410,190	22,826,264	6.4%	32,579,452	9.1%	24,261,895	6.8%	79,667,611	22.2%
Mallard	1,083,292,372	111,488,223	10.3%	53,576,054	5.0%	72,558,751	6.7%	237,623,028	21.9%
Four Mile	519,786,492	30,225,542	5.8%	46,888,129	9.0%	32,485,287	6.3%	109,598,958	21.1%
Lower Clarke	159,365,421	6,076,049	3.8%	11,968,914	7.5%	11,406,958	7.2%	29,451,921	18.5%
Back	220,318,303	10,533,749	4.8%	14,262,631	6.5%	13,404,226	6.1%	38,200,606	17.3%
Long	1,012,966,534	73,551,057	7.3%	41,859,244	4.1%	54,264,422	5.4%	169,674,723	16.8%
McDowell	905,271,870	56,891,760	6.3%	44,124,181	4.9%	48,695,468	5.4%	149,711,409	16.5%
Paw	557,434,531	38,662,390	6.9%	20,021,095	3.6%	29,530,018	5.3%	88,213,503	15.8%
Crooked	95,420,603	2,456,863	2.6%	4,929,394	5.12%	5,665,234	5.9%	13,051,491	13.7%
Lower Mtn. Island	183,809,468	4,729,435	2.6%	8,997,036	4.9%	7,940,543	4.3%	21,667,014	11.8%

Table 4.4 (continued)

McKee	164,255,589	1,997,557	1.2%	8,359,739	5.1%	8,217,457	5.0%	18,574,753	11.3%
Reedy	396,755,508	6,471,758	1.6%	19,342,873	4.9%	15,935,385	4.0%	41,750,016	10.5%
Lake Norman	598,908,378	22,211,866	3.7%	23,822,363	4,0%	15,583,417	2.6%	61,617,646	10.3%
Catawba	84,256,007	3,574,651	4.2%	1,203,388	1.4%	3,071,004	3.6%	7,849,043	9.3%
Lake Wylie	552,079,977	12,917,699	2.3%	17,809,619	3.2%	16,000,366	2.9%	46,727,684	8.5%
Goose	318,248,649	3,616,435	1.1%	11,879,837	3.7%	11,027,540	3.5%	26,523,812	8.3%
Rocky Creek	432,427,615	9,109,315	2.1%	15,215,948	3.5%	11,614,877	2.7%	35,940,140	8.3%
Beaverdam	204,082,240	5,012,587	2.5%	4,252,314	2.1%	7,223,593	3.5%	16,488,494	8.1%
Clarke	599,605,398	17,065,967	2.9%	17,233,033	2.9%	13,832,311	2.3%	48,131,311	8.0%
Clear	428,591,962	3,770,182	0.9%	12,452,114	2.9%	12,354,114	2.9%	28,576,410	6.7%
Caldwell	59,162,070	781,639	1.3%	753,414	1.3%	1,211,198	2.1%	2,746,251	4.6%
Upper Mtn. Island	149,605,484	773,881	0.5%	2,491,939	1.7%	1,567,805	1.1%	4,833,625	3.2%
Gar	230,047,841	897,508	0.4%	3,545,348	1.5%	2,743,028	1.2%	7,185,884	3.1%
Total (ft^2)	15,218,002,790	1,320,948,894	8.7%	811,252,760	5.3%	863,769,798	5.7%	2,995,971,452	19.7%
Total (ac)	349,357	30,325	8.7%	18,624	5.3%	19,829	5.7%	68,778	19.7%
Total (mi^2)	546	47	8.7%	29	5.3%	31	5.7%	107	19.7%

Notes: ac = Acres; ft^2 = Square feet; mi^2 = Square miles.

[a] Source: Mecklenburg County (2016); Environmental – Stormwater Watersheds (Creek Basins) Layer.
[b] Source: Mecklenburg County (2016); Impervious – Commercial Impervious Surfaces Layer.
[c] Source: Mecklenburg County (2016); Impervious – Residential Impervious Surfaces Layer.
[d] Source: Mecklenburg County (2016); Impervious – Other Impervious Surfaces Layer.

Table 4.5: ULSC – Impervious Area of Existing Land Use Cover

Existing Land Use Category [a]	Total Area [a]	Commercial Impervious Area [b]	Single-Family Impervious Area [c]	Other Impervious Area [d]	Composite % Impervious Area [e]
	(ft^2)	(ft^2)	(ft^2).	(ft^2)	(%)
Agriculture	7,358	0	0	0	0.0
Civic/Institutional	40,681,256	21,363,047	55,050	406,623	53.6
Horizontal - Residential/Non-Residential	546092	258,445	0	2,892	47.9
Horizontal Non-Residential	6,331,935	4,706,164	0	53,480	75.2
Industrial	23,036,554	9,126,522	10,152	50,452	39.9
Large Lot Residential	2,939,419	347,040	44,974	1,640	13.4
Multi-Family	40,035,354	18,210,485	67,908	289,699	46.4
Office	18,954,517	11,405,073	30,410	146,570	61.1
Open Space/Recreation	25,320,381	2,984,747	14,867	125,684	12.3
Parking	3,242,027	2,006,993	0	84,829	64.5
Retail	33,407,231	21,822,141	9,969	257,042	66.1
Single-Family - Attached	8,691,850	1,978,001	97,120	21,793	24.1
Single-Family - Detached	167,166,212	468,095	38,818,669	395,130	23.7
Transportation	15,277,632	3,642,900	0	134,501	24.7
Utility	3,005,814	242,853	927	29,447	9.1
Vacant	29,668,310	1,266,090	397,673	136,435	6.1
Vertical Mixed Use	3,300,819	2,863,180	0	101,051	89.8
Warehouse/Distribution	24,011,211	12,614,301	528	70,088	52.8
Total	445,623,972	115,306,077	39,548,247	2,307,356	35.3

Notes: ft^2 = Square feet; ULSC = Upper Little Sugar Creek.

[a] City of Charlotte (2016) – Existing Land Use Layer; [b] Impervious area within Intersect of Impervious – Commercial Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte 2016); [c] Impervious area within Intersect of Impervious – Residential Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte 2016); [d] Impervious area within Intersect of Impervious – Other Impervious Surfaces Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte 2016); [e] Total impervious area within specified Existing Land Use Category (City of Charlotte 2016), expressed in %.

Table 4.6: Six Mile Creek – Impervious Area of Existing Land Use Cover

Existing Land Use Category [a]		Total Area [a]	Commercial Impervious Area [b]	Single-Family Impervious Area [c]	Other Impervious Area [d]	Composite % Impervious Area [e]
		(ft^2)	(ft^2)	(ft^2)	(ft^2)	(%)
Agriculture		6,065,702	20,566	30,527	3,597	0.9
Civic/Institutional		19,488,934	4,388,592	13,646	97,935	23.1
Horizontal Non-Residential		520,527	299,964	0	5,895	58.8
Industrial		16,890,512	343,698	0	0	2.0
Large Lot Residential		4,923,362	159,338	198,014	1,206	7.3
Multi-Family		68,031,261	30,587,747	359	66,739	45.1
Office		2,410,482	1,478,148	0	34,125	62.7
Open Space/Recreation		67,444,578	3,195,159	27,385	184,292	5.1
Parking		12,362	7,196	0	0	58.2
Retail		7,592,829	4,992,518	0	28,555	66.1
Single-Family - Attached		348,751	97,170	715	2,114	28.7
Single-Family - Detached		131,722,252	57,533	31,865,511	406,129	24.5
Utility		632,749	5,389	104	2,466	1.3
Vacant		41,860,172	753,758	552,012	498,112	4.3
Warehouse/Distribution		236,981	77,376	0	90	32.7
Water		675,849	0	61	0	0.0
	Total	368,857,303	46,464,152	32,688,334	1,331,255	21.8

Notes: ft^2 = Square feet.

[a] City of Charlotte (2016) – Existing Land Use Layer; [b] Impervious area within Intersect of Impervious – Commercial Impervious Surfaces Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte (2016); [c] Impervious area within Intersect of Impervious – Residential Impervious Surfaces Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte 2016); [d] Impervious area within Intersect of Impervious – Other Impervious Surfaces Layer (Mecklenburg County 2016) and specified Land Use Category of Existing Land Use Layer (City of Charlotte 2016); [e] Total impervious area within specified Existing Land Use Category (City of Charlotte 2016), expressed in %.

Table 4.7: ULSC and Six Mile Creek Impervious Area % Compared to Characteristic Values of TIA and DCIA for Different Land Use Categories

Land Use Category[a]	NRCS (1986)	Booth and Jackson (1997)		CWP (2003)	USEPA (2011)[b]		Campbell et al. (2016)	ULSC[c]	SMC[d]	Corresponding City of Charlotte Existing Land Use Category (Charlotte 2016)
	% TIA	% TIA	% DCIA	% TIA	% TIA	% DCIA	% TIA	% IA	% IA	
Commercial and business	85	90	86	72.2	76	66.3[4]	73.6	66.5	65.0	Horizontal Mixed Use Res/Non-Res; Horizontal Mixed Use Non-Res; Office; Parking; Retail; Vertical Mixed Use
Industrial	72			53.4 (light)	56	41.9[d]	72	46.5	32.7[h]	Industrial; Warehouse/ Distribution
Institutional				34.4[i]	34[i]	19.8[d]	30	43.8	22.4	Civic/Institutional; Transportation; Utility
Municipals				35.4						
Schools				30.4						
Churches				39.9						
Res: MF		60	48	44.4	51	44.8[e]	70	46.4	45.1	Multi-Family
Res: TwnHm				40.9			65			
Res: 1/8 acre	65			32.6			65			Single-Family – Attached; Single-Family – Detached
Res: 1/4 acre	38	35	24	27.8	38	23.4[d]	38	23.7	24.5	
Res: 1/3 acre	30						38			
Res: 1/2 acre	25			21.2			30			
Res: 1 acre	20	20	10	14.3	19	6.0[f]	15	13.4	7.3	Large Lot Residential
Res: 2 acres	12	10	4	10.6						

Table 4.7 (continued)

Parks	12.5				12.3	5.1	Open Space/Recreation
Cemeteries	8.3						
Golf	5						
Forest		1.9	0.04 [g]				
Open Urban Land	8.6 [j]	11	3.6 [d]		6.1	4.3	Vacant
Agriculture	1.9	2	0.04 [g]	5	0.0	0.9	Agriculture

Notes: DCIA = Directly connected impervious area; IA = Impervious area; MF = Multi-family; Res = Residential; SMC = Six Mile Creek; TIA = Total impervious area; TwnHm = Townhome; ULSC = Upper Little Sugar Creek

[a] Land Use Categories and %TIA as presented in Table 2, CWP (2003), attributed to Cappiella and Brown (2001).

[b] All IA values from USEPA Rouge River Study except Institutional value from Cappiella and Brown (2001); DCIA calculated from Sutherland Equations, as noted (USEPA 2011).

[c] ULSC and SMC watershed IAs derived from intersect of City of Charlotte (2016) Existing Land Use Layer and parcel scale IA from Mecklenburg County (2016) Commercial, Residential and Other impervious area GIS layers. Weighted average IA from specified land use categories.

[d] Sutherland Equation: Average.

[e] Sutherland Equation: Highly Connected.

[f] Sutherland Equation: Somewhat Connected.

[g] Sutherland Equation: Mostly Disconnected.

[h] IA from Warehouse/Distribution land use only.

[i] CWP (2003) Institutional value is weighted average of municipal, church and school values; USEPA Institutional value is from Cappiella and Brown (2001). The weighted value is not independent and is therefore not double counted in quartile calculations.

[j] CWP (2003) Open Land value is weighted average of Parks, Cemeteries and Golf values. The weighted value is not independent and is therefore not double counted in quartile calculations.

Table 4.8: Soil, Slope, Bedrock and Groundwater Characteristics for ULSC and Six Mile Creek Watersheds

Soil	Name	HSG	Slope	Depth to Bedrock	High Water Table	Watershed
ApB	Appling Sandy Loam	B	2-8%	> 60-in.	> 6-ft.	ULSC, SMC
ApD		B	8-15%	> 60-in.	> 6-ft.	SMC
CeB2	Cecil Sandy Loam Clay, eroded	B	2-8%	> 60-in.	> 6-ft.	ULSC, SMC
CeD2		B	8-15%	> 60-in.	> 6-ft.	ULSC, SMC
CuB	Cecil Urban Complex	B	2-8%	> 60-in.	> 6-ft.	ULSC
CuD		B	8-15%	> 60-in.	> 6-ft.	ULSC
DaB	Davidson Sandy Clay Loam	B	2-8%	> 60-in.	> 6-ft.	SMC
DaD		B	8-15%	> 60-in.	> 6-ft.	SMC
DaE		B	15-25%	> 60-in.	> 6-ft.	SMC
EnB	Enon Sandy Loam	C	2-8%	> 60-in.	> 6-ft.	ULSC
EnD		C	15-25%	> 60-in.	> 6-ft.	ULSC
HeB	Helena sandy loam	C	2-8%	40-60-in.	Seasonal perch 1-2.5-ft. below surface	ULSC, SMC
HuB	Helena Urban Complex	C	2-8%	40-60-in.		ULSC
IrA	Iradell Fine Sandy Loam	D	0-1%	> 60-in.	Seasonal perch 1-2-ft. below surface	SMC
IrB		D	1-8%	> 60-in.		SMC
MeB	Mecklenburg Fine Sandy Loam	C	2-8%	48-60-in.	> 6-ft.	ULSC
MeD		C	8-15%	48-60-in.	> 6-ft.	ULSC, SMC
MkB	Mecklenburg Urban Land Complex	C	2-8%	48-60-in.	> 6-ft.	ULSC
MO	Monocan	C		> 60-in.	Seasonal perch 0.5-2-ft. below surface	ULSC, SMC
MS		C			Urban fill subject to flooding	ULSC
PaE	Pacolet Sandy Loam	B	15-25%	> 60-in.	> 6-ft.	ULSC, SMC
Ur	Urban Land					ULSC

Table 4.8 (continued)

VaB	Vance Sandy Loam	C	2-8%	> 60-in.	> 6-ft.	ULSC, SMC
VaD		C	8-15%	> 60-in.	> 6-ft.	SMC
w						ULSC, SMC
WkB	Wilkes Loam	C	4-8%	60-80-in.	> 6-ft.	ULSC
WkE		C	15-25%	40-80-in.	> 6-ft.	ULSC
WUD	Wilkes Urban Complex	C	8-15%	40-80-in.	> 6-ft.	ULSC

Notes: SMC = Six Mile Creek; ULSC = Upper Little Sugar Creek

Source: USDA (1980), Table 16, p.93.

Table 4.9: Classification of Commercial Property Types in Mecklenburg County Commercial Impervious GIS Layer

‘Descproper’ =	‘Accountyp’ =	Additional Characteristic	Commercial Property Type Classification
‘Null’	‘Exempt’		Government/Public
‘Null’	NOT ‘Exempt’		Commercial, Office, Warehouse
‘Attached Res’			Multi-Family Residential
‘Commercial’	‘Exempt’		Government/Public
‘Commercial’	NOT ‘Exempt’		Commercial, Office, Warehouse
‘Govt-Inst’	‘Exempt’	‘OwnerLastName’ used to further distinguish public ownership	Government/Public
‘Govt-Inst’	NOT ‘Exempt’		Institutional/Private
‘Hotel/Motel’			Commercial, office, warehouse
‘Multi-Family’	‘Exempt’		Government/Public
‘Multi-Family’	NOT ‘Exempt’		Multi-Family Residential
‘Office’			Commercial, office, warehouse
‘Single-Family’	‘Exempt’		Government/Public
‘Single-Family’	NOT ‘Exempt’		Multi-Family Residential
‘Warehouse’			Commercial, office, warehouse
‘WarehouseLg’			Commercial, office, warehouse

Table 4.10: ULSC – GIS Layer Development, Suitable Impervious Area Analysis for GI Retrofit and DCIA Reduction

Impervious Area Layer [a]	Subtheme [a]	HSG [b]	Slope [b]	High Water Table [b]	GI Measure [c]	Volume Reduction Multiplier [d]	Treatment Area Ratio [e]	Maximum Coverage Ratio [f]	Moderate Coverage Ratio [f]
Commercial - Government/Public	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg + Paved + Other	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	Bldg	Ur	All	> 2ft.	GR, RWH	0.40	0.75	0.90	0.20
	Paved + Other	Ur	All	> 2ft.	Bioretention	0.40	0.83	0.50	0.20
Commercial - Institutional/ Private	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg + Paved + Other	C	<8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	Bldg	Ur	All	> 2ft.	GR, RWH	0.40	0.75	0.90	0.20
	Paved + Other	Ur	All	> 2ft.	Bioretention	0.40	0.83	0.50	0.20
Commercial - Commercial, Office, Warehouse	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm pave	0.45	1.00	1.00	0.50
	Bldg + Paved +Other	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	Bldg	Ur	All	> 2ft.	GR, RWH	0.40	0.75	0.90	0.20
	Paved	Ur	All	> 2ft.	Bioretention	0.40	0.83	0.50	0.20

Table 4.10 (continued)

Commercial - Multi-Fam Residential [g]	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg + Paved +Other	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	Bldg	Ur	All	> 2ft.	GR, RWH	0.40	0.75	0.90	0.20
	Paved + Other	Ur	All	> 2ft.	Bioretention	0.40	0.83	0.50	0.20
Single-Family Residential [h]	Bldg	B	> 8%	> 2ft.	Raingarden	0.80	1.00	1.00	0.50
	Bldg	B	< 8%	> 2ft.	Disconnect IA	0.50	1.00	1.00	0.50
	Bldg	C	> 8%	> 2ft.	Raingarden	0.40	1.00	1.00	0.50
	Bldg	C	< 8%	> 2ft.	Disconnect IA	0.20	1.00	1.00	0.50
	Driveway	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Disconnect IA	0.50	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Disconnect IA	0.20	1.00	1.00	0.50
	Bldg + Driveway + Other	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.02	0.01
Other – Roadway EOP/Sidewalk	City EOP	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	City EOP	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	City EOP	Ur	All	> 2ft.	Tree pits/ trees	0.15	0.83	0.40	0.30
	City EOP	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	State EOP	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	State EOP	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	State EOP	Ur	All	> 2ft.	Tree pits/ trees	0.15	0.83	0.40	0.30
	State EOP	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00

Table 4.10 (continued)

	Unmaint EOP	B, C	All	> 2ft.	Tree pits/ trees	0.15	1.00	0.35	0.25
	Unmaint EOP	Ur	All	> 2ft.	Tree pits/ trees	0.15	0.83	0.35	0.25
	Unmaint EOP	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
	Sidewalk	B,C	All	> 2ft.	Tree pits/ trees	0.15	1.00	0.35	0.25
	Sidewalk	Ur	All	> 2ft.	Tree pits/ trees	0.15	0.83	0.35	0.25
	Sidewalk	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00

Notes: EOP = Edge of Pavement; ft. = feet; GI = Green Infrastructure; GR = Green roof; HSG = Hydrologic Soil Group; IA = Impervious area; LL Res = Large lot single-family residential; Perm Pave = Permeable pavement; RWH = Rainwater harvesting; ULSC = Upper Little Sugar Creek

[a] Source: Mecklenburg County (2016); Impervious – Commercial Impervious Surfaces Layer; Impervious – Residential Impervious Surfaces Layer, and Impervious – Other Impervious Surfaces Layer

[b] Soils within the ULSC watershed are considered suitable for a particular GI measure depending on HSG and high water table. Depth to bedrock of all soils within the watershed is sufficient for all GI measures. Characteristic slopes do not preclude GI use except in the case of Grassed Channels, Permeable Pavement and Disconnect of IA which are only used on slopes < 8%. Soils with high water table < 2 ft. (occurs only in some HSG C soils in ULSC) are only suitable for Grassed Channels because they do not require underdrains.

[c] GI measures are selected based on subtheme and soil characteristics.

[d] Sources: CSN (2009) and USEPA (2014c).

[e] The Treatment Area Ratio is 1.0 for all areas except on Urban Lands where the ratio is 0.75 for green roofs and rainwater harvesting systems due to building equipment space requirements and 0.83 for bioretention where building footprint to parcel area may not provide adequate space for bioretention footprint.

[f] Maximum Coverage Ratios is assumed to be 1.0 and Moderate Coverage Ratio is assumed to be 0.50 with the following exceptions: Tree pits/tree coverage ratios are based on median and traffic island values for City and State roadway EOP and on streetscape values for Unmaintained EOP and sidewalks from Deutsch et al. 2007, Table 3. All commercial building green roof coverage assumptions are based on either rowhome or commercial building values in Deutsch et al. 2007, Table 4.

[g] Ando and Freitas (2011) indicate that fewer rain barrels are bought by renters and multi-family property owner most likely because they have less control over landscape decisions. They are used for this research for mult-family dwellings because it is assumed that roof top collections systems and green roofs would be the only GI measures feasible in high density areas.

[h] Grassed channel are appropriate for large lot single-family residential (LL Res) areas. From the Existing Land Use layer for ULSC, LL Res accounts for approximately 2% of all single-family land use area. Therefore, this value is used as the maximum coverage ratio and half of that is used for the moderate coverage scenario.

Table 4.11: Six Mile Creek – GIS Layer Development, Suitable Impervious Area Analysis for GI Retrofit and DCIA Reduction

Impervious Area Layer [a]	Subtheme [a]	HSG [b]	Slope [b]	High Water Table [b]	GI Measure [c]	Volume Reduction Multiplier [d]	Treatment Area Ratio [e]	Maximum Coverage Ratio [f]	Moderate Coverage Ratio [f]
Commercial - Govt/Public	Bldg + Paved	B	All	> 2 ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg	C, D	All	< 2ft.	GR, RWH	0.40	1.00	0.90	0.20
	Paved + Other	C, D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
Commercial - Inst/Private	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg	C, D	All	< 2ft.	GR, RWH	0.40	1.00	0.90	0.20
	Paved + Other	C, D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
Commercial - Com, Office, WH	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg	C, D	All	< 2ft.	GR, RWH	0.40	1.00	0.90	0.20
	Paved + Other	C, D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00

Table 4.11 (continued)

Commercial - Multi-Fam Res [g]	Bldg + Paved	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	Bldg + Paved	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Other	B	< 8%	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Perm Pave	0.45	1.00	1.00	0.50
	Bldg	C, D	All	< 2ft.	GR, RWH	0.40	1.00	0.30	0.06
	Paved + Other	C, D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00
Single-Family [h]	Bldg	B	> 8%	> 2ft.	Raingarden	0.80	1.00	1.00	0.50
	Bldg	B	< 8%	> 2ft.	Disconnect IA	0.50	1.00	1.00	0.50
	Bldg	C	> 8%	> 2ft.	Raingarden	0.40	1.00	1.00	0.50
	Bldg	C	< 8%	> 2ft.	Disconnect IA	0.20	1.00	1.00	0.50
	Driveway	B	< 8 %	> 2ft.	Perm Pave	0.75	1.00	1.00	0.50
	Other	B	<8%	> 2ft.	Disconnect IA	0.50	1.00	1.00	0.50
	Other	C	< 8%	> 2ft.	Disconnect IA	0.20	1.00	1.00	0.50
	Bldg + Driveway + Other	C	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.04	0.02
	Bldg + Driveway + Other	D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.04	0.02

Table 4.11 (continued)

Other - Road EOP/Sidewalk	City EOP	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	City EOP	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	State EOP	B	All	> 2ft.	Bioretention	0.80	1.00	1.00	0.50
	State EOP	C	All	> 2ft.	Bioretention	0.40	1.00	1.00	0.50
	Unmaint EOP	B, C	All	> 2ft.	Tree pits/ trees	0.15	1.00	0.35	0.25
	Sidewalk	B, C	All	> 2ft.	Tree pits/ trees	0.15	1.00	0.35	0.25
	All EOP, Sidewalk	C,D	< 8%	< 2ft.	Grassed Chan	0.10	1.00	0.00	0.00

Notes: EOP = Edge of Pavement; ft. = feet; GI = Green Infrastructure; GR = Green roof; HSG = Hydrologic Soil Group; IA = Impervious area; LL Res = Large lot single-family residential; RWH = Rainwater harvesting; SMC = Six Mile Creek

[a] Source: Mecklenburg County (2016); Impervious – Commercial Impervious Surfaces Layer; Impervious – Residential Impervious Surfaces Layer, and Impervious – Other Impervious Surfaces Layer.

[b] Soils within the SMC watershed are considered suitable for a particular GI measure depending on HSG and high water table. Depth to bedrock of all soils within the watersheds is sufficient for all GI measures. Characteristic slopes do not preclude GI use except in the case of Grassed Channels, Permeable Pavement and Disconnect of IA which are only used on slopes < 8%. Soils with high water table < 2 ft. (occurs only in some HSG C and all HSG D soils in SMC) are only suitable for Grassed Channels because they do not require underdrains.

[c] GI measures are selected based on subtheme and soil characteristics.

[d] Sources: CSN (2009) and USEPA (2014c).

[e] The Treatment Area Ratio is 1.0 for all areas.

[f] Maximum Coverage Ratios is assumed to be 1.0 and Moderate Coverage Ratio is assumed to be 0.50 with the following exceptions: Tree pits/tree coverage ratios are based on streetscape values for Unmaintained EOP and sidewalks from Deutsch et al. 2007, Table 3. All commercial building green roof coverage assumptions are based on either rowhome or commercial building values in Deutsch et al. 2007, Table 4.

[g] Ando and Freitas (2011) indicate that fewer rain barrels are bought by renters and multi-family property owner most likely because they have less control over landscape decisions. They are used for this research for mult-family dwellings because it is assumed that roof top collections systems and green roofs would be the only GI measures feasible in high density areas.

[h] Grassed channel BMP is appropriate for large lot single-family residential areas on HSG C and D soils with high water table (< 2ft from surface). From the Existing Land Use layer for Six Mile Creek, LL Res accounts for approximately 4% of all single-family land use area. Therefore, this value is used as the maximum coverage ratio and half of that is used for the moderate coverage scenario.

Table 4.12: Catchment Scale GI Retrofit Evaluation Criteria Considered

No.	Criterion Description	Objective
1	Total Catchment Area	MIN
2	Commercial DCIA Area	MIN
3	SF Res DCIA Area	MIN
4	Other (Road EOP/Sidewalk) DCIA Area	MIN
5	Total DCIA	MIN
6	DCIA Density	MAX
7	Potential GovtPub DCIA Reduction	MAX
8	Potential InstPriv DCIA Reduction	MIN
9	Potential Commercial /Office/Warehouse DCIA Reduction	MIN
10	Potential MF Res DCIA Reduction	MIN
11	Potential SF Res DCIA Reduction	MIN
12	Potential Total Residential (MF Res + SF Res) DCIA Reduction	MIN
13	Potential Road EOP/ Sidewalk DCIA Reduction	MIN
14	Park Area	MAX
15	Pond/ Wetland Area	MAX
16	Gross Treatable DCIA	MIN
17	Total Potential DCIA Reduction	MIN
18	Total Potential DCIA Reduction as % of Total Catch Area	MAX
19	Total Potential DCIA Reduction as % of Total DCIA	MAX
20	Potential Govt/Pub DCIA Reduction as % Total Potential DCIA Reduction	MAX
21	Potential Inst/Priv DCIA Reduction as % Total Potential DCIA Reduction	MAX
22	Potential Commercial/ Office/Warehouse DCIA Reduction as % Total Potential DCIA Reduction	MAX
23	Potential MF Res + SF Res DCIA Reduction as % of Total Potential DCIA Reduction	MAX
24	Potential Other (Road EOP/Sidewalk) DCIA Reduction As % of Total Potential DCIA Reduction	MAX
25	Park + Pond/Wetland Area	MAX
26	Vacant Area	MIN
27	Vacant Area Density (% of Total Catchment Area)	MIN
28	No. Parcels	MIN
29	Capital Cost of Retrofits	MIN
30	No. Existing Surface BMPs	MAX

Notes: BMPs = Best management practices; DCIA = Directly connected impervious area; EOP = Edge of pavement; MF = Multi-family; No. = Number; Res. = Residential; SF = Single-family

Table 4.13: ULSC and Six Mile Creek Watersheds – Impervious Area Property Ownership and Parcel Subtheme Quantities

	ULSC			Six Mile Creek		
	Area (ft^2)	% of Total Watershed Area	% of Watershed Impervious Area	Area (ft^2)	% of Total Watershed Area	% of Watershed Impervious Area
Watershed Summary:						
Total Watershed Area:	538,174,904	100%	-	358,410,190	100%	-
Total Impervious Area:	215,949,835	40.1%	100%	79,667,611	22.2%	100%
Commercial Impervious Area	*115,317,619*	*21.4%*	*53.4%*	*22,826,264*	*6.4%*	*28.7%*
Single-Family Impervious Area	*39,573,572*	*7.4%*	*18.3%*	*32,579,452*	*9.1%*	*40.9%*
Other Imp. Area (Road EOP, Sidewalk)	*61,058,644*	*11.3%*	*28.3%*	*24,261,895*	*6.8%*	*30.5%*
Total Pervious Area:	322,225,069	59.9%	-	278,742,579	77.8%	-
Impervious Area Property Ownership:						
Commercial – Government (PUBLIC)	14,684,502	2.7%	6.8%	3,273,008	0.9%	4.1%
Building	*6,269,853*	*1.2%*	*2.9%*	*869,677*	*0.2%*	*1.1%*
Paved	*8,068,029*	*1.5%*	*3.7%*	*2,272,963*	*0.6%*	*2.9%*
Other	*346,620*	*0.1%*	*0.2%*	*130,368*	*0.04%*	*0.2%*
Commercial – Institutional	7,852,610	1.5%	3.6%	979,438	0.3%	1.2%
Building	*3,109,464*	*0.6%*	*1.4%*	*208,840*	*0.1%*	*0.3%*
Paved	*4,722,778*	*0.9%*	*2.2%*	*740,210*	*0.2%*	*0.9%*
Other	*20,368*	*0.004%*	*0.01%*	*30,388*	*0.01%*	*0.04%*
Commercial – Commercial, Office, WH	65,064,435	12.1%	30.1%	5,584,909	1.6%	7.0%
Building	*24,277,654*	*4.5%*	*11.2%*	*1,476,443*	*0.4%*	*1.9%*
Paved	*40,543,662*	*7.5%*	*18.8%*	*4,049,437*	*1.1%*	*5.1%*
Other	*243,119*	*0.0%*	*0.1%*	*59,029*	*0.02%*	*0.1%*

Table 4.13 (continued)

Commercial - Multi-Family Residential	27,376,386	5.1%	12.7%	12,967,820	3.6%	16.3%
Building	*11,919,967*	*2.2%*	*5.5%*	*4,949,029*	*1.4%*	*6.2%*
Paved	*15,131,353*	*2.8%*	*7.0%*	*7,549,212*	*2.1%*	*9.5%*
Other	*325,066*	*0.1%*	*0.2%*	*469,579*	*0.1%*	*0.6%*
Single-Family Residential	39,573,572	7.4%	18.3%	32,579,452	9.1%	40.9%
Building	*26,655,928*	*5.0%*	*12.3%*	*21,108,898*	*5.9%*	*26.5%*
Driveway	*10,722,603*	*2.0%*	*5.0%*	*8,043,495*	*2.2%*	*10.1%*
Other (walkway, patio, pool deck, etc.)	*2,195,041*	*0.4%*	*1.0%*	*3,427,059*	*1.0%*	*4.3%*
Other Impervious:	61,058,644	11.3%	28.3%	24,261,895	6.8%	30.5%
Road EOP – City (PUBLIC)	*40,434,358*	*7.5%*	*18.7%*	*13,344,505*	*3.7%*	*16.8%*
Road EOP – State (PUBLIC)	*11,367,305*	*2.1%*	*5.3%*	*6,503,716*	*1.8%*	*8.2%*
Road EOP – Unmaintained	*445,019*	*0.1%*	*0.2%*	*1,201,488*	*0.3%*	*1.5%*
Sidewalk (PUBLIC)[a]	*8,811,962*	*1.6%*	*4.1%*	*3,212,186*	*0.9%*	*4.0%*
Total PUBLIC Impervious Area	75,298,127	14.0%	35%	26,333,415	7.3%	33%
Total PRIVATE Impervious Area	140,312,022	26.1%	65%	53,313,107	14.9%	67%

Notes: EOP = Edge of pavement; ft^2 = Square feet; WH = Warehouse

[a] Area of private owned sidewalk impervious area is < 1% of total sidewalk impervious area.

Table 4.14: ULSC – Watershed Scale Runoff Reduction Potential

			Maximum Coverage Scenario					Moderate Coverage Scenario				
Impervious Area Layer	DCIA (ft^2)	% DCIA of Total Area ^{a}	Net Treat-able DCIA (ft^2) ^{b} (1)	Redcd DCIA (ft^2) ^{c} (2)	% Total Redcd DCIA ^{d}	Δ ^{e} (%)	Remain DCIA (ft^2)	Net Treat-able DCIA (ft^2) ^{b} (1)	Redcd DCIA (ft^2) ^{c} (2)	% Total Redcd DCIA ^{d}	Δ ^{e} (%)	Remain DCIA (ft^2)
Commercial: Govt/Public	14.7M	2.7%	9.7M	5.7M	5.9%	-1.0%	9.0M	3.8M	2.4M	5.2%	-1.6%	12.3M
Commercial: Inst/Private	7.9M	1.5%	6.2M	4.1M	4.3%	0.6%	3.7M	2.8M	1.9M	4.2%	0.5%	5.9M
Commercial: Com, Office, WH	65.1M	12.1%	43.1M	25.7M	26.5%	-3.6%	39.3M	17.6M	11.3M	24.3%	-5.9%	53.8M
Commercial: Multi-Family Res	27.4M	5.1%	21.1M	15.2M	15.6%	2.9%	12.2M	10.2M	7.4M	16.0%	3.3%	20.0M
Single-Family Res	39.6M	7.4%	35.1M	19.8M	20.4%	2.1%	19.8M	17.5M	9.9M	21.3%	2.9%	29.7M
Other (Road EOP/ Sidewalk)	61.1M	11.4%	41.1M	26.5M	27.3%	-1.0%	34.6M	22.6M	13.5M	29.1%	0.8%	47.5M
Total	215.6M	40.1%	156.3M	96.9M	100.0%	0.0%	118.7M	74.5M	46.5M	100.0%	0.0%	169.1M
% of Total Watershed Area	40.1%			18.0%			22.1%		8.6%			31.4%
% of Total DCIA			72.5%	44.9%			55.1%	34.6%	21.6%			78.4%

Notes: CVR = Coverage ratio; DCIA = Directly connected impervious area; HSG = Hydrologic soil group; HWT = High water table; EOP = Edge of pavement; ft^2 = Square feet; M = Million; Redcd = Reduced; Res= Residential; TAR = Treatment area ratio; ULSC = Upper Little Sugar Creek.

[a] Total watershed area = 538.2M ft^2; [b] Column (1) = $\sum$ DCIA (subtheme, HSG, slope, HWT)*TAR*CVR, see Table 4-10

[c] Column (2) = Column (2) * VRM, see Table 4-10; [d] Contribution to total DCIA reduction; [e] Relative contribution to total DCIA reduction.

Table 4.15: Six Mile Creek – Watershed Scale Runoff Reduction Potential

Impervious Area Layer	DCIA (ft^2)	% DCIA of Total Area [a]	Net Treat-able DCIA (ft^2) [b] (1)	Redcd DCIA (ft^2) [c] (2)	% Total Redcd DCIA[d]	Δ [e] (%)	Remain DCIA (ft^2)	Net Treat-able DCIA (ft^2) [b] (1)	Redcd DCIA (ft^2) [c] (2)	% Total Redcd DCIA[d]	Δ [e] (%)	Remain DCIA (ft^2)
Commercial: Govt/Public	3.3M	0.9%	2.3M	1.7M	7.2%	3.1%	1.6M	1.1M	0.8M	7.0%	2.9%	2.5M
Commercial: Inst/Private	1.0M	0.3%	0.93M	0.7M	3.1%	1.9%	0.3M	0.46M	0.4M	3.1%	1.9%	0.6M
Commercial: Com, Office, WH	5.6M	1.6%	3.4M	2.0M	8.4%	1.4%	3.6M	1.5M	0.9M	7.9%	0.9%	4.7M
Commercial: Multi-Family Res	13.0M	3.6%	8.5M	5.4M	23.4%	7.1%	7.5M	4.1M	2.7M	23.2%	6.9%	10.3M
Single-Family Res	32.6M	9.1%	14.5M	6.3M	27.1%	13.8%	26.3	7.2M	3.2M	27.4%	13.5%	29.4M
Other (Road EOP/ Sidewalk)	24.3M	6.8%	12.0M	7.2M	30.8%	0.3%	17.1M	6.2M	3.6M	31.4%	0.9%	20.7M
Total	79.7M	22.2%	41.6M	23.2M	100.0%	0.0%	56.4M	20.6M	11.5M	100.0 %	0.0%	68.2M
% of Total Watershed Area[1]	22.2%			6.5%			15.7%		3.2%			19.0%
% of Total DCIA			52.2%	29.2%				25.9%	14.4%			

Notes: CVR = Coverage ratio; DCIA = Directly connected impervious area; HSG = Hydrologic soil group; HWT = High water table; EOP = Edge of pavement; ft^2 = Square feet; M = Million; Redcd = Reduced; Res= Residential; TAR = Treatment area ratio.

[a] Total watershed area = 358.4M ft^2; [b] Column (1) = ∑ DCIA (subtheme, HSG, slope, HWT)*TAR*CVR, see Table 4-11

[c] Column (2) = Column (1) * VRM, see Table 4-10; [d] Contribution to total DCIA reduction; [e] Relative contribution to total DCIA reduction.

Table 4.16: ULSC Catchments and Sub-Basin Identification

No.	Catchment Name	Number of Sub-Basins	Hydrology Model Sub-Basin ID [a]	Total Area (acres)
1	ULSC-1	9	ULS_194, 195, 5, 6, 9, 10, 1, 272, 12	762
2	ULSC-2	5	ULS_265, 264, 193, 267, 11	407
3	ULSC-4	5	ULS_318, 312, 313, Basin_162, 156	390
4	ULSC-5	5	ULS_412, 306, 308, 309, BC_2	392
5	ULSC-6	6	ULS_325, 74, 77, 326, Basin_169, 172	428
6	ULSC-7	2	ULS_329, 331	188
7	ULSC-8	2	ULS_339, 337	225
8	ULSC-9	2	ULS_84, 336	199
9	ULSC-10	2	ULS_365, 362	263
10	ULSC-11	2	ULS_349, 98	219
11	ULSC-12	2	ULS_301, 303	264
12	ULSC-13	2	ULS_293, 311	204
13	ULSC-14	2	ULS_302, 299	198
14	ULSC-15	1	ULS_310	187
15	ULSC-16	1	ULS_70	157
16	ULSC-17	1	ULS_340	118
17	ULSC-18	1	ULS_327	152
18	Derita-1	10	ULS_421, 13, 14, 273, 247, 33	868
19	DairyBr [b]	8	“stream” = ‘Dairy Branch’	684
20	LittleHope-1	8	LLS_199, 104, 103, 242, 360, 200, 241, 123	774
21	LittleHope-Trib [b]	10	“stream” = ‘Little Hope Creek Trib’	855

Notes:

[a] Sub-basins from hydrology model GIS layer (City of Charlotte 2016)

[b] Sub-basins include all those selected using the “stream” attribute indicated.

Table 4.17: Six Mile Creek Catchments and Sub-Basin Identification

No.	Catchment Name	Number of Sub-Basins	Hydrology Model Sub-Basin ID [a]	Total Area (acres)
1	SixMile-1	12	Basin_487, 238, 603, 634, 36, 295, 519, 694, 362, 514, 200, 327	680
2	SixMile-2	3	Basin_111, 289, 496	160
3	SixMile-3	3	Basin_38, 435, 538	182
4	SixMile-4	2	Basin_568, 463	106
5	SixMile-5	9	Basin_118, 69, 697, 159, 521, 657, 732, 758, 312	610
6	SixMile-6	4	Basin_879, 369, 608, 188	132
7	SixMile-7	8	Basin_217, 454, 644, 703, 747, 914, 180, 309	619
8	SixMile-8	11	Basin_54, 86, 290, 65, 15, 505, 662, 695, 746, 769, 112	597
9	SixMile-9	8	Basin_123, 394, 639, 709, 370, 150, 96, 935	452
10	FlatBr-1	11	Basin_495, 619, 773, 1090, 795, 275, 446, 591, 648, 103, 339	787
11	FlatBr-2	6	Basin_98, 440, 701, 462, 263, 551	257
12	FlatBr-3	3	Basin_260, 421, 566	193
13	FlatBr-4	3	Basin_280, 497, 130	162
14	FlatBr-5	5	Basin_126, 485, 652, 122, 50	290
15	FlatBr-6	3	Basin_231, 389, 548	188
16	FlatBr-7	2	Basin_104, 366	115

Note:
[a] Sub-basins from hydrology model GIS layer (City of Charlotte 2016)

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Table 4.18: Results of Independence Tests for Catchment Scale GI Retrofit Evaluation Criteria

		ULSC	SMC	Combined ULSC and SMC
	Number of data pairs, N	21	16	37
	Degrees of freedom, df = N-2	19	14	35
	Critical Pearson r	0.549	0.623	0.418
No.	Criterion	Correlated to Criterion No. (Pearson r):		
1	Total Catchment Area	5 (0.91)	5 (0.87)	5 (0.83)
2	Commercial DCIA Area	5 (0.91)	5 (0.82)	5 (0.90)
3	SF Res DCIA Area	5 (0.65)	5 (0.77)	5 (0.61)
4	Other (Road EOP/Sdwk) DCIA Area	5 (0.94)	5 (0.97)	5 (0.95)
5	Total DCIA	✓	✓	✓
6	DCIA Density	19(-0.63)	✓	✓
7	Potential GovtPub DCIA Reduction	✓	✓	✓
8	Potential InstPriv DCIA Reduction	✗	7 (0.73)	19 (0.44)
9	Potential Commercial /Office/Warehouse DCIA Reduction	5 (0.71) 25 (0.63)	✗	5 (0.73)
10	Potential MF Res DCIA Reduction	5 (0.74)	5 (0.70)	5 (0.74)
11	Potential SF Res DCIA Reduction	5 (0.62)	✗	5 (0.65)
12	Potential Total Residential (MF Res + SF Res) DCIA Reduction	5 (0.68)	5 (0.71)	5 (0.72)
13	Potential Road EOP/ Sidewalk DCIA Reduction	5 (0.78)	5 (0.85)	5 (0.83)
14	Park Area	25 (1.00)	7 (0.76)	7 (0.55)
15	Pond/ Wetland Area	✗	✓	6 (-0.52)
16	Gross Treatable DCIA	5 (1.00)	5 (0.99)	5 (0.99)
17	Total Potential DCIA Reduction	5 (0.83)	5 (0.86)	5(0.87) 18 (0.50)
18	Total Potential DCIA Reduction as % of Total Catchment Area	19(0.72)	19(0.76)	19(0.74)
19	Total Potential DCIA Reduction as % of Total DCIA	✓	✓	✓
20	Potential Govt/Pub DCIA Reduction as % Total Potential DCIA Reduction	7 (0.58) 27 (0.57)	7 (0.91)	7 (0.76)
21	Potential Inst/Priv DCIA Reduction as % Tot. Pot. DCIA Reduction	✗	✗	✗
22	Potential Commercial/ Office/Warehouse DCIA Reduction as % Total Potential DCIA Reduction	27 (0.62)	✗	6 (0.48)
23	Total Potential MF Res + SF Res DCIA Reduction as % of Total Potential DCIA Reduction	19 (0.69) 27 (-0.71)	✗	6 (-0.62)

Table 4.18 (continued)

24	Pot. Other (Road EOP/Sidewalk) DCIA Reduction As % of Tot. Pot. DCIA Reduction	✖	27 (-0.68)	27 (-0.51)
25	Park + Pond/Wetland Area	✓	7 (0.72)	7 (0.51) 27 (0.46)
26	Vacant Area	27 (0.69)	27 (0.90)	27 (0.82)
27	Vacant Area Density (% of Total Catchment Area)	✓	✓	✓
28	No. Parcels	5 (0.76)	5 (0.95)	5 (0.79)
29	Capital Cost of Retrofits	5 (0.96)	5 (0.89)	5 (0.92) 6 (0.51) 7 (0.43)
30	No. Existing Surface BMPs	5 (0.56)	5 (0.63)	5 (0.56) 7 (0.43)
	Total number of non-redundant criteria selected for priority analysis (✓) =	5	6	5
	Total number of non-redundant criteria NOT selected for priority analysis (✖) =	4	5	1
	Total number of non-redundant criteria =	9	11	6

Notes: BMPs = Best management practices; DCIA = Directly connected impervious area; EOP = Edge of pavement; MF = Multi-family; No. = Number; Res. = Residential; Sdwk = Sidewalk; SF = Single-family; SMC = Six Mile Creek; ULSC = Upper Little Sugar Creek.

Table 4.19: Criterion Weights for Selected Weight Functions

	Criterion Weight, WT					
Number of Criteria, n = 5						
Criterion Priority Rank:	1	2	3	4	5	
Equal Weight:	0.20	0.20	0.20	0.20	0.20	
Rank Sum Weight:	0.33	0.27	0.20	0.13	0.07	
Rank Reciprocal Weight:	0.44	0.22	0.15	0.11	0.09	
Rank Centroid Weight:	0.45	0.26	0.16	0.09	0.04	
Assigned Weight:	0.30	0.30	0.30	0.07	0.03	
Number of Criteria, n = 6						
Criterion Priority Rank:	1	2	3	4	5	6
Equal Weight:	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
Rank Sum Weight:	0.29	0.24	0.19	0.14	0.10	0.05
Rank Reciprocal Weight:	0.41	0.20	0.14	0.10	0.08	0.07
Rank Centroid Weight:	0.41	0.24	0.16	0.10	0.06	0.03
Assigned Weight:	0.30	0.30	0.30	0.04	0.03	0.03

Table 4.20: Average Performance Values of Non-Redundant Evaluation Criteria for all Catchments

		ULSC	Six Mile Creek
Criterion	Objective	Average PV	Average PV
Total DCIA (ft^2)	MIN	6,675,061	3,512,991
DCIA Density (%) [a]	MAX	43.97%	24.14%
Total Potential GovtPublic DCIA Reduction (ft^2)	MAX	72,039	48,342
Pond and Wetland Area (ft^2) [b]	MAX	12,567	359,627
Total Potential DCIA Reduction as % of Total DCIA (%)	MAX	22.64%	16.33%
Park + Pond and Wetland Area (ft^2) [c]	MAX	466,278	1,733,933
Vacant Area Density (%)	MIN	9.19%	12.57%

Notes: DCIA = Directly connected impervious area; MAX = Maximum; MIN = Minimum; PV = Performance value; ULSC = Upper Little Sugar Creek

[a] DCIA Density is non-redundant only in Six Mile Creek and Combined cases.

[b] Pond and Wetland Area is non-redundant only in Six Mile Creek case.

[c] Park + Pond and Wetland Area is non-redundant only in ULSC case.

Table 4.21: Performance Values of Non-Redundant Evaluation Criteria for Top Six Catchments in Three Cases: ULSC, Six Mile Creek and Combined

	Total DCIA	DCIA Density [a]	Potential GovtPublic DCIA Reduction	Pond and Wetland Area[b]	Total Potential DCIA Reduction as % of Total DCIA	Park + Pond and Wetland Area [c]	Vacant Area Density
Objective	MIN	MAX	MAX	MAX	MAX	MAX	MIN
Catchment	ft^2	%	ft^2	ft^2	%	ft^2	%
ULSC-7	4,436,874	54.14%	132,157	0	26.22%	1,313,183	6.31%
ULSC-8	4,627,882	47.15%	152,868	269	29.47%	1,058,285	7.80%
ULSC-9	4,313,409	49.65%	14,601	51	35.10%	137,656	6.23%
ULSC-10	2,377,862	20.74%	68,405	614	54.35%	175,585	13.47%
ULSC-11	3,801,763	39.94%	0	812	32.09%	13,134	3.40%
ULSC-17	2,189,130	42.64%	5,236	0	34.43%	237,211	1.98%
Six Mile-1	4,930,086	16.64%	247,829	1,201,319	27.32%	12,031,067	17.33%
Six Mile-2	1,548,870	22.24%	0	170,509	30.05%	694,632	5.41%
Six Mile-3	841,865	10.65%	0	240,530	24.74%	240,530	12.80%
Six Mile-4	1,519,354	32.78%	78,875	58,217	32.66%	912,016	19.60%
Six Mile-7	6,687,332	24.79%	352,088	52,529	20.78%	3,987,483	14.76%
FlatBr-7	1,437,997	28.83%	0	0	14.81%	0	0.25%

Notes: Directly connected impervious area; MAX = Maximum; MIN = Minimum

[a] DCIA Density is non-redundant only in Six Mile Creek and Combined cases.
[b] Pond and Wetland Area is non-redundant only in Six Mile Creek case.
[c] Park + Pond and Wetland Area is non-redundant only in ULSC case.

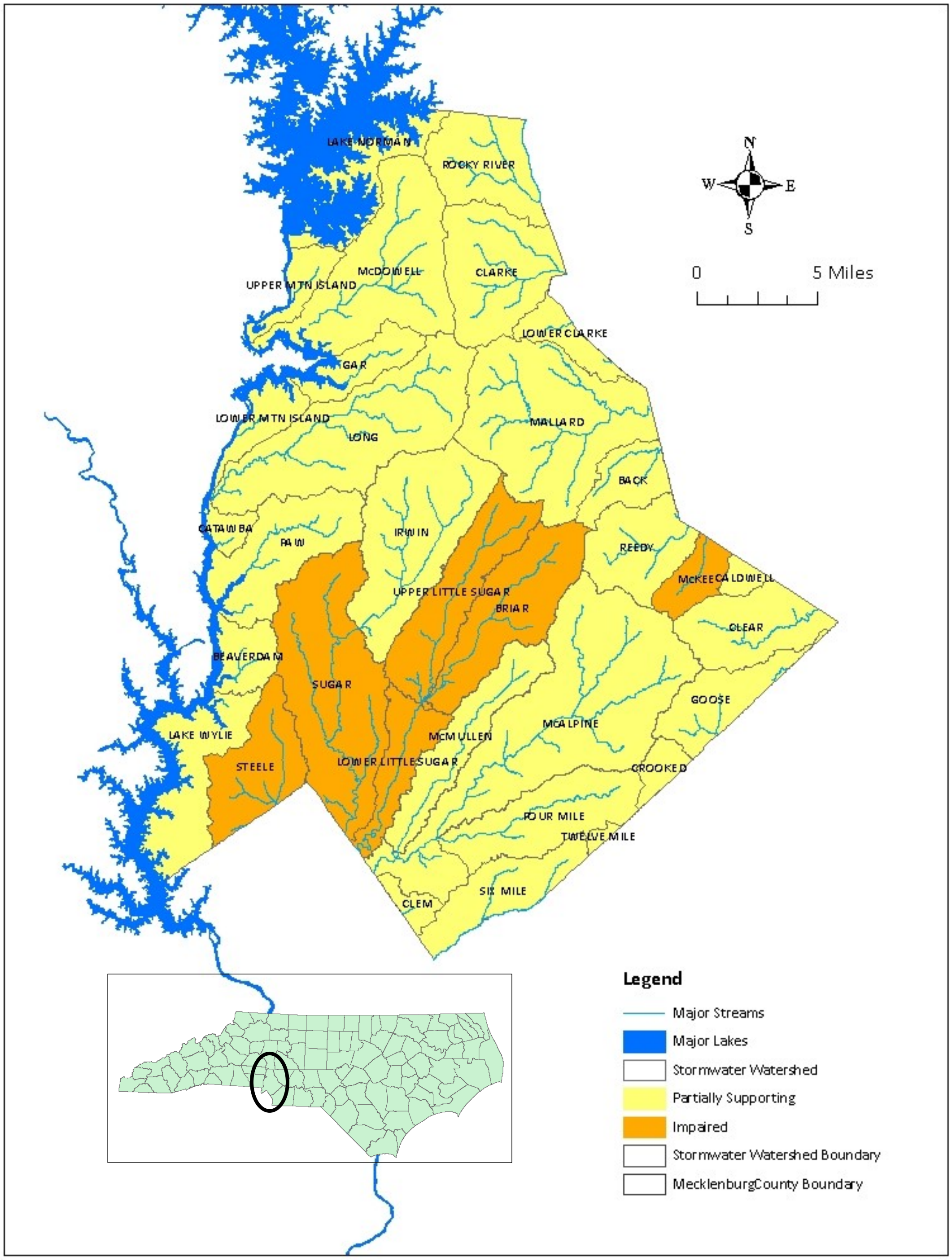

Figure 4.1: Mecklenburg County, North Carolina Stream Use Support Index

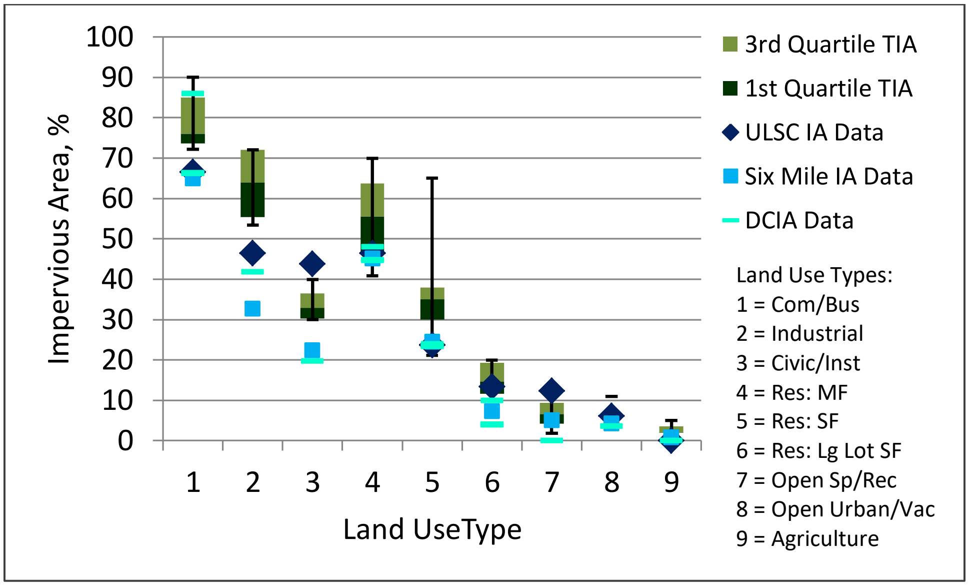

Figure 4.2: Charlotte Impervious Area Data vs. Published Values of TIA and DCIA

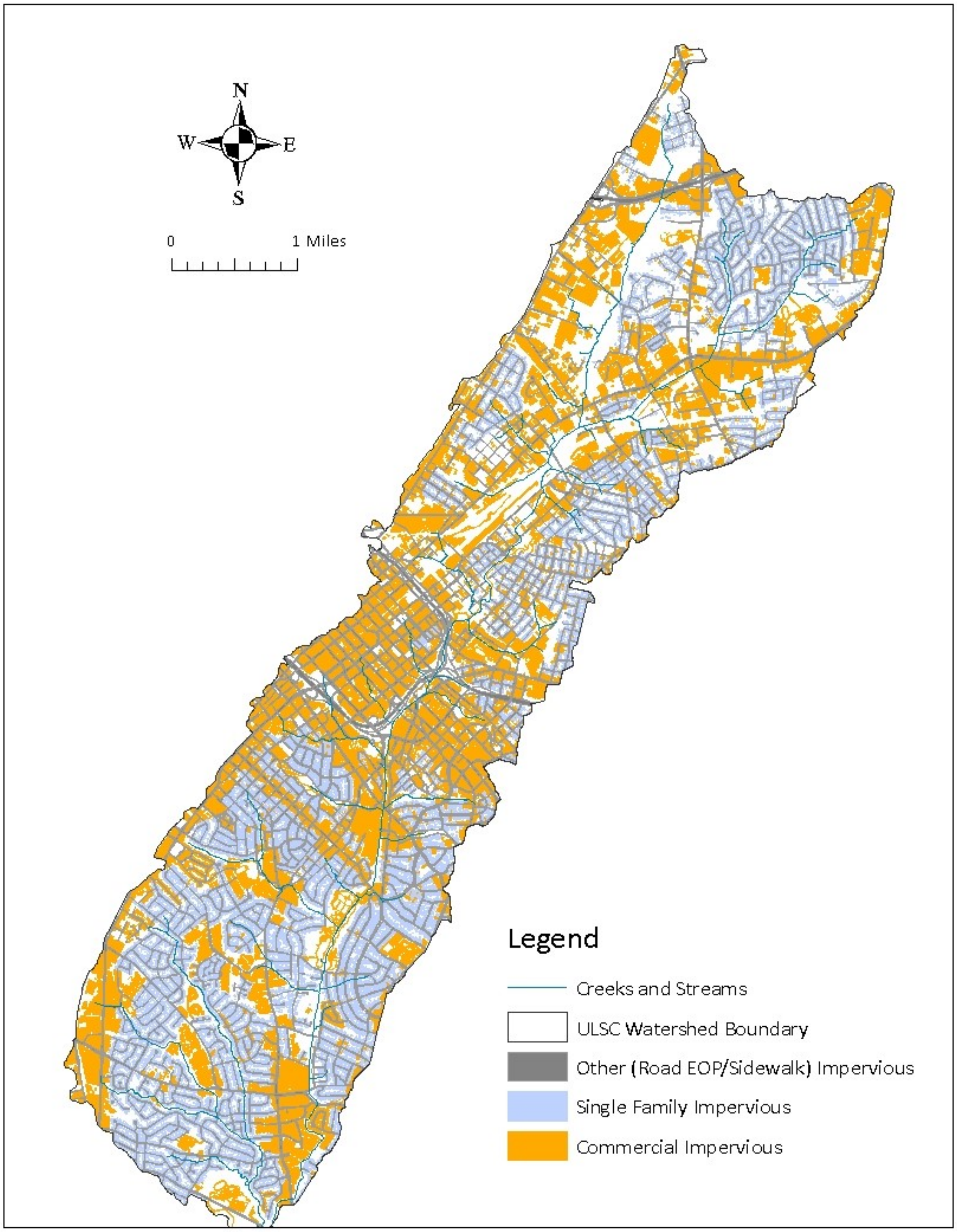

Figure 4.3: ULSC – Impervious Area

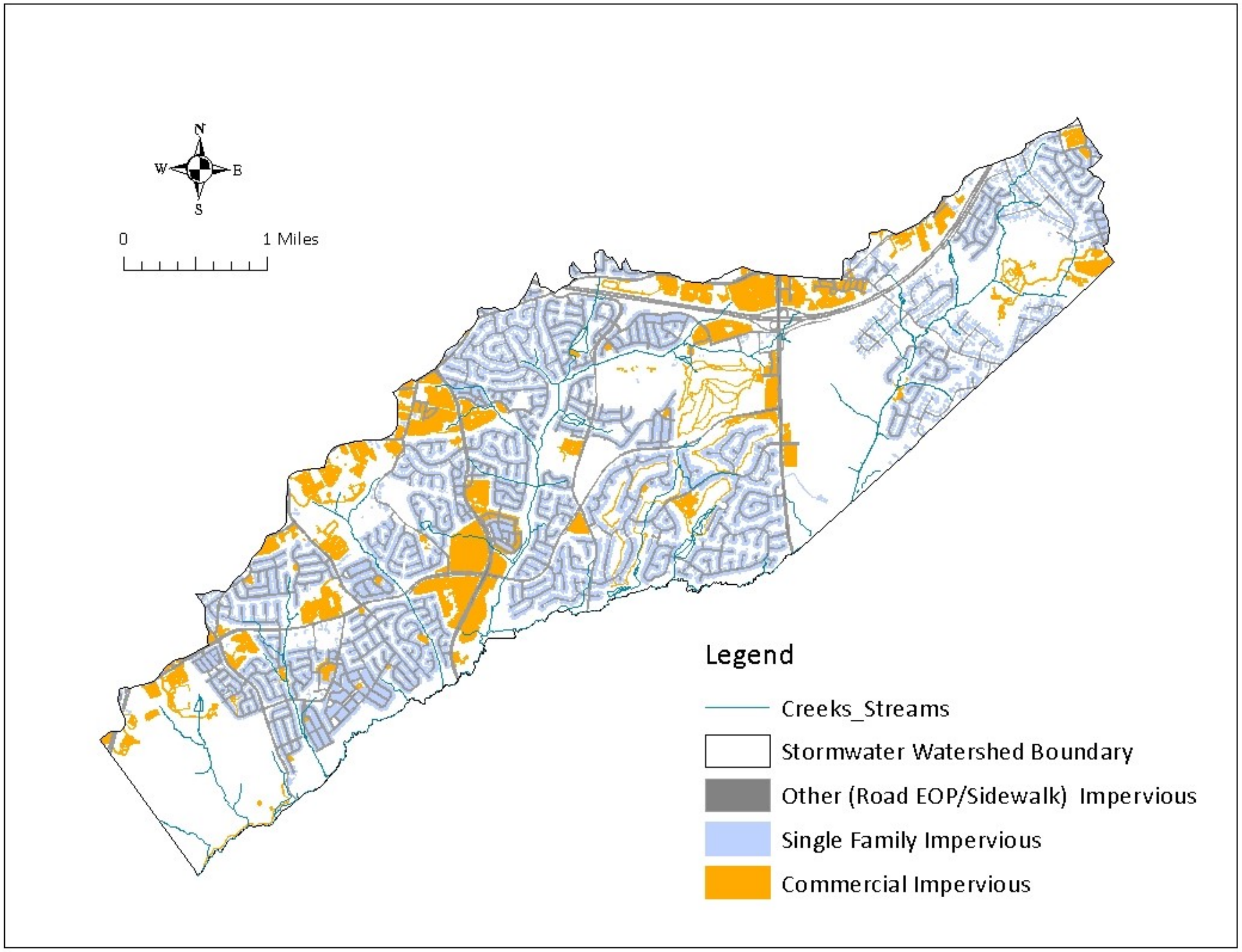

Figure 4.4: Six Mile Creek – Impervious Area

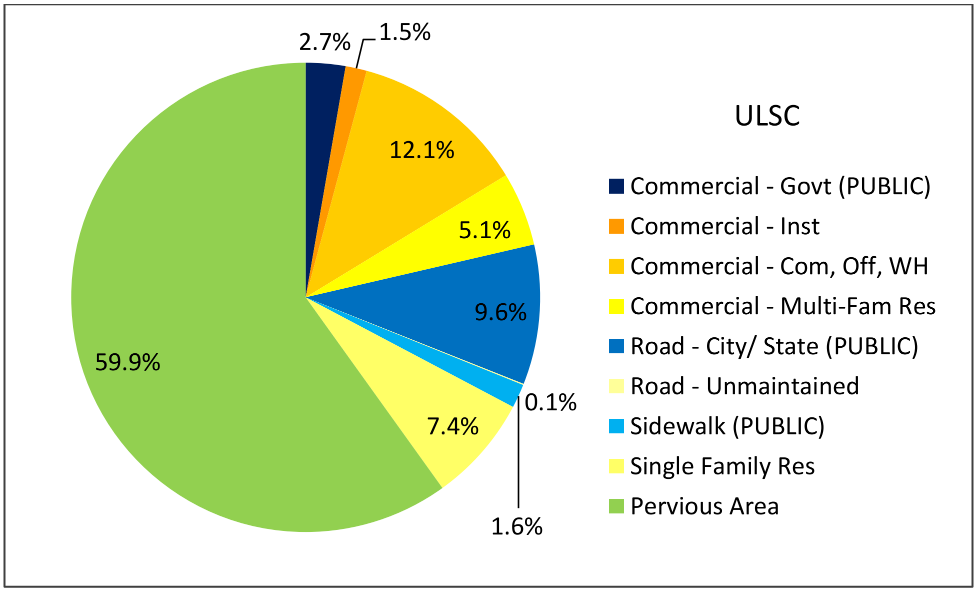

Figure 4.5: ULSC – Impervious Area Property Ownership Distribution

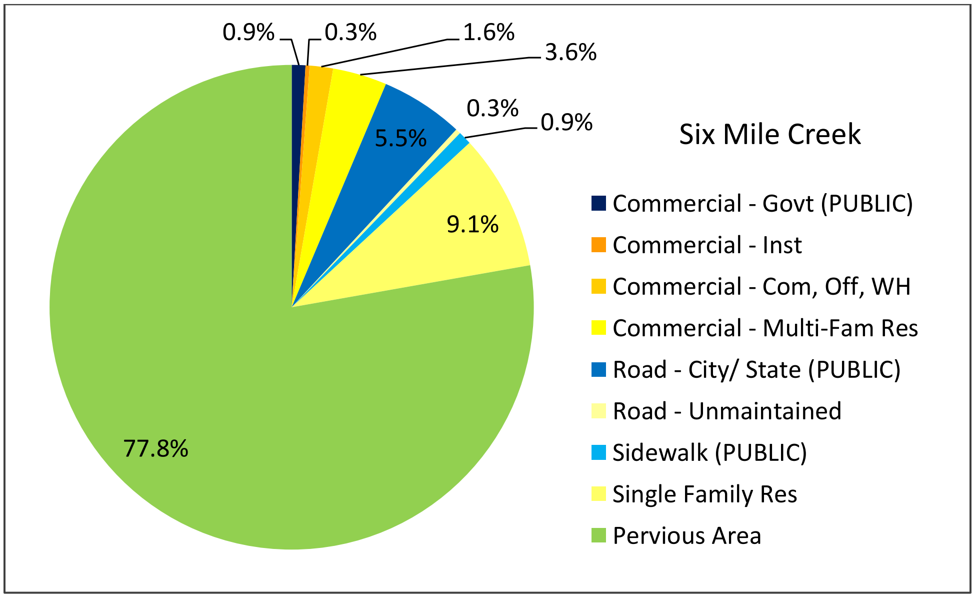

Figure 4.6: Six Mile Creek – Impervious Area Property Ownership Distribution

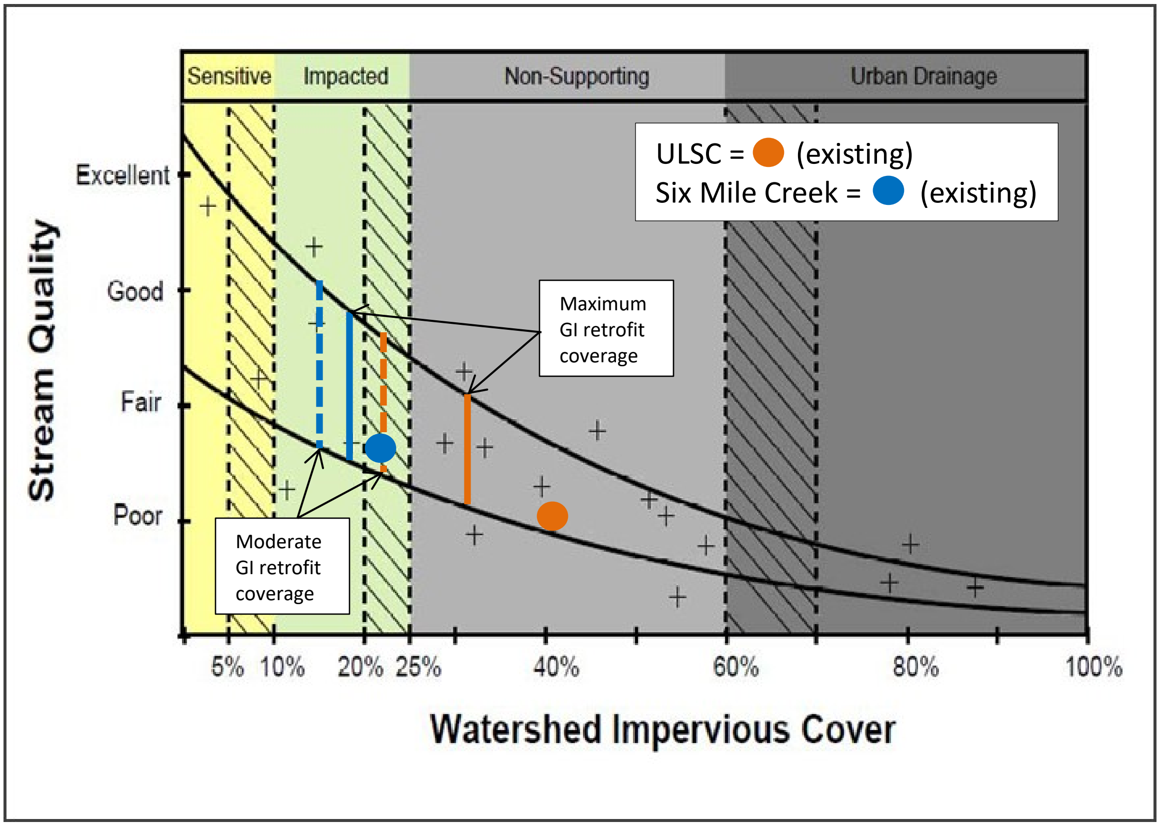

Figure 4.7: Potential Improvement to Stream Quality as a Result of GI Retrofits in ULSC and Six Mile Creek (adapted from Schueler et al. 2009)

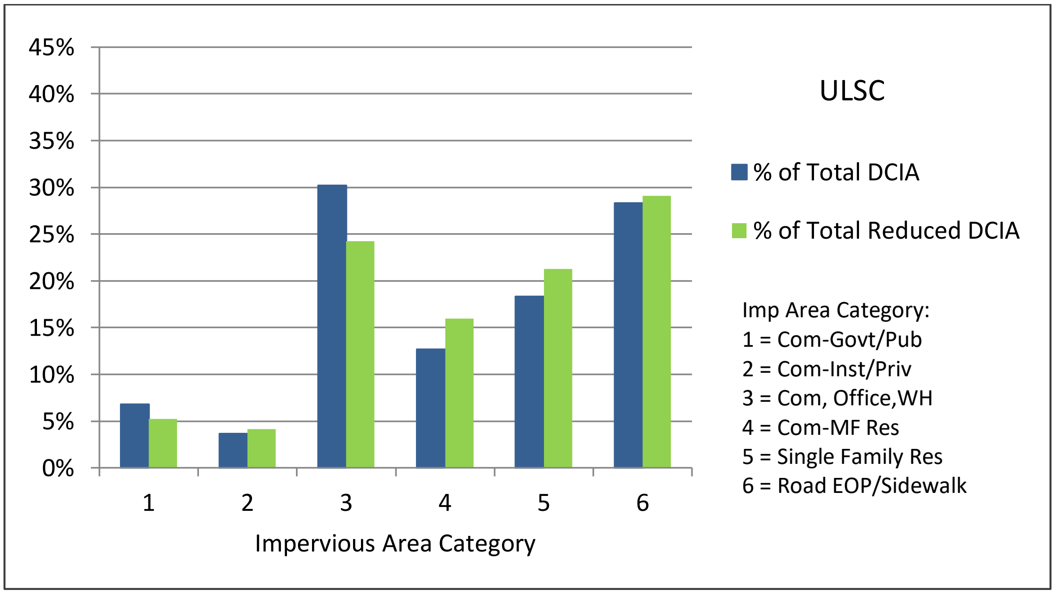

Figure 4.8: ULSC – DCIA Contribution vs. Reduction by Property Type

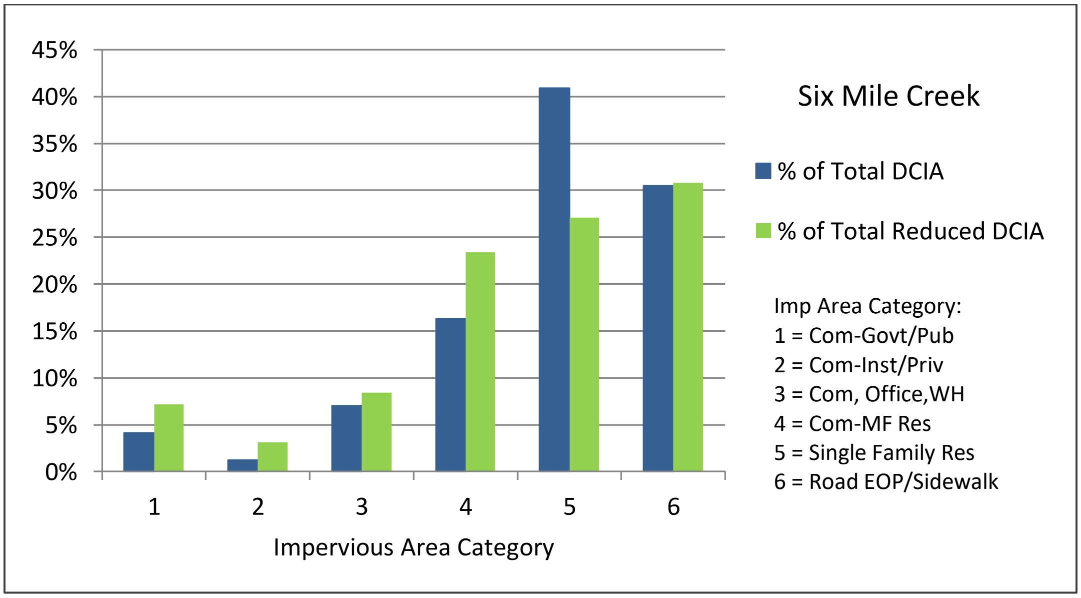

Figure 4.9: Six Mile Creek –DCIA Contribution vs. Reduction by Property Type

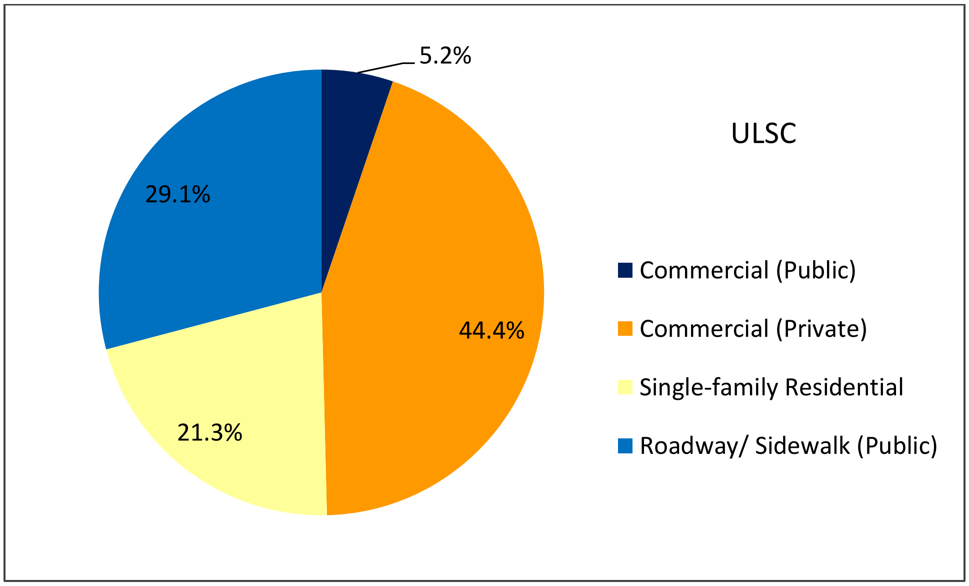

Figure 4.10: ULSC – Proportion of Reduced DCIA by Property Type

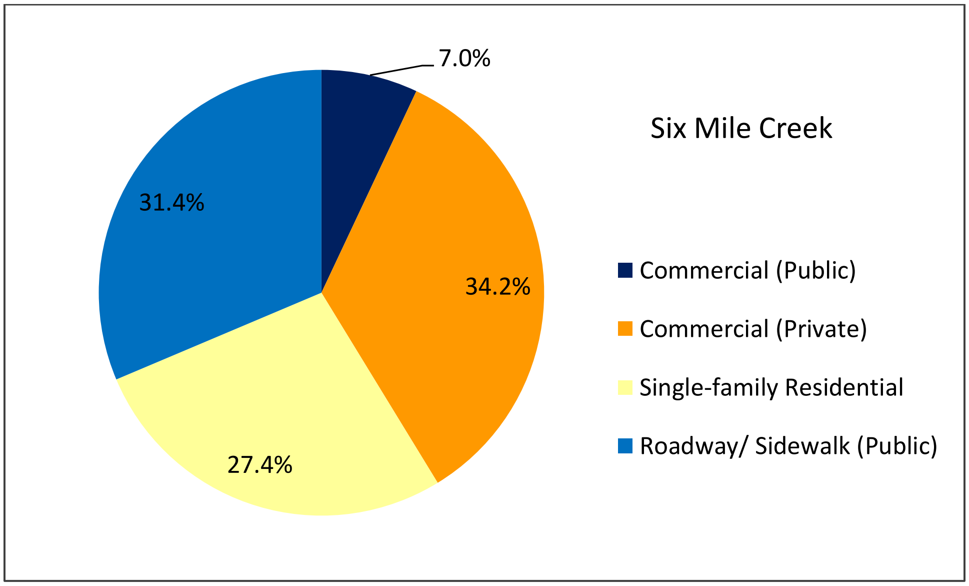

Figure 4.11: Six Mile Creek – Proportion of Reduced DCIA by Property Type

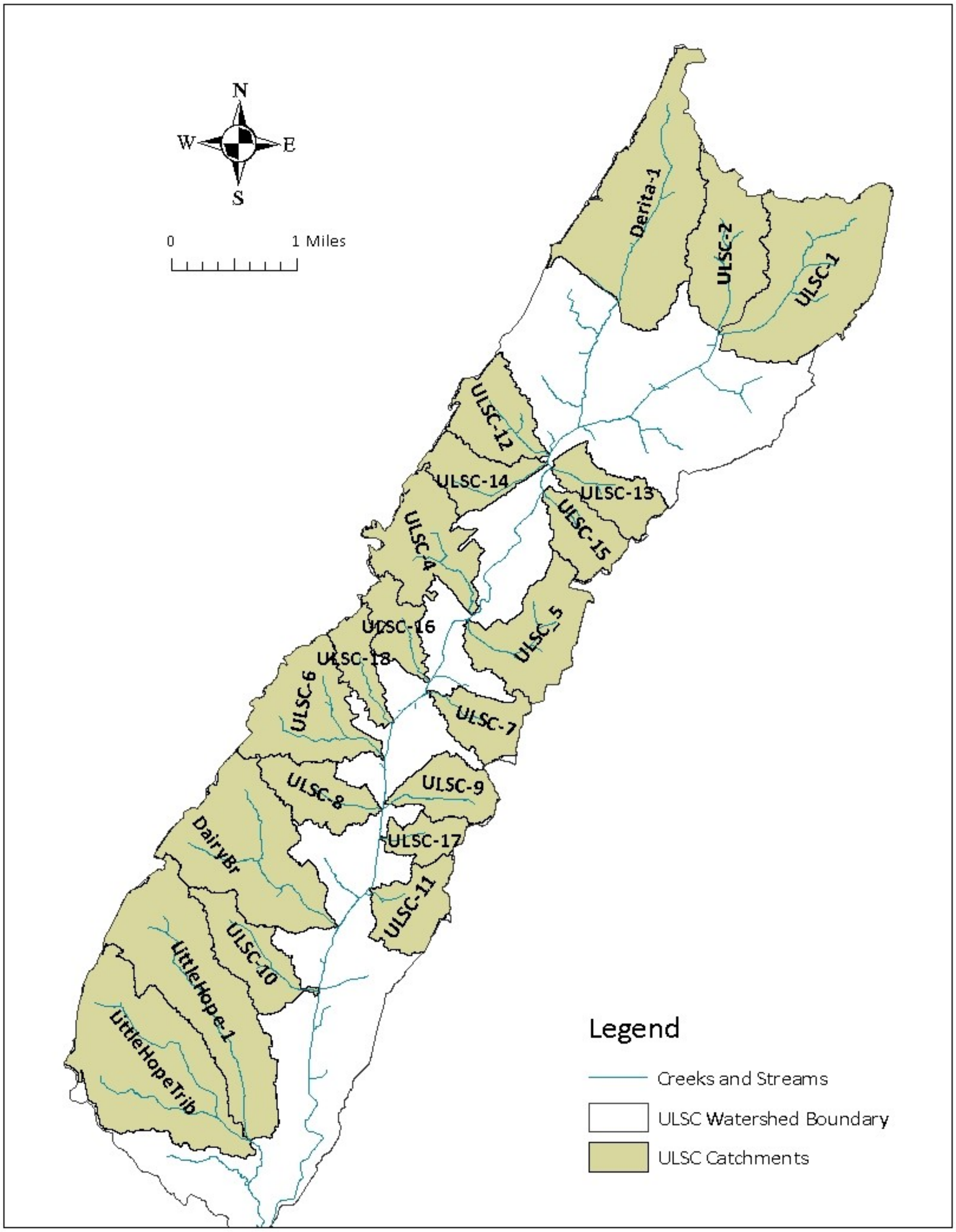

Figure 4.12: ULSC – Catchment Options for GI Retrofit Experimentation

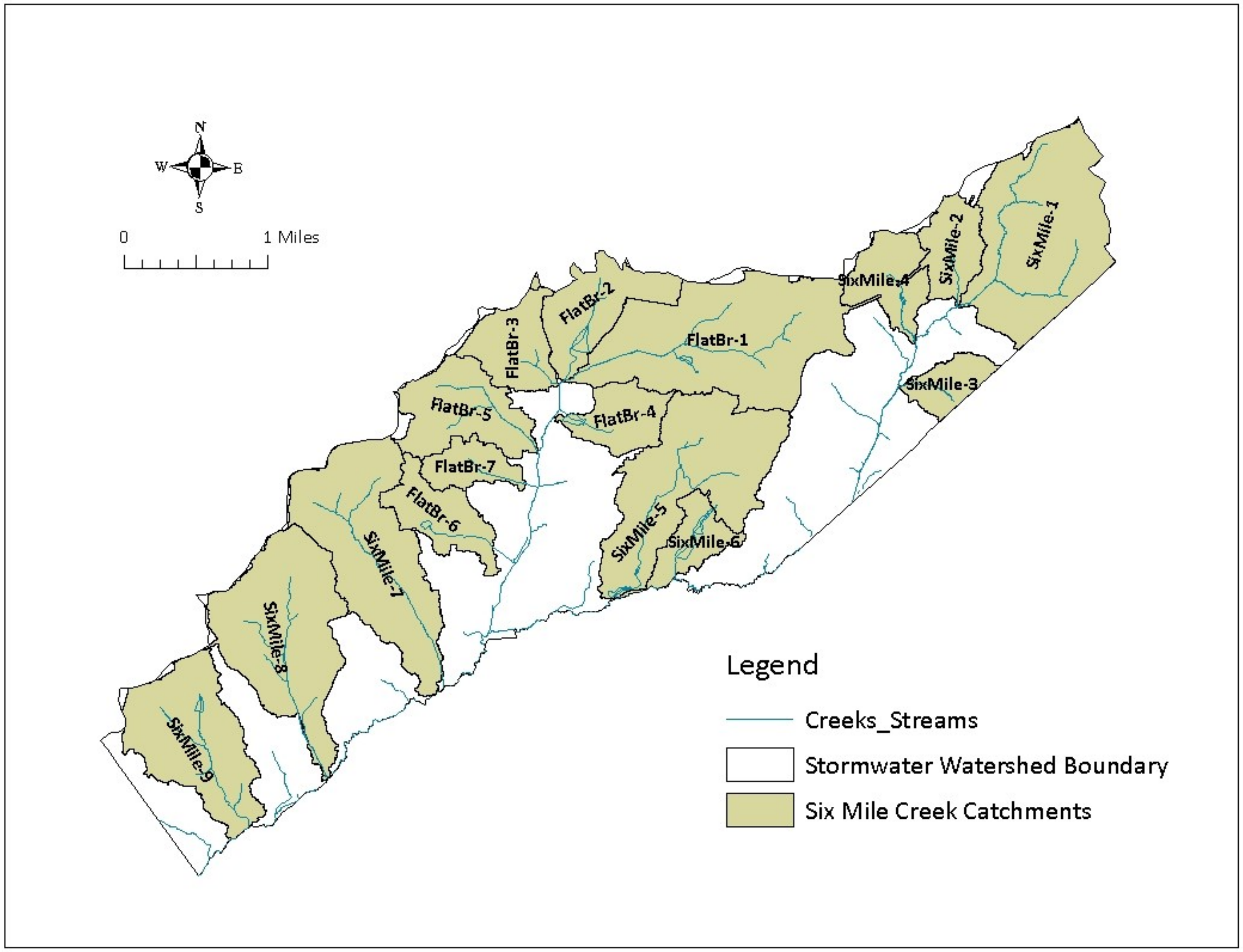

Figure 4.13: Six Mile Creek – Catchment Options for GI Retrofit Experimentation

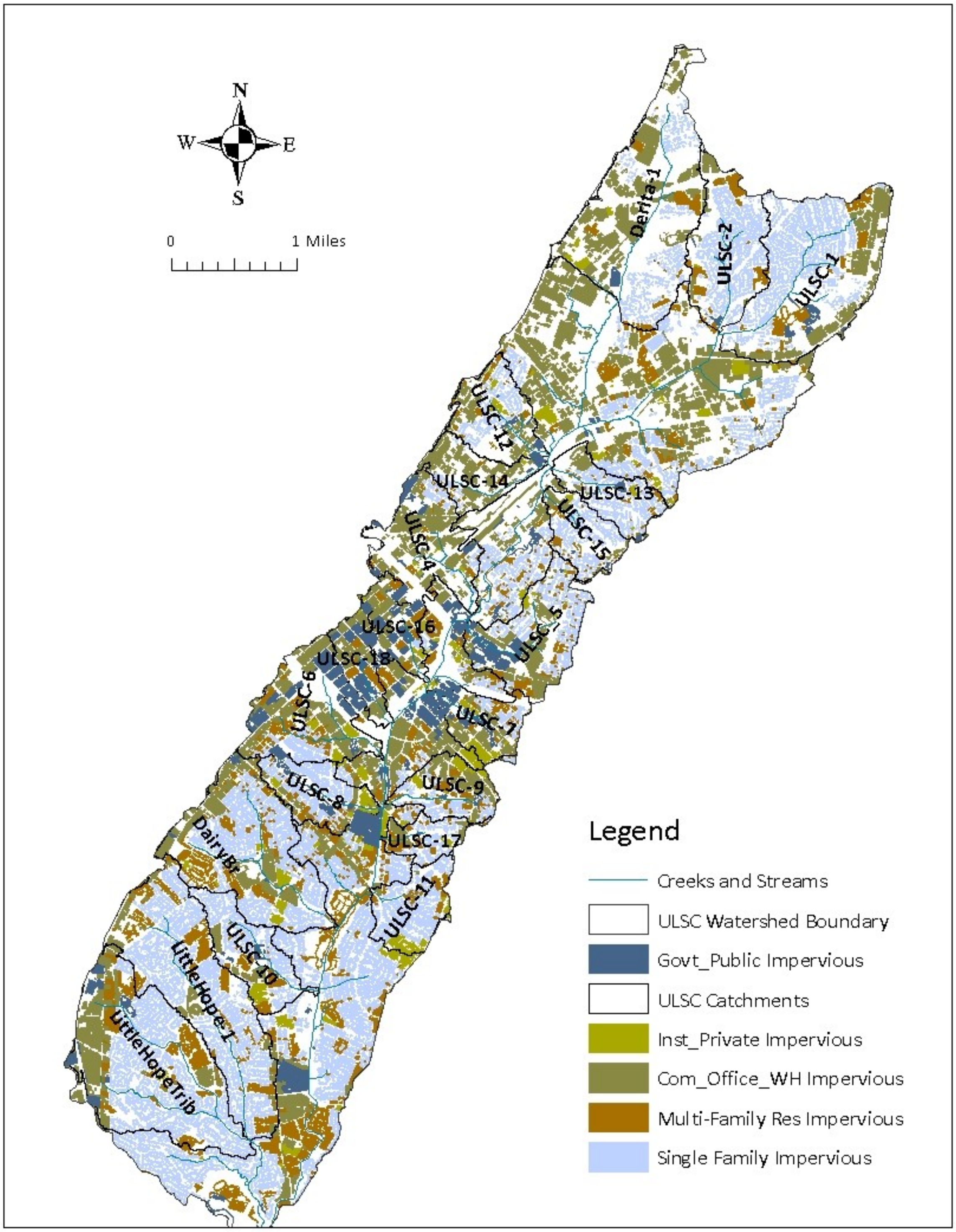

Figure 4.14: ULSC – Catchment Options and Extent of DCIA

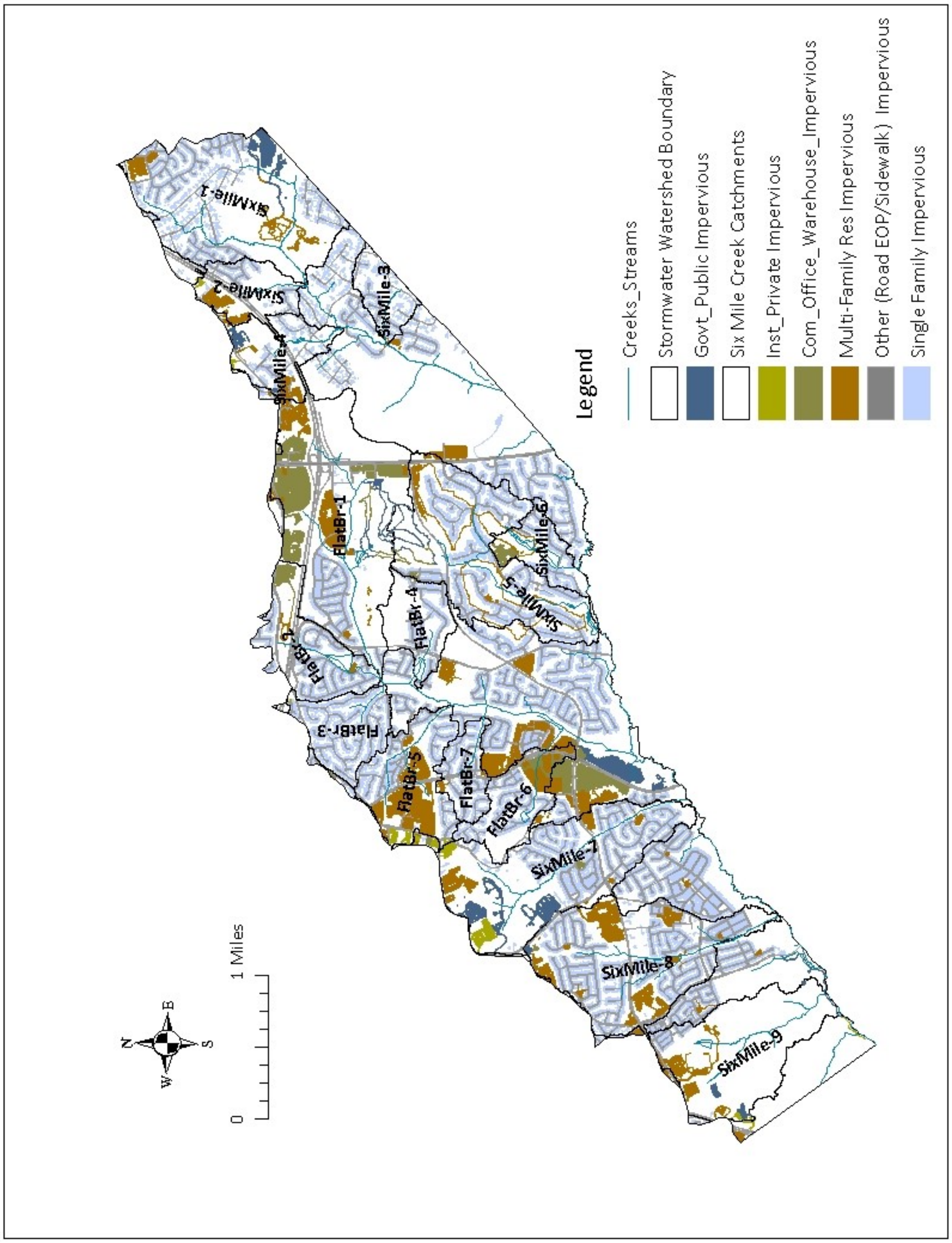

Figure 4.15: Six Mile Creek – Catchment Options and Extent of DCIA

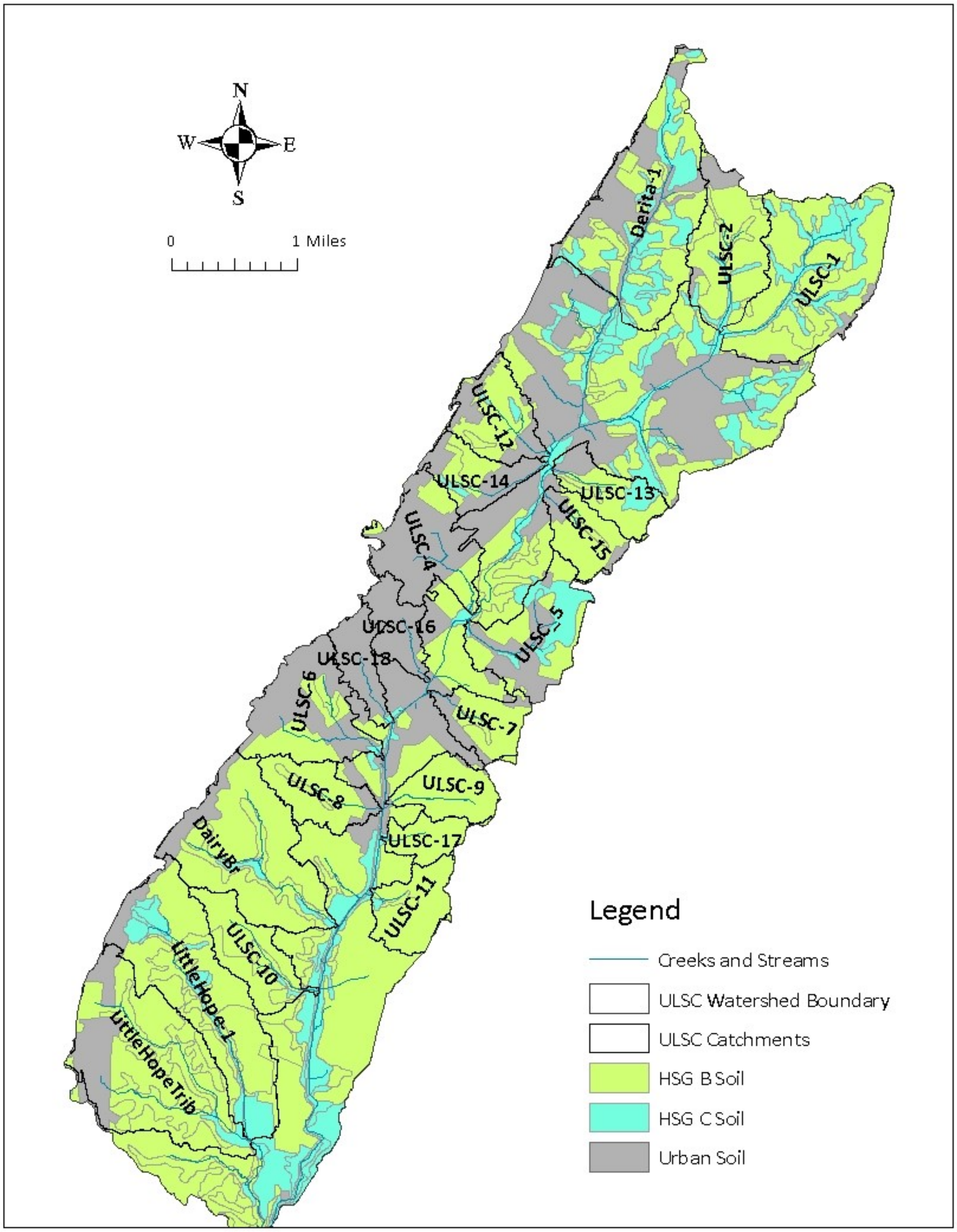

Figure 4.16: ULSC – Catchment Options and Hydrologic Soil Group

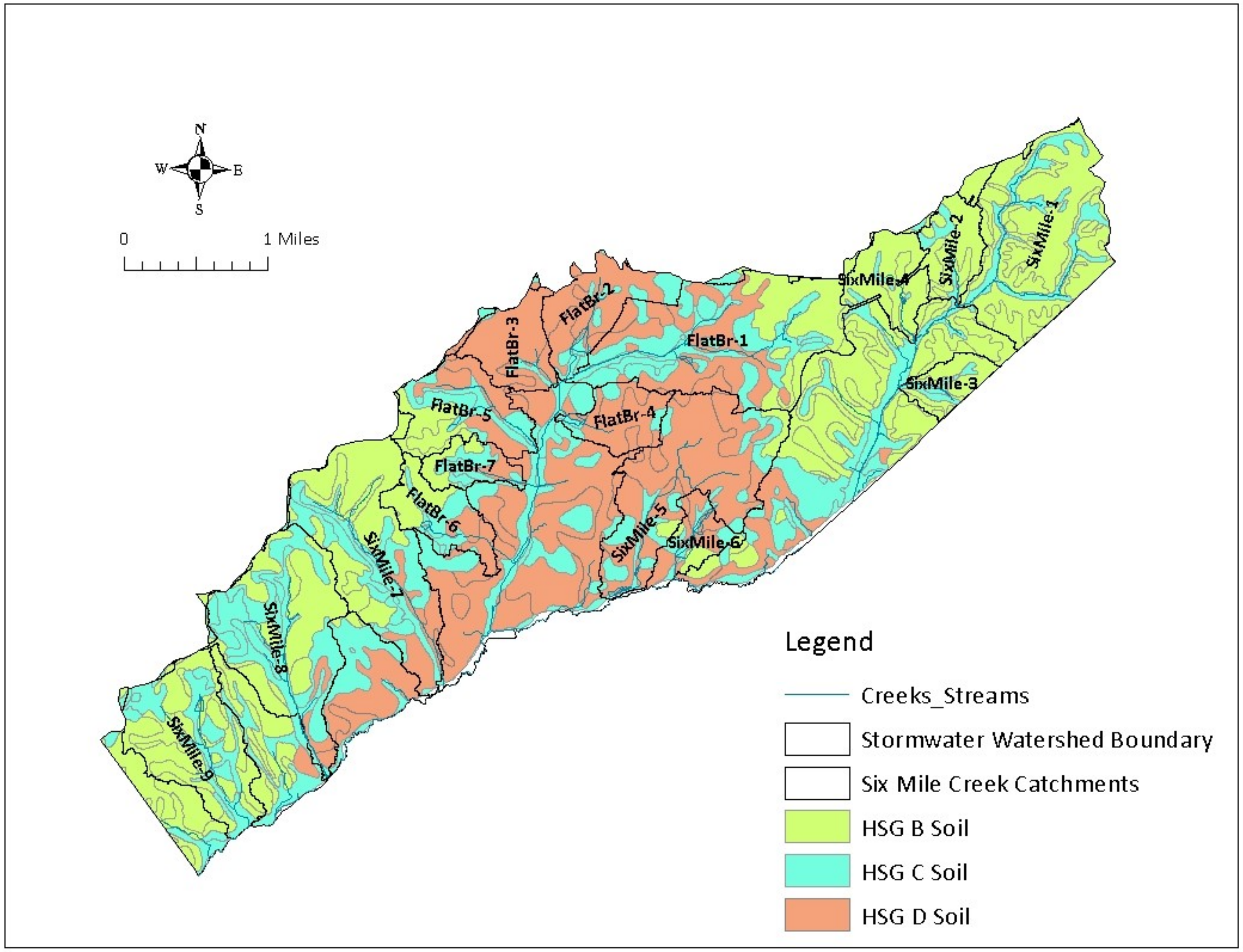

Figure 4.17: Six Mile Creek – Catchment Options and Hydrologic Soil Group

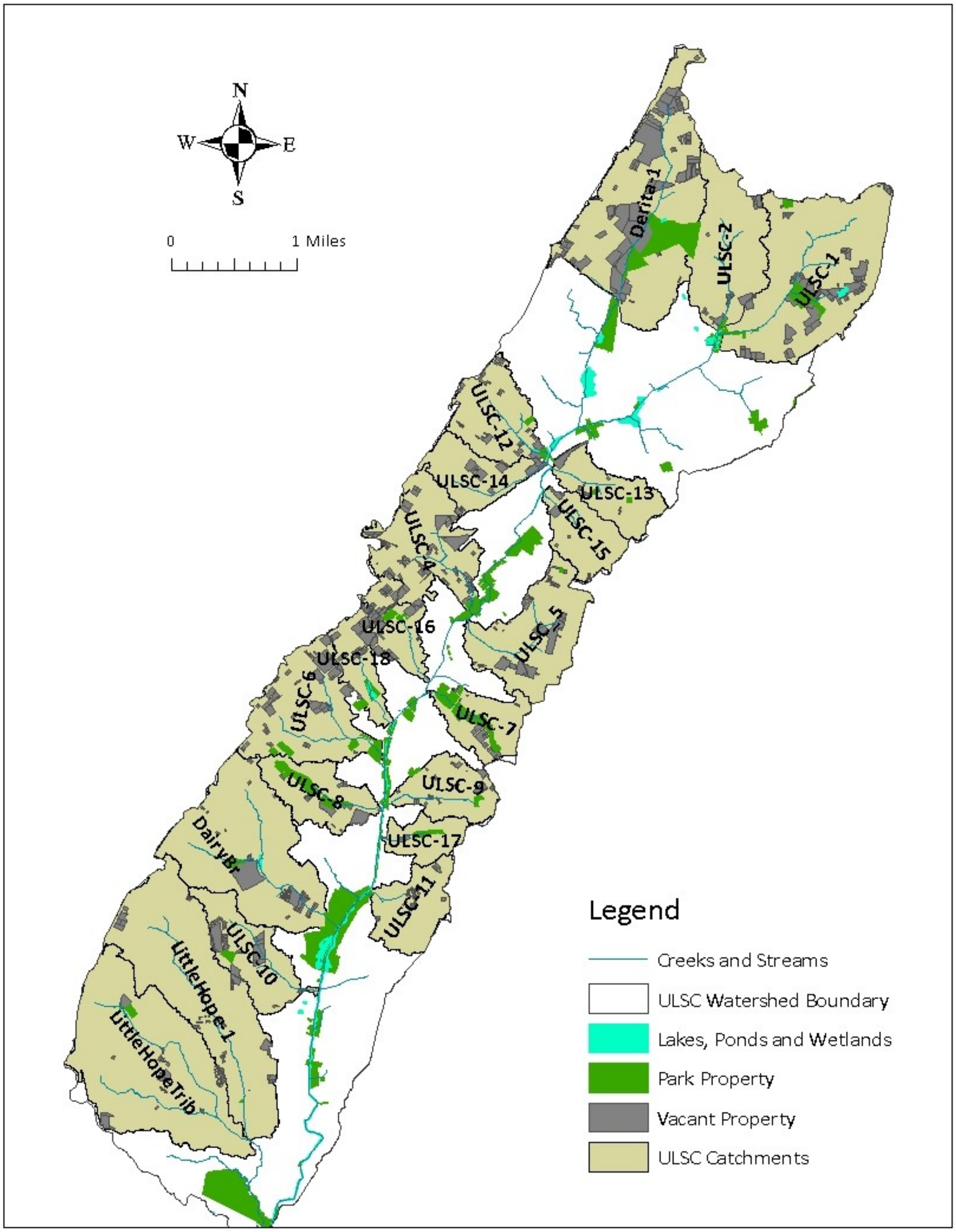

Figure 4.18: ULSC – Catchment Options and Additional Prioritization Criteria

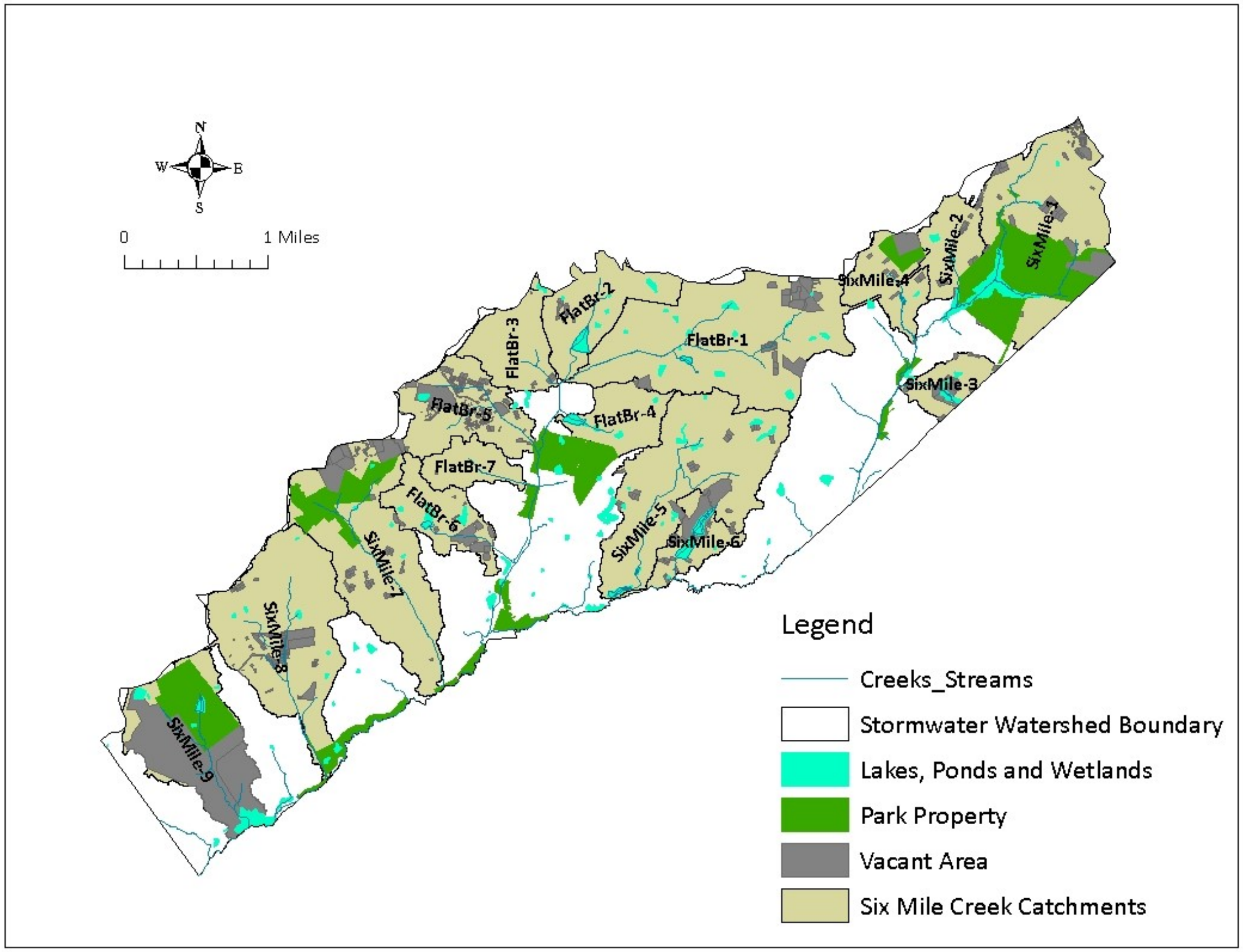

Figure 4.19: Six Mile Creek – Catchment Options and Additional Prioritization Criteria

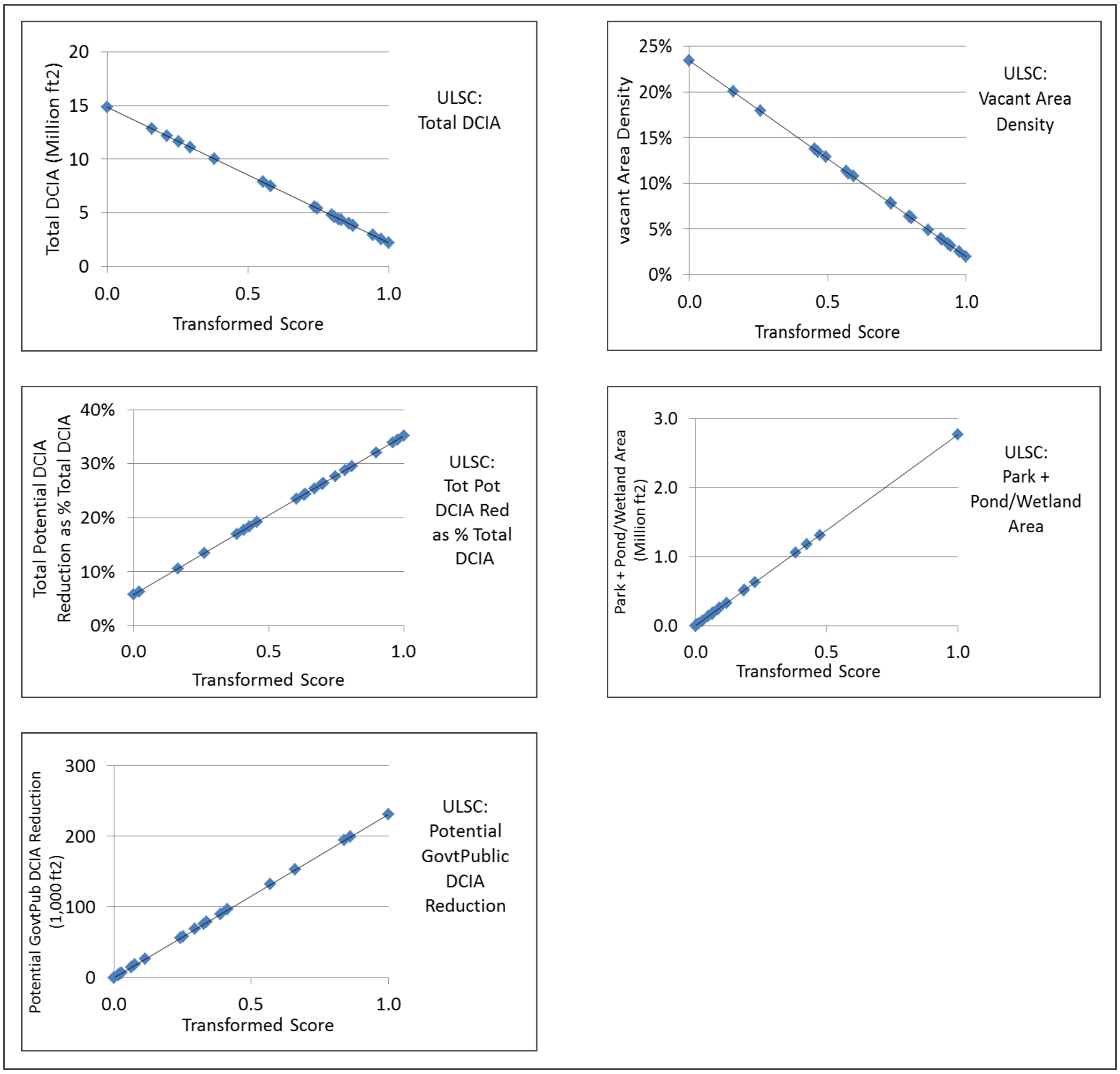

Figure 4.20: ULSC – Performance Value Transformation Utility Functions

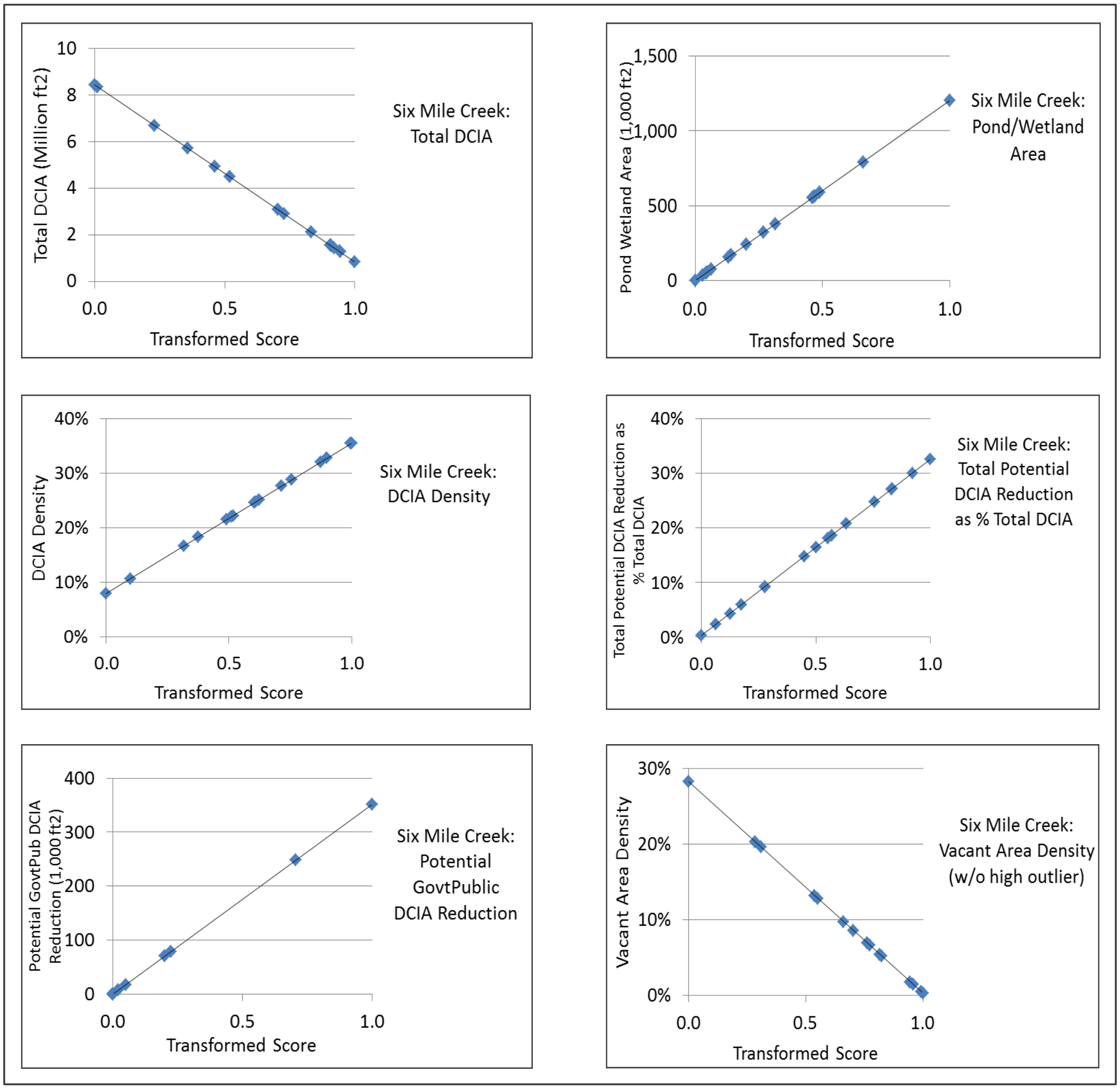

Figure 4.21: Six Mile Creek – Performance Value Transformation Utility Functions

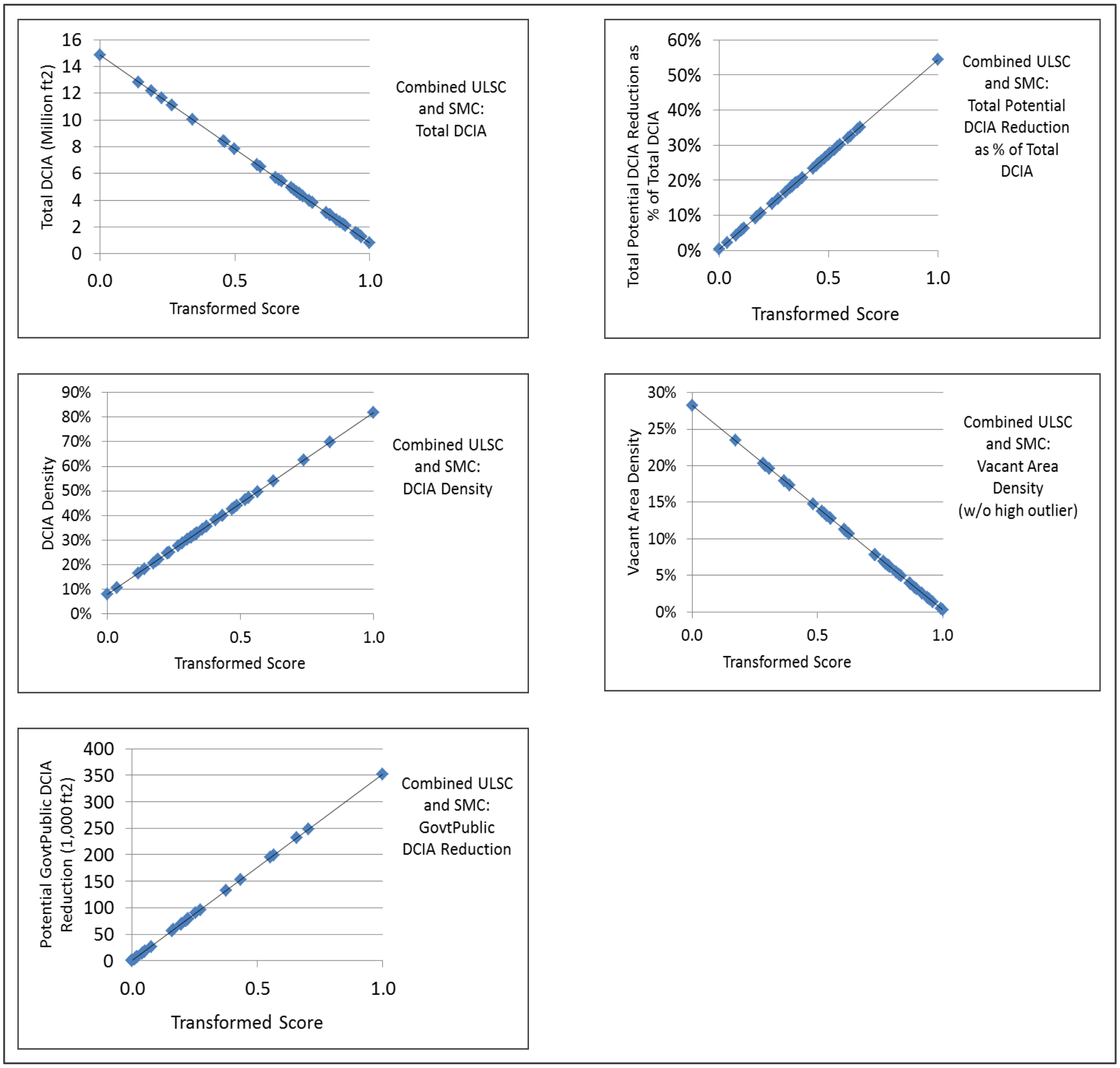

Figure 4.22: Combined ULSC and Six Mile Creek – Performance Value Transformation Utility Functions

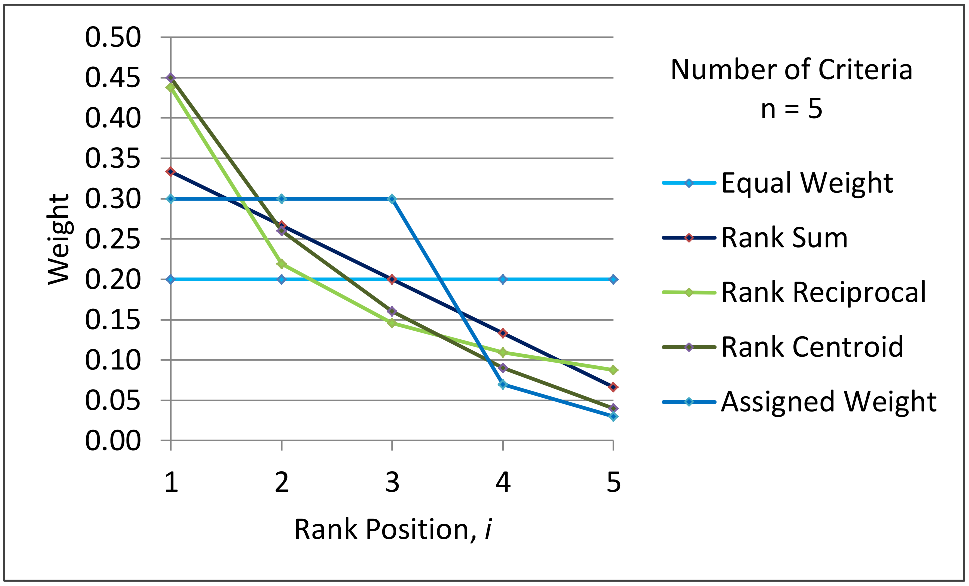

Figure 4.23: Criteria Weight Functions, n = 5

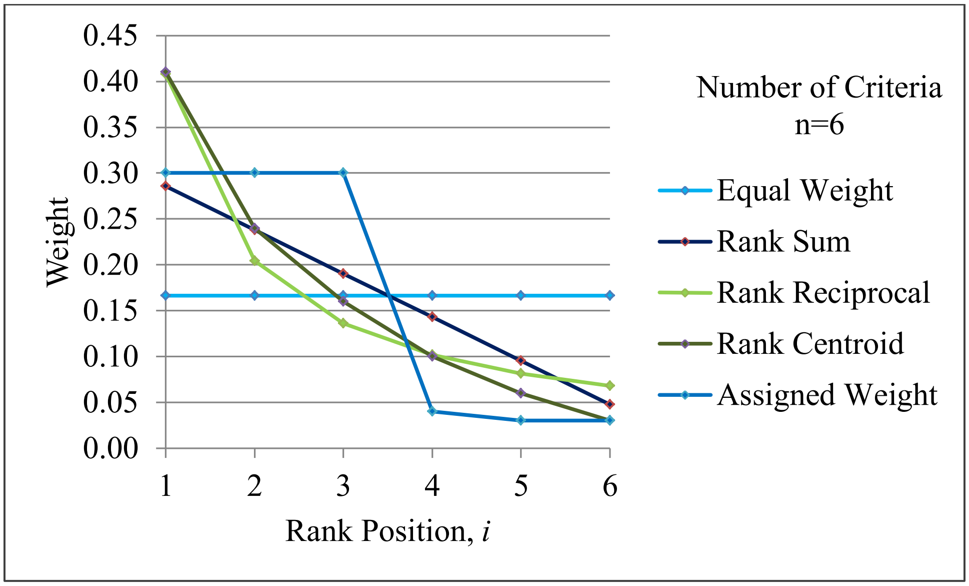

Figure 4.24: Criteria Weight Functions, n = 6

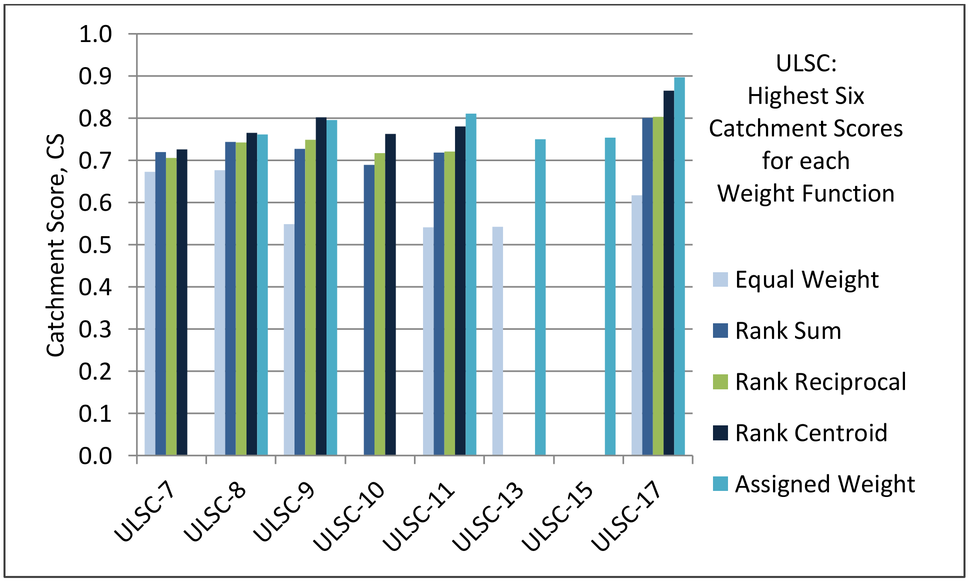

Figure 4.25: ULSC – Highest Six Catchment Scores for Each Weight Function

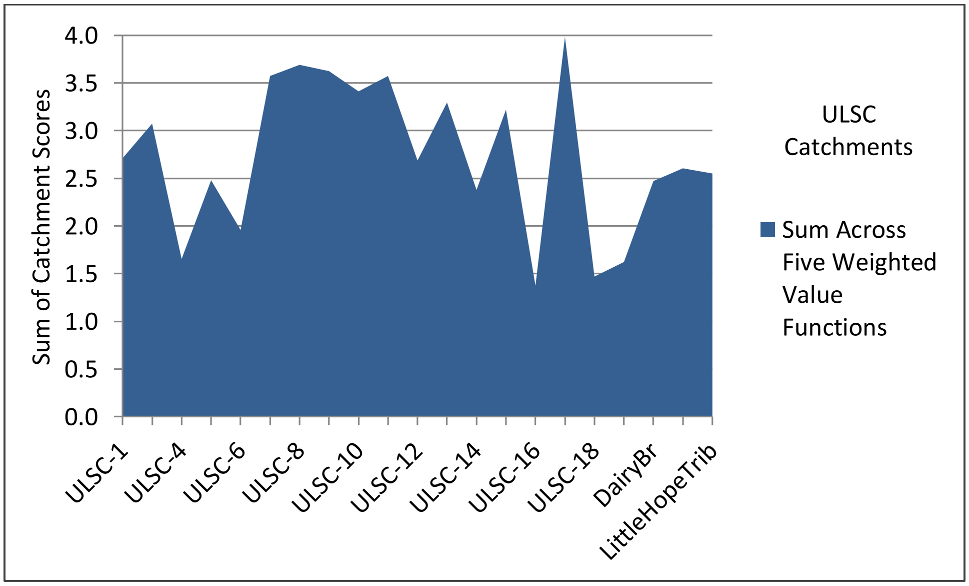

Figure 4.26: ULSC – Sum of Catchment Scores across Five Weight Functions

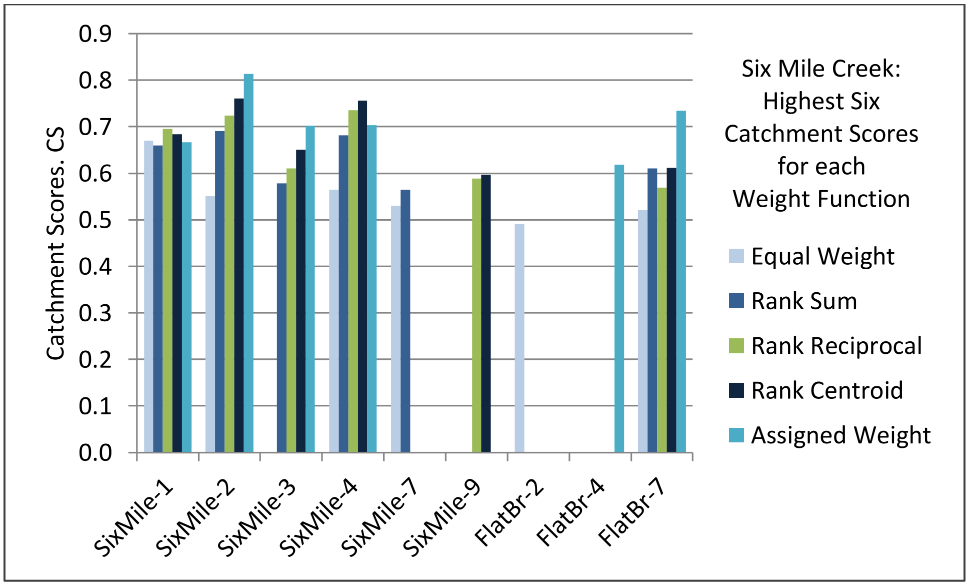

Figure 4.27: Six Mile Creek – Highest Six Catchment Scores for Each Weight Function

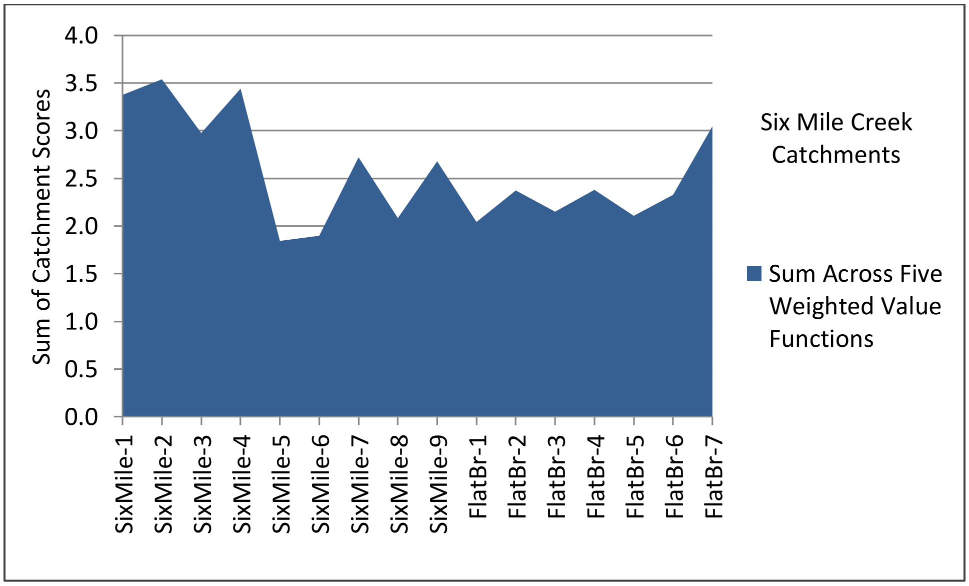

Figure 4.28: Six Mile Creek – Sum of Catchment Scores across Five Weight Functions

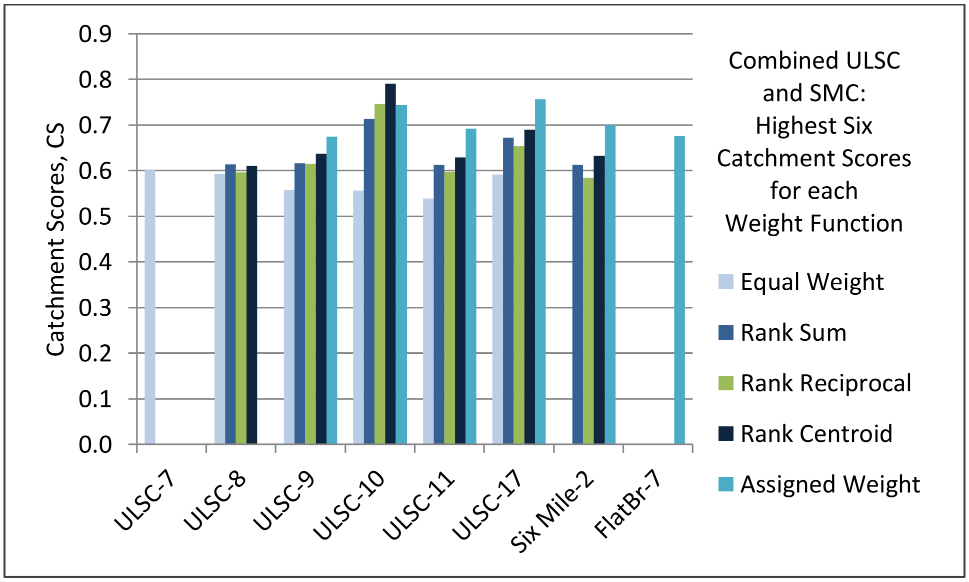

Figure 4.29: Combined ULSC and Six Mile Creek – Highest Six Catchment Scores for Each Weight Function

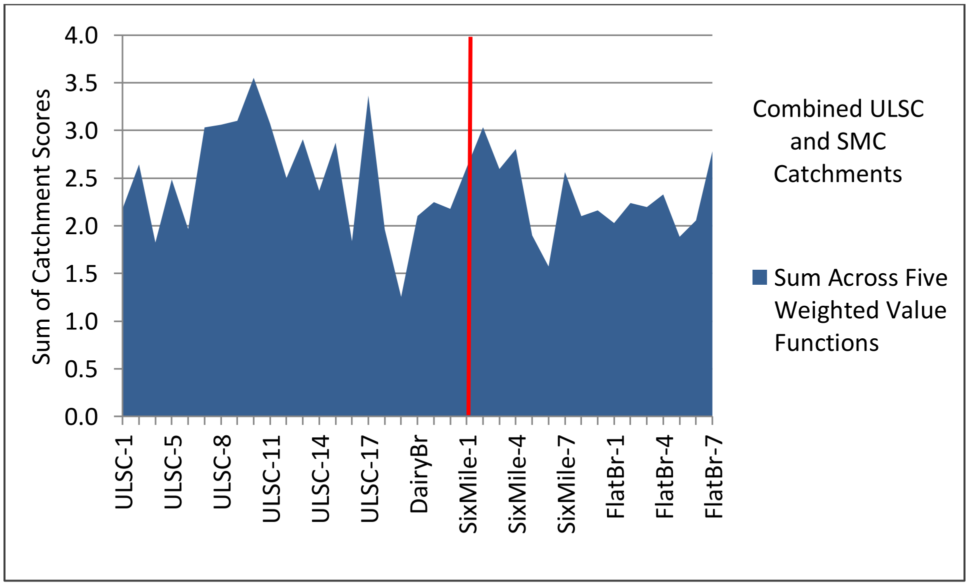

Figure 4.30: Combined ULSC and Six Mile Creek – Sum of Catchment Scores across Five Weight Functions

CHAPTER 5: PERSPECTIVES ON GI RETROFITS AND ECONOMIC INCENTIVES

5.1 Introduction

The low use of stormwater fee credits is a problem if the credits are to be used as an incentive to achieve the level of private participation in GI retrofitting needed to impact stream water quality in impaired watersheds. This problem is intensified due to growing regulatory pressure to implement GI retrofits in existing urban areas with severe stream impairments. The limited number of sites suitable for retrofit and the need for voluntary participation by private property owners, make it is essential to understand why participation in fee credit programs is so low and to assess the efficacy and economic equity issues of existing stormwater utility fee and credit programs (Doll et al. 1999). The overall objective of this portion of research is to determine the characteristics of an equitable stormwater fee and credit program for CMSWS that will provide effective incentives to private commercial property owners to invest in GI retrofits. This section describes the data, methodology and analyses conducted to meet this objective and to answer the research questions related to GI retrofits and economic incentives identified in Section 1.2.3.

This research is intentionally focused on commercial properties. Although single-family residential development contributes a substantial proportion of impervious area in an urban area (approximately 25% overall in the Charlotte-Mecklenburg area) and many municipalities that offer fee credits do so for both residential and commercial properties, CMSWS does not currently offer BMP fee credits for single-family properties. In addition, the results presented in Chapter 4 of this research indicate that commercial properties in the case study watersheds provide the greatest proportion of potential DCIA reduction due to the type of GI measures and their capacity for DCIA reduction.

5.2 Data

The major sources of data used in this portion of the research are GIS data from the CMSWS BMP Database (2016c); available capital and maintenance cost data for GI measures from various sources in the literature and CMSWS (2014 and 2016d); data regarding CMSWS's stormwater revenue, fees, fee credit rates and user criteria from a report prepared for CMSWS by Raftellis Financial Consultants (Raftellis 2015), and personal communication with City of Charlotte staff (Hammock 2015). Additional data available from CMSWS and in the literature are used as indicated in the specific methodology descriptions.

5.3 Methodology

An evaluation of stormwater utility fee and fee credit programs is conducted using available data regarding existing programs throughout the U.S., data available regarding CMSWS's existing and proposed programs, capital and annual maintenance cost data for GI measures available in the literature as well as DCIA reduction data developed as described in Chapter 4 of this document in order to answer the research questions related to GI retrofits and economic incentives. The methodology consists of three main components: identification and analysis of ownership characteristics and regulatory drivers of current CMSWS fee credits; an assessment of the economic value of various U.S. stormwater utility fee and credit structures, including CMSWS's existing and proposed programs, relative to GI investment value for both private commercial property owners and stormwater utilities.

5.3.1 Examination of Current CMSWS Stormwater Fee Credits

Four different types of fee credits are allowed by CMSWS: ‘BMP Credit’ for stormwater management facilities that control peak and/or volume of runoff from commercial properties; ‘County Line Credit’ for land parcels adjacent to the County line; ‘Catawba River Credit’ for parcels adjacent to the Catawba River; and ‘Pond Credit’ for parcels that have an existing natural pond. CMSWS’s BMP database (CMSWS 2016c) is used to identify all existing stormwater management BMPs and associated ‘BMP Credits’ within the CMSWS service area. Other fee credit classifications are not considered in this research because they are not based on construction of a stormwater management facility. The database provides information regarding the type, regulatory basis, ownership and fee credit status for each BMP. These data are examined in an attempt to draw conclusions regarding the motivation of fee credit users based on type of BMP, regulatory driver, and ownership characteristics.

5.3.2 The Economic Value of GI Retrofits for Private Commercial Property Owners

The economic value of GI is dependent upon the objectives of a specific project and the owner’s perspective (Vandermeulen et al. 2011). GI valuation for this portion of the research is from the perspective of a private commercial property owner and only the values that readily inform this perspective and are reflected in market transactions associated with GI retrofits (direct use and investment values) are considered. Intangible value is not considered. The result is an assessment of the value of a reduction in stormwater fee due to fee credits which are directly equated to individual property owner investment values for GI retrofits including capital and annual maintenance costs.

The economic value of three scenarios of a CMSWS stormwater fee and credit structure are assessed relative to the investment value of GI measures for private commercial property owners by calculating net present value (NPV) and internal rate of return (IRR) for various levels of capital investment/utility subsidy and annual cash flows equal to maintenance costs. The net present value (NPV) of a project's expected future cash flows is a measure of the project's value to the property owner. The internal rate of return (IRR) is the discount or interest rate at which the NPV of all cash flows, both positive and negative, of an investment, equal zero.

$$NPV = \sum_{t=0}^{T} \frac{CF_t}{(1+r)^t} \qquad \text{(Eq. 5.1)}$$

Where,

CF_t = Cash flow for period, t

r = Discount rate

t = Time period, t

T = Total time (= 10 years)

Capital and annual maintenance costs for various GI measures are obtained from several available sources in the literature. Quartile values are calculated using MS-Excel (Microsoft 2010) for use in the analyses. Land costs and tax effects on cash flows are not considered. A ten-year payback period is evaluated for NPV because that is the maximum time period typically accepted by commercial property owners for real estate investments (Valderrama et al. 2013).

The three scenarios assessed are: the existing CMSWS stormwater fee for commercial properties with the proposed fee credit for water quality and stream stabilization measures (control of 1-inch and 1-yr storms); existing CMSWS fee with an incentive credit; and an incentive fee with the proposed CMSWS fee credit for water quality and stream stabilization. These equate to alternatives of moderate fee/low credit, moderate fee/high credit and high fee/low credit, respectively. The results are compared to those obtained from a scenario using Philadelphia's stormwater fee and credit program rates which is a high fee/high credit structure relative to the CMSWS scenarios. The Philadelphia program is motived by a judicial consent decree which requires control of a portion of combined sewer overflows (CSOs) with GI. It is one of the most progressive and innovative GI retrofit programs in the U.S. at this time. In all of the scenarios, various combinations of quartile values for capital and annual maintenance costs are used.

5.3.3 Assessment of an Equitable GI Retrofit Program for CMSWS

A GI retrofit program must be economically viable for stormwater utilities as well. An assessment is conducted to determine the magnitude of fee and credit rates that will provide tangible investment value to private commercial property owners for implementing GI retrofits and will also provide investment value to stormwater utilities. NPV analyses of cash flows from the perspective of the stormwater utility are conducted using various levels of retrofit capital costs, stormwater fee revenue and fee credit payments, assuming a 20-year recovery period and a discount rate of 6%. The analyses are performed on a per impervious acre basis.

Although the annual stormwater fee is collected for impervious area on all single-family and commercial properties within the system, only a portion of commercial properties will install GI retrofits and receive the associated credit. Reduction of DCIA from single-family residential properties is not included in the credit program analysis for reasons previously indicated. Also, potential DCIA reduction from road surfaces is not taken into account even though it makes up 30% of potential reduction because road surfaces are not charged a stormwater fee. The proportion of commercial properties that will receive a fee credit due to GI retrofits is represented in the cash flow analysis by adjusting the initial capital expenditure and the annual fee credit expenditure by a DCIA reduction goal for commercial properties across the system.

As indicated in Chapter 4, DCIA reduction is on average approximately 60% of treated DCIA for the two CMSWS case study watersheds. This translates into a DCIA reduction goal of 12% if a treatment goal of 20% of DCIA is assumed. Although the DCIA treatment goal would be met by contributions from all land use types – commercial, single-family and roadway/sidewalk, for this assessment commercial property fee credits expenditures are assumed for the full 12% DCIA reduction. Capital and fee credit expenditures in the NPV calculations are multiplied by a factor of 0.12 to account for this. In addition, because the GI retrofits would be built over the course of the 20-year period, the full capital cost of these GI retrofits would not be paid out initially and the full expense of the fee credits would not be realized for the entire 20 years period but would be added gradually as retrofits are implemented. Therefore, the capital costs are divided in to four increments of 0.03 and the fee credit expenditure is increased by 0.03 at the beginning a each 5-year period.

Three sets of curves of fee vs. fee credit and capital cost vs. fee credit are developed based on three levels of potential annual maintenance costs which are assumed to directly drive the incentive for fee credits for private commercial property owners. To make a GI retrofit program equitable for CMSWS, the NPV of the program including a retrofit program should at least equal the existing NPV with no retrofit program in place. CMSWS's current fee and credit rate are used as a baseline for the analysis. The current stormwater fee rate for commercial properties is $1,975 per impervious acre and the average residential rate is $2,012 per impervious acre (CMSWS 2016a) and the proportion of non-roadway DCIA is 62% commercial and 38% single-family. Therefore, a weighted average stormwater fee rate of $1,989 per impervious acre, with no capital costs and no fee credit, is used to determine the baseline NPV goal over 20 years at 6%. This NPV is the goal for all combinations of capital cost, fee and fee credit for the low maintenance (Q1-25%) scenario. The fee credit is always equal to the annual maintenance cost in order to provide proper incentive to the property owner. Using the NPV goal, various levels of capital cost are input, the fee credit remains constant and the required fee to provide the NPV goal is determined.

For the median (Q2-50%) and high (Q3-75%) annual GI maintenance costs, which are higher than CMSWS's current stormwater fee, the NPV goal is set using a baseline fee determined by dividing the annual maintenance cost by 71% which is CMSWS's proposed maximum fee credit. Although this is not the maximum fee credit currently proposed for water quality measures it is assumed this would be the maximum credit CMSWS will consider in any type of incentive program going forward.

There are many simplifying assumptions made for this assessment. Fee rate increases, tax implications, depreciation and other detailed accounting costs are not considered in this analysis. These assumptions together with the evaluation at various magnitudes of incentive value provide results within conservative boundaries for policy discussion purposes.

5.4 Results and Discussion

5.4.1 Characteristics of CMSWS Stormwater BMP Fee Credits

CMSWS has approximately 250,000 stormwater accounts including 25,000 commercial accounts which are potentially eligible for BMP fee credits if stormwater control is provided on the property (Hammock 2015). Current CMSWS policy provides fee credits for structural stormwater BMP facilities on commercial properties that reduce peak discharge or control runoff volume (Charlotte 2008). The Charlotte BMP database (CMSWS 2016c) includes data for 2,823 stormwater BMPs.

Construction of stormwater BMPs in Charlotte-Mecklenburg is based on one or more of thirteen specific regulatory requirements identified in Table 5.1. Currently, eighteen different types of stormwater BMPs are used to meet these regulatory requirements: four are detention type facilities and are eligible to meet current CMSWS fee credit requirements; five are GI-type measures that have the capability to reduce runoff volume for smaller storm events and are not typically eligible for current CMSWS fee credits; five provide both some level of detention and volume reduction capability; and four are used to manage stormwater but do not provide detention or GI type control . Table 5.1 identifies the types and numbers of existing stormwater BMPs within the CMSWS service area and the regulatory driver for each. The number of each type of

BMP that currently receives a fee credit is also indicated by BMP type and regulatory driver.

A total of 2,569 BMPs or 91% of existing BMPs have the potential to provide some level of peak reduction and/or volume control, of which only 304 or 12% receive a fee credit. Assuming that each of the 2,823 stormwater BMPs corresponding to one of the 25,000 commercial accounts (some accounts may actually have multiple BMPs), approximately 11% of accounts provide stormwater control, 10% are potentially eligible to receive a fee credit under the current credit policy and 1.2% currently receive a stormwater BMP credit.

Detention facilities (dry ponds, underground detention basins, wetlands and wet ponds) account for just over 94% of all BMPs that receive a fee credit. This is not unexpected as these types of BMPs are primarily used to reduce peak discharges and detain runoff volume for a specified time period and have the greatest potential to meet CMSWS's current fee credit requirements. However, this represents only 8.7% of all existing detention type facilities. The remaining 6% of BMPs that receive a fee credit is equally split between bioretention basins (3%) and sand filters (3%) representing 5.8% of all sand filters and 1.7% of all bioretention basins. These lower rates of fee credit use for bioretention and sand filters are not unexpected as they are primarily designed according to water quality standards during smaller storm events, and not peak or volume control during larger events.

The primary regulatory driver for all BMP types, with or without fee credit eligibility, is the detention ordinance (44%), followed by the post-construction ordinance (PCO) (19%), low impact development requirements (LID) (13%), watershed overlay districts (6.2%) and conditional rezoning (4.1%). Municipal BMPs; the BMP pilot program; capital investment program (CIP)/stream restoration; and the 401, state and Surface Water Improvement and Management (SWIM) mitigation programs together account for approximately 6.2% of BMPs implemented. The regulatory driver for another 6.4% of BMPs is not identified and seven BMPs, or less than 1%, have been installed voluntarily.

The regulatory drivers which are associated with the highest number of BMP fee credits are the detention ordinance (195 BMPs or 16%), the PCO (37 BMPs or 6.9%) and conditional rezoning (14 BMPs or 12%). Another 48 BMPs (26%) with no identified regulatory mechanism receive a fee credit. Two of seven BMPs that were installed voluntarily receive fee credits. All seven are bioretention basins so those without fee credits most likely do not qualify for peak or volume control credit under the current requirements.

All of the BMPs regulated by the detention ordinance have the potential to meet the current credit criteria with just 16% receiving fee credits. A variety of BMPs have been implemented as a result of the PCO including several that are not eligible for credit. Fewer than 10% of eligible BMPs regulated by the PCO receive a fee credit. Proportionally, more eligible BMPs constructed per the detention ordinance receive fee credits than do those constructed per the PCO. In either case, usage of the current fee credit is low.

It is remarkable that so few eligible BMPs implemented in accordance with the PCO obtain a fee credit. The PCO requires property owners to execute a BMP maintenance agreement with CMSWS whether credit is received or not. It is possible that one of the reasons for low credit use prior to the PCO is that property owners were not required to execute a maintenance agreement for facilities constructed per the detention ordinance and were not willing to do so in exchange for the fee credit. However, the fee credit use data suggest that the required maintenance agreement per the PCO does not provide any more motivation for fee credit use than the detention ordinance.

Government ownership of a BMP also does not appear to affect fee credit use. Approximately 14% of all 2,569 BMPs that are potentially eligible for fee credits are government owned and only 7.0% of these obtain a credit.

An examination of available CMSWS fee credit data does not reveal any relationship between fee credit use and BMP type, BMP regulatory driver or ownership. Low fee credit use could be a function of BMPs not meeting the current peak and volume reduction requirements, a general lack of knowledge of the fee's existence on the part of property owners, the low value of the fee itself as suggested in the literature, and/or the low value of the credit.

5.4.2 Capital and Annual Maintenance Cost Data for Stormwater BMPs and GI

Table 5.2 presents capital cost data and Table 5.3 presents annual maintenance cost data available from the literature for GI and conventional stormwater BMPs. Capital cost data for bioretention basins and annual maintenance cost data for several GI measures and BMPs available from CMSWS are also included. Quartile values for both sets of cost data are calculated using MS-Excel (Microsoft 2010) and presented in Table 5.4. These quartiles are assumed to be the best overall national cost values available keeping in mind that land costs, space limitations and existing utilities can have a large effect on cost of GI and that incorporating GI retrofits on existing development is typically more expensive than on new development and redevelopment (Potts et al. 2015). In addition, specific cities and utilities will have varying costs based different local weather, age of infrastructure, growth, population, area served, combined sewer areas, separate sewer areas, regulatory requirements, local water quality, labor costs, and level of service. Quartile values for low (Q1 – 25%), median (Q2 – 50%) and high (Q3 – 75%) costs are used for both sets of costs in the economic value assessment cases.

5.4.3 The Economic Value of GI Retrofits for Private Commercial Property Owners

The quartile values for capital and annual maintenance costs are used as indicated in the three economic assessment scenarios of various Charlotte fee/ credit structures. The fourth assessment performed for the Philadelphia scenario uses the quartile values for annual maintenance costs but uses an aggregate capital cost per impervious acre that the City has been able to attain in its retrofit program of $90,000 (Valderrama et al. 2013) in place of the moderate and high capital quartile costs derived for this research.

The various fee and fee credit combination values for the scenarios are presented in Table 5.5. The NPV and IRR results are presented in Table 5.6 and shown in Figure 5.1. Figure 5.1 only shows one case for Charlotte Scenario 2 and three cases for Philadelphia Scenario 4. This is because the NPV for all other cases is less than 0 with an undefined IRR as indicated in Table 5.6.

The only viable scenario for a private commercial property owner with minimal capital subsidy is Philadelphia Scenario 4C (high fee and high credit in combination with low capital cost and low annual maintenance fee). Any other combination of capital and maintenance cost even with Philadelphia's high fee and credit require at least 70% capital subsidy to achieve a positive IRR. The only Charlotte scenario that has a positive IRR is the low capital/low maintenance case, 2C, with Charlotte's existing fee and the maximum proposed fee credit of 71% (moderate fee/high credit). This case would still require 85% capital subsidy.

The results of this assessment agree with the City of Philadelphia's well-established regulatory driven stormwater retrofit program that has demonstrated fee credits provide sufficient incentive to commercial property owners only when capital and other up-front costs of GI retrofits are subsidized and their annual value is comparable to recurring costs to maintain functionality of the BMPs and monetary value of the fee credits (Valderrama et al. 2013; Valderrama and Davis 2015).

5.4.4 The Economic Value of GI Retrofits for CMSWS: Recovery of Capital Cost and Fee Credit

The results of the NPV analyses from the perspective of a stormwater utility are presented in three sets of curves based on the three quartile values for annual maintenance. For each value of annual maintenance cost, two curves provide results of the NPV analysis as shown in Figure 5.2: one represents annual stormwater fee per impervious acre vs. fee credit percentage and the other represents capital cost per impervious acre vs. fee credit percentage. The curves of stormwater fee required vs. credit percentage offered are essentially indifference curves which show the combination of stormwater fee and fee credit at the value of annual maintenance cost at every point resulting in the correct economic incentive to property owners. The two curves together at each level of maintenance indicate the annual fee required to not only provide incentive to property owners by matching the annual maintenance cost at various levels of fee and credit but also to recover the associated fee credit as well as the maximum capital cost per impervious acre over a period of 20-years. Recall, the NPV analysis attempts to meet the NPV of the program with no fee credits or capital costs for GI retrofits. Also, only 12% of impervious area, which represents commercial retrofits, would be expected to be retrofitted over 20 years and receive the fee credit. Additional retrofit to meet the theoretical desired goal of DCIA reduction would come from roadways which do not pay a stormwater fee and would not be eligible for a credit. Additional retrofit/DCIA reduction would be attributed to single-family residential retrofits but are not accounted for in this analysis.

Using CMSWS's current stormwater fee of approximately $2,000 per impervious acre, the results indicate that to provide incentive to a commercial property owner to install a GI retrofit with a capital cost of $75,000 per impervious acre (CMSWS's estimated GI capital cost – CMSWS 2015b), the utility would have to increase the annual fee by 45% to approximately $2,900 per impervious acre and provide an annual credit of at least 38%. This scenario provides an annual credit equal to the low annual maintenance cost (25% quartile, Q1) of $1,117 per impervious acre. Different capital and/ or maintenance costs for a specific GI measures would result in different annual fee and credit requirements. Obviously, CMSWS would have to have strong justification for a 45% rate increase for all impervious areas within the service area.

Cities such as Philadelphia and Seattle have been able to provide proper justification for high fees due to system CIP requirements resulting from judicial actions related to CSOs. Although fee and credit programs of Maryland counties within the Chesapeake Bay watershed (see Table 2.6) have TMDL and NPDES permit requirements for impervious area treatment, the current magnitude of fees and credits do not appear to provide sufficient incentive for extensive private commercial retrofit according to the results of this analysis. However, those areas are concentrating primary retrofit efforts on public property and roadways with funding from water quality protection funds, bonds and state grants (MDE 2016). Credit incentives offered by these municipalities are mostly for small scale retrofits such as on residential property where the cost of capital and maintenance are much lower.

Unless MS4s come under stricter requirements for impervious area reduction similar to the levels being required in CSO areas, stormwater utilities will not have the need for or ability to justify the higher stormwater fees and credits necessary to incentivize private retrofit. Although the effectiveness of GI in reducing and delaying the volume of stormwater entering combined sewers has been proven, this is not the case for GI with regard to restoration of streams with aquatic and biological impairments. If the regulatory environment ever moves in that direction, measured performance from a GI retrofit experimentation programs would be extremely useful in proving the technology.

5.5 Conclusions

The results of this research indicate that current stormwater fee and fee credit rates of many U.S. stormwater utilities, including CMSWS, do not provide an equitable incentive for commercial utility customers to invest in GI retrofits.

An examination of the regulatory driver, BMP type and ownership characteristics of existing CMSWS stormwater BMPs that receive fee credit and those that do not, does not explain why fee credit use for existing eligible stormwater control facilities is so low. The are many potential reasons: the low value of the fee, which is the most common reason cited; lack of knowledge of the credit; low value of the credit relative to the cost involved in obtaining or keeping the credit; risks related to duration and terms of renewal policies; and/or ineligibility of the BMP in meeting current fee requirements (Reese 1996; Doll et al. 1999; Ellard 2011; Crisostomo 2015). The best way to credibly determine the actual reasons for low participation in the CMSWS stormwater BMP fee credit program or other municipal fee credit programs would be to interview or survey commercial property owners. A survey of this type would also be a good opportunity to gather information regarding commercial property owners' attitudes toward GI and willingness to participate in potential retrofits. Several studies are cited in the literature regarding the willingness of residential property owners, stormwater managers and construction professionals to implement GI; however, there are none that investigate this from the perspective of private commercial property owners.

Analysis of the economic value of GI to commercial property owners answers the question regarding incentive capacity of current fee credit programs in the U.S. The majority of stormwater fee and credit programs identified in this research do not provide an equitable incentive to commercial property owners to invest in GI retrofits. The only tangible value to private property owners to offset the capital and ongoing maintenance costs of GI retrofits are fee credits and rebates. The results of the NPV and IRR scenarios for the CMSWS case study show that with the current fee rate of approximately $1,975 per impervious acre for commercial properties and the proposed maximum potential credit of 71%, a capital subsidy of at least 87% is still required to obtain a positive IRR assuming an annual maintenance cost of $1,117 per impervious acre. The assumed fee credit of 71% is CMSWS's proposed maximum credit for peak control of the 100-year storm event, not for actual proposed fee credit for water quality controls of 18% and the annual maintenance cost is the low quartile value from the literature. Even with a moderate fee and high fee credit value the results indicate that only when capital costs are fully subsidized and the fee credit value is greater than annual maintenance costs is there sufficient incentive for private property owners to invest in GI retrofits.

The results of this research lead to the conclusion and an answer to the final question that a stormwater fee and credit combination based on the cost of capital and fee credits to the stormwater utility and fee credits equal to the cost of annual maintenance to property owners can provide equitable incentives to both groups to invest in GI retrofits. There are benefits to both stormwater utilities and commercial property owners of setting the fee credit to annual maintenance costs for GI or traditional BMPs. This is pay for performance and can potentially assure long term maintenance and performance of system-wide infrastructure and reduce utility inspection costs. Crisostomo (2014) indicates that few stormwater programs actually conduct regulatory inspection of private stormwater management facilities because of the cost involved. Property owners are paid for maintaining their assets and reporting requirements force documentation of maintenance activities. This has value in due diligence investigations for both buyers and sellers during commercial real estate sales transactions.

The literature cites potential additional tangible value of GI retrofits to commercial property owners such as tax credits, decrease in water and wastewater costs, and increases in property value; however, these are specific to individual GI measures and building characteristics and are difficult to estimate in a general manner (Jaffe 2010; Clements et al. 2013).

Current stormwater fee rates and the proportion allowed for credits related to water quality and/or GI for several U.S. municipalities are shown in Figure 5.3. Analyses of stormwater fees and credits in the majority of these other municipalities would provide similar results because the fees and maximum credit rates are lower than the values used in the Charlotte example. Lower annual maintenance costs, whether for an individual BMP or detailed regional costs, would provide a positive IRR at lower capital subsidy rates. Only two cities, Philadelphia and Seattle currently have fees and credits at levels to provide retrofit incentive value for private property owners assuming a large capital cost subsidy and a range of estimated annual maintenance costs. In these two cases, CSO judicial actions drive the retrofit programs and policies. According to this analysis, Montgomery County, MD and Prince Georges County, MD which are within the Chesapeake Bay watershed and subject to TMDL impervious area treatment goals do not have fees and credits high enough to provide retrofit incentives for private commercial property owners.

Unlike areas that are using incentive level fees and credits to comply with system-wide CSO abatement requirements such as Philadelphia and Seattle or separate storm sewer areas within the Chesapeake Bay watershed that are required to comply with TMDL and NPDES MS4 permit requirements, a regulatory based GI retrofit program in the Charlotte area would most likely be in relation to a TMDL and/or MS4 permit requirement for a specific stream impairment and would be implemented in an individual watershed. However, it is still appropriate to evaluate retrofit requirements at the watershed scale and to determine the system wide financial effects of a fee increase and credit program because the program would be administered system wide.

Table 5.1: CMSWS Stormwater BMP Types, Regulatory Basis and Fee Credits

	BMP Type [a, b]			BMP Regulatory Basis [c]												
	Total no. BMPs	No. with fee credit	% with fee credit	401 Mitigation	CIP stream restoration	Conditional rezoning	Detention ordinance	LID: Huntersville/ Watershed overlay	Municipal BMP	Other - Voluntary	Other – BMP pilot	Other – Not identified	PCO/PCO and watershed overlay	State/ SWIM mitigation	Watershed overlay	Not identified
Total no. BMPs	2,823	304	10.8%	31	62	117	1,250	380	54	7	19	38	539	8	174	144
No. with fee credit	304			2	0	14	195	0	0	2	0	0	35	1	5	48
% with fee credit	10.8%			6.5%	0%	12.0%	15.6%	0%	0%	28.6%	0%	0%	6.5%	12.5%	2.9%	33.3%
Bioretention [a, b]	527	9	1.7%	1	29	26	24	239	28	7 (2)	3		105 (7)		57	8
Stream buffer	5	0	0%										2	3		
Cistern [b]	1	0	0%		1											
Dry pond [a]	1,217	146	12.0%		1	14 (1)	926 (125)	76	11		1	27	91 (3)	1	17	52 (17)
Enhance grass swale [b]	33	0	0%		2	1		30								
Filter strip [b]	10	0	0%			7			1						2	
Grassed channel [b]	29	0	0%		2	12		11					3		1	
Infiltration trench [b]	9	0	0%					3			1		5			
Level spreader	1	0	0%		1											
Open space	144	0	0%			1	5						111			27
Rain garden [a, b]	1	0	0%		1											
Sand filter [a, b]	138	8	5.8%	2	1	8 (3)	1	12	4				102 (5)		4	4

Table 5.1 (continued)

Stream restoration	18	0	0%		17									1		
Underground detention [a]	234	23	9.8%			9	149 (19)	3	5		2	1	59 (4)			6
Underground sand filter [a, b]	4	0	0%										4			
Wetland [a]	59	6	10.2%	11 (2)	7	11	1	3	4		8		2 (1)	2	6	4 (3)
Wet pond [a]	388	112	28.9%	17		28 (10)	144 (51)	3	1		1	10	54 (17)	1 (1)	87 (5)	42 (28)
Not identified (permeable pavement and proprietary) [a, b]	5	0	0%								3		1			1

Notes: BMP = Best management practice; CIP = Capital investment program; CMSWS = Charlotte-Mecklenburg Stormwater Services; GI = Green infrastructure; LID = Low-impact development; PCO = Post-Construction Ordinance; SWIM = Surface water improvement and management.

[a] Eligible for current CMSWS stormwater fee credit due to peak reduction and/or volume control potential.
[b] GI measure that reduces runoff volume.
[c] Total number of BMPs within each regulatory category, number of BMPs with fee credit in parentheses.

Table 5.2: Capital Cost Data for GI Measures and Conventional Stormwater BMPs

GI Measure/ BMP	CNT (2009) [b]	King and Hagan (2011) [c]	Houle et al. (2013) [d]	Valderrama et al. (2013) [e]	CMSWS (2014) [f]	CH2M-Hill (Low) (2013) [g]	CH2M-Hill (High) (2013) [g]	USEPA (Low) (2015c) [h]	USEPA (High) (2015c) [h]
Capital cost in U.S. dollars per impervious acre [a]									
GI Measures:									
Bioretention	$131,875	$196,750	$26,830		$240,350		$90,100	$131,000	$174,000
Raingarden	$204,311			$187,800			$37,000		
Porous asphalt/ porous pavers			$27,890						
Porous asphalt	$32,387								
Permeable/ porous pavement	$32,387								
Permeable/ porous pavement	$662,296			$236,250			$113,000		*See Note ‘i'*
Permeable/ porous concrete	$210,394								
Grass/ gravel pavers	$186,166								
Interlocking pavers	$323,627								
Permeable pavement (w/o underdrain)		$256,530							
Permeable pavement (w/ underdrain)		$359,140							
Vegetated swale/ open channel	$18,568	$25,700	$15,370	$54,840			$90,000		*See Note ‘i’*
Bioswale		$45,000					$90,000		
Urban grass buffer	$186,654	$24,800							
Infiltration trench									

Table 5.2 (continued)

Tree planting		$35,300					$71,100		
Tree box									
Planter box				$269,610					*See Note 'i'*
Infiltration planter w/o parking	$215,064								
Infiltration planter w/ parking	$430,128								
Impervious area reduction		$103,100		$199,690					
Downspout disconnect (res)	$15,054			$15,990					
Rainwater harvesting	$62,387			$149,880		$15,500	$35,200	$87,000	$220,000
Green roof	$653,008			$1,598,500			$518,000	$1,300,000	$1,700,000
Conventional Stormwater BMPs:									
Wet Detention Pond		$68,530	$17,280						
Dry Detention Pond			$17,280						
Dry Extended Detention Pond		$72,300							

Table 5.2 (continued)

Notes:

[a] All costs are given in U.S. dollars per impervious acre. Costs have been converted to 2016 dollars using the Bureau of Labor Statistics' CPI Inflation Calculator at http://data.bls.gov/cgi-bin/cpicalc.pl, as noted.

[b] Costs from CNT (2009), National Green Values Calculator Methodology, are only from sources given in cost per impervious area treated. Costs have been converted to 2016 dollars from the source date provided in the reference document.

[c] King and Hagan (2011) provide pre-construction and construction costs for BMPs in Maryland (converted from 2011 to 2016 dollars). Costs provided are for retrofit where available and exclude land costs.

[d] Houle et al. (2013) provide costs for BMPs in New Hampshire (converted from 2012 to 2016 dollars).

[e] Valderrama et al. (2013) (also referred to as Natlab, 2013) are mid-range, 25% and 75% quartile, 2012 BMP construction costs from various sources and include design, engineering and contingency costs. Mid-range costs, converted to 2016 dollars, are reported here. Sources include "The Use of Best Management Practices in Urban Watersheds (EPA, 2004) and "Urban Stormwater Retrofit Practices Manual" (Center for Watershed Protection, 2007).

[f] Average cost of two bioretention basins, converted from 2014 to 2016 dollars (CMSWS 2014).

[g] CH2M-Hill (2013) costs are stand-alone 2013 costs per impervious area managed, converted to 2016 dollars.

[h] USEPA (2015c) costs are from the following sources: Green roofs costs are referenced to USEPA (2009a) which provides green roof costs from Peck and Kuhn (2001); raingardens/bioretention costs are from Coffman et al. (1999); these costs have not been converted to 2016 dollars. Other sources of costs reported in USEPA (2015c) are as indicated in Note 9, below.

[i] In USEPA (2015c), costs for planter boxes are from Valderrama et al. (2013); costs for permeable pavement and bioswales are from Valderrama et al. (2013) and King and Hagan (2011). These costs are already included in this table and are therefore not attributed to USEPA.

Table 5.3: Maintenance Cost Data for GI Measures and Conventional Stormwater BMPs

GI Measure/ BMP	CNT (2009) [b]	King and Hagan (2011) [c]	Houle et al. (2013)[d]	Geosyntec (2014) [e]	CMSWS (2016d) [f]	Potts et al. (Low) (2015) [g]	Potts et al. (High) (2015) [g]	USEPA (Low) (2015c) [h]	USEPA (High) (2015c) [h]
Maintenance cost in U.S. dollars per impervious acre [a]									
GI Measures:									
Bioretention		$1,603	$2,095	$1,063	$1,186	$1,200	$2,100		
Raingarden	$3,195			$1,072					
Porous asphalt/ porous pavers			$1,133			$2,000	$3,200		
Porous asphalt									
Permeable/ porous pavement	$278			$2,688		$1,600	$2,700		
Permeable/ porous pavement	$4,658								
Permeable/ porous concrete									
Grass/ gravel pavers									
Interlocking pavers									
Permeable pavement (w/o underdrain)		$2,330							
Permeable pavement (w/ underdrain)		$3,263							
Vegetated swale/ open channel	$593	$640	$967						
Bioswale									
Urban grass buffer		$919							
Infiltration trench									

Table 5.3 (continued)

Tree planting		$1,285						
Tree box				$2,701	$2,000	$3,300		
Planter box				$2,026				
Infiltration planter w/o parking	$2,131							
Infiltration planter w/ parking								
Imp. area reduction		$937						
Downspout disconnect	$29							
Rainwater harvesting				$4,696				
Green Roof	$1,156				$3,000	$5,000	$54,500	$87,000
Conventional Stormwater BMPs:								
Wet Detention Pond		$794	$3,319					
Dry Detention Pond		$1,284	$2,609	$930				
Dry Extended Detention Pond								

Notes:

[a] All costs are given in $ per impervious acre. Costs have been converted to 2016 dollars using the Bureau of Labor Statistics' CPI Inflation Calculator at http://data.bls.gov/cgi-bin/cpicalc.pl, unless otherwise noted.

[b] Costs from CNT (2009) National Green Values Calculator Methodology are only from sources given in cost per impervious area treated. Costs have been converted to 2016 dollars from the source date provided in the reference document.

[c] King and Hagan (2011) provide costs for BMPs in Maryland (converted from 2011 to 2016 dollars).

[d] Houle et al. (2013) provide costs for BMPs in New Hampshire (converted from 2012 to 2016 dollars).

[e] Geosyntec (2014) provide costs for BMPs in Florida (converted from 2014 to 2016 dollars).

[f] CMSWS (2016d) maintenance cost data spreadsheet.

[g] Potts et al. (2015) provide a range of costs for BMPs nationwide (costs have not been converted to 2016 because the conversion from 2015 to 2016 dollars would be insignificant relative to reading estimates from the source document graphic presentation).

[h] USEPA (2015c) green roof costs are referenced to USEPA (2009a) which provides a range of green roof costs from Peck and Kuhn (2001); these costs have not been converted to 2016 dollars.

Table 5.4: Quartiles of Capital and Annual Maintenance Cost Data for GI Measures and Conventional Stormwater BMPs

	Capital Cost, $/Impervious Acre					Annual Maintenance Cost, $/Impervious Acre				
GI Measure/ BMP	Min	Q1 (25%)	Q2 Median (50%)	Q3 (75%)	Max	Min	Q1 (25%)	Q2 Median (50%)	Q3 (75%)	Max
All GI measures	15,054	35,725	131,438	232,188	1,700,000	29	1,117	2,013	3,049	87,000
Bioretention and raingarden	26,830	100,325	152,938	194,513	240,350	1,063	1,157	1,402	2,096	3,195
Porous asphalt/ porous pavers/ porous concrete/ permeable pavement w/ and w/o underdrain	27,890	72,694	210,394	290,079	662,296	278	1,700	2,509	3,075	4,658
Vegetated swale/ open channel/bioswale/urban grass buffer	15,370	24,800	45,000	90,000	186,654	593	628	780	931	967
Tree planting	35,300	44,250	53,200	62,150	71,100	1,285	n/a	n/a	n/a	1,285
Tree box/ planter box/ infiltration planter	215,064	242,337	269,610	349,869	430,128	2,000	2,026	2,131	2,701	3,300
Impervious area reduction	103,100	127,248	151,395	175,543	199,690	937	n/a	n/a	n/a	937
Downspout disconnection	15,054	15,288	15,522	15,756	15,990	29	n/a	n/a	n/a	29
Rainwater harvesting	15,500	41,997	74,694	134,160	220,000	4,696	n/a	n/a	n/a	4,696
Green roof	518,000	653,008	1,300,000	1,598,500	1,700,000	1,156	3,000	5,000	54,500	87,000
Conventional Stormwater BMPs	17,280	17,280	42,905	69,473	72,300	794	930	1,284	2,609	3,319

Notes: BMP = Best management practice; GI = Green infrastructure; Max = Maximum; Min = Minimum; n/a = Not applicable; Q1 = Quartile 1 (25%); Q2= Quartile 2 (50%); Q3 = Quartile 3 (75%)

Table 5.5: Stormwater Fee and Credit Values for Private Commercial Property Owner GI Retrofit Investment Scenarios

	Scenario 1: Charlotte (Moderate Fee, Low Credit) [a]	Scenario 2: Charlotte (Moderate Fee, High Credit) [b]	Scenario 3: Charlotte (High Fee, Low Credit) [c]	Scenario 4: Philadelphia (High Fee, High Credit) [d]
Existing Annual Stormwater Fee	$1,975	$1,975	$5,135	$5,135
Maximum GI and/or Water Quality Credit %	18%	71%	18%	90%
Annual GI and/or Water Quality Credit Value	$356	$1,422	$924	$4,622

Notes:

[a] Charlotte existing non-residential stormwater fee (CMSWS 2016a), proposed Charlotte GI (4%) plus stream stabilization (14%) fee credits (CMSWS 2015d).

[b] Charlotte existing non-residential stormwater fee (CMSWS 2016a) and proposed Charlotte maximum (= incentive) fee credit GI (CMSWS 2015d).

[c] Philadelphia existing non-residential stormwater fee (Philadelphia 2016, proposed Charlotte GI (4%) plus stream stabilization (14%) fee credits (CMSWS 2015d).

[d] Philadelphia existing non-residential stormwater fee (does not include billing or gross area fee) and existing GI fee credit (Philadelphia 2016).

Table 5.6: Private Commercial Property Owner NPV and IRR Results for GI Retrofit Investment Scenarios

Scenario 1 – Charlotte: Moderate Fee, Low Credit [a, b]
1A = High capital cost (Q3); High annual maintenance cost (Q3)
1B = Median capital cost (Q2); Median annual maintenance cost (Q2)
1C = Low capital cost (Q1); Low annual maintenance cost (Q1)

Owner Capital Investment	% Capital Subsidy	1A		1B		1C	
		NPV	IRR	NPV	IRR	NPV	IRR
100%	0%	-$237,745	Undef	-$135,505	Undef	-$38,992	Undef
80%	20%	-$193,936	Undef	-$110,705	Undef	-$32,252	Undef
60%	40%	-$150,127	Undef	-$85,906	Undef	-$25,511	Undef
40%	60%	-$106,318	Undef	-$61,106	Undef	-$18,771	Undef
20%	80%	-$62,509	Undef	-$36,307	Undef	-$12,030	Undef
1%	97%	-$20,891	Undef	-$12,747	Undef	-$5,627	Undef

Scenario 2 – Charlotte: Moderate Fee, High Credit [a, c]
2A = High capital cost (Q3); High annual maintenance cost (Q3)
2B = Median capital cost (Q2); Median annual maintenance cost (Q2)
2C = Low capital cost (Q1); Low annual maintenance cost (Q1)

Owner Capital Investment	% Capital Subsidy	2A		2B		2C	
		NPV	IRR	NPV	IRR	NPV	IRR
100%	0%	-$230,340	Undef	-$128,100	Undef	-$31,587	-30.2%
80%	20%	-$186,531	Undef	-$103,300	Undef	-$24,847	-28.2%
60%	40%	-$142,722	Undef	-$78,501	Undef	-$18,106	-25.5%
40%	60%	-$98,913	Undef	-$53,701	Undef	-$11,366	-21.3%
20%	80%	-$55,104	Undef	-$28,902	Undef	-$4,625	-13.1%
1%	97%	-$13,486	Undef	-$5,342	Undef	$1,779	85.1%

Table 5.6 (continued)

Scenario 3 – Charlotte: High Fee, Low Credit [a, d]
3A = High capital cost (Q3); High annual maintenance cost (Q3)
3B = Median capital cost (Q2); Median annual maintenance cost (Q2)
3C = Low capital cost (Q1); Low annual maintenance cost (Q1)

Owner Capital Investment	% Capital Subsidy	3A		3B		3C	
		NPV	IRR	NPV	IRR	NPV	IRR
100%	0%	-$233,796	Undef	-$131,555	Undef	-$35,043	Undef
80%	20%	-$189,987	Undef	-$106,756	Undef	-$28,302	Undef
60%	40%	-$146,178	Undef	-$81,956	Undef	-$21,562	Undef
40%	60%	-$102,369	Undef	-$57,157	Undef	-$14,821	Undef
20%	80%	-$58,560	Undef	-$32,357	Undef	-$8,081	Undef

Scenario 4 – Philadelphia: High Fee, High Credit [a, e]
4A = Aggregate capital cost [f]; High annual maintenance cost (Q3)
4B = Aggregate capital cost [f]; Moderate annual maintenance cost (Q2)
4C = Low capital cost (Q1); Low annual maintenance cost (Q1)

Owner Capital Investment	% Capital Subsidy	4A		4B		4C	
		NPV	IRR	NPV	IRR	NPV	IRR
100%	0%	-$73,985	-23.4%	-$66,792	-17.9%	-$9,372	-0.3%
80%	20%	-$57,004	-21.1%	-$49,811	-15.2%	-$2,631	3.9%
60%	40%	-$40,023	-17.8%	-$32,830	-11.4%	$4,110	10.1%
40%	60%	-$23,042	-12.8%	-$15,849	-5.5%	$10,850	20.8%
20%	80%	-$6,061	-2.4%	$1,133	7.4%	$17,591	48.1%
1%	97%	$10,071	174.7%	$17,265	289.9%	$23,994	980.9%
1%	97%	-$16,942	Undef	-$8,798	Undef	-$1,677	Undef

Table 5.6 (continued)

Notes: IRR = Internal rate of return; NPV = Net present value; Undef = Undefined; Q1 = Quartile 1 (25%); Q2= Quartile 2(50%); Q3 = Quartile 3 (75%)

[a] Scenarios do not take into account the effect of tax consequences on NPV or IRR.

[b] Charlotte existing non-residential stormwater fee (CMSWS 2016a), proposed Charlotte GI (4%) plus stream stabilization (14%) fee credits (CMSWS 2015d).

[c] Charlotte existing non-residential stormwater fee (CMSWS 2016a) and proposed Charlotte maximum (= incentive) fee credit GI (CMSWS 2015d).

[d] Philadelphia existing non-residential stormwater fee (does not include billing or gross area fee) (Philadelphia 2016), proposed Charlotte GI (4%) plus stream stabilization (14%) fee credits (CMSWS 2015d).

[e] Philadelphia capital cost = $90,000/ impervious acre treated which is the estimated cost for aggregated projects reported by Valderrama et al. (2015).

[f] Philadelphia existing non-residential stormwater fee (does not include billing or gross area fee) and existing GI fee credit (Philadelphia 2016)

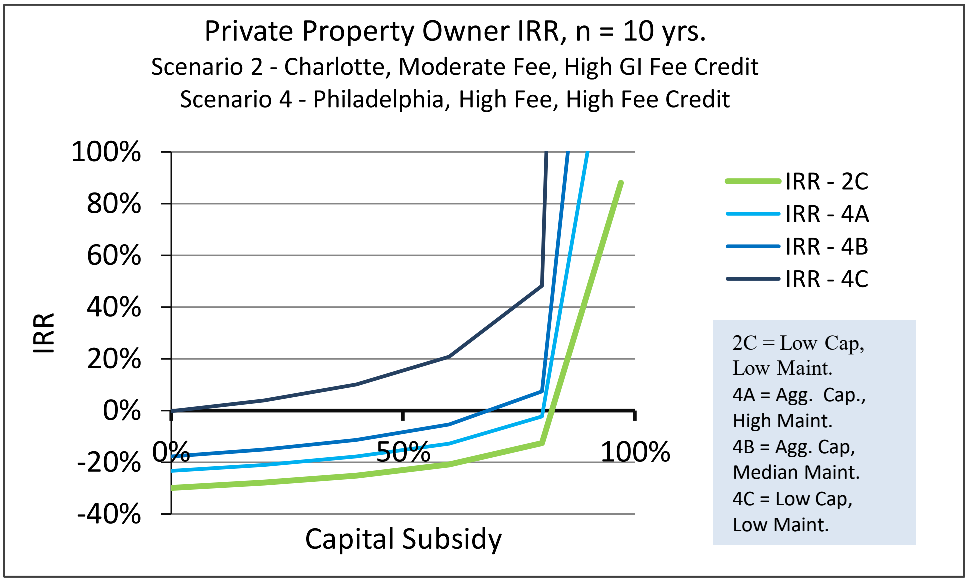

Figure 5.1: Private Commercial Property Owner GI Retrofit Investment Scenario IRR Curves

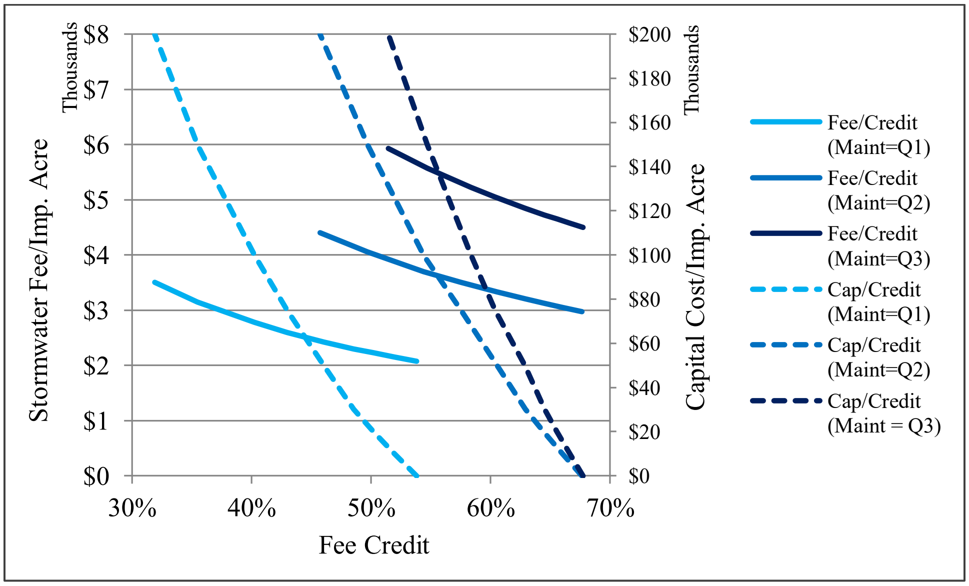

Figure 5.2: Annual Stormwater Fee and Fee Credit for Property Owner Incentive and Maximum Capital Cost for CMSWS Cost Recovery (n=20 yrs., r=0.06)

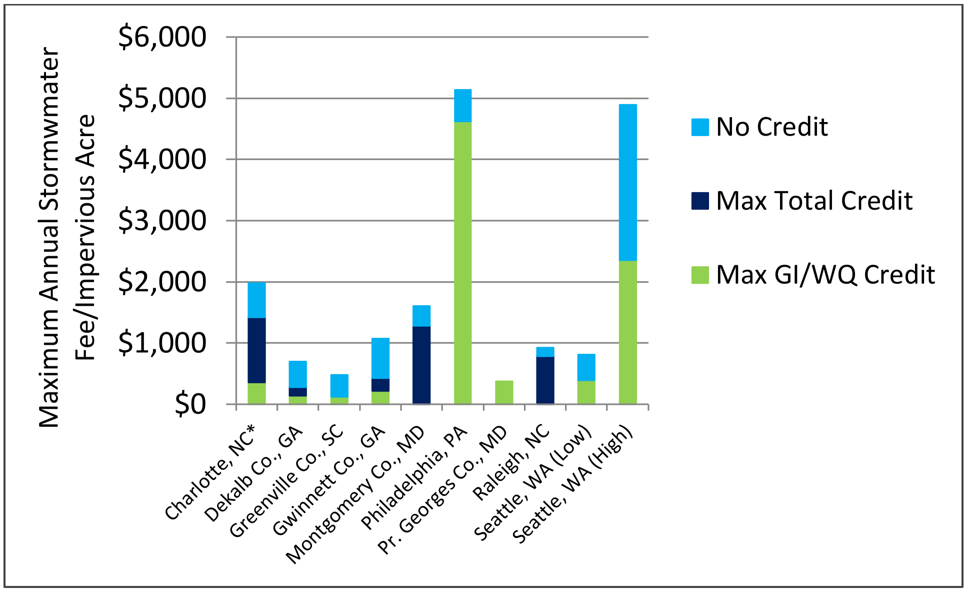

Figure 5.3: Comparison of U.S. Stormwater Utility Stormwater Fees and Fee Credits

CHAPTER 6: SUMMARY OF CONCLUSIONS AND IMPLICATIONS FOR SUSTAINABLE WATER INFRASTRUCTURE MANAGEMENT IN URBAN AREAS

6.1 Summary of Conclusions

The overall objective of this research is to investigate infrastructure management issues related to implementation of IWM and GI retrofits in urban areas. The conclusions drawn as a result of these investigations answer several questions addressing knowledge gaps from three different perspectives: energy savings, water quality improvements and economic incentives. These conclusions are summarized below.

6.1.1 Perspectives on IWM Measures and Energy Savings

1.) Aggregate energy savings due to reduction in water and wastewater demand from widespread implementation of rainwater harvesting and gray water reuse can be large for water utilities. Although disaggregated savings at the household scale are small, the knowledge of potential energy and cost savings to individual consumers is important for water utilities and policy makers when considering how to promote and incentivize consumers in the sustainable use of water.

2.) Life cycle energy values of rainwater harvesting, gray water reuse and other IWM measures should be adequately accounted for when evaluating the benefits and costs of alternative water management scenarios within a community or watershed and used to inform local incentive policies that promote sustainable water use. The defined analysis boundaries will have a great impact on overall results.

6.1.2 Perspectives on GI Retrofits and Water Quality Improvements

1.) The range of remaining DCIA percentages assuming maximum and moderate GI retrofit scenarios of 22% to 31% in ULSC and 16% to 19% in Six Mile Creek do not appear to be particularly promising relative to a stream health threshold of 10% TIA. However, in an adaptive management approach, actual measured improvements to water quality as a result of DCIA reduction will have greater meaning than the magnitude of DCIA reduction or remaining DCIA percentage.

2.) The results indicate that all property types except public commercial property have the capacity to substantially contribute to total DCIA reduction within a watershed and private commercial property provides the greatest proportion in both case study watersheds at 44% of total DCIA reduction in ULSC and 34% in Six Mile Creek. Public roadways provide the next greatest proportion of DCIA reduction at approximately 30% in both watersheds, but retrofitting roadways with GI is typically more costly than on other types of properties because of construction issues related to traffic and underground utilities. Single-family residential property can provide 21% and 27% of total DCIA reduction in ULSC and Six Mile Creek, respectively, whereas, public owned commercial property accounts for just 5% and 7% of the total in the respective watersheds.

3.) These results support a conclusion of the Shepherd Creek GI retrofit experimentation study that treatment of a significant amount impervious from parking lots and roadways in addition to that on residential property would be required to reach the extent of retrofits necessary to produce significant improvements to stream health (Roy et al. 2014). Public owned DCIA is a good place to start retrofits whether as part of a general retrofit program or an experimentation program but public money may be best spent subsidizing lower cost retrofits on private property (Valderrama et al. 2015). Targeting the most cost effective retrofits with the greatest capacity for DCIA reduction on all property types, public or private, will be a key strategy in any retrofit program in order to achieve the extent of DCIA reduction required for significant improvements to stream health.

4.) Several important prioritization criteria are identified as part of the research design with DCIA reduction as the key criterion. The selection of additional criteria is informed from the literature review and lessons learned in existing experimentation studies. Evaluation of criteria independence is used to further refine criteria selection for individual watersheds and reveals that the same key impervious area criteria are important in both watersheds despite differences in development characteristics. However, criteria values involving open areas such as park, pond and wetlands are specific to each watershed and can have a significant impact on criteria independence when data sets from watersheds with very different development characteristics are combined.

5.) The results of this research call into question the benefit of combining data sets from two watersheds with significantly different development characteristics when searching for a catchment for potential experimentation because the criteria values for the catchments from the more densely developed watershed dominate the priority MCDA results. This is a result of the specific criteria selected for this MCDA process and does not necessarily mean that selecting a catchment in a less densely developed watershed is a poor choice for GI retrofit experimentation, but it appears that catchments in a watershed dominated by single-family residential development may not provide the optimal DCIA density or potential DCIA reduction amount for an experimentation study in comparison to catchments from a more densely developed watershed. Catchment selection by targeted MCDA for individual watersheds may be more appropriate in this regard.

6.) Selection of a catchment for experimentation using the prioritization process developed by this research could be a first step in a research effort to determine the "minimum effect threshold and restoration trajectory for retrofitting catchments" suggested by Roy et al. (2014). Few catchments in the two case study watersheds approach the 10% TIA threshold as a result of DCIA reduction but the criteria used in the prioritization process focus the decision outcome on the greatest proportion of potential DCIA reduction relative to the existing condition so that quantifiable stream improvements can be expected. Using an adaptive management approach, the goal is not necessarily to reach 10% TIA but to retrofit enough DCIA to produce measurable improvements in stream health.

7.) This research provides a framework to identify the best or a few best catchment options within a priority watershed of interest to consider for an experimentation study. The MCDA approach can provide decision makers with information regarding the tradeoffs between different decision options. The final decision will involve judgement calls as there are tradeoffs to be made even when a few best options are identified; every criterion value is typically not optimal in any option scenario. Preferences by decision makers and other stakeholders, systematic variation of the priority ranks of the selected evaluation criteria and inclusion of performance values for additional decision options (catchments) will affect the final choice.

6.1.3 Perspectives on GI Retrofits Economic Incentives

1.) An examination of the regulatory driver, BMP type and ownership characteristics of existing CMSWS stormwater BMPs that receive a stormwater fee credit and those that do not, does not explain why fee credit use is so low. There are many potential reasons often cited: low value of the fee, lack of knowledge of the credit, low value of the credit relative to the cost involved in obtaining or keeping the credit, risks related to duration and terms of renewal policies; and/or ineligibility of the BMP in meeting current fee requirements (Reese 1996; Doll et al. 1999; Ellard 2011; Crisostomo 2015). The best way to credibly determine the actual reasons for low participation in the CMSWS stormwater BMP fee credit program is to interview commercial property owners. This would also be a good opportunity to gather information regarding the attitudes of property owners toward GI in general and willingness to participate in potential retrofits.

2.) The majority of stormwater fee and credit programs identified in this research do not provide an equitable incentive to commercial property owners to invest in GI retrofits. The only tangible value to private property owners to offset the capital and ongoing maintenance costs of GI retrofits are fee credits and rebates.

3.) The results of this research indicate that a stormwater fee and credit combination based on the cost of capital and fee credits to the stormwater utility and fee credits equal to the cost of annual maintenance to property owners can provide equitable incentives to both groups to invest in GI retrofits. There are benefits to both stormwater utilities and commercial property owners of setting the fee credit to annual maintenance costs for GI or traditional BMPs. This is essentially pay for performance to assure long term maintenance and performance of system-wide infrastructure and can potentially reduce costs for inspection. Crisostomo (2014) indicate that few stormwater programs actually conduct regulatory inspection programs of private stormwater management facilities because of the cost involved. Property owners are paid for maintaining their assets and maintenance agreement reporting requirements force documentation of maintenance activities. This has value in due diligence investigations for both buyers and sellers during commercial real estate sales transactions.

6.2 Implications for Sustainable Water Infrastructure Management in Urban Areas

Sustainable and efficient water infrastructure management is becoming increasingly necessary in urban areas due to growing municipal demand; competing uses between public water supply, electricity generation, and agriculture; stricter treatment standards; stormwater runoff quality and stream health issues; and, aging infrastructure. This research provides stormwater infrastructure managers with valuable perspectives on issues related to retrofitting urban areas with IWM and GI measures which can assist in meeting these challenges.

6.2.1 The Need for Catchment Scale Experimentation Studies

Catchment scale GI retrofit experimentation projects are needed because little information is available regarding the potential impact of implementation across a watershed relative to urban stream restoration efforts (Jaffe et al. 2010, Schueler et al. 2009). The catchment scale MCDA prioritization process developed for this research provides the foundation for a GI retrofit experimentation program and an overall planning strategy that uses the DCIA reduction potential of GI retrofits to define the magnitude of DCIA that is technically feasible to disconnect (Owen 2011; Ellis 2013; Schiff et al.

2014) and the subsequent potential to meet water quality goals (Schiff et al. 2014). This strategy goes beyond individual site suitability and considers catchment level restoration potential with a watershed system perspective.

The level of ecological restoration of urban stream realistically possible or achievable needs to be defined at the watershed scale and worked towards over a long period of time, therefore initial GI retrofit implementation programs should allow local stormwater managers to develop useful data that will strengthen or challenge the applicability of distributed watershed management measures in their unique watersheds. As the strategy is advanced and the benefits of GI are further quantified, the case for GI retrofits on all types of property can be strengthened. Due to the public's lack of knowledge regarding stormwater management issues in general and the new and innovative nature of GI measures specifically (Carlet 2015), an experimentation project would demonstrate the technology and be a showcase to educate the public and gather stakeholder support to further encourage retrofits on private property (Olorunkiya et al. 2012, Carlson et al. 2014).

In addition, the objectives of a GI retrofit experimentation program could go beyond improvements to in-stream water quality to include concomitant improvements in ecosystem services, urban heat island effects, air quality and social vulnerability (Meerow and Newell 2017). A water-quality based experimentation program could be designed with monitoring systems to measure all additional relevant parameters.

6.2.2 Watershed Scale GI Retrofit as Part of Overall Stream Restoration Strategy

The intention is for this prioritization strategy to be useful as a policy decision and management tool for stormwater infrastructure managers primarily in municipalities with

MS4 permit and TMDL requirements related to stormwater impairments to guide retrofit planning, pilot catchment selection, long-term performance monitoring, and public-private-partnerships. The strategy focuses on screening and prioritizing the highest priority and most restorable urban catchments and should be integrated into an overall watershed scale restoration approach that includes existing stream scale and riparian zone efforts. It will also be useful in addressing associated policy questions regarding stormwater fee-in-lieu of programs for infill and redevelopment projects within the target catchments to guide overall percent DCIA reduction target needed to achieve restoration goals.

A growing body of literature supports the view that while stream scale restoration efforts are effective at reducing streambank erosion, improvements to in-stream water quality and aquatic life habitat require a watershed or catchment scale strategy as well as mitigation of land use through the use of distributed onsite stormwater management facilities that reduce volume and pollutants of interest; and larger regional BMPs that provide flood control and some water quality benefits (Booth and Jackson 1997; Walsh et al. 2005b; NRC 2008; Roy et al. 2008; Selvakumar et al. 2010; Ellis et al. 2013; McMillan and Vidon 2104; Vietz et al. 2016).

6.2.3 Future Research Needs

The results of this research address implications for both water infrastructure providers and consumers regarding the development and coordination of appropriate economic incentives to encourage and optimize IWM implementation and GI retrofits by both groups. Questions regarding equitable utility fee and fee credit programs are addressed to guide overall stormwater management efforts for both water quality and water quantity within a municipal service area. Further research is needed to identify the specific barriers for private commercial property owner participation in existing fee credit programs in order to strengthen the case for fee credits as an incentive for storm water control on private property including GI retrofits.

Further research is also needed to quantify additional direct use value for commercial property owners as a result of investment of GI; to address uncertainties related to energy savings as an incentive for IWM and GI including LCAs that include the complete energy, economic and environmental impacts of community wide rainwater harvesting and gray water reuse scenarios, keeping in mind that the defined analysis boundary will have a great impact on the results; and, to obtain information regarding customers' willingness to participate in retrofit programs. The development of local incentive policies for IWM and GI measures will depend on reliable measured data and detailed analyses.

Stormwater utility fees are used to finance a large portion of the capital and maintenance costs of storm drainage, flood control and stream protection improvements (Reese 1996; Doll et al. 1999; Ellard 2011). Adding the cost of GI capital projects in the budget and then paying for maintenance of the distributed measures thru equitable fee credits would assure long term maintenance and performance and relieve the burden of maintenance of these facilities by the utility. Studies that quantify the extent to which GI also benefits flood control and other capital projects will further justify this approach. Areas with large CIP requirements should assess how GI could potentially reduce size of gray infrastructure needed and balance or optimize control across all storm events at minimal cost from 1-inch to 100-year.

This research provides a foundation to support future efforts to answer additional questions including: “What is the equitable portion of revenue a utility should use to incentivize GI; and, “Are the compliance costs of regulatory requirements placed on municipality (consent decree/ TMDL/NPDES permit requirements) sufficient justification to increase rates for all rate payers or if the ability of GI to reduce gray infrastructure costs should drive retrofit funding?” As large regulatory driven retrofit programs such as those in Philadelphia and Prince Georges County mature, the needs of future research will become clearer.

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