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CLIMATE CHANGE IMPACT ON URBAN STORMWATER SYSTEM AND USE OF GREEN INFRASTRUCTURE FOR ADAPTATION: AN INVESTIGATION ON TECHNOLOGY, POLICY, AND GOVERNANCE

Krishna Prasad Dhakal
Southern Illinois University Carbondale, krishna.gogreen@gmail.com

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by

Krishna P. Dhakal

B.S., Tribhuvan University, Kathmandu, Nepal, 1998
M.S., Western Michigan University, Kalamazoo, MI, 2010

A Dissertation
Submitted in Partial Fulfillment of the Requirements for the
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Approved by:

Dr. Lizette R. Chevalier, Chair

Dr. Christopher Lant

Dr. Bruce DeVantier

Dr. Guangxing Wang

Dr. Ajay Kalra

Graduate School
Southern Illinois University Carbondale
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MAJOR PROFESSOR: Dr. Lizette R. Chevalier

The world is urbanizing at an unprecedented rate, and cities are dominantly and increasingly becoming hubs for agglomerations of human population and economic activities, as well as major sources of environmental problems. Accordingly, humanity′s pursuit of global sustainability is becoming increasingly reliant on urban sustainability. Unfortunately, the traditional approaches of urbanization and urban stormwater management are inappropriate from the sustainability standpoint. By removing vegetation and topsoil and creating impervious structures, urbanization destroys natural biodiversity and hydrological processes. As a result, urban societies are disconnected from nature and deprived of ecosystem services including flood control, fresh air, clean water, and natural beauty. Due to disrupted hydrology, an urban landscape transforms most rainwater into stormwater runoff which is conveyed off the site through a system of curb-gutter-pipe, called gray infrastructure. While gray infrastructure efficiently mitigates the problem of flash floods in urban areas, it results in multiple other adverse environmental consequences such as loss of freshwater from urban landscapes, transfer of pollutants to receiving waters, and an increased potential of downstream flooding.

Green infrastructure (GI) is regarded as a sound alternative that manages stormwater by revitalizing the natural processes of soil, water, and vegetation, and restoring ecosystem structures and functions. Thus, the approach re–establishes the lost

socio–ecological connectivity and regenerates ecosystem services. However, despite being inevitably important for urban sustainability, and despite being the object of unrelenting expert advocacy for more than two decades, the approach is yet to become a mainstream practice.

To widely implement GI, cities need to address two critical challenges. First, urban stormwater managers and decision makers should be ensured that the approach can adequately and reliably manage stormwater. In the time when flooding problems are rising due to climate change, this concern has become more prominent. Second, if there exist any other barriers, they should be replaced with strategies that help expedite the use of GI. This multidisciplinary research dealt with these two challenges.

The study consisted of two major parts. In the first part, a computer model was developed for a combined sewer system of St. Louis, a city in the U.S. state of Missouri, using U.S. EPA SWMM. Simulations for historical (1971-2000) and future (2041-2070) 50-yr 3-hr rainfall scenarios were then run on the model with and without GI. The simulation results showed a significant impact of increased precipitation on the system, which was considerably reduced after adding select GI measures to the modeled system. The following 4 types of GI were used: bio–retention cell, permeable pavement, green roof, and rain barrel.

In the second part, a survey of relevant policies and governance mechanisms of eleven U.S. cities was conducted to identify potential barriers to GI and determine strategies to address them. The study also included the assessment of relevant city, state, and federal policies and governance structures. A total of 29 barriers were identified, which were grouped into 5 categories. Most of the identified barriers stem from cognitive barriers and socio–institutional arrangements. A total of 33 policies, also grouped into 5 groups, were determined to address the barriers. The investigation on governance revealed that current governance is highly technocratic and centralized, and hence has less opportunity for public involvement. Therefore, it is inherently inappropriate for GI, which requires

extensive public involvement. This dissertation proposes a two–tier governance model suitable for implementing GI.

DEDICATION

To my parents, wife, and kids.

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PREFACE

This dissertation presents the outcome of a multidisciplinary research conducted towards identifying a holistic solution to the urban stormwater management problem in the face of climate change. Specifically, the research was on the following issues: the impact of climate change on urban stormwater system, efficacy of green infrastructure to address the impact, barriers to green infrastructure implementation, and policies and governance suitable for implementing green infrastructure.

The dissertation consists of seven chapters. The first and second chapters provide background information and research framework; whereas the seventh chapter gives the overall conclusion. Specific details on the specific research issues are presented in chapters 3 through 6.

The third chapter, "Climate Change Impact on Urban Drainage System," discusses how I developed a model for a combined sewer system of St. Louis, Missouri, using U.S. EPA′s SWMM hydrologi-hydraulic model and GIS. The chapter presents the comparison of simulations results conducted for current and future 50-yr 3-hr rainfall scenarios and presents the quantitative measure of the impact of the increased rainfall on the system.

The fourth chapter, "Efficacy of Green Infrastructure for Climate Adaptation," utilizes the same model developed in the third chapter. I added various green infrastructure measures across the study area catchment of the model, conducted the simulation for same future 50-yr 3-hr rainfall scenario, compared the simulation results for the future rainfall scenario before and after the application of green measures, and quantified the efficacy of the green measures to address the impact.

For the fifth chapter, "Policies for Green Infrastructure Implementation: Barriers and Policy Solutions," I conducted an exploratory research of 11 U.S. cities and relevant state and federal policies, explored barriers to implementation of green infrastructure technology, and identified policies that can both address the barriers as well as expedite the implementation. I wrote a journal article entitled "Managing Urban Stormwater for Urban Sustainability: Barriers and Policy Solutions for Green Infrastructure Application" with the help of Dr. Lizette Chevalier. The paper has been published in *The Journal of Environmental Management*. The content of the fifth chapter, other than introduction, is taken from the published paper.

The sixth chapter, “Governance of Green Infrastructure: Barriers and Solutions” presents the investigation and analysis of urban stormwater governance from the perspective of implementation of green infrastructure. For this, I surveyed the existing governance in 5 U.S. cities, explored the barriers, and proposed a new two-tier urban stormwater governance model suitable for green infrastructure. An article entitled “Urban Stormwater Governance: The Need for a Paradigm Shift” that I wrote with the help of Dr. Lizette Chevalier has been published in *Environmental Management*. Other than the introduction section, content of the sixth chapter is taken from the published paper.

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CHAPTER 1
INTRODUCTION AND OVERVIEW

Background

The human society is becoming increasingly urban all over the world. According to a recent report of the United Nations Department of Economic and Social Affairs (UNDESA), the urban population makes up over 54.5% of the global population (UNDESA 2016). It was only 2% in 1800, 14% in 1900, and 30% in 1950 (Wu, 2010). The report projects that the urban population will increase to 60% of the global population by 2030, adding about 1 billion new urban residents. Fragkias and Seto (2012) approximate that during this period planet earth will add a new city of about one million people every 5 days. In the U.S., the urban population increased from 64% to 81.4% during 1950 to 2014 (UNDESA, 2014), and it is projected to increase to 88.9% by 2050 (Leonard and Egan 2014).

In parallel to the population, the global economy is also increasingly concentrated in urban areas. According to the World Bank (2015), cities contribute more than 80% of the global gross domestic product (GDP). In the U.S., large cities, defined as cities with 150,000 or more people, contributed 85% of the country′s GDP in 2010; whereas in China and Western Europe, the large cities generated 78% and 65% of their respective GDPs (Manyika et al. 2012).

The increase in the population and economic growth coupled with the changing pattern of development has caused an unprecedented expansion of urbanized land (Angel et al. 2011; Liu et al. 2005; Seto and Kaufmann 2003). The trend of lower density growth in recent years in the form of urban sprawl (Barrington-Leigh and Millard-Ball 2015; Lopez 2014) has made the rate of expansion two to four times higher than the rate of increase of population (Angel et al. 2011; Seto et al. 2011). According to Seto et al. (2011), the global urban area increased by 6 million hectares during the last three decades of the 20^{th} century. If the current trend continues, it will increase by 120 million hectares in the first three decades of this century, nearly tripling the total global urban surface that existed at the beginning of the century (Seto et al. 2012). In the U.S., urban area increased from 2.5% to 3.1% during 1990-2000, and it is projected to be 8.1% by the year 2050 (Nowak and Walton, 2005). The U.S. Census Bureau (2005) defines urban area as a block with a minimum population density of 500 people per square mile.

While serving as the economic and population centers, urban areas pose a significant adverse impact on the environment, within and beyond the urban boundary. In fact, though their physical geographical footprint is not that much, they are a primary source of global environmental problems (Wu 2008). Typically, the problems result from two major causes: structural perturbation of land surface during urbanization and socio-economic activities of the urban communities. Structural perturbation results in the most irreversible form of land use change (Seto et al. 2011) primarily due to four activities: removal of vegetation and top soil, drainage and burial of ponds and wetlands, gradation and compaction of land surface, and construction of impervious surfaces including roads, parking lots and buildings (Chow 1964; Leopold 1968; National Research Council 2009; Savini and Kammerer 1961). These activities result in two major impacts: destruction of biodiversity and disruption of natural hydrology. The destruction of biodiversity results from the removal of vegetation and topsoil that damages plant species and soil organisms as well as micro- and macro-habitat provided by the plants and the topsoil. Habitat fragmentation—which is caused by the loss of ecological connectivity due to the destruction of natural waterways, vegetative belts, and wetlands—also leads to the loss of biodiversity.

The disruption of hydrology results from the removal of vegetation, destruction of water-retaining surface features, and construction of impervious structures. These activities destroy the natural hydrologic functions of the landscape including interception, evapotranspiration, retention, and infiltration of rainwater. As a result, the urbanized landscape diverts a majority of rainwater into surface runoff, resulting in increased frequency and severity of flooding (Chow 1964; Leopold 1968; National Research Council 2009; Savini and Kammerer 1961). To mitigate this, the conventional approach employs a centrally managed network of curbs, gutters, and underground pipes, called gray infrastructure, whose objective is to collect and remove the surface runoff as fast as possible. First conceptualized and used in ancient cities (Burian et al. 2000), and later adopted by modern engineering, gray infrastructure is ubiquitous across cities all over the world. The civilians, engineers, societies, and politicians, are all accustomed to it. It is regarded as a basic requirement in developed countries, and a common step toward infrastructure development in developing countries.

However, the studies show that the gray approach is environmentally inappropriate for a number of reasons (Chow 1964). First, the system does not mitigate flooding problem but transfers the problem downstream of the point of discharge. In fact, since it expedites the removal of stormwater runoff, the flooding in the downstream becomes more intense. Second, the approach removes freshwater from the urban landscape. Third, it does not restore the hydrological functions of the landscape; as a result, the problem of water stress in the subsurface, groundwater depletion, and decreased base flow in the downstream water bodies remains unaddressed. Fourth, it carries numerous pollutants from urban areas and discharges into receiving water bodies. Examples of the pollutants include sediments, viruses, bacteria, nutrients, pesticides, oil, grease, and heavy metals (U.S. Environmental Protection Agency (U.S. EPA) 2003).

Socio-economic activities in the urbanized areas also have profound impacts on the environment. As global centers of production and consumption, cities draw in energy and matter from all over the ecosphere and return wastes back to the ecosphere (Rees and Wackernagel 1996). Currently, cities account for about 60% of all residential water use, 75% of energy use, and 80% of human greenhouse gas emissions (Wu 2014). They generate about 1.3 billion tonnes of solid waste per year, which is expected to increase to

2.2 billion tonnes by 2025 (Hoornweg and Bhada-Tata 2012). If not managed well, the solid wastes also pose significant adverse impact on the public health and the environment.

Thus, since cities are increasingly becoming socio-economic hubs, as well as primary sources of environmental impacts, the humanity′s pursuit of global sustainability is increasingly hinged up on urban areas (Beatley 2000; UNDESA 2014; Wu 2014; Young 2011). Sustainability refers to the goal of sustainable development (Diesendorf 2000), and has varying definitions depending on disciplines and contexts. In general, its fundamental universal theme is to guide human activities within the framework of carrying capacity of the earth to ensure the endurance of livability on the earth, while maintaining the social harmony. This theme is well reflected in the highly cited definition of sustainable development presented in the Brundtland Report of the United Nations (World Commission on Environment and Development (WCED) 1987). The report defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs,” and argues that the cities should be central to the pursuit of sustainable development. Since the publication of this report, the concepts of sustainable cities and urban sustainability have received significant attention internationally (Bulkeley and Betsill 2005). While embracing the concept, scholars conventionally define economic, environmental, and social aspects as its three essential components (Harris 2003). To this, Dhakal and Oh (2011, 2010) have recently argued to add two additional components: material use and financial sustainability. Given the size of the socio–economic activities, the extent of the environmental disturbance, the exploitation of natural materials, gigantic financial investments, and a huge stock of unsustainable built up infrastructures, pursuing urban sustainability is one of the most compelling and challenging task.

To this already difficult undertaking, anthropogenic climate change has added enormous unprecedented complications. Scientific findings have proved that the human–induced increase in atmospheric concentrations of greenhouse gases has caused global warming, which has increased the global average temperature by 0.65°C–1.06°C over the period 1880–2012 (Intergovernmental Panel on Climate Change (IPCC) 2013; U.S. Global Change Research Program (USGCRP) 2014). The U.S. national average temperature increased by 0.72°C–1.05°C during 1895–2012 (USGCRP 2014). Evidences show that the rate of warming is increasing in recent decades. Globally, according to the IPCC, each of the three last decades have become successively hotter than any preceding decade since 1850. In the U.S. as well, as reported by the USGCRP, the most recent decade was the hottest decade on record. The year 2015 was the hottest year on the planet, in the historical record which started in 1880, with the average global temperature 0.90°C above the 20^{th} century average (NOAA National Center for Environmental Information 2015). The global average temperature for January-August interval of 2016 was the highest in the 1820–2016 record and surpassed that of 2015 by 0.16°C (NOAA National Center for Environmental Information 2016).

According to the UN-Habitat, a United Nations program dedicated for urban future, the impacts of urbanization and climate change are converging in dangerous ways (UN-Habitat 2012). On the one hand, cities are major contributors to climate change, because they emit more than the three–fourth of the anthropogenic greenhouse gases, as cited earlier, primarily through energy production, transportation, industry, land use changes, and buildings (IPCC 2014). On the other hand, they are significantly vulnerable to climate change due to sea level rises, increased precipitation events (e.g. storms, floods, hurricanes, and cyclones), and more extreme heat and cold (UN-Habitat 2012; Younger et al. 2008). These effects have significant adverse impacts primarily on the public health and manufactured infrastructures. Examples of potential public health effects include cardiovascular and respiratory illness, altered transmission of infectious disease, and malnutrition from crop failures (Patz et al. 2005; Younger et al. 2008). Potential effects on infrastructures include failure of drainage system due to increased extreme rain events

(Thakali et al. 2016; Willems 2012) and structural failure of built structures due to corrosion of steel (Stewart et al. 2011).

Basic theory, most of the climate models, and empirical evidence show that warmer climate increases the atmospheric water vapor that leads to more intense and more frequent precipitation events (IPCC 2013). Niemczynowicz (1989) showed that 1 to 3°C increase in temperature results in 10 to 30% increase in precipitation. Researchers have expected that, due to global warming, rainfall will become more intense in almost all regions of the world in the 21st century (IPCC 2013; Olsson et al. 2009; Waters et al. 2003). In the U.S. also, studies have shown an increasing trend (Groisman et al. 2005; Karl and Knight 1998; Pathak et al. 2016, 2017; Thakur et al. 2017a). For example, Karl and Knight (1998) showed a 10% increase in total annual precipitation across contiguous U.S. since 1910. Groisman et al. (2005) reported an increase of 3.3% per decade in extreme precipitation events over the contiguous U.S. during 1910–1999. The U.S. Soil and Water Conservation Society (2003) defines extreme precipitation as the precipitation above the 99.9^{th} percentile, very heavy precipitation as the precipitation above the 99^{th} percentile and heavy precipitation as the precipitation above the 95^{th} percentiles. In the most recent report, the USGCRP has reported that every region of the U.S. experienced an increase in very heavy precipitation, defined as the heaviest 1%, during 1958–2012 (USGCRP 2014). It increased by 71% in the northeast, 37% in the Midwest, and 9 percent in the Southeast. The arid Southwest had 5% increase in the very heavy precipitation; whereas Northwest and Great Plains had 12% and 16% increase respectively.

The increase in frequency and intensity of heavy precipitation is also predicted to increase in the 21^{st} century (USGCRP 2014; Wuebbles et al. 2014). Cubasch and Cess (1990) predicted an increase in the amount of heavy rainfall events, even though the mean annual rainfall would decrease. Zwiers and Kharin (1998) showed that the frequency of intense rainfall events would increase, whereas the frequency of moderate intensity will decrease. Hengeveld (2000) projected that today′s 50-yr event would change to a 10-yr event by 2090. In its 2009 report, USGCRP (2009) reported that present 20-yr heavy rainfall event would be a 4–15-yr event by 2100, and will become 10–25% heavier than current event. The Canadian Climate Center Model (GCM2) predicted that, over North America, the depth of rainfall now associated with 20-yr return period will occur nearly every 10 years when the global carbon dioxide (CO_2) concentration in the atmosphere is doubled (Waters et al. 2003).

The size of the conventional drainage system is calculated based on the historical precipitation data assuming that the precipitation frequency and intensity will remain unchanged over the design life of the system. Since climate change results in increased precipitation intensity and frequency, the assumption becomes invalid, and the design capacity based on the faulty assumption becomes too small to accommodate the increased precipitation. As result, the stormwater system is very likely to fail during the heavy rain fall events. When the system fails, it leads to urban flooding which can damage other infrastructures such as buildings, roads, and underground utilities. Such failures often result in the huge loss of property and life.

The failure of urban drainage system due to extreme precipitation and the subsequent massive damage in the socio-economic systems have been increasingly evidenced in many cities. For example, when excessive runoff resulting from the intense rainfall exceeded drainage capacities in New York in August 2007, the subway system was disrupted causing an unprecedented impact on the city′s transportation system (Metropolitan Transportation Authority (MTA) 2008). Toronto faced its most expensive storm in August 2005, with more than 4,200 basement flooding, and loss of public property equivalent to 400-500 million dollars (Foster et al. 2011). The record breaking storm of September 2008 in Chicago, Illinois, with 6.7 inches of rain in a 24-hour period leading to massive flooding, resulted in evacuation of 10,000 homes and property damage of 155 million dollars (Dorfman et al. 2011). In July 2016, the city of Houston, Texas, suffered an estimated property damage of $45 million from the massive flood that occurred over the Memorial Day weekend (The Guardian 2015). According to the Guardian, more than 27 people lost their life in Texas. On 18th of April 2016, the city had even more precipitation, with 17 inches of rain in less than 24 hours, which killed 7 people, flooded 1,000 homes, and caused more than $5 billion in damage (CNN 2016). The day was described as the wettest April day on record in the city (KTIC Radio 2016; The Guardian 2016). In the fourth weak of August 2017, Houston faced even higher rainfall and subsequent devastating flood when the record high tropical storm "Hurricane Harvey." poured up to 51.88 inch of rainfall in and around Houston, breaking the previous record of any tropical storm in the contiguous U.S. (ABC News 2017). In some nearby cities—such as Port Arthur and Beaumont, the rainfall reached up to 26 inches in 24 hours (CNN 2017). According to a report by Greater Houston Partnership (2017), in Metro Houston, the storm destroyed 538 businesses, 97,212 single family houses, 15,662 apartment units, and 300,000 vehicles. The report revealed that the deadly storm took 82 lives—37 in Harris County which includes Houston—and resulted in an estimated economic loss of 97 billion dollars.

Thus, restoration and maintenance of biodiversity and landscape hydrology as well as climate change mitigation and adaptation are crucial for urban sustainability. Since our conventional infrastructures such as roads, buildings, parking lots, and drainage systems contribute to the creation of the problems discussed earlier, there is a critical need to adopt innovative approaches that can substitute them or help reduce their adverse effects. Green infrastructure is regarded as one such approach that utilizes soil and vegetation and replicates the natural hydrological processes of infiltration and evapotranspiration. The approach is called Sustainable Urban Drainage System (SUDS) in Europe and Water Sensitive Urban Design (WSUD) in Australia.

By employing the natural process of infiltration, retention, and evapotranspiration, green infrastructure captures rainwater on site and reduces and slows down stormwater flow. In addition, it provides a number of other environmental, economic, and social benefits including biodiversity restoration (McKinney 2002), water quality improvement (Novotny et al. 2010), carbon sequestration (U.S. EPA 2010), climate change adaptation (Kramer 2014), and groundwater recharge (U.S. EPA 2010, 2014b). Ecological economists define such services provided by the ecosystem to humans as ecosystem services (Costanza et al., 1997; MEA, 2005; Ruhl et al. 2008). Thus, through these services, green infrastructure re–establishes the socio-ecological connectivity destructed by urbanization (Gmez-Baggethun et al. 2013; Tzoulas et al. 2007). The technology helps improve the quality of life (Breuste et al. 2015a), increases property value (Wachter and Wong 2008; Ward et al. 2008), and is climate resilient (U.S. EPA 2015). Other benefits include cost-effectiveness (Baerenklau et al. 2008; Foster et al. 2011; Shaver et al. 2009; U.S. EPA 2015) and material efficiency, the two additional sustainability attributes according to Dhakal and Oh (2011, 2010). Therefore, pursuing urban sustainability critically requires to implement green infrastructure (Tzoulas et al. 2007; Young 2009).

In recent decades, urban sustainability is receiving increasing attention (Lorr 2012; Wu 2014), with green infrastructure as its underpinning element (Benedict and McMahon 2002; Dhakal and Chevalier 2017; Eisen 1995; Foster et al. 2011; Mazmanian and Blanco 2014; Mell 2009). Sustainable urban design concepts, including water-centric eco–cities (Joss 2010; Novotny 2008; Novotny et al. 2010; Novotny and Novotny 2012; Roseland 1997), green cities, and smart growth (Heaney and Sansalone 2012), have evolved as a new paradigm of urban development, which considers water and green infrastructure as core elements. It is argued that future cities will be based on green landscape systems (Novotny et al. 2010). Appreciating this, some cities have been successfully using green infrastructure for years in the US (Chen et al. 2013; Foster et al. 2011; U.S. EPA 2010), Europe, and Australia (Nickel et al. 2013).

Problem Statement

Despite being regarded as a sustainable, environment-friendly, and cost-effective approach that offers numerous ancillary benefits, green infrastructure has not yet been a widespread practice for urban stormwater management. While urban sustainability agenda has come to the forefront of academic and professional discourses for years, and green infrastructure is acknowledged as an inevitable aspect of urban sustainability, the technology has been adopted only by very few cities of some developed countries. On the other hand, despite the knowledge that gray infrastructure is environmentally destructive and financially demanding, the conventional approach is being constructed massively all over the world as a basic requirement for urban development. It is critically important for urban sustainability professionals and policy makers to address this gap between knowledge and practice.

To accommodate increasing heavy precipitation, many cities need to increase the capacity of existing systems. Aging systems in many other cities need complete replacement. In addition, emerging new cities will need to build a vast amount of new stormwater systems. Therefore, within next few decades, there will be a huge investment on repair, replacement, and construction of urban stormwater infrastructure globally. If green approach is not embraced, a massive amount of environmentally destructive gray infrastructures will be added on the planet earth as a big burden to future generations and a threat to sustainability.

To expedite the adoption of green infrastructure, four tasks are critically important. First, the stormwater managers need to be ensured that the green technology can significantly meet the desired level of stormwater control, when it is used to retrofit or replace gray infrastructure. Second, if there exist any other barriers that prevent the implementation of green infrastructures, they must be removed. Third, adequate policies that support green infrastructure implementation should be in place. And fourth, an appropriate governance mechanism should be established to effectively govern the green infrastructure application. This research dealt with these four tasks.

Research Objectives and Approach

Two primary objectives of this research were: (i) to assess the efficacy of green infrastructure to accommodate the increased precipitation due to climate change, and (ii) to identify appropriate socio–institutional frameworks to expedite the implementation of the technology. To pursue these objectives, the research was guided by the following four primary questions.

1. What will be the performance of an existing stormwater system when subjected to increased precipitation due to climate change?

2. What will be the performance of the current drainage system under increased precipitation if various measures of green infrastructure are applied?

3. What is the status of urban stormwater management law and policy? Are they supportive or preventive to implementation of green infrastructure? If there exist barriers, what innovative policy measures will be needed to remove the barriers and expedite the adoption of the technology?

4. Is the current stormwater governance supportive to green infrastructure? If not, what innovative governance will be appropriate for green infrastructure implementation?

For the first two questions, a case study of a combined sewer system (CSS), defined as a sewer system that carries both stormwater and wastewater, of the City of St. Louis, Missouri, the U.S., was conducted. First, the existing system was modeled by using U.S. EPAs Stormwater Management Model (SWMM). The modeled system was then subjected to future precipitation scenarios predicted by various climate models to quantify the impact of the increased precipitation on the existing drainage system.

Finally, some context sensitive green infrastructure measures were added to the model, and the model was run for the same future precipitation scenarios to determine the effect.

The third and fourth questions were addressed by conducting a critical review of existing stormwater policy and governance status primarily in the U.S. Research approaches are described in further detail in the respective chapters.

Research Significance

As opposed to the common practice in industry or academia where there exists a tendency of solving a real–world problem through a uni-disciplinary approach, this dissertation adopts an interdisciplinary and relatively holistic approach for pursuing urban sustainability. As a result, not only the research findings but also the research approaches are useful for a wide range of stakeholders. The quantification of the climate change impact on the drainage system helps managers and politicians to prospect for the oncoming problems. For design engineers, the findings help design efficient measures to retrofit existing drainage systems in advance to make them withstand the future precipitation and provide the desired level of service. The assessment of the efficacy of the select green infrastructure provides an idea about how much of the problem can be addressed by using green infrastructure. This also serves as a material for the public to understand the importance of adopting green infrastructure for stormwater management.

The research on policy and governance have explored numerous issues in the current institutional arrangements. This will help sensitize the policy makers at federal through local levels. For example, at federal levels, this will encourage federal legislators to revisit the Clean Water Act and other relevant federal policies to take steps for necessary amendments in favor of green infrastructure. The findings will be equally useful for the state and local policy makers for the similar reasons. The proposed models of stormwater policies and governance will help the policy makers to understand the context as well as specific solutions to be adopted. From an academic perspective, the research findings will add knowledge to urban sustainability, urban planning, and stormwater policy literature. The dissertation will also provide students with the knowledge of how technology, policy, and governance all have crucial roles to play interdependently. Specially, the research findings will be helpful for students working on urban hydrology to understand the importance of policy and governance to implement the technical solutions they design.

In this research, only the impacts deriving from changes in intensity of precipitation have been considered. The increase in runoff due to potential changes in the sites population and economic activities have not been considered. The research is primarily intended for non–coastal U.S. cities, which are located above the influence of sea-level rise. The nature of the problems associated with flooding from sea-level rise is different from the nature of the problem created from stormwater flooding in non-coastal cities. Flooding in coastal cities due to sea–level rise cannot be prevented without construction of levees and stormwater pumping stations. The use of green infrastructure cannot provide the desired level of protection in such cases. Therefore, addressing the problem of sea–level rise is beyond the scope of this research.

Dissertation Structure

This dissertation is organized into seven chapters. The first (current) chapter establishes the context, defines the objectives, and determines the approach and scope of the research. The second chapter sheds light on urban drainage concept and outlines the evolution of stormwater management techniques. It discusses concept of green infrastructure and gives a brief description about benefits of adopting it. The impact of climate change on urban drainage system is analyzed in the third chapter. For this, the study was conducted by using GIS and U.S. EPA′s SWMM model. The fourth chapter evaluates the performance of the same drainage system after the incorporation of some site–specific GI measures, which include bioretention cells, green roofs, permeable pavements, and rain barrels. The fifth and sixth chapters are dedicated for institutional arrangements. The fifth chapter deals with law and policy. First, it explores the barriers existing in the U.S. law and policy that prevent or discourage the implementation of green infrastructure. Then, it recommends a policy framework that addresses the barriers and facilitates the mainstreaming of the technology. The sixth chapter first explores the barriers in the conventional governance and then presents a new governance model appropriate for green infrastructure implementation for achieving long-term sustainability goals. Finally, the seventh chapter summarizes the overall work and concludes the dissertation.

CHAPTER 2

URBAN STORMWATER MANAGEMENT: EVOLUTION AND ISSUES

Urban Drainage System

Drainage Systems, Runoff, and Stormwater

When rain falls on the earths surface, it circulates through various natural and constructed elements of the surface and subsurface. The natural elements include soil, vegetation, stream channels, surface depressions, and subsurface geological materials, whereas, constructed features include pipes, culverts, detention ponds, pavements, roofs, and other artificial materials. All of these elements of the landscape, through which or over which water travels, constitute a drainage system (Booth 1991; Chocat et al. 2004). The National Research Council (2009) defines stormwater drainage systems as the constructed and natural features which function together as a system to collect, convey, channel, hold, inhibit, retain, detain, infiltrate, divert, treat, or filter stormwater.

Since the drainage system functions between the public and the environment, their management is crucial, both for the public and the environment. Given its complex nature and its symbiotic relationship with other systems, such as soil and plants, management of urban drainage is a complex undertaking. As such, it requires a comprehensive understanding of how water moves through the different elements of landscape after a rain event.

Of the total precipitation, a part of it is abstracted through processes including interception, evaporation, transpiration, depression storage, infiltration, and consumptive human uses. The portion of the precipitation remaining after abstraction is called runoff, which appears at the outlet of the watershed (Chow 1964; Novotny & Olem; NRC 2009). The runoff can be measured in downstream rivers, streams, gutters, or pipes shortly after the rain falls on the ground (National Research Council 2009). The volume of runoff is primarily governed by landscape characteristics, which are land slope, soil type, and type of vegetation cover (Leopold 1968). In literature, runoff is categorized into three types: surface runoff, subsurface runoff and groundwater runoff (Chow 1964; Novotny and Olem 1994).

The surface runoff (or surface stormwater runoff) is the part of precipitation excess that travels over the ground and through channels to reach the basin outlet. The portion of the precipitation that infiltration into the ground and travels laterally through the upper zone of the subsurface towards the stream is called subsurface runoff. This portion is also called interflow or storm seepage (Chow 1964). Groundwater runoff is the part of infiltrated water which percolates deep, moves into the ground water, becomes a part of it, and finally discharges into the stream. Of the subsurface runoff, a part of it enters the stream promptly after the storm as prompt subsurface runoff and the remaining part may enter the stream over a longer time in the form of delayed subsurface runoff (Chow 1964). The surface runoff and prompt subsurface runoff together constitute stormwater runoff. From regulatory perspectives, stormwater is that portion of the precipitation which passes through some type of engineered conveyance such as a gutter, a pipe, or a concrete canal (National Research Council 2009). The delayed subsurface runoff and groundwater runoff constitute base stream flow or base runoff (Chow 1964).

Impact of Urbanization on Drainage System

The native land, in general, has vegetation, porous soil, ponds, wetlands, ditches, and surface depressions (figure 2.1). When precipitation occurs, a significant portion of the precipitation is intercepted by vegetation and absorbed by top spongy soil; a large portion is retained by features such as ponds, wetlands, ditches, and surface depressions; and a large portion is infiltrated into the soil and flows into streams or groundwater. Only the remaining small portion flows over the surface as overland flow or surface runoff. As a result, there is a significantly less potential for flooding. In addition, there is an ample amount of water in the subsurface for biotic activities, plant uptake, and groundwater recharge. Due to prompt subsurface runoff, delayed surface runoff, and groundwater runoff, there is a relatively well-maintained temporal distribution of flow in the streams, which is crucial to support ecosystem structures and functions.

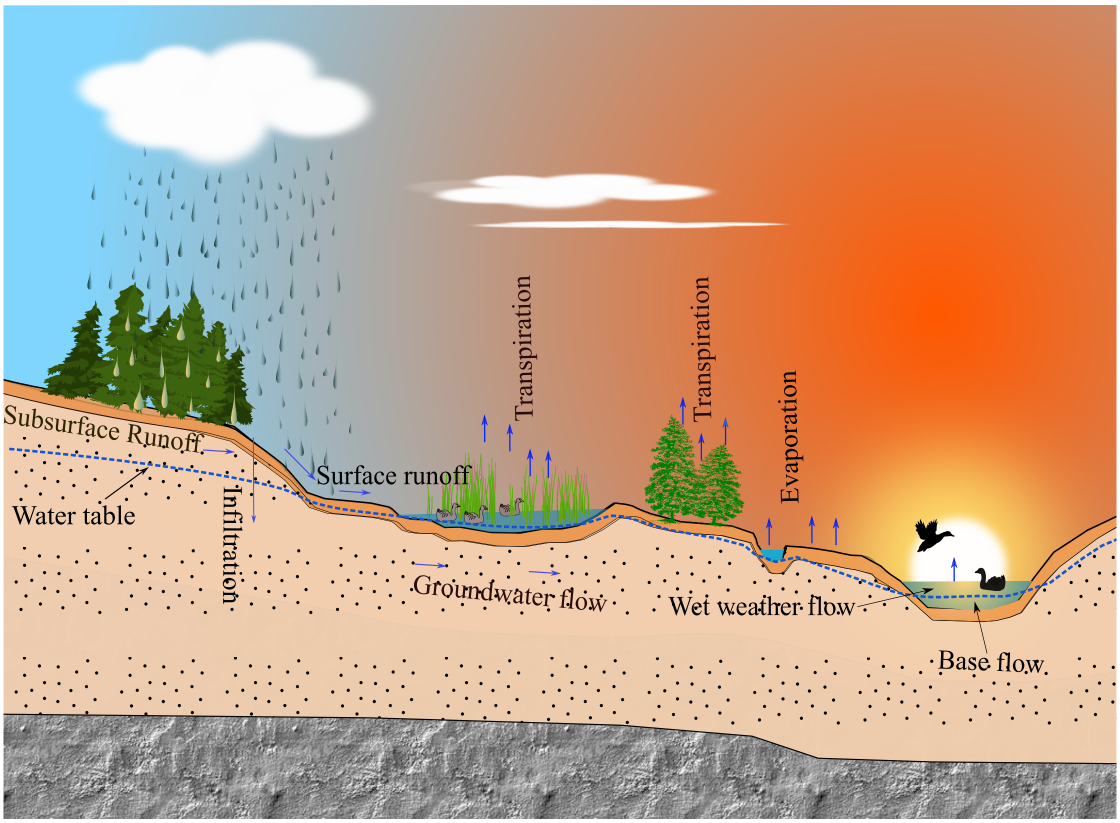

Figure 2.1. Landscape Before Urbanization

Urbanization involves the transformation of a native or an agricultural land to suburban or urban land. In the process, a sequence of changes occurs in the natural systems that significantly disturbs the natural hydrological processes discussed earlier. Example includes removal of vegetation and topsoil; burial of ditches, ponds, and wetlands; gradation and compaction of land; and construction of buildings, roads, and parking lots along with wells, septic tanks and drainage networks (figure 2.2).

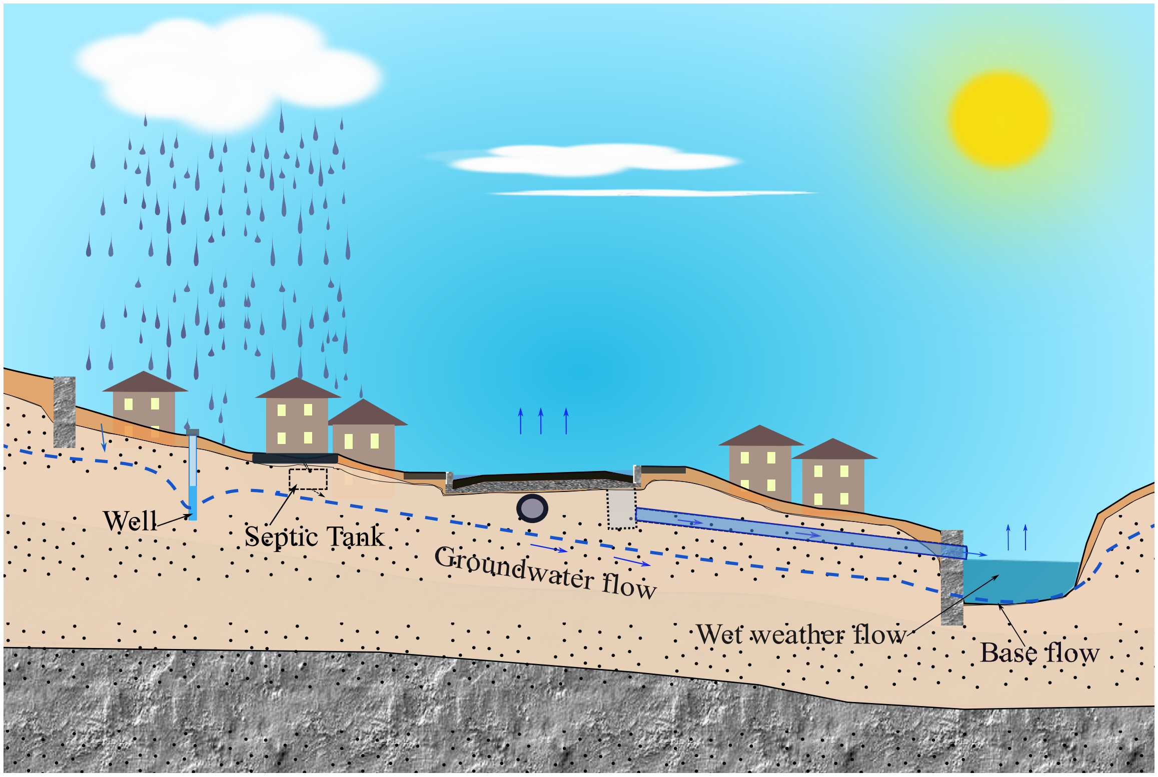

Figure 2.2. Landscape After Urbanization

Urbanization also involves straightening, deepening, widening, and in some cases, relocating of existing natural channels (Chow 1964). These activities have extensive effects on soil structures resulting in significant reduction in water retaining and infiltration capacity of the soil (Pitt et al. 2005). The loss of vegetation results in the reduced absorption of rainfall and decreased evapotranspiration. Thus, a significant alteration in the hydrologic regimes of the land occurs (Chow 1964; National Research Council 2009; WEF and ASCE/EWRI 2012). This causes an increase in time of concentration, peak runoff rates and total runoff volumes (Leopold 1968; National Research Council 2009; Novotny and Olem 1994). As a result, stormwater flows rapidly across the land surface and produces more frequent and higher peak flows in the streams resulting in radically different flow regimes in the downstream (National Research Council 2009).

On the other hand, the reduced infiltration results in the loss of subsurface flow and groundwater recharge. Thus, ground water table is reduced (figure 2), which eventually results in reduced base flow in the downstream water bodies. The altered flow—increased wet weather flow and decreased dry weather baseflow—in the downstream alters sediment transport pattern and geomorphology of the downstream water bodies, adversely affecting their ecosystem structures and functions (Leopold 1968; Niemczynowicz 1999; Paul and Meyer 2001; National Research Council 2009; Walsh et al. 2012). The decreased soil water retention in the subsurface—due to increased impervious surface, decreased soil porosity, and reduced groundwater table—leads to insufficient supply of water for plant uptake causing further loss of surface vegetation in the urban landscape.

The diminished water/air content in the soil also affects the presence of soil organism, because different organisms prefer different proportion of air and water content in the soil. For example, fungi, some nematodes, and arthropods live in air–filled pores, whereas bacteria, protozoa, and other nematodes live in water–filled pores (National Research Council 2012). When the soil water/air content is diminished, it can lead to the loss of these organisms. Since soil organismse.g. bacteria, fungi, plant roots, and burrowing wormsalter soil structure thereby changing hydraulic conductivity and infiltration rate (National Research Council 2012), the loss of these organisms can make the soil non–resilient to changes and make it permanently unsuitable for the biophysical processes. Urbanization is therefore considered as the most forceful driver of hydrological changes in a watershed (Leopold 1968).

Hynes′ (1975) argument that watershed regulates the stream conditions is clearly manifested in an urbanized watershed. It does not only reduce the base flow, as discussed earlier, but also causes significant changes in downstream channel form. When peak runoff increases due to increased imperviousness associated with urbanization, the capacity of the downstream channels can be insufficient to accommodate the increased runoff, which leads to flooding, channel bank erosion and land sliding (Booth 1991). While doing so, it disrupts the balance between sediment transport capacity and sediment supply. Removal of vegetation, realignment of channels, and increase of runoff can increase sediment supply, whereas the constructed dams and other impoundments can trap sediments and decrease the supply. When the supply is more, channel aggradation can occur. When the supply is less than the carrying capacity, channel degradation can occur in the form of incision, lateral adjustment or the combination of the two (WEF and ASCE/EWRI 2012).

Urbanization also impacts receiving water quality and freshwater ecosystems significantly by transporting numerous pollutants from urban landscape to the receiving water bodies (Allan 2004; Eisen 1995; Konard and Booth 2005; Leopold 1968; National Research Council 2009). The pollutants include viruses and bacteria (U.S. Environmental Protection Agency (USEPA) 2003; Gaffield et al. 2003); phosphorus and nitrogen nutrients (Paul and Meyer 2001; Barbosa et al. 2012); heavy metals such as copper, zinc, and lead (Paul and Meyer 2001; Barbosa et al. 2012; Petrucci et al. 2014); polycyclic aromatic hydrocarbons (Paul and Meyer 2001; Hwang and Foster 2006; Petrucci et al. 2014); polychlorinated biphenyl (Rossi et al. 2004; Barbosa et al. 2012); pesticides including insecticides, herbicides, and fungicides from lawns and gardens (Daniels et al. 2000; USEPA 2003; and thermal pollution (Somers et al. 2013). Stormwater also conveys other metals such as chromium, manganese, nickel, mercury, and cadmium (Paul and Meyer 2001).

Thus, urban stormwater alters the physical, chemical, thermal, and light regimes as well as sediment conditions of receiving waters which also degrade aquatic life (WEF and ASCE/EWRI 2012). In addition, the loss of vegetation and change in land use in the urban landscape alter the energy inputs into downstream water bodies (Vannote et al. 1980). This also leads to loss of freshwater ecosystems (Eisen 1995; Roy et al. 2008). In addition, the chemicals and pathogens present in the runoff pose pervasive and severe public health problems (National Research Council 2009).

Wastewater and Stormwater

Urban drainage systems need to deal with two types of water: stormwater and wastewater (Butler and Davies 2004). Stormwater is rainwater that originates from precipitation and appears after storm events. The amount of stormwater depends on the precipitation as well as the nature of the surface upon which the precipitation falls. It appears only during storm events and contains some pollutants originating from rain and the land surface. In the absence of proper management, it could cause flooding, leading to inconvenience, property damage, and public health risks (Butler and Davies 2004). Unlike stormwater that comes from precipitation, wastewater comes after use from humans for domestic, commercial or industrial activities. Its flow is continuous throughout the year. It is heavily contaminated with human waste and other pollutants and, if not treated properly, it can cause pollution and public health problems.

Different practices have evolved for the management of these two types of water along with the evolution of cities. A historical review (see the following section) indicates that the evolution of these practices has been driven by the level of understanding about the effects of the two waters on human wellbeing and the available technology to manage them. Conventionally, since the ancient times, both of these types of water have been considered a nuisance, and the goal of the drainage system has been to convey them out of the urban area in the fastest way possible. This has resulted in ubiquitous presence of pipe networks in the urban areas globally.

History of Urban Drainage Systems: An Overview

Drainage System in Ancient Time

The management practices of stormwater and wastewater trace back to ancient human civilization (Adams and Papa 2000; Butler and Davies 2004; Delleur 2003).

Historical evidences show that the earliest civilizations of the Middle East, the Mediterranean, and the Orient had constructed drainage systems (Delleur 2003). The expeditious water conveyance was preferred due to the convenience of removal of household waste and prevention of flood damage (Adams and Papa 2000). Examples of historical cities serviced with drainage systems are available in the literature (Adams and Papa 2000; Butler and Davies 2004; Delleur 2003; Novotny and Brown 2007).

The oldest known traces of domestic wastewater drainage elements, which date back to 6500 B.C., were found in El–Kown, Syria (Delleur 2003). These drainage systems consisted of plaster–covered gutters dug in the floor of houses crossing sills between rooms, holes in walls and pipes under the floor plaster. The first urban drainage layout with historical evidence is that of Habuba Kabira in 4000-3000 B.C., where the streets were equipped with a gutter forming a network of drainage channels that discharged their flows to the country sides. The channels were of three types: open channel with clay bottom and lime stone sides, U-shaped clay sections, and fitted clay pipes. In the pre-historic Indus Valley, where civilization flourished between 3000 B.C. and 1500 B.C, urban and sanitary drainage existed at the city scale. Wastewater was conveyed in baked clay conduits to covered gutters, then through canals dug under the streets and covered with bricks, and finally to large collectors. Settling tanks existed in this network to prevent clogging.

Around 1000 B.C., the underground conveyance system was emerged to accommodate increased urban runoff due to increased urban population. The best known drainage structure of antiquity is the Roman sewer Cloaka Maxima built around 600 B.C. (Delleur 2003). It has been functioning for more than two thousand years (Novotny and Brown 2007). In other European cities and North American cities, however, sewer construction started during the industrial revolution in the 18^{th} and 19^{th} centuries, and in Japan, only after World War II. Initially all of these sewers were intended for stormwater. It was after the introduction of flushing toilets in Europe and the U.S. that waste water was introduced into the sewer systems, creating the so–called combined sewer (Novotny and Brown 2007).

Centralized Combined Sewer System

Historical evidences show London as the pioneer in starting combined sewer systems. In London, before the first decade of the 19^{th} century, bodily waste was generally discharged into cesspits (Butler and Davies 2004). The population of London was increasing so rapidly that it exceeded one million by 1817. As a result, the cesspits became overloaded, resulting in overflows. As an ad hoc solution, cesspit overflows were connected to the sewers, which became a wide spread practice of combined sewer systems afterwards. All liquid wastes went straight from the flushing toilets and sinks to the nearest rivers or streams (Debo and Reese 2003). This moved the problem to the River Thames. By the middle of the 19^{th} century, the river was filthy and stinking, which was directly implicated in the spread of deadly cholera epidemics during 1848–1849, and in 1867, killing tens of thousands of Londoners (Butler and Davies 2004). As an alternative to the large brick–lined tunnels of the day, the Victorian sanitary reformer, Edwin Chadwik, argued for a dual system of drainage, and small–bore, inexpensive, self–cleansing sewer pipes (Burian et al. 2000). But his ideas were not put into practice at that time. Combined sewer systems were constructed in almost all of the old cities.

Burian et al. (2000) have reported an overview of development of drainage systems in the U.S. The repeated outbreaks of diseases, such as cholera and typhoid, between 1832 and 1873, and the growing public demand to replace decentralized privy vault-cesspool during the second half of the 19^{th} century, motivated municipalities to improve sanitation practices. Due to the lack of engineering expertise to tackle the changing wastewater procedures in the U.S., wastewater management efforts in the U.S. followed practices established in Europe. Since, the European cities were constructing and operating large centralized sewer systems, the European engineers promoted the use of the same technology in the U.S. The centralized management option thus became the favored management option over the failing decentralized privy vault-cesspool system. The first comprehensively planned combined sewer systems in the U.S. were constructed in Chicago and Brooklyn in the late 1850s. By the end of 18^{th} century, most major U.S. cities had constructed some form of sewer system, mostly combined. In 1909, the cities with a population of more than 30,000, had 42,040 miles of total sewers in which 77.5% were combined (Burian et al. 2000). This shows that combined sewer systems (CSS) were clearly the predominant choice over separate sewer systems (SSS). With the beginning of the 20^{th} century, there was growing realization that combined sewers were transferring the nuisances and public health risks to downstream riparian residents. This resulted in the development and adoption of treatment technologies.

The implementation of sewage treatment had to include a large number of sewer outfalls spread over many locations in the city. To avoid construction of a treatment plant for every outfall, effluents from the many outfalls were centralized to a single treatment plant by building huge interceptor pipes. During wet weather flow, the size of these interceptor pipes and the loading capacity of the treatment plants generally become too small to accommodate all of the discharge from the combined sewers. The excess flow is allowed to overflow without treatment. This overflow of raw flow is called combined sewer overflow (CSO), which releases untreated flow containing raw sewage directly into receiving waters. Since they release sediments, nutrients, gasoline, and other chemicals from urban surfaces into local waterways, as well as pathogens, and organic matter from human waste (Carson et al. 2013), CSOs are a significant source of water pollution. Many old cities in the developed countries including the U.S. still have CSS and CSO problems. In the U.S., for example, about 860 communities have combined sewer systems serving a total of approximately 40 million people (U.S. EPA 2016b).

Shift to Separate Sewer Centralized System

Treatment of the entire amount of combined flow consisting of both types of water (wastewater and stormwater) was a heavy financial burden, and only a few municipalities could afford to construct the treatment facilities to treat both. As a result, cities were motivated to separate stormwater and wastewater, resulting in separate sewer systems (SSS) referred to as municipal separate storm sewer system (MS4). In this system, wastewater and stormwater are transported by different sewer pipes, called sanitary sewer and storm sewer respectively. SSS provided the much more constant and treatable flow for wastewater and hence was favored by newly emerging urban areas. By the end of the 1930s, municipalities were augmenting CSSs to function as separate or partially separate systems or were completely replacing CSSs with new separate systems (Burian et al. 2000). Many already built CSSs in many cities still continue functioning because replacing them with SSSs would be technically difficult and financially prohibitive.

Some cities have a mixture of CSS and SSS, which is called a compound system. The compound system could result from construction of SSS during the expansion of a city whose old system is CSS. Old cities such as Chicago, St. Louis, New York, Boston, and many others have the compound systems. Centralized SSS and treatment facilities became the most dominant system of choice after the late 1930s, and before the passage of the Water Pollution Control Act, also called Clean Water Act, of 1972.

Challenges and Opportunities

Though the conventional approach has accomplished the primary goal of controlling runoff and improving public health in the urban area, it does not restore urban biodiversity and landscape hydrology destructed by urbanization. The system does not even mitigate flooding; it simply transfers the problem to downstream locations (Heaney et al. 1999). In fact, by further increasing the rate and quantity of flow and further decreasing the time of concentration, the gray system increases the potential of flooding and aggravates the problems in the downstream. The National Research Council (2009) concludes that the current gray infrastructure (CSS and SSS) are inefficient because of their focus on symptoms (large stormwater volumes) rather than on the cause of the problem, which is the imperviousness associated with urban development. With the current urban development practices, stormwater impacts are virtually unavoidable in urbanized areas, and it is difficult to return to or maintain the hydrologic regime of pristine environment (WEF and ASCE/EWRI 2012).

Climate change has brought an unprecedented challenge for drainage managers (Willems 2012). As discussed in the first chapter, our conventional infrastructures were designed based on the historical precipitation data assuming that the precipitation pattern will not change over the design life of the facility (Bedient et al. 2008; Chow 1964). Since the frequency and intensity of heavy rainfall events are projected to increase significantly (IPCC 2013), the capacity of the existing system will not be able to accommodate the excess rainfall. Managing the additional flow associated with climate change has been a concern for the drainage engineers. In the case of combined sewer system, if the hydraulic capacity of the combined sewer is exceeded due to excessive rainfall, there will be more combined sewer overflows posing increased regulatory challenges. When the sewer becomes surcharged, the flow can reverse and back up to the basement floor drains resulting in basement flooding, which leads to property damage and health threats (Adams and Papa 2000). The combined effect of climate and land use change also pose increased challenge to floodplain management in the downstream (Thakur et al. 2017b).

On the other hand, the growing realization of the need to restore urban hydrology for maintaining ecological health of the urban areas, enhancing ecosystem services, replenishing groundwater, mitigating flood, and restoring stream conditions are changing the human perspectives of urban drainage management. This implicates the necessity of a new paradigm in stormwater management, which can restore the hydrological and ecological functionality of the urban landscape while accommodating the increased precipitation due to climate change.

Along with the challenges, many innovative ideas and technologies have evolved. Green infrastructure is one such technology, which utilizes soil and vegetation to treat stormwater and restores urban biodiversity and landscape hydrology. Urban design concepts that utilize green infrastructure have also evolved. Examples include water-centric eco-cities (Joss 2010; Novotny 2008; Novotny et al. 2010; Novotny and Novotny 2012; Roseland 1997), green cities, and smart growth (Heaney and Sansalone 2012). Effective and timely implementation of these concepts and technologies can be instrumental to address the problems challenging cities and critical to pursuing urban sustainability.

Green Infrastructure: Concept and Benefits

What is Green Infrastructure?

The term green infrastructure is relatively new; however, the concept per se has a long history. It was conceived for the first time in planning and conservation efforts around mid-19th century to link natural spaces to counter fragmentation and benefit people as well as biodiversity (Benedict and McMahon 2002). Unfortunately, over more than hundred years, grey infrastructure became ubiquitous globally, overshadowing the green concept. It was only during the last decade of the 20th century that the concept received attention from the professionals, and the term green infrastructure was coined. Since then, the approach is getting increasing support in the U.S. and abroad. Currently, its innovation is rapidly unfolding (Elkind and Cady 2012).

The term, however, has no universal definition. The definition varies depending upon context (Benedict and McMahon, 2002; GIAS, 2008). In the context of stormwater management, it can be defined as a set of techniques, technologies and practices that uses soil and natural process to infiltrate, evapotranspire or reuse stormwater (Green

Infrastructure Action Strategy (GIAS) 2008). Thus, green infrastructure is a landscape based water–centric approach (WEF and ASCE/EWRI 2012). According to Benedict and McMahon (2002), green infrastructure is an interconnected network of green spaces that conserves natural ecosystem values and functions and provides associated benefits to human populations. They argue that green infrastructure provides an ecological framework needed for environmental, social, and economic sustainability. In a recent article by Norton et al. (2015), the term urban green infrastructure has been defined as the network of planned and unplanned green spaces, spanning both the public and private realms, and managed as an integrated system to provide a range of benefits.

Green infrastructure can be natural, such as open space, or restored or built. Several built green infrastructures are currently available. Examples include green roofs, permeable pavements, rain barrels, rain gardens, bio-swale, bio-retention cells, and tree planters.

Benefits of Green Infrastructure

In addition to restoring hydrology and helping to control runoff, green infrastructure offers multiple benefits to the public and the urban environment. It restores biodiversity (McKinney 2002), revives naturally functioning ecosystem structures (Andersson et al. 2014; Breuste et al. 2015b), and regenerates a host of ecosystem services (Breuste et al. 2015b; Jansson and Nohrstedt 2001). The ecosystem services include carbon sequestration (U.S. EPA 2010), water quality improvement (Novotny et al. 2010), climate change adaptation (Kramer 2014), and groundwater recharge (U.S. EPA 2010, 2014b). Through these ecosystem services, green infrastructure re–establishes the socio–ecological connectivity destroyed by urbanization (Gmez-Baggethun et al. 2013; Tzoulas et al. 2007) and improves the quality of life (Breuste et al. 2015a). It increases property value (Anderson and Cordell 1988; Benedict and McMahon 2002; Wachter and Wong 2008; Ward et al. 2008) and decreases the cost of public infrastructure and services such as flood control, water treatment systems, and stormwater management (Benedict and McMahon 2002). Green infrastructure also fosters community cohesiveness by engaging residents in planting and maintaining the green infrastructure in the neighborhoods (Wise 2008).

Additionally, green infrastructure is climate resilient (U.S. EPA 2015). Other benefits include cost-effectiveness (Baerenklau et al. 2008; Foster et al. 2011; Shaver et al. 2009; U.S. EPA 2015) and material efficiency, the two additional sustainability attributes as argued by (Dhakal and Oh 2011). The approach is also energy and water efficient (Heaney 2007). To summarize, green infrastructure is an essential tool to pursue urban sustainability (Tzoulas et al. 2007; Young 2009). The installation cost of green infrastructure is also less than the cost of conventional gray infrastructure (Benedict and McMahon 2002; Wise 2008). Portland, for example, saved $250 million by investing $8 million in green infrastructures instead of constructing hard infrastructure (Wise 2008). A case study of nine projects in the U.S. and New Zealand by Shaver et al. (2009) showed the cost of green infrastructure 14 to 64% less than that of conventional development. Thus, green infrastructure contributes to every dimension of sustainability.

CHAPTER 3

CLIMATE CHANGE IMPACT ON URBAN STORMWATER SYSTEM

Introduction

In addition to the land surface characteristics, rainfall intensity and frequency are two critical factors that significantly affect the design capacity of an urban drainage system. Current engineering practices assume these factors to remain stationary, and a system′s capacity is designed based on the frequency analysis of time series of historical precipitation data (Bedient et al. 2008; Chow 1964). Since climate change increases both intensity and frequency of heavy precipitations (IPCC 2013; USGCRP 2014), the assumption of stationarity is an incorrect assumption. When both the intensity and frequency of heavy rainfall events increase, it is very likely that the design capacity of sewer system determined from the analysis of past data will be insufficient to accommodate the increased precipitation. The insufficient capacity results in the failure of the system during heavy rainfall events leading to urban flooding which threats public health and safety and risks built infrastructure including the stormwater system itself. The evidences of flooding problems have become increasingly widely in the recent years as exemplified in the first chapter. In the case of a combined sewer system, increased precipitation may increase combined sewer overflow (CSO), adding more pollutants to the receiving water bodies and increasing regulatory challenges to cities.

As a legacy of the past, urban drainage infrastructure with the faulty design assumption is prevalent all over the world. To prevent the failure of the existing systems and avoid the potential damage, the existing systems need to be adequately retrofitted with reliable adaptation measures so that the existing system can accomodate the increased rainfall intensity. Prior to designing, such as adaption measures, it is crucial to evaluate the system′s performance under projected climate scenarios so that appropriate solutions can be determined accordingly. This chapter conducts a case study of a combined sewer system and evaluates the impacts on its performance under future rainfall scenarios.

The assessment of climate change impact in urban drainage systems is a relatively new task for urban hydrologists, and it lacks both tools and guidelines in the technical literature for the assessment (Semadeni-Davies et al. 2008). However, though limited in number, some researchers have investigated the impacts by applying different approaches. Some of those investigations are discussed here.

As a pioneer, Niemczynowicz (1989) conducted a case study of a 1770 ha Lund catchment in Sweden with combined sewers in the city center using U.S. EPA′s Storm Water Management Model (SWMM). The study showed that an increase in rainfall intensity by 20 to 30% caused significant problems in Lund′s drainage system, resulting in basement as well as street flooding and causing property damage. The research showed that when a 3-yr rainfall was increased by 30%, 6820 m of conduits were surcharged and more than half of the city center area was flooded. Combined sewer over flow volume also increased significantly. For example, for a 1-yr rainfall, the overflow volume was double the increase in rainfall.

Denault et al. (2002) used design storm rainfall scenarios projected from intensity–duration–frequency (IDF) curves for years 2020 and 2050 to evaluate the climate change impact on drainage pipe capacity of a 440 ha Mission/Wagg Creek Watershed in North Vancouver, Canada. The research showed that though the impact was not that significant for a 10-yr precipitation, about 1355m (out of 6200m) of major system was inadequate to convey projected 100-yr event.

Waters et al. (2003) also used SWMM for a case study in 23.3 ha Malvern Catchment in Ontario, Canada. The research showed that a 15% increase in design storm resulted in 19% increase in runoff volume and 13% increase in peak discharge, causing 24% of the drainage pipes to surcharge. Watt et al. (2003) also presented Malvern case study along with a case study of Central Park urban catchment in Ottawa, Canada, using the SWMM model for assessing impact and suggesting adaptation measures. In the Central Park case study, the research showed that the percent of pipes with capacity shortage was always greater than the percent of increase in storm intensity. For example, 20% increase in storm intensity resulted in surcharge of 30% of pipes.

Olofsson (2007) conducted urban drainage simulation using Model for Urban Sewers (MOUSE) to model urban drainage system of a 54ha suburban catchment in Sweden, containing 410 nodes. The system was designed with current design standard to accommodate minimum rainfall of 10-yr return period. The researchers selected 120 nodes and applied emission Scenarios A2 and B2 defined by the IPCC Special Report on Emission Scenarios (SRES). The SRES defines A2 as the scenario with heterogeneous world, increasing population, slow economic and technologic development; and B2 as the scenario with the world where emphasis is on local solution to the economic, social and environmental sustainability, increasing population, moderate economic development, and less diverse and more rapid technological development (IPCC 2007). Considering the two emission scenarios, Olofsson determined various parameters to assess the impact including maximum level in nodes, exceeded levels (number, frequency and duration of nodes in which flow exceeds the ground or critical level), and pipe flow ratio (flow-rate/full flow–rate). The result showed that the maximum water levels at the nodes were about 0.3m higher for the period 2011–2040, 0.4m higher for the period 2041–2070, and 0.8m higher for the period 2071–2100, as compared to the water level for the base period 1971–2000. Similarly, flow ratio was significantly higher in the period 2071–2100. Number of flooded nodes and the frequency of floods both increased in all of the future periods. The duration of the flood doubled for most of the nodes.

Kleidorfer et al. (2009) analyzed results from 250 virtual case studies and one real world case study and found that an increase of 20% in rainfall intensity has the same effect as an increase of impervious area of 40%. This finding showed that increase of rainfall intensity could be compensated by having increased infiltration measures in the catchment. The researchers finally concluded that the increase of rainfall intensities has the highest impact on the system performance followed by the impact of a variation in impervious area.

Nie et al. (2009) simulated the potential impact of climate change on a sewer system in a 364.3 ha Veumdalen catchment of Fredrikstad, Norway. The simulation showed that the increase in precipitation by 20%, 30%, and 50% above the 2004 base precipitation would increase the volume of water spilling from the flooding manhole by 43%, 121%, and 181% respectively, and the corresponding increase of total CSOs would be 36%, 54%, and 89%.

Forsee and Ahmad (2011) used the US Army Corps of Engineers′ Hydrologic Modeling System (HEC–HMS) for evaluating performance of stormwater infrastructure of the 40,000–ha Pitmann watershed, Las Vegas, under climate change. They assessed four different variables (inflow, discharge, elevation, and storage) and showed that if the 6-hr 100-yr rainfall depth is increased by a factor of 1.2, the maximum values for the four variables would increase by a factor from 1.1 to 1.7.

Relatively recently, Berggren et al. (2012) studied the separate sewer system in a 54-ha small suburban area near Kalmar, Sweden, using Model of Urban Sewers (MOUSE), a numerical model developed by Danish Hydrological Institute. The observed rainfall series for the period 1993–2002 was used as a baseline scenario, which was assumed to represent current climate and rainfall, and delta change method was used for the future rainfall events for global emission scenario A2. To measure the hydraulic impacts on the urban drainage system, they used two parameters: the water level in nodes and the pipe flow ratio in links. They measured water level in nodes as maximum from both ground level and so–called critical level, which was set 0.5 m below ground level. They found that the maximum increase in water level at nodes for the period 2071–2100 was 1.9 m (385%) above the baseline scenario of 1993–2002. About 18% nodes had the difference of more than 0.5 m and about 3% nodes had the difference of more than 1 m. During 2071–2100, the total frequency of flood increased to 75 as compared to base period flood frequency of 25. Overall, their research result showed that future precipitation would increase both the number of nodes flooded and the flooding frequency.

In this research, I conducted a case study on a combined sewer system in St. Louis, Missouri, United States, using ESRI′s ArcGIS and the U.S. EPA′s SWMM. GIS was used for watershed characterization, and the existing drainage system was modeled in SWMM under current and future rainfall scenarios. For the current climate scenario, the observed hourly rainfall data of 1971–2000 at Lambert Airport Station provided by NOAA was used. For future scenarios, a delta factor was calculated from modeled rainfall data for current (1971–2000) and future (2041–2070) scenarios, obtained from North American Regional Climate Change Assessment Program (NARCCAP), and the factor was applied to the current observed data to produce the future precipitation (2041–2070) scenario. Since the highest temporal resolution of the NARCCP data is 3-hr, the current hourly data obtained from NOAA was also aggregated to 3-hr rainfall data. Frequency analysis was conducted for the 3-hr annual maximums, and the drainage system was evaluated for 50-yr return rainfall for both the current and future scenarios. Due to the climate change, the systems performance at both the conduits and nodes considerably decreased with a significant increasee in node flooding, pipe surcharge, and CSO volume. Thus, the result suggested that the system requires retrofitting for it to perform at the desired level in the future.

Research Methodology

Study Area

Since this research evaluated the impact of precipitation, not sea level rise, any drainage system that is not affected by sea level rise could be appropriate for the case study. Many urban systems of this type exist in the US. To select the most suitable one for this study, following criteria were established: presence of adequately large sewer system, potential occurrence of flash floods, and data availability including drainage network, georeferenced land characteristics, rainfall data, and flow data. Based on these criteria, a site in the City of St Louis, in the state of Missouri (MO), the United States, was selected.

The city is located at 38° 37′ 38″ N and 90° 11′ 52″ W, and is along the bank of River Mississippi. The drainage system, both stormwater and wastewater, of the city is provided by the Metropolitan St. Louis Sewer District (MSD), which covers most of St. Louis County in addition to the City. The system provides services to approximately 1.4 million residents and 535 square-mile (sq mi) area (MSD 2011). As reported by the MSD, the collection system comprises of 9,600 mi of pipe, and is the fourth largest system in the US. Of the total area served by the MSD, 75 sq mi of St. Louis City and the adjoining St. Louis County are served by a combined sewer system. The selected catchment is in the combined sewer system area and is bounded by Adelaide Avenue in the north, Mississippi River in the east, Grand Avenue in the South, Carter Avenue in the west, and O'Fallon Park in the northwest (figure 3.1).

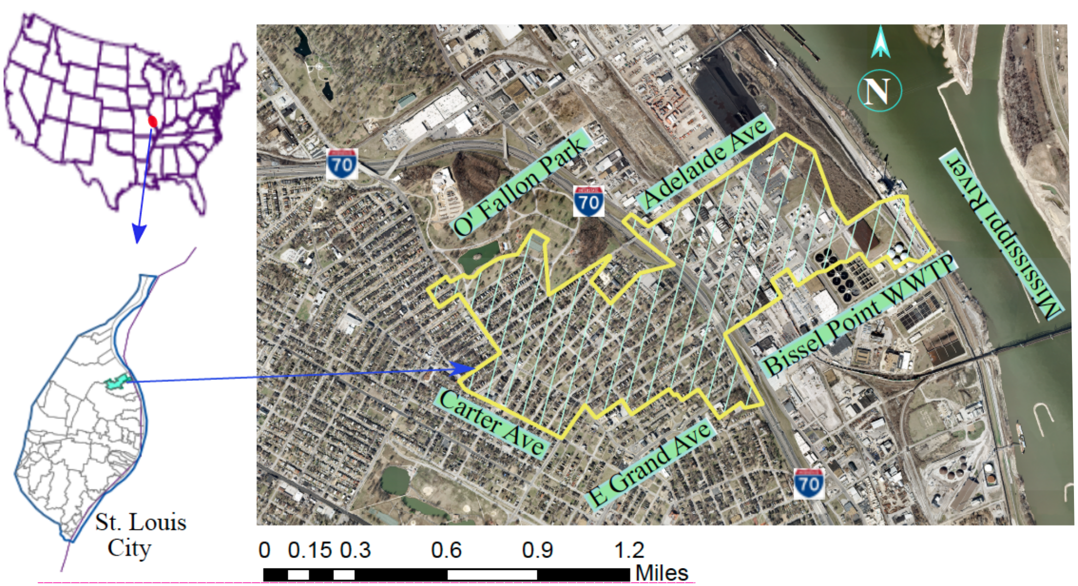

Figure 3.1. Location of Study Area

The catchment is in the domain of Bissel Point treatment plant, which is located close to the south-east corner of the catchment, by the side of River Mississippi, to which the whole area (169.23 hectare or 0.65 sq mi) of the selected catchment drains. No distinct surface channels exist within the basin, and hence the flow is either through constructed sewer system or overland. During dry days and light rainfall events the flow is conveyed to the Bissel Point waste water treatment plant through underground sewer networks, and, after treatment, is discharged into Mississippi River. However, during heavy rainfall events, when the combined flow exceeds the treatment plant capacity, the surplus flow is discharged directly into Mississippi River through two outfalls.

The selected site is divided into almost two halves by interstate 70 (I-70), the east of which has almost flat terrain with average slope of 0.33% and is occupied by industrial and unrestricted districts. The portion of the study catchment west of the interstate has relatively greater slope of 11.25% and is mostly occupied by two-family residential buildings. The site has mean annual precipitation of 36 to 47 inch and mean temperature of 52 to 59°F (NRCS 2016). The drainage system is maintained by Metropolitan St. Louis Sewer District (MSD). The hydrologic soil group of most of the site is C, though a fraction of the land has mixed soil group C/D (NRCS 2016).

Data Source and Processing

Data used in this study were: (a) georeferenced data including contour map, parcels, and sewer networks (b) observed rainfall and sewer flow data (c) 2012 georeferenced aerial image of the study area (d) soil data. These data were obtained from different sources including Metropolitan St. Louis Sewer District (MSD), North American Regional Climate Change Assessment Program (NARCCAP), Natural Resource Conservation Service (NRCS), National Oceanic and Atmospheric Administration (NOAA), and some published literature. Formats and sources of these data are summarized in table 3.1. These data were processed to obtain SWMM input data.

Table 3.1. Data Source and Format.

Data	Format	Source
2-ft contour, sewer networks, parcel data	GIS	MSD St. Louis
5-min rainfall and 5-min sewer flow data	Excel	MSD St. Louis
Aerial imagery, 6-in resolution, leaf off	TIFF	MSD St. Louis
Soil classification	Web	NRCS Website
Soil characteristics	Text	USDA/James et al. (2010)
Historical 1-hr rainfall	Excel	NOAA
Modeled 3-hr historical/future rainfall	NetC	NARCCAP

Model Selection

Numerous computer models are available to simulate rainfall-runoff phenomenon. Selection of an appropriate model depends upon the purpose and scope of the work as well as landscape characteristics and available information. For this study, U.S. EPA′s Stormwater Management Model (SWMM), version 5.1.012 released in March 2017, was used. SWMM is a dynamic rainfall-runoff computer model used for a single event or continuous long-term simulation of rainfall-runoff process, and is mainly used for urban areas (Rossman 2015). It is in the public domain and can be downloaded from the U.S. EPA′s website[1]. The model has been used by thousands of cities worldwide, and has arguably the most successful track record of application to urban water quantity and quality problems (Huber and Roesner 2013).

Since its inception in 1971, SWMM has undergone continuous development, and it resumes to be widely used globally for planning, analysis, design, management, and litigation related to stormwater runoff, combined sewers, sanitary sewers, and other drainage systems in urban areas (James et al. 2010). The version 5.1 is the most current version and simulates hydrology, hydraulics, and water quality of urbanized watersheds. As discussed by James et al., the model provides an integrated environment for editing study area input data, running hydrologic, hydraulic and water quality simulations, and

[1] https://www.epa.gov/water-research/storm-water-management-model-swmm#downloads

viewing the results in a variety of formats including color-coded drainage area and drainage system maps, time series graphs and tables, profile plots, and statistical frequency analysis. It incorporates various hydrologic processes including rain-fall, evaporation, interception in depression storage, infiltration, percolation into groundwater, and capture and retention by LID practices. SWMM is also capable of routing runoff and external inflows through the drainage system consisting of surfaces, pipes, channels, storage/treatment units and diversion structures. In addition to the runoff, SWMM also estimates pollutants present in runoff and/or wastewater. Further detail about its applicability is available in SWMM documents (e.g., James et al. 2010; Rossman 2015).

Conceptually, as discussed in James et al. (2010), SWMM represents a drainage system as a series of water and material flows between several environmental compartments including atmospheric, land surface, groundwater, and transport compartments. Precipitation, represented by rain gage, falls from the atmospheric compartment to the land surface compartment represented by a catchment where pollutants are deposited. The land surface compartment conveys flow in two forms: one, infiltration to the groundwater compartment; and the other, surface runoff and pollutant loading to the transport compartment. After receiving infiltration from the land surface compartment, the groundwater compartment transports a portion to the transport compartment which is modeled using aquifer objects. The transport compartment consisting of nodes and link transports the flow to outfalls or treatment facilities.

Model Development

Watershed Delineation

Watershed is a spatial unit, all of which drains through a common outlet. The process of drawing watersheds boundary is called watershed delineation. It is done by joining the highest elevations, using contour maps or by automatically processing digital elevation model (DEM) using GIS tools. In this research, GIS (various tools under

ArcToolbox) was used to convert contour map to DEM and delineate the study area watershed. The procedure is briefly outlined as follows.

First, the 2-ft contour data provided by the MSD was converted into Triangular Elevation Network (TIN) using 'Create TIN' tool (3D Analyst Tools → Data Management→TIN→Create TIN). The resulted TIN model was then converted to DEM using 'TIN to Raster' tool (3D Analyst Tools→Conversion→From TIN→TIN to Raster). Due to the presence of errors in the data, the DEM is likely to have cells whose flow direction cannot be assigned. Such cells are called sinks, which need to be filled before creating a flow direction map. The task was done by using 'Fill' tool (Spatial Analyst Tools→Hydrology→Fill). The DEM with filled sink was then converted to flow direction map, which shows the detail of the direction of the surface flow, by using 'Flow Direction' tool (Spatial Analyst Tools→ Hydrology→Flow Direction). To show the accumulation of the flow of surface water, the flow direction map was converted into flow accumulation raster using 'Flow Accumulation' tool (Spatial Analyst Tools→Hydrology→Flow Direction).

Now, it is required to identify location of the outlet or 'pour points' for watersheds to be delineated. A pour point should be located within an area of high flow accumulation because it is used to calculate the total contributing water–flow to that point. For this, a shape file was created and points were added to the grids with high flow concentration, displayed by the flow accumulation raster. One such point was added for each accumulated flow. To ensure that the created pour points were exactly located on the high flow accumulation, 'Snap Pour Points' tool under 'Hydrology' tool of 'Spatial Analysis' was used. The tool moves any incorrectly located pour points to its correct grid that has highest flow accumulation value. The 'Watershed' tool was then used to delineate a watershed for each snapped pour point. Finally, the watersheds thus created were converted into watershed polygons using 'Raster to Polygon' tool under 'Conversion' Tools. The steps and their results are depicted in figure 3.2.

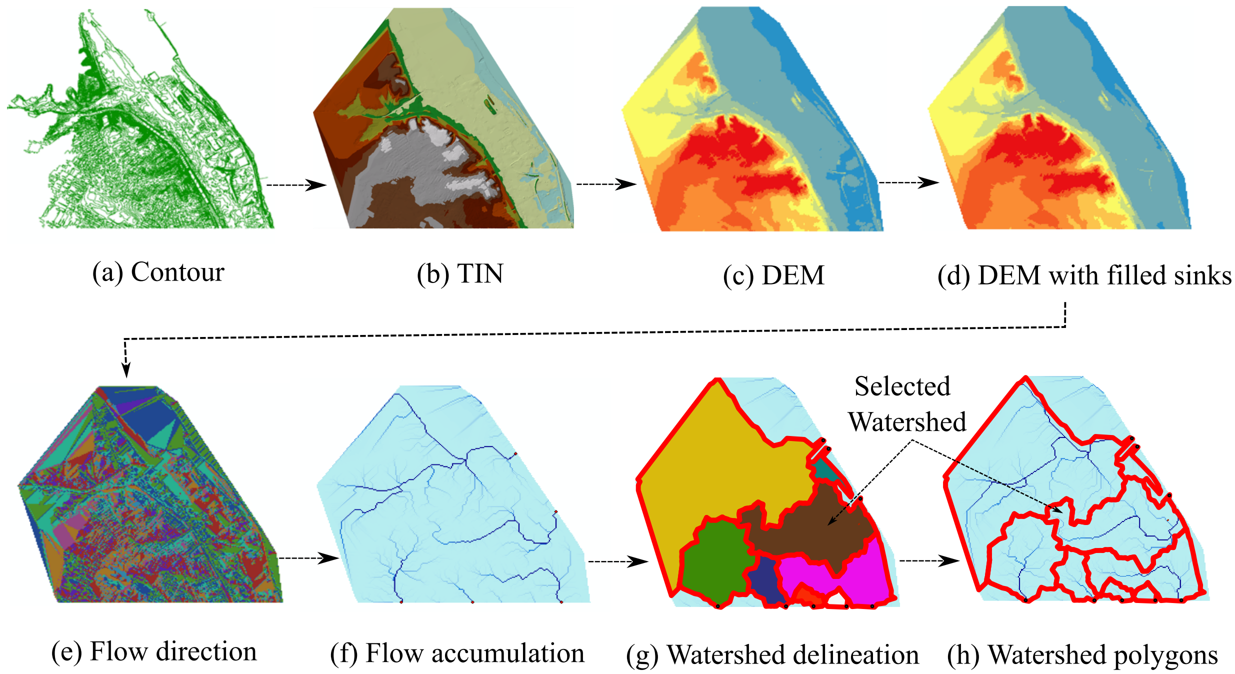

Figure 3.2. Watershed Delineation: Process and Result

Based on the availability of data and presence of sufficiently large drainage system, one appropriate watershed was selected for case study. The selected watershed is shown in figure 3.3. The blue colored arrows in the figure represent flow directions.

Subcatchment, Sewershed, and Sewer System

To appropriately incorporate the land′s spatial variability, SWMM requires partitioning the catchment into a group of subcatchments. A subcatchment is a smaller hydrologic unit whose surface runoff flows to a single discharge point called outlet. The division of the catchment into subcatchments depends on the extent of the spatial variability, direction of surface flow, and direction of wastewater flow. For these features contour map, aerial image, and sewer networks were used. Within the watershed boundary, several pour points were established on the flow accumulation raster, and subcatchments were delineated using the 'Watershed' tool. The subwatersheds thus

Figure 3.3. Extracted Watershed With Arrows Showing Flow Direction

created were then converted to subwatershed polygons (figure 3.4). The subwatersheds were overlaid on the sewer networks and the final sewershed was determined (figure 3.4). The finalized sewershed, which is named hereafter as study area watershed, or simply watershed, is the area included by the pink line in the figure 3.4.

The study area watershed with the delineated subwatersheds were then overlaid on the sewer networks, aerial imagery, parcel layers, and surface flow direction map created by GIS. Subcatchments were then finalized in the GIS platform. The result was then overlaid with the watersheds sewer system again and a scaled image was created in JPEG format to use as backdrop in SWMM. The JPEG image was uploaded into the SWMM platform on which the subcatchments and sewer networks were traced. The Auto–length tool of the SWMM was set 'ON' while drawing these objects so that the subcatchment areas and conduit lengths were calculated automatically. The invert and top levels of some nodes were available in the GIS data received from MSD. These data for other nodes were calculated based on assumed slope of conduit and available contour of the

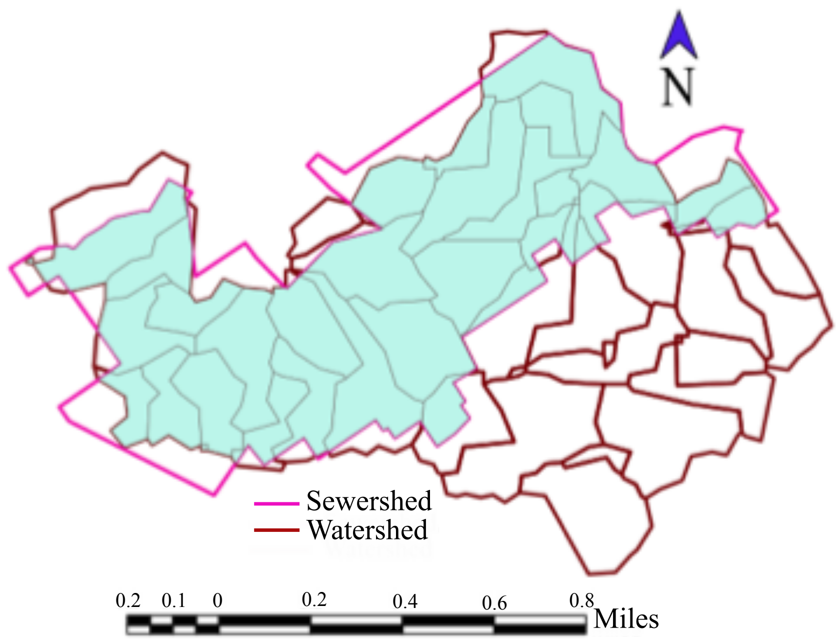

Figure 3.4. Sewershed/Watershed Overlay and GIS Generated Subcatchments

land surface. A rain gage object was added to supply precipitation to all of the subcatchments to incorporate rainfall. Before discharging sewer flow into Mississippi, the dry weather flow and a portion of wet weather flow were routed to interceptor tunnel through a control mechanism. This mechanism, which functions as a combined sewer overflow structure was represented in the model through a combination of weir and orifice structure as shown in the figure (detail A, figure 3.5). The dimensions of the control structures were determined to deviate total dry weather flow as well as wet weather flow generated by 0.75 inch of rainfall toward the interceptor tunnel. Any additional flow was discharged directly to Mississippi through outflow nodes outfall1 and outfall2, without treatment. The detail procedure for this process is available in SWMM User′s Manual (Rossman 2015). Figure 3.5 depicts the output of this process and figure 3.6 depicts the output with the background aerial image.

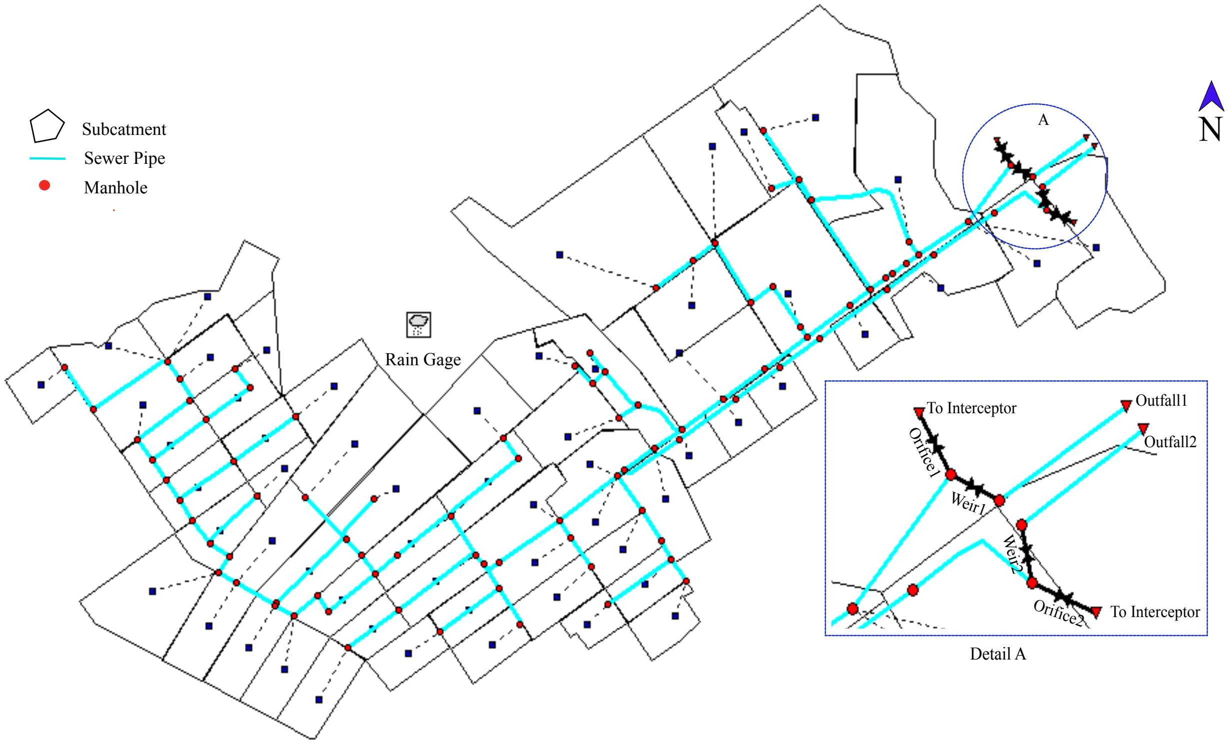

Figure 3.5. Subcatchments and Sewer System Network Modeled in SWMM5

Selection of Routing and Infiltration Processes

SWMM provides multiple options for computation of infiltration and routing of flow. For calculation of infiltration, the options available are Horton, Green-Ampt, and Soil Conservation Service′s SCS Curve number; whereas for flow routing in channels and pipes, the options include Steady Flow, Kinematic Flow, and Dynamic Flow routing. Depending on the modeling requirements and data availability, the user is required to select one option for each of these processes.

Infiltration rate depends on soil properties including hydraulic conductivity, diffusivity, and water holding capacity. These properties are determined by soil structure and extent of compaction which affect soil metric forces and porosity. While computing infiltration, these factors need to be considered. Horton′s and SCS Curve Number

Figure 3.6. Catchment and Sewer Network With Backdrop Image

methods are based on empirical observations and require field data to determine their parameters. Green–Ampt method is physically based. It assumes a sharp wetting front moving downward from the surface at the interface of saturated soil above and drier soil below and computes infiltration based on Darcy′s law (Rossman 2015). The method requires following parameters: soil suction head, saturated hydraulic conductivity, and initial moisture deficit (Chow et al. 1988). These parameters can be estimated even without field data, though field data is preferable (James et al. 2010). Since Green–Ampt method represents the catchment infiltration more realistically than the other two methods (Turner 2006), this method was used in this study.

Flow routing refers to a mathematical procedure for simulating speed and shape of flow through drainage system elements as a function of time. It is an important and complex component in hydrologic analysis, and requires a huge computational task. A wide range of flow routing models are available in literature, of which SWMM provides three options including Steady State, Kinematic Wave, and Dynamic Wave routing.

As discussed in SWMM manual (Rossman 2015), steady wave flow routing is the simplest method. It assumes that flow is uniform and steady in each computational time step. The method simply transforms inflow hydrographs at the upstream node of a conduit to the outflow hydrograph at the downstream node, with no delay or change in shape. Kinematic routing method solves the continuity and simplified momentum equations in each conduit. However, both methods cannot be applied to systems where backwater effects, surcharge, pressurized flow, and reverse flow exists. These scenarios can be represented by dynamic wave routing method, which solves the complete one-dimensional gradually–varied unsteady flow (Saint Venant) equations and arguably produces the most theoretically accurate results (Rossman 2015). Since the system modeled in this research involves the phenomena including backwater effects, surcharges, and pressurized flow, dynamic wave flow routing method was used.

As discussed in James et al. (2010), the dynamic wave flow routing receives hydrograph input at a node, performs dynamic routing of flow through the storm drainage system to the outfalls, and ultimately releases the flow to the receiving system. The program simulates branches and loops in the sewer system, backwater, free surface flow, pressurized flow, flow surcharge, and flow reversal. It also simulates flow transfer by facilities including weirs, orifices, pumps, and storage units.

Input Parameters

i. Subcatchment geometry and drainage elements

After having subcatchments and drainage systems, numerous input parameters need to be determined to feed into SWMM for a sufficient representation of topography, land surface heterogeneities, and hydrologic characteristics. As mentioned earlier, subcatchment areas and conduit lengths were calculated by using SWMMs auto-length tool while drawing the subcatchments and conduits on SWMMs study area map. The node inverts and top levels were either taken from the available GIS dada or estimated based on the available data. As discussed in James et al. (2010), the length of overland flow, defined as the distance the flow travels before it begins to consolidate into rivulet flow, of each subcatchment was determined by measuring the distance from the back of a representative lot to the center of street. In case of the three undeveloped subcatchments, the overland flow length of 152 m (500 ft) was adopted, as suggested by SWMM manual (James et al. 2010; Rossman 2015). The width of the subcatchments were determined by dividing subcatchment′s area by the length of overland flow.

ii. Surface and subsurface characteristics

The surface and subsurface characteristics that determine the hydrologic response of subwatersheds include slope, imperviousness, roughness coefficient, depression storage, and percent of impervious area without depression storage (James et al. 2010). The slope of the overland flow path, was calculated from GIS data. In case of varying slopes, area–weighted–average was taken.

Imperviousness is the percentage of the impervious surface present in the subcatchment. It is one of the most sensitive parameters in hydrologic characterization whose value ranges from 5 to 95% depending upon the extent of development (James et al. 2010). In this study, imperviousness was calculated for each subcatchment by directly measuring the area of impervious features on aerial photography (ortho imagery) of 2012, available from MSD. The measured total impervious area in a subcatchment was divided by the total area of the subcatchment to determine the imperviousness.

Roughness coefficient represents the amount of resistance of the land surface to overland flow. Since SWMM computes overland flow using Manning′s equation, this coefficient is the same as Manning′s roughness coefficient 'n' (James et al. 2010). Separate values of 'n' are required for the impervious and pervious portions of subcatchments. Depression storage indicates the volume to be filled prior to the occurrence of any runoff and represents initial abstractions such as surface ponding, interception by land features, and surface wetting (James et al. 2010). Typical values range between 0.05 inch for impervious surfaces to 0.3 inch for forested areas (James et al. 2010; Rossman 2015). Values provided in the SWMM′s user manual were used while developing the model. The percent of impervious area without depression storage is another parameter which accounts for the impervious areas that produce immediate runoff before depression storage is satisfied (James et al. 2010). This study adopted the SWMM′s default value of 25%.

The parameters required for Green-Ampt method were determined using two sources. First, the NRCS hydrologic soil group of the subcatchments were determined from USDA Natural Resource Conservation Service′s (NRCS) Web Soil Survey (WSS), produced by the National Cooperative Soil Survey and operated by the NRCS. According to the WSS data, the hydrological soil group of the most of study area soil is C (except 22.7% of the area whose soil is C/D mix), and the top soil layer is silt loam. According to James et al. (2010), the soil type selected should correspond to the surface layer of a catchment. Second, the values of the parameters for soil type C was taken from James et al. (2010), which are tabulated in table 3.2.

Table 3.2. Soil Characteristics

Parameter	Value
Initial moisture deficit at wilting point (silt loam)	0.32
Soil capillary suction head (silt loam)	12 in
Soil saturated hydraulic conductivity, (K_{sat})	0.26 (in/hr)

Calibration and Validation

Since drainage efficiency is challenged during high precipitation events, event–based evaluation is arguably the most appropriate method for evaluating the system performance. Therefore, high intensity short duration events were selected from the available 2013 rainfall data for calibration and validation. The model was first calibrated using one storm event, then it was validated with three isolated events shown in table 3.3.

Table 3.3. Selected Storms for Calibration and Validation

Process	Date	Rainfall(mm)	Rainfall(in)	duration (hr:min)
Calibration	5/31/2013	54.86	2.16	5:45
Validation	5/27/2013	21.84	0.86	3:00
Validation	5/20/2013	26.05	1.03	1:50
Validation	4/10/2013	38.78	1.53	3:3

Observed flow data provided by MSD contained discharge, velocity, and water-level in manhole recorded by four flowmeters installed at different locations across the study area. The water–level data recorded by the flowmeter located at E Prairie Ave 32 m downstream of N 20^{th} street (represented by node J23 in figure 3.7) was used for calibration and validation. Other records were not used because either the performance of the flowmeter was poor, as suggested by MSD, or the contributing area was significantly less.

As two dominating parameters (James et al. 2013), percent imperviousness (directly connected impervious area, DCIA) and subcatchment width were considered for calibration. The parameters were adjusted until the modeled and observed water–level at J23 were reasonably matched. SWMM′s ‘Calibration Data’ included under ‘Project’ menu was used to register the observed data for both calibration and validation, and ‘Create Time Series Plot’ was used to visualize the results. The tool produces a graph for both simulated and observed data, which can be visualized to see whether the simulated data

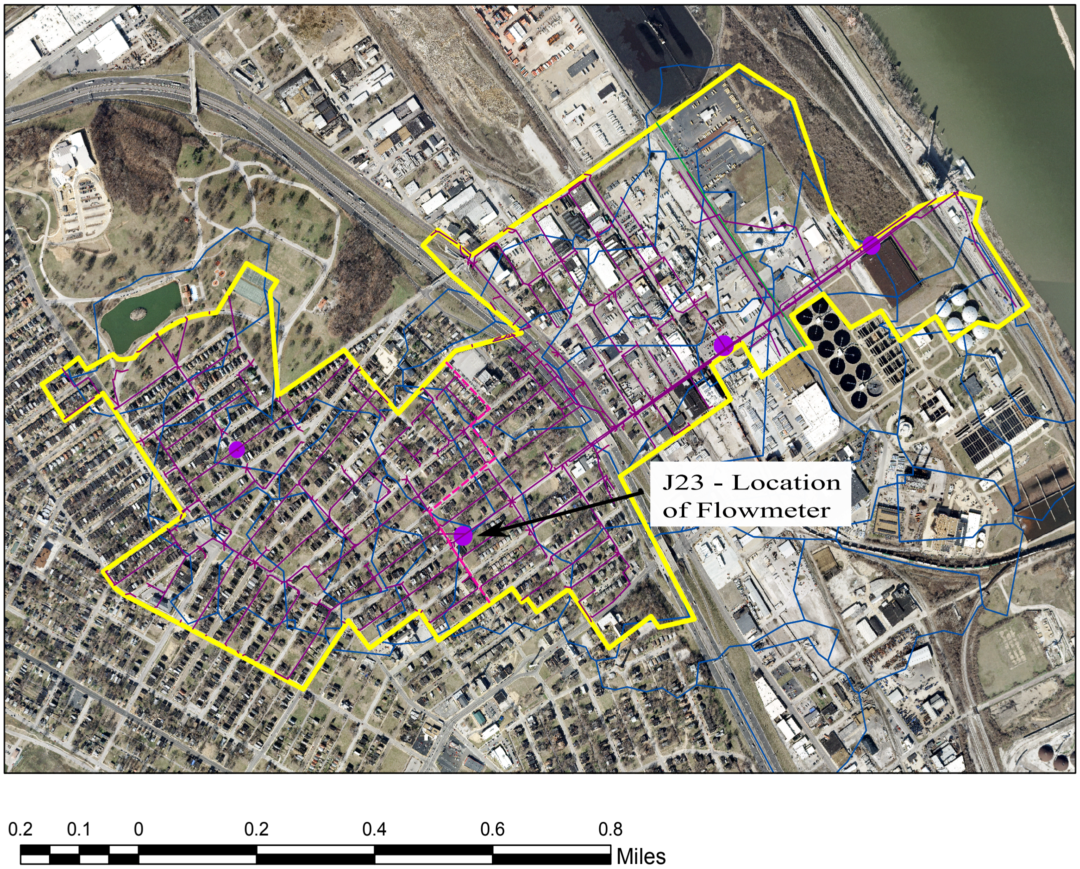

Figure 3.7. Location of Flowmeter Whose Data was Used for Calibration and Validation

match the observed data (figure 3.8). When the model parameters produced results that reasonably match the observed flow in shape, peak and timing for the May-31 event, the model was considered to be calibrated (figure 3.8: a). The model thus calibrated was run with three different storms of April 10, May 20, and May 27, as mentioned in table 3.3. Since the simulated depth approximately match the observed depth for all the three events (figure 3.8: b, c, and d), the model was validated.

In addition to the SWMM′s graphical technique, the model was also evaluated using Nash-Sutcliffe model efficiency coefficient (NSE). As discussed in Moriasi et el. (2007),

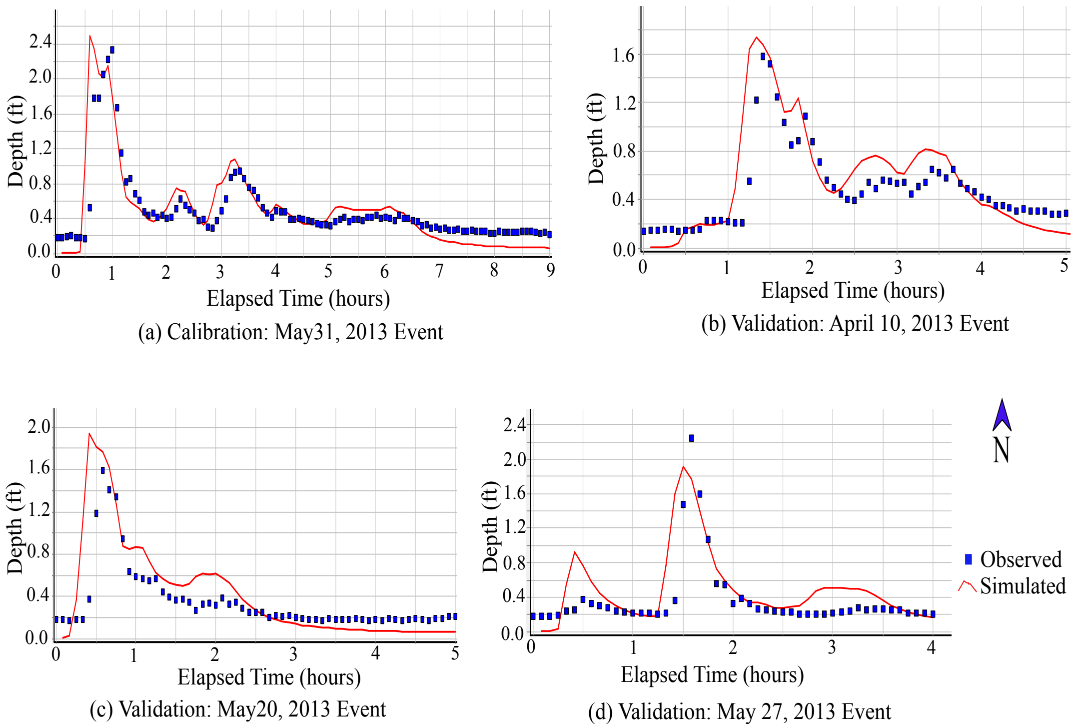

Figure 3.8. Model Calibration and Validation: Plot of Simulated and Observed Depths at Node J23

NSE is a normalized statistic which determines the ratio of residual variance (called "noise") to the measured data variance (called "information"), and is defined by equation (1).

$$\text{NSE} = 1 - \frac{\sum_{i=1}^{n}(O_i - P_i)^2}{\sum_{i=1}^{n}(O_i - \overline{O})^2} \qquad \text{----------------} \ (3.1)$$

where n is the total number of observations, O_i is the ith observation of the depth, P_i is the ith predicted depth, and $\overline{O}$ is the mean of the observed depths. The coefficient values calculated from the observed and model predicted depths for the four rainfall events used for calibration and validation are presented in table 3.4. An NSE coefficient above zero indicates that the mean simulated value is a better predictor than the simulated value; and hence, values between 0 and 1 are generally viewed as acceptable levels of performance (Moriasi et al. 2007). Since all four NSE coefficients (table 3.4) are well above zero, the developed model can be considered reliable for predicting the performance of the modeled system.

Table 3.4. Nash-Sutcliffe Model Efficiency Coefficients

Rainfall event	NSE coefficient
5/31/2013	0.65
5/27/2013	0.56
5/20/2013	0.34
4/10/2013	0.51

Projection of future rainfall scenarios

Study of the climate change impact requires the projection of future climate variables. For this study, the future rainfall scenario for the study area was estimated from three datasets available from two sources: (i) observed historical 30-yr (1971–2000) data available from NOAA, (ii) modeled historical 30-yr (1971–2000) data available from NARCCAP, and (iii) modeled future 30-yr (2041–2070) data available from NARCCAP. A delta change factor (DCF), the ratio of the model generated historical and future rainfall data, was calculated and the factor was applied to the observed historical point rainfall data to project the future point rainfall data. The overall procedure is described in the subsequent paragraphs.

For the observed historical data, 1-hr precipitation data from Lambert airport station (ID: 237455), which is at 16 km from the study site, was used. Though stations at St. Louis Science center (ID: 237452) and Eads Bridge (ID: 237460) are at 7 km and 6 km respectively, they did not have enough data for the 1971–2000 period. The station at the science center lacked all data from 1979 to 1983 and some data for numerous other years, whereas the Eads Bridge station had rainfall data only for years prior to 1968.

The NARCCAP provides various sets of future rainfall data for the U.S., Canada, and Mexico, generated by different regional climate models (RCMs) from the outputs of multiple atmosphere-ocean general circulation models (AOGCMs), also called global climate models (GCMs), under A2 emission scenario (Mearns et al. 2007). The A2 scenario is one of the many future scenarios of greenhouse gas emission determined by IPCCS′s Special Report on Emission Scenarios (SRES) and it refers to "a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in any other storylines" (Nakicenovic et al. 2000). As of Jan 2017, the NARCCAP produced 12 sets of current (historical) and future data, all of which are of 50-km spatial and 3-hr temporal resolution. From each dataset, the data associated with the grid centroid closest to the study area were extracted and evaluated. Of the datasets produced by 12 RCM/GCM combinations, only the data extracted from the following 6 RCM/GCM combinations were used (table 3.5), because datasets extracted from other combinations had insufficient data for the 30-yr historical (1971–2000) and/or future (2041–2070) periods.

From each of these datasets, 3-yr annual maximum rainfall was determined for current and future periods and each of the annual maximum series was fitted to six distribution models including generalized extreme value, log pearson3, lognormal, gamma, exponential, and normal. These distribution models are normally used in hydrologic analysis (Chow et al. 1988).

A software application named 'EasyFit' was used for fitting the data to different distribution models. The software analyzes the given data, determines the goodness of fit of various probabilistic distribution models to the sample, calculates the fitting parameters for each of the models, and determines the rank of the distribution models based on the extent of fitting. The software conducts goodness of fit test by three methods: Kolmogorov Smirnov, Anderson Darling, and Chi-square.

Table 3.5. RCM/GCM Combinations Used for Future Climate Data

RCM/GCM	RCM	GCM
ECP2/HadCM3	Regional Spectral	Hadley Center Coupled Model, version 3
ECP2/GFDL	Regional Spectral	Geophysical Fluid Dynamics Laboratory
HRM3/HadCM3	Hadley Regional Model 3	Hadley Center Coupled Model, version 3
HRM3/GFDL	Hadley Regional Model 3	Geophysical Fluid Dynamics Laboratory
MM5I/HadCM3	MM5-PSU/NCAR Mesoscale	Hadley Center Coupled Model, version 3
CRCM/CGCM3	Canadian Regional Climate	Third Generation Coupled GCM

Of the six distribution models, the software identified Generalized Extreme Value (GEV) as the best fitted distribution model for all 12 sets (two sets, historical and future, produced by each of the six RCM/GCM combinations). Overall, Log Pearson 3 was ranked as the second–best and the Gamma distribution was ranked as the third-best. The ranking from each of the test methods are summarized in table 3.6. The numbers inside the braces show the numbers of datasets with the second-best fit determined by the given test method. For example, out of the 12 data sets, Andersen test method ranked GEV as the best for 11 datasets and second best for 1 dataset.

Table 3.6. Ranking of GEV Distribution Fitted to Observed 3-hr Annual Maximum Rainfall

Distribution Models	Test Methods		
	Kolmogorov Smirnov	Anderson	Chi-squared
Generalized Extreme Value	8, [3]	11, [1]	6, [2]
Log Pearson 3	2, [6]	0, [9]	1, [6]
Log normal	2, [1]	1, [0]	0, [1]
Gamma	1, [1]	0, [2]	5, [1]
Exponential	0, [0]	0, [0]	0, [0]
Normal	0, [1]	0, [0]	0, [2]

For the observed historical data, GEV distribution was ranked as the best fit by Anderson test and third best fit by Kolmogorov and Chi-squared tests. Since all datasets fit to GEV, most of them best fit, I have used GEV for the return period analysis for all the datasets. The EasyFit generated GEV cumulative distribution function fitted to the observed data is depicted in fig 3.9.

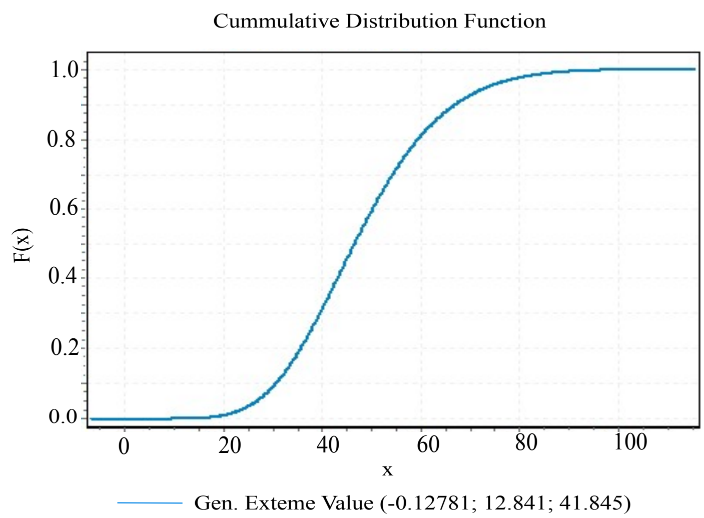

Figure 3.9. Cumulative Distribution Function of GEV Distribution Fitted to the 3-hr Annual Maximum Rainfall Observed at Lambert Station

Since the datasets were fitted to GEV distribution, the following GEV expression (equation 3.1) available from the literature (Coles 2001; Fawcett 2015) was used, and an extreme quantile, called return level (X_T), was determined corresponding to the return period T for each dataset.

$$X_T = \mu + \frac{\sigma}{\kappa}[(-log(1 - T^{-1}))^{-\kappa} - 1] \text{ ---------------- (3.2)}$$

where the letters μ, σ, and κ, are location, scale and shape parameters of the fitted GEV distribution.

Values of the three fitting parameters produced by the EasyFit software for each of the data set are given in table 3.7.

Substituting the values of the three parameters in equation 3.1, return level for 50-yr return period were calculated from each of the historical and future simulated datasets produced by the six RCM/GCM combinations. 50-yr return level was also calculated for

Table 3.7. GEV Fitting Parameters of Projected Current & Future 3-hr Annual Maximum Rainfall

Data Source	Current (1971-2000)			Future (2041–2070)		
	κ	σ	μ	κ	σ	μ
ECP2/HadCM3	-0.03634	2.585	10.248	0.19986	2.397	11.179
ECP2/GFDL	0.03189	2.0377	11.363	-0.1541	3.4734	10.859
HRM3/HadCM3	-0.00157	3.0877	7.532	0.11546	2.6183	7.6234
MM5I/HadCM3	0.19826	1.6262	7.170	0.05101111	2.6821	8.5949
HRM3/GFDL	-0.0636	2.501	7.4801	0.38994	2.9926	7.894
CRCM/CGCM3	0.0136	1.1633	6.7133	-0.10411	1.4926	8.1492
Observed	-0.12781	12.841	41.845	-	-	-

the observed historical dataset at Lambert Station. From the 50-yr return depths thus calculated, a ‘delta change factor’ (DCF), the ratio of future to historical depth, was determined for each of the six modeled datasets, and the 50-yr rainfall depth calculated from the observed historical data at lambert airport station was multiplied by the DCF to project the 50-yr future rainfall for the study area. Finally, the projected 50-yr 3-hr rainfall depths were tested in the calibrated SWMM to determine the impact of the changed precipitation due to climate change. For this, the 3-hr total rainfall depth was disaggregated into 6min depths using NRCS SCS type–II distribution method [2]. Since 3-hr distribution is not available from NRCS, the available 24-hr 6-min distribution was transformed to 3-hr 6-min distribution, as presented in table 3.8 and depicted by figure 3.10.

Result and Discussion

Projected increase in rainfall due to Climate change

A summarized result of the analysis of historical (1971–2000) and future (2041–2070) 50-yr 3-hr rainfall data modeled by the six RCM/GCM combinations is presented in table 3.9. Though a wide difference exists between model results, each model shows a

[2] https://www.nrcs.usda.gov/wps/portal/nrcs/detailfull/national/water/?cid=stelprdb1044959

Table 3.8. SCS Type II 3-hr Rainfall Distribution Fraction Derived from SCS Type II 24-hr Distribution

Interval	Fraction	Interval	Fraction	Interval	Fraction	Interval	Fraction
0	0.0000	48	0.0161	96	0.0319	144	0.0116
6	0.0091	54	0.0177	102	0.0280	150	0.0107
12	0.0097	60	0.0194	1087	0.0242	156	0.0100
18	0.0104	66	0.0401	114	0.0204	162	0.0095
24	0.0111	72	0.0799	120	0.0165	168	0.0091
30	0.0118	78	0.1285	126	0.0142	174	0.0086
36	0.0129	84	0.2304	132	0.0133	180	0.0081
42	0.0145	90	0.1599	138	0.0124		

significant increase in future precipitation depth. As shown by the delta change factor, the increase ranges from 9 to 74%.

Table 3.9. Model Projected Historical (1971-2000) and Future (2041-2070) 3-hr Rainfall Depth (mm) and Delta Change Factors (DCFs)

Data Produced By	Historic 50-yr 3-hr	Future 50 -yr 3-hr	DCF
ECP2/HadCM3	21.5	30.90	1.43
ECP2/GFDL	21.78	35.08	1.61
HRM3/HadCM3	22.10	24.13	1.09
MM5I/HadCM3	19.94	22.96	1.15
HRM3/GFDL	17.71	30.87	1.74
CRCM/CGCM3	12.4	13.73	1.11

From the six DCFs, the lowest (1.09) and highest (1.74) factors were adopted for the sewer system performance analysis. As a base case, 50-yr 3-hr rainfall depth was first calculated from observed historical data of 1968–2000. The calculated depth of 3.444 in was termed as scenario NCCS3.444, where the letters stand for no–climate–change–scenario and the number is the rainfall depth. This depth was then multiplied independently by the highest and lowest DCFs to calculate the corresponding 50-yr 3-hr rainfall depths, which were respectively 3.760 inch and 6.004 inch. These two depths were termed climate change scenarios CCS3.760 and CCS6.004 (table 3.10), where

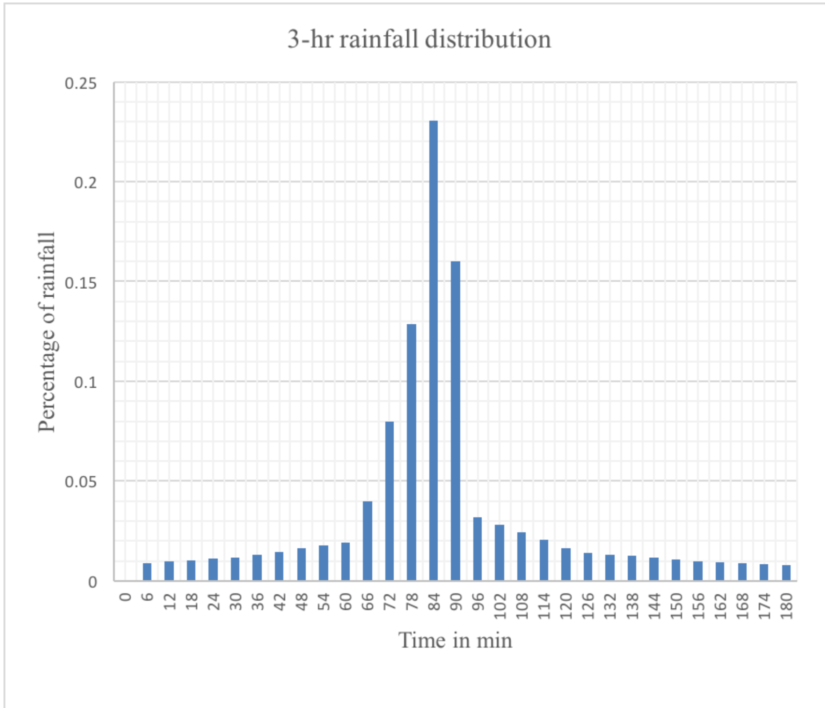

Figure 3.10. Plot of 3-hr Rainfall Distribution Over 6min Interval Derived from SCS Type II 24-hr Distribution

the letters stand for climate–change–scenario and the numbers represent rainfall depth.

Table 3.10. 50-yr 3-hr No Climate Change and Climate Change Scenarios

Climate Change Scenario	Description	Rainfall Depth	
		mm	in
NCCS3.444	Base case, no climate change	87.46	3.444
CCS3.760	Climate change scenario, DCF 1.09	95.48	3.760
CCS6.004	Climate change scenario, DCF 1.74	152.50	6.004

Impact of Climate change on the CSS

Each of the 50-yr 3-hr rainfall depths in three scenarios were temporally distributed into 6-min intervals to produce corresponding time series, each of which was input into the calibrated SWMM model using three different time series. The calibrated system was then run for each of the three climate scenarios. Table 3.11 presents a summary of the performance of the system. As presented in the table, six parameters were analyzed to evaluate the impact of climate change.

Table 3.11. Performance of Existing CSS Under Climate Change

Evaluated Parameters	Climate Scenarios		
	NCCS3.444	CCS3.760	CCS6.004
Flooded nodes (no.)			
Total nodes flooded	49	50	56
Nodes flooded ($\geq$ 30 min)	8	9	21
Nodes flooded ($\geq$ 1 hr)	1	1	5
Exhausted conduits (%)			
Conduites exhausted ($\geq$ 30 min)	12.5	13.97	18.55
Conduites exhausted ($\geq$ 1 hr)	1.6	2.43	10.82
Volume of CSO (million gallons)	4.74	5.25	8.45

Node (or manhole) flooding occurs when the water surface elevation (hydraulic grade line) reaches the manhole rim elevation and excess water overflows from the manhole top which, in real world scenario, results in flooding in the downstream. Therefore, "Node Flooding" in SWMM is a measure that can be utilized for urban flood forecasting. SWMM produces quantity and duration of flooding for each node. To assess the flooding scenario in this research, I used three parameters—total flooded nodes, number of nodes flooded for more than 30 min and number of nodes flooded for more than 1 hour.

The result shows that the modeled system will not be able to accommodate 50-yr 3-hr rainfall event even without climate change. Out of the 98 nodes of the modeled sewer, half of the nodes will overflow even for a 50-yr 3-hr historical rainfall. Of the flooded nodes, 8 nodes will overflow for more than half an hour and 1 node will overflow for more than an hour. The extent and duration of flooding both will increase when the sewer system is subject to climate change. As presented in table 3.11, climate change will cause additional 1–7 nodes to overflow.The number of nodes flooded for more than half an hour will increase by up to 13 and the number of nodes flooded for 1 hour will increase by up to 4.

Pressured pipe flow is another index to assess the performace of sewer system or urban flooding which can be assessed through "Hours Capacity Limited" under "Conduit Surcharge Summary" of the SWMM summary report. In SWMM, when the slope of the hydraulic grade line exceeds the conduit slope and the upstream link is full, the conduit becomes "capacity limited[3]." Practically, it results due to inadequate size or slop of the conduit which results in upstream manhole overflow leading to urban flooding. In this dissertation, I have termed the conduits with such limited capacity as exhausted conduits. The result shows that, in all of the scenarios, a significant portion of conduits will exhaust due to exceedance of their capacity. In no-climate-change scenario NCCS3.444, 12.5% of the total length (31184 ft) of the conduit was exhausted in capacity for 30 min or more, and 1.6% was exhausted for 1 hr or more. In climate change scenarios CCS3.460 and CCS6.004, 13.97% and 18.55% of the conduit length was exhausted for 30 min or more, and 2.43% and 10.82% of the total conduit was exhausted for 1 hr or more. Thus, the failure of system system was significantly increased due to climate change.

Another parameter to assess the performance of the modeled system is the total outflow produced by the model which is given as "Outfall Loading" in SWMM "Summary results." The parameter gives the total flow that leaves the system through outfall nodes. In the model I developed, there are four outfall nodes. The flows from two of the outfalls is routed to underground collection tunnel for treatment purpose, whereas the flow from out1 and out2 discharge into River Mississippi as combined sewer overflow (CSO). As CSOs have significant adverse impacts on the downstream water bodies, regulations generally require cities to control CSOs. Per the Consent Decree agreement with the U.S. EPA and according to the federal CSO Control Policy, the City of St Louis has regulatory obligations to reduce its CSOs for which the city has been implementing numerous strategies (MSD 2011). CSO volume as such is a critically important while analyzing the

[3]http://swmm5.posthaven.com/capacity-limited-links-in-swmm-5

performance of a combined sewer system in St. Louis. Therefore, for the purpose of this dissertation, the outfalls from out1 and out2 were added and CSO was calculated. As presented in table 3.11 above, the CSO volume produced by 3-hr 50-yr rainfall will increase from 4.74 million gallons to 5.25–8.45 million gallons due to climate change. While MSD is struggling for reducing the CSOs even under historical climate scenarios, the result of this study reveals that climate change will significantly increase the CSO volume adding further regulatory compliance burden on the MSD.

Conclusion

One of the projected consequences of climate change is the increase in frequency and intensity of heavy rainfall events. Since the existing urban drainage systems were designed to accommodate the historical storms, assuming that their pattern would remain stationary, it is very likely that the increased frequency and intensity will exhaust the systems capacity, leading to their failure and causing urban flooding. The recent evidences of increasing damage by floods in cities have substantiated this anticipation.

Failure of urban drainage may have substantial socio, economic, and environmental impacts. It does not only cause social inconvenience and property damage, but also poses threats to public health and safety in urban area as well as downstream. In the cities serviced with combined sewer system, the increased precipitation may increase CSOs and discharge additional pollutants to the receiving waters. To mitigate this problem, cities need to design and adopt optimal measures in advance, for which it is critically necessary to evaluate the potential performance of the existing system and calculate excess quantity to be accommodated. This study undertook such an evaluation of a combined sewer system of a 169.23-acre catchment in the City of St Louis, the U.S.

The system was modeled in the U.S. EPA′s SWMM5 hydraulic hydrologic modeling software, and was simulated for 50-yr 3-hr precipitation for historical (1971–2000) and future (2041–2070) scenarios. The rainfall scenarios were determined from observed 1-hr historical rainfall data provided by NOAA and modeled historical and future 3-hr rainfall data available from NARCCAP. In the simulation, the existing system underperformed when subjected to a 50-yr 3-hr storm event even without considering climate change. With climate change, the systems performance, at both the conduits and nodes, considerably decreased, resulting in significantly increased node flooding and CSO volume. Thus, the result suggested that the system requires retrofitting for it to perform at the desired level in the future.

CHAPTER 4

EFFICACY OF GREEN INFRASTRUCTURE FOR CLIMATE ADAPTATION

Introduction

Chapter 3 revealed that the portion of combined sewer system of St. Louis evaluated in this research will be significantly overwhelmed by the 50-yr 3-hr future precipitation. The failure of the system to accommodate the increased precipitation can lead to several adverse consequences including flooding, sewer breaks, social inconvenience, property damage, increased CSOs, and threats to public safety. To mitigate the adverse impacts and enhance the system′s resilience, it is essential to install appropriate adaptation measures. Adaptation is the adjustment in a system to reduce the estimated damage caused by the increased precipitation (Short et al. 2012; USGCRP 2009). The U.S. EPA determines that it is crucial to incorporate adaptation to the long-term planning of the nation′s drainage infrastructures and make them climate ready (U.S. EPA 2012b). In this dissertation, adaptation refers to the adjustment of the evaluated combined sewer system to the projected increase in rainfall.

One approach to accommodate the increased precipitation would be to increase the size of the gray approach. However, increasing the size of the existing system is physically, financially and socially very complicated and costly. The components of existing structures, such as gutters and underground pipes, are integrated with several other built infrastructure networks that are very likely to be damaged while replacing the stormwater systems. In addition, replacement causes service interruption for long duration resulting in social inconvenience and challenging socio economic activities. The cost becomes prohibitively expensive (Arisz & Burrel 2006; Waters et al. 2003; Watt et al. 2003) due to the resources required for removal of existing systems, installation of new systems, and repair of other damaged infrastructures, as well as due to the cost associated with social, environmental and economic effects caused by service interruption. From a cost-benefit perspective, the high cost could be justified if the present value of avoided cost of future property damage due to flooding would be higher than the cost of installing new infrastructure. However, estimating property damage from future climate change is difficult due to uncertainties in climate change projection, uncertainties in discounting of future economic cost, possibilities of discovery of better technological solutions, and external (e.g., political and social) influences on decision-making (Arisz & Burrel 2006).

In addition, since the nature of climate change is highly uncertain, adaptation will need to be revisited periodically (Mailhot & Duchesne 2010). This means that we cannot assign any certain optimum value to the design capacity of a drainage system such that the system will efficiently accommodate the increased precipitation. Construction of remedial measures, such as water management ponds, will also be difficult due to prohibitively high cost and lack of availability of land. More importantly, the capacity improvement of traditional infrastructures, such as detention ponds and intercepting tunnels, persists the hydrological disturbances in the watershed, continues shifting the problems downstream, and do not solve the ecological issues created by the conventional approach.

The problems associated with construction of new drainage systems or capacity improvement of existing drainage system indicate that it is necessary to have an innovative approach for climate change adaptation of stormwater systems. However, very limited studies have been conducted on adaptation approaches (Rosenberg et al. 2010). Over recent decades, green infrastructures (GI), or low impact development (LID), has been developed as an innovative stormwater control approach, which aims to mimic the landscape′s pre-development hydrology using decentralized micro-scale control measures (Coffman 2002). Though many such practices have been proven to be successful in managing stormwater runoff (Ahiableme & Engel 2012), there is a lack of sufficient research to know whether these practices can be efficient to adapt the existing drainage systems to prospected increase in rainfall intensity due to climate change (Foster et al. 2011).

Among the limited research, Waters et al. (2003) tested the efficacy of three adaptation alternatives for the Malvern Catchment: roof disconnection, surface storage enhancement and input rate reduction. The research showed significant amount of runoff reduction in all the three cases. The disconnection of 50% and 100% of roof areas from the drainage system, thereby allowing roof runoffs to spill onto landscaped areas, reduced peak discharge by 18% and 39%, respectively. The increase in surface storage (e.g., dry ponds, parks, open space) by $45m^3$ per impervious hectare reduced peak discharge by 14%. When the rate of stormwater inputs was reduced to 40m^3 of surface storage per impervious hectare on the streets, the peak discharge was reduced by 13%. Since surface storage requires sufficient area of public land, it is practically not suitable for urban areas, where public land is scarce.

Watt, Waters and McLean (2003) studied Malvern Catchment and Central Park Urban Catchment in Canada, and compared the functional and financial efficacy of pipe replacement, impervious area disconnection, surface storage addition, input rate reduction, pond volume enhancement and increase in infiltration (by allowing runoff to infiltrate). The authors reported various conclusions for each alternative. The pipe replacement is prohibitively expensive, unless the pipes are replaced because of a normal maintenance program. The impervious area disconnection, such as disconnecting roofs from storm sewers, is cost-effective but it needs sufficient permeable areas to infiltrate the water from disconnected roofs. The reduction in input water (by preventing stormwater to enter into drainage systems through inlet control) may be effective, technically and financially, but the resulting ponding of water on the street causes nuisance and may appear as a drainage failure to the public. Routing overland flow to public land can be cost effective, if such land is available. However, the flooded area may remain wet for an extended period which can cause an environmental nuisance to public due to mosquito and midge breeding. The suitability of an infiltration basin depends on availability of feasible land, soil infiltration capacity and costs.

In a case study in Greater Manchester UK, Gill et al. (2007) evaluated the runoff for the baseline 1961–1990 precipitation with the runoff for the precipitation expected by 2080, and assessed the efficiency of tree cover and green roofs to accommodate the increased runoff. The study showed that an increase of 10% of tree cover would reduce the runoff for 28 mm projected precipitation in 2080 by 5.7%. Adding green roofs to all the buildings in town centers, retail, and high density residential areas (where more than two-thirds of the total area is impervious) reduced the increase in runoff from 65.5% to 43.6%, 67% to 47.2%, and 67.6% to 44% respectively. The study showed that though green roof alone cannot accommodate all the increase in precipitation, the technology can address a significant portion of it.

Karamouz, Hosseinpour and Nazif (2011) employed different best management practices (BMPs) for the Tehran case study including the improvement of green space, the construction of detention ponds, capacity enhancement of the channel system, and the development of appropriate diversion systems. The researchers evaluated BMPs to test their effectiveness in reducing the runoff volume and peak flow with the least cost. They found that the combination of improvement of green space and construction of detention ponds as well as diversion systems would decrease the cost of flooding by 75%.

For this study, it was hypothesized that installation of an appropriate combination of GI measures on the study area helps accommodate the future increase in precipitation due to climate change. To test the hypothesis, bio-retention cells, permeable pavement, rain barrels, and green roofs were added to various subcatchments of the SWMM model developed in chapter 3; and the stormwater system was simulated to evaluate the performance of the system under the future (2041–2070) 50-yr 3-hr rainfall. The result was compared with the corresponding results, discussed in chapter 3, produced by the simulation of existing combined sewer system under the same future 50-yr 3-hr precipitation. The results revealed that the addition of the GI measures significantly lowered the impact of increased precipitation on the combined sewer system.

Research Methodology

Modeling Tool and GI Measures

The SWMM model developed in chapter 3 was used also to assess the hydrologic performance of GI. Multiple GI measures were added to the calibrated model using SWMMs low impact development (LID) module and percentage imperviousness of each subcatchment was adjusted accordingly. The LID module of the recent version of SWMM can model the hydrologic performance of eight types of GI measures that include bio-retention cells, rain gardens, green roofs, infiltration trenches, permeable pavement, rain barrels, rooftop disconnection, and vegetative swales. A summarized definition of each of these measures given in SWMM5 (Rossman and Huber 2016) is presented in table 4.1.

SWMM uses one of the following two approaches to incorporate GI controls. The first approach requires a user to create a new subcatchment dedicated entirely to a single GI control. In this approach, only one GI control can be used for a subcatchment and the subcatchments area, imperviousness, and width parameters of the existing model must be adjusted to compensated for the area occupied by the newly created GI subcatchment. The second approach allows to employ multiple GI control measures within a subcatchment, replacing an equal amount of non-GI area from the subcatchment. When multiple controls are employed to a single subcatchment, each control receives runoff from a different portion of the subcatchment and functions in parallel with all other controls. Given the existing surface features present in the study area, employing more than one GI measures is more appropriate for most subcatchments. Therefore, the second approach was used.

A study conducted by MSD in 2008 identified that bio-retention, green roofs,

Table 4.1. Definition of GI Measures Used in SWMMs LID Module

SN	GI Measures	Definition
1	Bio-retention Cells	Depressions with vegetation grown in an engineered soil placed above a gravel bed. Provide storage, infiltration, and evaporation of direct rainfall and runoff from surrounding areas.
2	Rain Gardens	A type of bio-retention cells that consists of just the engineered soil with no gravel bed underneath.
3	Green Roofs	Another type of bio-retention cell constructed as roof that consists of a soil layer above a thin synthetic drainage mat or a coarse aggregate to drain excess water off the roof.
4	Infitration Trenches	Narrow ditches filled with gravel that intercept runoff from upslope impervious areas, provide storage volume and additional time for the captured runoff, and infiltrate into the native soil below.
5	Permeable Pavement	*Continuous permeable pavement systems*: Street or parking areas paved with a porous concrete mix or asphalt mix that sits above a gravel storage layer. Rainfall passes through the pavement into the storage layer and infiltrates into the native soil. *Block paver systems*: Consist of paver blocks placed on a sand or pea gravel bed with a gravel storage layer below. Rainfall is captured in the open spaces between the blocks and conveyed to the storage zone where it can infiltrate to the native soil.
6	Rain Barrels	Containers that collect roof runoff during storm events and can either release or reuse the rainwater during dry periods.
7	Rooftop Disconnection	In this approach, runoff from roof is routed to pervious areas instead of storm drains.
8	Vegetative Swale	Channels or depressed areas with slopping sides covered with grass and other vegetation. By slowing down the conveyance of runoff the vegetative swales allow more time to infiltrate into the native soil.

permeable pavements, and rain barrels are among the appropriate measures for volumetric control in the CSS areas (Norton and Moore 2017). In this research, four types of GI measures including bio-retention cells, permeable pavement, rain barrels, and green roofs were used. Since the areas soil has relatively low infiltration capacity (hydrologic soil group C and D), GI measures requiring high infiltration capacity, such as infiltration trenches, were not used in this research.

For convenience, streets in the residential area were categorized into two types: front side streets (TYPE1) and rear side streets (TYPE2). The 9.14-meter (30-foot) wide (or wider) TYPE1 streets are wide enough for carrying two-way vehicular movement in addition to having a 2.23-meter (7-foot) wide parking lane on each side. A study of numerous neighborhoods conducted by a multidisciplinary team of professionals reveals that a width of 7.93 m (26 ft) is the most desirable neighborhood level roadway width which can have parking on both sides and allow delivery, sanitation and fire trucks to pass through freely (Burden 1999). In the parking lane, a 5.49-meter (18-foot) long and 2.23-meter (7-foot) wide parking space was allocated for each household and the remaining portion was used for bio-retention cells. For aesthetic purpose and to distribute evenly, the bio-retention cells were sized as 5.49-meter long and 2.23-meter wide rectangles and placed at regular intervals between parking spaces. Since the width of the TYPE2 roads was not enough to have bio-retention cells and the traffic load on the street was also significantly less, TYPE2 roads were modeled as permeable pavement.

Replacing roofs of the existing aging buildings with green roofs in residential area can be technically, financially, and politically unfeasible. Therefore, green roofs were not employed in residential subcatchments. However, they were adopted in the industrial subcatchments where deemed appropriate. To treat the roof runoff in the residential area, four rain barrels (or cisterns) with 200 gallons in capacity were employed to each household. Larger cisterns with 3000 gallons in capacity were also added to subcatchments of industrial area at various locations based on site conditions as observed by aerial photography and field visits. Since infiltration capacity of the native soil in the study area is low (soil type C), bio-retention cells were provided with a drainage system to discharge excess captured runoff off the site and avoid the area from flooding during heavy storms. To use the full storage volume before draining occurs, and to allow maximum infiltration into the soil, the drain was placed at the top of the storage layer.

SWMM′s LID module has the provision of such drainage system for carious measures including bio-retention, rain barrels, and permeable pavement systems. The GI measures used in this study are presented in table 4.2

Table 4.2. Type and Quantity of GI Measures Used in the Study

GI Control	Symbol	Description	Total Quantity
Bio-retention Cells	BR_RT1	5.59-m (18-ft) long and 2.13-m (7-ft) wide cells applied to TYPE1 roads in residential area	1470 (no.)
	BR_HW	A 305-m long cell applied to a highway section, catchment S3	1 (no.)
Permeable Pavement	PR_RT2	Applied to inner access TYPE2 roads in residential area	50,679 (m^2)
Rain Barrels	RB200	200-gallon capacity cisterns applied to the residential area	1820 (no.)
	RB300	3000-gallon capacity cisterns applied to the industrial area	50 (no.)
Green Roof	GR_IA	Green roofs applied to the industrial area	41,898 (m^2)

Determination of Parameters

As discussed in SWMM5 users manual (Rossman and Huber 2016), numerous design parameters of GI affect the hydrologic performance. The parameters include size of unit, properties of soil and gravel media contained in the unit, thickness of the media, and discharge coefficient of the underdrain mechanism. Based on the values used by various local and state agencies, the manual has presented values—or a range of values—of key parameters for various GI measures. In this study, parameter values were adopted from multiple sources and through judgement. The sources include SWMM manual, models default values, MSD documents (MSD 2017), and other literature. In the case of range of values, different values were tested in the model and the results were analyzed to select the value that produces the best performance.

The parameters used for bio-retention cells are presented in table 4.3. The depths of the soil and storage layers were so that the units performance is maximized without being affected by the ground water below it. To allow maximum storage on the storage layer and avoid flooding on the surface during heavy precipitation, a drain system was kept at the top of the storage layer. No clogging of the unit was assumed.

Table 4.3. Bio-retention Cell Parameters

Layers	Parameters	Values
Surface	Berm height (in)	6
	Vegetation volume fraction	0.2
	Surface roughness ‘n’	0.1
	Surface slope (%)	1
Soil	Thickness (in)	18
	Porosity (volume fraction)	0.6
	Field Capacity (volume fraction)	0.2
	Wilting point (volume fraction)	0.08
	Conductivity (in/hr)	5
	Conductivity slope	10
	Suction head (in)	3.5
Storage	Thickness (in)	18
	Void ratio (void/solid)	0.3
	Seepage rate (in/hr)	0.5
	Clogging factor	0
Drain	Flow coefficient	60
	Flow exponent	0.5
	Offset height	18

The LID module of SWMM represents permeable pavement through a combination of three layers: surface, pavement, and storage layers. Soil layer is optional. To maximize the capacity of storage layer soil layer was not used. The module also has an optional underdrain system, which was provided at the top of the storage layer, as in the case of bio-retention and for the same reason. The parameters of permeable pavement used in the model are presented in table 4.4. The pavement type adopted in this research is continuous pavement.

Green roof captures only direct rainfall and is represented in SWMM by three layers:

Table 4.4. Permeable Pavement Parameters

Layers	Parameters	Values
Surface	Storage depth	0.1
	Vegetation volume fraction	0
	Surface roughness ‘n’	0.1
	Surface slope (%)	1
Pavement	Thickness (in)	6
	Void ratio	0.15
	Impervious surface fraction	0
	Permeability	100
	Clogging factor	0
	Suction head (in)	3.5
Storage	Thickness (in)	24
	Void ratio (void/solid)	0.3
	Seepage rate (in/hr)	0.5
	Clogging factor	0
Drain	Flow coefficient	100
	Flow exponent	0.5
	Offset height	6

surface, soil, and drainage. The parameters of green roofs used in this dissertation are presented in table 4.5. When compared with bio-retention cell, green roofs hydraulic conductivity is much higher (Rossman and Huber 2016).

The “Rain Barrel” of the LID module represents both rain barrels and cistern through two layers: storage unit and a drain system. Generally, rain barrels are 50–100 gallons in capacity and are used in individual household lots to capture roof runoff; whereas cisterns are 250 to 30,000 gallons and are used for capturing rainwater from households to commercial facilities (Rossman and Huber 2016). This dissertation used 200-gallon cisterns in residential area and 3000-gallon cisterns in industrial area. Since the definition of rain barrels and cistern differ only in size and both are represented in SWMM by Rain Barrel module, the 200-gallon and 3000-gallon cisterns used in this study were defined as rain barrels and were named as RB200 and RB3000 respectively. The outflow from all rain barrels were routed to pervious areas after they were full. To utilize

Table 4.5. Green Roof Parameters

Layers	Parameters	Values
Surface	Berm height	0
	Vegetation volume fraction	0.1
	Surface roughness ‘n’	0.1
	Surface slope (%)	1
Soil	Thickness (in)	6
	Porosity	0.52
	Field capacity	0.4
	Wilting point	0.1
	Conductivity	50
	Conductivity slope	10
	Suction head (in)	3.5
Drainage mat	Thickness (in)	2
	Void fraction	0.3
	Roughness	0.02

the full storage space before draining occurs, drain was placed at the top of the rain barrel. The parameters used for rain barrels are presented in table 4.6.

Table 4.6. Rain Barrel Parameters

Components	Parameters	Values
Storage	Barrel height (RB200) (in)	59
	Barrel height (RB3000) (in)	120
Drain	Flow coefficient	100
	Flow exponent	0.5
	Offset height (RB200) (in)	59
	Offset height (RB3000) (in)	120
	Drain delay (hr)	6

After finalizing the parameters, the GI modules were assigned to each subcatchment and the GI added model was run for future 50-yr 3-hr climate change precipitation scenario CCS6.004. As described in chapter 3, CCS6.004 refers to 50-yr 3-hr climate change scenario rainfall depth of 6.004 inch and NCCS3.444 refers to 50-yr 3-hr no climate change scenario rainfall depth of 3.444 inch. The model result was then compared with the simulation results (chapter 3) produced by the model before incorporating the

GI measures.

Result and Discussion

The model was run successfully with mass balance continuity errors of -0.54% for runoff and -0.22% for routing. In SWMM simulation, these system wide errors are considered negligible (Rossman 2015) and the errors less then 1% indicate that the simulation is of excellent quality (Dickinson 2010).

SWMM can produce individual performance report for each LID control type in addition to a system wide status report and summary results. For generating a separate report file for each LID type in each subcatchment, a Detailed Report File can be provided in the "LID Usage Editor" while assigning the LID control to the subcatchments. Since the purpose of this research was to assess the overall system performance, it was not necessary to have the results of individual performance. For assessing overall system performance, the simulation results were analyzed for 6 parameters that exhibit the flooding and CSO conditions. The result was then compared with the simulation results produced by the model before the application of GI. The comparison of the results is presented in table 4.7. An upward arrow in the table indicates an increase in impact, whereas a downward arrow indicates a decrease in impact.

Table 4.7. Comparison of Simulation Results with and without GI

Parameters Compared	Scenario NCCS3.444 No GI	Scenario CCS6.004 No GI	Scenario CCS6.004 with GI	Impact addressed by GI (%)
Flooded nodes (no.)				
Total flooded nodes	49	56 [↑ 7]	52 [↓ 4]	57.14
Flooded (≥ 30 min)	8	21[↑ 13]	15 (↓ 6)	46.5
Flooded (≥ 1 hr)	1	5[↑ 4]	2 [↓ 2]	50.00
Exhausted conduits (%)				
Exhausted (≥ 30 min)	12.5	18.55[↑ 6.05]	15.33 [↓ 3.22]	53.22
Exhausted (≥ 1 hr)	1.6	10.82[↑ 9.22]	6.12 [↓ 4.70]	50.97
CSO volume (million gallons)	4.74	8.45 [↑ 3.71]	6.98 [↓ 1.47]	39.62

As described in chapter 3, the parameter "total nodes flooded" refer to those nodes in which water level exceeds the rim level and excess water overflows, which practically leads to flooding. Table shows that the number of such flooded nodes, which was increased by 7 (from 49 to 56) due to climate change, was decreased by 4 (from 56 to 52) after the application of LID. Thus, based on the decrease in number of flooded nodes, the GI application addressed 57.14% of the impact of climate change. The duration of node flooding was analyzed for two categories, one for nodes that flooded for 30 minutes or more, and the other for nodes that flooded for 1 hr or more. The result showed that there was a significant decrease in the number of flooded nodes in both the categories. The number of nodes flooded for more than 30 min, which increased from 8 to 21 due to climate change, reduced from 21 to 15 after LID application. Similarly, the number of nodes flooded for more than 1 hr, which increased from 1 to 5 due to climate change, decreased to 2. In other words, the application of LID measures addressed 46.5% and 50% of the impact on the two categories of the node flooding.

As presented in the table, the impact of climate change on the capacity of conduits was also significantly addressed. The increase in percentage of the conduits exhausted for 30 min or more and 1 hr or more were reduced by 53.22% and 50.97% respectively. The increase in CSO volume was also significantly addressed. Of the total additional volume of 3.71 million gallons added due to climate change, GI was able to hold 1.47 million gallons of water, reducing 39.62% of the increased CSO volume. This shows that GI can be useful to a significant extent also to help MSD fulfill its regulatory obligations to reduce the CSOs required by the Consent Decree Agreement with the U.S. EPA.

Conclusion

This chapter examined the efficacy of GI to address the impact of increased precipitation on the combined sewer system of St. Louis, a U.S. city in the State of Missouri. Four GI measures, including bio-retention cell, permeable pavement, rain barrel, and green roof, were considered for evaluation. One or more of the four selected GI types were added to various subcatchments of the SWMM model developed for the study area, and the model was run for the future (2041–2070) 50-yr 3-hr rainfall scenario (CCS6.004) which was also used for quantifying the impact in chapter 3. Analysis of the simulation outputs indicated that the impacts caused by the increased precipitation were significantly lowered after the addition of GI measures. For example, the increases in the number of node flooding and CSO volume caused by the increased precipitation were reduced by 57.14% and 39.62% respectively. Impact on conduit capacity was also significantly reduced. The increases in the percent of conduits with limited capacity for 30 minutes and 1 hour were reduced by 53.22% and 50.97% respectively. Though the impacts caused by increased precipitation were not fully addressed by the GI measures employed in this study, the produced results were highly encouraging. In both residential and industrial areas GI measures were added only to a limited extent. For example, in residential area, the 200-gallon capacity rain barrels were added only to 70% of the households and flow from other impervious areas was not routed to bio-retention cells and permeable pavements. In addition, no treatment was applied for sidewalks and other impervious areas in the building premises. The number and capacity of rain barrels can be increased, sidewalks and other impervious areas in the buildings premises can be either converted to permeable pavements or their flow can be routed to other GI measures such as roadside bio-retension cells. If needed, rain gardens can also be constructed in the residential plats and excess flow from rain barrels and other areas can be routed to them. Though bio-retention cells might not be feasible to treat pavements in the industrial area due to insufficient depth to ground water, the paved area can be reduced by reducing lane width to an optimal level and by putting a more stringent cap on the impervious areas. Numerous policy strategies can be adopted for reducing imperviousness which are discussed in the succeeding chapters.

CHAPTER 5

POLICIES FOR GREEN INFRASTRUCTURE IMPLEMENTATION: BARRIERS AND SOLUTIONS

Introduction

The simulation results presented in chapter 4 revealed that if employed appropriately GI measures can serve as a means for adaptation of existing combined sewer system to climate change. Other numerous sustainability benefits of GI were discussed in chapter 1 and chapter 2. The benefits can be socially significant only when the technology is implemented in a sufficiently large scale. However, despite being an inevitable element of urban sustainability and despite being an object of unrelenting expert advocacy for more than two decades, GI implementation remains slow. On the other hand, the practice of traditional gray infrastructure, which is known to have significant adverse effects on the environment, is still ubiquitous in urban areas throughout the world. This relationship between knowledge and practice seems unaccountable, which has not yet received adequate attention from academia, policy makers, or research communities. This chapter presents the barriers preventing the widespread implementation of GI policy solutions that can expedite the use of technology.

It is important to note that there are some struggles with finding the causes behind the sluggishness in using GI. Among the limited peer-reviewed literature available, Roy et al. (2008) conducted a comparative study of the U.S. and Australian contexts and identified these 7 barriers common to both countries: uncertainties in cost and performance, lack of engineering standards and guidelines, fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, funding constraints, and resistance to change. Brown and Farrelly (2009a) reviewed the available literature to examine the status of sustainable water management over a wider context, local to international, and identified 12 barrier types, mostly related to governance, resources, regulations, and perceptions. In a subsequent paper, the authors (Brown and Farrelly 2009b) surveyed three Australian cities, Perth, Melbourne, and Brisbane, from the perspective of urban stormwater management, and grouped the identified barriers into three major categories: management arrangements and responsibilities, regulation and approval processes, and capital and maintenance costs. Recent case studies from the UK conducted in England and Ireland (Matthews et al. 2015) and Newcastle (O′Donnell et al. 2017) also revealed the presence of socio-institutional, perceptual, and resource-related issues as major obstacles. Despite the variability in geography, time, scope, scale, context, and the name and number of listed barrier categories, all the above studies implicate similar barriers, most of which stem from personal perception and existing socio-institutional setups including policy and governance. These findings are consistent with what Niemczynowicz (1999) earlier presented as the future challenges of urban water management. Many of the identified barriers outlined by the above studies are rooted in social and organizational cultures, practices, and processes, and hence are difficult to overcomeas argued by Brown and Farrelly (2009a). As indicated by many of the above studies (e.g. Brown and Farrelly 2009a; Niemczynowicz 1999; Roy et al. 2008), overcoming such barriers requires not only developing a new individual and socio-institutional mindset through education and awareness, but also improving socio-institutional arrangements such as governance and policies. This paper focuses on policies.

We analyzed local policies of 10 U.S. cities, relevant state and federal policies, and other available literature to diagnose the obstacles and explore policies that could both overcome the barriers and expedite the adoption of GI. We identified 29 barriers and grouped them into 5 categories. The findings show that most of the barriers stem from cognitive limitations and socio-institutional arrangements. Accordingly, I suggest a set of 33 policies, also grouped into 5 policy types, which span from conducting education and awareness programs to changing existing policies and governance structures.

Study Approach and Scope

The research consists of two phases. The first phase explored the existing barriers through a critical analysis of available literature. The materials that were analyzed included pear reviewed journal articles, books, U.S. Constitution, U.S. laws and regulations, court decisions, and U.S. EPA case study reports. Literature on ecosystem services were also reviewed. Ruhl et al. (2007) provides a comprehensive analysis on the status of U.S. law and policy on ecosystem services and National Research Council (2009) provides a detailed review of urban stormwater management challenges in the U.S. These two publications were analyzed in detail. To explore the city level barriers, six individual reports published by the U.S. EPA on green infrastructure barriers and opportunities in each of the six U.S. cities, including Dallas, TX; Camden, NJ; Macatawa watershed, MI; Neosho, MO; Phoenix, AZ; and Los Angeles, CA (U.S. EPA 2016a), were analyzed. Another case study of 12 cities conducted by the U.S. EPA in 2010 (U.S. EPA 2010) was also reviewed.

In the second phase, I synthesized normative policy recommendations to address the barriers identified in the first phase. For this, policy tools and strategies adopted by four U.S. cities (Seattle, Washington; Portland, Oregon; Chicago, Illinois; and Philadelphia, Pennsylvania) were analyzed against the identified barriers. These cities have been using green infrastructure relatively widely (Chen et al. 2013). The documents examined included ordinances, codes, manuals, and standards that influence the adoption of green infrastructure and protection/enhancement of ecosystem services. Finally, based on the findings, a policy framework was purposed. Though the focus of the study was on select U.S. cities, the relevant publications on non-U.S. cities, specially cities in the UK and Australia, were also analyzed.

While the options of green measuressuch as green roofs, rain barrels, infiltration trenches, and rain gardensvary significantly from location to location, this study reveales that adopting GI faces similar cognitive and socio-institutional challenges of implementation regardless of location. Cognitive barriers, for example, stem from a lack of awareness, a particular socio-cultural mindset, and reliance on traditional institutional arrangements, whether it is in the U.S., the UK, Australia, or any other country. Therefore, with some location-specific adjustments, the findings of this paper should be applicable to non-U.S. cities as well.

Findings and Discussions

Barriers

The barriers identified in the study are presented in table 5.1, and are discussed as follows.

Federal and State Policy Barriers

The study revealed significant barriers prevailing across federal and state policies including but not limited to provisions in the U.S. Constitution, case laws, and statutory laws. While private property rights are considered fundamental to a free and democratic society, the constitutional protection of the right under the Fifth Amendment to the U.S. Constitution, which prohibits both the physical and regulatory taking of private property for public purposes, also can prevent municipalities from implementing GI on private property.

Though such "takings" are allowed if just compensation is made, the Fourteenth Amendment guarantees a due process before such takings, which creates legal and political proceedings that can give rise to complications for GI implementation. Furthermore, a lack of further constitutional clarification on takings and just compensation (Ruhl et al. 2007) can result in controversies that lead to litigations.

Historically, stormwater, or diffused surface water, was perceived as a nuisance. Courts therefore established case laws (also known as court laws) for draining it off the site instead of using on-site (Dellapenna 1991). Accordingly, the laws were also called the

Table 5.1. Barriers to Implementation of GI

Types	Specifics	Description
1. Federal and state policy barriers	1.1. Constitutional protection of private property	Prevents enforcement of GI on private parcels.
	1.2. Court law	
	1.2.1. Common Enemy Rule	Contradictory to the concept of GI
	1.2.2. Law of Natural Drainage	Restrictive to urban development
	1.2.3. Reasonable Use Rule	Relatively GI-friendly, but not sufficient
	1.3. Federal Statury Law	
	1.3.1. Insufficient statutory goal	Maintenance of hydro-ecological integrity is not included in the goal of the CWA
	1.3.2. Responsibility versus authority dilemma	Cities have no direct authority to control stormwater from private parcels but have responsibility to manage it.
	1.3.3. No flow control provision exists in law	Legal provisions focus only on pollutant loading, but not flow quantity.
	1.4. State Statury Law	Some states have preventive policies.
	1.5. Lack of stewardship of ecosystem services	No economic incentive for owners to maintain flow of ecosystem services.
	1.6. Decoupling of intercoupled jurisdictions	For example, quality and quantity control duties are under different agencies.
	1.7. Lack of design and maintenance standards	National standards/codes are not adequately available.
2. City policy barriers	2.1. Regulatory threshold	Too high to trigger SWM requirement.
	2.2. Problems in codes and guidance documents	Presence of conflicting or confusing provisions but absence of suitable ones.
	2.3. No provision for off-site mitigation	Code does not allow owners to manage stormwater off-site.
	2.4. Use restriction	Prevention in the use of available mandatory open spaces to install GI.
	2.5. Requirement to use gray	Mandatory provisions to route flow to existing gray infrastructure.
	2.6. Restriction on harvesting	Rainwater harvesting is not allowed.
	2.7. No max. limit on facility size	Provision for min requirement, not max.
	2.8. Pavement material requirement	Requirement of traditional pavement material
	2.9. Curb requirement	Generally, curb is mandatory in the code.
	2.10.Lack of financial incentives	No direct benefit for private parcel owners.
3. Governance barriers	3.1. Pro-gray governance	Centralized and technocratic governance
	3.2. Fragmented governance	Fragmented spatial and functional jurisdiction
	3.3 Lack of coordination	Both within and outside the government
	3.4. Lack of public engagement	Citizens have limited role in decision making.
4. Resource barriers	4.1. Lack of financial resources	Lack of public/private investment on GI
	4.2. Lack of data on cost/performance	Historical performance data is not available.
	4.3. Dearth of human resources	Shortage of workforce trained on GI.
5. Cognitive barriers	5.1. Pro-gray mind-set	People accustomed to using gray infrastructure.
	5.2. Unawareness about gray and GI	People unaware of harms/benefits of gray/green.
	5.3. Perceived risk on cost/perormance	Fear of higher cost and lower performance.
	5.4. Risk aversion attitude and reluctance to change	Unwillingness to shift to a new technology due to fear of perceived risks of using it.
	5.5. Hesitation to take maintenance responsibility	Due to fear of lack of maintenance knowledge as well as intention to avoid perceived burden.

drainage laws and were defined according to one of the three doctrines: the Common Enemy Rule, the Law of Natural Drainage, and the Reasonable Use Rule (Dellapenna 1991; Urban Drainage and Flood Control District 2008; Weston 1977). The Common Enemy Rule regards stormwater runoff as a common enemy and allows a landowner to protect his/her land by any means necessary, regardless of the possible consequences to others (Dellapenna 1991). This can encourage hydrologic disruptions, which is contrary to the concept of GI. As discussed earlier, GI regards stormwater as a resource, not an enemy, and utilizes it on-site by reestablishing the disrupted hydrology. The Law of Natural Drainage, or the Civil Law Rule, restricts any modifications of land that disturb the natural flow of surface water. It can, however, prevent development, and is therefore not appropriate in an urban context. The Reasonable Use Rule allows for the modification of land and drainage. It also allows for a negative impact on other properties if (i) there is a reasonable necessity; (ii) reasonable care be taken to prevent the possible damage; and (iii) the benefit reasonably outweighs the harm (Urban Drainage and Flood Control District 2008; Weston 1977). Since GI has the potential to prevent damage by on-site treatment, it can be used to satisfy the second condition. However, the difficulty can arise due to the transaction cost required to acquire information on the possible damage and due to an arguably high potential of controversy over what level of care is the reasonable care. Such controversies can lead to litigations. If the ecosystem services provided by GI had an economic value with its property right assigned to the landowner, GI would potentially satisfy the first and third conditions as well. However, since the U.S. law provides no property rights for them and most ecosystem services have no economic value (Lant et al. 2008; Ruhl et al. 2007), no one has an incentive to protect or install GI on their private parcels.

The primary federal statute that governs stormwater in the U.S. is the Clean Water Act (CWA) (33 U.S.C. §§1251–1387). Its objective is to restore and maintain chemical, physical, and biological integrity of the Nations waters (§101(a)), but not to restore and maintain the hydrological integrity of landscapes, an inevitably important component of urban ecology. The CWA does not only ignore hydrologic attributes such as surges in volume and timing of discharge (National Research Council 2009), its implementation also overlooks two of its own statutory concerns, physical and biological integrity, by focusing only on chemical integrity (Adler 2007). The act is based on a permit scheme, called the National Pollutant Discharge Elimination System (NPDES) (§402), which requires an NPDES permit if there is a discharge of pollutants by a person from a point source into navigable waters (§301, §502). However, as defined by the statute, stormwater is neither a pollutant nor does it come from statutorily defined point sources. Since the parcels that generate stormwater do not have 'discernable, confined, and discrete conveyance,' which are the three essential statutory conditions for a source to be a point source (§502(14)), they are not point sources, and hence are not subject to NPDES. Thus, the NPDES scheme puts the responsibility of managing Municipal Separate Storm Sewer System (MS4) upon cities without providing legal authority to control private parcels, which comprise a significant portion of the actual sources generating the flow. This results in the "responsibility versus authority dilemma," as termed by Dhakal and Chevalier (2016). Total Maximum Daily Load (TMDL) (§303), which refers to the maximum allowable amount of a pollutant that a water body can receive and still meets quality standards (McCulley 2002; U.S. EPA 2009), is another provision of the CWA which is applied to control pollutants in the impaired waters. However, since stormwater is not a pollutant, its quantity cannot be regulated by using TMDL. In Virginia Departmet of Transportation v. United States Environmental Protection Agency (2013), a federal court did not authorize the EPA to control stormwater flow as a surrogate for sediment. In addition, TMDL is normally activated only after waters get impaired, but has no role in land development activities (National Research Council 2009). Thus, the CWA does not have provisions that require the restoration of hydrologic processes and vegetation, two fundamental features of GI.

Barriers also exist in state laws and policies. For example, the State of New Jersey does not authorize cities to charge landowners a fee based on the amount of stormwater generated from their land, thereby barring cities to implement an effective economic incentive, discussed later. In Missouri, though the state law does not prevent such a fee, recently the State Supreme Court disallowed the city of St. Louis the implementation of a user charge based on impervious areas, deeming the charge a tax and requiring voters approval pursuant to the State Constitution ((Zweig v. Metropolitan St. Louis Sewer Dist 2013).

Even as a kind of natural capital that provides numerous other ecosystem services, the status of GI in the U.S. law and policy is discouraging. Due to the absence of marketable values for most ecosystem services, such as air purification and natural beauty, owners cannot sell them in markets for profit. Legal avenues exist neither for owners to charge recipient of the services, nor for the recipients to ensure the unabated supply of the services from the owners (Ruhl et al. 2007). As a result, a rational landowner is encouraged to destroy natural capital and develop his/her land to maximize the economic benefits. Ecosystem services thus lack the stewardship they require and are destined to be ruined. Ruhl et al. (2007) term this predicament the "tragedy of ecosystem services."

The decoupling of stormwater regulation and land-use regulation in the federal regulatory arrangement (National Research Council 2009) poses another significant obstacle to GI. In such a scenario, the land-use policy, which controls development activities, is likely to disregard landscape hydrology and result in developments noticeably contrary to the concept of GI. The absence of design and maintenance standards or general guidelines for GI at the national level has become a problem that discourages urban stormwater system designers from adopting GI. This has the effect of motivating them toward a gray approach, since the standards and guidelines for a gray approach are already available.

City Policy Barriers

We explored 10 major issues in city policies that can obstruct the adoption of GI (Table 5.1). One is the threshold area that sets into motion a citys regulatory requirement of stormwater management. Currently, a wide variation exists across cities. For example, in Camden, NJ and Neosho, MO stormwater management is required if the development area exceeds 1011.71 m^2 and 929.03 m^2 respectively; whereas in Dallas, TX, the threshold is 4046.86 m^2. These values are significantly higher than the thresholds set by some other cities such as Washington DC and Portland, each of which has a threshold value of 464.52 m^2. If the threshold value is too high, such as the one in Dallas, it may result in the uncontrolled development of a significantly large area.

The presence of conflicting or confusing provisions and the absence of suitable provisions in codes and guidance documents are other obstacles. For example, in Camden, the land development ordinance (§577) states that it allows turf blocks for off-street parking; paradoxically, it does not permit materials that are susceptible to vegetative growth. The State of Missouri requires land development permits for a disturbance of one acre or more, while Neosho, a city in the state, does not require such a permit, challenging the states requirements. The city code of Dallas does not define, permit, or encourage GI as a means of stormwater management. Though the city has created a voluntary Integrated Stormwater Management (iSWM), the code is not clear about whether using the iSWM complies with the city code. Some cities such as Dallas and Phoenix, do not allow off-site mitigation, which prevents landowners from installing GI off-site or paying an in-lieu fee to city agencies in case it is technically or financially not feasible for them to install GI on-site. The absence of a provision for off-site mitigation prevents the establishment of an allowance market, discussed later. The restriction on the use of open spaces also prevents the installation of GI on such spaces. In Phoenix, for example, the zoning ordinance does not include GI in the list of the elements allowed in the open spaces. Camdens code prevents the use of rain barrels and cisterns near building foundations, whereas in the Greater Los Angeles Region, the public right-of-way is not allowed for stormwater control access. Camden follows the National Standard Plumbing Code 2009, which requires to route runoff from impervious surfaces to a storm sewer where available. The code also does not have provisions to use harvested rainwater for activities such as toilet flushing and irrigation. In Phoenix, rainwater harvesting has been deemed impractical due to the local precipitation regime (U.S. EPA 2013), essentially restricting the use of rain barrels.

Traditionally, engineering design standards only consider engineering functionality and enforce minimum requirements on the size of facilities such as parking space (in both geometry and number), lane width, and roundabout radius. Since the standards generally disregard the impacts of land disturbance, they do not generally set the maximum limits. Consequently, the current requirements for various amenities differ from city to city. For example, the Phoenix City Code requires a minimum length of 5.5 m for parking spaces, while 4.57 m is enough (U.S. EPA 2013). For double-loaded aisles, 6.7 m is enough, but the zoning code requires a minimum width of 11.27 m. In Dallas and Macatawa, the minimum required width for a travel lane is 3.653.96 m, which can be reduced to 3.04–3.65 m or even less . The city codes of Phoenix and Camden require a minimum of 15.24 m for a cul-de-sac radius, which can be 10.67 m or less (U.S. EPA 2013, 2014a). Fire codes also require paved wide streets, the full width of which is used only rarely. Such requirements result in the creation of unnecessarily large impervious areas.

There are some city codes, which require specific pavement materials, and do not allow pervious materials on streets, sidewalks, parking lots, driveways, and other hard surfaces. For example, the Street Planning and Design Guideline of Phoenix requires asphalt for on-street parking and alleyways. The citys code also does not explicitly allow pervious paving materials in off-street parking. The code requires all sidewalks to be surfaced with Portland cement. Curb requirement provisions are other barriers which prevent the flow of road runoff into adjacent vegetated areas. For example, in Phoenix, the zoning code requires curbs where the urban density equals or exceeds 3 lots per gross area. Camden also requires raised curbs and does not allow curb cuts, flush curbs, curb pullouts, or bumpouts. A lack of financial incentive and an absence of necessary regulations are also critical barriers in some cities. For example, the City of Phoenix does not offer any incentives, such as cost sharing, reduction in street width/parking requirements, or assistance with maintenance, to property owners who utilize pervious materials (U.S. EPA 2013). In Camden, though the Land Development Ordinance sets impervious cover limits, there are no additional incentives for further reductions.

Governance Barriers

Governance has a leadership role in the implementation of infrastructure technologies. The current governance was designed for and is adept at governing centralized gray infrastructure (Dhakal and Chevalier 2016), therefore it inherently supports gray, not GI. As opposed to GI, which is a decentralized approach requiring the involvement of many stakeholders, the existing governance is centralized and exclusively technocratic. Another major governance barrier is the prevailing institutional fragmentation of both spatial and functional jurisdictions for stormwater management at both local and higher levels. Spatially, the mismatch of hydrologic and political boundaries results in the different governance entities for different portions of the same hydrologic unit. Functionally, even the highly-interrelated functions are under different leadership. For example, water quality control is governed by the U.S. EPA, whereas flood control is under the jurisdiction of the U.S. Army Corps of Engineers. Since different agencies generally have differing, and sometimes conflicting, priorities and goals, interjurisdictional collaboration is inevitable for effective implementation of GI. However, previous case studies show that generally there is a lack of such collaboration in many cities (e.g., Cettner et al. 2013; Huron River Watershed Council 2014).

Inadequacy of motivation and opportunities for public involvement is another obstacle in the current governance model (Dhakal and Chevalier 2016). Though, the Stormwater Phase II Rule[4] adopted by the U.S. EPA requires “public participation and involvement,” the current practice of public involvement is generally limited to participation in education, outreach and cleanup programs. In case when public comment is requested as required by the Stormwater Phase II Rule, these comments are highly likely to be disregarded in the final decision (Dhakal and Chevalier 2016).

Resource Barriers

One of the most cited barriers in earlier studies is the lack of financial resources (e.g., Copeland 2014; Huron River Watershed Council 2014; Keeley et al. 2013; Porse 2013; Thurston 2012; Tryhorn 2010). Given its cost-effectiveness and other general benefits, the GI approach should not have been financially problematic, at least in comparison to the gray approach. However, a problem exists for two reasons. First is the existing practice of using funds from general revenue, the stormwater management portion of which is intended for gray infrastructure development and maintenance on public land. The legal restrictions generally discourage investing these public funds on private properties (Keeley et al. 2013). Second is the absence of market for most ecosystem services, other than provisioning services. Since these services are not monetized due to the lack of a proper tool. As a result, the financial benefit of GI is undervalued. Consequently, the payback period for GI projects becomes longer than a decade, discouraging private investors (Valderrama et al. 2013) and resulting in a lack of financial market for project financing (Clune and Braden 2007). As observed by Valderrama et al. (2012), currently there is no existing approach for bringing private investments into stormwater retrofit projects. Additionally, stormwater issues cannot compete with other more critical aspects of existence, such as food, security, and shelter, in securing an appropriate budget from the general fund. As a dedicated funding source, many cities have established stormwater

[4]https://www3.epa.gov/npdes/pubs/fact1-0.pdf

utility fees (Porse 2013), which have faced legal challenges in some other cities (Keeley et al. 2013).

A lack of data on cost and performance is another highly cited barrier in most of the studies (e.g., Copeland 2014; Huron River Watershed Council 2014). In the absence of such data, the adoption of GI appears risky to the municipal staff, policy makers, and the public, discouraging them to embrace the technology. In addition, the lack of formal coursework and research opportunities in university engineering programs, along with the limitations of other training opportunities in the market (Clune and Braden 2007), leads to a dearth of sufficient professionals with GI expertise in the job market (Tian 2011; U.S. EPA 2014a). As a result, many cities face a shortage of staff for its design and installation (Barbosa et al. 2012; LaBadie 2010; National Research Council 2009).

Cognitive Barriers

Our study reveals that mindset, unawareness, fear, attitudes, and perceptions are other factors that discourage landowners, water resource managers, and policy-makers to use GI. We have categorized these intangible factors as cognitive barriers. On one hand, there is some doubt among professionals about the reliability of GI (Brown 2008; Copeland 2014; Porse 2013) giving rise to some fear of liability concerns on the implementation of the technology (Olorunkiya et al. 2012). On the other hand, there is a legacy of unrestrained access to citys gray infrastructure for discharging runoff from private parcels without paying the direct costs. As a result, there exists reluctance in the public to switch to GI from gray. The perceived risk to cost and performance of GI due to the absence of historical data, combined with a risk aversion attitude, are highly cited factors in literature (Clune and Braden 2007; Nylen and Kiparsky 2015) that lead to such reluctance. The reluctance persists also due to the unawareness among the public about how the gray system is environmentally inappropriate and how GI manages stormwater sustainably. Moreover, due to the fear of improper maintenance (Hammitt 2010) and attitudes to avoid perceived burden, landowners hesitate to take maintenance responsibility and are encouraged to oppose the installation of GI on their land.

Driving GI ahead: The Suggested Policies

Policy, which provides the guidelines for collective human actions for shared outcomes (Meehan 1985), is crucial to drive a technologys implementation (Ahern 2007; Holzer and Schwester 2016). As discussed by Birkland (2010), and for the purpose of this paper, by policy we mean constitutions, laws, statutes, regulations, court decisions, and agency or leadership decisions. Governance is an inevitable aspect of policy, since it provides a platform for the political process required for policy making and plays a leadership role for implementation. Based on this scope and definition of policy, I suggest 33 policy tools grouped into 5 categories: federal and state level policies; city policies; alternative governance; innovative funding mechanisms; and education, awareness, awards, and recognition (table 5.2).

Federal and State Level Policies

Amending the constitution in regard to private property rights is very complex, not only because of the politically complicated process it requires but also due to the challenges it may pose to the basic rights of freedom and democracy. As the Drainage Law doctrines were developed through court cases, their modification evolves over time with changes in circumstances or new knowledge—as acknowledged by Justice Scalia in (Lucas v. South Carolina Coastal Council 1992). Therefore, constitutional amendment and change in drainage law are beyond the scope of this paper. For relatively prompt policy actions, other statutory and regulatory approaches are required within the given constitutional framework. Recently, some initiatives have been proposed and even accepted at the federal level. For example, the U.S. Congress recently added §313 to the CWA to require the federal government to pay stormwater fees as a reasonable service

Table 5.2. Policy Measures for Overcoming Barriers and Encouraging GI Implementation

Policy categories	Policy measures	Targeted barriers
1. Federal and state policies	1.1. Add hydro-ecological integrity the goal of the CWA.	1.3.1
	1.2. Establish flow (or its surrogate) as a control measure.	1.3.3
	1.3. Enact statutory provisions to allow cities to enforce flow control regulations on private parcels.	1.1,1.2, 1.3.2
	1.4. Require cities to conduct planning and development based on hydrologic features.	1.6, 3.2
	1.5. Integrate intercoupled functions under one institutional umbrella	1.6, 3.2, 3.3
	1.6. Audit & amend other policies & standards to incorporate GI.	1.7, 1.4, 2.2
	1.7. Establish national design/maintenance standards/guidelines for GI	1.7
	1.8. Provide federal/state tax exemptions/credits on GI materials/works.	2.10
	1.9. Enact a more meaningful nationwide land development threshold that triggers stormwater management requirements.	2.1
2. City policies	2.1. Audit codes and eliminate/amend conflicting and confusing provisions.	2.12.9
	2.2. Remove mandatory requirements for curb and allow curb cuts.	2.9
	2.3. Remove requirements for impervious pavement material in driveways.	2.8
	2.4. Remove requirement for minimum parking space in transit-served areas.	2.2, 2.7
	2.5. Remove requirement to route stormwater to gray system.	2.5
	2.6. Create guidance documents & manuals for design/maintenance of GI.	2.2, 1.7
	2.7. Enact ordinance that requires on-site stormwater retention using GI.	2.2
	2.8. Allow use of GI in open spaces where technically feasible.	2.4
	2.9. Allow rainwater harvesting where climatically feasible.	2.6
	2.10. Assign fair share of responsibility to each stormwater generator.	2.10
	2.11. Adopt market-based incentives (table 5.3) to motivate private landowners.	1.5, 2.10, 4.1
	2.12. Allow off-site mitigation or in-lieu fee.	2.3, 2.10, 4.1
	2.13. Enact liability transfer ordinance to allow landowners to transfer maintenance liability to a third party licensed by the city.	4.3, 5.5
3. Alternative governance	3.1. Restructure the governance to establish two-tier model as discussed in Dhakal and Chevalier (2016).	3.13.4
	3.2. Establish a regional watershed level agency to facilitate and fund research, education, data collection, collaboration, and creation of market for ES.	1.5, 4.1, 4.1, 4.2
	3.3. Establish a functional mechanism at each level for communication, interaction, and coordination within government agencies and with stakeholders outside. ernment.	3.13.4
4. Innovative funding mechanism	4.1. Establish stormwater fee and allowance trading as revenue sources as well as incentive mechanism.	1.5, 2.10, 4.1
	4.2. Ensure stable policies, such as 10–15 yr fee schedule to tackle uncertainty & motivate private financiers (Valderrama et al. 2013).	4.1
	4.3. Create municipal green bonds	4.1
5. Education, awarenwss, award, and recognition	5.1. Establish education/outreach programs to raise public awareness on benefits of GI, harms of gray, and about how GI works.	1.2, 3.4, 5.15.5
	5.2. Have programs in place to train existing staff responsible for stormwater management and other related functions.	4.3
	5.3. Encourage universities to offer research opportunities and courses on GI to graduate and undergraduate civil engineering students.	1.2, 4.2, 4.3
	5.4. Include course on GI and ecosystem services in K-12 (Kindergarten-12^{th} grade) curriculums.	1.2, 5.15.5
	5.5. Establish awards and recognition programs to encourage individual and social capital.	3.4, 5.1

charge to the concerned city agencies or utilities which provide stormwater management services for the federal properties. Some bills have been introduced in the house to support the implementation of GI (e.g., H.R. 4648, 2016; H.R. 1775, 2015), which have included many important provisions, such as federal financial assistance for research and implementation. However, the bills do not include provisions to address many of the barriers in the CWA. An example of this is the absence of restoring hydro-ecological integrity in the statement of statutory goals.

At the federal and state levels, I suggest nine policy actions (table 5.2) including the amendment of the CWA (§101(a)) to add hydro-ecological integrity of the urban landscape as one of its goals. The inclusion of hydro-ecological integrity as a statutory goal will equip and encourage the U.S. EPA to formulate and enforce regulations for installing GI on private parcels. It is also necessary to add a statutory provision to the CWA that incorporates flow or impervious cover as a measure of stormwater loading (National Research Council 2009). Subsequently, a provision allowing cities to enforce flow control on private parcels will become necessary. Such flow control provisions would establish the CWA′s jurisdiction over water quantity, and help the U.S. EPA and cities enforce regulations to control stormwater quantity on-site. Congress has already established such a statutory provision in the Energy Independence and Security Act of 2007, where all new federal developments with a footprint larger than 464.5 m^2 require the restoration of predevelopment hydrologic characteristics like temperature, rate, volume, and duration of flow. Similar provisions with a more stringent threshold should be added to the CWA to control land development under any ownership. I also suggest adopting a federal statutory provision that requires planning, zoning, and development in conformity with the hydrologic features of the landscape. This will ensure that development activities cause as little damage as possible to the vegetation and natural hydrology. For this, interconnected functions such as land-use planning, stormwater management, and flood control need to be brought under one federal institutional umbrella, or, at the very least, have an effective coordination that will overcome conflicting policies and actions that discourage GI implementation.

Existing national standards and codes for the design and maintenance of roads, parking lots, plumbing, and fire safety need to be updated to incorporate the concept of GI to the maximum practical extent. As for other civil engineering infrastructures, national standards and guidelines should be created for the design, construction, and maintenance of GI. Such standards not only overcome potential risks of inappropriate design and maintenance, but also encourage design and maintenance staff to incorporate GI, and furthermore help maintain consistency. To minimize the area of paved surface, the maximum limit on the size of facilities (e.g., lane width and radius of roundabouts) should be fixed nationally. Additionally, as a financial incentive to install GI, I suggest providing federal and state tax exemptions or credits on GI material and installation cost to motivate landowners, developers, and manufacturers to adopt the technology.

In the absence of a federally enforced threshold of land development that initiates stormwater management regulations, states have enforced their own thresholds. However, a wide variability exists in such thresholds, most of which are too high. Currently over three-fourths of statessuch as Texas, Missouri, Illinois, and Michiganhave a threshold of 4046.86 m^2 of disturbed area; whereas, other statessuch as Washington, Florida, Delaware, and Marylandhave more stringent thresholds (U.S. EPA 2011). In Maryland and Delaware, the threshold is 464.5 m^2 of disturbed land, whereas in Florida it is 371.6 m^2 of impervious cover. The State of Washington has enforced thresholds on both disturbed areas and impervious surfaces, which are 650.3 m^2 and 185.8 m^2 respectively. The threshold of 4046.86 m^2 currently adopted by most states is too high because it leaves a significant portion of land development activities, especially on private residential parcels, out of regulatory control from stormwater management perspectives. Though a high threshold value at federal and state level does not restrict a city from adopting a more stringent threshold, it also does not encourage a city to do so. Consequently, a city, such as Dallas (discussed earlier), can adopt the parent states too high threshold. Therefore, we recommend adopting a more meaningful national threshold for both disturbed and impervious areas so that most of the land perturbation activities in all cities would come under regulatory control.

City Policies

In the U.S., a city can enact legislation as authorized by its parent state to govern activities within its jurisdiction. Since land-use planning, zoning, and storm water management are carried out by cities, the city policies play a crucial role for adopting GI. Generally, courts also uphold local decisions in matters of land use (Thomas 2008). Even within the current federal and state policy regimes, many cities, such as Portland, Seattle, Chicago, and Philadelphia, have enacted several city policies and this has resulted in the significant implementation of GI. This shows that, while a change in federal and state policies is necessary to facilitate and encourage cities, cities by themselves can develop and enforce several policies that drives GI implementation. I suggest 13 city-level policies, which are presented in table 5.2.

As suggested in many studies, we recommend that each city also audit its existing policies; find unclear, contradictory, and pro-gray language; and remove or amend them. For example, the provisions that require raised curbs for roads, impervious pavement for residential driveways and parking lots, and minimum parking spaces for transit-served areas should be eliminated. Any code, such as the National Standard Plumbing Code, which requires impervious areas to drain to a sewer system, should be either amended or replaced by a new code. Provisions in fire codes that require paved streets wide enough for fire trucks should be ammended to reduce the additional pavement because the additional width required is very rarely used. Appropriate vegetative or other pervious surfaces could be used on the additional width. Any regulatory restrictions on open spaces, including setbacks, that prevent the use of the spaces for GI should be repealed and technically viable GI should be allowed in such open spaces. Rainwater harvesting should also be allowed where doing so is climatically feasible.

Having guidance documents and manuals is critically important for the design, installation, and maintenance of GI. In the absence of such documents, other cities′ documents (such as those of Seattle and Portland) can be adopted with some context-sensitive adjustments. When viable, cities should enact command and control ordinances that require on-site stormwater retention to maintain or restore predevelopment hydrology. They can also use GI as a condition of development permit approval. Many cities in the U.S. and abroad have embraced such policies. For example, Portland requires new/redevelopment projects to manage stormwater on-site and all new city buildings to construct a green roof over at least 70% of their roof area. Chicago requires any building with a footprint over 1393.5 m^2 or any parking lot over 696.75 m^2 to either detain the first half inch of rain on-site or reduce the prior imperviousness by 15%. Command and control ordinances are exercised in other countries as well. Tokyo, Japan, requires private buildings larger than 1000 m^2 and public buildings larger than 250 m^2 to have 20% of the rooftop greened; whereas Linz, Australia, requires green roof on all new buildings larger than 100 m^2 (Carter and Fowler 2008). I also suggest having a policy that ensures a fair share of stormwater management responsibility among all storm water generators based on the relative extent of hydrological disruption and the additional discharge generated due to the land development activities. For example, among two landowners with equal impervious areas, the responsibility of the owner whose impervious area is constructed on more pervious soil should be greater. Such a policy will discourage development on more pervious land, and help correct the responsibility versus authority dilemma discussed earlier.

When regulatory options are insufficient, market-based tools can be viable alternatives to act beyond the regulatory limits, especially for encouraging private landowners to install GI. Because they are voluntary, they are less likely to be opposed by residents. Currently available potential market instruments and their example applications are presented in table 5.3. Though some of these tools, such as an allowance market, are still in the nascent stages in the field of stormwater management, many other options have been increasingly used in some pioneering cities in the U.S. and other developed countries. In the U.S., more than 400 cities, towns, and utility districts utilize parcel-based fee systems based on impervious area (Valderrama et al. 2012). A survey of 70 utilities conducted by Valderrama et al. (2012) in 20 states showed that a majority offered credits against stormwater fees for installing GI. As discussed earlier, the U.S. Congress has also added provision to the CWA requiring the federal government to pay stormwater fees (§313). When designed appropriately, the system of fee (or charge) and allowance trading can arguably combine to establish a functioning market. If an owner cannot install GI due to cost or other technical constraints, the landowner should be allowed off-site management within a designated geographical boundary. The off-site control may be owned and operated by any private party or a government agency. If it is owned and maintained by the government, the landowner can pay an in-lieu fee, which should be used exclusively for GI. Portland has already adopted this policy, where the collected off-site management fee is put in a mitigation account to be used to mitigate the impacts of off-site discharge. However, while the mechanisms of stormwater fees and allowance credits can help channel private investment to the projects yielding the highest environmental benefits (Valderrama et al. 2012), such mechanisms may pose two significant challenges.

First, low-income families may not be able to pay the required fee or install GI on their property. To address this problem, cities need to develop financial assistance programs to help the needy residents pay their stormwater bills. As an example, Portland has already established such assistance in various forms that include bill discounts and crisis vouchers. Second, because discharge is a local problem, if a market is created for it, this can easily result in an insufficient number of buyers and sellers, leading to a failure of the allowance market. The viability can be increased by including other co-benefits, such as pollutant control and carbon storage, for trading and expanding the market to larger geo-political jurisdictions. For example, water quality trading can be expanded to regional watersheds and carbon trading can be expanded both nationally and internationally. However, institutional arrangements, such as regional governance discussed in the subsequent section, should be created accordingly. To address the fear among the landowners about maintenance of GI, a city can enact liability transfer ordinance that allows a landowner to purchase maintenance services from a company licensed by the city and transfer the maintenance liability to the company. The involvement of a company in the installation and maintenance of GI helps create a business. There are other co-benefits of GI, such as natural beauty and a reduction in the urban heat island effect, that are considered public goods for being non-excludable and non-rivalry. In such cases, direct payment to owners will encourage them to continue having GI and supplying such services. Development incentives could be another attractive policy with no financial burdens on the government. The market options are explained with example applications in table 5.3.

Alternative Governance

Since urban GI requires the involvement of a large number of stakeholders, including societies, individuals, private sectors, institutions, and formal and informal organizations, many scholars (e.g., Dhakal and Chevalier 2016; Novotny et al. 2010; Roy et al. 2008) indicate that small scale neighborhood-level governance could be appropriate for GI. Novotny et al. (2010) propose small units called "interconnecting clusters" or "ecotones" around the first or second order surface water body. Lant et al. (2008) argue for establishing ecosystem service districts to govern ecosystem service and recommends delineating their boundaries in coherence with watershed boundaries. I have proposed a two-tier governance model for stormwater governance, consisting of hydrologic districts at

Table 5.3. Potential Market (or Quasi-Market) Mechanisms and Examples.

Policy Mechanisms	Example Applications
Stormwater fee and discount: This scheme enforces a fee on runoff quantity or impervious area and provides discounts for installing GI.	Seattle enforces annual flat fee for single family and duplex smaller than 929 m^2. For all other cases, the annual fee is based on impervious area. Portland enforces off-site (65%) and on-site (35%) charges separately. Flat rate for single family to 4-plex residences, rate per 92.9 m^2 of impervious area in other cases. The Clean River Rewards program provides up to 100% of discounts for on-site portion of the charge.
Allowance market: In this scheme, tradable allowances of discharge are distributed among landowners, who are required to manage additional quantity. One who can manage more than required, can sell his/ her allowances to others willing to buy and use them for their retention requirements.	Stormwater Retention Credit (SRC) program in Washington DC, U.S. Landowners obtain SRCs for voluntary reduction of stormwater runoff (one SRC per additional gallon reduced above required reduction) using GI. The owners can bank for future use or trade their SRCs in an open market to others who are willing to buy and use to meet regulatory requirements for retaining stormwater (Hoffmann et al. 2013). First of its kind in the nation.
Payment of ecosystem services: Owners are payed for providing ecosystem services such as flood mitigation, carbon storage, and water purification.	In use by U.S. cities—such as New York, NY; Syracuse, NY; Boston, MA; Portland, OR; Seattle, WA—for protection of watershed that are their critical sources of water supply (Mercer et al. 2011). Used for many other ecosystem services in countries including the U.S., China, South Africa, Mexico, Costa Rica, and Nicaragua (Schomers and Matzdorf 2013).
Rebates, credits, and installation financing: This includes financing, tax credits, or reimbursements to landowners who install GI.	In Philadelphia, the Tree Vitalization Rebate Program provides a $25 rebate for planting a tree. The Rain Check program provides rain barrels for free and/or helps construct downspout planter, rain garden, or porous paving for a reduced price. In Seattle, the City and King County pays up to the total cost of rain gardens and cisterns.
Development incentives: Developers receive benefits including expedited permitting, and bonuses for floor area, height, density, and space.	Chicago offers expedited permitting process for projects meeting Leadership in Energy and Environmental Design (LEED) criteria. For installing green roof, Philadelphia provides floor area ratio and height bonuses up to to 400% and 10.97 m respectively; whereas Portland provides floor area bonus up to 300% of the area of ecoroof installed.
Grants and awards: Provides money directly to individual landowners or communities for installing GI	In Chicago, the Green Roof Grant program provides $5,000 to residential and small (<929 m^2) commercial buildings. In Portland, the Community Watershed Stewardship Program provides up to $10,000 for watershed restoration activities. Philadelphia has Stormwater Management Incentive Program (SMIP) to provide grants for qualified non-residential owners, and Green Acres Retrofit Program (GARP) to provide grants for qualified contractors, companies or projector aggregators.

neighborhood level and a city agency at city level (discussed in Dhakal and Chevalier (2016) and presented in the next chapter). The hydrologic districts would provide small scale governance within the local hydrological boundary, whereas the city agency would utilize the current city jurisdictions to establish coordination among other stakeholders, such as between the city and upper level government. We recommend using this model to govern GI and ecosystem services because neighborhood level governance would provide a better opportunity for face-to-face interactions and hence foster stakeholder engagement (Cohen 2012), which is critical for sustainability (Ellis et al. 2010). The stakeholder engagement leads to a shared sense of community and increases a communitys sense of ownership (Tryhorn 2010). The resulted increase in social capital (Mazmanian and Blanco 2014) will enhance the stewardship of GI. Thus, there will be better care and management of GI assets by the community without being entirely dependent on recurrent funding from the government (Wong and Eadie 2000). Since the current stormwater permit scheme leaves a great deal of discretion to the regulated community to set their own standards and to self-monitor compliance (National Research Council 2009), such community stewardship is critically important. Hundreds of thousands of successfully functioning neighborhood scale governance in the U.S. and abroad—such as homeowners′ associations in the U.S. (McCabe 2011; Scheller 2015) and neighborhood associations in Japan (Tsujinaka et al. 2014)—justify the viability of such neighborhood scale governance.

The problem of fragmented jurisdictions at city and state levels that results from the prevailing mismatch of hydrologic and political boundaries is a problem the scope of which demands further research. However, I have some suggestions that can help begin a conversation. I suggest establishing a regional watershed-scale governancein each regional watershedwhose jurisdictional boundary would follow the boundary of the watershed. Such a governance mechanism would be in the form of an alliance among those states whose territories lie partially or wholly within its boundary. The regional governance would create guidelines for GI, monitor GI related activities, establish a functional coordination among states within its jurisdiction, and provide both technical as well as financial support to those cities which cannot afford GI. It would also function as a clearing house to collect and share information on GI. Moreover, it would provide a platform for trading ecosystem services other than those of local character, such as carbon sequestration and water quality. Historically, different forms of regional governments have been tried at different times in the U.S., including the extension of a center city to encompass the region, the formation of regional councils for regional planning and coordination, and voluntary cooperation among governance and sectors through public and private partnership (Olberding 2002). Currently, numerous metropolitan areas are also working as regional governments with the intent to share resources between city cores and their surrounding settlements (Squires 2002). However, since these traditional mechanisms generally do not follow wathershed boundaries, they would not be able to solve the fragmented governance that results from the mismatch of political and hydrologic boundaries. I realize that there is a necessity to reexamine all forms of the current regional governance and restructure them under the regional watershed governance of the type proposed in this dissertation.

Innovative Funding Mechanism

Previous studies by other scholars show that, in general, GI costs less than gray infrastructure (e.g., Baerenklau et al. 2008; Foster et al. 2011; Shaver et al. 2009; U.S. EPA 2015). However, the approach requires investments not only for installation and maintenance but also on multiple other fronts including education, outreach, research, new governance structure, rebates, and rewards. Fortunately, unlike traditional approach, GI has multiple potential revenue sources other than general revenue funds. Examples include revenue collected from stormwater fees (or charges), in-lieu fees, allowance trading, and green bonds, discussed earlier. If designed appropriately, these sources can generate a considerable amount of revenue. As outlined in Valderrama et al. (2013), if regulatory certainty, such as long-term fee schedules, can be ensured, private financiers can invest in GI projects for the revenue to be generated in the form of the avoided stormwater fee. Another way to attract investments is municipal green bonds, which, though currently used on a small scale, is gaining popularity in the U.S. as well as abroad. Recently, for example, Seattles Sound Transit sold nearly $1 billion of green bonds to help fund regional transit projects; whereas, Johannesburg issued a green municipal bond of $136 billion (Bloomberg and Lille 2016). Such a bond can be used to construct large scale GI projects. However, at the beginning, especially unless these multiple resources become fully functional, public funds may be required for education, awareness, outreach, demonstration projects, awards and grants, research and development, and the establishment of regional and community-level governance. Currently, gray infrastructure annually requires billions of dollars of public revenue, a significant amount of which will be saved due to GI. If managed appropriately, the saving will provide a significant portion of the funding required by the recommended activities. However, the long-term solution is to develop GI as a business rather than a burden on general revenue.

Education, Awareness, Awards, and Recognition

In a democratic society, social acceptance plays a central role in mainstreaming a technology. The increased social acceptance can also foster a market, leading to an enhanced GI stewardship as a business, which contributes to establishing a sustainable financing mechanism. A study conducted in the Shephard Creek watershed in Cincinnati, Ohio (Green et al. 2012 2013) has revealed that the social acceptance of GI can be increased by investing in enhancing human and social capital through education and awareness. Human capital is embodied in the skills, knowledge, and capabilities of an individual, and the relationships among the individuals form the social capital (Colemn 1988) On the other hand, the social capital provides a collective forum for human capital

(Green et al. 2012) and shapes the activities of human capital through socially constructed norms and moralities (Onyx and Bullen 2000). A community with a high social capital also monitors the behaviors of its members, making them accountable for their actions (Bowles and Gintis 2002). In other words, human and social capitals work synergistically to enhance social acceptance. By removing cognitive barriers and boosting social and individual capital, education and awareness thus play critical roles in expediting the adoption of GI. While the regulatory requirement in the Stormwater Phase II Rule for public education and outreach provides a useful tool to increase public awareness, the policy is insufficient. To have sufficient human resource to fulfill current and future demands, cities should have policies to train their current staff and enhance their expertise in GI. Furthermore, universities should be encouraged to offer courses and research opportunities to graduate and undergraduate civil engineering students who want to specialize in stormwater management. To have a pro-GI society in the future, I suggest teaching GI to K–12 students as well. Federal policies and programs are needed for encouraging academic programs in academic institutions. Awards and recognition are other critical tools which work by motivating people to come forward and play a leadership role, which is critically required for driving GI application. Many cities have adopted such award and recognition programs. Mayor Daleys Green Works Community Award in Chicago and Philadelphias Sustainability Award are notable examples.

Conclusion

Though GI is known to have numerous ecosystem benefits and is regarded as an underpinning element of urban sustainability, its adoption by cities is slow. This paper explores 29 barriers under 5 categories that cause the delay and suggests 33 policy strategies under 5 categories that can both overcome these barriers and expedite implementation. The study suggests that the most critical barriers are cognitive barriers and socio-institutional path dependence. Other barriers, such as resource and policy barriers, are essentially the result of these two barriers. Social acceptance is arguably the most decisive driver of a technology and an addresser of its impediments. Enhancing the knowledge of GI through education and awareness, and the resulting removal of cognitive barriers, can develop social acceptance. If social acceptance is high, formulating other pro-GI policies and programs at any level becomes easier. A high social acceptance encourages courts and legislatures to make favorable policy decisions, which will inevitably result in the development of both common and statutory laws. The enhanced social acceptance will also help update engineering standards to incorporate GI. Additionally, it tends to foster markets and bring about GI stewardship as a business that contributes to the generation of sustainable financing.

In addition to social acceptance, the availability of expertise, skilled personnel, champions, and leaders are of paramount importance for driving GI implementation. Therefore, I suggest adopting policies that focus on awareness, education, recognition, training, coordination and engagement. In the short run, policies of "carrots and sticks" would be more effective. The hydrologic district in the proposed two-tier governance (Dhakal and Chevalier 2016) provides opportunities to restructure the governance in compliance with hydrological features at the local level, whereas the proposed regional governance addresses the problem of fragmented governance within the watersheds boundary. We also suggest encouraging universities, especially civil and environmental engineering departments, to develop and offer curriculum that include GI and provide research opportunities to students. We should encourage vocational schools to offer training and produce the professionals that will be required by current and future cities to implement GI. To create a pro-GI society in the future, we need to teach K-12 students about the concept, importance, and the reliability of GI through class work and demonstration projects.

Since the focus of our investigation was on 10 U.S. cities, the identified barriers and recommended policy solutions as such are more relevant to U.S. cities. However, our examination of available literature from non-U.S. cities, especially in the UK and Australia, shows that most of the barriers and solutions are of global nature. While the selection of alternative forms of green measures—such as green roof, rain barrel, infiltration trench, and rain garden—is highly dependent on location, the study reveals that adopting GI as an approach faces similar cognitive and socio-institutional challenges in cities irrespective of where they are located. Because it is always eventually cost-effective, GI is arguably more suited to low income countries, where many cities are facing unprecedented growth and limited resource. However, due to the prevailing methods of infrastructure planning, the decreased availability of open spaces in traditional cities, and relatively low socio-economic development, the barriers and solutions in existing low-income cities may be somewhat different, which will require further research. Further research is also recommended for defining the institutional structures, functional jurisdictions, authority, and resources for the proposed regional governances as well as hydrologic districts.

CHAPTER 6

GOVERNANCE FOR GREEN INFRASTRUCTURE: BARRIERS AND SOLUTIONS

Introduction

While policy provides guidelines for shared activities of stakeholders to achieve common outcomes, as discussed in chapter 5, governance provides the mechanism for formulating those guidelines and monitoring stakeholder actions to ensure compliance. In other words, governance governs policy, which in turn governs collective activities including the governance itself. Thus, governance works in tandem with policy to foster collaboration and cooperation among stakeholders for achieving their preferred outcomes. Green infrastructure implementation is a shared undertaking because it involves numerous stakeholders including landowners, business community, civic organizations, environmental groups, and government agencies. Therefore, in addition to policies, any issues in existing governance can also prevent green infrastructure implementation. Policy was dealt in chapter 5; this chapter evaluates the governance and formulates a new approach.

In general, governance is a broad notion with no unanimous definition. However, it has some universal functions and attributes. It provides a framework for decision making (Porse 2013) to regulate human interactions in a shared environment (Oakerson 2004). It refers to collective action accomplished for public purpose (Heaney 2007) within a defined jurisdiction, and comprises a broader scope than government (Evans 2005; Feiock 2004). In addition to government, it encompasses a range of other aspects such as societies, individuals, private sectors, laws, regulations, institutions, and formal and informal organizations (Porse 2013; Tortajada 2010). In other words, governance regulates the works of people both inside and outhside the government (Oakerson 2004). As Bovaird and Loffler (2009) outline, governance is the way an organization works with its partners, stakeholders, and networks to influence the outcomes of public policies. Based on the definitions given by different international institutions including the World Bank, United Nations agencies, and the European Union, Biswas and Tortajada (2010) determine that accountability, transparency, participatory, and decentralized decision making are common essential attributes of governance. For the purpose of this dissertation, stormwater governance is defined as the organizational authority that formulates as well as impliments stormwater policies and programs. As such, this chapter focuses on leadership mechanism and functional jurisdiction of its various components, but not on policies. The study is primarily focused on the US context.

The existing stormwater governance has a hierarchical structure comprising various levels of government. At the federal level, the U.S. congress enacts laws (e.g., Clean Water Act), which the U.S. EPA enforces through standards and regulations upon the states and cities. Under the federal laws and guidelines, states can enact and implement more stringent standards on city (or county) governments, which carry out the stormwater management activities. The city governments implement the federal and state laws and can also enforce their own discretionary standards and regulations keeping their minimum standards in compliance with the state and federal standards. In a city, the governance is heavily centralized on its designated agency which governs all stormwater governance activities through its technocratic administration.

The existing centralized and technocratic governance was structured to govern the gray infrastructure, which is highly centralized and engineered. However, green infrastructure is distributed, and it employs natural hydrologic process of soil and vegetation instead of complex engineering structures. The existing governance also does not possess other attributes of modern governance discussed earlier. For example, it ensures the involvement of government agencies in the decision-making process, not the stakeholders outside of the government. Though public participation is required as per Phase II rule, incorporating the participants suggestions is not mandatory. The final decision is made at the discretion of the city agencys staff. Since the decision authority is solely on the city agency, there is arguably a lack of transparency.

A number of previous studies have defined current governance as a major barrier to mainstreaming of the green technology (Ellis et al. 2010; Rijke et al. 2013). Scholars have used different phrases to discuss the barriers, examples include socio-institutional barriers (Brown and Farrelly 2009a; Clune and Braden 2007; Rijke et al. 2013), organizational barriers (Cettner 2012; Keeley et al. 2013), and administrative inertia (Brown 2008 2005). Unfortunately, there is a lack of comprehensive evaluation of governance from this perspective (Van de Meene et al. 2011). This elucidates the critical research need for exploring the government issues regarding its suitability for the green approach and addressing them. This chapter attempts to fulfil this need.

The approach used in this study was largely exploratory. Five U.S. cities—Portland, Oregon; Seattle, Washington; Philadelphia, Pennsylvania; Chicago, Illinois; and Syracuse, New York—were selected for study. Their stormwater governance was studied from city codes and other published materials. For each city, an assessment of the use of gray infrastructure versus green infrastructure was considered and barriers to the full implementation to green infrastructure were identified. Finally, a new stormwater governance model conducive to green infrastructure implementation was proposed.

Major Issues of Stormwater Governance

Major issues identified by the study are presented as follows.

Intrinsic Issues

Existing urban stormwater governance inherently lacks many of the essential attributes of governance discussed earlier. The approach is highly centralized and dominantly technocratic, in which engineers of a designated city agency centrally manage stormwater through a command-and-control approach. The technocrats are trained for, experienced with, and inclined to design, construct, maintain and repair gray infrastructure, not green infrastructure. This approach in part instills into their minds a reluctance to implementing a green infrastructure (Brown 2008). Though cities solicit public input in program development and implementation process, as per Stormwater Phase II Rule, technical complexities of gray infrastructure may often discourage the public to actively participate in the process. Even if citizens participate and provide their opinions, it is very likely that the opinions appear technically less important to the technocrats and are disregarded in the final decision. Since landowners do not have to pay for the stormwater management costs directly from their pocket, because the budget comes from the city′s general revenue funds, they perceive stormwater management as city′s responsibility, not theirs. Hence, there is no incentive for the landowners to participate in the governance. Due to this, the public may not show much concern to stormwater governance activities, which potentially leads to lack of transparency. Thus, traditional governance lacks the essential attributes of modern democratic governance outlined by Bishwas and Tortaza, cited earlier.

Decoupled Governance of Intercoupled Functions

Urban stormwater is an integral part of an urban water system and is a subsystem of urban environmental system. However, it is governed not as a subsystem (Brown 2005; Wilkinson et al. 2013), but as an isolated and independent undertaking. Its governance, in general, does not encompass other urban activities that impact hydrology, such as city planning, land use policy decisions, development control, and building construction. Not only the the governance of the mutually functioning urban vegetation and urban stormwater are disconnected, but also the three components of urban water system, viz. stormwater, waste water, and water supply, are generally governed separately under different agencies. Though the idea of Integrated Water Management and/or Sustainable Water Management has come into discussion among scholars for decades, it has not yet made considerable advancements (Biswas and Tortajada 2010; Foster and Ait-Kadi 2012). As a result, viability of Integrated Water Management (Biswas 2004) and Sustainable Water Management (Biswas and Tortajada 2010) has come into question, despite being strongly advocated as efficient approaches by experts.

Runoff from Private Parcels: Responsibility vs. Authority Dilemma

Under current governance regime, a major predicament for city government to implement green infrastructure is associated with managing stormwater runoff from private land, which occupies most of the city area. The CWA requires a National Pollutant Discharge Elimination System (NPDES) permit for a discharge of pollutants by a person from a point source into navigable waters. Since municipal separate storm sewer systems (MS4s) are point sources, it is mandatory for a city to obtain NPDES permit for a MS4. Unfortunately, the cities cannot enforce the permits on private parcels, which are major sources of MS4 discharges, since the statutory definition does not consider stormwater as a pollutant and land parcels as point sources. Thus, the CWA for a city is a liability, not a tool to manage stormwater. In other words, the statute gives cities responsibility but not authority to control stormwater from a private property. City governments also cannot enforce other regulatory measures to install green infrastructure because of the exclusive constitutional right given to private property owners. The Fifth Amendment prohibits both physical and regulatory taking of private property for public purpose "without just compensation." But the constitution, as Ruhl et al. (2007) observe, does not further define what it means by "just compensation". Additionally, the Fourteenth Amendment guarantees "due process" and prohibits government control of private property without legislative authorization, which as such is a very complex process. Therefore, implementing green infrastructure on private land by the conventional centralized governance through a command-and-control approach is very challenging.

Pro Gray Mindset

Social mindset favoring gray infrastructure is another obstacle for the governance to implement green infrastructure on private lands (Brown and Farrelly 2009a; Niemczynowicz 1999; Wilkinson et al. 2013). The long-established practice of gray infrastructure has made people accustomed to unrestrained access to city maintained gray systems to discharge runoff from their property without paying the direct costs. Due to this, green infrastructure appears costlier, hence noncompetitive, to the residents, even when they would result in lower costs in the long run (Goddard 2012). This may encourage landowners to oppose implementation of green infrastructure on their land. Consequently, policies and programs supporting green infrastructure on private parcels are likely to lose political support, because politicians, in general, do not want to put their political career at risk by supporting the policies opposed by their voters.

Mismatch of Political and Hydrologic Boundary

Jurisdictional boundaries of political entities, such as cities, counties, and residential districts, rarely match with those of hydrologic units. This mismatch results in fragmented governance of a single hydrologic unit such as a watershed. Though this incompatibility does not limit any governance entity from implementing source control measures within its jurisdiction, it inhibits the implementation of the measures across the whole hydrologic unit and integrate them to function as an integrated system, unless all the governance entities within the hydrologic boundry coordinate to formulate consistent policies and collaborate to implement them. This also results in piece-meal decision making by different intities of governance Since, more often than not, different governing entities have conflicting visions, priorities, and goals (Keeley et al. 2013), formulating consistent policies and implementing them is politically and socially complex.

Need for a Regime Change

Governance is not a static concept (Grigg 2011). For effective functioning, it needs to be continuously updated to incorporate growing scientific knowledge as well as changing socio-technical context. However, stormwater governance has essentially remained unchanged since the inception and spread of gray infrastructures in the19th and 20th century, despite significant changes in technology, public perception, and other contexts. A change in governance regime is, therefore, required to address the problems inherent in the current governance discussed earlier, as well as to incorporate the changes discussed below.

Shift in Perceptions and Attitudes

In recent decades, there has been a fundamental shift in the way stormwater is perceived. It is now regarded as a freshwater resource (Cettner 2012; Karvonen 2011; Marsalek et al. 2007; Novotny et al. 2010) rather than a nuisance (Marsalek et al. 2007; Wong and Eadie 2000). Understanding of the importance of ecological health for urban livability has also increased significantly (Wilkinson et al. 2013). Cities are designing and implementing strategies for hydrological restoration of urban watersheds. Adoption of ecological principles for urban design is on the rise (Hill 2007; Wu 2014) leading to the emerging sustainability paradigm of urban development (Novotny and Brown 2007; Wu 2014), which sets maintaining or mimicking hydrological integrity of landscapes as a central theme.

Technological Innovation

The changed perception and attitudes founded on the increased understanding of ecological value of stormwater has resulted in the innovation of green technology, which is fundamentally different from gray technology in many aspects including objectives, materials, design, construction, and maintenance. Gray is largely an artificial method requiring highly skilled engineers to govern, whereas green is largely a natural approach involving soil and vegetation, and requiring collaboration among experts from multiple disciplines including hydrologists, soil scientists, plant biologists, and landscape designers. Since the two approaches are substantially different and the old governance cannot address many aspects of the new approach, as illustrated in the previous sections, a new governance approach is warranted.

Evolving Goals and Objectives

Historically, the only objective of stormwater management was to control flood by draining stormwater through hydraulically efficient conveyance systems (Grigg 2013; Novotny et al. 2010; Wong and Eadie 2000). The engineers were concerned only with technical performance and economic efficiency (Delleur 2003). Now, stormwater management has become a highly integrated (Fletcher et al. 2014) and multi-objective (Fletcher et al. 2014; Grigg 2013; Wong and Eadie 2000) undertaking that includes flood control, water quality control, visual amenity, recreational value, and ecological protection (Zhou 2014). The other objectives include restoration of infiltration in the urban landscape, recharge of groundwater, and maintenance of more natural flow regimes in the receiving water bodies (Fletcher et al. 2014; Walsh et al. 2012). To achieve these multiple objectives, a governance approach with wider scope is required.

Altered Management Hierarchy

Traditional approach to stormwater management relies on collecting stormwater from individual parcels to central system that conveys and discharges into receiving waters. Most of the components of gray infrastructure are in the public domain under city control. Accordingly, management responsibility is on the city government. Conversely, in the new approach, management tendency is to promote flow distribution instead of collecting it, and the system components has to be installed on the private properties as well. Thus, the management reverses from central collection to distribution. For landowners, the out-of-sight ought-of-mind undertaking in the old approach now becomes a responsibility, requiring their involvement in decision making as well as implementation.

Change in Actors of Governance

In traditional approach, a designated city agency is the only actor of governance. Since green approach requires on-site management, it shifts some of the governing responsibilities from government to the private landowners (Novotny et al. 2010), who generate stormwater by changing their land features. Thus, actors of governance are expanded from a government agency to multiple stakeholders including landowners, business owners, community organizations, other city agencies, and outside government agencies. This alters the decision-making structure of governance. Instead of dominantly discretionary decision-making by city engineers who design and maintain a gray approach, a green approach requires harmony among decisions of all stakeholders involved in the process including landowners (Ellis et al. 2010).

Are the Frontrunner Cities on the Right Path?

Stormwater Governance in Five U.S. Cities

Recently, some U.S. cities have been implementing green infrastructure with encouraging results (Chen et al. 2013; Foster et al. 2011; Novotny et al. 2010; U.S. EPA 2010). Among those, governance of five cities (Portland, Oregon (OR); Seattle, Washington (WA); Philadelphia, Pennsylvania (PA); Chicago, Illinois (IL); and Syracuse, New York (NY)) were studied to explore changes, if any, adopted to implement green infrastructure. A recent study (Chen et al. 2013) shows that these cities are among the leader cities in the U.S. for implementing green infrastructure. They are adopting strategies including incentives for private party involvement, dedicated funding, long-term green infrastructure plans, and stormwater retention standards.

To analyze the stormwater governance, the city functions that have major impacts on hydrology were grouped into following five categories: 1) city planning; 2) development control; 3) water, wastewater, and stormwater management; 4) roads and streets; and 5) parks and open spaces. The functional jurisdictions of city agencies were then analyzed based on these categories. City codes were studied to identify the governance structures and functional jurisdictions of the respective agencies. In cases where the city codes did not provide sufficient information, other sources, such as official web sites and reports, were used. The findings are summarized in Table 6.1.

Seattle, Wasington

In Seattle, planning, zoning and development control responsibilities are assigned to the Department of Planning and Development (DPD) (Seattle Municipal Code 2014, 3). The Seattle Public Utilities (SPU) is responsible for the management of stormwater, water, solid waste, and wastewater. SPU and DPD share the inspection and response responsibilities. All activities in the city right-of-way are the responsibility of the Seattle Department of Transportation (SDOT). The Department of Parks and Recreation implements stormwater codes in its jurisdiction. King County is responsible for wastewater treatment (Seattle Public Utilities 2014). The city also participates in regional programs, such as the Stormwater Outreach for Regional Municipalities (STORM) and the Puget Sound Start Here (PSSH) regional campaigns. The SPU is a member of Water Supply Forum, a regional organization of public water systems and local governments from King, Pierce, and Snohomish counties (Seattle Public Utilities 2014). The SPU engages the public through community advisory councils and green infrastructure partnerships. It conducts academic programs in schools for K–12 youths, and organizes annual watershed forums and public tours for community people. For community participation for cleanup, the SPU also sponsors programs such as 'Adopt-a-Street' and 'Adopt-a-Drain.'

Table 6.1. City Functions Affecting Stormwater and Responsible City Agencies

City Functions	Cities and Their Responsible Agencies				
	Seattle	Portland	Philadelphia	Chicago	Syracuse
City planning	Department of Planning and Development	Bureau of Planning and Sustainability	City Planning Commission	Department of Planning and Development	City Planning Commission
Development control	Department of Planning and Development	Bureau of Development Services	License and Inspection	Department of Planning and Development, Department of Building	Department of Neighborhood and Business Development
Water (w) wastewater (ww) and stormwater (sw)	Seattle Public Utilities: w, ww, sw King County: ww treatment	Water Bureau:w, Bureau of Environmental Services: ww, sw	Philadelphia Water Department	Department of Water, Department of Building	Department of Water: w, Department of Public Works, Department of Engineering
Road/ street	Seattle Department of Transportation	Bureau of Transportation	Department of Streets: Projects in right–of–way	Department of Streets and Sanitation: sanitation and median planting, Department of Transportation: road construction	Department of Engineering : street grades, Department of Public Works: plan & design of streets
Park and recreation	Department of Parks and Recreation	Bureau of Parks	Department of Parks and Recreation	Chicago Park District	Department of Parks, Recreation and Youth
Others	Office of Sustainability	Office of Neighborhood Involvement	Mayor′s Office of Transportation and Utility	Sustainability Council (chaired by mayor)	Department of Community Development

Portland, Oregon

In Portland, the Bureau of Planning and Sustainability (BPS) develops, modifies, and updates comprehensives plans and land use plans (the City Code of Portland 2014, 3). The BPS establishes and updates sustainability principles, climate change mitigation/adaptation practices, and other sustainability policies. The Bureau of Development Services (BDS) implements and enforces planning, zoning, and building regulations, and controls construction and land modification activities. The Bureau of Environmental Services (BES) is the lead agency for sewage and stormwater collection and treatment. The water supply system is under the Portland Water Bureau (PWB). The Bureau of Parks is responsible for the construction and maintenance of parks and golf courses. For public participation, the BES conducts watershed-specific as well as citywide public activities including Clean Rivers Education programs for K–12 students, community stewardship programs, and community activities. The BES also participates in the Regional Coalition for Clean Rivers and Streams. It collaborates with the Port of Portland, which manages stormwater in approximately 5,500 acres within the citys urban service boundary. It also works with neighborhood associations, stream side property owners, and Army Corps of Engineers. For public participation, the city has instituted the Development Review Advisory Committee, which consists of representatives from 17 stakeholders such as communities, professionals, and business organizations. The committee provides public inputs into the development review process.

Philadelphia, Pennsylvania

In Philadelphia, the City Planning Commission (CPC) prepares the physical development plan and zoning code, which is implemented by the Department of License and Inspection (DLI) (Philadelphia Code 2014, 5). The Philadelphia Water Department (PWD) is responsible for water supply, stormwater management, and wastewater management services that include wastewater treatment. Construction and maintenance in streets and right-of-ways are under the jurisdiction of the Department of Streets (DOS). Facility construction and maintenance in parks fall under the responsibility of the Department of Parks and Recreation. The PWD encourages stakeholder involvement through programs such as education, outreach, and clean-up. It collects public inputs on goal setting, and mobilizes the community to identify vacant land appropriate for green infrastructure installation (Philadelphia Water Department 2014). The PWD collaborates with outside government agencies for shared jurisdictions. For example, the city collaborated with Delaware, Montgomery, and Chestar counties for Darby-Cobbs Creek in 2004 (Philadelphia Water Department 2014). The city is working with the U.S. EPA to use the city as a “learning laboratory” for green infrastructure (Chen et al. 2013).

Chicago, Illinois

The Department of Planning and Development (DPD) is responsible for city planning and land use policies and regulations in Chicago (Chicago Municipal Code 2014, 2). The Department of Building regulates construction activities, and approves and enforces the stormwater management plan for development projects. Stormwater and wastewater management are shared between the Department of Water Management (DWM) and the Metropoltan Water Reclamation District (MWRD), which is a state agency. The DWM collects the stomwater and wastewater through its combined sewer system and routes to the MWRD′s interceptor sewers, after which the flow comes under the responsibility of MWRD for storage, treatment, and discharge. The Department of Streets and Sanitation (DSS) performs cleaning and sanitation works for public ways. It is also responsible for planting trees on parkways and medians. The Chicago Department of Transportation (CDOT) is responsible for the construction works on local transportation projects, and controls activties on the right-of-way and public sidewalks. It also supervises the dredging, deepening, and widening of waterways. All the parks and open spaces are the responsibility of the Chicago Parks District (CPD). The DWM coordinates with city departments and agencies to integrate green infrastructures into City projects. For example, in coordination with MWRD, Chicago Public Schools (CPS), and CDOT, the DWM identified 39 green projects for 2014. It also involves community non-profit organizations including the Metropolitan Planning Council, Chicago Wilderness, Space to Grow, and the Center for Neighborhood Technology.

Syracuse, New York

In Syracuse, the City Planning Commission (CPC) prepares and maintains a comprehensive development plan for the city including all lands located within three miles of the citys jurisdictional boundary (the Charter of the City of Syracuse-1960, 2014, §5). The CPC also prepares a zoning plan subject to the City Councils adoption. The Department of Neighborhood and Business Development (NBD) formulates and approves building code of the city. The NBD also coordinates neighborhood development activities. The Engineering Department (ED) performs engineering and survey services for the construction activities. The Department of Public Works (DPW) is the lead department for collection, treatment, and disposal of wastewater and stormwater. It is also responsible for the construction, repair, and cleaning of city streets and bridges. The Department of Parks and Recreation (DPR) constructs facilities in the citys parks. The CPC works in collaboration with other outside agencies, such as Syracuse-Onondaga County Planning Agency, which comprises representatives from both the CPC and the County Planning Agency. The CPC coordinates all the planning activities affecting the County and the City.

Summary of the Findings

The study of the five cities elucidated the following facts:

- Each city in this study has a dedicated centralized agency (utility, department, or bureau) designated to function as the lead agency for stormwater management. The agency governs stormwater predominantly through a command-and-control approach. Therefore, the overall governance is dominantly centralized and technocratic.

- The major functions, such as city planning, zoning, development control, and construction and maintenance works in parks and right-of-ways, that have major impacts on landscape hydrology and stormwater management are not under the jurisdiction of the lead stormwater management agency. This leads to fragmented governance, which are prone to conflicting policies and programs.

- Some cities share stormwater management responsibilities with other government agencies (e.g., county or state agencies). Examples include Chicago and Seattle, where the city bears the responsibility of the collection system but not the treatment work. The treatment work is the responsibility of MWRD in Chicago, and Metropolitan King County in Seattle. The agencies sharing such responsibilities have been working in collaboration to accomplish their designated task.

- The problem of incongruence between political and hydrological boundary remains unaddressed. Though cities collaborate with other local governments in shared regional watersheds (e.g., Seattle participates in STORM and PSSH), the collaboration is voluntary, which lacks decision-making and enforcement authority.

- As required by Stormwater Phase II Rule, cities encourage public participation in stormwater management activities through programs such as education, outreach, and cleanup campaigns. They also solicit public comments on major public projects and policy formulation. However, since incorporating public suggestions in the final decision-making is at the discretion of the agency leadership, it is likely that public suggestions are not implemented. This may discourage the public to participate.

- There is no formal community-level governance mechanism to involve individual landowners and other local stakeholders (e.g., community organizations, neighborhood groups, and business organizations) in the development of policies, programs, and management needed to implement green infrastructure. Existing subdivisions, such as residential districts and wards (e.g., Chicago), neither have any such mechanisms and responsibilities nor are they delineated by their hydrological boundaries.

- The city agencies have taken initiatives to motivate their staff to implement green infrastructure through approaches such as training, enactment of new regulations, and adoption of new manuals. These initiatives are important to shift mindset of agency staff as well as developers.

- Currently, green infrastructure implementation is predominantly limited to public land. However, it is estimated that 65–75 percent of land is private residential property (Rodrigue 2013), where cities cannot enforce the programs due to constitutional protection of private property from uncompensated governmental takings. Many incentives (e.g., fee discount, development incentives, rebates and installation financing) and other programs (e.g., education, outreach, and cleanup) offered to private landowners have produced encouraging results. However, they have not been sufficient to make green infrastructure a common practice on private parcels.

The findings reveal that though initiatives taken by the cities have shown positive results, the general problems associated with governance discussed earlier remain in place preventing the mainstreaming of green infrastructure.

The Road Ahead: Two-tier Model of Stormwater Governance

Designing a new governance approach is a critically challenging task. In the governance literature, three governance approaches are commonly identified: hierarchical, market, and network (Van de Meene et al. 2011). As a legacy of the past, we have a hierarchical approach, which is not appropriate for green infrastructure implementation because of multiple barriers outlined previously. Since the stormwater programs need to be in compliance with federal, state, and city standards, some degree of hierarchical oversight is, however, required. Markets for stormwater can be established by distributing allowances of runoff or impervious area to each landowner within a hydrologic boundary and permitting those allowances to transfer through a free trade. However, as stormwater is largely a local issue having small market only within a hydrological boundary, it is likely that it cannot be governed totally by market alone. Yet some degree of market is desirable among local landowners (Parikh et al. 2005). The market can greatly increase if price tag can be put on other ecosystem services (e.g., air purification, community aesthetic, and carbon sequestration) as well.

Network governance emerges from a wide range of self-organized stakeholders (Kjaer 2004; Lemos and Agrawal 2006; Provan and Kenis 2007; Van de Meene et al. 2011). Since it stimulates colaborative actions among stakeholders (Rijke et al. 2013), it is viewed as a favorable approach to govern multi-stakeholder systems (Provan and Kenis 2007) such as stormwater. However, some governmental oversight is required, otherwise the self-organized network may tend to function without regard to government policies and regulatory compliance and subsequently risk accountability as noted by Kjaer (2004).

Hence, any one of the three approaches cannot sufficiently address governance issues alone. As such, a hybrid model that utilizes some attributes of each of the three approaches is required to better address the governance needs (Lemos and Agrawal 2006). Therefore, a two-tiered hybrid model consisting of a local hydrological district and a city level agency is proposed (figure 6.1).

A Local hydrological district, similar to school and fire districts, would serve as a neighborhood-level mechanism to involve landowners and other stakeholders within its jurisdiction determined by hydrological boundary. The jurisdiction of such a district

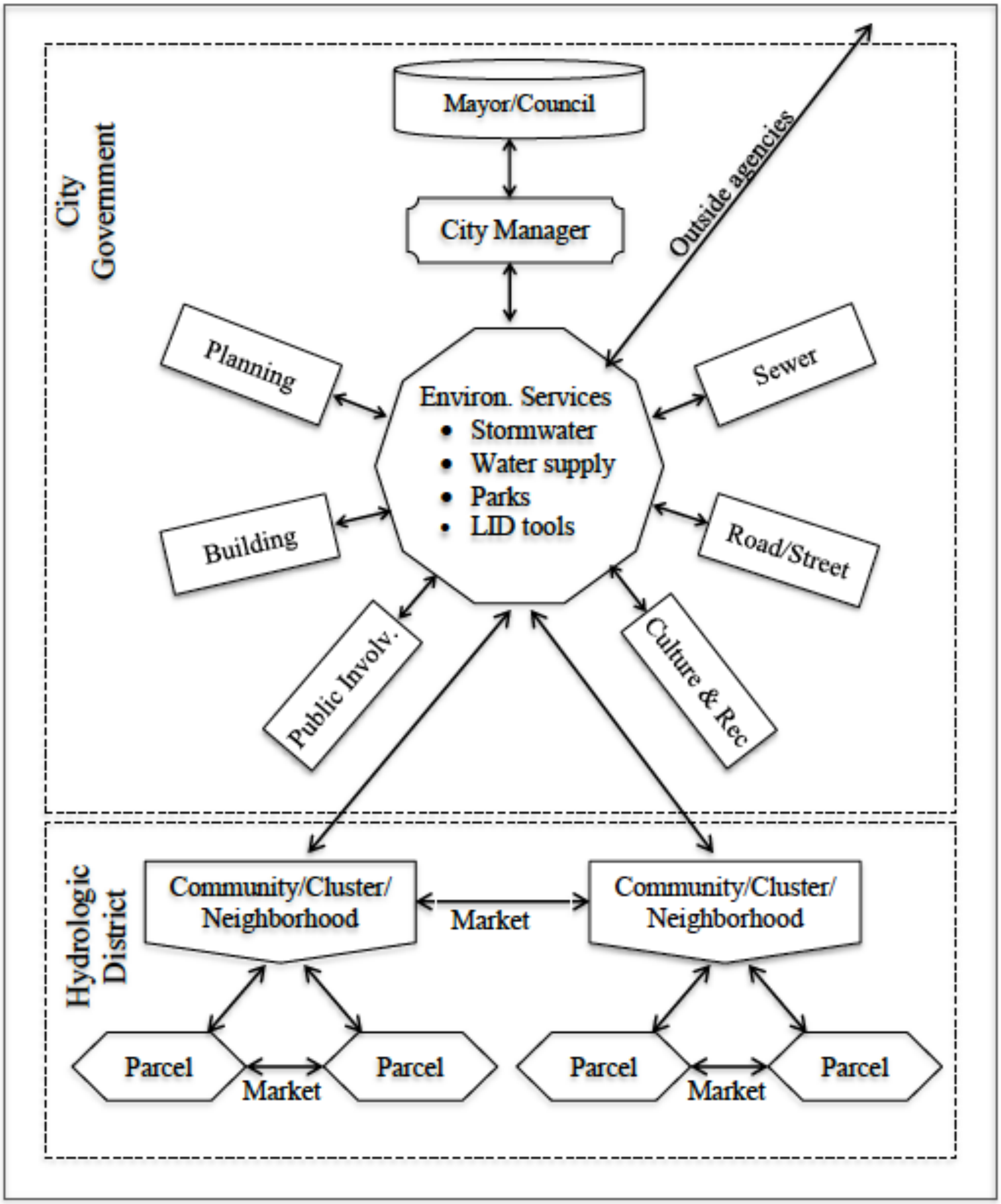

Figure 6.1. Two-tier Model of Urban Stormwater Governance

would encompass all local land features, under public property regime, that can be utilized for stormwater management. Examples include community parks, open spaces, ponds, and road side rain gardens. The governing body would have democratically elected representatives from all the stakeholders who own land or businesses within its jurisdiction. The body would coordinate planning and implementation with individual landowners, other local stakeholders, and city government. Since its jurisdictional boundary would be defined by the local hydrological boundary, the hydrologic district would help address the problem of mismatch between political and hydrological boundaries.

It should be noted that several neighborhood-level governances (e.g., Homeowners′ Associations and Neighborhood Associations) are successfully conducting many governance functions across U.S. cities (Chaskin and Greenberg 2013). Though they may not necessarily fit the proposed hydrologic districts defined by hydrologic boundaries to govern stormwater, their successful functioning shows that hydrological districts would be viable. The viability of such governance is further justified from the fact that thousands of other districts, whose intended goal lies in the domain of environmental protection and enhancement, such as soil conservation, resource conservation, and flood control districts, are currently working across the U.S. under different government agencies. Scholars have also suggested similar mechanism, called ecosystem services district, at local level to govern natural resources (Heal et al. 2001; Lant et al. 2008). These districts could be rearranged under the hydrologic districts to bring governance of all interdependent activities of environmental domain under the same umbrella.

Based on the city, state, and federal requirements, the proposed city level agency would enforce standards and monitor the performance of the hydrologic districts. Since management of stormwater requires sufficient knowledge of quality as well as quantity control, the city agency would also provide resources including technical expertise, training, and outreach materials to all its hydrological units. This would minimize the transaction cost for the hydrological districts. Since most cities have already been funding stormwater management, resources to local hydrologic districts would require minimal additional cost. The savings from the avoided cost of gray infrastructure related works would provide the balance.

The city would determine the required level of stormwater control needed for each hydrologic district based on modeled pre-development hydrology. Each hydrological district would then distribute the stormwater control responsibility to its landowners in commensurate with the lands stormwater generation potential determined by an independent third party engineering consultant using hydrologic modeling. If a landowner can control more stormwater than the required quantity, the landowner would be allowed to sell that additional quantity in the form of tradable credits to any other landowner, within the hydrologic district, who cannot control stormwater from his land to the required level due to cost or space reasons. Thus, a market can be created among the landowners within the jurisdiction of a hydrologic district. The potential benefits from the allowance trading would provide incentive for a landowner to pay for the third party to evaluate the stormwater generation potential of his/her land and install green measures. Hydrologic district would also function as a clearing house to facilitate the trading of stormwater credits within its jurisdiction. Similar markets can also be established in the similar fashion among hydrologic districts within the regional watershed.

At the city level, an agency, potentially named the Department of Environmental Services, would govern stormwater, water supply, parks, open spaces, and LID tools. It would also provide leadership to the hydrologic districts within the city and coordinate with other city and outside agencies. Based on the city, state and federal requirements, the agency would enforce standards on and monitor the performance of the hydrological districts. Since cities have already established separate agencies, such as utilities, bureaus, or departments, to govern the five functions that have direct or indirect impact on stormwater, some of the functions would need to be re-arranged. For example, each city has a dedicated department for parks and recreation except in Chicago where recreation is not under the jurisdiction of the Chicago Park District. Since parks and open spaces can be instrumental in stormwater management, the proposed model would bring them under the Department of Environmental Services, which would be responsible for managing stormwater as well as controlling activities, across the city jurisdiction, that impact hydrology. As such, the Environmental Services would prepare and adopt the hydrological map of the urban jurisdiction. The recreational and cultural activities would be grouped into a separate agency named Culture and Recreation Department.

Since gray and green differ in nature and functioning as well as the expertise required, a separated department (Department of Sewer) is proposed for governing gray infrastructures. The Department of Sewer would be responsible for sanitary sewers, combined sewers, large size storm sewers (e.g., collectors), and wastewater treatment plants. Small storm sewers would be under the jurisdiction of hydrologic district. The collaboration between the Environmental Services and the Planning Department would be redefined to match planning and land use zoning with the hydrological map. The Department of Building, which controls the construction of building and associated infrastructures (e.g., driveways and parking lots), would work in collaboration with the Environmental Services to regulate any addition of impervious areas. Similarly, the Street Department would work with the Environmental Services for road alignment, grading, and management of stormwater runoff within the right-of-way. If managing runoff within right-of-way using green infrastructure is technically infeasible, the excess runoff would be routed to a green infrastructure beyond its right-of-way operated by hydrologic district or a private owner through allowance market. If managing stormwater using green infrastructure within hydrologic district is infeasible, the runoff would be conveyed through storm sewer maintained by the hydrologic district to the collector sewer maintained by the Department of Sewer for a fee.

The Environmental Services would function as a focal agency to establish horizontal (e.g., with other city departments, environmental advocacy groups, and civic organizations) and vertical (e.g., with hydrologic districts, and upper management in the city, state and federal agencies) coordination to perform its stormwater management functions. Since each hydrologic unit is defined according to the hydrologic characteristics, an umbrella organization that integrates all the hydrologic units can be instituted at the watershed scale. This can assure the implementation of watershed scale measures subsequently reducing fragmented governance.

The governance problems discussed in this paper also prevail in cities of other developed countries, such as Australia (Brown 2005; Brown and Farrelly 2009b; Roy et al. 2008). A comparative study of urban stormwater management in the U.S. and Australia by Roy et al. (2008) identified problems including fragmented responsibilities, lack of institutional capacity, lack of legislative mandate, lack of market incentives, and resistance to change as major barriers not only in U.S. cities but also in Australian cities. This supports the rationale for the use of the proposed model in cities of the developed countries other than the U.S.

In developing countries, cities suffer from a lack of financial resources and technical expertise than cities in developed countries. Since green infrastructure is less demanding than gray from both the technical and cost perspectives, it would be more suitable in those cities. With the establishment of a city agency as a facilitator, the proposed model would be appealing. Successfully functioning neighborhood organizations (called Tol Sudhar Samiti in Nepali language) in the City of Butwal in Nepal reveal not only viability but also necessity of such governance model in developing countries. For years, hundreds of such organizations have been working citywide as neighborhood stewards. Currently, the city provides guidance; and each household pays a flat monthly fee and provides at least one volunteer for three hours on the first Saturday of every month for activities such as neighborhood cleanup (S. Gyawali, vice president of Indreni Tol Sudhar Samiti, telephone interview, August 23, 2015). According to Gyawali, the household which cannot send a volunteer, pays a fine. If neighborhood groups are rearranged according to hydrological boundaries, and the city provides knowledge, guidance, and technical support, these organizations would be able to work as the hydrologic districts of the kind proposed in the two-tier model.

Due to the nature of many benefits GI provides to the society, and since the implementation of GI requires extensive community involvement, governing GI can be considered as governing commons. The necessity and viability of the the proposed governance model is in line with Ostrome′s design principles for governing commons (Ostrom 1999). In fact, the proposed governance and the design principles are complementary to each other. For example, Ostrom's principles require to define clear group boundaries, which will be hydrological boundary proposed for hydrological districts. The rules to be formulated for hydrologic districts will be formulated by the local stakeholders based on local needs which will fulfil Ostrom′ another principle. The proposed hydrologic district governance will be formed by the community people which are directly affected. This will ensure Ostrom′ third principle. The hydrologic district will also help fulfil Ostrom′s other principles, such as providing opportunity for community members to guarantee their rule making rights, monitoring members behavior, using sanctions for rule violators, and resolving dispute among the members cost-effectively. The two-tier model along with the regional level watershed governance proposed in the dissertation will provide a frame work for Ostrom′s "nested tiers" for building "responsibility from the lowest up to the entire inconnected system."

Conclusion

This chapter has three main areas of focus. First, it has identified the problems inherent in traditional stormwater governance that prevent wide scale adoption of green infrastructure. Second, it has examined the stormwater governance of five U.S. cities, which have been implementing green infrastructure for some years, to see how they are addressing the governance problems. Finally, the paper proposes a new governance model to address the problems.

Traditional urban stormwater governance was adopted to govern highly engineered and centralized gray infrastructure. As such, the approach is highly technocratic and centralized, which functions through enforcement of government regulations. In contrast, green infrastructure uses natural processes and is distributed throughout the landscape. It involves a wide range of stakeholders in the governance process, including individual parcel owner, business organizations, social organizations, and government agencies, since the generation of stormwater is characterized by the hydrological processes in the landscape controlled by their activities. Therefore, the governance needs to be highly collaborative and coordinated between them. The existing discord between political and hydrological boundaries needs to be addressed to restore and enhance the watershed health. In addition, the existing fragmentations of governance within a watershed, due to presence of multiple authorities with multiple (sometimes conflicting) visions and goals, have created significant problems. This also needs to be addressed.

The survey of the cities revealed that the current practice of public involvement in cities is merely limited to participation in education, outreach, and cleanup programs. In cases when public comment is requested by government or regulatory agencies, as required by Stormwater Phase II Rule, the decision authority is, however, not required to implement these comments. The coordination is also limited within government agencies. The collaboration with stormwater generators and other local stakeholders out of the government office is lacking.

The proposed two tier model can address the problems existing in the traditional stormwater governance. The local hydrologic district is a neighborhood level body with the hydrological boundary as its jurisdictional boundary. The governing body would consist of representatives from land owners, community, civic-organizations, environmental organizations, and businesses. The city agency would enforce regulatory standards and provide technical expertise, administrative support, and other resources to the hydrologic district. The agency would function as an umbrella organization at the city level, integrating the functions of all the hydrologic districts. The hydrologic district would also work as a local ecosystem services district. In addition, markets for stormwater trading can be established among parcels within a hydrologic district as well as among hydrologic districts within a regional watershed.

The proposed model would provide opportunity for distributed governance, ensure public involvement, and foster collaboration among stakeholders. This would also help revive the decline in civic institutions outlined in Emerson et al. (2012). Since the decision authority would be solely on the hydrologic district, integration of these hydrologic districts at watershed level would minimize the fragmented governance. However, additional research is needed to identify methods for appropriate and effective integration. Additional research is also required to define the authority, logistics, and the procedures of formation of the governing body, which may be unique to each city. If for no other reasons, the hydrologic conditions are location-specific, case specific research is needed to define the spatial scale of the hydrologic district. With minor adjustments to incorporate a citys socio-political context, the model could be used globally, in developed as well as developing countries.

CHAPTER 7
OVERALL CONCLUSION

Summary

In addition to being a sustainable approach of stormwater management, green infrastructure offers numerous other ancillary benefits that are crucial for urban sustainability. However, the approach is yet to become a mainstream practice. To encourage cities for implementing it, there is a critical need to overcome two primary challenges. First, urban stormwater managers and decision makers should be ensured that the approach can adequately and reliably manage stormwater. In the time when cities are facing increasing flooding problems due to climate change, this concern has become increasingly prominent. Second, if there exist any barriers that discourage the implementation of GI, the barriers should be removed and strategies that can expedite the use of GI should be adopted. This multidisciplinary research dealt with these challenges.

Specifically, the study focused on four central questions: What will be the performance of a current drainage system when subjected to increased precipitations due to climate change? What will be the performance if GI is applied? What barriers are preventing the application of GI as a common practice? And what socio-institutional arrangement can remove the barriers and expedite the implementation of GI?

For the first two questions, I conducted a case study on an existing 169.23-hectare combined sewer system of St Louis, a U.S. city located in the state of Missouri. To evaluate the impact of climate change, the system was modeled using U.S. EPA′s SWMM hydrologic-hydraulic model and was simulated for historical (1971-2000) and future (2041-2070) 50-yr 3-hr storms. The observed historical precipitation data was obtained from NOAA and the future data was calculated by using a delta change factor. The delta change factor was obtained from historical and modeled future 30-year data produced by GCMs and obtained from NARCCAP. Finally, the simulation for the past and future rainfall scenarios were compared to quantify the impact. The results showed significant impacts on the performance of the system. For example, total number of nodes flooded increased by up to 14.28% and CSO volume increased by up to 78%. The details of this investigation are presented in Chapter 3 of this dissertation.

To assess the efficacy of GI to address the climate change impact, four GI measures, including bio-retention cells, permeable pavements, green roofs, and rain barrels, were added to the subcatchments of SWMM model, and the model was run for the future 30-yr 3-hr rainfall data. The results showed that addition of GI significantly reduced the impact of the increased rainfall. For example, the increase in the number of flooded nodes was decreased by 57.14% and the increase in the CSO volume was decreased by 39.62%. Details of the research on the performance of GI is presented in chapter 4.

To address the third and the fourth research problems, I critically examined the available literature on the relevant areas. The study was focused on the U.S. context, for which I reviewed peer reviewed journal articles, books, U.S. constitution, U.S. laws and regulations, court decisions, and U.S. EPA case study reports related to the issues. In addition, I examined ordinances, codes, manuals, and standards of 11 U.S. cities including Seattle, Washington; Portland, Oregon; Chicago, Illinois; Philadelphia, Pennsylvania; Syracuse, New York; Dallas, Texas; Camden, New Jersey; Macatawa, Michigan; Neosho, Missouri; Phoenix, AZ; and Los Angeles, California. From the study, 29 barriers were identified which were grouped into the following five types: federal and state policy barriers, city policy barriers, governance barriers, resource barriers, and cognitive barriers. To address these barriers and encourage GI implementation, 33 policies were suggested which were also grouped into five corresponding categories including federal and state policies, city policies, alternative governance, innovative funding mechanism, and EAAR (education, awareness, awards and recognition). The fifth chapter of the dissertation has presented the details of this study.

A further investigation was done for exploring governance barriers as well as for finding a new governance framework. Through exploratory research of literature and by surveying current governance in five U.S. cities (Seattle, Portland, Chicago, Philadelphia, and Syracuse), we identified multiple barriers inherent in current governance that prevent adoption of GI. Major barriers identified included: centralized and technocratic approach, fragmented governance, lack of public involvement opportunities, lack of coordination, and lack of authority to control flow from private parcels. A two-tier new governance model was proposed to address the barriers. The research procedure and outcomes are presented in detail in chapter 6.

Conclusion

The research results indicated that the increase in precipitation due to climate change will have a significant impact on the system evaluated in the research. With increased precipitation, the system′s performance at both the conduits and nodes, considerably decreased, resulting in increased flooding and CSO volume. Thus, the system should be retrofitted to enable it to address the increased the precipitation. After the addition of various combinations four GI measures (bio-retention cells, permeable pavements, rain barrels, and green roofs) to the model, the impacts were significantly lowered. Since there is room for adding significantly more GI measures in the study area catchments, it can be deduced that if GI is added adequately and appropriately, the impacts of increased precipitation will be addressed fully.

The study also concluded that currently there exist numerous barriers that prevent implementation of GI. Most critical barriers are the current socio-institutional set-up and cognitive status quo, which inherently support conventional gray infrastructure. Other barriers, such as those related to resource, policy, and governance, are essentially the result of these two barriers.

Social acceptance is arguably the most decisive driver of a technology and an addresser of its impediments. Enhancing the knowledge of GI through education and awareness and the resulting removal of cognitive barriers can boost social acceptance. If social acceptance is high, formulating other pro-GI policies and programs at any level becomes easier. A high social acceptance also encourages courts and legislatures to make favorable policy decisions, which will result in the development of GI-friendly common and statutory laws. The enhanced social acceptance will also help update engineering standards to incorporate GI. Additionally, it can foster markets and help establish GI stewardship as a business that contributes to the generation of sustainable financing. In addition to social acceptance, the availability of expertise, skilled personnel, champions, and leaders are of vital importance for driving GI implementation. Therefore, I suggest adopting policies that focus on awareness, education, recognition, training, coordination and engagement.

Since GI involves a wide range of stakeholders, its governance needs to be highly collaborative, coordinating, and participatory. However, the current governance structured for gray infrastructure is highly technocratic and centralized, and functions through enforcement of government regulations. In addition, the unaligned political and hydrological boundaries have traditionally resulted in fragmented governances, which generally leads to inconsistent policies and actions. I concluded that the current governance is not suitable for GI, and proposed a two-tiered new governance approach. Through hydrologic districts and city level agencies, the proposed model can address the existing governance barriers. Since the hydrological districts will be structured according to local hydrological boundaries, and since the decision authority would be on the hydrologic districts, integration of these hydrologic districts at regional watershed level would minimize the fragmented governance. In addition, since the districts function at neighborhood level, they will provide better opportunity for public participation. They will also function as ecosystem services districts and establish stormwater trading among parcels within the hydrological district and among hydrological districts within the parent regional watershed. The city-level agency will establish coordination among hydrological districts as well as with city and/or other higher-level agencies.

Recommendations

This study gives rise to many potential agenda for future research. Particularly, I make the following recommendations.

- The SWMM model developed in this study is for a single rainfall event. The model can be enhanced for modeling continuous events to evaluate the performance of the system and assess the efficacy of GI measures for such events.

- A significant uncertainty exists in GCM/RCM outputs. However, with the increase in knowledge base and computational capacity, increasingly improved data are being available. Model should be updated with the updated future rainfall data for assessing the impact and adaptation more realistically.

- The climate change scenario analysis and assessment of GI performance conducted here is just a demonstration only for this dissertation. To get to a more realistic and applicable results, more analysis, involving more scenarios and more watersheds, is necessary. Similarly, efficiency of each GI option needs to be evaluated for each context and an optimal combination needs to be worked out. Further research is needed for these works.

- The selected GI measures applied in the SWMM model were based on my personal judgment, and were not optimized. A research is necessary to identify the most suitable GI measures and their best combinations to have optimal performance.

- Research also remains to be done to identify the most cost-effective combinations of GI options. Since cost plays a vital role in making implementation decisions, it is essential to find optimally cost-effective approaches.

- The study to explore barriers, policies, and governance structure was focused on some U.S. cities, though some case studies for some cities in Europe and Australia were also examined. However, due to the prevailing methods of infrastructure planning, the decreased availability of open spaces in traditional cities, and relatively low socio-economic development, the barriers and solutions in cities in developing countries may be somewhat different, which necessitates further research.

- A research is also needed to establish market among the parcels within a hydrologic district and among hydrologic districts within a regional watershed.

- The study indicated a need to create a pro-GI society in the future by teaching K–12 students about the concept, importance, and the reliability of GI through class work and demonstration projects. Further research is needed to design the scope, material, and modality of the teaching.

- Research is also necessary to design study materials and modality for university students as well as to design training materials and methods for current city staffs.

  Further research is also recommended for defining institutional structures, procedures of formation of the governing body, functional jurisdictions, authority, and resources for the proposed regional governance as well as the hydrologic district.

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VITA

Graduate School
Southern Illinois University

Krishna P. Dhakal

krishna.gogreen@gmail.com

Tribhuvan University
Bachelor of Science, Civil Engineering, November 1997

Western Michigan University
Master of Science in Civil Engineering, December 2010

Dissertation Title:

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