DEVELOPING AN INTEGRATED PLANNING-LEVEL APPROACH FOR OPTIMIZING GREEN TO GREY STORMWATER MANAGEMENT SOLUTIONS

by

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ABSTRACT

Urbanization is expected to persist in cities across the world, resulting in increased percent imperviousness, alterations to the hydrologic regime, degraded water quality, and deteriorated ecosystems. Stormwater Control Measures (SCMs) have been developed to mitigate some of the impacts of urban development, but come in a wide range of designs and have variable hydrologic performance based on their primary function. SCMs exist on a continuum that ranges from green (typically above ground infrastructure that includes vegetation) to grey (large storage facilities or underground distributed infrastructure). The decision-making process for an optimal stormwater management plan on a watershed-scale is complex and multi-faceted. Conflicting stakeholder interests need to be considered when determining the optimal suite of SCMs for a particular watershed. Hydrologic models, such as the EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) can be used to simulate water quantity and quality as well as evaluate the implementation of SCMs on a watershed-scale. Decision support tools can assist stakeholders and decision makers in optimizing between varying SCM types based on the needs and priorities of their specific watershed and communities. The research in this dissertation uses a hydrologic model and decision support tool and aims to improve stormwater modeling by 1) exploring the feasibility of meeting regulatory compliance with the implementation of SCMs, 2) investigating the performance and tradeoff of greener to greyer SCMs using optimizations, and 3) improving the decision-making process by incorporating life cycle costs and a benefit analysis with stormwater modeling.

A multi-watershed analysis conducted in Los Angeles County found that meeting water quality regulations when implementing SCMs on a watershed-scale is dependent on percent imperviousness and land use characteristics which impact baseline water quantity and quality. Despite routing runoff from 90% of the watershed to greener SCMs only three of the six simulated SCM solutions reached compliance in the Ballona Creek watershed and none were successful in the Dominguez Channel and Los Angeles River watersheds, highlighting the need for a more robust planning-level approach to determine the optimal stormwater management plan. The investigation of greener vs greyer SCMs in the Berkeley Lake neighborhood, (Denver, CO) found that all SCM types offer varying hydrologic benefits based on their design and function. For example, underground infiltration (greyer) and infiltration trenches (greener) are optimal for reducing average annual flow volume while underground detention (greyer) and vegetated swales (greener) are better at reducing pollutant average annual concentrations. Optimizing (maximizing a benefit and minimizing cost) between thousands of SCM solutions and rating benefits based on stakeholder preferences identified that while the primary goal of a watershed may initially put more weight on particular SCM types, the consideration of multiple benefits exposes which additional SCMs should be included in order to maximize the benefits of a watershed. A comparison between capital and life cycle costs (LCC) for SCM types identified two differences which significantly impact optimal solutions, cost magnitude and cost order. LCC were found to be millions to billions of dollars higher than capital costs and shifted the relative cost order of SCMs in a watershed (lowest to highest). Finally the use of varying management criteria, classified by hydrologic and vegetative benefits and specific to the respective watershed, determined that while a hybrid solution (green and grey SCMs) is optimal for more stakeholders in Ballona Creek watershed (Los Angeles, CA) a greener solution is optimal in the Berkeley neighborhood watershed (Denver, CO).

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I dedicate this dissertation to my two grandmothers. To my late grandmother, Marilynn C. Yates, one of the brightest and sharpest people I have met in life. It was she who first instilled a "if you don't know the answer, look it up" mentality in me by always telling me to look up the definition of a word in her monstrous dictionary she kept on a pedestal in her home. To my grandmother, Anita Gallo, for showing me how to uphold strength and a positive attitude throughout difficult times. So yes Grandma, I did indeed "get it from you", as you like to joke with people. I promise not to tell anyone, as I know you thoroughly enjoy that joke.

CHAPTER 1

INTRODUCTION

1.1 Background

1.1.1 Impacts of Urbanization on Stormwater

Urbanization is a phenomenon across the world. As cities experience population growth, the need for more infrastructure to accommodate rising populations results in densifying of the city and thus an increase in percent imperviousness (Brabec, Schulte, and Richards 2002; Espy, Morgan, and Masch 1966; Stankowski 1972). Alterations to the hydrologic regime of a watershed, due to an increase of imperviousness, include larger volumes of stormwater runoff and higher and flashier peak flows (Roesner, Bledsoe, and Brashear 2001; Booth and Bledsoe 2009; Shuster et al. 2005). Changes to stormwater runoff volumes of water has implications on ecosystems and human health, as well as the available water for anthropogenic uses. Changes in stream velocities can result in a change in vegetative cover due to erosion and alterations to water temperature and quality (Bhaskar et al. 2016; Klein 1979) which are detrimental to ecosystems. Larger volumes of water and higher peak flows may result in flooding of houses and underground infrastructure or contamination of groundwater (Bhaskar et al. 2016).

Urbanization has also been found to impact water quality in bodies of water (Lee et al. 2012). Increased imperviousness leads to elevated levels of pollutants washing off of the land surface and into receiving bodies of water (Booth and Bledsoe 2009; Arnold Jr. and Gibbons 1996; Tsihrintzis and Hamid 1997; Roesner, Bledsoe, and Brashear 2001). Nonpoint source water quality degradation in rivers and receiving water bodies is a major issue in urban systems (USEPA 2018a, 2018b). Urban pollutants such as heavy metals, nutrients, and TSS have reached levels that are detrimental to both society and the environment (USEPA 1999; Brabec, Schulte, and Richards 2002; Gaffield et al. 2003; Mandelker 1989; Stein and Ackerman 2007). Alterations to the hydrologic regime and the issue of nonpoint source pollution is expected to persist as population growth, and thus urbanization continues in the future (United Nations 2014).

1.1.2 Stormwater Control Measures

Storm water control measures (SCMs), also referred to as best management practices or low impact developments, have become the most widely accepted solution to manage stormwater due to their ability to mitigate the impacts of urbanization (NRC 2008; USEPA 1999; Liu et al. 2017; UDFCD 2010a; Bracmort et al. 2006). SCMs achieve varying hydrologic goals based on the function that which they are designed for. These goals include meeting water quality standards such as total maximum daily loads (TMDLs) (Bracmort et al. 2006; Barrett 2005; Koch et al. 2014; USEPA 1999), reducing peak flows (Roesner, Bledsoe, and Brashear 2001), groundwater infiltration (Sun et al. 2014; Roesner, Bledsoe, and Brashear 2001), and/or improved eco-hydrologic conditions (Karr and Dudley 1981). SCMs are often classified based on whether they are infiltration-based, designed to capture and retain stormwater until infiltrated, or treat-and-release-based which are designed to route stormwater through the infrastructure, actively treat pollutants, and release stormwater directly back into the storm drainage network (Roesner, Bledsoe, and Brashear 2001).

An alternative way to classify and compare varying SCM types is based on where they fall along the grey-to-green design continuum which is dependent on construction materials, drainage area, dominant hydrologic and water quality processes, costs, and benefits (Colin D Bell et al. 2019). SCMs that fall on the greyer side of the continuum include large centralized storm drainage systems, waste water treatment plants, or regional storage facilities. These large concrete structures, do not include vegetation, but serve large treatment areas, and are sometimes built in conjunction with treatment facilities (C. D Bell et al. 2019; District of Greater Chicago 2013; LADPH 2016; USEPA 2001). SCMs that fall on the greener side (i.e. bioretention or vegetated swales) of the continuum are typically designed as a smaller scale distributed systems that utilize vegetation and/or geo-media as part of the design (C. D Bell et al. 2019; UDFCD 2010b) . Green infrastructure is typically the focal point of stormwater management plans as they are encouraged by institutions such as the U.S. Environmental Protection agency (USEPA 1999). Distributed grey and hybrid SCMs fall between the greener and large grey SCMs and include above and underground storage systems designed to either retain and infiltrate into the subsurface or detain and slowly release stormwater back into the storm drainage network

(USEPA 2001; NYCDEP 2012; LADPH 2016; UDFCD 2010a). These SCMS are lesser known but are recently gaining popularity due to their potential benefits and improved flexible designs.

1.1.3 Decision-Making for Stormwater Management

The implementation of SCMs are increasingly being incorporated into city water resources planning, referred to as an integrated water management plan (IWMP), to integrate and manage urban water resources such as wastewater, groundwater, stormwater, and drinking water, in an effort to maximize the economic and social welfare of a city or state (Global Water Partnership Technical Advisory Committee 2000). However, there is rarely consensus over the best way to utilize water resources as the priorities of varying stakeholders differs. For example, some benefits of treat-and-release SCMs include sustained water levels for ecological habitat and recreation purposes while tradeoffs include less water allocated toward infiltration to the groundwater and regional aquifers. Similarly, greener SCMs are typically considered an integral component of stormwater management as they incorporate green space into the urban environment, however, green infrastructure also tends to increase property values which can lead to gentrification. A sustainable water management plan will attempt to distribute the benefits and costs equally across all varying stakeholder priorities.

Hydrologic modeling is a practice commonly used to assist in solving problems and making decisions about stormwater management, particularly given the complicated water quantity and quality issues of urban environments (Liu et al. 2017). While many studies have been conducted on greener SCM performance [for example Liu et al. (2017)], there is a paucity of studies that have modeled greyer or hybrid SCMs as there is a lack of information on water quantity and quality performance from these structures (Mcintosh et al. 2015; Smart 2020; Zawiliski and Sakson 2008; Jayanti and Narayanan 2004; Martino et al. 2011; Wang et al. 2004). Additionally, there exists uncertainty in how distributed SCMs (both green and grey), that are designed to capture a specific stormwater runoff volume from one site, will scale up and impact a watershed as an integrated system (Jefferson et al. 2017; Golden and Hoghooghi 2018).

1.1.4 Planning-level Hydrologic Modeling Approach

Stormwater modeling studies typically use SCM placement (Limbrunner et al. 2013; Hipp, Lejano, and Smith 2006; Perez-pedini, Limbrunner, and Vogel 2006), a single regulatory constraint (Baek et al. 2015; Yang, Fong, and Chui 2018; Jenq et al. 1983), or a site-scale analysis (Loáiciga et al. 2015; Mays and Bedient 1982; Sample et al. 2001) to facilitate choosing the best SCM type for a study area. However, for a stormwater management plan to be truly integrated with other water sectors or consider varying stakeholder priorities, the most effective SCMs need to be determined before site-scale or design-based modeling takes place. A planning-level analysis, or a strategic plan (Downs 2018), can help decision makers assess the needs of their watershed, set priorities, and determine the best pathway to achieve those priorities. In regards to stormwater management, this includes a watershed-scale, multi-SCM, and multi-benefit analysis over a wide range of solutions. Models that use optimizations, such as EPAs System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN), can be used to evaluate multiple SCM types and thousands of different solutions to analyze the performance and impacts of SCMs (Shoemaker et al. 2009). However, SUSTAIN currently only includes green SCMs and a limited selection of hydrologic processes to optimize, such as peak flow and pollutant reduction.

This dissertation research is part of the development of an integrated Decision Support Tool (i-DST) that includes both a watershed-scale and site-scale hydrologic model, life cycle cost and assessments, and benefits to explore the tradeoffs of green to grey stormwater infrastructure is being developed [See related published works (C. D Bell et al. 2019; K. M. Spahr et al. 2020; Grubert and Stokes-Draut 2020; Shojaeizadeh et al. 2019)]. The watershed-scale module utilizes a modified version of the EPA's SUSTAIN model (Shoemaker et al. 2009) called i-DST SUSTAIN. i-DST SUSTAIN builds on SUSTAIN by including four novel above and underground grey infrastructure (underground infiltration, underground detention, underground gravel bed, and above ground storage) and seven new evaluation factors for optimization (groundwater recharge potential, evapotranspiration, and seasonal flow volume, loads and concentration). This new type of model is needed in order to determine the optimal suite of grey to green SCMs for a particular watershed that will maximize benefits that are crucial to varying stakeholders working to develop an integrated water management plan.

1.1.5 Importance of Life Cycle Costs and Benefit Analyses

In addition to a planning-level watershed modeling approach, life cycle costs and a benefit analysis are also critical for a holistic integrated decision-making process on stormwater management. While some stormwater modeling studies attempt to include maintenance costs, many only use capital costs; however capital costs may be misrepresenting the full cost to both society and the environment. Life cycle costs (LCC) and life cycle assessments (LCA) are used to assess the performance of SCMs as well as evaluate the stream of benefits and costs over time (Grubert 2017; Mcauley and Knights 2015; Liao et al. 2014; Rebitzer, Hunkeler, and Jolliep 2003).

SCMs offer a wide variety of benefits beyond those that are strictly considered hydrologic (water quantity and quality) (Jaffe 2010; McGarity et al. 2015; C. D Bell et al. 2019; K. Spahr 2020). For example, health benefits are not directly related to the implementation of SCMs and cannot be quantified using a hydrologic model. Instead a planning-level assessment is needed to discuss the potential benefits such as improved air quality due to vegetation or increased recreation as a result of added green spaces. While these other benefits are not necessarily the driving motivation for stormwater managers and municipalities to manage stormwater, it has been found that community members care just as much about additional benefits as they do about flood management and water quality conditions (Cadavid and Ando 2013; K. Spahr 2020).

1.2 Research Objectives

This dissertation explores how hydrologic models can be used to make decisions about the optimal stormwater management plan for urbanized watersheds given the unique physical properties and stakeholder priorities. The following section summarizes the objectives of each chapter in this dissertation and the subsequent research questions and hypotheses used to explore those objectives.

1.2.1 Objective 1: Investigate Greener Stormwater Management Options on a Watershed-Scale Level

The research goal to address objective 1 of this dissertation is to investigate potential variability in achieving water quality compliance in adjacent watersheds and demonstrate how observed differences may impact the decision-making process when optimizing SCMs for a watershed.

Question 1.1: To what degree does percent imperviousness and land use type impact water quality degradation in a given watershed?

> ***Hypothesis 1.1*:** Water quality degradation will be the worst in watersheds that have both a higher percent imperviousness and a higher percent of land uses that are known to have elevated pollutant mean concentrations, such as industrial.

Question 1.2: At what level will SCMs need to be implemented throughout a watershed in order to eliminate heavy metal TMDL exceedances throughout Los Angeles County?

> ***Hypothesis 1.2*:** Routing stormwater runoff from the majority of a watershed to SCMs will be needed to achieve average annual load reduction goals. Elimination of TMDLs will be achievable in watersheds with lower percent imperviousness and a higher percent of vacant land uses while it will not be achievable in watersheds with a higher percent imperviousness and higher percent of industrial land uses.

Question 1.3: Are infiltration-based or treat-and-release-based SCMs more successful at eliminating TMDL exceedances?

> ***Hypothesis 1.3*:** Treat-and-release-based SCM solutions will outperform infiltration-based solutions in terms of eliminating TMDLs as they actively treat stormwater and release the cleaner diluted water back into the storm drainage network, resulting in overall better water quality at the outlet of the watershed which is also the location of established TMDLs.

Question 1.4: How does the primary hydrologic objective of achieving water quality compliance impact decision-making in a watershed?

> ***Hypothesis 1.4*:** Watersheds that successfully eliminate TMDL exceedances have more flexibility in deciding between treat-and-release vs infiltration-based SCM types thus allowing for consideration of other factors, such as capital cost or groundwater recharge potential, which will determine the optimal solution.

1.2.2 Objective 2: Evaluating Performance and Tradeoffs of Greener to Greyer Stormwater Infrastructure

The research goal to address objective 2 of this dissertation is to use stormwater modeling optimization and a planning-level approach to compare the relative hydrologic performance of green to grey SCMs and how varying stakeholder priorities can shift whether greener vs greyer SCMs solutions are considered optimal.

Question 2.1: How do greener vs greyer SCMs perform relatively in terms of hydrologic criteria when implemented on a watershed-scale?

> ***Hypothesis 2.1*****:** Underground infiltration (greyer) and infiltration trenches (greener) are optimal for reducing average annual flow volume. Underground detention (greyer) and vegetated swales (greener) are better at reducing pollutant average annual concentrations.

Question 2.2: What SCM types are optimal for maximizing reducing average annual flow volume and minimizing cost?

> ***Hypothesis 2.2*****:** Greener SCMs will be dominant in optimization solutions that both minimize capital cost and maximize average annual flow volume reduction.

Question 2.3: What impact does weighting hydrologic benefits based on City of Denver preferences or Denver Public preferences, have on the optimal SCM types?

> ***Hypothesis 2.3*****:** Vegetated swales and infiltration trenches will be optimal to meet the preferences of the City of Denver, as they are the lowest cost, perform relatively best at reducing average annual flows, and add green spaces. However, bioretention and underground detention are needed to meet the preferences of the Denver Public, prioritizing average annual concentration.

1.2.3 Objective 3: Incorporating Life Cycle Costs and Benefits with Stormwater Modeling

The research goal to address objective 3 includes using an integrated decision support tool to demonstrate the importance of utilizing life cycle costs and a benefit analysis that assess both hydrologic and vegetative benefits in conjunction with a planning-level hydrologic model. This was done by comparing results across two watersheds in different cities of the U.S. while exploring varying management criteria specific to those watersheds.

Question 3.1: To what extent do the differences in capital costs and life cycle costs impact the decision-making process?

> ***Hypothesis 3.1*****:** The differences between capital costs and LCC, cost magnitude and the cost order, will significantly impact optimal solutions.

Question 3.2: What impacts do watershed specific regulatory compliance have on the ratio of % runoff captured by greener vs greyer SCM type?

> ***Hypothesis 3.2*****:** Berkeley neighborhood watershed has a relatively less strict regulatory compliance goal than Ballona Creek (5% reduction in average annual flow volume vs 80% reduction in average annual load, respectively) and thus more diversity in viable stormwater solutions (up to 100% green and 100% grey) whereas viable solutions Ballona Creek will have to utilize both green and grey.

Question 3.3: How will varying management criteria impact whether the green, grey, or hybrid solution is the optimal solution in each watershed?

> ***Hypothesis 3.3*****:** Water quality and infiltration-based criteria will drive the optimal solution in Ballona Creek to be the hybrid solution. LCC, ET, and vegetation-based criteria will drive the optimal solution in Berkeley neighborhood watershed to be the greener solution.

CHAPTER 2

STORMWATER MANAGEMENT OPTIONS AND DECISION-MAKING IN URBANIZED WATERSHEDS OF LOS ANGELES, CALIFORNIA

Reproduced with permission[1] from ASCE and the *Journal of Sustainable Water in the Built Environment*[2]

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2.1 Abstract

Hydrologic modeling is a crucial tool to understand the physical and hydrologic characteristics that contribute to water quality degradation in urban areas and the effectiveness of stormwater best management practices (BMPs) for meeting subsequent regulatory compliance. In this study, three highly urbanized watersheds, the Ballona Creek (BC), the Dominguez Channel (DC), and the Los Angeles River (LAR), located in Los Angeles, are modeled using the EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN). The primary goal is to identify the key characteristics that contribute to water quality impairment, analyze the efficacy of utilizing specific BMPs to comply with regulatory compliance, and discuss how results can inform optimal stormwater management plans for each watershed. The BC watershed has the least degraded water quality and multiple BMP scenarios result in elimination of exceedances, while the DC watershed has the most degraded water quality and none of the modeled BMP scenarios meet water quality regulations. The LAR watershed is a large, diverse watershed and results show better water quality compliance than the DC watershed despite land use characteristics that would indicate otherwise. Watersheds that reach compliance with multiple BMP types have more available options when considering ancillary benefits.

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[2] This material may be downloaded for personal use only. Any other use requires prior permission of the American Society of Civil Engineers. This material may be found at https://doi.org/10.1061/JSWBAY.0000905.
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Modeling results such as those presented here are critical for informing stakeholders' decision-making process and facilitating optimal BMP implementation for integrated water management.

2.2 Introduction

Nonpoint source water quality degradation in rivers and receiving water bodies is a major issue in urban systems throughout the United States (USEPA 2018a, 2018b). Urban pollutants, including heavy metals such as copper, lead, and zinc, have reached levels that are detrimental to both society and the environment (USEPA 1999; Brabec, Schulte, and Richards 2002; Gaffield et al. 2003; Mandelker 1989; Stein and Ackerman 2007). Urbanization occurs as cities experience population growth and require more infrastructure to handle the influx of people. The issue of nonpoint source pollution is expected to persist as population growth, and thus urbanization, is expected to continue in the future (United Nations 2014). Urbanization is directly related to an increase in percent imperviousness (Brabec, Schulte, and Richards 2002; Espy, Morgan, and Masch 1966; Stankowski 1972), which has been shown to alter the hydrologic regime of a watershed. These alterations result in larger volumes of stormwater runoff, higher peak flows (Roesner, Bledsoe, and Brashear 2001; Booth and Bledsoe 2009; Shuster et al. 2005), and elevated levels of pollutants washing off of the land surface and into receiving bodies of water (Arnold Jr. and Gibbons 1996; Tsihrintzis and Hamid 1997).

Percent imperviousness and pollutant concentrations in the runoff from different land uses are major physical factors contributing to the degradation of water quality and are key characteristics in assessing effective watershed planning (Brabec, Schulte, and Richards 2002; Morisawa and LaFlure 1979; Arnold Jr. and Gibbons 1996; Bannerman et al. 1993). Brabec et al. (2002) reviewed the literature and published studies on the correlation between impervious surfaces and water quality, and found that the threshold at which the average percent imperviousness of a watershed results in water quality degradation can range from 3.6% to 50% of the total area. Brabec et al. (2002) states that the percent imperviousness per land use also needs to be considered when comparing the relative threshold for degradation in a watershed. Specific land uses tend to have varying average percent imperviousness levels (e.g., industrial land uses tend to have a higher percent imperviousness than most other land uses, such as residential) (Ross and Dillaha 1993). Thus, just as watersheds with a higher imperviousness tend to be more degraded, land uses with a higher percent imperviousness tend to contribute more to water quality degradation.

As part of the Clean Water Act section 303(d), the EPA has required states to establish total maximum daily loads (TMDLs) for any body of water that is impaired [USEPA 303 (d) Program 2018]. States must manage both the point source and nonpoint sources using waste load allocation and load allocation, respectively, until the bodies of water meet established TMDLs. The implementation of stormwater best management practices (BMPs) is the most common and widely accepted method for managing stormwater (NRC 2008; USEPA 1999; Liu et al. 2017; UDFCD 2010a) and meeting water quality standards (Bracmort et al. 2006; Barrett 2005; Koch et al. 2014; USEPA 1999). BMPs achieve many stormwater management goals such as peak flow reduction (Roesner, Bledsoe, and Brashear 2001), groundwater infiltration (Sun et al. 2014; Roesner, Bledsoe, and Brashear 2001), and improved eco-hydrologic conditions (Karr and Dudley 1981).

Different types of BMPs have varying functions and are more or less effective at flow or pollutant reduction based on their design. Infiltration-based BMPs such as infiltration trenches and bioretention are designed to capture and retain stormwater until infiltrated into the subsurface. Infiltration-based BMPs are highly effective at reducing peak flows from small storms and pollutant loads (Roesner, Bledsoe, and Brashear 2001). However, while infiltration BMPs may reduce pollutant loads more than non-infiltration BMPs (J. M. Wolfand et al. 2018; C. Driscoll et al. 2015), the resulting pollutant concentrations may be higher because there is a lower percent of treated stormwater in the river channel (J. M. Wolfand et al. 2018, 2019). Treat-and-release BMPs, such as detention ponds and vegetated swales, are designed to route stormwater through the infrastructure, actively treat pollutants, and then release stormwater directly back into the storm drainage network (Roesner, Bledsoe, and Brashear 2001). It has been found, especially in semiarid climates, that TMDL compliance depends on the effluent quality leaving and bypassing the BMP rather than the percent removal of the pollutant (i.e., percent load reduction) (Urbonas 2003). Water resource planners, managers, and decision makers (referred to as stakeholders hereafter) should use a systematic approach and decision-making process to consider the tradeoffs between BMP types and determine the optimal suite of BMPs that will satisfy the needs of their specific watershed.

The implementation of stormwater BMPs are typically part of a larger plan to integrate and manage urban water resources such as wastewater, groundwater, stormwater, and drinking water in an effort to maximize the economic and social welfare of a city or state (Global Water Partnership Technical Advisory Committee 2000). This concept is referred to as an integrated water management plan (IWMP) and is a framework widely accepted by water planners, managers, and other stakeholders (Cardwell et al. 2006). The most economically efficient and sustainable water management plan will distribute the benefits and costs equally across all pollutant sources. However, IWMPs are enduring and costly (Hooper, McDonald, and Mitchell 1999), and thus the tradeoffs between varying objectives must be considered across all IWMP sectors (Cardwell et al. 2006). The decisions made for stormwater management may have positive or negative implications on other sectors such as groundwater. For example, some benefits of treat-and-release BMPs include sustained water levels for ecological habitat and recreation purposes while tradeoffs include less water allocated toward infiltration to the groundwater. A poorly managed stormwater plan prioritizes treat-and-release BMPs when the primary need of a watershed is to maximize potential groundwater recharge. Time and money were allocated towards an IWMP with BMPs that are not designed to infiltrate stormwater. So while it is imperative that stakeholders have as much information as possible on the source of water quality degradation and the BMPs needed to reach water quality compliance, it is equally important to understand the implications and benefits of varying stormwater management plans on the IWMP as a whole.

Stormwater models are developed to simulate water quantity and quality within a watershed (Liu et al. 2017). These models are driven by observed precipitation time series as well as urban physical characteristics of a watershed, such as percent imperviousness and pollutant runoff concentrations from different land uses, and thus reproduce the unique hydrologic regime found in the watershed under study. In addition to hydrology, the EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) model is able to simulate thousands of BMPs on a watershed-scale, analyze their impact on water quantity and quality, and assist in the decision-making process to determine the optimal suite of BMPs needed to reach water quality compliance for a specific watershed. While many studies have been conducted on BMP performance [see for example Liu et al. (2017)], there are few studies that analyze the effect of BMPs on water quality and the ancillary benefits at the watershed-level

(Mika et al. 2018; Read et al. 2018; J. M. Wolfand et al. 2018) or compare the efficacy of stormwater management plans across multiple watersheds.

In the current study we utilize three watersheds located within Los Angeles (LA) County to investigate: (1) the urban physical characteristics found in each watershed and their impact on water quality degradation (specifically heavy metals including copper, lead, and zinc); (2) whether TMDL exceedances can be eliminated when capturing the 85th percentile storm (defined in the study area section) with BMPs; (3) whether infiltration-based or treat-and-release-based BMPs need to be prioritized in order to eliminate or minimize TMDL exceedances; and (4), the resulting benefits and tradeoffs to be considered when deciding the optimal suite of BMPs for each watershed. Our goal is to investigate potential variability in achieving water quality compliance in adjacent watersheds and demonstrate how observed differences may impact the decision-making process when optimizing BMP implementation for a watershed.

2.3 Study Area

LA County, located in southern California, is 10,578 km2 with a total population of over 10 million people (U.S. Census Bureau 2012). Extensive urbanization throughout LA County has altered the hydrologic regime and degraded water quality (Read et al. 2018; Sheng and Wilson 2009). The region is considered semiarid and averages 381 mm of rain per year, with long periods of antecedent dry days separating rain events. These precipitation patterns allow pollutants to build up for an extended period of time, resulting in large loads of pollutants washing off the land surface during storm events. Three rivers, the Ballona Creek (BC), the Dominguez Channel (DC), and the LA River (LAR), capture a large portion of the stormwater falling within the LA County boundary (Figure 2.1) and are the focus of this study.

Recent droughts in California have placed stress on the state’s water supply and have resulted in an increased sense of urgency in many cities to develop secure, sustainable, and resilient water management plans. The city of LA has been working on implementing an IWMP, which includes implementing policies and setting future sustainability goals. While water quality improvement is a key driver for stormwater management planning, increased water supply security (especially through local supply) is also a major theme and goal for LA. Thus, the development of an IWMP throughout LA includes the consideration of stormwater, recycled water, groundwater, and local water supplies (Mika et al. 2018).

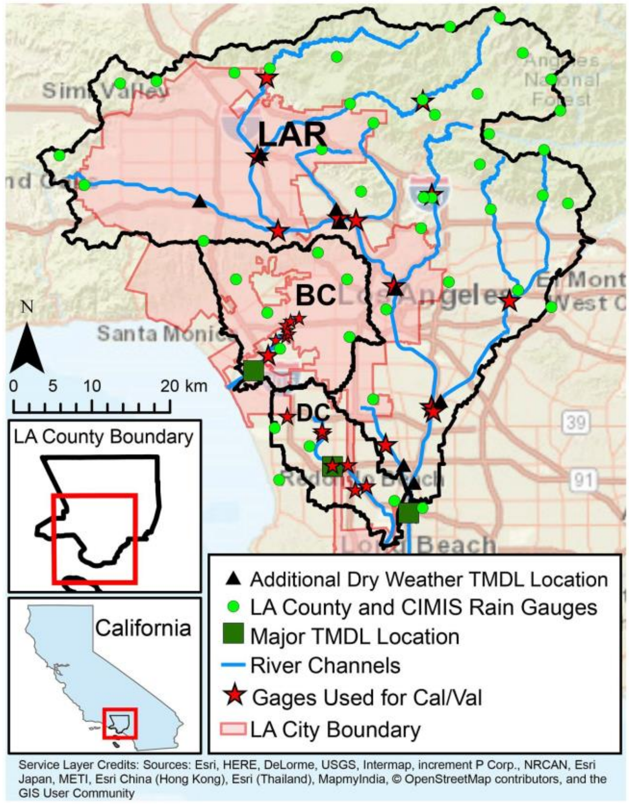

Figure 2.1 Ballona Creek (BC), Dominguez Channel (DC), and Los Angeles River (LAR) watersheds. Precipitation, Water quantity/quality, and TMDL monitoring locations are included for each watershed.

2.3.1 Ballona Creek Watershed

The 319 km2 BC watershed has the highest watershed population density of the three study watersheds (Figure 2.1, Table 2.1). In comparison to the other two watersheds, the BC watershed has the highest percentage of vacant land and the lowest percentage of industrial land. The roughly 12-km-long Ballona channel drains into the Santa Monica Bay (Ballona Creek Watershed Management Group 2016). Observed discharge data for the model simulation period (WY 1999–2008) obtained from the LA Department of Public Works Stormwater Monitoring data (California Regional Water Quality Control Board 2013b; Los Angeles Department of Public Works 2014) shows that the BC watershed has the lowest runoff ratio (0.51), the highest average precipitation, and the highest 85th percentile storm depth out of the three watersheds (Table 2.1). The 85th percentile storm depth is determined by analyzing observed accumulation precipitation depths that occur over a 24-h rainfall event. For example, 85% of rainfall events in BC will produce less than or equal to 26.4 mm of rain over 24 h.

2.3.2 Dominguez Channel Watershed

The 184-km2 DC watershed is the smallest but most heavily developed and impervious of the three watersheds. The DC watershed area is unique in that the watershed has a high percentage of industrial land uses, highly concentrated in certain areas of the watershed ("Southern California Association of Governments Land Use Data" 2005). The 24-km DC channel drains into the LA Harbor (Dominguez Channel Watershed Management Area Group 2015). Flow gauges (Los Angeles Department of Public Works 2014) only record data from the upper, less developed half of the watershed. Water quality data (Los Angeles Department of Public Works 2014) is recorded from the upper half as well as from three subwatersheds in the lower half of the watershed. Using the available observed data (WY 2001–2011), it was determined that the DC watershed has the highest runoff ratio (0.72), the lowest average precipitation, and the lowest 85th percentile storm depth.

2.3.3 Los Angeles River Watershed

The 2,150-km2 LAR watershed, the largest of the three study watersheds, encompasses a diverse landscape including the Santa Monica and San Gabriel Mountains in the headwaters and the heavily urbanized downtown LA area (Edgley 2016). Table 2.1 characterizes the LAR watershed with and without the forested region. This allows for a better comparison of the three watersheds, especially in terms of the more urbanized land cover. The urbanized portion of the LAR watershed has the highest residential area out of the three studied ("Southern California Association of Governments Land Use Data" 2005). The LAR watershed drainage network consists of a complex network of underground storm drains and tributaries with several dams, spreading grounds, and water reclamation facilities. Between its confluence and discharge, the LAR is segmented into six reaches based on subwatershed and water quality compliance locations. The average annual precipitation varies across the area with the mountainous regions receiving 686 mm/yr and the coastal regions receiving 340 mm/yr (County of Los Angeles Department of Public Works 2014).

2.3.4 Water Quality Regulations

Metals, fecal indicator bacteria, trash, and nutrients have impaired water bodies in LA County (California Regional Water Quality Control Board 2016). Heavy metals are the focus of water quality regulations in the three watershed studies due to the available well documented water quality and BMP performance data as well as their conservative nature (i.e., do not easily degrade or transform into nontoxic substances). Heavy metals, including copper, lead, and zinc are persistent, conservative, and accumulate easily (Warren and Zimmerman 1994; Gasperi et al. 2010). Dry weather and wet weather TMDLs have been established for these pollutants within the three watersheds (Table 2.1).

Wet weather days are defined as any day in which the average flow at the TMDL location exceeds a specified discharge value (dry versus wet weather threshold in Table 2.1) (Mika et al. 2018). When the flow exceeds the wet weather identifier, wet weather TMDLs are calculated by multiplying the average flow of that day by the established acute exposure concentration. Total compliance (i.e., 100%) occurs when none of the observed pollutant loads on wet weather days exceeds the TMDL. Dry weather TMDLs have one predetermined constant daily load limit for all dry weather days. Dry weather TMDLs are determined by multiplying the chronic exposure concentration by the observed median daily flow found in the watershed (California Regional Water Quality Control Board 2013a). It should be noted that the implementation of BMPs effect the ratio of wet to dry weather days per year as BMPs capture stormwater and result in lower river discharge values (Read et al. 2018). Throughout this paper, including Figure 2.3, the term compliance refers to the ratio of number of days that do not exceed the wet or dry TMDL to the total number of wet or dry weather days. The total number of dry or wet weather days represents the total possible number of days that can be exceeded.

The LA regional water quality control board has established the capture of the 85th percentile storm depth as a method for reaching water quality compliance (California Regional Water Quality Control Board: Los Angeles Region 2012). In the current study, implementation of BMPs throughout the three watersheds are designed and modeled to capture the 85th percentile storm volume in order to assess the efficacy of this approach in meeting compliance (City of Los Angeles 2016). The 85th percentile storm values were determined by first acquiring the 85th percentile rain storm for each subwatershed garnered from an LA County contour map (Willardson and Walden 2004) illustrating the location and depth of the 85th percentile storm over the county. This map was georeferenced in ArcGIS and overlain by the subwatershed shape files in order to calculate the weighted average 85th percentile storm depth. For each watershed, the weighted average storm depth, subwatershed area, and runoff ratio from the modeled time period were multiplied to calculate the 85th percentile storm volume. The resulting volume of stormwater runoff was the expected runoff that the BMP scenarios must capture.

Table 2.1 Cross Watershed Comparison

Watershed characteristics	BC	DC	LAR with forested	LAR without forested
Physical characteristics				
Total area (km^2)	319	184	2,150	1,326
Total population	1,665,714	714,964	4,623,724	4,618,299
Percent imperviousness (%)	60.9	71.1	38.2	57.6
Average precipitation/year (mm)	371	272	340/686[a]	340/686[a]
Hydrological characteristics				
Stormflow data period used for model simulation (Water year)	1999–2008	2001–2011	2004–2013	2004–2013
Runoff ratio	0.51	0.72	0.36	0.58
Average annual flow (m^3)	78,313,645	44,595,236	291,662,513	186,026,053
85th percentile storm depth (mm)	26.4	21.8	26.4	24.4
85th percentile storm volume (m^3)	4,466,431	2,902,378	20,157,530	12,823,258
Cu average annual load (kg)	1,854	1,309	16,411	NA
Pb average annual load (kg)	1,156	547	16,121	NA
Zn average annual load (kg)	10,806	6,360	57,875	NA
Dry weather versus wet weather threshold [daily peak (cms)]	1.81	1.78	14.2	NA
Baseline observed WW days/year	106	32	32	NA
Primary TMDL name	MES M01	TS28	Reach 1	NA
Primary TMDL location	Sawtelle Boulevard	Artesia Boulevard	Atlantic Avenue	NA
Wet weather TMDL at primary location				
Cu (ug/L)	13.7	9.7	17	NA
Pb (ug/L)	76.7	42.7	94	NA

Table 2.1 Continued

Zn (ug/L)	104.7	69.7	159	NA
Dry weather TMDL at primary location[b]				
Cu (kg/d)	1.47	None	1.47	NA
Pb (kg/d)	0.82	None	0.82	NA
Zn (kg/d)	18.57	None	0.16[b]	NA
Land use type (% watershed)				
Agriculture	0.1%	1.1%	0.7%	1.1%
Commercial	14.2%	19.9%	7.3%	11.8%
Education	3.0%	3.9%	2.0%	3.3%
Industrial	4.0%	20.9%	38.3%	9.6%
Multifamily residential	21.7%	11.5%	6.0%	11.1%
Other	1.3%	0.7%	6.9%	0.5%
Parks and recreation	3.1%	4.1%	2.7%	4.3%
Single-family residential	37.4%	30.1%	30.1%	48.8%
Transportation	2.1%	5.1%	2.4%	4.0%
Vacant	13.3%	2.3%	2.1%	3.4%
Water	0.0%	0.6%	1.3%	2.1%
Forested	0.0%	0.0%	38.3%	0.0%

Note: NA = Not available; Cu = Copper; Pb = Lead; Zn = Zinc; MES = Mass emission station; and TS = Tributary station.

[a]LAR receives 686 mm=year in the mountainous regions while the coastal regions receive 340 mm=year.

[b]LAR only has one dry weather TMDL location for Zn, which is located at the Rio Hondo location.

2.4 Methods and Data

2.4.1 SUSTAIN Model Framework and Modeling Overview

The SUSTAIN model (Shoemaker et al. 2009) was utilized to simulate water quantity and quality at the watershed-scale for each of the three study basins. The internal land simulation module, used for calibration and validation, simulated runoff and pollutant loadings using algorithms adapted from the Stormwater Management Model (USEPA 2015). SUSTAIN was chosen for its external BMP simulation module, which implements aggregate BMPs on a watershed-scale and assesses BMP efficacy on the calibrated and validated stormwater flow and pollutant loads first simulated in the internal land simulation. Several case studies (e.g., Lee et al.

2012 and Shoemaker 2013) throughout the United States have utilized SUSTAIN to analyze BMP performance and assist stakeholders in prioritizing BMPs and present alternative solutions to improve water quality.

2.4.2 Related Past SUSTAIN Modeling Efforts

This analysis synthesizes results from past SUSTAIN modeling efforts in each of the watersheds individually. Therefore, the calibration procedures and BMP scenarios (described in the subsequent section) are slightly different between watersheds. However, all past studies address the selection of stormwater alternatives for the elimination of TMDL exceedances and are suitable for cross watershed comparison, especially considering that the TMDLs also vary across watersheds. The BC watershed, modeled first, was set up to explore the treatment of varying drainage areas, BMP treatment volumes, and BMP types (Beck 2014; Radavich 2015; Gold et al. 2015). BC modeling results gave insight into how best to set up the model for both the LAR watershed (modeled second) and the DC watershed (modeled third) (Mika, Gallo, et al. 2017; Mika, Hogue, et al. 2017). The analysis of the LAR watershed was slightly different because it was set up to explore varying suites of BMP types (i.e., infiltration versus treat-and-release), while keeping the drainage area and BMP treatment volume set to the optimal values determined by the BC modeling results. The analysis of DC was set up to be the same as the LAR watershed (Edgley 2016; Mika, Hogue, et al. 2017; Read et al. 2018).

Because this analysis focuses on the addition of new BMPs only, existing BMPs throughout the three watersheds were not implemented into the model given that the flow and water quality data at mass emission stations used for model calibration already accounts for those BMPs and the baseline (status quo) conditions. SUSTAIN simulates specific BMP scenarios with a set number of BMP units and analyzes several water quantity and quality outputs on an hourly time scale (Shoemaker et al. 2009). Specific BMP scenarios were analyzed at the junction in the SUSTAIN conveyance network that correlate to the primary TMDL location (Table 2.1). The models were used to simulate specific BMP scenarios for the three watersheds.

2.4.3 Characterization of Watersheds in SUSTAIN

The three study watersheds were delineated with respect to LA County mass emission stations to ensure that all watersheds and subwatersheds are hydrologically distinct. Each model was constructed with multiple subwatersheds (8, 8, and 15 for BC, DC, and LAR, respectively) to account for major hydrologic features and TMDL compliance locations. Subwatersheds were downloaded from the (Los Angeles County GIS Data Portal 2005) and reshaped based on mass emission stations located throughout the full watershed. Although a storm drain network downloaded from the (Los Angeles County GIS Data Portal 2016) was used to further refine the subwatershed shape so that all rainwater falling on a subwatershed exits only through the downstream gauge and to identify their hydrologic connectivity, actual pipe flow was not simulated in SUSTAIN.

A 0.81-hectare resolution land use raster was acquired from the Southern California Association of Governments ("Southern California Association of Governments Land Use Data" 2005). All land use shape files were aggregated into 11 distinct land use classifications (Table 2.1) and were utilized to determine the average percent imperviousness and total area for each watershed, which are both model inputs, used to simulate runoff volumes and pollutant loads.

2.4.4 Water Quality and Quantity Data in SUSTAIN

The land simulation module in SUSTAIN was driven by hourly precipitation and daily climatology data (temperature, evapotranspiration, and wind speed) acquired from LA County rain gauges (County Of Los Angeles Department Of Public Works 2016) and the California Irrigation Management Information System (California Department of Water Resources 2016), respectively. The inverse distance-weighting method was used to determine a single time series of precipitation to represent each subwatershed from multiple rain gauge locations spatially distributed throughout the individual watersheds. The BC, DC, and LAR watersheds utilized 15, 8, and 8 spatially distributed precipitation time series, respectively. The precipitation as well as the area and percent imperviousness of each of the 11 distinct land uses, acquired from the Southern California Association of Governments data, was used to estimate stormwater runoff volumes on an hourly time step.

The event mean concentration (EMC) method in SUSTAIN was used to simulate pollutants. Water quality sampling from discrete land use types (Southern California Coastal Water Research Project 2007) was compiled from both the LA Department of Public Works (LADPW) Stormwater Quality Monitoring Program and the Southern California Coastal Water

Research Project and was used to compose EMC values. This master data set includes EMC values for multiple land use types across the LA region. Water quality samples were taken between water years 1994–2001 with the number of samples per land use ranging from 3 (parks and recreation) to 69 (transportation). The median EMC data from the database was utilized to determine a distinct pollutant runoff concentration (EMC value) for each of the 11 land uses in SUSTAIN to simulate pollutant loadings. Observed discharge and water quality data from several monitoring stations (Figure 2.1) throughout the watersheds were used to calibrate and validate the model outputs.

2.4.5 Model Calibration and Validation

Each SUSTAIN model was calibrated using 5 years of data and then validated using the following 5 years (Table 2.1).Water quantity calibration in SUSTAIN included manually adjusting specific watershed parameters such as percent imperviousness (Barco et al. 2008; Sangal and Bonema 1994), hydraulic conductivity, overland flow width, and Manning's n for impervious area. These parameters were the focus due to their higher sensitivity, as determined in an initial model sensitivity analysis (Beck 2014). Other parameters that were adjusted include percent slope, Manning's n for pervious area, depression storage for pervious area, and % zero impervious area. Parameters were varied until modeled individual storm volumes matched observed volumes. This process included using a statistical analysis as well as visually comparing the shape of individual storms after each parameter adjustment. Several statistics, such as percent bias, root mean square error, Nash Sutcliffe Efficiency (NSE), as well as minimum, maximum, and mean flow, were used to compare observed flow time series to those modeled during calibration. NSE, which assesses the predictive power of a hydrologic model, was prioritized in the water quantity calibration and validation process for all watersheds. While the total modeled and observed volumes of flow for seven individual storm events and total water years were utilized to calculate the calibrated relative error and NSE values for the BC watershed (Beck 2014), the full daily modeled and observed time series (Table 2.1) were utilized for validation of the BC watershed and calibration/validation for the DC and LAR watersheds. Calibrated parameters were then used to run the model for the validation period. The model was validated using these same statistics.

After validating water quantity, water quality was calibrated by adjusting the pollutant EMC value for each land use type and pollutant in the model. EMC values were derived using the dataset of observed land use specific EMCs discussed in the preceding section. While the 50th percentile value from EMC data is traditionally used in water quality modeling, the resulting modeled pollutant loads at the outlet of the watershed did not match the observed water quality pollutant loads recorded at the mass emission station gauges. Thus, modeled EMCs were calibrated by testing several EMC percentile values. The EMC percentiles were adjusted until modeled pollutant loadings in simulated streamflow best matched daily minimum, maximum, and total observed loads in each watershed and for each solute. For example, in the BC watershed, the 50th percentile EMC resulted in modeled copper pollutant loads that were lower than observed while the 60th percentile EMC modeled pollutant loads were too high. The final calibrated landuse EMC for copper in the BC watershed was the 55th percentile EMC value (Table 2.2). Once calibrated and validated, water quantity and quality simulated at the watershed outlet using the internal land simulation module in SUSTAIN were disaggregated for each land use type at an hourly time step. The validated land use time series data drives the external BMP simulation module in SUSTAIN.

Table 2.2 Initial and calibrated land use pollutant EMCs

Watershed	Initial All	Calibrated BC	Calibrated DC	Calibrated LAR
Cu (mg/L)				
EMC percentile	50	55	79	96
Agriculture	0.022	0.033	0.074	0.079
Commercial	0.024	0.038	0.055	0.076
Education	0.016	0.038	0.036	0.083
Industrial	0.022	0.070	0.061	0.133
Multifamily residential	0.013	0.026	0.116	0.214
Single-family residential	0.014	0.030	0.038	0.053
Other	0.032	0.032	0.037	0.037
Parks and recreation	0.032	0.038	0.037	0.037
Transportation	0.040	0.010	0.097	0.160
Vacant	0.007	0.008	0.041	0.118
Pb (mg/L)				

Table 2.2 Continued

EMC percentile	50	75	60	95
Agriculture	0.006	0.012	0.008	0.041
Commercial	0.012	0.031	0.017	0.096
Education	0.008	0.031	0.010	0.029
Industrial	0.013	0.036	0.033	0.085
Multifamily residential	0.010	0.043	0.013	0.051
Single-family residential	0.015	0.009	0.028	0.073
Other	0.013	0.021	0.013	0.014
Parks and recreation	0.013	0.025	0.013	0.014
Transportation	0.010	0.005	0.017	0.044
Vacant	0.007	0.002	0.021	0.113
Zn (mg/L)				
EMC percentile	50	61	62	95
Agriculture	0.188	0.243	0.417	0.504
Commercial	0.196	0.362	0.268	0.561
Education	0.109	0.362	0.142	0.254
Industrial	0.367	0.599	0.529	1.587
Multifamily residential	0.104	0.208	0.154	0.900
Single-family residential	0.079	0.087	0.125	0.198
Other	0.122	0.234	0.124	0.125
Parks and recreation	0.122	0.132	0.124	0.125
Transportation	0.234	0.093	0.311	0.877
Vacant	0.063	0.023	0.080	0.437

2.4.6 Comparison of Baseline Water Quality across Watersheds

The calibrated models of all three sites were used to assess the baseline (no new BMPs or status quo) water quality conditions by comparing simulated average annual loads to the values stipulated for average annual loads by the wet weather TMDLs. This allowed us to estimate the amount of load that must be reduced in each watershed to meet compliance. The wet weather TMDLs were applied to the average annual flow volume (Table 2.1) to calculate the average annual TMDL. An estimate of the total allowable loads of pollutants per year based on the average annual flow volume, average annual load, and TMDL numeric targets were calculated.

For example, the DC average annual flow volume of 44,595,236 m3 is multiplied by the copper TMDL of 9.7 ug/L, using the appropriate conversions to get units in pounds, to get an average annual TMDL of 434 kg. Comparing this number to the modeled baseline average annual loads of 1,310 kg of copper, it is determined that a pollutant load reduction of 67% is required to reach the estimated average annual TMDL of 434 kg (Figure 2.2). This is a rough estimate to allow the comparison of pollutant reduction needed to meet TMDL requirements across the three watersheds and can also be used to compare the baseline water quality in each watershed before implementation of BMPs.

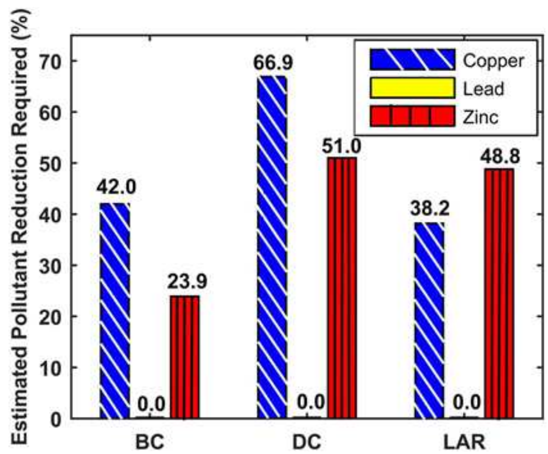

Figure 2.2 Estimated pollutant reduction required to meet TMDLs.

2.4.7 BMP Scenarios for TMDL Compliance

2.4.7.1 BMP Parameterization

Watershed modeling efforts included an assessment of a variety of specific scenarios with a unique suite of BMPs to identify opportunities to achieve an Municipal Separate Storm Sewer System (MS4) permit and TMDL compliance. BMPs that were selected to be simulated in SUSTAIN for this research included unlined bioretention, porous pavement, vegetated swales, infiltration trenches, and dry ponds (Table 2.3). Dry ponds and vegetated swales perform as treat-and-release BMPs. Bioretention, infiltration trenches, and porous pavement perform as infiltration BMPs. These BMP types were selected based on available design and performance data found in the International BMP Database ("International Stormwater BMP Database" 2016) and their ability to improve water quality and decrease storm peak flows, especially in semiarid climates such as LA. Each of the five BMP types had a unique physical dimension, cost, and pollutant decay constant (Mika et al. 2018).

Table 2.3 Dimensions and metal pollutant removal efficiencies for selected BMPs

Parameter	Vegetated Swale	Bio-retention	Dry Pond	Infiltration Trench	Porous Pavement
Median Capital Cost	10.07	14.6	5.88	6.03	15.69
Length (m)	76.2	14.0	13.7	27.4	18.9
Width (m)	3.0	7.0	4.6	13.7	9.1
Depth (m)	0.2	0.5	1.5	1.5	0.3
Cu decay rate (hr-1)	1.7	0.55	0.6	0.6	0.01
Pb decay rate (hr-1)	20	0.2	0.65	0.65	0.01
Zn decay rate (hr-1)	60	0.85	1.08	1.08	0.01

BMP dimensions and cost for each BMP type were determined by averaging values from several BMP projects found throughout LA including those from Standard Urban Stormwater Mitigation Plans (California Water Boards 2018) IBMPD ("International Stormwater BMP Database" 2016), Proposition O (LA Sanitation Watershed Protection Program 2018), and other city project reports. Radavich et al. (2015) conducted a sensitivity analysis on modeled BMP flows and pollutant loadings with the determined BMP dimensions and parameters. The values were ultimately utilized in all three watersheds in order to validate the physical BMP model and ensure selected design parameters fall within a range that is representative of southern California.

The current study uses a first-order decay model to simulate BMP performance. Pollutant decay rates were determined by adjusting the decay rates in SUSTAIN and comparing modeled influent and effluent concentrations to those reported in the International Stormwater BMP Database for LA (Beck 2014). Beck et al. (2014) calibrated the pollutant decay rates for seven types of BMPs, including the five simulated in this study, for four pollutants (TSS, copper, lead, and zinc) by comparing median effluents of modeled storm events to the median effluent for each BMP type in the International Stormwater BMP Database. The number of BMP sites used for calibration for each BMP type from the International BMP Database ranged from 30 to 79. This ensured BMP first-order decay rates were reasonably predicting storm event pollutant loads. Calibrated decay rates were found to be consistent with studies in the region (Ackerman and Stein 2008; Beck 2014; Mika, Hogue, et al. 2017). Mika et al. (2017b) conducted a post modeling sensitivity analysis in the DC watershed to determine how sensitive pollutant decay rates are to the resulting quantified total load-based pollutant exceedances per year. It was found that even when simulating decay rates that were 100 times greater than the original calibrated rates, the number of exceedances/year only decreased from 11 to 9 for copper and from 5 to 4 for zinc (Mika, Hogue, et al. 2017).

2.4.7.2 TMDL Scenarios

Each watershed was run with a distribution of BMPs sufficient to capture the 85th percentile storm volume. The number and type of BMPs chosen (Table 2.4) were determined by previous SUSTAIN modeling in the three watersheds (Mika, Hogue, et al. 2017; Gold et al. 2015). All modeled scenarios (Table 2.4) provide unique information in each watershed such as the types and numbers of BMPs simulated, total treatment volume, and capital cost. The maximum number of simulated BMPs allowed in subwatersheds was determined by comparing the BMP footprint to area of urban public land uses (e.g., education, recreation, transportation) (Mika, Gallo, et al. 2017; Mika, Hogue, et al. 2017; Edgley 2016). BMPs were assumed to be placed only on urban public land uses in these scenarios, which do not come with land acquisition costs and are more readily available for BMP placement by the city and other public agencies. Placing BMPs on private land requires purchasing land or rights of way from private landowners or initiating large programs to encourage or require private landowners to install and maintain BMPs on site.

While some variations existed between BMP scenarios set up for each watershed (Table 2.4), all scenarios were designed with a primary goal of eliminating dry and wet weather exceedances. In the BC watershed, five BMP scenarios with a unique suite of BMPs to capture and treat runoff from different land use types, drainage areas, and BMP treatment volumes were explored. The goal of the BC modeling was to determine the optimal drainage area and BMP treatment volume needed to eliminate exceedances. It should be noted that each modeled scenario captured a unique storm volume that was less than the 85th percentile storm volume of 4,466,431 m3 (Table 2.1). Scenario 1 in the BC watershed routed 90% of the urban watershed to all five types of BMPs. Scenarios 2 and 3 routed water from 85% of the urban watershed to only infiltration BMPs (Scenario 2) or treat-and-release BMPs (Scenario 3). A suite of BMPs to capture runoff from private (77% of the watershed) or public (23% of the watershed) land uses were utilized in Scenarios 4 and 5, respectively.

Based on preliminary modeling in the BC watershed, it was determined that routing runoff from 90% of all urban area to BMPs (Scenario 1) and maximizing the BMP treatment volume (Scenario 3) was optimal for the elimination of TMDL exceedances (Radavich 2015; Gold et al. 2015). Thus, the simulations for DC and LAR were then designed to combine these attributes so that each scenario routed water from 90% of the watershed to BMPs with a total volume capacity to capture and manage the full 85th percentile storm. Six scenarios (1, 1b, 2, 2b, 3, and 3b) with different suites of BMPs were developed and modeled (Table 2.4). Scenario 1 utilized bioretention to assess the performance of infiltration BMPs, Scenario 2 utilized vegetated swales and dry ponds to assess the performance of treat-and-release BMPs, and Scenario 3 utilized vegetated swales and infiltration trenches to assess the combination of the two performance types. Scenarios 1b, 2b, and 3b added porous pavement to the first three scenarios.

Table 2.4 Modeled scenarios and summary statistics for each watershed

Scenario	BR units	DP units	IT units	PP units	VS units	% Land routed to BMPs	Treatment volume (m^3)	Capital Cost ($ billion)
Ballona creek								
1	7,256	4,737	2,794	555	5,761	90	1,359,295	0.55
2	—	—	5,400	—	—	85	3,096,035	0.67
3	—	32,400	—	—	—	85	3,096,035	0.64
4	20,564	—	—	17,958	26,140	77	2,800,000	1.07
5	2,317	—	—	1,994	2,967	23	314,537	0.12
Dominguez channel								
1	65,436	—	—	—	—	90	2,902,378	1.51
1b	51,610	—	—	10,830	—	90	2,902,378	1.51
2	—	24,088	—	—	17,450	90	2,902,378	0.70
2b	—	18,043	—	10,830	17,450	90	2,902,378	0.89
3	—	—	4,020	—	16,860	90	2,902,378	0.70
3b	—	—	3,017	10,830	16,860	90	2,902,378	0.90
Los Angeles river								
1	286,003	—	—	—	—	90	12,823,258	6.60
1b	152,926	—	—	112,986	—	90	12,823,258	6.80
2	—	83,019	—	—	138,126	90	12,823,258	3.80
2b	—	36,066	—	112,986	96,776	90	12,823,258	5.20

Table 2.4 Continued

3	—	—	13,836	—	138,126	90	12,823,258	3.80
3b	—	—	6,011	112,986	96,776	90	12,823,258	5.20

Note: BR = Bioretention; DP = Dry Pond; IT = Infiltration trench; PP = Porous pavement; and VS = Vegetated swale.

2.5 Results

2.5.1 Calibration and Validation

Calibrated parameters for the BC watershed resulted in a range of relative error values of 8% to −1.8% for the seven individual storm events and an NSE value of 0.37 for the annual volume from water year 2004 to 2008. However, the wet season volume resulted in an NSE of 0.77. The BC watershed validation compared the full daily modeled versus the observed water quantity time series from water year 1999 to 2003. The BC watershed NSE value for the validation was 0.87. The DC and the LAR watershed compared the full daily modeled and observed water quantity time series for calibration and validation using NSE. The DC watershed NSE values for the calibration and validation were 0.83 and 0.85, respectively. The LAR watershed NSE values for the calibration and validation were 0.85 and 0.51, respectively. It should be noted that the low NSE validation value for LAR is likely due to the highly variable precipitation during the 5-year time span that was used for the validation. According to Moriasi et al. (2007), a NSE value that falls between 0.75 and 1.00 is considered a very good hydrologic model, and therefore all calibrated models were deemed acceptable for further assessment (Moriasi et al. 2007).

Water quality validation within the BC watershed showed that while it is difficult for the model to replicate high pollutant load outliers, the modeled and observed mid-quartiles generally overlap with modeled median values slightly exceeding those of the observed (Beck 2014; Radavich 2015; Gold et al. 2015). This indicates that the model is generally successful at replicating pollutant loads for most storm events. Similar results were found in the water quality validation for the DC and LAR watersheds. EMC percentile values were adjusted from the 50th percentile land use EMC value (Southern California Coastal Water Research Project 2007) and considered calibrated when the daily modeled mean, max, and total loads matched the observed loads at monitoring stations. The initial and final EMC values for each watershed are presented in Table 2.2. The BC watershed-calibrated EMC percentiles for copper and zinc are lower than those for the DC and LAR watersheds. The LAR watershed required the highest EMC percentiles (~95th) to match modeled loads to observed loads. Other watershed-scale modeling exercises using SUSTAIN also validated pollutant loads in this manner (Shoemaker et al. 2013).

2.5.2 Baseline Water Quality

The estimated reduction in average annual baseline loads required for each watershed to reach TMDL requirements can be seen in Figure 2.2. Zero percent reduction is required for lead in all three watersheds. This is expected because lead is already in compliance for TMDLs in the baseline scenario (no BMPs). DC has the highest predicted required copper and zinc reduction (67% and 51%, respectively). While BC has the lowest predicted required zinc removal (24%), LAR has the lowest copper required removal (38%).

2.5.3 BMP Scenarios for TMDL Compliance

Figure 2.3 displays the final ancillary and water quality criteria determined from modeling results at all three sites. Ancillary criteria include the BMP area, peak flow reduction, and cost. Water quality criteria include the number of dry/wet weather days, TMDL exceedances for both dry and wet weather, and percent of days on which compliance is met. The developed color scale highlights the performance of scenarios from best to worst for each watershed in terms of the several listed criteria. For example, in the BC watershed, Scenario 2 has the darkest shading of green under the peak flow reduction column because it performs best out of the five BC scenarios, Scenarios 1 and 4 have lighter shades of green because they do not perform as well as Scenario 2, and Scenarios 3 and 5 are not shaded because they perform the worst.

	Scenario (BMPs)		Volume Capture (m^3)	BMP Area (km^2)	Peak Flow Reduction	Cost (Billions)	DW Days/yr **	Load Based Exceedances/yr (TMDL Compliance [%])***						WW Days/yr **	Load Based Exceedances/yr (TMDL Compliance [%])***					
								Cu DW		Pb DW		Zn DW			Cu WW		Pb WW		Zn WW	
BC	Baseline*	No New	0	-	-	-	259	86	(66.8)	0	(100.0)	0	(100.0)	106	105	(0.9)	0	(100.0)	19	(82.1)
	1	All	1,358,766	3.52	43.0%	0.55	336	0	(100.0)	0	(100.0)	0	(100.0)	29	10	(65.5)	0	(100.0)	1	(96.6)
	2	IT	3,094,830	2.02	95.0%	0.70	354	0	(100.0)	0	(100.0)	0	(100.0)	11	10	(9.1)	0	(100.0)	8	(27.3)
	3	DP	3,094,830	2.02	10.0%	0.69	339	0	(100.0)	0	(100.0)	0	(100.0)	26	6	(76.9)	0	(100.0)	0	(100.0)
	4	VS+BR+PP	2,798,910	11.18	65.0%	1.40	340	0	(100.0)	0	(100.0)	0	(100.0)	25	11	(56.0)	0	(100.0)	2	(92.0)
	5	VS+BR+PP	314,415	1.24	11.0%	0.20	278	73	(73.7)	0	(100.0)	0	(100.0)	87	84	3.4	0	(100.0)	18	(79.3)
DC	Baseline*	No New	0	-	-	-	333	-	-	-	-	-	-	32	18	(43.8)	0	(100.0)	17	(46.9)
	1	BR	2,901,249	6.42	69.6%	1.51	357	-	-	-	-	-	-	8	7	(12.5)	0	(100.0)	6	(25.0)
	1b	BR+PP	2,901,249	6.68	55.7%	1.51	359	-	-	-	-	-	-	6	5	(16.7)	0	(100.0)	5	(16.7)
	2	VS+DP	2,901,249	5.54	4.4%	0.71	354	-	-	-	-	-	-	11	11	(0.0)	0	(100.0)	5	(54.5)
	2b	VS+DP+PP	2,901,249	7.04	34.0%	0.89	356	-	-	-	-	-	-	9	9	(0.0)	0	(100.0)	7	(22.2)
	3	VS+IT	2,901,249	5.41	45.4%	0.70	357	-	-	-	-	-	-	8	8	(0.0)	0	(100.0)	7	(12.5)
	3b	VS+IT+PP	2,901,249	6.92	55.3%	0.90	358	-	-	-	-	-	-	7	7	(0.0)	0	(100.0)	6	(14.3)
LAR	Baseline*	No New	0	-	-	-	333	307	(89.8)	127	(95.8)	214	(35.7)	32	6	(81.3)	2	(93.8)	14	(56.3)
	1	BR	12,818,268	27.97	47.0%	6.60	358	68	(97.9)	51	(98.4)	18	(95.0)	7	1	(85.7)	0	(100.0)	6	(14.3)
	1b	BR+PP	12,818,268	15.02	53.0%	6.80	360	71	(97.8)	53	(98.4)	18	(95.0)	5	2	(60.0)	0	(100.0)	5	(0.0)
	2	VS+DP	12,818,268	37.30	29.0%	3.80	350	62	(98.0)	47	(98.5)	15	(95.7)	15	0	(100.0)	0	(100.0)	3	(80.0)
	2b	VS+DP+PP	12,818,268	24.86	46.0%	5.20	358	69	(97.9)	52	(98.4)	18	(95.0)	7	1	(85.7)	0	(100.0)	6	(14.3)
	3	VS+IT	12,818,268	37.30	55.0%	3.80	361	75	(97.7)	57	(98.2)	19	(94.7)	4	0	(100.0)	0	(100.0)	2	(50.0)
	3b	VS+IT+PP	12,818,268	24.86	57.0%	5.20	361	75	(97.7)	57	(98.2)	19	(94.7)	4	2	(50.0)	0	(100.0)	4	(0.0)

* Baseline Scenario is not included in the developed color scale which highlights the performance of BMP scenarios from best to worst for each criteria.

** DW and WW Days/year equals the total possible dry and wet weather exceedances with an exception to LAR Dry weather Cu and Pb. Multiply the DW Days/yr by 9 (TMDL locations) to get the total possible exceedances for LAR Cu and Pb.

*** TMDL Compliance represents the percentage of days that which the TMDL will be met
e.g. WW TMDL Compliance = (WW Days/yr - Exceedances/yr) ÷ WW Days/yr * 100

Figure 2.3 Multi-criteria decision matrix for evaluating tradeoffs between BMP scenarios and comparing watersheds to one another,

2.5.4 Ballona Creek

Modeling results from BC show that the scenarios that captured smaller storm volumes (Scenarios 1 and 5) required fewer BMPs and thus cost less. However, Scenario 5 for example, which captured only 314,537 m3 from public land uses, also had the highest number of TMDL exceedances and lowest average annual load reduction as a lower volume of stormwater was managed. While scenarios that captured more stormwater have higher costs, they have a lower number of dry and wet weather exceedances. With the exception of Scenario 5, all modeled scenarios resulted in zero dry weather exceedances for copper (lead and zinc were at zero dry weather exceedances in the baseline and remained there in the modeled Scenarios). Even though Scenario 5 had 73 (Figure 2.3) dry weather copper exceedances, the volume captured is significantly lower than the 85th percentile storm. Thus, capturing and treating more stormwater should result in zero exceedances. Additionally, the BC copper wet weather exceedance results are expected to decrease due to implemented brake laws (California Stormwater Quality Association 2016; Ballona Creek Watershed Management Group 2016). While only one scenario, Scenario 3, resulted in zero wet weather exceedances for zinc, two others, Scenarios 1 and 4, had only 1 and 2 exceedances, respectively. These three scenarios simulate treat-and-release BMPs. While Scenario 2 simulates only treat-and-release BMPs and only has 10% peak flow reduction, Scenarios 1 and 4 simulate a suite of BMPs with peak flow reductions of 43% and 65%, respectively. Scenario 2, simulating only infiltration BMPs, has a 95% reduction in peak flows but only 27.3 % zinc wet weather compliance. When considering the number of exceedances, it is important to compare the actual number of exceedances to the total possible number of exceedances, referred to as TMDL compliance (Figure 2.3). Each scenario has a different number of wet and dry weather days based on the type of BMPs simulated and the volume of stormwater they capture. For example, Scenario 2 (8 wet weather zinc exceedances) may be initially considered more successful than Scenario 5 (18 wet weather zinc exceedances). However, Figure 2.3 shows that Scenario 2 is in compliance only 27.3% of the time (8 actual exceedances out of 11 possible exceedances) while Scenario 5 is in compliance 79.3% of the time (18 actual exceedances out of 87 possible exceedances). Scenarios that include treat-and-release-based BMPs (Scenarios 1,3, and 4) have the best compliance (92%–100% in compliance with two or less exceedances per year). TMDL compliance is not only dependent on BMP performance to reduce pollutant loadings but also how BMPs impact the number of dry versus wet weather days per year.

2.5.5 Dominguez Channel

All of the DC scenarios were designed to manage the 85th percentile storm volume, and thus cost can be more directly compared to one another than in the BC scenarios. Scenarios 2 and 3 are the cheapest options because the BMPs they utilize have a lower cost per treatment volume while Scenarios 1 and 1b are the most expensive. Scenarios with infiltration-based BMPs (Scenarios 1, 1b, 3, and 3b) have a higher peak flow reduction than the treat-and-release Scenarios 2 and 2b. Because porous pavement is an infiltrating BMP, it does increase the peak flow reduction from 4.4% in Scenario 2 to 34% in Scenario 2b. Scenario 2, despite having a low peak flow reduction, has the highest number of wet weather days because it maintains higher volumes of stormwater in the channel. DC scenarios were only simulated for wet weather because no dry weather TMDLs for metals have been established in the DC watershed. None of the DC scenarios resulted in eliminating load-based exceedances for copper or zinc; 5–11 copper exceedances and 5–7 zinc exceedances remained after BMP implementation (Figure 2.3). The treat-and-release Scenario 2 (vegetated swales and dry ponds) resulted in the fewest wet weather zinc exceedances per year and the best compliance (Figure 2.3). However, Scenario 2 did not have the fewest wet weather copper exceedances. It should be noted that even though pollutant loadings are reduced, wet weather TMDL compliance is worse with BMPs than without BMPs in the DC watershed, except for Scenario 2. This is due to the wet weather threshold (1.78 cm) staying stagnant while the number of days that exceeds that threshold decreases (due to the implementation of BMPs and thus flow reduction). For example, before BMPs were implemented, there were 32 total possible wet weather exceedances and 17 zinc wet weather exceedances for a compliance percentage of 46.9%. With implemented BMPs in Scenario 1, there were eight total possible wet weather exceedances and six zinc wet weather exceedances for a compliance percentage of 25.0%. The number of exceedances decreased (17–6) but compliance worsened (46.9%–25.0%). None of the BMP scenarios is successful at eliminating copper exceedances. Copper exceedances occurred on 100% of wet weather days in Scenario 2, 2b, 3, and 3b (0% compliance). Scenarios 1 and 1b copper exceedances occurred on all wet weather days with an exception of one day (12.5% and 16.7% compliance, respectively). Additional modeled scenarios were run as part of a posthoc analysis, and they show that even when increasing the volume of water captured, increasing BMP decay rates, and lowering the EMCs throughout the watershed, compliance does not reach 100% (Mika et al. 2017b). The water quality is so poor in the DC watershed that the modeled BMPs will not be sufficient in eliminating exceedances.

2.5.6 Los Angeles River

The BMP scenario ancillary criteria is similar to those modeled in the DC watershed with treat-and-release scenarios exhibiting lower peak flow reduction but a higher number of wet weather days. Infiltration-based BMP scenarios are more successful at reducing peak flows. The addition of porous pavement results in lower TMDL compliance. Scenarios 3 and 3b, simulating infiltration and treat-and-release–based BMPs, performs fairly well in terms of all ancillary criteria because the benefits of both BMP types are gained. None of the LAR BMP scenarios eliminated dry or wet weather exceedances entirely when capturing the 85th percentile storm. Copper wet weather compliance in the LAR BMP scenarios resulted in only two or less exceedances per year. None of the BMP scenarios completely eliminated zinc wet weather exceedances. However, results show that Scenario 2 performs well with 100% TMDL compliance for copper and 80% compliance for zinc. While Scenarios 2 and 3 performed well with 3 and 2 zinc wet weather exceedances, respectively, Scenario 3 has a significantly higher compliance rate. Both Scenario 2 (treat-and-release) and Scenario 3 (treat-and-release and infiltration) perform better than Scenario 1 (infiltration) in both exceedances per year and compliance. It should be noted that there are dry weather TMDLs at nine separate locations in the drainage network for copper and lead but only one for zinc. Thus, as copper and lead have TMDLs for all nine tributaries, the total possible number of potential dry and wet weather exceedances was 9 × 365 ¼ 3,285 per year. The total number of possible dry and wet weather exceedances for zinc is only 365 because Rio Hondo is the only tributary with a zinc TMDL. Dry weather load-based exceedances per year in Figure 2.3 account for all exceedances for the nine tributaries. While dry weather exceedances for all metals were still present after implementing BMPs, compliance is greater than 95% for all scenarios and pollutants. Further analysis showed that some of these remaining exceedances are due to an increase in total possible dry weather exceedances per year. For example, there are 333 dry weather days per year without BMPs. However, when BMPs are implemented throughout the watershed, the number of dry weather days increases (between 17 and 28 days per year) due to the capture and infiltration of stormwater (and thus lower in channel flows). Scenario 2 (treat-and-release) resulted in the lowest exceedances per year for dry weather TMDLs in LAR.

2.6 Discussion

2.6.1 Sources of Water Quality Degradation

The results reinforce that water quality is more degraded in watersheds with a higher percent imperviousness and pollutant loading. DC has the most degraded water quality. It is the most urbanized of the three studied with the largest percentage of industrial, transportation, and commercial land uses, which have the highest relative pollutant EMCs in runoff. The BC watershed has the lowest impervious area and calibrated EMCs, and thus it has the least degraded water quality. Water quality found throughout the LAR watershed is worse than that seen in the BC, which is due to having similar percent imperviousness but higher percentage of land uses with elevated EMCs. However, water quality in LAR is less impaired than the DC watershed despite having the highest calibrated EMC values. Urban runoff is directly related to watershed imperviousness (Brabec, Schulte, and Richards 2002). Although percent imperviousness does not directly contribute pollutants to the rivers, it alters the hydrology, which in turn affects both water quantity and quality (Roesner, Bledsoe, and Brashear 2001; Booth and Bledsoe 2009; Shuster et al. 2005). Watersheds with a higher percent imperviousness have a higher runoff ratio resulting in a larger percentage of the stormwater falling onto the watershed area flowing over urban land surfaces and thus a higher portion of pollutants being transported to the channel rather than infiltrating. Additionally, watersheds with a higher percent imperviousness are associated with land uses that tend to have high pollutant loads. For example, industrial land uses are highly impervious and have relatively higher EMCs. Variety in a watershed land use distribution, such as the forested non urbanized region in LAR, mitigates water quality degradation by contributing cleaner water with low heavy metal pollutant loads. Therefore, when a watershed is both highly impervious and has elevated pollutant EMCs, the changes in hydrology combined with the additional loading to the watershed lead to great loads in the river, and more challenges when meeting TMDLs. In some cases, water quality can be degraded to the point that reaching water quality compliance may be unfeasible. It is imperative to characterize the urban physical properties of an urban watershed in order to accurately to improve the decision-making process for a unique watershed.

2.6.2 Feasibility of Water Quality Compliance

Land use characteristics and baseline water quality affect the feasibility of reaching water quality compliance even with the implementation of BMPs. While TMDL exceedances can be successfully eliminated in the BC watershed, only two of the LAR BMP scenarios and none of the DC scenarios eliminated all copper or zinc exceedances, and exceedances occurred on almost all wet weather days. The BC watershed has the least degraded water quality and is the only watershed in which the modeled BMP scenarios were successful in eliminating all exceedances, including those that do not capture the full 85th percentile storm. The baseline modeled water quality in the DC watershed is so poor that BMPs are not sufficient even when capturing the 85th percentile storm. While dry weather exceedances are dramatically decreased in the LAR watershed when BMPs are implemented, there are still a large number of exceedances for all heavy metals. It was also found that the majority of the LAR dry weather exceedances occur at specific TMDL locations. It is unfeasible to capture and treat or infiltrate 100% of the stormwater, so in watersheds dominated by impervious land surfaces with high EMCs, the pollutant loads in the river channel are too great to mitigate. Additionally, in such watersheds, water quality compliance is not necessarily improving, even though in-channel pollutant loads are successfully decreased, and is sometimes worse with the implementation of BMPs. While exceedances decrease when BMPs are implemented, the number of total possible wet weather exceedances also decreases, which results in a net increase in the rate of exceedances. Watersheds that have a more degraded baseline water quality, DC, exhibit a smaller difference between total possible and actual exceedances with BMPs.

2.6.3 Comparing BMPs for Water Quality Objectives

When hydrologic modeling results show that the primary objective of a watershed management plan is difficult to achieve even with the implementation of BMPs, the available option of BMP types is limited and depends on water quality degradation and the ability of a BMP type to eliminate exceedances. Because eliminating TMDL exceedances is a major priority in LA, this criterion should be considered before others, such as peak flow reduction and BMP area, when determining the appropriate types of BMPs. Water quality mitigation performance varies across different types of BMPs; thus the efficiency and performance of different suites of BMPs is also unclear (Liu et al. 2017). Treat-and-release BMPs are more effective at eliminating wet weather exceedances because they return treated, lower concentrated water to the channel to dilute remaining pollutants. This study found that infiltration-based BMPs are not as effective at eliminating load-based TMDL exceedances in semiarid urbanized watersheds and thus should not be relied on to eliminate exceedances. The BC watershed has the least degraded water quality and multiple BMP scenarios eliminated TMDL exceedances, allowing for the option to use both treat-and-release–based as well as infiltration-based BMPs. The DC watershed has the most degraded water quality and none of the BMPs scenarios eliminated exceedances. BMPs that treat and release the water, such as DC Scenario 2, perform the best because they have the lowest number of exceedances and highest TMDL compliance percentage; therefore, treat-and-release BMPs should be prioritized. The LAR watershed has variable water quality degradation and mixed results, due to the multiple compliance locations and complex drainage network. The LAR BMP scenarios were not as successful as the BC watershed but achieved better compliance than the DC watershed. While treat-and-release BMPs should be prioritized in more urbanized portions of the LAR watershed, infiltration-based BMPs can be implemented in areas that have less degraded water quality. When conventional BMPs, such as those utilized in this study, are not efficient in eliminating TMDLs (J. M. Wolfand et al. 2018), additional efforts may also need to be considered. Wolfand et al. (2018) found that enhanced BMPs that utilized media such as granulated activated carbon are much more efficient than existing conventional BMPs. Additionally, source control, such as the restriction on copper brake pads, which could reduce urban runoff copper levels by 46%–57% by 2024 (California Stormwater Quality Association 2016) or targeting of pollutant hot spots (such as industrial dischargers in the DC watershed), would help to reduce urban runoff loadings and decrease the reliance on BMPs. A third option includes the use of in-stream BMPs, which is a novel practice and an area for future research.

2.6.4 Deciding the Optimal Pathway for IWMPs

While water quality regulation compliance is the primary factor guiding stormwater BMP implementation within this study, other available benefits and tradeoffs should be considered during the decision-making process. The secondary or ancillary benefits of stormwater management to be considered for an IWMP are limited to the BMP types available for implementation. It is important to incorporate the preceding discussion points while considering tradeoffs because they guide the decision-making process to determine the optimal suite of BMPs based on the needs of the watershed. Stakeholders within the BC watershed can put more weight on different benefits and discuss the tradeoffs when deciding which types of BMPs to implement because they have an option of both treat-and-release as well as infiltration-based BMPs. When stakeholders, such as those in the DC watershed, are limited to choosing BMPs (treat-and-release) that will actually achieve water quality compliance, the decision-making process is restricted. The ancillary benefits associated with other BMP types (infiltration), such as ground water recharge and reduced peak flows (Roesner, Bledsoe, and Brashear 2001), will not be available in that decision-making process. In cases where a watershed is diverse, such as the LAR watershed, multiple BMP types should be considered in subwatersheds or areas that are not as urbanized in order to maximize the benefits available to the whole watershed.

Analyzing the tradeoffs of different types of BMPs is crucial for an economically efficient and environmentally sustainable IWMP. For example, infiltration BMPs that promote groundwater recharge offer monetized benefits, such as reducing the price of imported water by increasing local supplies through recharge (Tetra Tech 2016). However, in rivers that are concrete lined, such as those in LA, infiltration-based BMPs reduce in-channel flows and could potentially eliminate dry weather baseflow in highly channelized, semiarid regions such as LA (Caraco and Schueler 2000). Treat-and-release BMPs that do not infiltrate maintain higher volumes of water in the channel (Read et al. 2018). It should be noted that the impact of BMPs on base or interflows is highly dependent on the inputs and outputs of baseflow considering natural physiographic features, anthropogenic features, and whether the river channel is hydrologically connected to the groundwater system (Bhaskar et al. 2016). Sustaining higher volumes of water in the river is not only beneficial for the health of the ecosystem (Bhaskar et al. 2016) but also promotes recreation, which are both important tradeoffs to consider. While cost is also a crucial tradeoff to evaluate, capital costs alone were utilized to drive the SUSTAIN cost algorithm for this research and were based on previous BMP construction projects found throughout LA. To understand the full implications of costs, a life cycle cost analysis needs to be included. Scenarios that include BMPs with a higher cost per unit, such as porous pavement, may not be a feasible option for stakeholders that are budget-limited in their decisions to satisfy water quality, cost, BMP footprint, and infiltration criteria. However, regional BMPs, which include infiltration trenches, have a lower cost per unit volume of water treated and thus BMP solutions that include them are a less expensive solution but still offer the benefits of infiltration-based BMPs.

Stakeholders also need to consider and compare the available BMP options across all watersheds that are part of the IWMP. The lack of options in one watershed may alter the decisions in the adjacent watersheds. For example, if LA is working toward groundwater recharge, they may need to consider using infiltration BMPs throughout the BC watershed in order to optimize groundwater recharge because there is little opportunity for this in the DC watershed. Similarly, in the LAR watershed, subwatersheds that are more urbanized, and thus more similar to the DC watershed, might prioritize treat-and-release BMPs while subwatersheds that are not as urbanized, such as the BC watershed, may use the opportunity to promote groundwater recharge by using infiltration-based BMPs. Finally, this research shows that stakeholders cannot assume that a water management plan that is successful in one watershed will automatically be successful in an adjacent watershed. Each watershed needs to be modeled and analyzed separately.

2.7 Conclusion

Determining the optimal suite of BMPs to eliminate TMDL exceedances is complex and multifaceted, as indicated in our results. However, determining the optimal suite of BMPs based on water quality compliance alone is unrealistic when creating an IWMP. Stormwater models utilize unique urban physical characteristics found in watersheds (such as land use and EMCs) and BMP performance to simulate water quantity and quality, and can provide stakeholders accurate and detailed implications of varying water management options to ensure they are making the most informed decision possible. Modeling results confirm that when land use properties and calibrated EMC values are unique enough, different watersheds have varying water quality degradation. Water quality compliance results when BMPs are implemented also vary based on the baseline water quality degradation. Depending on water quality compliance results, different BMP types may need to be prioritized in order to eliminate exceedances. Treat-and-release BMPs are most successful at eliminating exceedances within highly urbanized watersheds located in a semiarid climate. Treat-and-release BMPs also result in a larger difference between total possible exceedances and actual exceedances. Less urbanized watersheds with less degraded water quality are able to implement both infiltration- as well as treat-and-release–based BMPs. However, several deciding factors must be considered when developing an IWMP, such as cost, pollutant load reduction, peak flow reduction, and groundwater recharge. While treat-and-release BMPs are optimal for eliminating load-based TMDL exceedances, infiltration-based BMPs are optimal for reducing peak flow and increasing groundwater recharge potential. Stakeholders must consider the tradeoffs of different types of BMPs by using several criteria, especially when taking into account the specific needs of their watershed. However, stakeholders must also consider the balance of tradeoffs between adjacent watersheds. Less urbanized watersheds may need to prioritize infiltration-based BMPs in order to make up for the lack of options in adjacent watersheds part of the same IWMP that are more urbanized and have more degraded water quality. Another important implication to note is that if BMP scenarios that are successful in less urbanized watersheds are assumed to be successful in more urbanized watersheds, several issues can arise and billions of dollars can be spent on a water management plan that would not necessarily reach compliance. This research shows that even though three watersheds are adjacent to one another within the same city, they must be modeled and analyzed separately when determining the optimal suite of BMPs to implement as part of an IWMP.

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CHAPTER 3

INVESTIGATING TRADEOFFS OF GREEN TO GREY STORMWATER INFRASTRUCTURE USING A PLANNING-LEVEL DECISION SUPPORT TOOL

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3.1 Abstract

Integrated decision support tools are needed to investigate the tradeoffs of stormwater control measures (SCMs) and determine the optimal suite of SCMs based on the needs of a watershed. In this study, an urbanized watershed undergoing infill development, the Berkeley neighborhood located in Denver, CO, USA, is modeled using a modified version of the EPA's System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN). The primary goal is to compare the relative performance between green and grey SCMs, use optimizations and a planning-level approach to assist in decision-making, and discuss how the preferences of stakeholders and the community can shift which SCMs are optimal for the watershed. Green and grey SCMs have variable hydrologic performance based on design and function, and both offer benefits that may be important to decision makers. Results show that infiltration trenches and underground infiltration are optimal for reducing flow volumes while vegetated swales and underground detention are optimal for pollutant concentration reduction. As stakeholders value both of these benefits, the optimal stormwater solution in Berkeley neighborhood includes a mix of green and grey SCMs. Determining the optimal SCMs while considering tradeoffs in costs and associated benefits is complex and multi-faceted. Modeling results such as those presented here are critical for informing stakeholders' decision-making process.

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3.2 Introduction

Alterations to the hydrologic regime and degradation to water quality are major issues associated with rising percent imperviousness in cities undergoing urbanization (Booth and Bledsoe 2009; Brabec, Schulte, and Richards 2002; Paul and Meyer 2001; M. O. Driscoll et al. 2010; USEPA 2018b). Cities across the United States and the world have adopted stormwater management plans that utilize stormwater control measures (SCMs) (also known as best management practices, low impact development, and/or green/grey infrastructure). SCMs mitigate the impacts of urbanization (NRC 2008; USEPA 1999; Liu et al. 2017; UDFCD 2010b; Bracmort et al. 2006) that are detrimental to both public health and the environment (Ando and Netusil 2018; Charlesworth and Booth 2016). There is usually a primary driver for municipalities to manage stormwater, such as reducing flood risk or meeting water quality regulations such as those derived from the Clean Water Act (Clean Water Act 2011). However, there can be incentives to implement SCMs for the multiple hydrologic and ancillary benefits they offer (K. Spahr 2020; Brown 2008; Fitzgerald and Laufer 2017) such as groundwater recharge potential (Roesner, Bledsoe, and Brashear 2001; Sun et al. 2014) or improved eco-hydrologic conditions (Karr and Dudley 1981).

SCMs come in a wide range of designs that exist on a grey-to-green continuum where a particular SCM is considered either “greener,” “greyer,” or “hybrid” based on design materials, drainage area, dominant hydrologic and water quality processes, community benefits, and cost (C. D Bell et al. 2019). Examples of SCMs that fall on the greener side (henceforth, *green SCMs*) of the continuum include bioretention, dry ponds, infiltration trenches, and vegetated swales. Green SCMs serve to incorporate green space into the urban environment by using vegetation as part of the design, and are considered an integral component of stormwater management plans (C. D Bell et al. 2019; UDFCD 2010b). The U.S. Environmental Protection Agency (EPA) has encouraged municipalities to implement green SCMs throughout their watersheds (USEPA 1999). On the far grey side of the continuum, large concrete structures, such as waste-water treatment plants and regional storage facilities, are built and designed to store and retain stormwater (C. D Bell et al. 2019; CMWR 2013; LADPH 2016; USEPA 2001). These systems are occasionally designed in conjunction with a treatment facility. Green and large grey SCMs are well documented and have been extensively modeled.

Lesser-known SCMs that fall on the continuum in between the green SCMs and large grey SCMs include smaller distributed grey and hybrid SCMs (henceforth, *grey SCMs*). Grey SCMs include above and underground storage systems that are designed to either retain and infiltrate stormwater into the subsurface (infiltration-based) or temporally detain and slowly release stormwater (treat-and-release) back into the storm sewer network (USEPA 2001; NYCDEP 2012; LADPH 2016; UDFCD 2010b). Grey SCMs deviate from the well-known combined sewer systems by incorporating both small- and large-scale vaults, pipes, and gravel beds that have a wide variety in design (Contech 2019). While these systems have been utilized and implemented since at least 2001 ("International Stormwater BMP Database" 2016), they are recently gaining popularity due to improved designs and the benefits they offer (Cessna 2017; New York State 2015). Their flexible design and ability to be implemented underneath parking lots, structures, and parks in areas with limited space makes them a viable option, especially for high density cities such as New York City, USA (UDFCD 2010b; NYCDEP 2012). However, there is a paucity of water quantity and quality data from these structures as well as studies that have modeled them (Mcintosh et al. 2015; Smart 2020; Zawiliski and Sakson 2008; Jayanti and Narayanan 2004; Martino et al. 2011; Wang et al. 2004).

Hydrologic modeling is a practice commonly used to assist in solving problems and making decisions about stormwater management particularly given the complicated water quantity and quality issues of urban environments (Liu et al. 2017). However, there exists uncertainty in how distributed SCMs, that are designed to capture a specific stormwater runoff volume from one site, will scale up and impact the watershed as a whole (Jefferson et al. 2017; Golden and Hoghooghi 2018). Jefferson et al. (2017) and Golden et al. (2018) conducted extensive literature reviews on watershed-scale SCM studies and found that green SCMs in general will provide water quantity benefits as well as water quality improvement. Benefits such as these are often used as a primary objective, or evaluation factor, in modeling studies. However, these studies only explore the use of green SCMs. Additionally, there is a lack of studies that evaluate the hydrologic impacts of green versus grey SCMs on hydrology. This is important to consider as Gallo et al. (2020) and Wolfand et al. (2019) demonstrated the importance in considering multiple SCM types to determine which types most effectively achieve the primary goal of a watershed. Additionally, Spahr et al. (2020), demonstrated in a cross-city public survey that the consideration of multiple benefits is important to the general public. Grey SCMs may be able to provide some of these benefits.

Strategic planning is defined as “the process by which the guiding members of an organization envision its future and develop necessary procedures and operations to achieve that future” (Nolan, Goodstein, and Goodstein 2008). A strategic plan helps to direct decision makers to set priorities and determine a pathway that will best achieve those priorities (Downs 2018). In regards to stormwater management, the most effective SCMs need to be determined before more site-scale or design decisions are made. A planning-level modeling approach can help stakeholders take the first step in identifying optimal SCM solutions based on the specific needs of their watershed. Models that use optimizations, such as the EPA’s System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN), can be used to evaluate multiple SCM types and thousands of different solutions to analyze the performance and impacts of SCMs (Shoemaker et al. 2009). However, SUSTAIN currently only includes green SCMs. Additionally, most studies that have used optimizations to decide between SCMs focus on SCM placement (Limbrunner et al. 2013; Hipp, Lejano, and Smith 2006; Perez-pedini, Limbrunner, and Vogel 2006), a limited number of SCM types or hydrologic outputs (Zhang et al. 2012; Baek et al. 2015; Yang, Fong, and Chui 2018; Jenq et al. 1983; Schleich and White 1997), or a site-scale/design-level analysis (Loáiciga et al. 2015; Mays and Bedient 1982; Sample et al. 2001). While these design-level considerations may initially identify which SCMs may be optimal to achieve a primary goal, the consideration of multiple benefits may expose which additional SCMs should be included to achieve other goals of a watershed-scale stormwater plan. Multi-SCM and multi-benefit analyses are needed at watershed-scales in order to determine the suite of SCMs that will maximize environmental and community benefits that are crucial to an integrated water management plan.

In the current study, we develop a modeling framework that encompasses green and grey SCMs to 1) compare the relative hydrologic performance of green to grey SCM designs on a watershed-scale, 2) demonstrate how to use optimizations to perform a planning-level analysis, and 3) investigate how the varying priorities of stakeholders can shift which SCM solutions are considered optimal based on their needs. We apply the model to the Berkeley neighborhood watershed in Denver, Colorado, to demonstrate its use.

3.3 Study Area

The Berkeley neighborhood, located in northwest Denver, is a 419-ha watershed that had 53% impervious cover in 2014 (C. L. Panos et al. 2018). This neighborhood is undergoing rapid infill development, also referred to as redevelopment, which is a phenomenon where developed parcels of land are redeveloped into denser land uses resulting in less green space and higher imperviousness (Thomas 2009; USEPA 2016). Residential parcels with moderately sized structures and vacant areas are being redeveloped into high-density residential parcels with structures that take up a larger percentage of the parcel area (Cherry et al. 2019). Cherry et al. (2019) predicted that between 2014 and 2024, 15% of the total parcels in Berkeley will undergo infill development resulting in a 1% absolute increase in imperviousness percentage. Panos et al. (2018) applied the work done in Cherry et al. (2019) to a calibrated and validated hydrologic model in PCSWMM to assess the impacts of infill development on current stormwater runoff volumes. In the Panos et al (2018) study, a *Current Baseline* scenario was developed and represented the Berkeley watershed land use and runoff volumes in the year 2014 with an assumption that no infill development had taken place. A *Future Baseline* scenario in the same study represented land use characteristics and resulting runoff volumes due to a moderate scenario of predicted future infill development of 4.7% increase in impervious percentage in the Berkeley neighborhood. Panos et al. (2018) found that a 4.7% increase in imperviousness will result in an increase of 7.3%, 5.7%, and 4.1% in total watershed runoff volume from the Current Baseline scenario for the 2-yr, 10-yr, and 100-yr, 24-hr rainfall events, respectively. Simulations from Panos et al. (2018) were chosen to be further explored in this study. Table 3.1 shows land use area throughout the watershed for the Current Baseline total area, Future Baseline non-infill developed area, and Future Baseline infill developed area. In the Future Baseline scenario, single family homes are redeveloped into multi-family units, so all infill developed area in the Future Baseline scenario is classified as a residential land use (Table 3.1). A small area of vacant open space is also redeveloped to residential land use (Table 3.1). The impacts of redevelopment include surcharging, or overflowing, of the stormwater drainage network and increased risk of flooding and thus the need for planning-level stormwater management (C. L. Panos et al. 2018; Cherry et al. 2019).

Table 3.1 Land use area in the Berkeley neighborhood for the Current Baseline and Future Baseline scenarios. The Future Baseline scenario is split into infill developed and non-infill developed areas.

	Current Baseline (No infill development) [ha]	% of Total	Future Baseline (non-infill developed area) [ha]	% of Total	Future Baseline (infill developed area) [ha]	% of Total
Commercial	18	3.81	18	4.68	0.00	0.00
Industrial	13	2.68	13	3.30	0.00	0.00
Residential	222	46.72	134	34.69	89	100.00
Transportation	134	28.15	134	34.60	0.00	0.00
Parks	65	13.63	64	16.56	0.00	0.00
Surface Water	24	5.02	24	6.17	0.00	0.00
Total Area	475	100.00	387	100.00	89	100.00

Urbanization occurring throughout the City of Denver has placed stress on the storm drainage network and engineered channels that were not designed to accommodate the resulting larger volumes of water. The City and County of Denver has an established Storm Drainage Master Plan which gives guidance on the implementation of stormwater management strategies in accordance to regulations and policies to reduce the risk of flooding (City and County of Denver 2013, 2019; City and County of Denver Public Works 2018; UDFCD 2010b). One objective of this plan includes on-site detention of flood flows for all development and infill development projects that are 0.202 ha or greater. It should be noted that Panos et al. (2018) determined that the average area of parcels predicted for redevelopment in the Berkeley neighborhood is 0.053 ha. A second objective is to reduce pollutant loadings while also achieving a wide range of ancillary benefits (City and County of Denver Public Works 2018). While nitrate and E. coli are the only established Total Maximum Daily Loads (TMDLs) regulations in Denver, there is concern about other urban pollutants such as nutrients, heavy metals, and Total Suspended Solids (TSS) (City and County of Denver Public Works 2018), and many other large cities are regulated on these pollutants (e.g., Los Angeles, California). The Berkeley neighborhood watershed was scored as medium-high risk for E. coli, medium-low for TSS, and medium-high for nutrients (City and County of Denver Public Works 2018). Additional objectives include maximizing benefits associated with the implementation of green infrastructure such as reducing effects of urban heat island, improved equity, and increased biodiversity and habitat (City and County of Denver Public Works 2018). The Berkeley neighborhood watershed was chosen as a case study to demonstrate the capabilities of a planning-level watershed tool to achieve these objectives.

3.4 Methods

3.4.1 Model

This work used an integrated Decision Support Tool (i-DST) that includes both a watershed-scale and site-scale hydrologic model, life cycle cost and assessments, and a benefit assessment to explore the tradeoffs of green to grey stormwater infrastructure in the Berkeley neighborhood. We performed an analysis with the i-DST to help determine the optimal number and suite of SCMs to mitigate the impacts of future infill development in the Berkeley neighborhood. The i-DST watershed-scale module utilizes the EPA's SUSTAIN model (Shoemaker et al. 2009). The external SCM simulation module in SUSTAIN implements aggregate SCMs on a watershed-scale and assesses SCM performance on calibrated and validated stormwater flow and pollutant load time series. These time series outputs can be acquired from either the SUSTAIN internal land simulation or any other hydrologic model that outputs calibrated and validated flow and loads. To improve the tool and better address the needs of stormwater managers, several changes were made to the SUSTAIN code in order to represent a larger suite of SCMs (including grey SCMs) and allow a larger list of stakeholder criteria (called *evaluation factors*), resulting in an updated version of SUSTAIN called *i-DST SUSTAIN*.

An extensive literature review on grey/hybrid/underground infrastructure was conducted to determine a representative group of grey SCMs to be added to i-DST SUSTAIN (Contech 2019; NYCDEP 2012; LADPW 2010; UDFCD 2010b; Minneapolis Public Works 2017; USEPA 2001; State of Michigan 2017; CMWR 2013; IDEQ 2020). Four grey-SCMs were added to i-DST SUSTAIN including underground infiltration structure (UIS), underground detention structure (UDS) (no infiltration), underground gravel beds, and above ground storage. It should be noted that designs and names of these systems vary across the United States even though their functions may be the same. For example, UIS is called an infiltration gallery in Los Angeles, CA but an underground infiltration system in Minneapolis, MN. UIS and UDS designs may take the form of a box, pipe, or half pipe within i-DST SUSTAIN. Grey-SCMs were simulated in i-DST SUSTAIN by turning off evapotranspiration and infiltration (when applicable). The i-DST

SUSTAIN function table (a table in the i-DST SUSTAIN executable input file that allows users to define surface area, volume, weir flow rate, and orifice flow rate at each defined water depth for a specified SCM) was used to represent accurate stage-volume-surface area relationships in pipes and half pipes, as well as ensure bypass when the maximum volume capacity of the SCM is reached. Seven new evaluation factors (annual and seasonal groundwater recharge potential and evapotranspiration, and seasonal flow volume, loads, and concentration) were also added to i-DST SUSTAIN as targets for the optimization algorithms. Table 3.2 lists all available SCMs and evaluation factors in i-DST SUSTAIN.

Table 3.2 Available SCM types and evaluation factors in i-DST SUSTAIN. *New option that was not originally available in SUSTAIN

SCM Types	Evaluation Factors
Green Roof	Annual & Seasonal* Average Flow Volume
Bioretention	Flow Exceedance Frequency
Infiltration Trench	Flow Duration Curve
Vegetated Swale	Peak Discharge Flow
Dry Pond	Annual & Seasonal Groundwater Recharge Potential*
Wet Pond	Annual & Seasonal Average Evapotranspiration*
Buffer Strip	Annual & Seasonal* Average Loads
Porous Pavement	Annual & Seasonal* Average Concentration
Rain Barrel	Days Above Concentration Threshold
Underground Detention Structure*	
Underground Infiltration Structure*	
Underground Gravel Bed*	
Above Ground Gravel Bed*	

3.4.1.1 Water Quantity Data

Only the external SCM simulation and optimization modules of SUSTAIN (Shoemaker et al. 2009) were utilized in this study and incorporated in the updated i-DST SUSTAIN tool. The external SCM simulation module is driven by monthly average evapotranspiration data and land use time series of surface runoff volumes. Monthly evapotranspiration values were derived from the Denver Water Administration Building gauging station (C. L. Panos et al. 2018) and used to simulate evapotranspiration processes in each SCM in the model. Validated and calibrated land use time series of surface runoff volumes were acquired from the Panos et al. (2018, 2020) modeling efforts to simulate water quantity in the model. Two sets of time series were extracted from the outlet in the Berkeley neighborhood PCSWMM hydrologic model. The first set of time series includes the 2-yr, 5-yr, and 10-yr, 24-hr design storms. The second set of time series includes continuous summer month (April – September) time series from 2013-2017. The design storms were used for a validation between the distributed PCSWMM model and the i-DST SUSTAIN lumped model while the continuous time series were used to drive the external i-DST SUSTAIN SCM module and simulate the optimization scenarios presented in this work.

3.4.1.2 Water Quality Data

Pollutant load reduction is a component of the Green Infrastructure Implementation Strategy throughout Denver (City and County of Denver Public Works 2018). Therefore, water quality was included in this study. However, water quality was not simulated in the Panos et al. (2018, 2020) modeling efforts, thus event mean concentration (EMC) data was obtained from a study that developed regional values from the National Stormwater Quality Database (C. D. Bell, Wolfand, and Hogue 2019). Runoff concentrations from the "southwest" NCDC climatic region for Total Suspended Solids (TSS), Total Phosphorous (TP), and Total Zinc (Zn) have been identified as pollutants of concern for wet weather flows in the study area and were chosen to be simulated in the model. The median EMC values, which are similar to those presented in other Denver studies (City and County of Denver Public Works 2018), were chosen to be used in this study given that the EMC values are consistent across multiple aggregate statistics in terms of relative land use EMC levels (Table 3.3). Nitrate and E. coli were not modeled in this study even though Denver has established TMDLs for these pollutants. It was determined that municipal wastewater treatment facilities are the primary point source discharges of nitrate, thus it is not considered a major nonpoint source pollutant (City and County of Denver Public Works 2018). Dry weather flows not associated with stormwater runoff were identified as the source of bacteria, thus the only established TMDL for E. Coli is for dry weather and not relevant to this study (City and County of Denver Public Works 2018).

Table 3.3 Land Use EMC values extracted from Bell et al. (2019) for TSS, TP, and Zn. Median values were used for analyses in this study. The light to dark grey shadings show which land use has a lower EMC (white shading) and a higher EMC (darkest grey shading) for each pollutant type and statistic.

Pollutant EMCs (mg/L)	Mean	Min	25th	Median	75th	Max
TSS						
Commercial	210.33	1.00	37.83	118.00	275.27	1940.00

Table 3.3 Continued

Paved Area	125.92	0.50	33.08	68.00	130.00	4800.00
Industrial	507.04	16.00	186.00	370.00	773.00	2325.00
Open Park Space	602.07	194.05	293.57	516.00	845.94	1400.00
Residential	201.76	0.30	49.00	112.50	247.49	2732.43
TP						
Commercial	0.40	0.008	0.14	0.26	0.48	6.30
Paved Area	0.39	0.070	0.15	0.28	0.42	2.60
Industrial	0.94	0.030	0.27	0.72	1.30	7.90
Open Park Space	0.52	0.210	0.33	0.53	0.64	1.00
Residential	0.56	0.03	0.29	0.45	0.71	4.96
Zn						
Commercial	0.34	0.015	0.16	0.26	0.40	3.61
Paved Area	0.24	0.001	0.08	0.16	0.28	2.10
Industrial	0.54	0.005	0.31	0.47	0.69	2.40
Open Park Space	0.26	0.040	0.09	0.20	0.35	0.73
Residential	0.16	0.0025	0.07	0.13	0.20	1.50

Note: EMC = event mean concentration; TSS = total suspended solids; TP = total phosphorous; Zn = zinc

An area-weighted approach using the land use area values in Table 3.1 and the median EMC values in Table 3.3 were used to determine a single representative EMC value (Table 3.4) for each aggregate land use runoff time series in the model (Current Baseline, Future Baseline non-infill developed, and Future Baseline infill developed). These EMC values were applied to the five-minute land use surface water runoff time series to simulate land use pollutant loading in the model. The model was not validated for water quality as there is a lack of observed data throughout the Berkeley neighborhood watershed; however, pollutant removal performance was calibrated for each individual SCM (discussed in the Modeled SCMs section).

Table 3.4 Pollutant EMCs, calculated by using land use area-weights, for Current Baseline and Future Baseline scenarios.

EMCs [mg/L]	Current Baseline (no infill development)	Future Baseline (non-infill developed area)	Future Baseline (infill developed area)
TSS	157.46	164.82	112.47
TP	0.39	0.38	0.45
Zn	0.15	0.16	0.13

Note: EMC = event mean concentration; TSS = total suspended solids; TP = total phosphorous; Zn = zinc

3.4.1.3 Modeled SCMs

SCMs selected to be simulated in i-DST SUSTAIN for this research included three green (bioretention [BR], infiltration trench [IT], and vegetated swale [VS]) and three grey (underground infiltration structure [UIS], underground detention structure [UDS], and porous pavement [PP]). All SCMs represent designs similar to those proposed in the City and County of Denver Ultra-Urban Green Infrastructure Guidelines as well as the Mile High Flood District (MHFD) stormwater management manual (City and County of Denver 2016; UDFCD 2010b). While it is recommended in Denver that underground SCMs are not used unless surface treatment has been proven to not be possible, (UDFCD 2010b) their flexible design offers alternatives to above ground infrastructure in space-limited sites and stormwater redevelopment applications, such as those in the Berkeley neighborhood watershed.

Table 3.5 displays all model inputs and design parameters used for the six individual SCMs in the model. SCM capital cost data was originally determined by using several SCM projects found throughout Los Angeles (E. Gallo et al. 2020). Projects from several sources were used for VS, BR, IT, and PP. Cost data acquired from a proprietary company, StormTrap, was used for UDS and UIS (StormTrap 2018). All cost data was then projected to be representative of the Denver area using the RSMeans 2019 city construction cost data (RSMeans 2019)

All SCMs were designed to capture stormwater runoff from a uniform design drainage area which was chosen as the average area of predicted infill developed parcels in the Future Baseline scenario, or 0.053 ha as determined by Panos et al. (2018, 2020). SCMs in Denver are commonly sized to be 5% of the impervious drainage area (City and County of Denver 2016). In addition, infill developed areas are predicted to be 70% impervious on average, thus above ground storage-based SCMs (BR, IT, and PP) were sized to be 0.0018 ha or 18.53 m^2. Width and length of these SCMs fall within the recommended guidelines for Denver. The MHFD Stormwater Best Management Practice Design Workbook was used to assist in the design for vegetated swales, named ‘grass swales’ in the workbook. Construction project design data from a proprietary company, StormTrap, was used to assist in design of the UDS and UIS systems (StormTrap 2018).

All storage-based SCMs (BR, IT, PP, UDS, and UIS) were designed to be able to capture and treat runoff produced by the Water Quality Capture Volume (WQCV) event, which in the study area corresponds to the 80^{th} percentile storm and a 17.5 mm rainfall depth (C. L. Panos et al. 2018; UDFCD 2010b) . Design of surface storage and soil storage layers were informed by this criterion. SCM design was based on this event because it was found by a study of 36 years of data in Denver that capturing and effectively treating the runoff produced by this event will significantly improve water quality (Urbonas, Guo, and Tucker 1989). BR, IT, and PP were all designed with underdrains as this is the typical practice in Denver due to underlying native clay soils (UDFCD 2010b; City and County of Denver 2016). UDS does not infiltrate and does not need an underdrain. Finally, while UIS may be designed with or without an underdrain, the authors opted to include one so that the performance and benefits of a system with full infiltration can be compared to other designs in the study.

A software package, named DeCal for "decay calibration" was developed in order to assist users in calibrating pollutant first order decay rate, K, or K-C* pollutant treatment parameters for SCMs utilized in water quality models. The tool uses a stochastic approach and requires inputs of observed data (influent and effluent EMCs, storm influent volumes, storm influent duration, and precipitation) as well as SCM parameters (design geometry and substrate properties) to perform a statistical analysis and find the best fitting K or K-C* values. The current study used a first-order decay model to simulate SCM performance. Pollutant decay rates were calibrated using the DeCal tool within i-DST SUSTAIN by using influent and effluent concentrations from SCM sites reported in the international BMP database (IBMPD) ("International Stormwater BMP Database" 2016). Projects from Lakewood, Colorado were used for BR, IT, UDS, and UIS. Due to the lack of data in the IBMPD originating from the southwest area, projects from southern Los Angeles, with a similar climate and soil type to Denver, were used for VS. Finally, while there are a limited number of studies that do report influent and effluent values for PP, this study errs on the conservative side and assumes a decay rate of zero due to the limited SCM sites and number of storms reported in the IBMPD ("International Stormwater BMP Database" 2016; UDFCD 2010b).

Table 3.5 SCM capital cost, design parameters, soil parameters and pollutant decay rates.

Parameter	VS	BR	IT	UDS	PP	UIS
Capital Cost [per m^3]	281.50[I]	408.23[I]	168.80[I]	493.69[J]	438.61[I]	424.13[J]
Surface Storage Layer						
Width [m]	0.30[A]	1.52[B]	1.52[B]	2.52[F]	1.52[B]	2.31[F]
Length [m]	11.06[A]	12.19[B]	12.17[B]	2.52[F]	12.17[B]	2.31[F]
Surface Area [m^2]	16.86	18.54	18.54	6.35	18.54	5.35
Green space added [m^2]	16.86	18.54	18.54	0	0	0
Slope [A]	5.5%	-	--		-	-
Weir Height [m]	0.15[A]	0.15[B]	0.23[B]	1.45[C]	0.01[B]	1.45[C]
Weir Width [m]	-	0.30	0.30	NA	1.52	NA
Vegetative Fraction [E]	0.2	0.2	0.2	0.2	0.2	0.2
Orifice height [m]	-	0.01	-	0.03	-	-
Orifice diameter [cm] [A]	-	0.39	-	0.39	-	-
Soil Storage Layer						
Infiltration Method	Green Ampt	Green Ampt	Green Ampt	Green Ampt	Green Ampt	Green Ampt
Soil Depth [m] [B, F]	0.15	0.79	0.65	-	0.65	0.65
Porosity [D]	0.42	0.435	0.41	-	0.435	0.41
Field Capacity [E]	0.1	0.1	0.1	0.1	0.1	0.1
Wilting Point [E]	0.095	0.095	0.095	0.095	0.095	0.095
Soil types	Sandy clay loam	Sandy loam	Loamy sand	-	Sandy loam	Loamy sand
Soil layer infiltration [cm/hr][A]	0.13	0.25	0.55	0	0.25	0.55
Suction Head [m] [E]	0.91	0.91	0.91	0	0.91	0.91
Underdrain Storage Layer						
Consider underdrain?	no	yes	yes	no	yes	no
Void Ratio [E]	-	0.3	0.3	-	0.3	-
Back infil rate [cm/hr] [G]	-	0.08	0.08	-	0.08	-
Media below drain [m] [B]	-	0.03	0.15	-	0.08	-
Pollutant decay rates						
IBMPD Data [H]	CA RVTS System	Lakewood CO Iris Garden	Lakewood CO Dry Pond	Lakewood CO Retention Vault	NA	Lakewood CO Retention Vault
TSS (1/yr)	0.122	2.15	0.757	0.396	0.00	0.396
TP (1/yr)	0.00	0.0997	0.059	0.00015	0.00	0.00015
Zn (1/yr)	4.864	0.72	0.615	0.038	0.00	0.038

Note: BR = Bioretention; IT = Infiltration Trench; PP = Porous Pavement; VS = Vegetated Swale; UDS = Underground Detention Structure; UIS = Underground Infiltration Structure; TSS = Total Suspended Solids; TP = Total Phosphorous; Zn = Zinc

A = (UDFCD 2010b)

B = (City and County of Denver 2016)
C = (Contech 2019; StormTrap 2018)
D = (Clapp and Hornberger 1978),(Minnesota Stormwater Design Team 2013) ,(Shoemaker et al. 2009)
E = (C. Panos 2020)
F = Based on required WQCV event : (Urbonas, Guo, and Tucker 1989),(UDFCD 2010b)
G = (USGS 2017)
H = ("International Stormwater BMP Database" 2016)
I = (E. Gallo et al. 2020) using (RSMeans 2019) to project values for Denver
J = (StormTrap 2018) using (RSMeans 2019) to project values for Denver

3.4.1.4 Model Routing

The Berkeley neighborhood model was set up in i-DST SUSTAIN as a lumped model. The Current Baseline time series was simulated through i-DST SUSTAIN as one single land use time series with the total watershed area of 419 [ha]. First, flow was routed directly to the virtual outlet without the implementation of any SCMs to represent the two scenarios without SCM implementation: Current Baseline and Future Baseline. Then, the Future Baseline output flow was split into two separate land use time series representing two lumped watersheds: one for the non-infill developed area (331 ha) which is routed to the outlet and one for the infill developed area (88 ha) which is routed to SCMs. This new scenario is referred to as *Future SCM*. i-DST SUSTAIN can simulate SCMs as an aggregate unit, or in other words, simulate a specified number of SCMs simultaneously and in parallel. Total outflow from the aggregate SCM (i.e., through underdrains or surface overflow) is then routed to the virtual outlet where evaluation factors are analyzed and optimized.

3.4.2 Model Validation

The i-DST SUSTAIN model output of hourly water quantity flow for the Current Baseline, Future Baseline, and Future SCM scenarios were compared to the PCSWMM results (C. Panos 2020) to provide model validation. Bioretention units were used in the Future SCM scenario for this analysis and all BR design parameters used in Panos et al. (2020) were used in i-DST SUSTAIN. BR units were sized to 1% and 5% of the parcel area draining to the SCM. Several statistics including Nash Sutcliffe Efficiency, R^2, and Percent Bias were used to compare PCSWMM model outputs to the i-DST SUSTAIN outputs.

3.4.3 Optimization Module

The SUSTAIN optimization uses algorithms (NSGA-II or Scatter Search) to determine optimal SCM solutions by simulating thousands of SCM combinations and optimizing (i.e., reducing) cost while achieving a specific target evaluation factor, such as pollutant load reduction (Shoemaker et al. 2009). The scatter search algorithm is meta-heuristic and utilizes a deterministic and probabilistic approach to generate a diverse population of near optimal solutions based on a specific target value. The non-dominated sorting genetic algorithm (NSGA-II) is a multi-objective evolutionary objective algorithm that finds the optimal solutions along the 1st non-dominated Pareto front within the specified target value range. Optimization controls that define the optimal solution include cost minimization and a cost effectiveness curve (Shoemaker et al. 2009). Cost minimization aims to minimize cost while achieving a certain evaluation factor goal (Equation 3.1). A cost effectiveness curve aims to both minimize cost and maximize an evaluation factor (listed in Table 3.2) within a target range simultaneously (equation 3.2).

$$Minimize \sum Cost\ (SCM_i)\ \ subject\ to\ Q_j \leq\ Q_{maxj}\ \&\ L_k \leq L_{\max k} \tag{3.1}$$

$$Minimize \sum Cost\ (SCM_i)\ \&\ Maximize \sum EF \tag{3.1}$$

SCM_i = set of SCM solutions associated with location i
Q_j = computed amount of water quantity factor at assessment point j
Q_{maxj} = the maximum value of the water quantity factor targeted at assessment point j
L_k = computed amount of water quality factor at assessment point j
$L_{\max k}$ = the maximum value of the water quality factor targeted at assessment point j
EF = the management evaluation factor (EF) at one given assessment point, and the EF can be any of the options listed in Table 3.2

The optimization module in i-DST SUSTAIN can be used to simulate a range of optimization analyses by using various criteria and constraints (See Appendix B for further details on optimization criteria and constraints). In this study, optimization scenarios are designed to identify the optimal number of SCMs and evaluate the tradeoffs of varying types to manage the increased volumes of urban stormwater runoff due to infill development. Each scenario has a primary goal of reducing total runoff volume while assessing additional tradeoffs of the varying SCM types, such as pollutant load reduction or green space added. Plotting the average annual flow volume (AAFV) from each SCM solution simulated in the optimization against the respective cost to implement that SCM solution creates a scatter plot referred to as a Pareto curve. The varying optimization algorithms and controls drive the shape of the Pareto curve and how the model searches for the optimal solutions. It is crucial for the model user to understand these controls and how they may affect the solutions that are being outputted by the model as these controls can drive the model in certain directions (supplemental material). This study used scatter search and cost minimization in order to allow consideration of multiple criteria but also maintain more diverse solution sets in the optimization rather than search for a single optimal solution.

3.4.4 Individual Optimization

An individual optimization analysis was conducted independently on each of the six SCM types to compare relative performance. The minimum number of simulated SCMs in the watershed was one unit (capturing runoff from one 0.053 ha parcel of land) while the maximum number of simulated SCMs allowed was set to 2000 units, enough to capture all runoff from the infill developed area. Each individual optimization was simulated 1000 times with a SCM step of two units. Thus, this analysis explored the additional added hydrologic benefit as two additional SCM units were added to the watershed until the maximum redeveloped area was treated.

A single solution from each of the six individual optimizations was identified. As the primary goal of this study was to evaluate stormwater management options that returns AAFV to the Current Baseline conditions, the first solution that reached this AAFV goal was identified. Each SCM individual optimization solution has a different number of units. The six individual SCM types were compared in terms of their cost and the relative hydrologic performance based on several hydrologic variables including peak flow, total evapotranspiration, and average annual loads and concentrations for various pollutants.

3.4.5 Full Optimization

The full optimization scenario was simulated to allow consideration of all six SCM types simultaneously. The number of SCM units set for each SCM type was 1 to 300 units with a step of 30 units. Only one full optimization scenario was simulated which was set up to optimize several evaluation factors at once as a multi-objective search algorithm. Spahr et al. (2020)

demonstrated in a public survey that the benefits participants found most important in Denver include reduced impacts from flooding, improved water quality, increased local groundwater resources, and community redevelopments and revitalization. The i-DST SUSTAIN model has evaluation factors that can optimize on the first three of these benefits. Thus, the full optimization was set up to optimize AAFV, Zn average annual load (Zn AAL), Zn average annual concentration (Zn AAC), and ground water recharge potential (GWRP) simultaneously while minimizing cost. The primary evaluation factor target goal was set to reach at least a 5% reduction in AAFV (minimum required reduction to return Future Baseline flows back to Current Baseline flow values). As there are no reduction targets set in Denver for the remaining evaluation factors a 5% decrease was also set for Zn AAL and Zn AAC while a 5% increase was set for GWRP.

3.4.5.1 Selection Criteria Sensitivity Analysis

Determining the optimal solutions from a full optimization Pareto curve may be subjective based on the decision maker. While it is typical in stormwater modeling for hydrologists to identify the optimal solutions as those located in the "elbow" of the Pareto curve (maximize a single benefit and minimize cost) (Branke et al. 2004), it is unclear how these solutions align with varying stakeholder priorities. Three sensitivity analyses, with varying selection criteria, were explored to isolate solutions from the full optimization Pareto curve in order to explore the best way to identify optimal solutions on a planning-level. *Sensitivity Analysis 1* reflects when a stakeholder aims to maximize a primary goal (AAFV in this study) and minimize cost. The solutions that meet these criteria are expected to fall along the "elbow" of the curve, also referred to as the Pareto frontier. *Sensitivity Analysis 2* reflects when a stakeholder prioritizes meeting the primary goal and has a flexible budget. The solutions that meet these criteria must therefore fall below the Current Baseline AAFV but can fall along a range of costs. *Sensitivity Analysis 3* introduces the consideration of a third variable, Zn AAC (where reductions in AAC do not exhibit a direct relationship to reductions in AAFV thus presenting a tradeoff), within a wide AAFV and cost range. For this analysis, solutions that meet the AAFV goal, along any cost, and within a specified AAC range were identified.

3.4.5.2 Aggregate Multi-Criteria (AMC) Selection

While Sensitivity Analyses 1 and 2 identify SCMs that perform best at achieving the AAFV goal, SCMs also co-produce various levels of other benefits including (1) water quality improvement, (2) groundwater recharge, and (3) added green space. Though potentially correlated in their provision, the benefits to society are distinct. As such, just as a public good (Samuelson 1954) creates non-rival benefits that should be summed across individuals, these benefits should be counted separately and aggregated. At times, non-primary benefits can rival the scale and importance of the targeted goal, making them important to consider (Plantinga and Wu 2003). Thus, Sensitivity Analysis 3 was determined to be the most efficient method for a planning-level analysis. To further improve Sensitivity Analysis 3, this study used an aggregate multi-criteria (AMC) selection methodology to identify the optimal solutions from the full optimization by aggregating multiple hydrologic benefits and applying a user prioritization by weighting the benefits. This methodology first splits all of the solutions (j in Equation 3.3 and 3.4) up into ten evenly distributed cost bins (i in Equation 3.3 and 3.4). It should be noted that cost bins may be further divided to suit needs of a model user. Solutions within each cost bin were then compared to one another based on their performance in terms of each evaluation criteria. A rating system was used to weight criteria that are more important on a scale of 1 to 5, where a rating of 5 receives higher priority. Finally, each solution was given an overall score. Five benefits (n in Equation 3.3 and 3.4), AAFV, Zn AAL, Zn AAC, GWRP, and potential green space added (Table 3.5), were weighted and aggregated for each solution. Equation 3.3 and 3.4 calculate the benefit score for each solution and benefit type in each of the ten cost bins. Equation 3.3 was used for GWRP and green space added as higher values are preferred. Equation 4 was used for AAFV, AAC, AAL as lower values are preferred. Equation 3.5 calculates the overall score, respectively, for each SCM solution in each of the ten cost bins. The solution with the highest overall score was determined to be the optimal solution for that cost bin.

$$Benefit\ Score_{j,i,n} = \left[\frac{Benefit\ Value_{j,i,n} - \min[Benefit\ Value_{i,n}]}{\max[Benefit\ Value_{i,n}] - \min[Benefit\ Value_{i,n}]}\right] * Rating_n \qquad (3.3)$$

$$Benefit\ Score_{j,i,n} = 1 - \left[\frac{Benefit\ Value_{j,i,n} - \min[Benefit\ Value_{i,n}]}{\max[Benefit\ Value_{i,n}] - \min[Benefit\ Value_{i,n}]}\right] * Rating_n \qquad (3.4)$$

$$Overall\ Score_{j,i} = \frac{\sum_n Benefit\ Score_{j,i}}{\sum Rating_n} \qquad (3.5)$$

where j = Future SCM Solutions (2000); i = Cost Bin (10); n = Benefit Type (5)

While using weights indicative of monetary marginal values across various benefits would arguably achieve a SCM mix that optimizes aggregate efficiency (Ando and Netusil 2018), this would need to be done with local estimates rather than transferring values from studies elsewhere. Local policymakers could endeavor to take on such steps by scaling the weights by the relative economic measures, or they can balance preferences of the city as expressed through alternative non-monetary means. This study explored four sets of ratings using the AMC methodology as displayed in Table 3.6. AMC1 and AMC2 explored two general rating systems that are not directly related to the preferences of Denver. AMC1 prioritized all factors equally while AMC2 prioritized only Zn AAC. AMC 3 and AMC4 use ratings that are established by the City and County of Denver (City and County of Denver 2016) and results from the Spahr et al. (2020) public survey, respectively.

Table 3.6 Ratings used for four separate benefit weighting options in the Berkeley neighborhood. Ratings are on a scale of 1 to 5, where a rating of 5 is higher priority.

Benefit Ratings	AMC1 (Equal)	AMC2 (Prioritize AAC)	AMC3 (City of Denver)	AMC4 (Public Survey)
AAFV	5	0	4	3
Zn AAC	5	5	4	5
Zn AAL	5	0	5	3
GWRP	5	0	0	2
Green Space Added	5	0	4	1

Note: AMC = Aggregate Multi-Criteria; AAFV = Average Annual Flow Volume; AAC = Average Annual Concentration; AAL = Average Annual Load; GWRP = Ground Water Recharge Potential

3.5 Results

3.5.1 Model Validation Results

The i-DST SUSTAIN Current Baseline and Future Baseline time series are identical to PCSWMM results (C. Panos 2020) with an R^2 of 1, NSE of 1, and % Bias of -0.007. This is expected as the PCSWMM model outputs were used to drive the i-DST SUSTAIN model. Table 3.7 displays summary statistics (Nash Sutcliffe Efficiency (NSE), R2, and % Bias) for the 2, 5, and 10-year, 24-hr design storm time series between i-DST SUSTAIN and PCSWMM with 1% sizing and 5% sizing for BR. The 1% and 5% BR sizing scenarios are very similar to the PCSWMM modeling results with R^2 values of 0.994 – 0.997.

Table 3.7 Statistical values for the comparison between i-DST SUSTAIN and PCSWMM Future SCM scenarios with BR.

	Current Baseline	Future Baseline	Future BR 1% Sizing	Future BR 5% Sizing
2 Year Storm				
NSE	1	1	0.991	0.844
R^2	1	1	0.996	0.996
% Bias	-0.007	-0.0008	-1.710	1.920
5 Year Storm				
NSE	1	1	0.995	0.933
R^2	1	1	0.997	0.997
% Bias	-0.007	-0.0008	-1.953	-6.276
10 Year Storm				
NSE	1	1	0.996	0.936
R^2	1	1	0.994	0.996
% Bias	-0.007	-0.0008	-1.682	-7.041

3.5.2 Individual Optimization Results

3.5.2.1 Water Quantity Results

Figure 3.1 displays the average annual flow volume (AAFV) results based on the number of SCM units installed (Figure 3.1A) and the total capital cost (Figure 3.1B) for the six SCM types. The Current AAFV Baseline (361,430 m^3), which is the primary goal for the Berkeley neighborhood, is represented by the black horizontal line in Figure 3.1. All solutions above this line are considered non-viable stormwater solutions as they do not successfully reduce AAFV back to the Current Baseline. Green and grey SCMs show mixed performance. The two grey underground SCMs have very different water quantity results based on their varying designs. UIS reaches the Current Baseline AAFV with the lowest number of installed SCM units. UDS does not reduce AAFV as the design is a concrete box without infiltration. The remaining grey SCMs (PP) and three green (BR, IT, and VS) all have results that fall between UDS and UIS. The three above ground storage-based SCMs (IT, PP, BR) perform similarly in terms of AAFV reduction while the above ground flow rating-based SCM (VS) requires more SCM units.

VS reaches the Current AAFV Baseline with the lowest cost (Figure 3.1B) even though the largest number of SCM units is required to do so. In addition to having a relatively lower capital cost per cubic feet, VS are flow rating-based and thus require less volume per parcel of land treated as VS are designed to ensure flow requirements are met rather than the capture of the WQCV. IT performs similarly to VS even though they have a higher storage volume; this is due to having the lowest capital cost per cubic foot out of the six SCM types. BR units reach the AAFV reduction goal at the highest cost while UDS does not reach the AAFV goal at any cost.

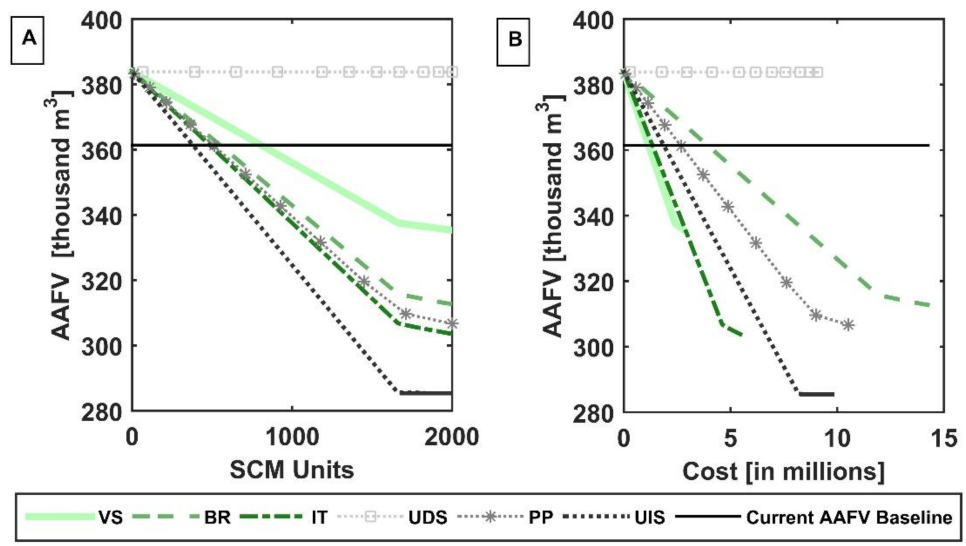

Figure 3.4 Water quantity results from the individual optimizations for each of the six SCM types. Plots show the impact of SCMs on AAFV with an incremental increase in SCM units implemented (A) and total capital cost (B). Viable SCM solutions fall below the Current AAFV Baseline.

3.5.2.2 Water Quality Results

Figure 3.2 displays the resulting water quality evaluation factors, pollutant average annual load (AAL), and average annual concentration (AAC) based on the number of SCM units installed for the six SCM types. Similar to Figure 3.1, results show that the green and grey SCMs have mixed results. All SCMs reduce pollutant AAL (Figure 3.2A, B, and C) except for UDS Total Phosphorous which is due to the combination of a low decay rate and a lack of infiltration. Infiltration-based SCMs (UIS, IT) are better at reducing AAL than treat-and-release-based SCMs (UDS and VS). BR and PP perform relatively average in terms of AAL reduction with BR slightly outperforming PP despite being a treat-and-release-based SCM. Results for reduction in AAC (Figure 3.2D, E, and F) are very different from the AAL-based results. While treat-and-release SCMs (UDS, VS, and BR) generally perform better in terms of reducing pollutant AAC in the SCM effluent compared to the influent, as they return more diluted water to the storm sewer network, it should be noted that five out of six SCMs (BR, IT, VS, UIS, PP) result in higher TSS AAC and two out of six SCMs (UIS, PP) result in higher Zn AAC at the watershed outlet.

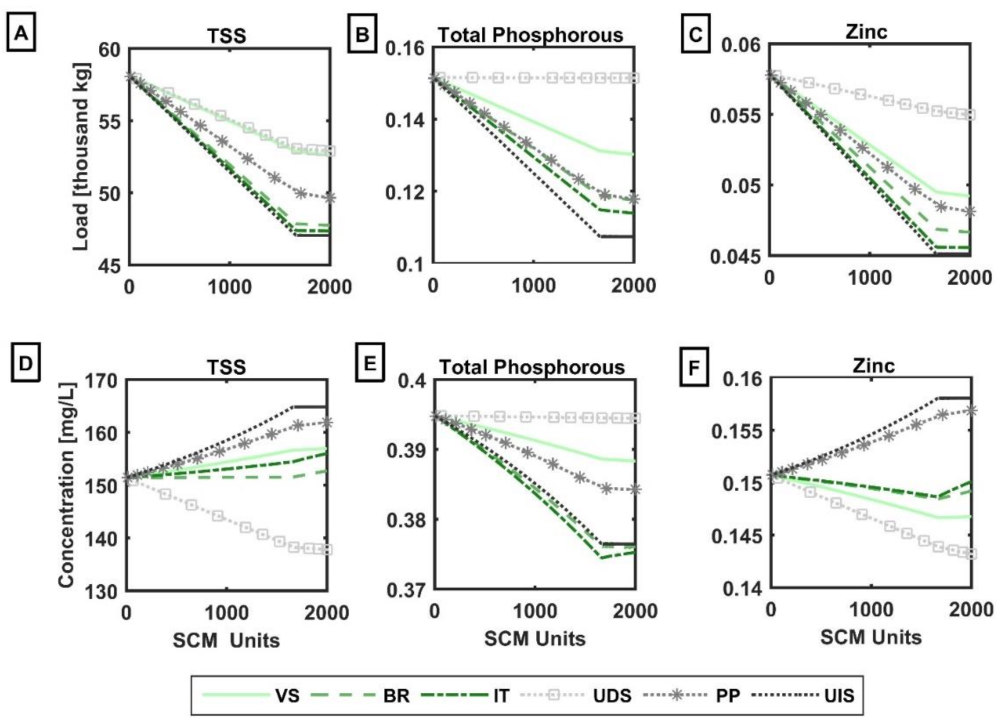

Figure 3.5 Water quality results from the individual optimizations for each of the six SCM types. Plots show the impact of SCMs on pollutant AAL (A, B, C) and pollutant AAC (D, E, F) with an incremental increase in SCM units implemented.

3.5.2.3 AAFV Criteria Solution Selection Results

Table 3.8 displays the range of hydrologic results for each SCM type and the respective solution that first reached the Current AAFV Baseline. Hydrologic results include those based off design properties, number of SCMs simulated, water quantity results, and water quality results. The developed color scale highlights the SCMs that perform the best (dark grey shading) and worst (white shading) in terms of the several criteria listed. All SCMs that perform in between are shaded in a light grey. For example, BR is shaded white for total capital costs which reflects the high cost requirement in order to reach the Current AAFV Baseline while VS has the dark grey shading as it requires the lowest cost. BR and IT both perform on average or above average for all criteria. However, while VS, PP, and UIS have mixed results across all criteria, in some cases they outperform IT and BR. For example, while IT performs the best in terms of reducing the peak flows from large storms, VS performs the best in terms of reducing smaller storm peak flows. Finally, UDS performs relatively the worst out of the six SCM types across the board with an exception to required storage volume, TSS AAC, and Zn AAL and AAC, in which UDS outperforms the other five SCM types.

Table 3.8 Hydrologic results from the six SCM individual optimization solutions that first achieve the Current AAFV Baseline. SCMs that perform best at a hydrologic criteria are highlighted in dark grey while SCMs that perform the worst are shaded white. All SCMs that perform in between are shaded light grey.

	VS	BR	IT	UDS	PP	UIS
% difference from Current AAFV Baseline	0.007	-0.002	-0.014	+6.20*	-0.014	0.003
Units of SCMs	806	548	485	545	507	379
Area treated [ha]	42.73	29.05	25.71	28.89	26.88	20.09
Cost per cubic foot [$]	281.45	408.23	168.8	493.69	424.13	438.61
Total capital Cost [$ mil]	1.16	3.91	1.34	2.47	2.66	1.87
Surface area [ha]	1.36	1.02	0.90	0.00	0.94	0.00
Surface Storage Volume [m^3]	2,060	1,542	2,048	5,008	123	2,936
Soil Storage Volume [m^3]	876	3,503	2,405	0	2,677	543
Watershed Outlet Peak Flow [cms]	5.51	5.28	5.12	5.35	5.40	5.24
95th Percentile Peak Flow above 0 [cms]	1.59	1.51	1.49	1.63	1.51	1.52
25th Percentile Peak Flow above 0 [cms]	0.016	0.016	0.017	0.018	0.017	0.017

Table 3.8 Continued

Peak flow downstream of aggregate SCM [cms]	1.38	1.27	0.99	1.30	1.27	1.08
Total ET [m^3]	13,065	37,722	33,244	0	34,720	0
Average Annual GWRP [m^3]	19,806	14,939	15,855	0	15,493	22,396
AAL TSS at outlet [kg]	55,573	54,733	54,984	56,461	55,640	55,592
AAC TSS at outlet [mg/L]	153.77	151.44	152.15	147.09	153.97	153.82
AAL TP at outlet [kg]	141.67	140.75	140.85	151.51	141.69	141.50
AAC TP at outlet [mg/L]	0.392	0.389	0.390	0.395	0.392	0.392
AAL Zn at outlet[kg]	53.81	54.24	54.28	56.99	55.00	54.95
AAC Zn at outlet [mg/L]	0.149	0.150	0.150	0.149	0.152	0.152

Note: BR = Bio-retention; DP = Dry Pond; IT = Infiltration Trench; PP = Porous Pavement; VS = Vegetated Swale; UDS = Underground Detention Structure; UIS = Underground Infiltration Structure; TSS = Total Suspended Solids; TP = Total Phosphorous; Zn = Zinc; AAFV = Average Annual Flow Volume; AAC = Average Annual Concentration; AAL = Average Annual Load; GWRP = Ground Water Recharge Potential
*UIS never reaches the Current AAFV Goal as it does not allow infiltration or evapotranspiration

3.5.3 Full Optimization Results

Results from the full optimization in the Berkeley neighborhood show that while AAFV, AAL, and ground water recharge potential (GWRP) have a generally linear relationship with cost of SCM implementation (as AAFV decreases, AAL decrease and GWRP increases) there is not a linear relationship between AAFV, AAC, and green space added (Figure 3.3). For example, the solutions with the lowest AAC values (dark blue shading) are found throughout the whole optimization curve. However, there are groupings of solutions that perform similarly. For example, a group of solutions with high Zn AAC (0.1515 mg/L) is located between 332,000 and 340,000 m^3 of AAFV range and between the 3.5 and 4.5 million dollar cost range.

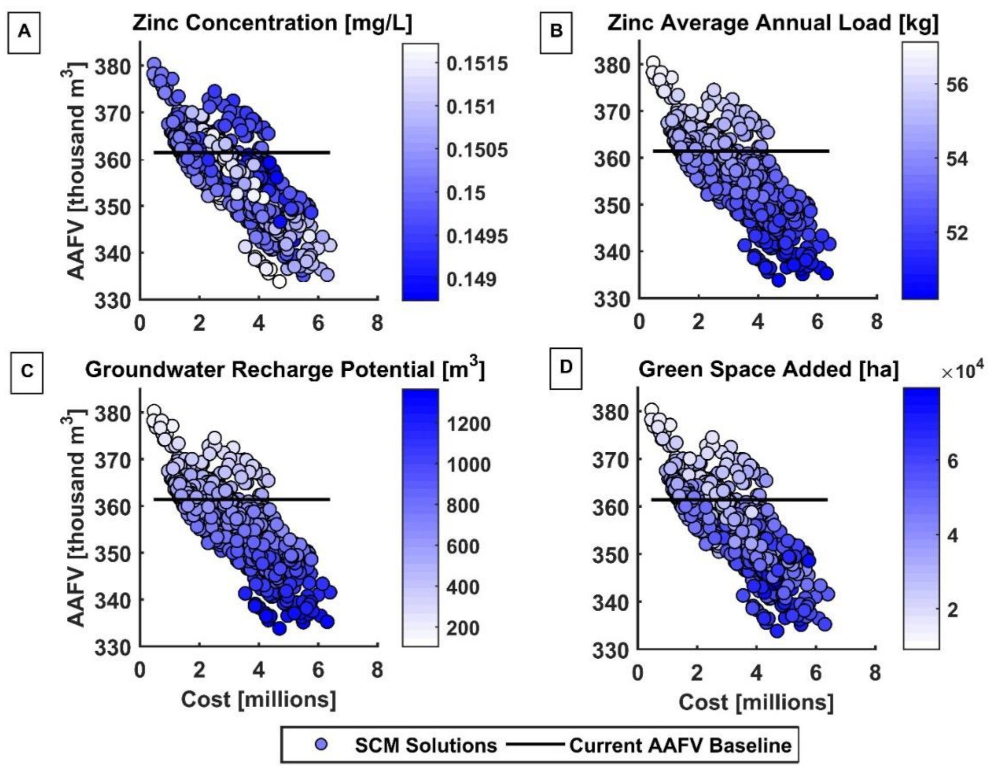

Figure 3.6 Full optimization results from the Berkeley neighborhood. Each subplot shows the same solutions from the full optimization, each with a different color based on a different additional benefit. Darker shading represents solutions that perform better in terms of the subplot benefit. Viable SCM solutions fall below the Current AAFV Baseline.

3.5.3.1 Selection Criteria Sensitivity Analysis Results

Figure 3.4 (A, B, and C) shows the optimal 100 solutions based on the full optimization sensitivity analysis. Figure 3.4 (D, E, and F) uses a whisker box plot to show the spread of the number of SCM units simulated for each type across all selected 100 solutions. For example, the minimum number of VS units simulated in Figure 3.4D is 231 units while the maximum number of units simulated is 300. The 100 solutions identified with Sensitivity Analysis 1 (achieve AAFV goal and minimize cost) are dominated by a high number of VS and IT units, with between 175 and 300 SCM units of each type. This is because these two SCMs reduce AAFVs at the lowest cost as seen in the individual optimization results. The other four SCM types (BR, PP, UDS and UIS) do not exceed 125 units. With the 100 solutions identified using Sensitivity Analysis 2 (achieve AAFV goal without a cost restriction), the spread of the solutions widens for all SCM types (with fewer units for VS and IT and more units for BR, PP, DS, and UIS). This is because this criterion introduces solutions that prioritize SCMs that may cost more to reach the

Current AAFV Baseline (such as BR and PP, Table 3.8). Considering zinc AAC in Sensitivity Analysis 3 (achieve the AAFV goal and minimize Zn AAC) shows a further increase for the spread of BR and UDS as they perform the best in terms of reducing Zn AAC values. As more benefits are considered, the solutions become more diverse in that they include a wider range of SCM types as multiple SCM types will result in solutions with more available benefits. The solutions for Sensitivity Analysis 1 (Figure 3.4D) show a high preference for green SCMs, but as more diverse criteria are included in the selection process for the "optimal" solutions (Sensitivity Analyses 2 and 3; Figure 3.4E and 3.4F), a larger mix of green and grey SCMs are simulated to meet the specified requirement (evaluation factor) of the model user. A mix of treat-and-release-based and infiltration-based SCMs is observed in all situations.

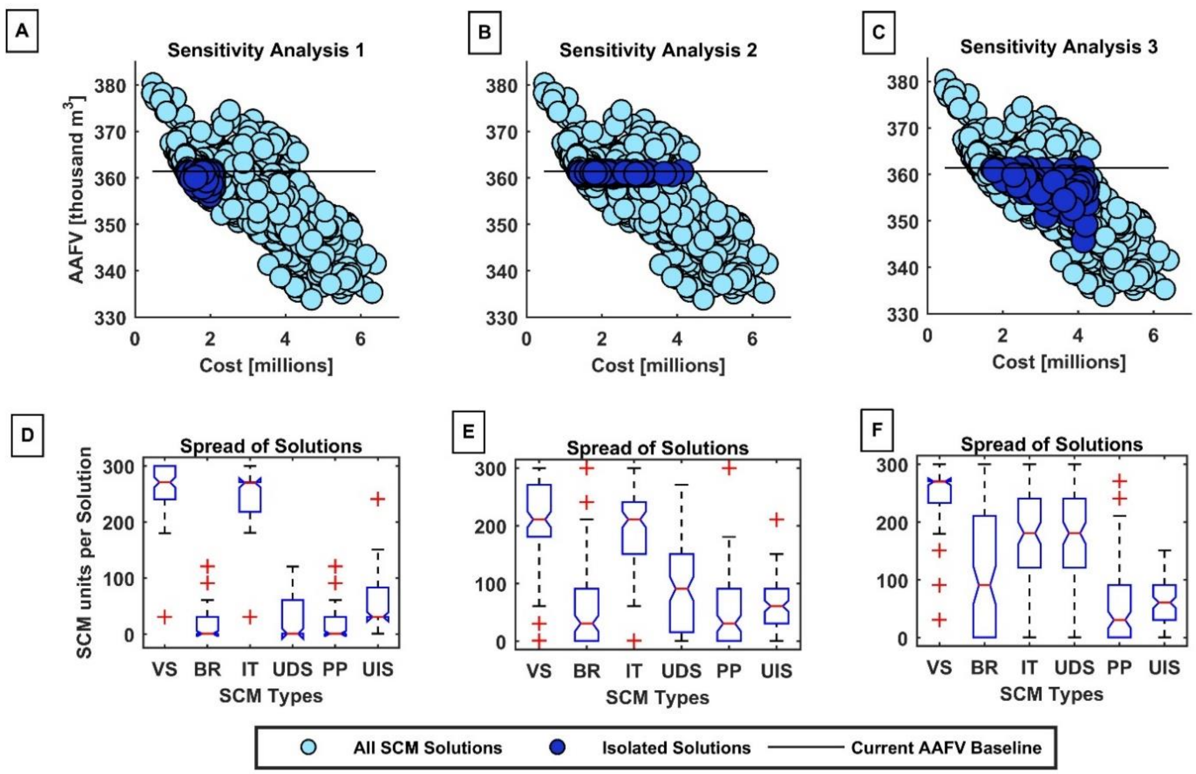

Figure 3.7 A, B, and C: Location of the 100 "isolated" solutions based on the three sensitivity selection criteria. A = Achieve Current AAFV Baseline goal and minimize cost. B = Achieve Current AAFV Baseline Goal. C = Achieve Current AAFV Baseline Goal and minimize AAC. D, E, F: Spread of the number of simulated SCM units for the 100 "optimal solutions", each SCM type, and the respective three Sensitivity Analysis.

3.5.3.2 Aggregate Multi-Criteria Results

Solutions identified using the aggregate multi-criteria (AMC) methodology can be seen in Figure 3.5. The ten cost bins were determined by using the minimum (1.5 million dollar) and maximum (4.5 million dollar) cost that falls along the Current AAFV Baseline goal. The optimal solutions identified with AMC1 and AMC2 (rate all equally and City of Denver ratings, respectively) fall along the Pareto frontier (Figure 3.5A and 3.5C). The City of Denver rating system generally weights all benefits equally with an exception to GWRP. Solutions identified using AMC4 (Denver public survey) fall closer to the Pareto frontier (Figure 3.5D) while solutions that prioritized AAC (AMC2) are found throughout the whole Pareto curve (Figure 3.5B). When AAC is prioritized (AMC2 and AMC4) the optimal solutions shift away from the Pareto frontier and towards the Current AAFV Baseline line where the solutions simulate a higher number of BR and UDS, which both have a higher capital cost and perform better at reducing Zn AAC. While the optimal solutions from the Denver Public Survey rating (AMC4), which weights AAFV reduction and added green space higher, do vary from AMC1 and AMC3 (rate all equally and City of Denver ratings, respectively) in that all of the solutions do not fall as closely along the Pareto frontier, they do not shift as close to the Current AAFV Baseline as the solutions that solely prioritize AAC (AMC2).

The number of SCM units by type simulated in the optimal solutions identified with the four AMC ratings are highlighted in Figure 3.6. The green SCMs (BR, IT, and VS) are shown in shades of green while the grey SCMs (PP, UDS, and UIS) are shown in shades of grey. Comparing AMC1 (rate all equally) to AMC2 (prioritize AAC) shows that the optimal solution in all ten cost bins changed. When AAC is weighted higher, the solutions shift to implement more of the treat-and-release-based SCMs, BR and UDS (best at reducing AAC), and less of the infiltration-based SCMs (IT, PP, and UIS). The number of IT units simulated across all cost bins in AMC1 is consistent. However, AMC2 (prioritize AAC), shows a decline in simulated IT units as the cost bin increases. This is because while IT do reduce Zn AAC they do not perform as well as BR, UDS, and VS which become more prevalent in the higher cost bins as they cost more. VS are dominant and consistent in all solutions in both Figure 3.6A and 3.6B as they reduce AAFV at the lowest cost and also perform well in terms of reducing Zn AAC.

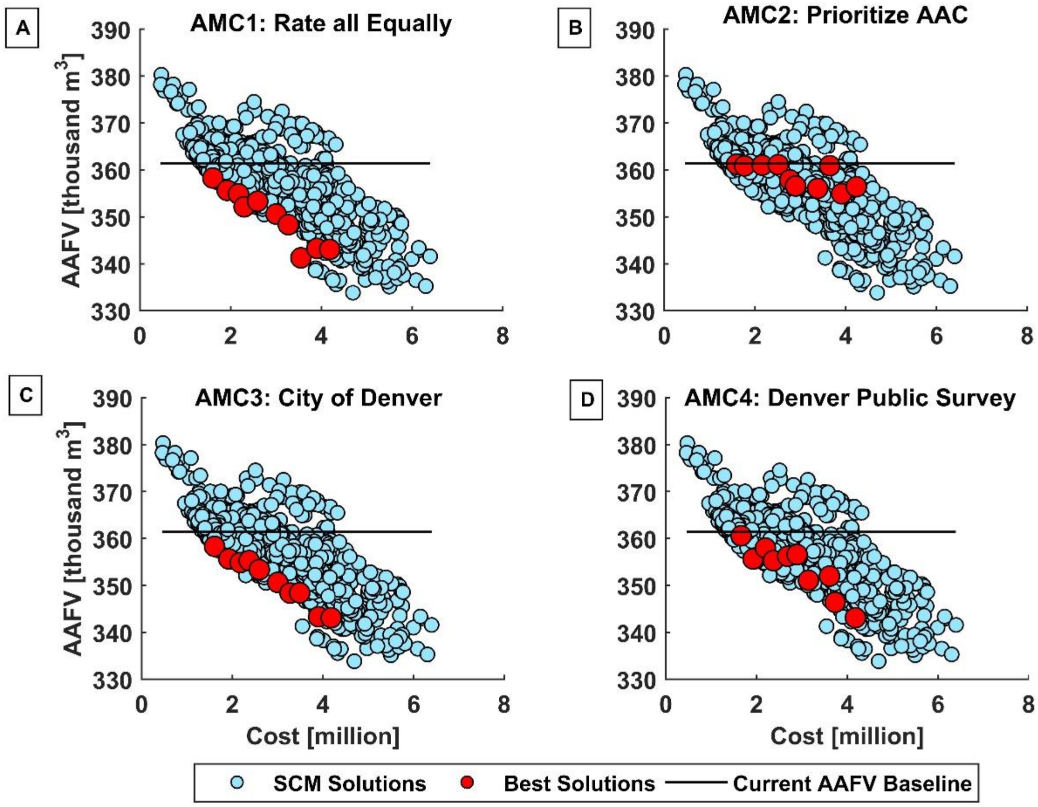

Figure 3.8 Location of the 10 "optimal" solutions (1 per cost bin) based on the four multi-benefit aggregate rating systems. Cost bins were set to fall between ~1 million and ~4.5 million dollars, where SCM solutions fall along the Current AAFV Baseline.

Comparing AMC3 to AMC4 shows that the optimal solution in 7 of the 10 cost bins changed when shifting from the City of Denver ratings to the Denver Public Survey ratings. The Denver Public Survey solutions favor more BR and UDS and less PP. IT and VS are dominant and consistent in all solutions in AMC3 and AMC4. It should be noted that for all solutions from the four AMC ratings, green SCMs are generally favored over grey. However, there is a presence of grey in all solutions and in some cases, the rating shifts solutions to include more grey SCMs so that there is an equal balance of green and grey SCMs. Only two solutions (cost bins 4 and 8) differ between AMC1 (rate all equally) and AMC3 (City of Denver ratings) (Figure 6A and 6C).

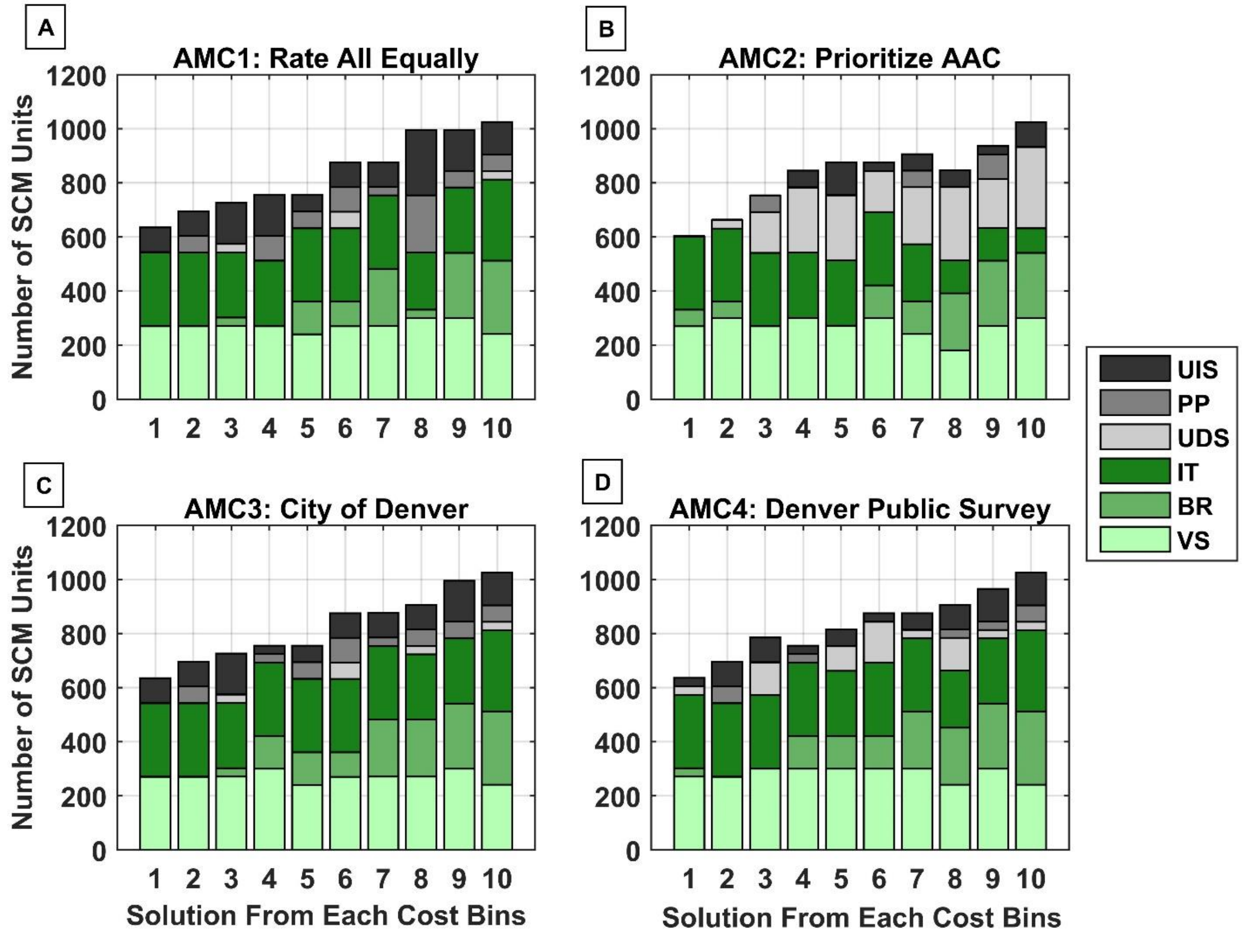

Figure 3.9 Number of each SCM type simulated in all solutions identified using the multi-benefit aggregate equation. Bar plots are stacked in the same order as displayed in the legend, VS on the bottom and UIS on the top.

3.6 Discussion

3.6.1 Benefits and Tradeoffs of Green to Grey Infrastructure

3.6.1.1 Hydrologic Performance of Green to Grey Infrastructure

Relative hydrologic performance depends more on the primary function an SCM is designed for rather than where the SCM falls on the green to grey continuum. Results show that UIS and UDS (both underground grey SCMs) have contrasting performance in AAFV, AAL, and AAC reductions while all other SCMs (BR, IT, PP, and VS) perform somewhere in between. The above ground storage-based SCMs (BR, IT, and PP) perform similarly in terms of water quantity criteria due to designing the SCMs to have the same surface area, same drainage area, and inclusion of underdrains and orifices. The flow rating-based SCM in this study, VS, performs fairly independent of the other five SCMs. Overall, infiltration-based SCMs (UIS, IT, and PP) perform generally better in terms of reducing volumes of water and loads of pollutants than treat-and-release-based SCMs (UDS, BR, VS). It should be noted that PP and BR performed similarly in terms of pollutant AAL reductions. BR has a high pollutant removal decay rate thus they perform similarly to the infiltration-based SCMs. PP is only reducing pollutants by way of infiltration and has a decay rate of zero, thus it does not perform as well. Treat-and-release-based SCMs generally perform better at reducing pollutant concentrations as they are designed to treat stormwater and then release the mitigated stormwater back into the storm drainage network (E. Gallo et al. 2020; Jordyn M Wolfand et al. 2018). However, results showed that the implementation of SCMs may actually increase pollutant AAC at the watershed outlet. This is because the SCMs are treating water from only the infill developed residential land uses which have a lower TSS and Zn EMC than other untreated land uses (Table 3.3 & 3.4). The SCMs are removing water from the infill developed area by way of infiltration, thus removing water that was previously working to dilute overall watershed discharge. The treated water that does return to the whole network from the SCMs is not enough to counter-balance this phenomenon. UDS is the only SCM type that does not increase pollutant AAC for all three pollutant types as it does not promote any infiltration. This study assumes that residential EMCs remain constant between their pre-redeveloped and redeveloped (infill) states; there is not enough available data to explore the potential differences from pre-redeveloped to infill developed conditions. One way to account for these potential differences is to use single-family vs multi-family residential land use EMCs. Some cities, such as Los Angeles, have this data available. Policies are needed to incentivize treatment of stormwater from other land uses. Individual optimization results demonstrate the multiple tradeoffs between varying SCM types based on their design and primary function which dictates their relative performance.

Results show that both green and grey infrastructure offer hydrologic benefits that may be important for stakeholders, thus a range of SCMs should be considered when developing a stormwater management plan. Even though green SCMs tend to perform better in a wider range of benefits, results demonstrate how grey SCMs outperform green in some cases (Table 3.8). For example, UIS requires the smallest number of SCM units to reach the Current AAFV Baseline and promotes the highest GWRP. Additionally, it should also be noted that grey SCMs are flexible in terms of both their water quantity and quality design. While UDS has relatively poor performance in water quantity criteria for the Berkeley neighborhood, which is likely due to the orifice design and lack of infiltration, they can be designed with a more controlled release of water which would drastically reduce peak flows. The use of controlled outflow and water quality removal systems in greyer underground SCMs allows for a design that is tailored to the needs of the watershed. Overall, green SCMs performed best at achieving the primary goal in the Berkeley neighborhood and thus were prioritized in the model optimization (IT and VS reduce AAFV at the lowest cost in the Berkeley neighborhood watershed). However, the use of other green and grey SCMs offers the ability to maximize the available hydrologic benefits to both the environment and the community. A planning-level modeling analysis such as presented in this work can assist in evaluating the tradeoffs and benefits of SCMs for the watershed in question.

3.6.1.2 Cost of Green to Grey Infrastructure

While cost at first shows a clear distinction between green vs grey SCMs, a more in-depth analysis shows the complexities and tradeoffs that exist. Capital cost per cubic foot clearly shows that green SCMs have a lower cost than grey (IT, VS, BR, PP, UIS, UDS in order from lowest to highest cost). This is due to less use of grey materials such as concrete. However, when considering the total cost per SCM unit, taking into account the cost per cubic foot as well as storage, soil, and underdrain volumes required for construction, there is a shift in the benefit-to-cost ratio (VS, IT, UIS, UDS, PP, BR, in order from lowest to highest cost). BR has the highest cost per SCM unit while VS has the lowest cost. UDS has the highest capital cost per cubic foot; however, construction does not require excavation for soil or underdrain storage, so it has a relatively lower cost per SCM unit. It should also be noted that as grey SCMs increase in project size, the cost per cubic foot decreases. Thus, larger underground grey structures, when designed to be more centralized than distributed, may be more cost efficient to implement.

When considering hydrologic performance relative to cost several tradeoffs were presented. For example, while UIS achieves the AAFV goal with the lowest number of SCM units, VS achieves the AAFV goal at the lowest cost despite requiring the highest number of SCM units. However, VS does not perform as well in other hydrologic criteria. Even though BR has the highest cost per SCM unit and thus requires the highest cost to reach the AAFV in the Berkeley neighborhood, they have more available benefits and outperform other SCMs in most criteria. This discussion on capital cost begins to show how a more in-depth cost analysis is needed and can shift the decision-making process towards different SCMs. A full cost analysis of varying stormwater alternatives including life cycle costs and life cycle assessments should be used to evaluate the array of benefits and costs of SCMs over time (Mcauley and Knights 2015; Liao et al. 2014; Rebitzer, Hunkeler, and Jolliep 2003) especially at a watershed-scale (Panagopoulos, Makropoulos, and Mimikou 2011). Life cycle costs including planning and permitting, construction, operation, maintenance, decommissioning, and relative lifespan and replacement costs (C. D Bell et al. 2019) may shift which SCMs are most cost effective, especially in terms of green vs grey SCMs.

3.6.1.3 Added Greenness of Green to Grey Infrastructure

There is a clear distinction between the green and grey SCMs in terms of potential green space added which may be more accurately described as a vegetated-related benefit rather than a hydrologic benefit. Grey SCMs do not contribute green space to an urbanized watershed while green SCMs may include grasses, shrubs, and trees. In a time when cities are defining stormwater management plans around greenness, this is a crucial criterion to consider. Green SCMs offer a way to both improve stormwater management while also introducing the suite of benefits that are associated with an increase of greenness or vegetation. One positive tradeoff of underground grey SCMs is that they can be implemented in highly dense areas that do not have room for the implementation of green SCMs. The flexibility in design can allow for construction below parking lots or other infrastructure. SCMs offer a wide variety of ancillary benefits beyond those that are strictly considered hydrologic (Jaffe 2010; McGarity et al. 2015). While these other benefits are not necessarily the driving motivation for stormwater managers and municipalities to manage stormwater, it has been found that community members care just as much about the ancillary benefits as they do flood management and water quality conditions (Cadavid and Ando 2013; K. Spahr 2020). While these positive ancillary benefits (ecological, environmental, and social) are not directly measured and optimized in a hydrologic model, they can be estimated or extrapolated based on SCM design. It is crucial to represent these ancillary benefits in order to maximize the net benefits of the watershed (Ando and Netusil 2018).

3.6.2 Impact of Decision Maker Priorities on Planning-level Decisions

While the individual SCM analysis provides important insight on relative performance and cost, comparing stormwater solutions that include multiple types of SCMs is more representative of the impact stormwater management will have on a watershed as a whole. How decision makers and stakeholders choose the optimal solutions from an optimization curve has implications on the environment and the community and is a critical step in a planning-level analysis. Results show that solutions in the typical "elbow" of the optimization curve (i.e., "Pareto Frontier") may not be optimal based on the needs of the watershed or the preference of the community. In the Berkeley neighborhood, the use of IT and VS should be prioritized if stakeholders want a stormwater management plan that will achieve the AAFV goal while minimizing cost. If stakeholders have more flexibility in their budget, a wider range of SCM types is available for implementation as all SCM types will achieve the AAFV goal, with an exception of UDS. The ability to consider multiple SCM types also allows for the consideration of a wider range of benefits. For example, stormwater management solutions that perform well at reducing pollutant AAC, in addition to achieving the Current AAFV Baseline, exhibit a fairly equal balance of VS, IT, UDS, and BR. Results show that solutions that fall in higher cost bins have more diversity in SCM types. Even though the cost may be higher for these solutions rather than one that only uses VS and IT, a stormwater management plan that considers multiple SCMs will maximize environmental and social benefits, thus justifying the higher cost for some stakeholders. If decision makers had chose solutions from the elbow of the curve without these considerations, a stormwater management plan may be implemented that does not achieve additional goals of the watershed. If a stakeholder prioritizes only one criterion, they should restrict the selection criteria to optimize only the SCMs that achieve their goal. However, if stakeholders care about maximizing the environmental benefits across the watershed, they need to consider multiple criteria and SCM types.

While the primary goal of a watershed may initially put more weight on particular SCM types, the consideration of multiple benefits and use of a rating system exposes which additional SCMs should be included in order to maximize the benefits of a watershed. All of the final solutions identified using the AMC methodology show a dominance of VS and IT to reach the primary goal of this study as they reduce AAFV and minimize cost most efficiently and thus were prioritized by the i-DST SUSTAIN optimization algorithms. However, all solutions also include a mix of the other four SCMs (UDS, BR, PP, UIS). Results show that user priorities and weights shift which of these four SCM types are prioritized in addition to the dominant VS and IT. For example, when weighting AAC higher above all other criteria there is a shift to include a higher number of BR and UDS units, as they perform better at reducing pollutant AAC. Stakeholders with differing priorities such as those concerned about river ecosystems and fish health, may use this rating system to reflect their priorities within the model optimization. The City of Denver ratings weight all benefits similarly except for GWRP which explains why solutions do not change much from the scenario that weights all criteria equally (AMC1). The City of Denver has laid out in its stormwater and green infrastructure plans that volume control and the benefits of green space added are priorities to the City. Reducing pollutant AAL and AAC for possible future water quality regulations is also a goal. Prioritizing green SCMs with some UIS is most likely to reach all of these goals. Finally, the Denver public survey did not weight green space as highly as the City and weighted GWRP potential higher, thus the solutions have a higher number of UIS units. It should be noted that these ratings are Denver specific. Other cities will have a different rating system based on their needs. For example, the City of Los Angeles would weight AAL and GWRP higher than the City of Denver. Incorporating community preference into the decision-making process is one way to ensure that the selected stormwater management plan will benefit both the environment and the community.

Even though green SCMs tend to have a higher ratio of SCMs for all tested scenarios, all solutions have a mixture of green and grey SCMs as well as a mixture of SCMs with varying primary functions. While the SCMs needed to address primary goals may be obvious, the additional considerations and criteria come into play and ultimately determine what additional SCMs should also be included in order to have a well-balanced stormwater management plan that maximizes all benefits. While grey SCMs perform similarly to green in terms of reaching a primary hydrologic goal, such as AAFV, and presents tradeoffs with green in terms of capital costs, benefits related to vegetation and life cycle costs are expected to change the prioritization of grey or green SCMs.

3.7 Conclusion

Determining the optimal stormwater management strategy requires the consideration of multiple SCM types, associated benefits, and the consideration of stakeholder and community preferences. However, combining all of these variables into one analysis is complex and there is a lack of available tools for stakeholders to use. The i-DST SUSTAIN hydrologic model uses a multi-SCM optimization approach to simulate a wide range of hydrologic benefits for thousands of solutions on a watershed-scale. This provides decision makers a first step planning-level analysis to evaluate the tradeoffs of green to grey SCMs while taking into account the stakeholder and community preferences for associated benefits. Modeling results show that green and grey SCMs have variable performance across multiple hydrologic outputs and that they each individually provide at least one benefit that may be valuable to the environment and community. Results also show that there exist tradeoffs between SCM types in terms of both hydrologic performance and capital costs. SCM types that perform best at the primary goal of a watershed may not necessarily provide the best “bundle” of benefits. Similarly, SCMs that have a higher cost may actually perform on or above average across multiple types of benefits making the extra cost potentially worth it.

While evaluating different SCM types against each other individually provides insight on their relative performance, a realistic stormwater management plan will incorporate multiple SCM types throughout the watershed. Thus, the simulation of SCM solutions that include multiple SCM types is needed. Optimization curves is one way to identify the optimal solutions for a watershed. However, results show that the priorities and needs of a watershed may shift where the optimal solutions fall within an optimization. Using an aggregate multi-criteria selection methodology to identify solutions that maximize the available benefits based on stakeholder or community preference is one way to determine the optimal stormwater management plan. While all solutions identified in this study using the AMC equation prioritized green SCMs, grey SCMs were also prevalent, and in some cases replaced a green SCM type depending on which benefits were weighted higher. This research shows the importance of using a planning-level approach to identify the optimal suites of SCMs that both achieve the primary goal of a watershed but also maximize the benefits that are important to stakeholders and the community.

3.8 Acknowledgments

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CHAPTER 4

IMPROVING THE DECISION-MAKING PROCESS FOR STORMWATER MANAGEMENT USING LIFE CYCLE COSTS AND A BENEFIT ANALYSIS

Modified from a manuscript in preparation for publication

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4.1 Abstract

Stormwater management, using green to grey infrastructure, is a multi-objective decision-making process. Integrating life cycle costs (LCC) and a benefit analysis with hydrologic modeling can enhance planning-level analyses by expanding available information for decision makers. In this study two urbanized watersheds, located in Los Angeles, CA, and Denver, CO, are modeled using an integrated decision support tool for green to grey stormwater infrastructure. The primary goal is to compare capital costs to LCC, explore the preference of greener vs greyer solutions using varying management criteria, ultimately used by stakeholders, and discuss appropriate interventions taking into account vegetative benefits under the lens of the 4 C's methodology (context, community, connectivity, and canopy). Results show that optimizing on capital costs alone produces qualitatively different results than optimizing on life cycle costs, which are substantially higher. Additionally, a shift in relative cost order between SCM types, when comparing modeling results using capital costs and LCC, in a watershed can misguide decision makers on which SCMs minimize cost while achieving regulatory compliance. While management criteria relevant to Los Angeles stakeholders do not share the preferred optimal stormwater solution given hydrologic benefits, the large and diverse land use characteristics of the watershed allows for consideration of vegetative benefits and some flexibility. Watershed specific management criteria in the Berkeley neighborhood all prefer greener solutions which also aligns with vegetative benefits discussed using the 4 C's. Modeling results presented here show how an integrated approach provides decision-relevant information about optimal

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stormwater solution given the costs to the community and environment, hydrologic performance, and vegetative benefits that meet watershed priorities.

4.2 Introduction

Stormwater control measures (SCMs) are being implemented in cities across the world as a way to mitigate the impacts of urbanization on the hydrologic regime and nonpoint source water quality (NRC 2008; USEPA 1999; Liu et al. 2017; Bracmort et al. 2006; Ando and Netusil 2018), increase greenness in highly developed areas, and maximize the benefits to the environment and community that may be accrued over time (K. Spahr 2020; Brown 2008; Fitzgerald and Laufer 2017). There is a large selection of SCM types that range from greener to greyer for decision makers and stormwater managers to implement in their watershed (C. D Bell et al. 2019; E. M. Gallo, n.d.). Greener SCMs, such as bioretention and vegetated swales, typically have a smaller contributing area and incorporate vegetation in their design. Greyer SCMs range from smaller distributed underground infrastructure to large regional storage facilities. All SCM types provide certain hydrologic and/or vegetative benefits based on their primary function and design (K. Spahr 2020). Selecting the appropriate suite of SCMs for a particular watershed is a multi-faceted and complex decision-making process (E. M. Gallo, n.d.; E. Gallo et al. 2020) that requires knowledge on 1) how different SCM types will impact the watershed as a whole, 2) a detailed cost assessment throughout the full life cycle of SCMs, 3) and whether the potential benefits of varying stormwater solutions will achieve the goals of stakeholders and the general public alike.

Hydrologic models such as Storm Water Management Model (SWMM) (Rossman 2015), National Stormwater Calculator (Rossman and Bernagros 2017), and System for Urban Stormwater Treatment and Analysis INtegration (SUSTAIN) (Shoemaker et al. 2009) are used to determine how varying SCM types perform across a range of hydrologic processes such as peak flow or pollutant load reduction (Liu et al. 2017). Studies that explored the use of SCMs found that they will provide both water quantity and quality benefits based on the primary function that they are designed for (Jefferson et al. 2017; Golden and Hoghooghi 2018). Hydrologic model outputs give stormwater managers insight on the relative performance across SCM types to assist in the decision-making process. It is common for stormwater modeling studies to use either SCM placement (Limbrunner et al. 2013; Hipp, Lejano, and Smith 2006; Perez-pedini, Limbrunner, and Vogel 2006), a single regulatory constraint (Baek et al. 2015; Yang, Fong, and Chui 2018; Jenq et al. 1983), or a site-scale analysis (Loáiciga et al. 2015; Mays and Bedient 1982; Sample et al. 2001) as a guide to choose the best SCM type for a study area. However, a planning-level analysis that includes watershed-scale, multi-benefit, and multi-SCM analysis over a wide range of solutions should be conducted before these type of design-level studies (E. M. Gallo, n.d.). Knowledge on how the implementation of SCMs effect modeling results on a watershed-scale is crucial to determine the feasibility of meeting regulatory requirements (E. Gallo et al. 2020; J. M. Wolfand et al. 2018). A multi-benefit analysis demonstrates how a stormwater management plan will impact other water sectors that are part of an integrated water management plan (USEPA 2013, 2014). The consideration of multiple SCM types over a wide range of solutions is crucial to ensure that all options have been explored before the site specific design and placement of SCMs ("Panos Paper 3," n.d.). Gallo et al. used optimizations (to minimize cost and maximize stormwater volume reduction) and a modified version of EPA's SUSTAIN to conduct a planning-level analysis on a watershed-scale to determine the appropriate suite of green and grey SCMs given varying management criteria and stakeholder priorities. However, that analysis only uses capital cost for SCM types when optimizing in the model and a preliminary benefit analysis based on hydrologic model outputs.

Stormwater management plans are costly projects (millions to billions of dollars for an urbanized watershed) to implement and maintain (Hooper, McDonald, and Mitchell 1999). Cost is an important factor to take into consideration when choosing between variable stormwater solutions (Pizzol et al. 2015). Money allocated towards a stormwater management plan that does not achieve the goals of stakeholders and the communities where projects are being installed can have negative impacts that can extend up to decades after implementation and may be irreversible (Taguchi et al. 2020; Gluch and Baumann 2004; Gough and Ward 1996). While some stormwater modeling studies attempt to include maintenance costs (Weiss, Gulliver, and Erickson 2007; Pomeroy and Houdeshel 2009; Razif et al. 2015), many only use capital costs. However, promoting the implementation of SCMs requires demonstrating cost control especially on a watershed-scale and throughout time (Panagopoulos, Makropoulos, and Mimikou 2011) which cannot accurately be represented using only capital costs. Life cycle costs (LCC) and life cycle assessments (LCA) are used to assess the performance of SCMs as well as evaluate the potential benefits and costs over time (Grubert 2017; Mcauley and Knights 2015; Liao et al.

2014; Rebitzer, Hunkeler, and Jolliep 2003). LCC assessments include planning and permitting, construction, operation, maintenance, decommissioning, and relative lifespan and replacement costs (C. D Bell et al. 2019). The assessment of environmental impacts of different SCMs over time is referred to as a LCA (Pizzol et al. 2015; Kloepffer 2008; Grubert and Stokes-Draut 2020; Rebitzer, Hunkeler, and Jolliep 2003). This includes the impacts starting with the extraction of materials, to operations, and through disposal. Environmental costs are important as SCM implementation does not have a strictly positive impact on the environment (Grubert and Stokes-Draut 2020).

While hydrologic models give insight into the performance of SCMs across multiple water quantity and quality measurements, they do not provide a system-level analysis needed to associate the impacts of SCM interventions across varying management criteria and thus stakeholders. For example, peak discharge flow gives insight into flooding risk which is important for home owners close to flood zones (Cadavid and Ando 2013; Roesner, Bledsoe, and Brashear 2001). Similarly infiltration impacts ground water recharge potential which is important for local water supply (Sun et al. 2014). Additionally SCMs offer a wide variety of ancillary benefits beyond those that are strictly considered hydrologic (Jaffe 2010; McGarity et al. 2015; C. D Bell et al. 2019; K. Spahr 2020). While these other benefits are not necessarily the driving motivation for stormwater managers and municipalities to manage stormwater, it has been found that community members care just as much about additional benefits as they do flood management and water quality conditions (Meerow and Newell 2017; Cadavid and Ando 2013; K. Spahr 2020). These additional benefits include those not directly calculated by a hydrologic model, such as human health improvements which are usually linked to added greenness and vegetation. While some models attempt to include vegetation with SCMs this is difficult to accurately represent as vegetation in a SCM depends on climate, region, type, design, and time. For example, the impacts or positive effects of vegetation for a bioretention unit would be different in two different cities (i.e. Atlanta, GA vs Albuquerque, NM) based on time it takes for trees to grow to full size and the type of vegetation that can survive in that region (Berland et al. 2017). A planning-level assessment of vegetative benefits is needed so that decision makers can use the available knowledge to make decisions specific to their watershed. This includes considering which benefits are important to varying stakeholders and the community as well as assessing the appropriateness of proposed interventions. Finally, some studies (Alves et al. 2018;

E. M. Gallo, n.d.) demonstrate how incorporating stakeholder and community preference in the decision-making process is important as it shifts which SCMs may need to be prioritized in order to maximize the benefits for both the environment and the community.

While there currently exists several non-proprietary stormwater decision support tools and databases none of them integrate hydrologic modeling, LCC assessments, and a benefit analysis. In this study we use a planning-level integrated decision support tool to 1) investigate the optimal stormwater management plan in two cities with varying regulatory constraints 2) demonstrate the importance of using a full LCC assessment by showing the impacts on modeling results and 3) conduct a full hydrologic and vegetative benefit analysis while considering varying management criteria ultimately used by stakeholder. The two watersheds in this study are the Ballona Creek watershed located in Los Angeles, CA and the Berkeley neighborhood watershed located in Denver, CO. Using two studies shows the importance of using location specific LCC, model input data and setup unique to the watershed, and management criteria relevant to stakeholders from the area.

4.3 Study Area

4.3.1 Ballona Creek Watershed, Los Angeles CA

The Ballona Creek watershed is 319 km2 (Table 4.1) and is highly urbanized with a percent imperviousness of 60.9% (Ballona Creek Watershed Management Group 2016; E. Gallo et al. 2020). This watershed is located in Los Angeles County in southern California and has a semi-arid climate which averages 381 mm of rain per year (California Department of Water Resources 2016). Extensive urbanization has resulted in an altered hydrologic regime and water quality degradation throughout watersheds in Los Angeles (Read et al. 2018; Sheng and Wilson 2009). The large number of antecedent dry days in between rain events leads to an extensive buildup of pollutants which are washed off the land surface and transported to receiving bodies of water during storm events. The Ballona Creek is listed on the impaired rivers list and has total maximum daily loads (TMDLs) established for a range of pollutants including heavy metals, copper (Cu), lead (Pb), and zinc (Zn) (California Regional Water Quality Control Board 2016; USEPA 2018b). There is a large incentive to implement stormwater infrastructure and manage nonpoint source pollution in order to be in compliance with water quality regulations; this is the driving regulatory constraint for stormwater management.

Recent droughts in California have placed stress on the state's water supply thus, the City of Los Angeles has been working on implementing an integrated water management plan (IWMP). While water quality improvement is a key driver for stormwater management planning, increased water supply security, especially through local supply, is also a major goal for Los Angeles. Recent concerns and studies in the Los Angeles area also includes improving recreation in the rivers and ensuring adequate water quantity and quality conditions for a healthy ecosystem (Mika et al. 2018; E. Gallo et al. 2020).

4.3.2 Berkeley Neighborhood Watershed, Denver CO

The Berkeley neighborhood watershed is a 4.18 km2 urbanized area (C. L. Panos et al. 2018) located in northwest Denver, CO. The watershed is highly residential (54%) and impervious (53%). Berkeley neighborhood is undergoing infill development, a phenomenon where single- and multi-family residential houses are being torn down and replaced with housing that has a significantly larger footprint. This increases the imperviousness of the overall watershed and thus runoff volumes (Cherry et al. 2019). It is expected that a significant portion of land will be redeveloped in the near future which will result in a 4.7% increase in imperviousness and a 7.1% increase in stormwater volumes flowing off of the land surface (C. L. Panos et al. 2018). The watershed is currently experiencing surcharging when the 5-yr, 24-hr storm occurs. There is an incentive to implement stormwater management infrastructure as parcels are redeveloped in order to mitigate the potential flooding hazards. Ensuring average annual flow volumes remain constant or decrease in the future with redevelopment is the driving regulatory constraint for stormwater management in the Berkeley neighborhood watershed.

The City and County of Denver has an established Storm Drainage Master Plan which gives guidance on the implementation of stormwater management strategies in accordance to regulations and policies to reduce the risk of flooding (City and County of Denver 2013, 2019; City and County of Denver Public Works 2018; UDFCD 2010b). One objective of this plan includes on-site detention of flood flows for all development and infill development projects that are 0.5 acres are greater. A second objective is to reduce loadings of high risk pollutants with the expectation that TMDLs will be established in the near future (City and County of Denver Public Works 2018). These pollutants include nutrients, heavy metals, and Total Suspended Solids (TSS) (City and County of Denver Public Works 2018). Additional objectives includes maximizing benefits associated with the implementation of green infrastructure such as reducing effects of urban heat island, improved equity, and increased biodiversity and habitat (City and County of Denver Public Works 2018).

Table 4.1 Physical and policy characteristics of the two study area watersheds.

Watershed Characteristic	Ballona Creek	Berkeley neighborhood
Location	Los Angeles, CA	Denver, CO
Area ($km^{2)}$	319	4.19
Climate	Semi-arid	Semi-arid, Continental
Percent Impervious [%]	60.9	53
Pollutants of Concern	Heavy Metals	E. Coli, Total Phosphorous, TSS, Heavy Metals
Watershed Management Goal	Elimination of TMDL exceedances	Manage alterations to stormwater volumes due to infill development

4.4 Methods

4.4.1 Model

An integrated decision support Tool (i-DST) that includes modules for both a watershed-scale and site-scale hydrologic model, LCC and assessments, and benefit assessment has been developed to conduct a planning-level analysis and assist in decision-making for stormwater management. While the most holistic approach is using all modules of the i-DST, each module can also be used individually. When all of the modules are used this tool offers a comprehensive analysis on the tradeoffs of green to grey stormwater infrastructure, a resource needed by decision makers and stakeholders. This paper performs analysis with the watershed-scale hydrologic model, LCC, and benefit modules of the i-DST to generate results that can assist in determining the optimal stormwater management plan for the study areas in question.

4.4.2 I-DST SUSTAIN Watershed-Scale Model

The i-DST watershed-scale module utilizes a modified version of EPA's SUSTAIN model (Shoemaker et al. 2009; E. M. Gallo, n.d.). The external SCM simulation module implements aggregate SCMs on a watershed-scale and assesses SCM performance on calibrated and validated stormwater flow and pollutant loads acquired from either the SUSTAIN internal land simulation or any other hydrologic model. Several changes were made to the SUSTAIN code for the i-DST in order to represent a larger suite of SCMs, including greyer SCMs (underground infiltration, underground detention, underground gravel bed, and above ground storage), and allow a larger list of evaluation factors (groundwater recharge potential, evapotranspiration, and seasonal flow volume, loads and concentration) resulting in an updated version of SUSTAIN called i-DST SUSTAIN (E. M. Gallo, n.d.).

4.4.2.1 Related Past Modeling Efforts

This analysis synthesizes and builds onto work from past SUSTAIN and i-DST SUSTAIN modeling efforts in the Ballona Creek watershed (E. Gallo et al. 2020; Mika et al. 2018) and Berkeley neighborhood watershed (E. M. Gallo, n.d.), respectively. Therefore, most input data, calibration efforts, SCM design parameters, and model routing networks were retained for this study. Updates and improvements in i-DST SUSTAIN from the past studies to the current study include inclusion of grey infrastructure in the Ballona Creek watershed and novel optimizations modeling for both watersheds.

4.4.2.2 Water Quantity Data

The Ballona Creek watershed external SCM simulation model is driven by daily climatology data (temperature, evapotranspiration, and wind speed) acquired from the California Irrigation and Management Information System (California Department of Water Resources 2016) and the calibrated and validated land use time series of surface runoff (11 distinct land use types) from previous modeling efforts (Beck 2014; Radavich 2015; E. Gallo et al. 2020). The Ballona Creek stormflow data period used for model simulation includes continuous hourly flow from water years 1999 to 2005 (Los Angeles Department of Public Works 2014).

The Berkeley neighborhood watershed module is driven by monthly average evapotranspiration data (C. L. Panos, Wolfand, and Hogue, n.d.) and land use time series of surface runoff volumes base off future redeveloped scenarios (E. M. Gallo, n.d.; C. L. Panos, Wolfand, and Hogue, n.d.). Monthly evapotranspiration values were derived from the Denver Water Administration Building gauging station (C. L. Panos et al. 2018). Validated and calibrated land use time series of surface runoff volumes were acquired from the Panos et al. (2018, 2020) modeling efforts. The Berkeley neighborhood stormflow data period used for model simulation is continuous summer month (April – September) time series from 2013-2017 and includes a non-redeveloped and redeveloped time series which both include multiple land use types within. The land use time series are used to simulate water quantity in i-DST SUSTAIN which drives the external i-DST SUSTAIN SCM module and simulates optimization results presented in this work.

4.4.2.3 Water Quality Data

Calibrated and validated land use times series of pollutant loadings were acquired from the original Ballona Creek modeling efforts (Radavich 2015; E. Gallo et al. 2020). Water quality sampling from discrete land use types (Southern California Coastal Water Research Project 2007) was compiled from both the LA Department of Public Works (LADPW) Stormwater Quality Monitoring Program and the Southern California Coastal Water Research Project and was used to compose EMC values. Observed water quality data for stream gauges was used to calibrate and validate the EMC values used for each pollutant and land use type.

Pollutants simulated in the Ballona Creek watershed include heavy metals Cu, Pb, and Zn as they are the primary concern. Land use time series of pollutant loading used in the Berkeley neighborhood modeling efforts (E. M. Gallo, n.d.) were simulated using the median EMC values obtained from a study (C. D. Bell, Wolfand, and Hogue 2019) that developed regional values from the National Stormwater Quality Database as there is a lack of observed water quality data in the Berkeley neighborhood watershed. Three pollutants (TSS, TP , and Zn) were simulated in the Berkeley neighborhood watershed based on their risk levels assessed in the stormwater master plans of Denver (City and County of Denver Public Works 2018).

4.4.2.4 Modeled SCMs

SCMs selected to be simulated in i-DST SUSTAIN for the Ballona Creek watershed included seven types (bioretention [BR], infiltration trench [IT], dry pond [DP], vegetated swale

[VS], underground infiltration structure [UIS], underground detention structure [UDS], and porous pavement [PP]). SCM dimensions (Table 4.2) for BR, IT, DP, VS, and PP in the Ballona Creek watershed were determined by averaging values from several SCM projects found throughout LA resulting in varying dimension for each SCM type ("International Stormwater BMP Database" 2016; E. Gallo et al. 2020; Mika et al. 2018). Design data from a proprietary company, StormTrap, was used to assist in sizing of the UDS and UIS SCMs (StormTrap 2018). The 25th and 75th percentile volume capacity from projects based out of Los Angeles were used for UDS and UIS (StormTrap 2018), respectively to investigate the use of both a smaller and a larger underground design.

Six SCMs were simulated in the Berkeley neighborhood watershed (all SCMs simulated in Ballona Creek with an exception to DP) (E. M. Gallo, n.d.). The Berkeley neighborhood watershed is smaller in size than Ballona Creek and dominated by residential land uses so larger regional-scale SCMs such as DP are likely not feasible for implementation thus were not simulated. SCMs in Berkeley neighborhood were designed using guidelines from the City and County of Denver ultra-urban green infrastructure guidelines as well as the Urban Drainage and Flood Control District stormwater management manual (City and County of Denver 2016; UDFCD 2010b). All SCMs were sized to be 5% of the impervious parcel drainage area and to have a surface and soil storage that can capture and treat runoff form the Water Quality Capture Volume event, the 80th percentile storm and a 17.5 mm rainfall depth. Thus, while each SCM in Ballona Creek watershed has a different capture volume, all SCMs in the Berkeley neighborhood have the same capture volume which reflects design guidelines from the specific watersheds.

This study uses a first-order decay rate model to simulate SCM performance. Pollutant decay rates in the Ballona Creek watershed (Table 4.2) for four of the original SCMs (VS, IT, DP, BR) were determined by adjusting the decay rates in SUSTAIN and comparing modeled influent and effluent concentrations to those reported in the International Stormwater BMP Database for LA (Beck 2014; E. Gallo et al. 2020). The i-DST DeCal tool, decay calibration software package was used to calibrate pollutant decay rates for UIS and UDS in both the Ballona Creek and Berkeley neighborhood watershed. The DeCal was also used for BR, IT, and VS in the Berkeley neighborhood watershed (E. M. Gallo, n.d.; "International Stormwater BMP Database" 2016). Finally, while there are a limited number of studies that do report influent and effluent values for PP, this study takes a conservative approach by assuming a decay rate of zero due to the limited SCM sites and number of storms reported in the IBMPD ("International Stormwater BMP Database" 2016; UDFCD 2010b).

Table 4.2 Physical dimensions and pollutant removal efficiencies for modeled SCMs in the Ballona Creek and Berkeley neighborhood watersheds

SCM	VS	BR	DP	IT	UDS	PP	UIS
Ballona Creek							
SCM Dimensions							
Width [m]	3.0	7.0	4.6	13.7	19.6	9.1	27.5
Length [m]	76.2	14.0	13.7	27.4	19.6	18.9	27.5
Depth [m]	0.2	0.5	1.5	1.5	1.5	0.3	3.0
Soil Layer Depth [m]	0.3	0.9	0.3	1.8	--	1.2	3.7
Pollutant decay rates							
IBMPD Data Source	2015 IBMPD Summary Report	2015 IBMPD Summary Report	2015 IBMPD Summary Report	2015 IBMPD Summary Report	Lakewood, CO Retention Vault	NA	Lakewood, CO Retention Vault
Cu (1/yr)	1.7	0.55	0.60	0.60	0.396	0.00	0.396
Pb (1/yr)	20	0.2	0.65	0.65	0.00015	0.00	0.00015
Zn (1/yr)	60	0.85	1.08	1.08	0.038	0.00	0.038
Berkeley neighborhood							
SCM Dimensions							
Width [m]	1.5	1.5	--	1.5	2.5	1.5	2.3
Length [m]	11.1	12.2	--	12.0	2.5	12.2	2.3
Depth [m]	0.2	0.2	--	0.2	1.4	0.01	1.4
Soil Layer Depth [m]	0.2	0.8	--	0.7	--	0.7	0.7
Pollutant decay rates							
IBMPD Data Source	CA RVTS System	Lakewood, CO Iris Garden	--	Lakewood, CO Dry Pond	Lakewood, CO Retention Vault	NA	Lakewood, CO Retention Vault
TSS (1/yr)	0.122	2.15	--	0.757	0.396	0.00	0.396
TP (1/yr)	0.00	0.0997	--	0.059	0.00015	0.00	0.00015
Zn (1/yr)	4.864	0.72	--	0.615	0.038	0.00	0.038

4.4.2.5 Model Routing

The Ballona Creek and The Berkeley neighborhood watershed models were both set up in i-DST SUSTAIN as lumped models. Land use and runoff and pollutant loading time series are first routed to an aggregate SCM. The Ballona Creek watershed is made up of 11 distinct land use types and thus time series. Runoff and pollutant loadings from 90% of all land use types was routed to the Ballona Creek aggregate SCM. Thus 10% of the watershed is bypassing the aggregate SCM. The Berkeley neighborhood watershed is made up of two separate areas of land, non-redeveloped and redeveloped. Runoff and pollutant loadings from 100% of the redeveloped area are routed to the aggregate SCM in The Berkeley neighborhood watershed while 0% of the non-redeveloped area bypasses the aggregate and flow directly to the virtual outlet. Total outflow from the aggregate SCMs as well as bypassed flow is then routed to a virtual outlet where evaluation factors are analyzed and optimized on for the two watersheds.

4.4.3 Life Cycle Cost Calculator

The Life Cycle Costing Module developed by Krieger et al. (2020), is an Excel workbook that utilizes a bottom-up approach, user-input data (location, time, and SCM dimensions), and a central database of associated costs to calculate a comprehensive LCC and first-order assessment of monetized environmental impacts for 16 SCM types, all of which are included in the i-DST SUSTAIN watershed-scale module. The module uses a unit cost approach, which is made up of multiple cost types that are specific to each SCM type, location of a watershed, and year of project implementation. Cost for each life stage (i.e. construction, operation and management (O&M), and end-of-life) are included in the final cost. O&M and end-of-life costs are calculated using a process-based approach, based on specific activities and the associated labor, material, equipment, and energy costs, rather than a percent of construction costs. Environmental impacts are calculated through monetization of environmental impacts, including but not limited to, ozone depletion, global warming, acidification, eutrophication, and smog. The final LCC for a particular SCM includes an itemized calculation of life cycle stage (construction, O&M, and end-of-life) as well as cost type (materials, labor, equipment, energy, other direct, and environmental) (Krieger and Grubert 2020).

A separate LCC workbook was set up for the two study watersheds. State and city are specified in the tool to ensure that the correct costs are being estimated for the Ballona Creek and

Berkeley neighborhood watersheds. Start year for construction was set for 2020 with a 50 year unit lifetime interval between replacements for all SCM units. Costs are adjusted based on inflation and category-specific escalation rates. The LCC calculator is set up to calculate 50 years of service. In terms of global inputs, the LCC module was set up to calculate costs with all other global input set to the default (i.e. internal labor, owned equipment, an hour of equipment unit time, medium costs, medium maintenance frequency and all default values for annual discounts and inflation rates). SCM dimensions from the respective watersheds (Table 4.2) was inputted into the tool to calculate LCC based on the actual sizes being simulated in the hydrologic model. The number of SCM units in the LCC calculator was set to 1 unit in order to calculate the LCC per SCM unit. The final total financial and monetized environmental cost for each SCM type was used as the total SCM cost per SCM unit in the i-DST SUSTAIN optimization module.

4.4.4 Hydrologic Model Optimization Scenarios

4.4.4.1 Regulatory Constraints

The i-DST SUSTAIN optimization uses algorithms (NSGA-II or Scatter Search) to determine optimal SCM solutions by simulating thousands of SCM combinations and optimizing (reducing) cost while achieving a specific target evaluation factor, such as pollutant load reduction (Shoemaker et al. 2009). The Ballona Creek and Berkeley neighborhood watershed optimizations were set up to optimize on a watershed specific regulatory constraints and LCC. The primary motivation for managing stormwater in the Ballona Creek watershed is to be in compliance with established TMDLs. Previous modeling results in the Ballona Creek watershed demonstrated that an AAL reduction of 70% and an AAC reduction of 12% is required to reach 100% Zn wet and dry weather compliance (E. Gallo et al. 2020; Mika et al. 2018). Thus the model is set up to optimize on Zn AAL and AAC with a target goal of 3,635 pounds of Zn and a concentration of 0.083 mg/L. The Berkeley neighborhood watershed has a main objective of mitigating stormwater runoff volumes from redevelopment and increased future imperviousness. It was determined that a reduction of at 5% in AAFV was needed in order for future projected runoff to remain constant with the current baseline (E. M. Gallo, n.d.). Thus, a target of 361,401 m^3 was set as the optimization goal for the Berkeley neighborhood watershed.

4.4.4.2 Capital Cost vs LCC Sensitivity Analysis

A cost sensitivity analysis was conducted on both watersheds. The cost per SCM unit using capital and LCC is first compared to evaluate the differences between the two estimations. The LCC are then further broken down by life cycle stage and cost type reported by the LCC module to compare difference in SCM types within the same watershed as well as across the two watersheds.

Two full optimizations were simulated in each watershed. Full optimizations were simulated with both capital costs and LCC to evaluate the impacts on modeling results when a LCC assessment is used to drive the i-DST SUSTAIN optimization module. These modeling results were then used to conduct two sensitivity analyses, using varying selection criteria to isolate specific solutions within the Pareto curve. The first sensitivity analysis, SA-elbow, was comprised of the 100 solutions that fall in the "elbow" of the Pareto curve, minimize cost while achieving regulatory compliance. The second sensitivity analysis, SA-reg, was comprised of the 100 solutions that fall along the regulatory constraint across all costs. Results were used to further explore the impacts of LCC on which SCMs are prioritized in the model.

4.4.4.3 Selection Criteria for Inter-Watershed Comparison

Three final solutions were isolated from the full LCC optimizations for the final benefit analysis in both the Ballona Creek and the Berkeley neighborhood watersheds. While there are multiple methodologies that can be used to select the final solutions, this study focuses on a greener, greyer, and hybrid approach. Solutions that fall within the LCC SA-reg conducted above, meet regulatory compliance across all costs, were first isolated. These were then ranked in terms of percent runoff captured by SCM type: greener SCMs (VS, IT, BR, and DP) vs greyer SCMs (PP, UDS, UIS). The greenest (maximum percent of capture by greener SCMs), greyest (maximum percent of capture by greyer SCMs), and a hybrid (50% capture by both greener and greyer) were selected for the final benefit analysis in this study.

4.4.5 Benefit Analysis

Spahr et al. (2020) conducted an extensive literature review on current methodologies for incorporating hydrologic and vegetated benefits into hydrologic modeling (K. Spahr 2020). Existing studies that measure benefits do so by either monetizing the benefits or by quantifying benefits based on vegetation. While those methodologies quantify the benefits of stormwater infrastructure, there is a need for a planning-level analysis. Spahr et al. (2020) developed a methodology that uses a multi-criteria assessment matrix to assess the hydrologic benefits and the 4 C's methodology to evaluate and consider vegetative benefits.

4.4.5.1 Hydrologic Benefit Analysis

A multi-criteria assessment matrix methodology was used to compare the hydrologic benefits associated with the greenest, greyest, and hybrid solutions from both watersheds. This approach first compares the three solutions within one watershed to one another based on their relative performance in terms of multiple hydrologic modeling outputs. These outputs are linked to specific hydrologic benefits identified by Spahr et al. (2020). For example, peak discharge flow is used for reduced impacts of flooding. Using a vector normalization approach the three solutions are given a benefit vector normalization value (Equation 4.1) for each hydrologic benefit and each solution. Eight hydrologic benefits are compared in this analysis including cost, vegetated benefits (potential vegetated area based on modeling results), reduced impacts from flooding, increased groundwater resources, neighborhood cooling, and improved water quality (load-based and concentration-based). The first benefit analysis compares the solutions without any weight applied to hydrologic benefits.

A rating systems was then used to weight hydrologic benefits (Equation 4.2) based on varying management criteria using a scale of 0 to 5, where a rating of 5 receives a higher priority weighting. This analysis is used to identify which solution is preferred based on hydrologic benefits that apply to a certain management criteria. These varying management criteria mimic stakeholder priorities specific to the retrospective watersheds as they may be applied when stakeholders are making decisions. For this study the associated benefits that are important to a management criteria is rated 5 while all other benefits are rated with a value of 0. Each solution is given a final overall score (Equation 4.3) based on the management criteria priority rating system. Three varying management criteria explored in the Ballona Creek watershed including regulatory compliance (rating AAL, AAC, and cost with a value of 5), recreation (rating AAFV, vegetation, AAC, and cost with a value of 5), and local water supply (rating GWRP and cost with a value of 5) (Ballona Creek Watershed Management Group 2016). The three management criteria explored in the Berkeley neighborhood watershed include regulatory compliance (rating

AAFV, PDF, and cost with a value of 5), climate change mitigation (rating ET and cost with a value of 5), and increased biodiversity and habitat (rating AAC and cost with a value of 5) (City and County of Denver Public Works 2018). It is assumed that cost is always one the most important factors thus cost was rated a value of 5 in all management criteria scenarios.

$$Benefit\ Vector\ Normalization\ Value_{j,n} = \left[\frac{Benefit\ Value_{j,n}}{\sqrt{\sum_j Benefit\ Values^2{}_n}}\right] \tag{4.1}$$

$$Benefit\ Preference\ Score_{j,n} = Benefit\ Vector\ Normalization\ Value_{j,n} * Rating_{j,n} \tag{4.2}$$

$$Overall\ Score_j = \frac{\sum_n Benefit\ Score_j}{\sum Rating_n} \tag{4.3}$$

where j = SCM Solutions (3); n = Benefit Type (8)

4.4.5.2 Vegetative Benefit Analysis

In order to discuss the vegetative benefits associated with each solution in each watershed the 4 C's approach outlined in Spahr et al. (2020) is used. The 4 C's which include community, context, connectivity, and canopy, are used to discuss benefits that are related to and linked to vegetation but cannot necessarily be directly calculated using a hydrologic model(K. Spahr 2020). Vegetative benefits include increased recreational opportunities, increased terrestrial biodiversity, increased property values, neighborhood beautification, human health and social well-being, improved air quality, and neighborhood cooling from tree canopy. Vegetation-based benefits of SCMs need to be considered at the systems level using demographic data (community), the physical trends of a watershed (context) as well as the interaction with other urban green infrastructure which includes open spaces, parks, informal green spaces, bike paths, and tree canopy (connectivity and canopy). The three varying management criteria explored in the hydrologic benefit analysis will be further explored and discussed in terms of the 4 C's for the final analysis on stormwater solutions in the Ballona Creek and Berkeley neighborhood watersheds.

4.5 Results

4.5.1 Life cycle Costs vs Capital Costs

Table 4.3 displays the capital cost (estimated using construction projects) and LCC (calculated using the i-DST life cycle costing module) for each SCM type simulated in the Ballona Creek and Berkeley neighborhood watersheds. Capital costs are displayed as both per cubic foot and as per SCM unit. The Ballona Creek capital costs were lower than the total LCC of the SCM by a percent difference of 1% (UIS) to 760% (VS). The difference in costs are not as dramatic for the larger systems (UIS, UDS, and IT all have a percent difference <100%) as they are for the smaller systems (VS, BR, DP, IT all have percent difference of > 100%). It should be noted that the total capture volume capacity for SCMs in the Ballona Creek watershed is variable across all SCM units whereas the SCMs in the Berkeley neighborhood watershed are all designed with the same total capture volume capacity. The Berkeley neighborhood capital costs were lower than the total LCC of the SCM by a percent difference of 380% (BR) to 2,900% (VS). The difference in costs is much higher in the Berkeley neighborhood than the Ballona Creek as the design for volume capture is much lower. BR and PP have the smallest percent difference (<1000%) while VS, IT, UIS, and UDS have the largest percent difference (>1000%).

Relative cost order of SCM types shifts from capital costs to LCC. For example, while VS has the lowest cost per SCM unit with capital costs it only has the fourth lowest cost per SCM unit with LCC in the Ballona Creek watershed. This shift is also seen in the Berkeley neighborhood watershed for vegetated swales. Similarly, BR has the highest capital cost per SCM unit in the Berkeley neighborhood watershed but the second lowest LCC.

Table 4.3 Comparison of capital vs LCC for each SCM type in the Ballona and Berkeley neighborhood watersheds. % difference is between the capital cost per SCM unit and LCC per SCM unit. Capital costs were calculated using construction projects while LCC were calculated using the i-DST life cycle costing module.

	Ballona Creek				Berkeley neighborhood			
	Capital Cost per cubic meter	Capital Cost per SCM unit	LCC for per SCM unit	% Diff.	Capital Cost per cubic meter	Capital Cost per SCM unit	LCC for per SCM unit	% Diff.
VS	355.62	20,140	172,376	760	281.45	1,446	43,060	2,900
IT	212.95	180,719	312,453	73	168.80	2,772	33,237	1,100

Table 4.3 Continued

BR	515.60	41,706	135,426	230	408.23	7,167	34,639	380
DP	207.65	21,035	117,249	460	--	--	--	--
PP	554.10	75,876	160,867	110	424.13	5,262	42,405	700
UDS	623.30	346,187	440,186	27	493.69	4,541	103,130	2,200
UIS	365.15	839,215	846,830	1	438.61	4,936	107,647	2,100

Figure 4.1 displays the LCC broken up by life cycle stage (4.1A & B) and cost type (4.1C & D) for both of the watersheds. Life cycle stage costs include construction, O&M, and end-of-life. In the Ballona Creek watershed the largest proportion of life cycle stage costs is dedicated to construction for the two greyer underground systems, UIS and UDS while majority of costs are allocated towards the O&M stage for the five above ground SCMs (PP, DP, BR, IT, VS). A very small portion of the total LCC is required for the end-of-life stage. The three infiltration-based SCMs (UIS, PP, IT) have the highest end-of-life costs. In the Berkeley neighborhood watershed, the majority of the LCC are allocated towards the construction stage for UIS, UDS, and IT while PP, BR, and VS require the highest proportion of costs for the O&M stage. The end-of-life stage is also much lower compared to the construction and O&M stages in the Berkeley neighborhood watershed. LCC types include materials, labor, equipment, energy, other direct (which may include costs like taxes, profit margins, or lump sum bids for which unit cost data are not available), and environmental costs. All SCMs in both watershed allocate the largest proportion of money towards materials with an exception to IT in the Ballona creek which is dominated by labor and equipment. SCMs that are larger and/or more vegetated tend to have relatively higher labor costs than those SCMs that are smaller and less vegetated. SCMs that are larger and/or underground tend to have a larger proportion of environmental costs in both watersheds. Finally, it should be noted IT has the highest LCC in the Ballona Creek watershed for the above ground SCMs while it has the lowest LCC for above ground SCMs in the Berkeley neighborhood watershed.

It can be seen that VS has a lower construction cost in the Ballona Creek watershed but the fourth highest O&M cost. This explains the relative change in cost order from capital costs (construction only) to LCC seen in Table 4.3. The shift in SCM order in the Berkeley neighborhood can also be explained using figure 4.1. For example, BR has a relatively average or higher materials and labor cost compared to the other above ground SCMs. However it has lower equipment, energy, other direct and environmental costs.

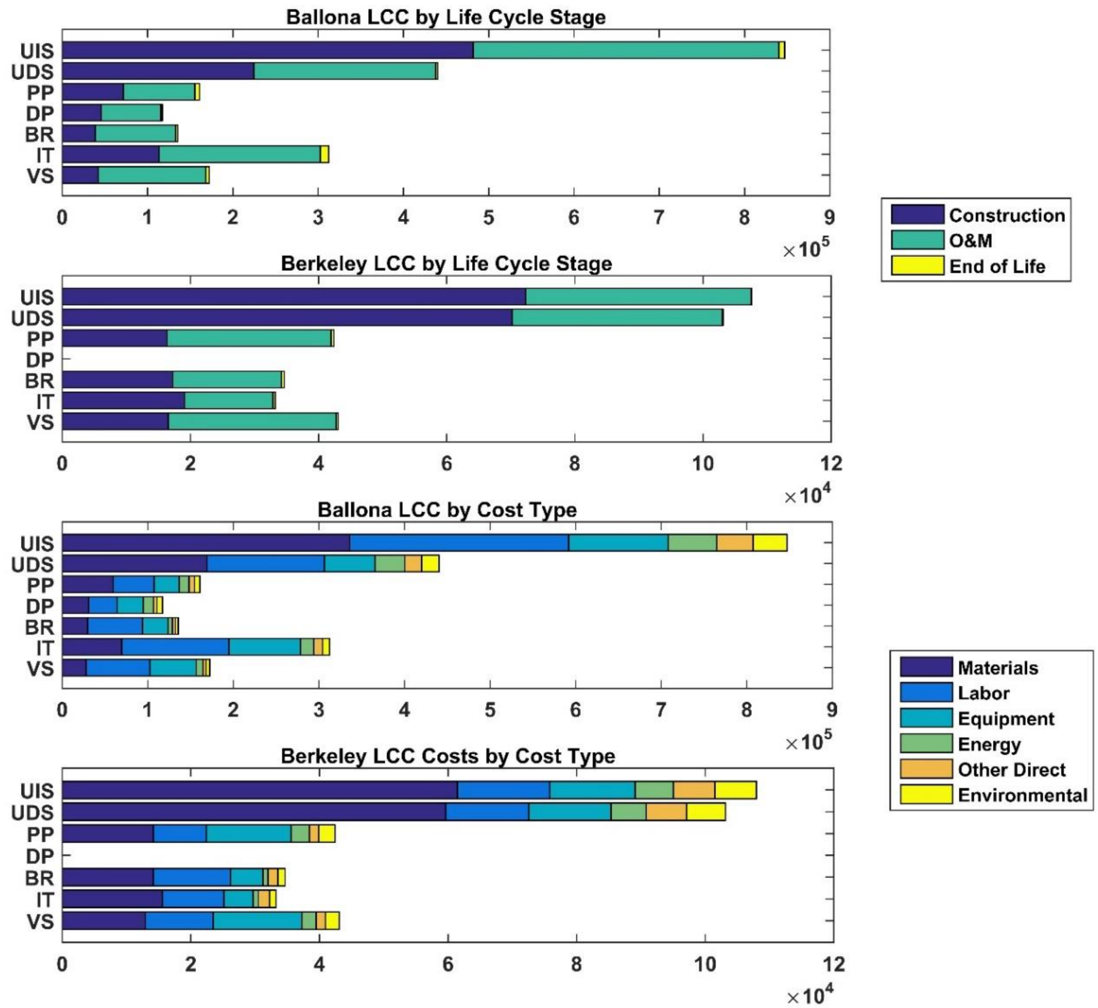

Figure 4.1 LCC broken down by life cycle stage and cost type for each SCM type in the Ballona Creek and Berkeley neighborhood watersheds. Reminder that DP were not simulated in the Berkeley neighborhood watershed.

Results from the full i-DST SUSTAIN optimizations (using capital costs and LCC) in the Ballona Creek (Figure 4.A) and Berkeley neighborhood (Figure 4.2B) watersheds show the dramatic effect the LCC have on the Pareto curves in terms of cost vs evaluation factor. While the AAL and AAFV range remains the same across cost types in each watershed, the cost ranges increase by a maximum of ~80 billion and ~90 million U.S. dollars for the Ballona Creek and Berkeley neighborhood watersheds, respectively. It should be noted that the maximum cost solutions are utilizing ~500,000 and ~1,600 SCM units in the Ballona Creek and Berkeley neighborhood watersheds, respectively. These are the maximum number of units available, which equate to placing an SCM on every available space throughout the whole watershed, which is likely not feasible or realistic. It is up to modelers to understand the constraints in terms of realistic implementation of SCMs. The difference in costs become more extreme with solutions that promote a higher cost difference from the modeling baseline levels. For example, in the Ballona Creek watershed, there is only a ~1 billion cost difference between LCC and capital cost solutions that results in 1% reduction in AAL while there is a 30 billion difference between solution that result in a 80% reduction in AAL. Viable solutions, or those that will successfully meet the regulatory constraint, for the two watersheds fall below the black horizontal line in Figure 4.2A and B. It can be seen that there are less viable solutions in the Ballona Creek watershed as it requires a larger percent reduction in the evaluation factor (i.e. required more SCM units and larger percentage of the available resources) in comparison to the Berkeley neighborhood watershed. Thus, viable solutions in the Ballona Creek watershed have a higher difference between capital and LCC costs.

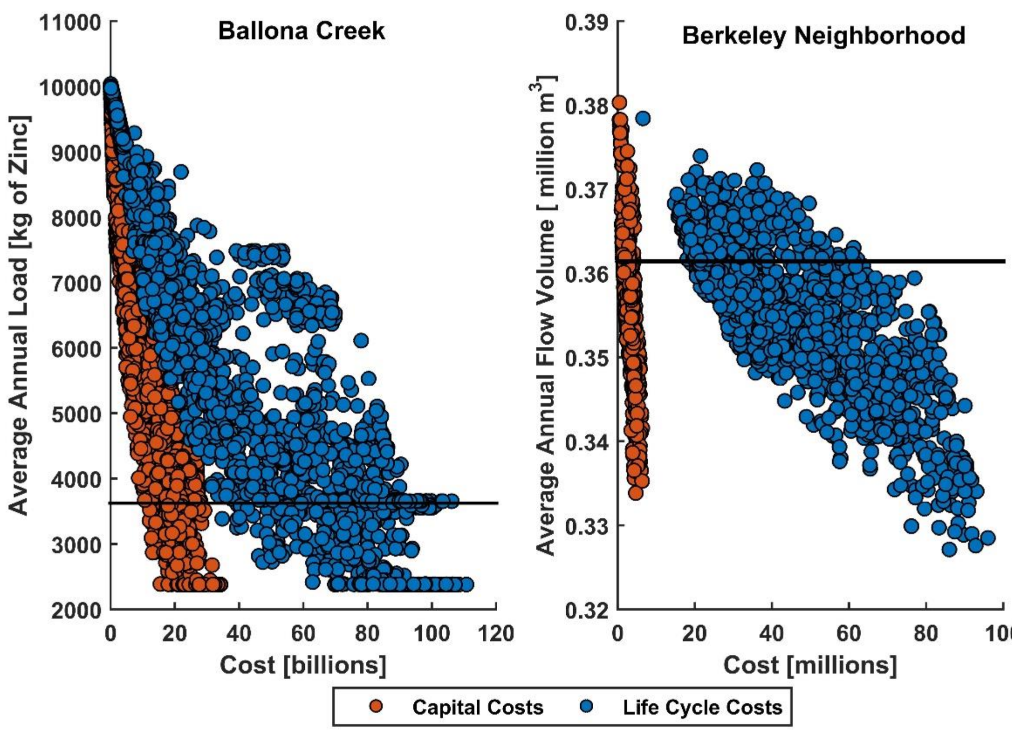

Figure 4.2 A (left) and B (right): Full optimization results for the Ballona Creek and Berkeley neighborhood watersheds with capital cost solutions in orange and LCC solutions in blue. Viable solutions for each watershed (based on regulatory compliance) fall below the black horizontal line.

Figure 4.3A and B shows a whisker box plot of the spread of the percent available SCM units for each SCM type across all 100 solutions isolated for the cost sensitivity analysis. This plot shows the shift in the number of SCMs the model is optimizing based on cost type (capital vs LCC) and location of solution within the Pareto curve (SA-elbow [minimize cost while meet regulatory constraint] and SA-reg [meet regulatory constraint across all costs]). For example, in the Ballona Creek watershed, the model implements a smaller range of VS when using LCC rather than capital. This is reflective of the shift seen in Table 4.3 where VS go from the lowest to the fourth lowest SCM cost. VS have a relatively higher cost per SCM with LCC costs thus the model did not prioritize them as much and less units were being simulated. Similarly the model simulated a larger range of VS units when looking at the LCC SA-elbow solutions vs LCC SA-reg solutions as there is no cost restriction. In the Ballona Creek watershed the shift from capital cost to LCC resulted in a higher mean number of SCM units simulated for BR, UDS, and UIS in the 100 SA-elbow solutions and a higher mean number of SCM units simulated for all SCMs except for UIS when shifting from capital to LCC in the SA-reg solution set. In the Berkeley neighborhood watershed the shift from capital cost to LCC resulted in a higher mean of SCM units simulated for BR and IT in the 100 SA-elbow solutions and a higher mean of SCM units simulated for only BR when shifting from capital to LCC in the SA-reg solution set.

The overall spread for all SCM types is fairly similar in the Ballona Creek watershed while they are visibly different in the Berkeley neighborhood watershed. A reduction of 80% in Zn AAL requires the use of almost all of the available SCM units in the model. Thus, the model is trying to maximize the available resources in order to reach that goal. However, in general, the infiltration-based SCMs (BR, IT, PP, and UIS) use the highest percentage of the available units, compared to other SCM types, in Ballona Creek due to the fact that they reduce AAFV the most effectively. The Berkeley neighborhood requires only a 5% reduction of AAFV volume thus the model does not need to simulate all of the available resources and can be more selective. It can be seen that VS, BR, and IT are the dominant SCM types being simulated in the Berkeley neighborhood watershed. These three SCMs have the lowest LCC and perform best in terms of Zn AAL reduction. The largest shift in SCM order from capital costs to LCC for a single SCM type in the sensitivity analysis results, Figure 4.3, is BR in Berkeley neighborhood which is reflective of BR having the highest capital cost and the second lowest LCC. BR also perform fairly well as it is a infiltrating-based SCM thus the combination of an above average performance and lower LCC resulted in the model prioritizing BR. Finally, it should be noted that as UIS has a relatively higher cost from a LCC perspective in the Berkeley neighborhood so their presence in the modeling results is very low.

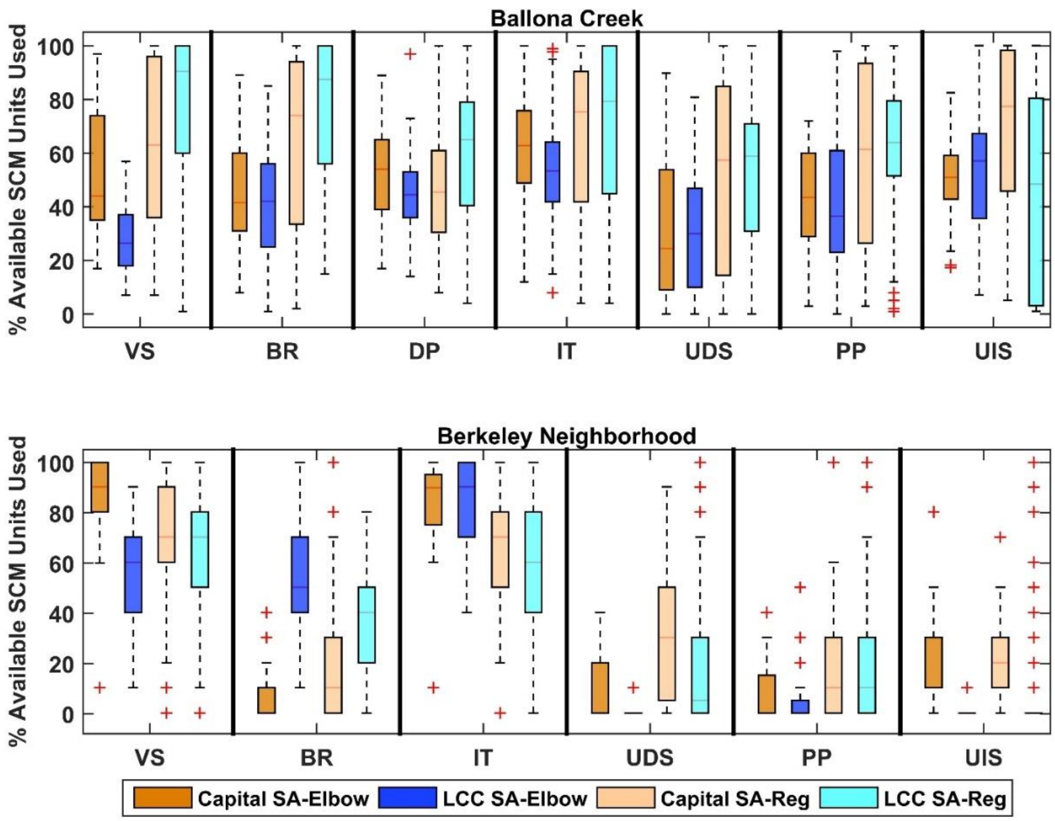

Figure 4.3 A (top) and B (bottom): Spread of the percent available SCM units used for each SCM type and each sensitivity analysis from the full optimizations. i.e. the Berkeley neighborhood 100 capital cost SA-elbow solutions uses between 60% to 100% of total available VS units but only 0% to 40% of the total available BR units.

4.5.2 Selected SCM LCC Solutions for Inter-Watershed Comparison

The three solutions (greener, greyer, and hybrid) that were identified from the full LCC optimizations for both watersheds using the selection methodology can be seen in Figure 4.4Aand B for Ballona Creek and Berkeley neighborhood, respectively. The three solutions identified for Ballona Creek all fall within a very similar cost range of ~75 billion dollars. The greenest solution in Figure 4.4C, has a 80:20 ratio in terms of percent runoff captured by greener vs greyer SCMs while the greyest solution has a 40:60 ratio for percent runoff captured by greener vs greyer. While the hybrid and greyer solutions identified in the Berkeley neighborhood have a similar cost of 45 million dollars the greenest solution has a cost of only 28 million dollars. The greenest solution, Figure 4.4D, has a 100:0 ratio in terms of percent runoff captured by greener vs greyer SCMs while the greyest solution has a 0:100 ratio for greener vs greyer. It should be noted again that the Ballona Creek watershed is having to use more resources in order to reach the strict regulatory compliance goal and thus even the greenest and greyest solutions utilize a fair amount of the opposite type of infrastructure. The Berkeley neighborhood watershed however has a more easily achievable regulatory compliance goal and thus more flexibility, 100:0 ratios for the greenest and greyest solutions.

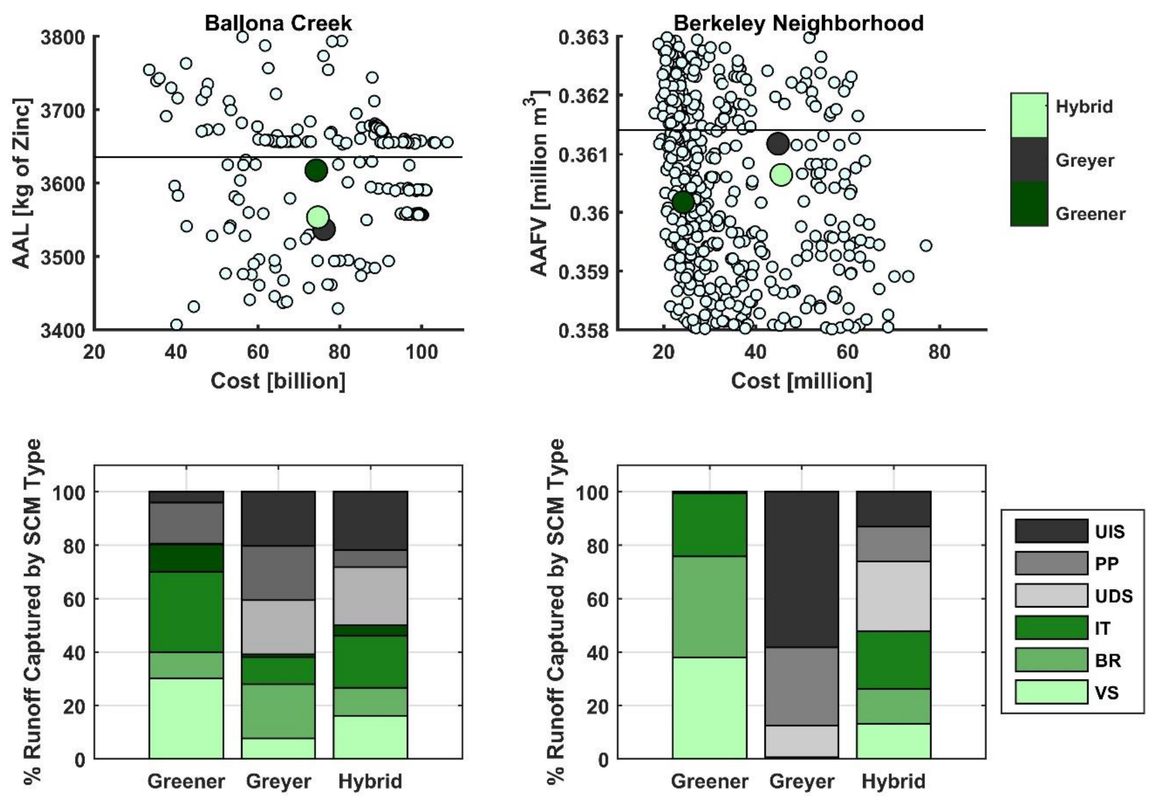

Figure 4.4 A (top left) and B (top right): Location of the three final solutions identified for the Ballona Creek and Berkeley neighborhood watershed, respectively. C (bottom left) and D (bottom right): Percent total runoff captured by each SCM type for the final greener, greyer, and hybrid solutions in the Ballona Creek and Berkeley neighborhood watersheds, respectively. Bar plots are staked in the same order as displayed in the legend, VSDP on the bottom and UIS on the top.

4.5.3 Hydrologic Benefit Analysis

Table 4.4 displays the hydrologic benefits for the three final solutions in both watersheds. The blue shading highlights the performance of SCMs based on most preferred to least. For example, the greener solution in Ballona Creek has a darker shading under vegetated benefits as it has the largest total potential vegetated area out of the three solutions. The hydrologic results without any preference ratings are similar to one another as the final selected solutions were isolated from a narrow range within the Pareto curve that all perform similarly in terms of AAL and AAFV reduction for Ballona Creek and Berkeley neighborhood, respectively. For both watersheds the greener solution has a higher overall relative performance in more categories. The greener solutions performs best in the vegetative benefits and reduced impacts from flooding in the Ballona Creek watershed. The greener solution outperform greyer in terms of cost, vegetative benefits, and neighborhood cooling in the Berkeley neighborhood. The greyer solutions perform best in terms of increased groundwater resources for both watersheds as they utilize both UIS and PP, both infiltrative SCMs. The hybrid solution generally performs in between the greener and greyer solution for both watersheds. The difference in hydrologic performance values are more variable in the Berkeley neighborhood watershed (i.e. normalized values of 0.88 vs 0.00 for vegetative benefits).

The three varying management criteria can be seen at the bottom of Tables 4.4 a and b . However, it can be seen how varying priorities results in a higher preference for some solutions over others. In the Ballona Creek watershed the hybrid solutions have the highest preference values when prioritizing regulatory compliance and local water supply while the greenest solution has the highest preference rating when prioritizing recreation. It should be noted that the three solutions in Ballona Creek tend to have similar preference values (<0.1 of each other) as there is only a small difference in terms of performance. For example there is only a difference of 60 pounds in AAL for the three solutions (Figure 4.4) and a difference of 7900 pounds of AAL across all simulated solutions (Figure 4.2). In Ballona Creek, the greenest and greyest solutions have the lowest preference ratings when prioritizing local water supply and recreation, respectively. The greenest solution in the Berkeley neighborhood watershed has the highest preference ratings for all management criteria while the greyest solutions has the lowest preference ratings.

Table 4.4 Hydrologic benefits (in blue) and management criteria scores (in grey) for the greener, greyer, and hybrid solutions identified for the Ballona Creek (top) and Berkeley neighborhood (bottom) watersheds. The color scale compares how each solution perform relatively to one another with darker shading representing more preferred and lighter shading representing less preferred.

	Metric	Lower Value Preferred?	Greener	Greyer	Hybrid
Ballona Creek Benefit Table					
-	Total LCC	Yes	0.57	0.59	0.57
Vegetated benefits	Total potential vegetated area	No	0.71	0.42	0.57
Reduced impacts from flooding	PDF	Yes	0.46	0.71	0.53
Increased groundwater resources	Total groundwater recharge potential	No	0.59	0.60	0.53
Neighborhood Cooling	Total evapotranspiration	No	0.57	0.55	0.62
Improved water quality	Average annual load of TP	Yes	0.59	0.57	0.57
Improved water quality	Average annual concentration of TP	Yes	0.58	0.57	0.57
Regulatory Compliance	**(AAL & AAC)**		**0.42**	**0.42**	**0.43**
Local Water Supply	**(GWRP)**		**0.47**	**0.50**	**0.52**
Recreation	**(AAFV, Vegetation, AAC)**		**0.53**	**0.46**	**0.49**
Berkeley Neighborhood Benefit Table					
-	Total LCC	Yes	0.35	0.67	0.66
Vegetated benefits	Total potential vegetated area	No	0.88	0.00	0.47
Reduced impacts from flooding	PDF	Yes	0.58	0.58	0.57
Neighborhood Cooling	Total evapotranspiration	No	0.76	0.26	0.60
Increased groundwater resources	Total groundwater recharge potential	No	0.54	0.64	0.55
Improved water quality	Average annual load of TP	Yes	0.57	0.58	0.58
Improved water quality	Average annual concentration of TP	Yes	0.58	0.58	0.57
Regulatory Compliance	**(AAFV & PDF)**		**0.35**	**0.25**	**0.26**
Climate Change Mitigation	**(ET)**		**0.70**	**0.29**	**0.47**
Increased Biodiversity and Habitat	**(AAC)**		**0.53**	**0.37**	**0.39**

4.5.4 Vegetative Benefit Analysis

Total potential vegetated area, which is based on the SCM footprint, is the only measurement of vegetation that can be calculated with a hydrologic model. However, it is not a full analysis of the vegetative benefits that may be accrued over time with the implementation of SCMs. The 4 C's methodology not only assesses the potential vegetative benefits for specific watershed but also promotes the use of available data, such as demographic and land characteristics, to ensure that SCMs are implemented in a way that maximizes the potential vegetative benefits.

Ballona Creek is a large watershed (319 km2) with a diverse demographic and land use characterization. This allows for flexibility on a whole watershed-scale for considering which types of SCMs would be more appropriate in certain areas. This approach also aligns with the hybrid solution being the most preferred by two out of the three management criteria. For example, in terms of continuity and context placement of SCMs that promote vegetative benefits may best be placed along or closer to the river to help promote recreation, neighborhood cooling, health benefits, and increased terrestrial biodiversity. Similarly greener SCMs may be also be chosen to be implemented in more industrial or commercialized areas which would lead to beautification and improved air quality in areas that would otherwise be fairly impervious and typically lack canopy. Placement of green infrastructure in these areas would increase greenness of the overall watershed and could counterbalance areas that should focus on greyer infrastructure. Highly urbanized locations that do not have space for greener infrastructure may need to utilize greyer and underground SCMs. Greyer SCMs are also optimal in areas that are trying to avoid increases in property values and thus gentrification (community). Greyer infrastructure may also work well in residential areas that already have decent canopy coverage as the implementation of green infrastructure may not actually attribute vegetative benefits relative to the parks and canopy that already exist (connectivity).

The Berkeley neighborhood watershed is much smaller in size (4.19 km2) and is dominated by residential land uses. For context, residential land uses are typically the one being redeveloped and thus produce a potential parcel of land available for SCMs. While underground SCMs may work well with highly impervious areas and infill development where a large portion of the parcel footprint is taken up, underground systems require more O&M cost on a regular basis and may not be appropriate for private residential areas. In terms of canopy and continuity, the larger footprint building on the parcels of land will be removing older trees that once provided canopy and greenness. Thus, the green infrastructure will help preserve greenness in the neighborhood as well as promote neighborhood cooling.

4.6 Discussion

4.6.1 Importance of LCC

Two differences exist between capital costs and LCC, cost magnitude and cost order. Using capital costs alone when planning for stormwater management are significantly lower in magnitude than the full cost to society as capital costs only account for a fraction of a LCC. Results show that capital costs, on an individual SCM basis, are lower than LCC of SCMs by a percent difference of 1-750% and 380-2,900% in the Ballona Creek and Berkeley neighborhood watersheds, respectively. O&M costs are a significant portion of the LCC and in some cases contribute to more of the overall cost than just the construction costs (capital). Even the original capital costs per SCM may be lower than the full construction costs. Without the inclusion of labor, equipment, energy, and environmental cost in addition to the materials, decision makers and planners cannot fully understand the full cost and implications towards society which impacts their ability to make the best decision for their watershed. Finally, just as capital costs and LCC are different metrics, and may be useful for different organizations or budget types, the multiple LCC types and stages is an important breakdown of costs for allocation of money and consideration of funding sources such as grants.

The second difference between capital costs and LCC is the cost order between SCM types in a watershed which also has large implications. For example, VS went from the lowest capital cost SCM to the 4th lowest LLC cost in Ballona Creek while BR went from the highest capital cost SCM to the second lowest cost SCM in Berkeley neighborhood watershed when shifting from capital cost to LCC. This cross-SCM cost consideration is very important to decision makers when choosing between the various SCM types, as cost plays a large factor in the decision-making process. For example, BR is an infiltrating-based SCM so it performs well in terms of AAFV reduction which is the primary goal in the Berkeley neighborhood watershed. However, if using the capital cost for SCM units, decision makers would have to note that BR is the highest cost SCM, and thus may make the decision that the cost is not justifiable. In reality, BR is one of the lowest cost SCMs when considering LCC. Not only does BR cost less than the other SCM types, it also perform well at meeting regulatory compliance, so it should actually be prioritized. Using capital costs alone would have been a missed opportunity to minimize LCC while maximizing a hydrologic benefit that is needed.

The same differences in costs also has impacts on a watershed-scale. Results show that stormwater management solutions are shifted up by 80 billion dollars in Ballona Creek and 90 million in the Berkeley neighborhood when using LCC. Additionally, capital cost is a metric of the money needed instantaneously for implementation while LCC is a metric for the cost needed over a 50 year lifespan. So while the differences between costs on an SCM unit basis is extreme, it is even more exacerbated when considering the full cost on a watershed-scale as hundreds to thousands of SCM units are being implemented

The difference in cost order has implications on the watershed-scale modeling results in terms of which SCMs are being prioritized. The only change in modeling between the capital cost solutions and LCC solutions is the cost, all hydrologic and water quality outcomes are retained. Changes in the optimizations are being driven by cost differences. For example, in the Ballona Creek watershed, results show a shift in SCMs that are reflective of cost. VS are significantly less dominant in the LCC SA-elbow solutions in Ballona Creek while BR is significantly more prioritized in LCC SA-elbow solutions in the Berkeley neighborhood watershed. This is reflective of the shift in costs seen in Table 4.3 as well as cost types in Figure 4.1. While BR has a higher construction and labor cost than the other above ground SCMS (PP, IT, VS) it has lower equipment, energy, other direct, and environmental costs. Similarly, UDS and UIS are practically non-existent in Berkeley neighborhood LCC SE-elbow solutions as they have high LCC costs, especially in terms of the construction stage and material costs. The same shifts can be seen in the SA-reg solutions. In Ballona Creek UIS has such a high LCC cost that almost all other SCM means shift up as the UIS drops. Modeling results and discussion show that capital cost is not a good proxy for LCC in an optimization trying to minimize total cost, both due to selection differences and total cost differences.

4.6.2 Impacts of Watershed Specific Regulatory Constraints on Solutions

The Ballona Creek and Berkeley neighborhood watershed are two very different watersheds in terms of size, demographics, policy, and physical characteristics. Because of this, modeling results to reach regulatory compliance are also different between the two watersheds. It is important to note these differences. For example, the differences between the capital cost and LCC metrics have more implications in the Ballona Creek watershed which has a stricter regulatory compliance goal of 80% reduction in Zn AAL in comparison to 5% reduction in AAFV in the Berkeley neighborhood watershed. A reduction of 80% in AAL is a difficult goal to reach thus Ballona Creek has less viable solutions than the Berkeley neighborhood. This restricts number of options decision makers have to choose from and also eliminates flexibility of stormwater management solutions.

Additionally, the stormwater solutions in Ballona Creek are having to maximize the use of all available resources, including SCM types with higher costs. We see this in the greenest and greyest solution isolated in Figure 4.4; nether is 100% green or grey as the model has to maximize the available resources, SCM types and numbers in order to reach the AAL reduction goal. This means that the cost difference of reaching a regulatory constraint goal is more extreme in Ballona Creek than it is in Berkeley neighborhood. The Berkeley neighborhood watershed only requires a 5% reduction in AAFV, thus there are larger number viable solutions to choose from and more variability in the available solutions. The greenest and greyest solutions are both 100% green and grey, respectively. However, while there is a smaller cost difference than seen in Ballona Creek, the impacts on prioritized SCMs is more extreme due to the flexibility that the optimization module has in choosing between SCM types. However, Ballona Creek is also a much larger watershed with more variability in demographic, land use types and distribution, and pre-existing hydrologic/ vegetative characteristics. This allows for more flexibility in terms of siting and actual considerations that go into implementation. This is an example of how factors that are not modeling results need to be weighed in and considered when choosing the optimal stormwater solutions.

4.6.3 Optimal SCM Solutions Based on Management Criteria

Using the 4 C's is a way to consider community, context, connectivity, and canopy in terms of the vegetative benefits to help with implementation of SCMs in order to maximize the benefits associated with vegetation. This type of analysis can help with the final discussion on which SCM types and solutions are most appropriate and can be used as a way to bridge the planning-level to design-level analysis. In the Ballona Creek, taking into account size and variable land use types and characteristics the hybrid solution may be the most appropriate. The hybrid solution is cheaper than the greyest and similar to the greenest in terms of LCC, performs average in terms of the hydrologic benefits, and aligns with the priorities of two of the varying management criteria which helps with overall consensus. The greenest solution is the most appropriate solution in the Berkeley neighborhood taking into account the residential dominance in land use and possibility of lowered greenness due to future redevelopment. The greenest solution is also the lowest LCC cost, outperforms both the greyest and hybrid in terms of hydrological benefits, and aligns with all of the varying management criteria.

4.7 Conclusion

Decision-making on a watershed-scale for stormwater management options requires a holistic approach that incorporates LCC and benefit analyses in addition to hydrologic modeling. However, there is a lack of available tools for decision makers to conduct a planning-level analysis with all of these considerations. The i-DST is an integrated decision support tool developed that includes modules specifically designed to addresses the need for watershed-scale hydrologic modeling, a full LCC analysis, and a final stormwater benefit analysis that includes both hydrologic and vegetative benefits for greener, greyer, and hybrid stormwater management options. Results show that capital costs are much lower than the full cost to the society and the environment both on an individual SCM unit-scale and a full stormwater management-scale. Additionally, the relative cost order of SCMs within a watershed are different between capital costs and LCC. SCMs that have lower capital costs do not necessarily have lower LCC, and vice versa. The implications of using two different cost metric that have differences in magnitude and order can result in lack of funds for a project to be completed or the implementation of SCM types that do not actually meet the goals of a watershed, thus rendering the costs put toward a stormwater management plan wasted. When comparing solutions simulated by a hydrologic model it is important to consider the hydrologic and vegetative benefits separately. While hydrologic benefits are those that can be directly related to model outputs vegetative benefits are those that can be directly related to model results. Instead it is important to consider the vegetative benefits of SCM types and solutions using the 4 Cs. Using the 4 C's is a way to do a final analysis to determine whether different SCM types and solutions are appropriate considering community, context, connectivity, and canopy. This research shows how important each step of the planning analysis is (watershed modeling, LCC, and benefit analysis) and how they are all interconnected and impact each other. Combining these three planning-level analyses creates a portfolio of information that can be used to make informed decision taking into account specific SCM, physical, and policy characteristics of a watershed which all combined can provide the tools to begin a design-level analysis.

4.8 Acknowledgments

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CHAPTER 5

CONCLUSIONS

5.1 Conclusions

The following section discusses the findings in each chapter and how they achieve the main objectives.

5.1.1 Objective 1: Investigate Greener Stormwater Management Options on a Watershed-Scale Level

Question 1.1: To what degree does percent imperviousness and land use type impact water quality degradation in a given watershed?

***Hypothesis 1.1*:** Water quality degradation will be the worst in watersheds that have both a higher percent imperviousness and a higher percent of land uses that are known to have elevated pollutant mean concentrations, such as industrial.

> ***Findings 1.1:*** The cross watershed comparison of baseline water quality showed that characterization of a specific watershed can help identify sources of nonpoint source pollutant loading and assist determining ways to mitigate water quality degradation. For example, the EMC data found throughout the three watersheds indicates that certain land uses (industrial, commercial, transportation) have relatively higher EMC values than others (single- and multi-family residential, vacant, and parks and recreation). Additionally, the land uses with elevated levels of EMCs also tend to have a higher percent imperviousness. Thus, watersheds with a higher concentration of imperviousness and specific land use types exhibit larger volumes of runoff, less infiltration to the groundwater, and thus larger loads of pollutants transported to water bodies.
>
> The Dominguez Channel watershed has the highest percent imperviousness and largest percentage of industrial, commercial, and transportation land uses. Baseline water quality in this watershed was the worst out of the three studies. The Ballona Creek watershed had the lowest percent imperviousness as well as land use EMCs, thus it was the least degraded. Finally, water quality in the LAR watershed was worse than BC as it has a higher percent imperviousness. However, LAR had better water quality than DC despite having more elevated EMCs for all land use types. The diversity in land use type and

distribution (large areas of vacant and forested) mitigated water quality degradation by contributing cleaner water to the whole system.

Question 1.2: At what level will SCMs need to be implemented throughout a watershed in order to eliminate heavy metal TMDL exceedances throughout Los Angeles County?

Hypothesis 1.2**:** Routing stormwater runoff from the majority of a watershed to SCMs will be needed to achieve average annual load reduction goals. Elimination of TMDLs will be achievable in watersheds with lower percent imperviousness and a higher percent of vacant land uses while it will not be achievable in watersheds with a higher percent imperviousness and higher percent of industrial land uses.

> ***Findings 1.2:*** Routing stormwater from at least 90% of the watershed area is needed to eliminate heavy metal TMDL exceedances in Los Angeles. In some cases, routing 90% of the watershed and capturing the 85^{th} percentile storm with SCMs still is not enough to eliminate TMDL exceedances. Baseline water quality directly impacts the feasibility of meeting water quality standards in the three watersheds. TMDL exceedances were found to be successfully eliminated with multiple SCM scenarios for dry and wet weather days in the Ballona Creek watershed. However, only two of the LAR SCM Scenarios and none of the DC scenarios eliminated TMDL exceedances. Further analyses determined that the majority of exceedances in LAR occurred at specific TMDL locations, demonstrating how some areas may be contributing to overall watershed water quality degradation. Water quality compliance was the worst in the DC watershed, as it has the most degraded baseline water quality.

Question 1.3: Are infiltration-based or treat-and-release-based SCMs more successful at eliminating TMDL exceedances?

Hypothesis 1.3**:** Treat-and-release-based SCM solutions will outperform infiltration-based solutions in terms of eliminating TMDLs as they actively treat stormwater and release the cleaner diluted water back into the storm drainage network, resulting in overall better water quality at the outlet of the watershed which is also the location of established TMDLs.

> ***Findings 1.3:*** We found in this study that SCM scenarios that were successful and resulted in better water quality compliance when prioritizing treat-and-release-based

SCMs (vegetated swales and dry ponds). Treat-and-release SCMs are designed to retain runoff, actively treat the water to remove pollutants, and then release diluted water back into the storm drainage network, thus improving water quality of the whole watershed. On a whole watershed-scale, infiltration-based SCMs removed runoff and did not contribute to improving baseline water quality conditions in the river channels.

Question 1.4: How does the primary hydrologic objective of achieving water quality compliance impact decision-making in a watershed.

***Hypothesis 1.4*:** Watersheds that successfully eliminate TMDL exceedances have more flexibility in deciding between treat-and-release vs infiltration-based SCM types thus allowing for consideration of other factors, such as capital cost or groundwater recharge potential, which will determine the optimal solution.

Findings 1.4: Knowledge on watershed characteristics, baseline water quality, and relative SCM performance drives available stormwater solution options and decision-making in specific watersheds. SCM scenarios that successfully eliminated TMDLs in the BC watershed included both types of SCMs, thus decision makers can implement either type while also consider ancillary benefits, such as peak flow or groundwater infiltration to help choose between SCM types. While none of the SCM scenarios eliminated TMDL exceedances in the DC watershed, treat and release SCMs had overall better compliance, thus decision makers may need to prioritize treat-and-release-based on their primary objective. This restricts criteria that can be used in decision-making process and available ancillary benefits available to the watershed. The LAR watershed had variable compliance, but results also showed that TMDL exceedances were concentrated in more urbanized areas, thus treat-and-release SCM should be prioritized there while infiltration-based can be used in areas that are not as urbanized. Cross watershed communication will be necessary to fulfill the goals of an integrated water management plan. For example, Ballona Creek may need to implement more infiltration-based SCMs in order to promote ground water recharge since the Dominguez Channel and Los Angeles may have to focus more on treat-and-release SCMs

5.1.2 Objective 2: Evaluating Performance and Tradeoffs of Greener to Greyer Stormwater Infrastructure

Question 2.1: How do greener vs greyer SCMs perform relatively in terms of hydrologic criteria when implemented on a watershed-scale?

***Hypothesis 2.1*:** Underground infiltration (greyer) and infiltration trenches (greener) are optimal for reducing average annual flow volume. Underground detention (greyer) and vegetated swales (greener) are better at reducing pollutant average annual concentrations.

> ***Findings 2.1:*** Relative hydrologic performance depends more on the primary function of a particular SCM rather than where they fall on the green to grey spectrum. This supports the argument that for a planning-level analysis - many SCM types need to be explored in terms of performance before implementation as both green and grey SCMs offer hydrologic benefits that may be important to varying stakeholders. While most stormwater managers may lean towards using green SCMs, as they outperform grey SCMs in most hydrologic benefits and add green space to a watershed, we found that grey SCMs outperform green in some benefits (i.e. ground water recharge potential), can be tailored to the needs of a watershed as they have flexibility in terms of their design, and can be implemented underground in highly dense areas that don't have room for above ground SCMs.

Question 2.2: What SCM types are optimal for maximizing reducing average annual flow volume and minimizing cost?

***Hypothesis 2.2*:** Greener SCMs will be dominant in optimization solutions that both minimize capital cost and maximize average annual flow volume reduction.

> ***Findings 2.2:*** In stormwater management, solutions that fall in the "elbow" of the Pareto curve are considered optimal. In this study we isolated 100 solutions from the elbow of the Pareto curve. As hypothesized, greener SCMs, specifically vegetated swales and infiltration trenches, are prioritized by the optimization module when set up to maximize average annual flow volume reduction and minimize capital cost. These two SCMs have the lowest capital cost per SCM unit and both perform relatively well in terms of AAFV reduction. However, we also found that the SCM types prioritized by the model shifts

based on the criteria used to isolate solutions throughout the whole Pareto curve. For example, the 100 solutions that reach the average annual flow volume goal without any cost restriction sees an increase in greyer SCMs, as they have a relatively higher capital cost but still perform well at reducing average annual flow volume. Finally, the 100 solutions that reach the average annual flow volume goal and minimizes average annual concentration shows an increase in bioretention and underground detention (a mix of greener and greyer), as those SCMs perform relatively well at improving water quality. These findings show that accounting for multiple benefits, beyond those that are the primary objective, results in a shift of SCM types that may need to be implemented in order to reach the goals of multiple stakeholders and also that a mix of green and grey SCMs is a common theme in the modeling results.

Question 2.3: What impact does weighting hydrologic benefits based on City of Denver preferences or Denver Public preferences, have on the optimal SCM types?

Hypothesis 2.3**:** Vegetated swales and infiltration trenches will be optimal to meet the preferences of the City of Denver, as they are the lowest cost, perform relatively best at reducing average annual flows, and add green spaces. However, bioretention and underground detention are needed to meet the preferences of the Denver Public, prioritize average annual concentration.

Findings 2.3: While the primary goal of a watershed may initially put more weight on particular SCM types, the consideration of multiple benefits and use of a rating system exposes which additional SCMs should be included in order to maximize the benefits of a watershed. All of the final solutions identified using stakeholder preferences show a dominance of VS and IT to reach the primary goal of this objective, as they reduce AAFV and minimize capital cost most efficiently. However, all solutions also include a mix of the other four SCMs (UDS, BR, PP, UIS). We found that user priorities and weights shift which of these four SCM types are prioritized in addition to the dominant VS and IT. For example, weighting average annual concentration higher (Denver Public Preferences) includes a higher number of bioretention and underground detention storage while greener SCMs are more dominant in optimal solutions based on City of Denver preferences which rates added green space relatively higher. Even though green SCMs tend to have a higher ratio of SCMs for all tested scenarios, all solutions have a mixture of green and grey SCMs as well as a mixture of SCMs with varying primary functions. While the SCMs needed to address primary goals may be obvious, it is the additional considerations and criteria ultimately determine what additional SCMs should also be included in order to have a well-balanced stormwater management plan that maximizes all benefits.

5.1.3 Objective 3: Incorporating Life Cycle Costs and Benefits with Stormwater Modeling

Question 3.1: To what extent do the differences in capital costs and life cycle costs impact the decision-making process?

***Hypothesis 3.1*:** The differences between capital costs and LCC, cost magnitude and the cost order, will significantly impact optimal solutions.

Findings 3.1: LCC were found be millions to billions of dollars higher than capital costs. mostly due to operation and management costs that occur over a span of 50 years. LCC calculate the full cost to society and the environment, whereas capital costs only account for a fraction of LCC. Additionally, LCC also breaks down the full cost by cost type and cost life cycle stage, which may be useful for organizations or budgets that need to concentrate on specific cost metrics or types.

The relative cost order of SCMs in a watershed (lowest to highest cost) shifts when using LCC. For example, BR has the highest capital cost in Berkeley neighborhood but the second lowest LCC. This has implications on both modeling results and the decision-making process. An optimization set up to minimize cost will not prioritize BR with capital costs. Using the capital cost metric alone is a missed opportunity to minimize LCC. Capital costs are not a good proxy for LCC in an optimization or planning-level analysis trying to minimize total cost, because of SCM selection differences and total cost differences.

Question 3.2: What impacts do watershed specific regulatory compliance have on the ratio of % runoff captured by greener vs greyer SCM type?

***Hypothesis 3.2*:** Berkeley neighborhood has a relatively less strict regulatory compliance goal than Ballona Creek (5% reduction in average annual flow volume vs 80% reduction in average annual load, respectively) and thus more diversity in viable stormwater solutions (up to 100% green and 100% grey) whereas viable solutions Ballona Creek will have to utilize both green and grey.

> ***Findings 3.2:*** Ballona Creek has a strict regulatory compliance goal. Average annual load reductions of ~80% are needed to reach water quality regulations for zinc. As hypothesized, a large percentage of the available resources (number of SCM units) is required to reach the average annual load reduction goal. This means the model is simulating as many SCM types and number of SCM units as possible in each solution. Thus, the greenest viable solution in the Ballona Creek watershed routes 80% of runoff to greener SCMs and 20% to greyer while the greyest solution routes 40% of runoff to greener SCMs and 60% to greyer. The number of viable solutions to choose from is also limited. In contrast, the Berkeley neighborhood watershed only requires 5% reduction in average annual flow volume which is more easily achieved. Thus, viable solutions range from 100% of runoff routed to greener SCMs to 100% of runoff routed to greyer SCMs. Baseline conditions impact flexibility of SCM solution options and thus the decision-making process.

Question 3.3: How will varying management criteria impact whether the green, grey, or hybrid solution is the optimal solution in each watershed?

Hypothesis 3.3**:** Water quality and infiltration-based criteria will drive the optimal solution in Ballona Creek to be the hybrid solution. LCC, ET, and vegetation-based criteria will drive the optimal solution in Berkeley neighborhood to be the greener solution.

> ***Findings 3.3:*** Several management criteria, specific to each watershed were used to determine whether the greenest, greyest, or hybrid solution is optimal. In the Ballona Creek watershed, greener and hybrid solutions have a lower LCC than greyer. The hybrid solution is optimal based on regulatory compliance (prioritize average annual load, average annual concentration, and cost) and increasing water supply (prioritize ground water recharge potential and cost) while the green solution is optimal for recreation (prioritize average annual flow volume, vegetation, average annual concentration, and cost). Given the 4 C's (community, context, connectivity, and canopy) the hybrid solution is preferable in terms of vegetative benefits as well.

The greener solution in Berkeley neighborhood has a much lower cost than the greyer and hybrid solution. In the Berkeley neighborhood watershed the greenest solution is optimal based on all three explored management criteria including regulatory compliance (prioritize average annual flow volume and cost), climate change mitigation (prioritize evapotranspiration and cost), and increased biodiversity and habitat (prioritize average annual concentration and cost). The greener solution is also optimal given the 4 C's vegetative benefit analysis. A benefit analysis that provides a system-level analysis needed to associate impact of SCM interventions across varying management criteria enhances stakeholders' abilities to determine the optimal solution given the specific needs of their watershed and stakeholder preferences.

5.2 Broader Impacts

Contributions to the science community:

Urban stormwater modeling is a common area of research, however there still exists uncertainty in terms of how SCMs affect watersheds system wide. Additionally, most watershed-scale and optimization studies focus on design-level analyses. This includes choosing the optimal SCM type or design based on SCM placement, a single regulatory constraint, or a site-scale analysis. Few studies investigate stormwater decision-making on a planning-level analysis, one that should occur before a design-level analysis. This research progresses the field of stormwater modeling by demonstrating how SCMs impact a watershed as a whole and the implications of varying stormwater management options. The classification and modeling of distributed underground grey SCMs has the potential to raise awareness about the variety of SCM types available for decision makers to choose from, including those that fall on the greyer side of the stormwater continuum. Finally, methodologies presented in this work can be used by stormwater managers and modelers in the future as this work is the first to integrate optimizations, stakeholder preferences, life cycle costs, and benefit analysis to determine a stormwater management plan that maximizes the benefits to both the environment and society.

Contributions to society:

One of the goals of this research was to reach an audience beyond those that are strictly stormwater modelers or managers. The intention to submit Chapter 2 and 3 to open source journals is so that a wider audience may be able to access this work. Stormwater infrastructure impacts the community of an area in which they are implemented. This research has the potential to enhance the public's knowledge on what SCMs are and the benefits they may offer, how the decision of choosing one SCM type over another is made by stormwater managers, policy makers, and practitioners, and understand how those decisions may or may not affect their community. Chapter 2 and 3 explore varying stakeholder preferences (Denver Public Survey in Chapter 2) and management criteria that may apply to society, such as increased recreation or reduction flooding of flooding risk (Chapter 3), in order to demonstrate how the public's preferences may actually shift which SCM types are considered optimal instead of those that simply meet the primary stormwater objective. This work contributes to the planning-level decision process by assisting varying stakeholders in how to voice their preferences and participate in the decision-making process.

Contributions to the industry:

This work has directly contributed to the development of an integrated decision support tool (i-DST) that allows for the optimization and comprehensive life-cycle cost assessment of greyer, greener, and hybrid stormwater infrastructure. Not only will i-DST maintain the robustness of hydrologic models by utilizing an updated version of SUSTAIN, it will be user friendly for those are not necessarily hydrologic modelers. The i-DST tool is well anticipated by the i-DST science advisory board, which is made up of professionals from the government, consulting firms, and academia from across the country. For example, collaboration with the City of Charlotte, North Carolina to model the Reedy Creek Watershed is ongoing.

5.3 Recommendations for Future Work

Exploring the use of additional efforts with conventional SCMs to reach regulatory compliance.

When conventional BMPs, such as those utilized in Chapter 1 this study, are not efficient at meeting regulatory compliance, such as eliminating TMDLs, additional efforts may also need to be considered. Wolfand et al. (2018) found that enhanced SCMs that utilized media such as granulated activated carbon are much more efficient than existing conventional SCMs. Additionally, source control, such as the restriction on copper brake pads, which could reduce urban runoff copper levels by 46%–57% by 2024 (California Stormwater Quality Association

2016), or targeting of pollutant hot spots (such as industrial dischargers), would help reduce urban runoff loadings and decrease the reliance on SCMs. A third option includes the use of in-stream SCMs, which is a novel practice and an area for future research. The combined impact of SCMs with these alternative options needs to be explored in order to further the knowledge on the optimal stormwater solution on a watershed-scale.

Assessment of sensitivity to adjusted wet weather flow TMDL cutoffs.

Research in Chapter 1 of this work discovered the limitation of using a wet weather threshold based on historical flow records. For example, the Ballona Creek watershed wet weather threshold was determined using the 90th percentile daily average flow from 1987 to 2012. Past flow records in a river channel do not account for future implementation of SCMs. As SCMs are implemented, promotion of groundwater recharge, evapotranspiration, and diverging practices may lower the average flow levels in a river channel. Modeling results in Los Angeles showed days that were considered wet weather days before implementation of SCMs shifted to a dry weather day with SCMs. This lowered the number of wet weather days and made wet weather TMDL compliance extremely difficult to achieve. It is recommended that stormwater management criteria, such as TMDLs, be drafted or revised based on current flow records.

Changes to pollutant event mean concentrations pre- and post-infill development.

Modeling results in Chapter 2 found that while placing SCMs on parcels of land undergoing redevelopment is one way to incentive stormwater management implementation and reduce stormwater flow volumes, there was a negative impact on water quality. Multi-family residential parcels of land have relatively lower EMC values than land uses such as industrial and commercial. Thus, removing water from these areas actually increased pollutant concentrations on a watershed-scale. However, this study assumed a constant EMC value pre- and post-development. It is recommended that future work includes a more robust land use EMC characterization, particularly the potential changes in EMCs post redevelopment. This is important to understand the implications of future redevelopment on urbanized areas and stormwater planning.

Translating management criteria to a value that can be optimized on in a model.

This research presents a tool that can optimize on a wide range of variables. Further research on how to take varying management criteria, such as climate mitigation or recreation, and translating those into a single target goal would further enhance planning-level analyses.

Further development of grey SCMs in hydrologic models.

While this study is the first to include distributed underground greyer SCMs in a watershed watershed-scale hydrologic modeling analysis there were limitations due to lack of data. Design, soil property, flow, and pollutant removal data would improve validation of these SCM types for future modeling. Additionally, i-DST SUSTAIN is the first framework that incorporates these SCMs as a viable option. Hydrologic models in general need to be updated to include these SCM types.

Sensitivity of SCM maximum drainage area in a model with aggregate SCMs and the impacts on water quantity, water quality, and total cost.

Studies have shown how area routed to an SCM is a sensitive model parameter. This study set a maximum drainage area for SCM types in Chapter 2 and 3. To further improve the knowledge on this model parameter for a planning-level analysis a sensitivity analysis on SCM drainage area should be conducted. This would demonstrate to stormwater modelers the implications on a watershed-scale model, including water quantity and water quality model outputs as well as number of SCMs required to reach regulatory compliance and the resulting cost.

Further improving hydrologic optimization models.

A limitation of the SUSTAIN model is that the area of land routed to a SCM type within an aggregate does not shift. For example, if a model is set up to route 50% of a watershed to vegetated swales and 50% to infiltration trenches, the model does not shift to route 100% of a watershed to vegetated swales and 0% to infiltration trenches. Modelers should be aware of this limitation when setting up an optimization. Optimization modeling can be improved by allowing this model parameter to change with each solution based on the number of SCM units being simulated.

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APPENDIX A

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Elizabeth Gallo <emgallo@mymail.mines.edu>

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PERMISSIONS <permissions@asce.org> Tue, Jun 2, 2020 at 10:32 AM
To: Elizabeth Gallo <emgallo@mymail.mines.edu>

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2 messages

Elizabeth Gallo <emgallo@mymail.mines.edu> Mon, Jun 1, 2020 at 10:55 AM
To: Katie Mika <ktmika@gmail.com>

Hi Katie,

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Will you please give me your permission to include this paper in my dissertation? If so, please respond to this email, and I will use your email response as documentation of your permission and include it with my dissertation submission.

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Elizabeth Gallo

PhD Candidate
Hydrologic Science and Engineering
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Colorado School of Mines

404-626-1593
emgallo@mymail.mines.edu
e.mariegallo@gmail.com

Katie Mika <ktmika@gmail.com> Mon, Jun 1, 2020 at 12:45 PM
To: Elizabeth Gallo <emgallo@mymail.mines.edu>

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Elizabeth Gallo <emgallo@mymail.mines.edu>

Permission to publish our paper in my dissertation

2 messages

Elizabeth Gallo <emgallo@mymail.mines.edu> Mon, Jun 1, 2020 at 5:07 PM
To: mark.gold@resources.ca.gov

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Best Regards,

Elizabeth Gallo

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404-626-1593
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Gold, Mark@CNRA <Mark.Gold@resources.ca.gov> Mon, Jun 1, 2020 at 5:10 PM
To: Elizabeth Gallo <emgallo@mymail.mines.edu>

In case you need both.

I support your inclusion of the aforementioned paper in your dissertation.

Best of luck on your defense.

Mark

Mark Gold, D.Env.

Deputy Secretary for Ocean and Coastal Policy

Director, California Ocean Protection Council

1416 9th St., Ste. 1311

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Elizabeth Gallo <emgallo@mymail.mines.edu>

Permission to publish our paper in my dissertation

2 messages

Elizabeth Gallo <emgallo@mymail.mines.edu> Mon, Jun 1, 2020 at 5:12 PM
To: Chelsea Panos <cpanos@mymail.mines.edu>

Hi Chelsea,

Because you are a co-author of the paper titled "Investigating Tradeoffs of Green to Grey Stormwater Infrastructure Using a Planning-level Decision Support Tool" submitted to *Water Special Issue: Innovative, Smart and Sustainable Solutions for Urban Stormwater Management* in 2020, I need your permission to include this paper within my dissertation.

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Best Regards,

Elizabeth Gallo

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Chelsea Panos <cpanos@mymail.mines.edu> Mon, Jun 1, 2020 at 5:17 PM
To: Elizabeth Gallo <emgallo@mymail.mines.edu>

Hi Elizabeth,

You have my permission to include this paper in your dissertation.

Regards,
Chelsea Panos
[Quoted text hidden]

--
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APPENDIX B

CHAPTER 2 SUPPLEMENTAL INFORMATION

It is crucial for the model user to understand the varying optimization algorithms and controls, and how they may affect the solutions that are being outputted by the model as these controls can drive the model in certain directions. For example, NSGAII finds the optimal solutions along each Pareto frontier and creates the following populations based on those optimal solutions. Thus, the solutions tend to have the same suite of SCMs without any variability. Setting the optimization controls to be stricter is useful when the user knows a certain goal that they wish to meet. However, on a planning level, not restricting the model allows a wider range of potential solutions over a large cost and target evaluation range. The following optimization controls play a factor in the optimization module of i-DST SUSTAIN and should be considered.

- Algorithms: Scatter search and NSGAII determine how the optimization module creates a population of solutions and how that population evolves over time based on the optimal solutions (determined by the controls). While scatter search uses a clumping of the best solutions, NSGAII uses the single best solution along the Pareto frontier.

- Controls: Cost minimization and a cost effectiveness curve determine how the optimization module determines the optimal solutions. Cost minimization aims to minimize cost while achieving a certain evaluation factor goal. A cost effectiveness curve aims to both minimize cost and maximize an evaluation curve within a target range simultaneously.

- Number of SCM units: This sets the lower and higher bounds of the number of SCM units the model can simulate in each solution. Users can set these bounds to be wide so that the model looks at only implementing one SCM unit all the way to enough SCM units to capture water from the whole watershed. The user can also set a stricter bound if they know a general range of SCMs that will reach a desired goal.

- Step of SCM unit: This sets the step at which the optimization module may select SCM units. For example, if the user sets a step of five, the model will only simulate 5, 10, 15, etc units of a certain SCM type.
- Target evaluation range: The target evaluation range is what tells the optimization module where to look for the optimal solutions. Cost minimization only uses one target evaluation number. The model looks for the best solutions that reach this goal at a minimum cost. The cost evaluation control uses two evaluation targets. The optimization module looks for the optimal solutions within that range.