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Investigating Tradeoffs of Green to Grey Stormwater Infrastructure Using a Planning-Level Decision Support Tool

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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 watersheds. In this study, an urbanized watershed undergoing infill development (the Berkeley neighborhood located in Denver, CO, USA) was modeled using a modified version of the U.S. Environmental Protection Agency's (EPA) System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN). The primary goal was 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 stakeholder and community preferences 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. Our results showed that infiltration trenches and underground infiltration were optimal for reducing flow volumes while vegetated swales and underground detention were optimal for pollutant concentration reduction. Stakeholders value both of these benefits and so the optimal stormwater solution in the Berkeley neighborhood included a mix of green and grey SCMs. Determining the optimal SCMs while considering tradeoffs in costs and associated benefits was complex and multifaceted. Modeling results such as those presented here are critical for informing stakeholders' decision-making process.

Keywords: stormwater; green infrastructures; grey infrastructures; sustainable water management; decision support tool; urban planning; evaluation framework; urban flooding risk mitigation; water quality control

1. Introduction

Alterations to the hydrologic regime and degradation to water quality are major issues associated with rising percent imperviousness in cities undergoing urbanization [1–5]. 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 [6–10] detrimental to both public health and the environment [11,12]. 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 [13]. However, there can be incentives to implement SCMs for the multiple hydrologic and ancillary benefits they offer [14–16], such as groundwater recharge potential [17,18] or improved eco-hydrologic conditions [19].

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/water quality processes, community benefits, and cost [20]. 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 [9,20]. The U.S. Environmental Protection Agency (EPA) has encouraged municipalities to implement green SCMs throughout their watersheds [7]. 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 [20–23]. 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 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 [9,22–24]. 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 of designs [25]. While these systems have been utilized and implemented since at least 2001 [26], they are recently gaining popularity due to improved designs and the benefits they offer [27,28]. 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 [9,24]. However, there is a paucity of water quantity and quality data from these structures as well as studies that have modeled them [29–34].

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 [8]. However, there exists uncertainty in how distributed SCMs, are designed to capture a specific stormwater runoff volume from one site, will scale up and impact the watershed as a whole [35,36]. 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 [35,36]. Benefits such as these are often used as a primary objective, also known as an 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. (2018) demonstrated the importance in considering multiple SCM types to determine which types most effectively achieve the primary goal of a watershed [37,38]. 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 [14].

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" [39]. A strategic plan helps direct decision makers to set priorities and determine a pathway that will best achieve those priorities [40]. In regard 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 [41]. However, SUSTAIN currently only includes green SCMs. Additionally, most studies that have used optimizations to decide between SCMs focus on SCM placement [42–44], a limited number of SCM types or hydrologic outputs [45–49], or a site-scale/design-level analysis [50–52]. 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.

2. Study Area

The Berkeley neighborhood, located in northwest Denver, is a 419-ha watershed that had 53% impervious cover in 2014 [53]. 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 [54,55]. 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 [56]. 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 [56]. 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 [53,56]. Panos et al. (2018) developed a Current Baseline scenario and represented the Berkeley watershed land use and runoff volumes in 2014 with an assumption that no infill development had taken place [53]. 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, showing a 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-year, 10-year, and 100-year, 24-hour rainfall events, respectively [53]. Simulations from Panos et al. (2018) were chosen to be further explored in this study [53]. Table 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 areas in the Future Baseline scenario is classified as a residential land use (Table 1). A small area of vacant open space is also redeveloped to residential land use (Table 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 [53,56].

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 established a 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 [9,57–59]. 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 [53]. A second objective is to reduce pollutant loadings

while also achieving a wide range of ancillary benefits [59]. 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) [59], 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 [59]. 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 [59]. The Berkeley neighborhood watershed was chosen as a case study to demonstrate the capabilities of a planning-level watershed tool to achieve these objectives.

Table 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

3. Methods

3.1. Model

This work used an integrated decision support tool (i-DST), which is currently being developed and will be available to the public when completed, 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 [41]. 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 [9,21,23–25,60–63]. Four grey-SCMs were added to i-DST SUSTAIN, including underground infiltration structure (UIS), underground detention structure (UDS) (no infiltration), underground gravel beds, and aboveground 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. An evaluation

factor is a single summary value calculated from the model output timeseries. In an optimization, the model records the evaluation factor from each iteration or SCM solution in order to compare relative SCM performance. Seven new evaluation factors (annual/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. Ground water recharge potential and evapotranspiration were already calculated at each time step during model simulation but were unavailable to be optimized. Seasonal factors were added in order to offer users multiple time scales on which to optimize. Table 2 lists all available SCMs and evaluation factors in i-DST SUSTAIN.

Table 2. Available stormwater control measures (SCMs) types and evaluation factors in integrated decision support tool (i-DST) System for Urban Stormwater Treatment and Analysis IntegratioN (SUSTAIN). * New option that was not originally available in SUSTAIN.

SCM Types	Evaluation Factors
Green roof	Annual and seasonal * average flow volume
Bioretention	Flow exceedance frequency
Infiltration trench	Flow duration curve
Vegetated swale	Peak discharge flow
Dry pond	Annual and seasonal groundwater recharge potential *
Wet pond	Annual and seasonal average evapotranspiration *
Buffer strip	Annual and seasonal * average loads
Porous pavement	Annual and seasonal * average concentration
Rain barrel	Days above concentration threshold
Underground detention structure *	
Underground infiltration structure *	
Underground gravel bed *	
Aboveground gravel bed *	

3.1.1. Water Quantity Data

Only the external SCM simulation and optimization modules of SUSTAIN [41] 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 [53] 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 for both non-redeveloped and redeveloped land use conditions [53,64]. 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-year, 5-year, and 10-year, 24-hour 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.

3.1.2. Water Quality Data

Pollutant load reduction is a component of the Green Infrastructure Implementation Strategy throughout Denver [59]. Therefore, water quality was included in this study. However, water quality was not simulated in the Panos et al. (2018, 2020) modeling efforts [53,64], thus event mean concentration (EMC) data was obtained from a study that developed regional values from the National Stormwater Quality Database [65]. 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 [59], 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). 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 [59]. 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 [59].

Table 3. Land use event mean concentration (EMC) values extracted from Bell et al. (2019) for total suspended solids (TSS), total Phosphorous (TP), and total Zinc (Zn) median values were used for analyses in this study [65]. 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
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 1 and the median EMC values in Table 3 were used to determine a single representative EMC value (Table 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.

Table 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.

3.1.3. 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 [9,66]. While it is recommended in Denver that underground SCMs are not used unless surface treatment has been proven to not be possible, [9] 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 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 [37]. 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 [67]. All cost data was then projected to be representative of the Denver area using the RSMeans 2019 city construction cost data [68].

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) [53,64]. SCMs in Denver are commonly sized to be 5% of the impervious drainage area [66]. 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 [67].

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 80th percentile storm and a 17.5 mm rainfall depth [9,53]. 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 [69]. BR, IT, and PP were all designed with underdrains as this is the typical practice in Denver due to underlying native clay soils [9,66]. 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) [26]. 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 [9,26].

Table 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/hour) [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 infill rate (cm/hour) [G]	-	0.08	0.08	-	0.08	-
Media below drain (m) [B]	-	0.03	0.15	-	0.08	-
Pollutant decay rates						
IBMPD data source [H]	CA RVTS System	Lakewood CO Iris Garden	Lakewood CO Dry Pond	Lakewood CO Retention Vault	NA	Lakewood CO Retention Vault
TSS (1/year)	0.122	2.15	0.757	0.396	0.00	0.396
TP (1/year)	0.00	0.0997	0.059	0.00015	0.00	0.00015
Zn (1/year)	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; RVTS = roadside vegetated treatment site; TSS = total suspended solids; TP = total phosphorous; Zn = Zinc. A = [9], B = [66], C = [25,67], D = [41,70,71], E = [72], F = Based on required WQCV event: [9,69], G = [73], H = [26], I = [37] using [68] to project values for Denver, J = [67] using [68] to project values for Denver.

3.1.4. Model Routing

The Berkeley neighborhood model was set up in i-DST SUSTAIN as a lumped model (Figure 1) for a planning-level analysis to focus on the impacts of implementing SCMs on the future infill developed area as a whole. Distributed models should be used after a planning-level analysis for a more design-level analysis once the appropriate and preferred SCMs are identified. The Current Baseline time series (no infill developed area) was simulated through i-DST SUSTAIN as one single land use time series (surface runoff volumes and pollutant loadings) based on 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 (Figure 1): 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.
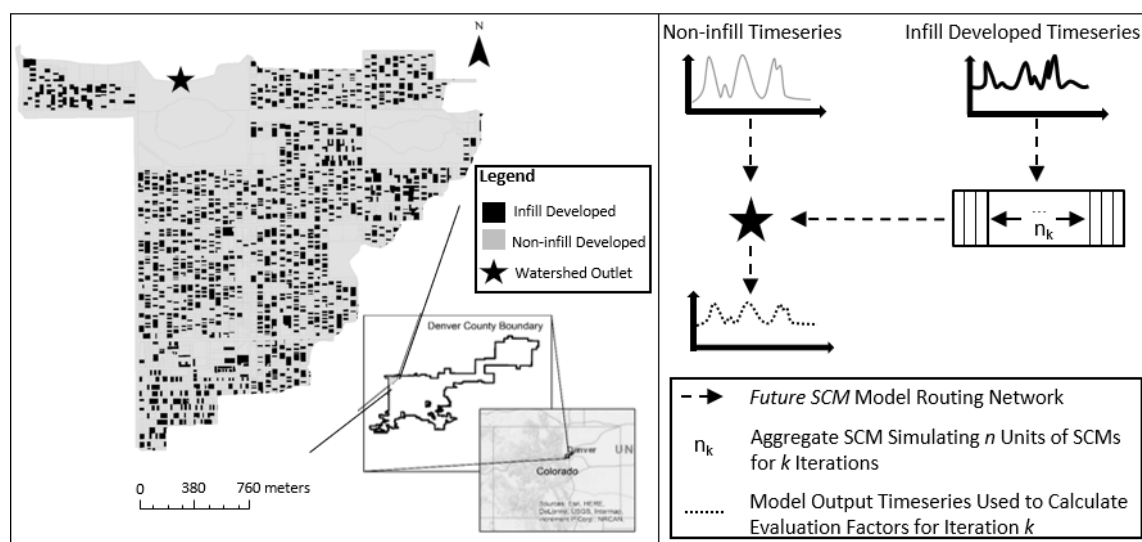

Figure 1. Berkeley neighborhood watershed study area (left) with the identified parcels of land that may undergo future infill development. Study area map was adapted from Panos et al. (2020) [64]. Conceptual routing network for the Future SCM i-DST SUSTAIN model (right).

3.2. Model Validation

This study uses previously calibrated surface water runoff timeseries from the PCSWMM modeling of Panos et al. (2020) to drive the model, thus calibration of flow in the i-DST SUSTAIN model was not required [64]. 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 calibrated modeling results [72] to provide model validation for i-DST SUSTAIN. 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 [64]. BR units were sized to 1% and 5% of the parcel area draining to the SCM. Several statistics, i.e., Nash Sutcliffe Efficiency, R^2, and percent bias, were used to compare PCSWMM model outputs to the i-DST SUSTAIN outputs.

The model was not validated for water quality, as there is a lack of observed data throughout the Berkeley neighborhood watershed. Additionally, the purpose of modeling water quality in this study was to compare relative water quality improvements across variable SCM types. Pollutant removal performance was calibrated for each individual SCM (discussed in Section 3.1.3.).

3.3. Optimization Scenarios

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 [41]. 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 first 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 [41]. Cost minimization aims to minimize cost while achieving a certain evaluation factor goal (Equation (1)) [41]. Cost minimization can optimize on multiple evaluation factors at once. A cost effectiveness curve aims to both minimize cost and maximize an evaluation factor (listed in Table 2) within a target range simultaneously (Equation (2)) [41]. The cost effectiveness curve optimization control can optimize on only one evaluation factor.

$$Minimize \sum Cost\ (SCM_i)\ subject\ to\ Q_j \leq\ Q_{maxj}\ and\ L_k \leq L_{\max k} \tag{1}$$

$$Minimize \sum Cost\ (SCM_i)\ and\ Maximize \sum EF \tag{2}$$

where

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 k
$L_{\max k}$ = the maximum value of the water quality factor targeted at assessment point k
EF = the management evaluation factor (EF) at one given assessment point, and the EF can be any of the options listed in Table 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 A 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.

3.3.1. Individual Optimization

An individual optimization analysis was conducted independently on each of the six SCM types to compare relative performance. While the model is set up to optimize on average annual flow reduction and minimize cost, a wide range of model results were outputted. 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.

3.3.2. Full Optimization

The full optimization scenario simulated 2000 total solutions and was set up 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 [14]. 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.

3.3.3. Full Optimization Selection Criteria Sensitivity Analysis

Selecting 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) [74], it is unclear how these solutions align with varying stakeholder priorities. Three sensitivity analyses, with varying selection criteria, were explored to isolate 100 solutions from the full optimization Pareto curve simulated in Section 3.3.2. 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. The 100 solutions isolated for this analysis fall within a AAFV range of 356,000–361,430 m^3 and a cost range of 1–2 million dollars. 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. The 100 solutions isolated for this analysis fall within a AAFV range of 361,000–361,430 m^3 and a cost range of 1–4.5 million dollars. 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. The 100 solutions isolated for this analysis identify the solutions with the lowest Zn AAC that fall within a AAFV range of 340,000–361,430 m^3 and a cost range of 1–4.5 million dollars.

3.3.4. Full Optimization 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 [75] 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 [76]. 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 Equations (3) and (4)) up into ten evenly distributed cost bins (*i* in Equations (3) and (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 Equations (3) and (4)), AAFV, Zn AAL, Zn AAC, GWRP, and potential green space added (Table 5), were weighted and aggregated for each solution. Equations (3) and (4) calculate the benefit score for each solution and benefit type in each of the ten cost bins. Equation (3) was used for GWRP and green space added as higher values are preferred. Equation (4) was used for AAFV, AAC, and AAL as lower values are preferred. Equation (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.

$$Benefit\ Score_{j,i,n} = \left[\frac{Benefit\ Value_{j,i,n} - \min[Benefit\ Value_{i,n}]}{\max[Benefit\ Value_{i,n}] - \min[Benefit\ Value_{i,n}]} \right] \times Rating_n \tag{3}$$

$$Benefit\ Score_{j,i,n} = 1 - \left[\frac{Benefit\ Value_{j,i,n} - \min[Benefit\ Value_{i,n}]}{\max[Benefit\ Value_{i,n}] - \min[Benefit\ Value_{i,n}]} \right] \times Rating_n \tag{4}$$

$$Overall\ Score_{j,i} = \frac{\sum_n Benefit\ Score_{j,i}}{\sum Rating_n} \tag{5}$$

where *j* = Future SCM Solutions (2000); *i* = Cost Bin (10); and *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 [11], 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 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 [66] and results from the Spahr et al. (2020) public survey [14], respectively.

Table 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.

4. Results

4.1. Model Validation Results

The i-DST SUSTAIN Current Baseline and Future Baseline time series are identical to PCSWMM results [72] 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 7 displays summary statistics (Nash Sutcliffe Efficiency (NSE), R2, and % Bias) for the 2, 5, and 10-year, 24-h 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 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

4.2. Individual Optimization Results

4.2.1. Water Quantity Results

Figure 2 displays the average annual flow volume (AAFV) results based on the number of SCM units installed (Figure 2A) and the total capital cost (Figure 2B) 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 2. 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 2B) 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.
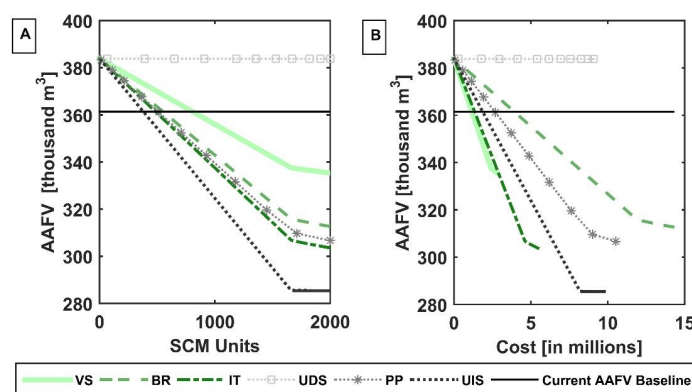
Figure 2. Water quantity results from the individual optimizations for each of the six SCM types. Plots show the impact of SCMs on AAFV with an incremental increase in SCM units implemented (**A**) and total capital cost (**B**). Viable SCM solutions fall below the Current AAFV Baseline.

4.2.2. Water Quality Results

Figure 3 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 2, results show that the green and grey SCMs have mixed results. All SCMs reduce pollutant AAL (Figure 3A–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 3D–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.
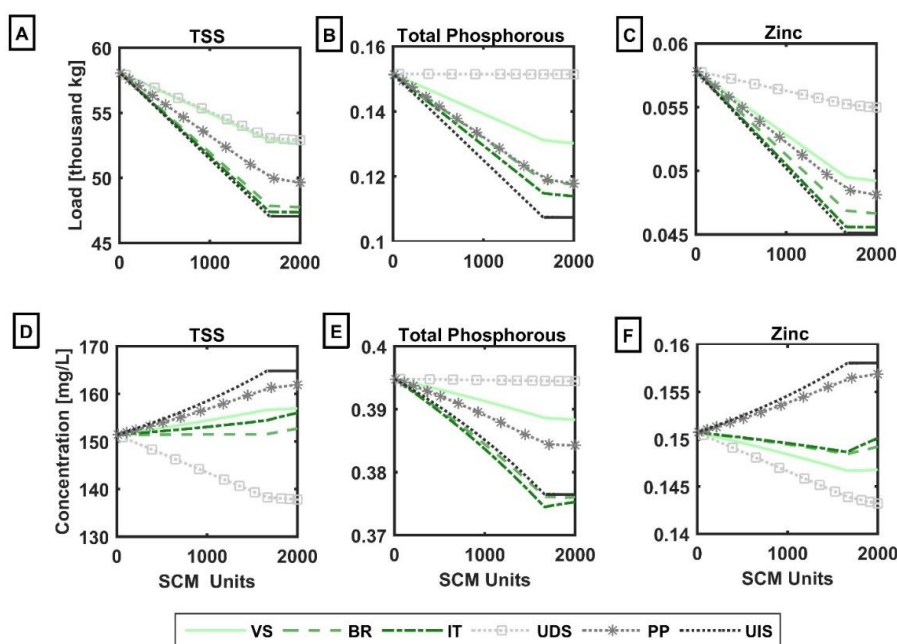

Figure 3. Water quality results from the individual optimizations for each of the six SCM types. Plots show the impact of SCMs on pollutant AAL (**A**–**C**) and pollutant AAC (**D**–**F**) with an incremental increase in SCM units implemented.

4.2.3. AAFV Criteria Solution Selection Results

Table 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 8. Hydrologic results from the six SCM individual optimization solutions that first achieve the Current AAFV Baseline. SCMs that perform best at a hydrologic criterion 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 ($)	281.45	408.23	168.8	493.69	424.13	438.61
Total capital cost ($)	1,165,900	3,919,800	1,341,900	2,475,000	2,664,200	1,871,100
Surface area (ha)	1.36	1.02	0.90	0.00	0.94	0.00
Surface storage volume (m³)	2060	1542	2048	5008	123	2936
Soil storage volume (m³)	876	3503	2405	0	2677	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
Peak flow downstream of aggregate SCM (cms)	1.38	1.27	0.99	1.30	1.27	1.08
Total ET (m³)	13,065	37,722	33,244	0	34,720	0
Average annual GWRP (m³)	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.

4.3. 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 decreases and GWRP increases) there is not a linear relationship between AAFV, AAC, and green space added (Figure 4). 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 m³ of AAFV range and between the 3.5- and 4.5-million-dollar cost range.
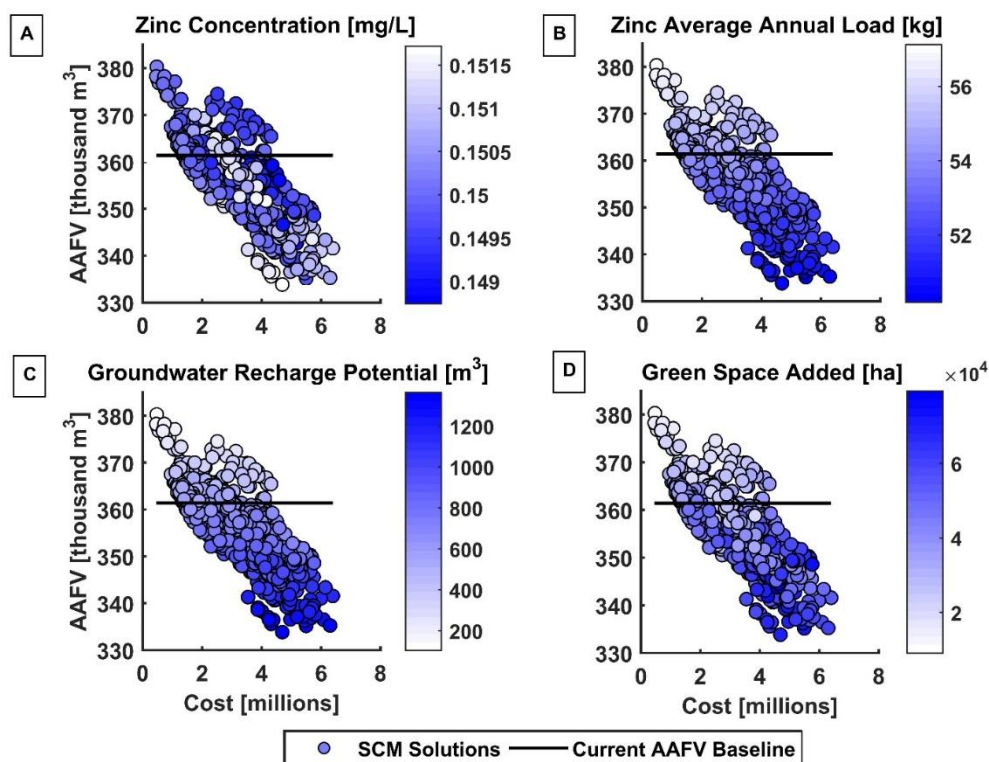
Figure 4. Full optimization results from the Berkeley neighborhood (**A**) Zinc concentration, (**B**) Zinc average annual load, (**C**) groundwater recharge potential, (**D**) green space added. Each subplot shows the same solutions from the full optimization, each with a different color based on a 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.

4.3.1. Selection Criteria Sensitivity Analysis Results

Figure 5A–C shows the optimal 100 solutions based on the full optimization sensitivity analysis. Figure 5D–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 5D 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 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 5D) 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 5E,F), 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.
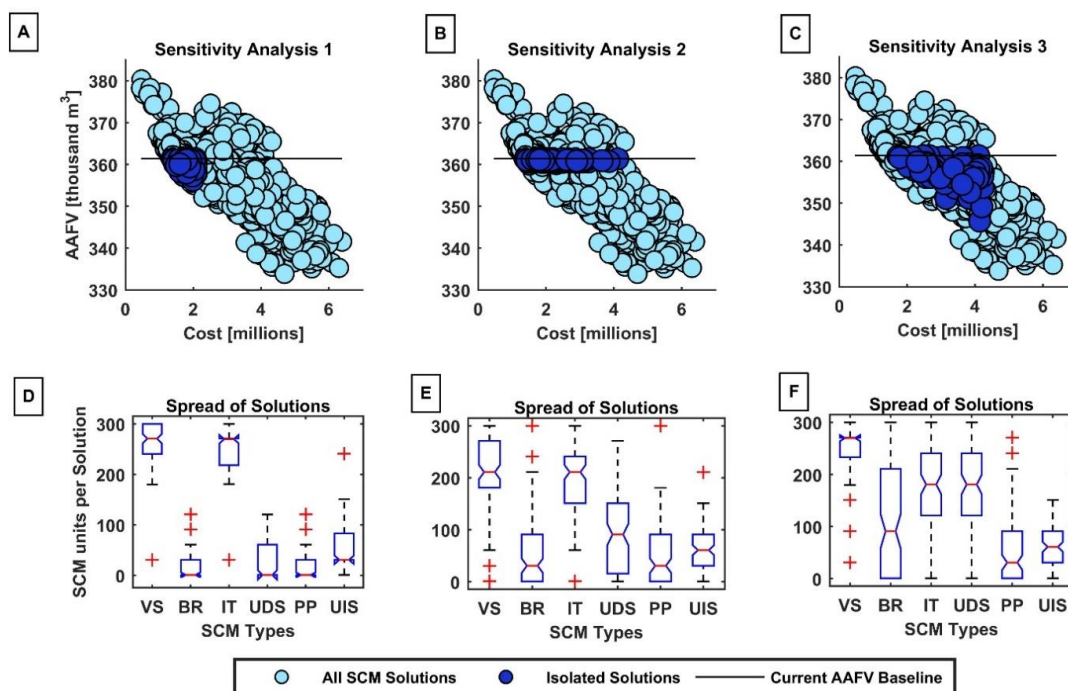
Figure 5. (**A–C**): Location of the 100 "optimal" isolated solutions based on the three sensitivity selection criteria. **A** = Achieve Current AAFV Baseline goal and minimize cost. **B** = Achieve Current AAFV Baseline Goal. **C** = Achieve Current AAFV Baseline Goal and minimize AAC. (**D–F**): Spread of the number of simulated SCM units for the 100 "optimal solutions", each SCM type, and the respective three Sensitivity Analysis.

4.3.2. Aggregate Multi-Criteria Results

Solutions identified using the aggregate multi-criteria (AMC) methodology can be seen in Figure 6. The 10 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 6A,C). 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 6D) while solutions that prioritized AAC (AMC2) are found throughout the whole Pareto curve (Figure 6B). 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 7. 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 7A,B as they reduce AAFV at the lowest cost and also perform well in terms of reducing Zn AAC.

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 7A,C).
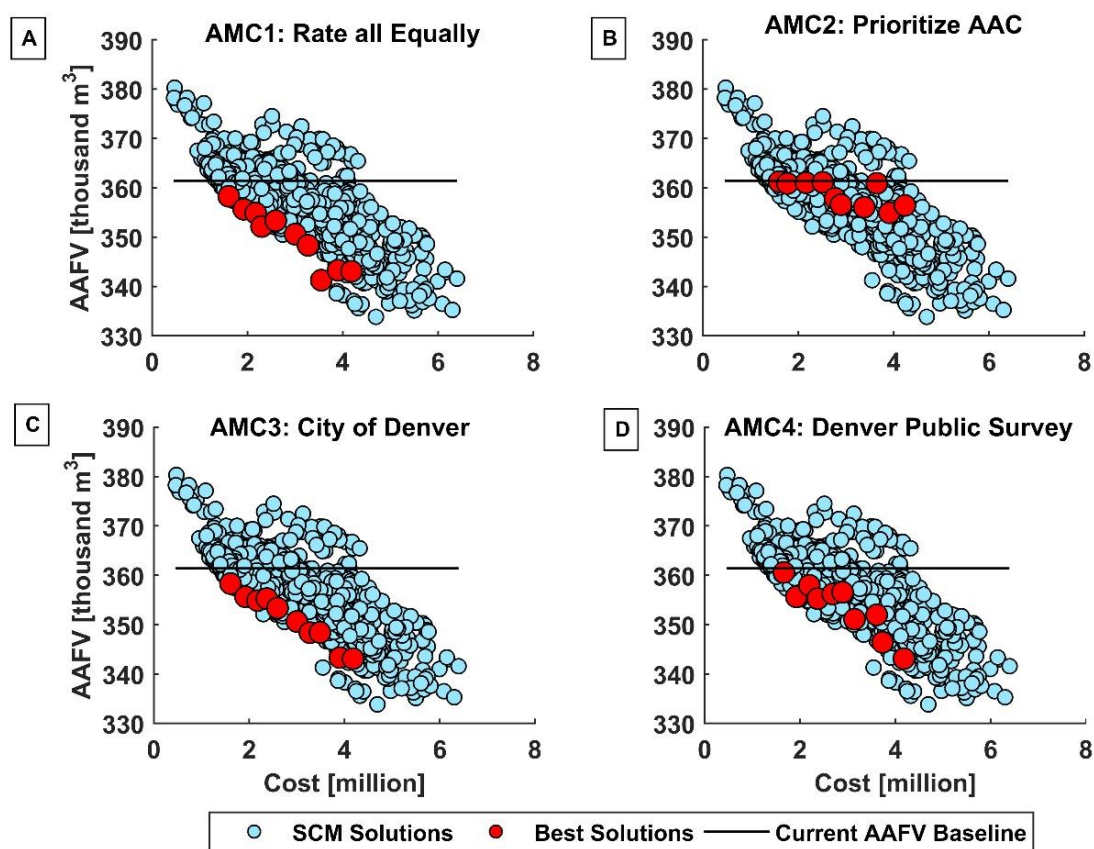

Figure 6. Location of the 10 "optimal" solutions (1 per cost bin) based on the four multi-benefit aggregate rating systems (**A**) rate all equally, (**B**) prioritize AAC, (**C**) City of Denver, (**D**) Denver Public Survey. Cost bins were set to fall between ~1 million and ~4.5 million dollars, where SCM solutions fall along the Current AAFV Baseline.
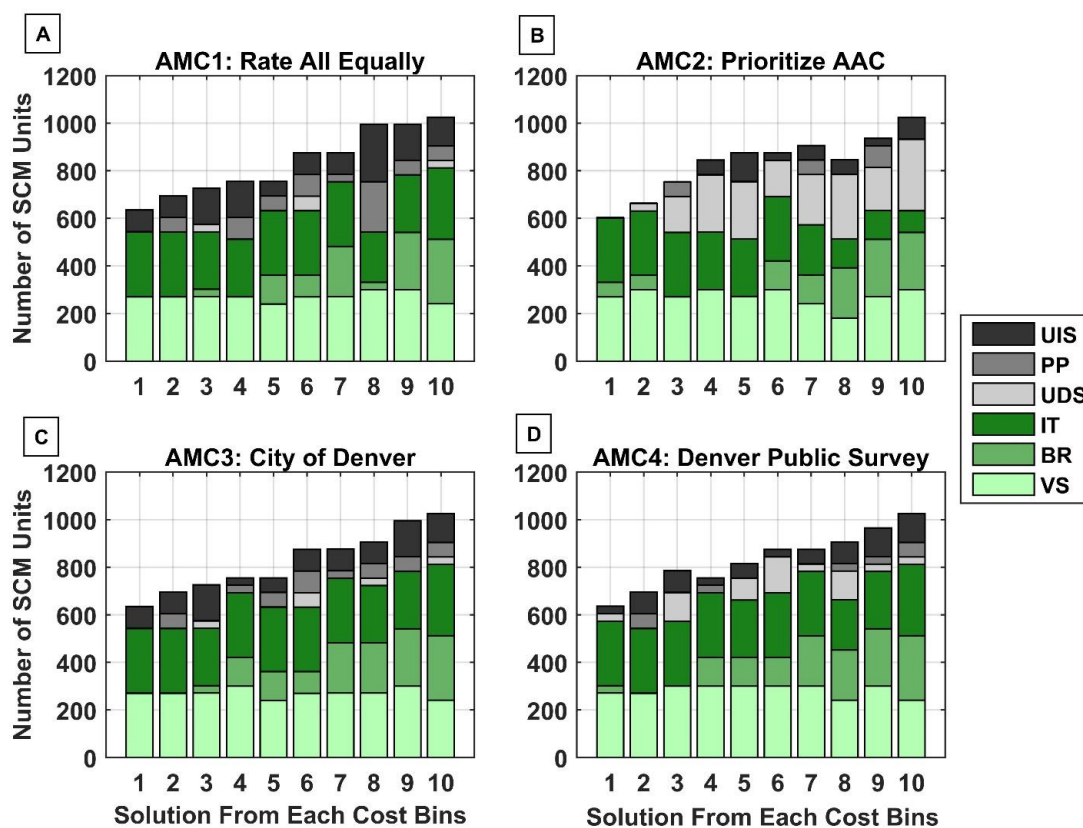
Figure 7. Number of each SCM type simulated in the ten solutions identified using the multi-benefit aggregate equation for the four rating scenarios (**A**) rate all equally, (**B**) prioritize AAC, (**C**) City of Denver, and (**D**) Denver Public Survey. Bar plots are stacked in the same order as displayed in the legend, VS on the bottom and UIS on the top.

5. Discussion

5.1. Benefits and Tradeoffs of Green to Grey Infrastructure

5.1.1. Hydrologic Performance

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 and 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 [37,38]. 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 (Tables 3 and 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 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.

5.1.2. Cost

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, and 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, and 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 [77–79] especially at a watershed-scale [80]. Life cycle costs including planning and permitting, construction, operation, maintenance, decommissioning, and relative lifespan and replacement costs [20] may shift which SCMs are most cost effective, especially in terms of green verses grey SCMs.

5.1.3. Added Greenness

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 [81,82]. 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 [14,83]. 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 [11].

5.2. 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 chosen 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. These results and discussion were found to be similar to a relevant study by Alves et al. (2020), which also looked at using optimizations

to maximize multiple benefits associated with green, blue, and traditional grey infrastructure [84]. 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.

6. Conclusions

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 performances 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 are one way to identify the optimal solutions for a watershed. However, results show that watershed priorities and needs 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.

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Appendix A

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.

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