MAKING THE SHIFT FROM GREY TO GREEN INFRASTRUCTURE FOR STORMWATER MANAGEMENT: A CASE STUDY OF AUSTIN, TEXAS

by

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ABSTRACT

Austin, Texas is the eleventh most populous city in the United States as of July 2019, and the population is swiftly growing (U.S. Census Bureau, 2020). Increasing urbanization inadvertently leads to pollutant deposition and build-up that is consequently washed-off with stormwater runoff into the receiving waters (Goonetilleke & Lampard, 2019). The culmination of this changing land use is a higher likelihood of flooding, severe stream-bank erosion, and degraded water quality throughout the city's watersheds. Therefore, I evaluated whether shifting away from a traditional stormwater management approach towards a green infrastructure strategy would be beneficial to Austin. I focused on the Slaughter Creek Watershed within the city. To model pollutant concentrations in runoff, I evaluated historical daily precipitation data for a 51-year period from a station in central Austin was evaluated to calculate the average precipitation value of the two-year storm. Twenty years of water quality data for untreated stormwater were acquired from a monitoring location in central Austin and paired with the precipitation values. Regression analysis was used to determine a relationship between measured precipitation and the concentration of each of four pollutants: total suspended solids, total nitrogen, total phosphorus, and *E. coli*, in stormwater runoff. The pollutant removal efficacy of two traditional stormwater management features, underground detention vaults and sand filters, and two green infrastructure features, bioretention and permeable pavers, was evaluated against the calculated pollutant concentrations. The EPA-funded Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs tool was used to determine implementation costs and co-benefits of three stormwater management scenarios in the Slaughter Creek Watershed. The results of the model indicate that a hybrid approach, combining both green and traditional infrastructure features, is the most inexpensive and captures the most runoff by volume. However, the green infrastructure approach has significantly more co-benefits and has greater positive water quality impacts. The traditional infrastructure scenario was the most expensive, had the fewest co-benefits and water quality impacts, and captured the least runoff volume. The information in this study indicates that the Slaughter Creek Watershed will benefit from a revised hybrid approach featuring primarily green infrastructure practices yet incorporating traditional features where more practicable.

INTRODUCTION

Austin, located in central Texas, is the eleventh most populous city in the United States as of July 2019. The population in Austin is rapidly growing: From 2010 to 2019 it increased by 22.1% (U.S. Census Bureau, 2020). This swift population growth typically brings changes in land use from vegetated into developed areas. New construction compacts soils and adds impervious land-cover surfaces, both of which reduce stormwater infiltration. Impervious surfaces also accelerate the travel time of runoff by increasing surface flow resulting in more rapid rain event response times within watersheds. These land-use changes increase the flashiness, or speed and magnitude of stream discharge response to storms or other inputs. A flashy watershed produces a more rapid rise to a high peak flow in response to precipitation, followed by a rapid decline (P. Hook, personal communication, September 23, 2019). Increasing urbanization inadvertently leads to pollutant deposition and build-up that is consequently washed-off with stormwater runoff into the receiving waters (Goonetilleke & Lampard, 2019). The culmination of all these factors is a higher likelihood of flooding, severe stream-bank erosion, and degraded water quality throughout the city's watersheds (USGS, n.d.).

Effective stormwater management is a key component for increasing resiliency of developed areas from the impacts of our changing climate. The frequency and intensity of extreme weather events is expected to increase, resulting in even greater flooding and water quality issues (USGCRP, 2018). In 2018, the National Oceanic and Atmospheric Administration increased the precipitation frequency estimates in response to finding significantly higher rainfall frequencies in parts of Texas than previously thought (NOAA, 2018). Historically, stormwater infrastructure was designed to move rainwater offsite as quickly as possible, often directing runoff through a storm sewer system directly into nearby waterways and thus altering natural flows. With these increasing risks for heavy precipitation, it is very important for municipalities to implement alternative, watershed-scale stormwater management strategies to increase resilience (EPA, 2016).

The primary goals of stormwater management are to improve water quality and reduce both the volume and peak discharge (EPA, 2014). Reducing the maximum flow rate of runoff by decreasing the volume and lengthening the duration of discharge into local waterways alleviates risks for localized flooding. Reducing pollutant levels is not only important for preserving the aquatic life and vegetation, but also for protecting drinking water. If water is polluted with sediment or other contaminants, the water treatment plants may struggle to treat the water to a quality safe for consumption. In Austin, drinking water is diverted from the Colorado River, which is the receiving water body for the city's creeks.

Flash floods have also affected the city historically. Texas receives most of its rainfall in a few large storms as opposed to numerous small rain events. Austin is also positioned at the edge of, and downhill from, the Hill Country where the soils are thin with large areas of exposed bedrock and relatively sparse vegetation (Votteler, 2002). In Central Texas, there have been three major flooding events within the past decade (Table 1). The storm in 2018 resulted in elevated levels of silt within the Colorado River, with turbidity levels 80 times typical conditions, that significantly increased the time required for water filtration at the City's three treatment plants. As a result, Austin Water issued a four-day mandatory boil water notice as the turbidity within treated water had exceeded the state standard (City of Austin, 2018).

Table 1. Recent flood events on the Colorado River, Texas (Gruca, 2018), (NOAA, 2021).

Date	Total Rainfall (inches)
October 30 – November 1, 2013	4.7
May 23 - 25, 2015	7.4
October 13 - 19, 2018	4.7

There are several different engineered approaches to handle runoff. Traditional, also termed "grey", stormwater infrastructure techniques involve channelization and sewer collection systems that convey stormwater directly to nearby surface water. This can also include features such as sand traps and underground detention vaults that hold and filter water. Low Impact Development, also referred to as "green" stormwater infrastructure, involves the implementation of systems that use or mimic natural processes to store, infiltrate, and evaporate water where it falls as opposed to being transported. Examples include rain gardens, permeable pavers, and green roofs.

My case study aims to evaluate whether shifting to a green infrastructure stormwater management approach would be beneficial to the City of Austin, by focusing on one of the city's many watersheds, Slaughter Creek. The objective is to produce an Austin-specific plan for stormwater management that prescribes best management practices that are cost effective and appropriate for the numerous small urban watersheds. Green infrastructure is promoted as being the future of sustainable stormwater management; however, it may be difficult or costly to implement in a highly developed urban area. I will identify both the challenges and benefits in implementing a large-scale green infrastructure strategy while comparing against more traditional engineered approaches. With the frequency and intensity of severe storms increasing, this will be a timely strategy to mitigate localized flooding and negative water quality impacts.

STORMWATER MANAGEMENT

The principal goal of stormwater management is to minimize localized flooding, with additional benefits consisting of improved water quality, recreational opportunities, and protection of ecosystems (Monk & Chalmers, 2007). The foundation of its management relies on an understanding of how a particular land area and its drainage system can impact or be impacted by the stormwater runoff passing through it. Specifically, when alterations to the land area or drainage network are being made, it is crucial to anticipate how the changes are likely to affect the volume, flow rate, and quality of the runoff. Subsequently it is important to consider how the stormwater runoff will affect the people, property, and natural resources in the area (Minnesota Pollution Control Agency, 2020).

Traditional Approach

Construction of early sewer systems began in the United States around the mid-1800s, and they were often designed, built, and maintained by private individuals or companies. Eventually, municipalities took them over. These early sewers simply provided an underground path for runoff and sewage to be quickly conveyed from the point of origin to nearby waterways (Schladweiler, 2014). The channelization and sewer collection systems that convey stormwater directly to nearby surface water are considered “traditional”, also termed “grey”, stormwater infrastructure techniques. When these systems of conveyances are owned by local government or public entities and are dedicated to stormwater, they have been designated as municipal storm sewer systems (MS4).

In the United States, it was not until the Clean Water Act was passed in 1972 that stormwater regulations were enforced. The act regulates discharge of pollutants to navigable waters from point sources. Point sources are defined by the EPA as any single identifiable source of pollution from which pollutants are discharged, such as a pipe from a sewage treatment plant or oil refinery. Originally only targeted at large manufacturing facilities, the regulations have strengthened over the years, as with the passage of the Water Quality Act. Now, municipal separate storm sewer systems, including that of the City of Austin, have individual permits (Franzetti, 2016). The City of Austin has held a Phase I MS4 permit since the late 1990s due to it serving a population of 100,000 or greater based on the 1990 U.S. Census. This requires the city to develop and implement a stormwater management plan with the goal of reducing the discharge of pollutants to the maximum extent practicable (Texas Commission on Environmental Quality, 2021).

Traditional stormwater infrastructure is designed to move stormwater away from the built environment and into the closest waterway as quickly as possible. It can include channels, gutters, dams, levees, piping, and collection systems. Typically, grey infrastructure collects and conveys stormwater from impervious surfaces, such as roads and rooftops, into a series of piping that eventually discharges the untreated stormwater into a local water body (EPA, 2021). It is called “grey” infrastructure because it is often constructed of concrete. This can also include features such as sand traps and underground detention vaults that hold and filter water.

Detention tanks and vaults are underground structures constructed of concrete or corrugated metal pipe and have the added benefit of attenuating peak stormwater flows. These vaults are primarily used in urban environments where space is limited. Underground detention systems can control significant volumes of runoff in parking lots, adjacent to rights-of-way, and in medians where they are easily accessed for maintenance. Systems are comprised of a series of pipes interconnected by a junction box or main pipe with an outfall structure (Figure 1). Outfalls are generally designed with flow control structures to slow the water's release (Federal Highway Administration, n.d.a).

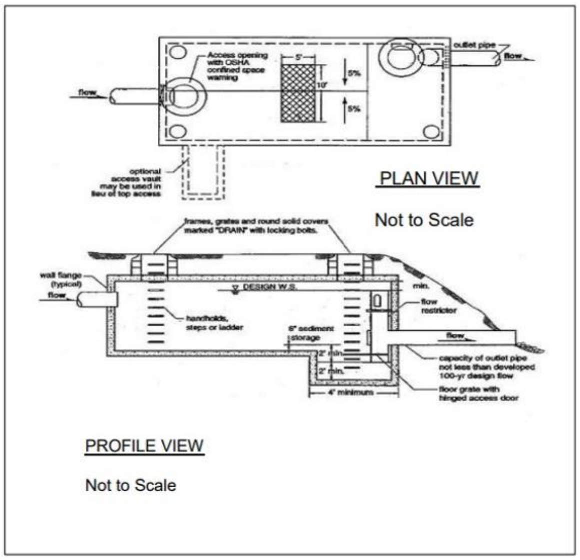

Figure 1. Underground detention vault (Chattanooga-Hamilton County, 2021).

Sand filters normally consist of multi-chamber underground vaults accessible by surface level manholes. These features are also well adapted for urban areas with limited land area. Their size and shapes are flexible and can be adjusted based on a site's needs. In addition to temporarily storing stormwater runoff, sand filters also provide water quality treatment through a combination of sedimentation and filtration. Water will flow into an underground chamber that provides pretreatment by settling, similar to a detention vault (Figure 2). The runoff then flows by gravity into a filter chamber where it flows through the sand filter. Next, the water is collected in underdrains and is discharged into a nearby storm line or channel. The first chamber acts as pretreatment by removing large diameter suspended solids and captures hydrocarbons. The sand filter will then collect much of the smaller suspended particles in the runoff. Subsequently, the sand filter must be monitored and changed out when sediment accumulates, typically every three to five years (District Department of the Environment, n.d.). These treatment devices are intended to manage the first flush, which often contains the highest concentration of pollutants (Federal Highway Administration, n.d.b).

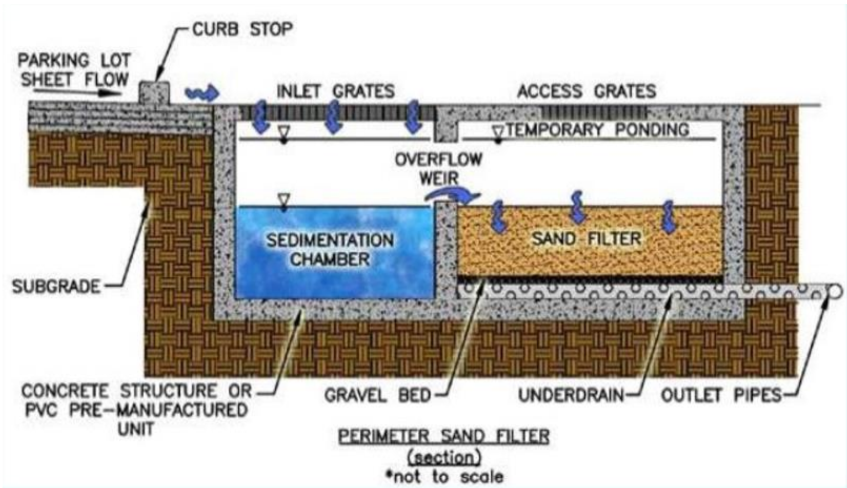

Figure 2. Underground sand filter (Annapolis, n.d.).

Low Impact Development Approach (Green Infrastructure)

The low impact development approach, referred to as “green” stormwater infrastructure (GI), takes stormwater management a step further. In addition to conveying stormwater, GI systems are designed to mimic natural processes by promoting storage, infiltration, and evaporation of water where it falls as opposed to being transported. Outcomes include reduced volume of off-site runoff, pollutant control, and improved groundwater recharge. These outcomes ultimately support the primary goal of green infrastructure, which is to ensure the maximum protection of the ecological integrity of the receiving waters by maintaining the watershed's hydrologic regime.

In the mid-1980s, the introduction of bioretention technology (described below) initiated the development of low impact development principles. Bioretention was developed by Prince George's County in Maryland in response to a need to address growing environmental and economic limitations of traditional stormwater management practices (Low Impact Development Center, 1999). Other techniques have since been developed, including permeable pavers, green roofs, and tree planter boxes.

Different green infrastructure systems have varying pollutant removal efficiencies. Removal can depend on several factors including the type of system and the materials used. A bioretention cell that has had a heavy layer of compost applied to promote vegetation growth may end up leaching additional nutrients into the runoff it is designed to treat. Green infrastructure systems typically help with reduction of total suspended solids (TSS) via physical filtration of the particulates during percolation through the soil profile. They can also help with nutrient removal, such as nitrogen and phosphorus. Different soil media additives have been shown to increase nutrient removal and help offset the N and P generated by compost leaching (Shrestha et al., 2018). Plants can also be important pollutant removal mechanisms through their uptake of dissolved nutrients. Although fecal indicator bacteria levels, such as *Escherichia coli*, are partially reduced by GI features, it is often not enough to decrease effluent concentrations to acceptable primary contact recreation standards. By reducing the magnitude of stormwater runoff volumes, they are still able to reduce the overall bacterial loading into streams (Clary et al., 2016). Other pollutants removed include metals and hydrocarbons.

Ecosystem services are ecological functions which provide benefits to the population and enhance human welfare. They can be grouped into four categories: the provisioning of production services, regulation services, supporting services, and cultural services (National Wildlife Federation, n.d.). Stormwater management features are commonly considered for their ability to offer regulation services such as improved water quality and for providing mitigation against natural risks like erosion and flooding (Semeraro et al., 2017). It is important to also consider the other ecosystem services green infrastructure provides.

There are cultural services such as spiritual or intellectual enrichment, aesthetic, and recreational values. Aesthetics are an important sensory experience, and green views from a window have been shown to be an important predictor of neighborhood satisfaction. Local communities can find a sense of local identity and social inclusion by volunteering to help maintain green infrastructure in parks, and economic benefits include increased real estate values. Recreation benefits can be direct in the form of a hike and bike trail around a series of rain gardens, or indirect benefits such as improved water quality resulting in the authorization of contact recreation activities in the watershed's receiving stream (O'Brien et al., 2017). Indirect supporting services including habitat creation, biodiversity conservation, nutrient cycling, and soil formation. These are very important, however, their effects on human well-being are indirect or observed over a long period.

Although their goals are the same, the various green infrastructure features can look considerably different. Green roofs are layers of vegetation planted in engineered soils over a waterproofing system installed on a building's roof. They can be either intensive with large trees and shrubs, or extensive with small succulents and grasses. Tree cells are modular suspended pavement systems, often beneath sidewalks, that hold lightly compacted soil while also supporting traffic loads. The void space provided allows unrestricted tree root growth while also treating and retaining additional stormwater onsite.

Bioretention cells are small scale, vegetated depressions that receive stormwater from small contributing areas to slow, store, and treat runoff by vertical infiltration through soil and plant roots into storm drains or receiving waters. Small scale versions are also called rain gardens. They can be either single or connected cells for flow control, water quality treatment, and conveyance (Figure 3). The plants and engineered soil media physically filter and chemically bind contaminants. They can have geotextile liners to eliminate infiltration into native soils if in environmentally sensitive areas or adjacent to buildings. There is also an option to include an underdrain pipe system that connects to the stormwater infrastructure (National Green Infrastructure Certification Training, Bioretention lecture, February 2021). The City of Austin requires the soil mixture to meet the following specifications: sand content of 70-90% by weight, clay content of 3-10% by weight, silt + clay content ≤ 27% by weight, and a percent organic matter of 0.5-5% by weight (City of Austin, 2021a).

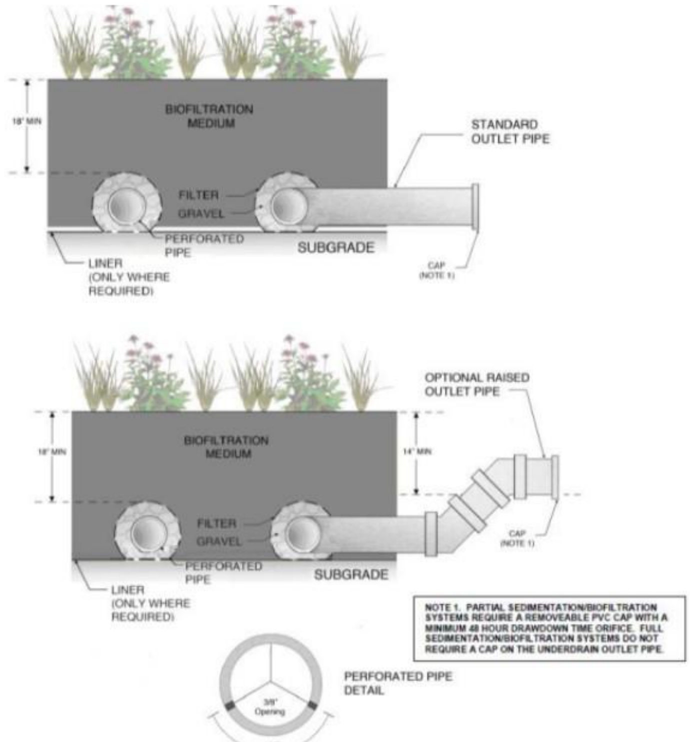

Figure 3. Biofiltration cell (City of Austin, 2021b).

The green infrastructure category of permeable pavements includes pervious concrete, porous asphalt, and permeable pavers. The first two features are designed to allow water to infiltrate through the pavement surface, aggregate base, and into subgrade soils. I am interested in using the third option, permeable pavers, which allow water to pass through voids between the pavers. There are two types, open-jointed block pavement and interlocking concrete pavement. The latter style has durable, angular, porous, open-graded aggregate in the openings to promote rapid infiltration while preserving porosity and permeability (Figure 4). If infiltration rates in the native soils permit, these systems can be designed with only gravel storage layers beneath them and not include an underdrain system as well. Pavers are capable of supporting heavy loads and are usually installed in low-speed areas such as parking lots, driveways, or loading docks (NGICP Training, Permeable Pavement lecture, February 2021).

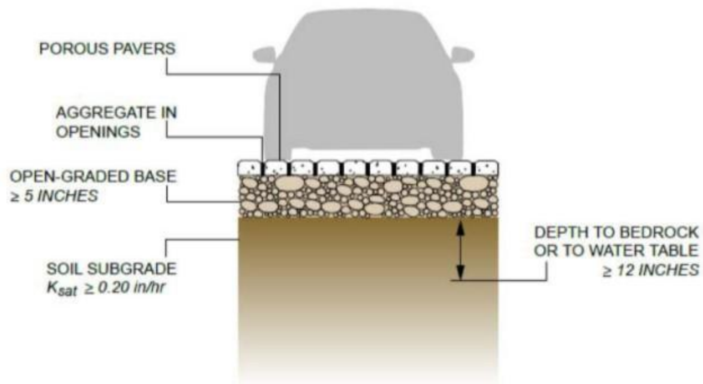

Figure 4. Permeable pavement (City of Austin, 2021b).

METHODS

Study Area: Slaughter Creek Watershed, Austin TX

The climate in Austin is humid subtropical, typically with long, hot summers and mild winters. The general landform is rolling hills, with thin layers of soil covering limestone (Weather Atlas, n.d.). The native habitat is dominated by scrub-shrubland with mesquite, live oak, prickly pear cactus, and other densely growing vegetation. There is slight seasonal variation in precipitation, with a wetter season lasting from April to September followed by seven months of a drier season (Weather Spark, n.d.).

Austin is a city filled with creeks, sprawling within the contributing drainage areas of over 68 watersheds (City of Austin, 2015). The watershed evaluated during this case study was Slaughter Creek. It was selected due to its proximity to the city center, approximately 13 kilometers, and although still urban there are more opportunities for implementation of a watershed-wide stormwater management plan than with the more highly developed watersheds downtown.

The Slaughter Creek Watershed is in south Austin (Figure 5). Primary land use is a mixture of single-family housing, apartment complexes, and commercial/industrial areas as well as a few parks scattered throughout. It has a catchment area of 80 square kilometers, with a creek length of 29 kilometers. The total impervious cover is 19.4% as estimated in 2013 (City of Austin, 2017). An EPA classification system based on impervious cover percentages classifies the watershed as a degraded or impacted system generally unable to support a high-quality stream system (EPA, n.d.). The creek is also listed on the Texas Commission on Environmental

Quality's (TCEQ) 2020 Texas Integrated Report of Surface Water Quality as having an impaired macrobenthic community (TCEQ, 2020).

The creek traverses through small greenbelts and parks flanked by heavily developed neighborhoods and commercial developments. It is an intermittent stream with perennial pools and is prone to flash flooding during intense rain events with heavy precipitation. It is also common for Slaughter Creek to dry up during periods of drought or little precipitation. The small tributary stream flows into Onion Creek, which then feeds into the Colorado River just east of the city.

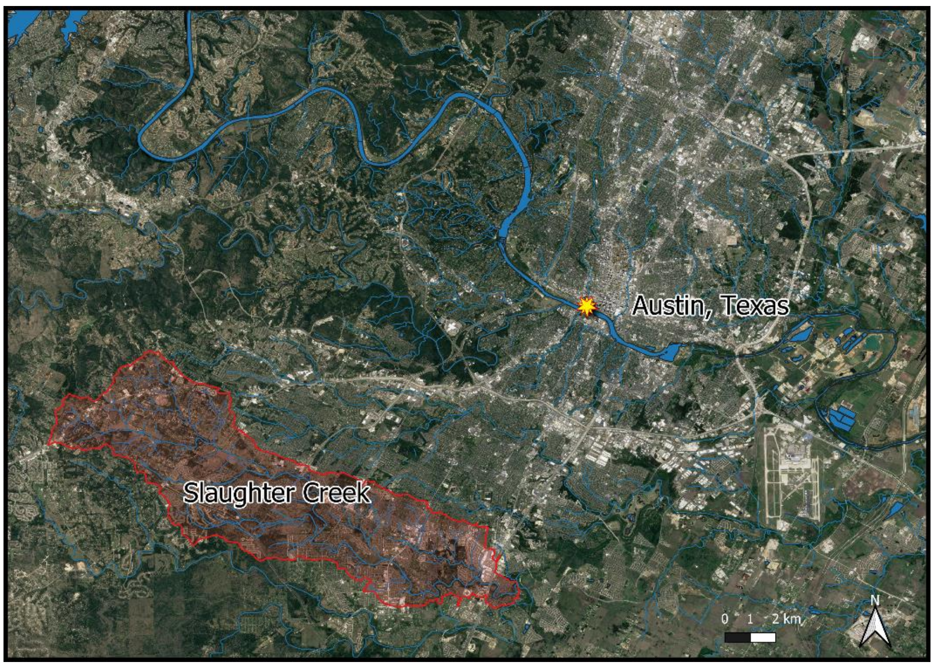

Figure 5. Slaughter Creek Watershed in Austin, Texas.

Model Storm

I evaluated historical daily precipitation data for a 51-year period (January 1970 to June 2021) from NOAA station USW00013598, Camp Mabry, an army base located in central Austin.

This was the most centrally located station with reliable and complete precipitation records. To calculate the area's specific rainfall exceedance probabilities, I employed the method outlined in the EPA's Technical Guidance on Implementing Stormwater Runoff Requirements (EPA, 2009). First, I removed data for small rainfall events that are less than 0.1 inches. They do not typically cause runoff and could potentially cause the analyses of the storm runoff volumes to be inaccurate. Next, I sorted rainfall events from highest to lowest in an excel spreadsheet. Last, I calculated the annual exceedance probability (AEP) or rainfall events greater than each ranked event by dividing the rain event's number by the total number of events.

From this, I calculated the annual recurrence interval (ARI) and the value of the two-year storm to be 0.57 inches (14.5 mm). With more infrequent storm events, the simple relationship of ARI = 1/AEP can be used. However, more common events require more complex equations to remain accurate. I used the AEP of 0.3935 for the two-year ARI (Geoscience Australia, 2019). There were four measured storm events with an AEP close to 0.3935, all of which equaled 0.57 inches (Table 2).

Table 2. Four measured storm events with annual exceedance probabilities equivalent to two-year annual recurrence interval (NOAA, 2021).

Date	Annual Exceedance Probability	Precipitation (in.)	Precipitation (mm.)
5/19/1997	0.393	0.57	14.5
11/12/1997	0.393	0.57	14.5
3/31/2005	0.394	0.57	14.5
8/27/2009	0.394	0.57	14.5

I chose the two-year precipitation event to represent the model storm based off language in the City of Austin's code: "It has been recognized that the runoff from the two-year return frequency storm results in bank-full conditions in natural streams in undeveloped watersheds…

On-site control of the two-year storm is required by Section 25-7-61 of the Land Development Code. These guidelines shall be considered the minimum requirements for compliance with that section of the Code" (City of Austin, 2021c, Section 1.6.8). This precipitation frequency estimate was used to evaluate the characteristics of average pollutant concentrations versus precipitation.

I acquired twenty years of water quality data for untreated stormwater from a monitoring location in central Austin and paired them with the historical precipitation values from the same weather station as the exceedance probability analysis. The stormwater samples were collected quarterly from 1999 through 2021 at a representative monitoring location in compliance with a TCEQ issued MS4 permit. Sampled rain events consist of both a grab sample collected during the first two hours of discharge, and flow-weighted composite samples of either the first three hours of discharge or the entire rain event. Samples were analyzed by a TCEQ accredited laboratory. The complete dataset can be found in Appendix A. I chose four constituents: total suspended solids, total phosphorus (total P), total nitrogen (total N), and *Escherichia coli.* Total suspended solids (TSS), phosphorus (P), and nitrogen (N) are known to have negative effects on aquatic ecosystems, discussed more below. *E. coli* is a strong indicator of sewage or animal waste contamination, a common pollutant of concern for urban watersheds. In Austin specifically, the TCEQ has identified bacterial impairments in five creeks (TCEQ, 2020).

Before modeling, I removed values from the data set based on several criteria. Values were removed if there was not sufficient information, either the pollutant value was missing, or the amount of precipitation was not enough to be considered significant. This criterion was the same as the exceedance probability calculations, less than 0.1 inches. Outlier values were also removed if the values were 1.5x greater than the neighboring data in the trend when pollutant values were sorted by precipitation amount. For *E. coli*, entries were also removed when they were marked with a greater than sign, as there was no certain way to know the exact value. Sufficient values remained for each parameter after cleaning up the data (Table 3).

Table 3. Number of water quality entries used in pollutant concentration vs. stormwater runoff sampling.

Pollutant	Values in Data Set During the Period 1999 – 2021 (No.)
TSS	54
Total N	55
Total P	55
E. coli	55

It is important to note that there were some stormwater samples from dates where the precipitation station data was equal to zero inches. My speculation is that there was a small, localized storm event that did not register at the Camp Mabry station. It is unlikely that the sample was of baseflow conditions because the TCEQ's stormwater permit requires a rain event for it to be a qualified sample (TCEQ, 2018a).

In order to model concentration in stormwater runoff, I ran regression analysis on the four pollutants of interest. For TSS and *E. coli*, I derived linear relationships with precipitation. I log-transformed values of total nitrogen and total phosphorus to obtain better relationships. To project pollutant concentrations in runoff for the model storm, I used the calculated precipitation value for the two-year storm event in the regression equations.

Projected Water Pollutant Concentration Reductions

I evaluated four stormwater management features for pollutant removal efficiency: two traditional infrastructure features, underground detention vaults and sand filters, and two green infrastructure features, rain gardens, and permeable pavers. To discern all four pollutants' reduction and effluent concentrations within each practice, I multiplied the modeled two-year storm pollutant concentrations by the feature's individual pollutant removal efficiencies.

I calculated the pollutant removal efficiencies from various sources. The City of Austin Environmental Criteria Manual (ECM) states expected effluent concentrations for sand filters and bioretention (rain gardens). The ECM also has pollutant concentration data based on their local monitoring data and analysis (City of Austin, 2021d). I utilized those treated effluent pollutant concentration values to determine the effectiveness of the selected stormwater control measures on the modeled storm. I subtracted the City's treated effluent values from the City's surface runoff pollutant concentration values. I then divided the resulting value, the amount the pollutant was reduced, by the runoff concentration to obtain the pollutant concentration removal rate. I applied value to the model storm's runoff pollutant concentration values to acquire the model storm's treated effluent value. For permeable pavers and detention vaults, I sourced pollutant concentration removal rates were sourced from the Texas Integrated Stormwater Management program, or iSWM (iSWM, 2010).

Life Cycle Costs

Life cycle costs vary widely for different stormwater management practices. They can be broken out into several categories, including the initial capital costs and operations and maintenance (O&M) fees. Although difficult to assign a direct monetary value, it is also crucial to consider co-benefits in the form of ecosystem services. I used the EPA-funded Community-enabled Life cycle Analysis of Stormwater Infrastructure Costs (CLASIC) tool to compare costs and benefits of several stormwater management scenarios involving grey and green infrastructure practices. The tool enables comparing cost, performance, and co-benefits of stormwater technology scenarios by utilizing life cycle cost analysis. It highlights the costs most closely tied to implementing, managing, and budgeting for stormwater assets. The activities the model considers as part of the life cycle include the pre-usage supply chain, use and the process of supplying use, end-of-life and the processes supplying end-of-life steps or rehabilitation (One Water Solutions Institute, 2021).

Maintenance costs for each feature also account for differing maintenance frequencies and effort, as well as the replacement/rehabilitation costs associated with those maintenance frequencies. The costs of land purchases are not included. The tool does include a 20% cost allocated toward engineering and contingency. All costs are regionalized based on a study prepared specifically for CLASIC (One Water Solutions Institute, 2021). The region I selected for use in this case study was “Houston” as it was the closest, only approximately 257 kilometers east of Austin. The tool also displays the costs as equivalent annualized costs, or costs broken down into equal amounts every year to understand the cash flow in any given year for the lifespan of the feature over the study period.

The co-benefit analysis is informed via multicriteria decision analysis (MCDA) output using the weighted average method. MCDA provides quantitative outputs to compare co-benefits across different scenarios of technology selections. The model’s approaches were developed from peer reviewed literature and other accepted co-benefit analysis tools. The tool considers a wide variety of factors to estimate co-benefit indicators (Table 4) (One Water Solutions Institute, 2021).

Table 4. Approach to estimate co-benefit indicators as defined in the Community-enabled Life cycle Analysis of Stormwater Infrastructure Costs model. Ecosystem services equally weighted sub-indicators: pollinators, biodiversity, green corridor.

Economic	Social	Environmental
Property Values	Health impacts from air quality	Ecosystem services
Costs from Illness	Mental health	Groundwater flow
Potential Impacts from nuisance floods	Thermal comfort	Carbon sequestration
Building energy efficiency	Increased supply from harvested stormwater	
Avoided Water Treatment	Public awareness of stormwater and water systems	
Employment Opportunity	Potential avoided social strain associated with nuisance flooding	

I made several modifications to the model to produce representative results accurate to Austin, Texas. To create the project, I uploaded a shapefile of the Slaughter Creek Watershed boundary. The model then divided the watershed into 43 “block group” subunits and pulled land use (NLCD) and soils data (SSURGO). The most recent land use data available for the model was 2016. It was highly likely that land use intensity and impervious percentages had changed significantly since 2016 considering the rapid population growth rate of Austin. To remedy this, I extrapolated land use development densities and impervious percentages in QGIS from the NLCD 2019 data (MRLC Consortium, 2021). I calculated the area of each subunit, after which I used the percentage of each that is developed (low, medium, and high density) as the new impervious cover percentage value. I then uploaded these data, including the developed open, low, medium, and high-density percentages, into the model.

I set the precipitation and evaporation data to the same weather station and 30-year time range as the evaluated stormwater quality data, 1999 to 2020. I also input the calculated pollutant runoff concentrations and removal efficiencies for TSS, Total P, Total N, and *E. coli* into the model for the water quality and technology effluent parameters. Last, I built three scenarios utilizing only the four stormwater features modeled: bioretention, permeable pavers, underground detention vaults, and sand filters. I applied the technologies to subunits in the watershed at incremental impervious cover percentages (Table 5).

Table 5. Community-enabled Life cycle Analysis of Stormwater Infrastructure Costs model results of stormwater management technology locations for three scenarios.

	Green Scenario		Hybrid Scenario		Grey Scenario	
Technology	Number of features	Applied impervious percentage range	Number of features	Applied impervious percentage range	Number of features	Applied impervious percentage range
Bioretention (small)	11,079	45 to 74	--	--	--	--
Bioretention (large)	47	15 to 44	66	15 to 44	--	--
Permeable Pavers	25	> 75	15	> 75	--	--
Detention Basins (small)	--	--	37	45 to 74	--	--
Detention Basins (large)	--	--	--	--	60	15 to 44
Sand Filter (small)	--	--	2,618	> 75	5,620	> 75
Sand Filter (medium)	--	--	--	--	183	45 to 74

Watershed Management Strategies

My primary objective for this case study was to develop a stormwater management strategy for the Slaughter Creek Watershed. I accomplished this through a comparison of three different scenarios. The first scenario used two green infrastructure features, rain gardens and permeable pavers. The second scenario used two traditional features, underground detention vaults and sand filters. The third scenario combined all four of the infrastructure features to model a hybrid approach. I accounted for factors including available public space, available private space and the public's willingness to assist, target impairment of concern, and co-benefits. To target the impaired macrobenthic community, I prioritized reduction of total suspended solids, total phosphorus, and total nitrogen pollution. Excessive sediment is known to inhibit macrobenthic community growth through smothering (New Jersey Department of Environmental Protection, 2004). Total phosphorus and nitrogen also lower dissolved oxygen levels by encouraging explosive algal growth, thus limiting the oxygen available to other organisms (Minnesota Pollution Control Agency, 2009).

To address availability of space, I evaluated the land required for each scenario. Additionally, since a large majority of the watershed is single family homes, resident acceptance is crucial. The City of Austin is currently testing the Rain Catcher Pilot Program in a small 2.8 square kilometer portion of the Waller Creek headwaters in north Austin. Neighborhood homeowners were offered incentive packages to install rain gardens and cistern systems to control a minimum of 5,700 liters of runoff per property. A 75% adoption rate, approximately 1,200 homes, is anticipated within the neighborhood between 2020 to 2023. The city offers discounts and rebates, including a free site assessment to identify drainage problems and a free consultation with a landscape designer (City of Austin, 2021e). To be conservative, my case study assumed only 50% of the offered residents will participate in managing stormwater on their property.

The city’s watershed protection department is primarily (> 95%) funded by drainage charges assessed. They are the department charged with the goal of managing the city’s creeks, drainage systems, and water quality programs. The drainage charge is calculated individually for every property based on the amount and percent of impervious cover (City of Austin, 2021f). This could be used as a source of funding for implementing watershed-wide stormwater management strategies.

RESULTS

Projected Water Pollutant Concentration Reductions

When analyzed, the untreated stormwater water quality data showed varying relationships when precipitation was used as a predictor. I used regression analysis to find reasonable equations with which to model the pollutant concentrations in the runoff of a two-year storm event (0.57 inches) (Table 6).

Table 6. Modeled pollutant concentration values for the two-year storm.

Pollutant	Unit	Modeled Value
TSS	mg/L	59
Total N	mg/L	2.6
Total P	mg/L	0.3
E. coli	MPN/100ml	40,000

The relationship between total nitrogen and precipitation was the most statistically significant with a small p-value of 0.006, although the R^2 value was also relatively low (Figure 6). This points to a significant model, however it does little to explain much of the data variation. The regression equations for the other three pollutants were not statistically significant based on the coefficient of determination or probability value, however reasonable trends can still be gleaned from the data.

Nutrients generally increase initially along with increasing rainfall intensity and then gradually stabilize once they become diluted with the extension of rainfall duration (Hathaway et al., 2012). This trend is reflected in this study's data for total nitrogen (Figure 6) and total phosphorus (Figure 7). Total suspended solids are physically mobilized by runoff and usually increase with additional runoff (Figure 8). The weak relationship displayed by the *E. coli* data is not atypical (Figure 9). *E. coli* is notoriously difficult to model due to large variability from sheet flow samples, with inconsistent patterns even when sampled at the same location within the same storm event (Shergill & Pitt, n.d.). *E. coli* inputs are generally from non-point sources, such as animal or human waste transported by precipitation, and can include leaking sewer lines in addition to fecal material mobilized from off the ground leading to fluctuating input loads.

It is important to note that there may be variations between the modeled values and actual measured pollutant concentrations in the Slaughter Creek watershed due to geographical differences. A few potential variables include: the sampled drainage area may have more pets than the neighborhoods in the Slaughter Creek Watershed or it may have older and less maintained sanitary sewer infrastructure.

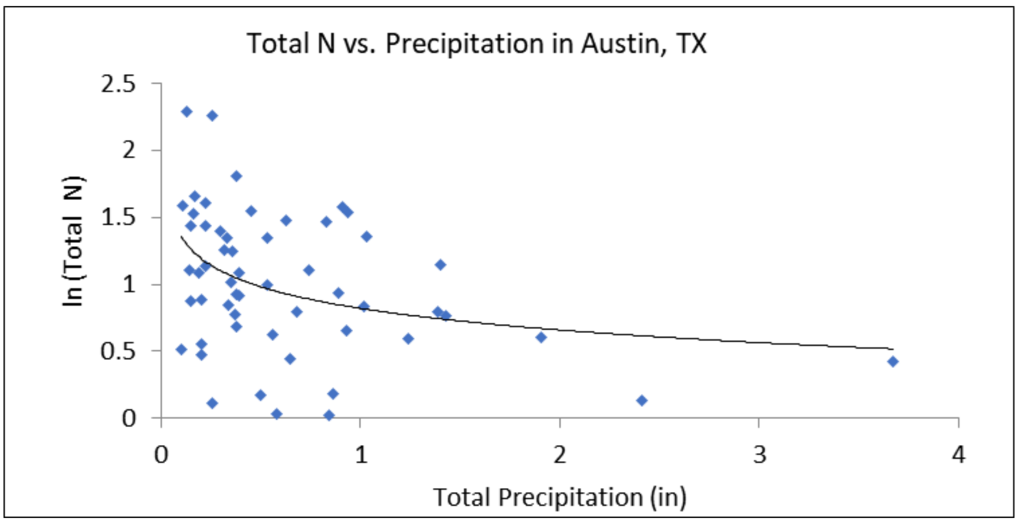

Figure 6. Total N versus daily precipitation, 1999-2021 (n = 55, r2 = 0.13, p-value = 0.006). I added a constant of 0.3 to all values to avoid negative values after the natural log transformation due to several data points < 1 (f(x)= ln(x)+0.3).

Total N regression equation: $y = -0.23\ln(x) + 0.82$

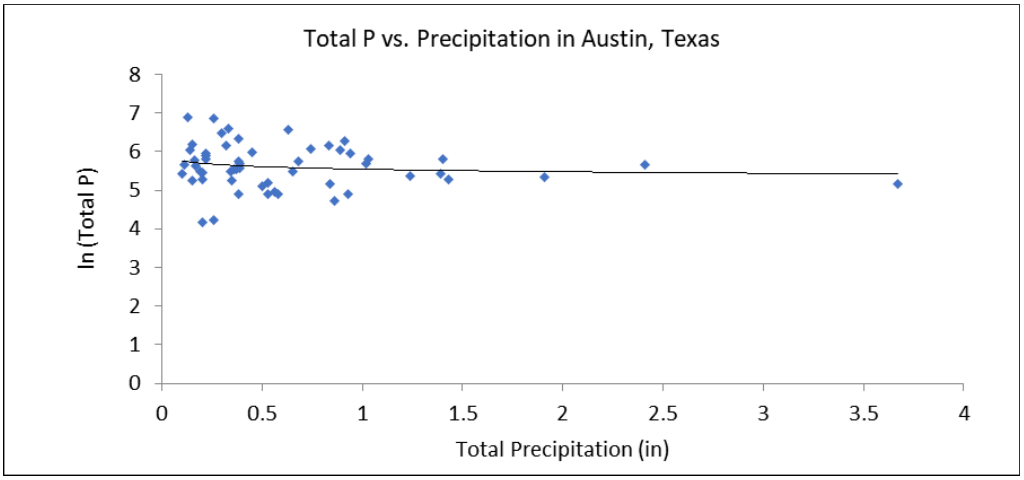

Figure 7. Total P versus daily precipitation, 1999-2021 (n = 55, r2 = 0.019, p-value = 0.31).

Total P regression equation: y = -0.095ln(x) + 5.5

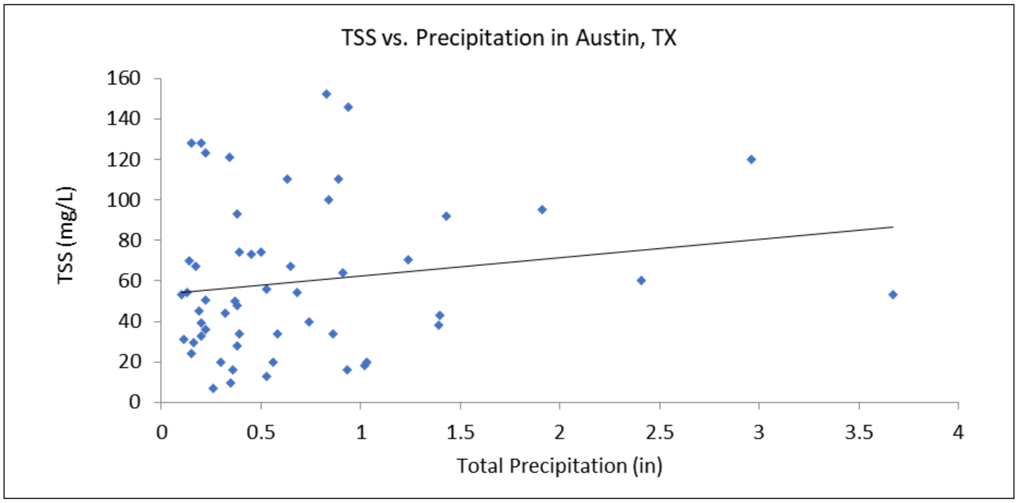

Figure 8. TSS versus daily precipitation, 1999-2021 (n = 54, r2 = 0.028, p-value = 0.23).

TSS linear regression equation: y = 8.99x + 53.6

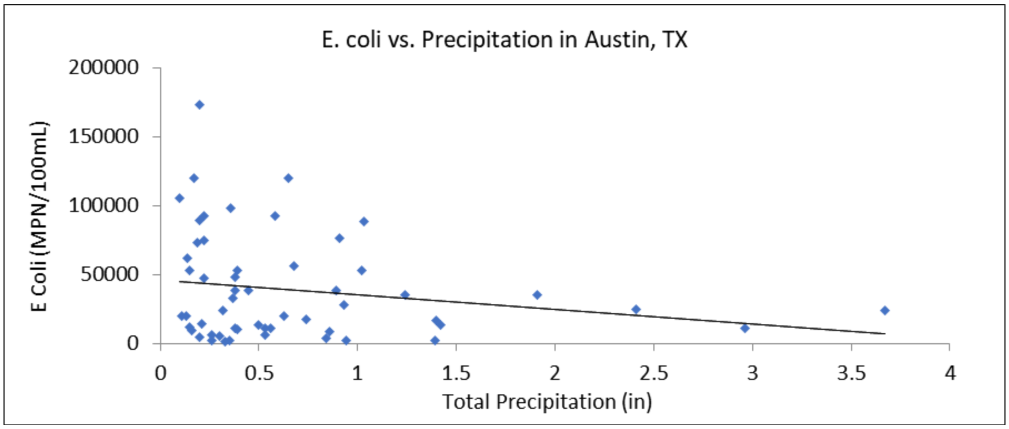

Figure 9. E. coli versus daily precipitation, 1999-2021 (n = 55, r2 = 0.039, p-value = 0.198).

***E. Coli* linear regression equation:** y = -10,700x + 46,200

Using the modeled pollutant concentration values in the two-year storm, I then calculated effluent concentrations for the four different technologies (Table 7).

Table 7. Pollutant removal efficiencies and modeled effluent pollutant concentration values.

Pollutant	Modeled Pollutant Concentration Value (2-yr storm)	Sand Filter		Detention Vault		Bioretention		Permeable Pavers	
		Removal rate	Effluent conc.	Removal rate	Effluent conc.	Removal rate	Effluent conc.	Removal rate	Effluent conc.
TSS (mg/L)	59	88%	7.3	--	59	88%	7.3	--	59
Total N (mg/L)	2.6	52%	1.3	--	2.6	52%	1.3	80%	0.5
Total P (mg/L)	0.3	75%	0.07	--	0.3	75%	0.07	80%	0.05
E. Coli (MPN/ 100ml)	40,000	80%	8,000	--	40,000	80%	8,000	--	40,000

Life Cycle Costs

The Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC) model's life cycle cost outputs are structured to provide feasibility level municipal budget estimates over time for a variety of stormwater control method construction and maintenance costs. After executing three different scenarios involving different stormwater technologies, it provided an assessment of the total cost of asset ownership facilitating comparison. These costs included initial capital costs, O&M fees, rehabilitation maintenance costs. The model's output also included associated co-benefits in the form of ecosystem services. The three scenarios modeled in the CLASIC tool consisted of green infrastructure only, grey infrastructure only, and a hybrid model including all four of the evaluated technologies.

Life cycle costs for the three scenarios are split out into three categories: construction, maintenance, and rehabilitation (Figure 10). When compared, the life cycle costs of the three approaches do not differ significantly. The average annual costs over design life are also similar overall, however the costs per category vary (Appendix B). Co-benefits for the scenarios were also scored in three categories: social, economic, and environmental (Figure 11). The breakdowns of each individual co-benefit indicator for the three categories illustrate substantial differences between the strategies (Appendix C). The model also produced a concise summary of the hydrologic data and stormwater managed throughout the watershed (Table 8).

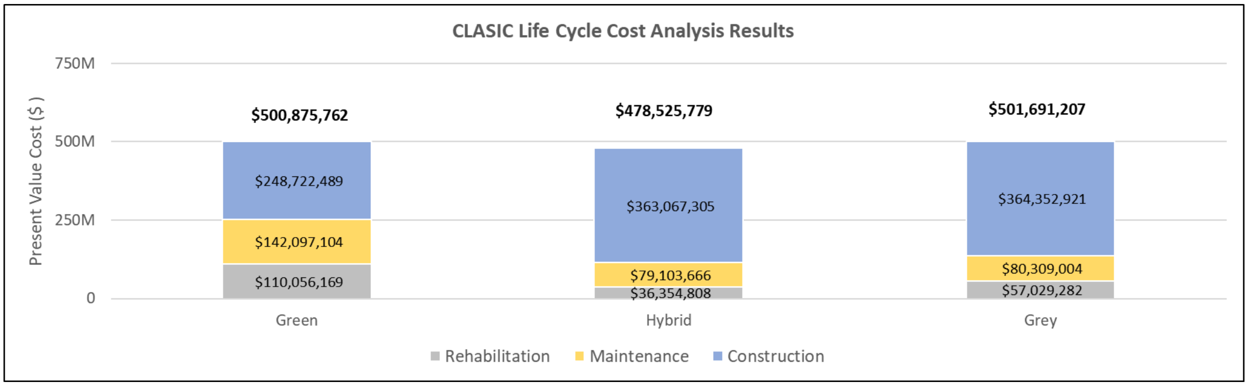

Figure 10: Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs model life cycle cost analysis results of three stormwater management scenarios.

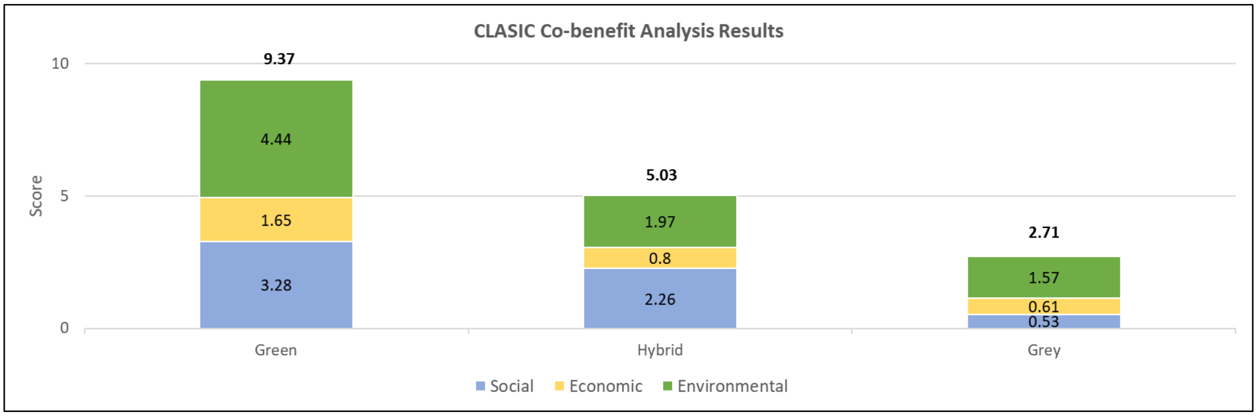

Figure 11. Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs model co-benefit analysis results of three stormwater management scenarios. Maximum possible score is 15.

Table 8. Scenario details and hydrologic data for the three stormwater management scenarios executed by the Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs model.

Result Category	Green Scenario	Hybrid Scenario	Grey Scenario
% impervious		37	
Total impervious area (hectares)		2,900	
Total area captured (hectares)	350	300	180
% impervious area captured	12	10	6
Total tech area (hectares)	80	110	8
Total volume captured (m^3)	110,000	140,000	50,000

DISCUSSION

Watershed Management Strategies

Effluent concentrations of *E. coli* and total suspended solids were significantly lower than influent concentrations when sand filters and bioretention were employed. Both features resulted in stormwater discharge levels of 8,000 MPN/100ml and 7.3 mg/L respectively. Permeable paver installations had a negligible effect on those two constituents; however, they had the greatest effect when reducing total nitrogen with an effluent of 0.5 mg/L. Additionally, pavers had the greatest impact on total phosphorus levels, although sand filters and bioretention were also effective (Table 9). Detention vaults had a negligible effect on water quality for all four pollutants. When compared against recommended water quality concentrations, permeable pavers were able to meet water quality recommendations for all constituents except *E. coli*, and consequently would be the most helpful technology to use in the Slaughter Creek Watershed.

Table 9. Effluent concentrations and water quality pollutant limits for four stormwater management technologies. Values in green meet or exceed standards.
*recommended pollutant limits. a (MPCA, 2021) b (EPA, 2001) c (TCEQ, 2018b).

Pollutant	Water Quality Limit	Sand Filter Effluent Conc.	Detention Vault Effluent Conc.	Bioretention Effluent Conc.	Permeable Pavers Effluent Conc.
TSS (mg/L)	73 to 75*[a]	7.3	59	7.3	59
Total N (mg/L)	0.28 to 0.65*[b]	1.3	2.6	1.3	0.5
Total P (mg/L)	0.038 to 0.09*[b]	0.07	0.3	0.07	0.05
E. Coli (MPN/100ml)	126[c]	8,000	40,000	8,000	40,000

Traditional Approach

The traditional stormwater management scenario used sand filters and detention vaults to control and treat runoff. This strategy scored the lowest in every co-benefits category and for all but one indicator. Regarding social indicators, these practices do nothing to address health impacts from air quality, improve mental health, or provide thermal comfort. The strategy provided some public awareness of stormwater systems and slight relief to social strain associated with nuisance flooding. It did gain a score of 3.3 out of 5 for providing economic opportunities during the features' construction and maintenance. Regarding environmental co-benefits, the scenario scored high for groundwater flow increases, but was not marked to provide any ecosystem services or carbon sequestration. Overall, the traditional infrastructure approach modeled in this scenario scored only a 2.7 out of 15 for its total co-benefits score.

Based on the uploaded 2019 NLCD, the Community-enabled Lifecycle Analysis of Stormwater Infrastructure Costs (CLASIC) model estimated 37% imperviousness throughout the watershed, with a total impervious area of 2,900 hectares. Of that, the grey scenario was only able to capture 180 hectares, which is 6% of the watershed's impervious area. The total volume of runoff captured was 50,000 cubic meters, less than half the volume the other two scenarios were able to capture. This scenario did take up significantly less space, with only 8 total hectares occupied by the various features. Most likely it is because these features are installed underground and do not take up much aboveground space besides manholes or other maintenance access points. This would make it easy to implement in areas that are already developed and where space is limited, such as shopping centers. The total cost for implementing this strategy is $502,000,000, which is the most expensive albeit only by $1,000,000, however it treats the least impervious area, and has the fewest co-benefits.

Hybrid Approach

The hybrid stormwater management scenario applied a combination of all four of the evaluated technologies across the Slaughter Creek Watershed. The social co-benefits score is higher than the grey scenario in every category and almost every indicator. Each individual indicator is scored out of 5, and the maximum total co-benefits score is up to 15. Of the available social indicators, this scenario ranked in every category besides supply from harvested stormwater, which was due to the omission of cisterns from this study. The hybrid scenario scored the highest of all evaluated scenarios, the maximum of 5, for one social indicator: providing thermal comfort. It also scored relatively high for public awareness of stormwater systems (3.5) and mental health (2.7). Although only receiving scores of 1 and 1.4, this scenario does provide some benefits for alleviating health impacts from air quality and for avoided social strain associated with nuisance flooding. The scenario scored a modest 3.2 for employment opportunity and is assigned minor economic benefits for minimizing nuisance floods and reducing costs from illness. Regarding environmental indicators, the hybrid approach also scores a high 4.9 for increasing groundwater flow. It provides minimal ecosystem services and does not aid with carbon sequestration. The hybrid scenario scored a 5 out of 15 for its total co-benefits score.

An estimated 300 hectares, or 10%, of total impervious area were captured by this scenario. The total volume of runoff captured was 140,000 cubic meters. This is more captured runoff than either of the two other scenarios. This is likely because the scenario chose smaller underground sand filters or detention vaults to capture runoff in areas with limited space where the larger aboveground practices cannot fit. The scenario is then able to capture more runoff in more open and less developed areas, by employing green infrastructure practices on a residential neighborhood scale. The technology utilized in this scenario used the most space, 110 hectares, yet cost the least at $480,000,000. This is an affordable option that allows the largest flexibility in stormwater management technologies; however, it is still relatively weak when looking at co-benefits.

Low Impact Development Approach

The low impact development, or green infrastructure, approach was modeled to include varying sizes of bioretention and installations of permeable pavers throughout the watershed of interest. This scenario scored the highest in every co-benefit category and all but one individual indicator. It scored above a 3.5 out of 5 on multiple individual indicators: providing thermal comfort, creating public awareness of stormwater, mitigating health impacts from air quality, and improving mental health. It scored a 1.5 on ability to reduce social strain associated with nuisance flooding, which was the highest score of the three scenarios. The green infrastructure scenario also achieved top scores on both employment opportunities associated with implementation and reducing costs from illness. It scored roughly the same as the hybrid approach for reducing costs from nuisance floods. Like the other two strategies, it scored very high for groundwater flow increase. Unlike the others, it was given a top score for carbon sequestration and a 3.3 for ecosystem services. The low impact development approach had an overall co-benefit score of 9.4 out of 15 which is significantly higher than the other two scenarios.

In addition to being the top model for co-benefits, the model also treated the most impervious area captured, at 12% or 350 hectares. The green infrastructure scenario captured 110,000 cubic meters of stormwater runoff, over twice the amount as the grey scenario but 30,000 cubic meters less than the hybrid scenario. This is likely due to the aboveground space requirement that can make installation difficult in highly developed areas. Despite capturing only slightly less volume than the hybrid scenario, it did utilize 30 less hectares of installed area, for a total of 80 hectares dedicated to the features. The CLASIC model's lifecycle cost analysis calculated the construction, maintenance, and rehabilitation costs to be $501,000,000. This is higher than the hybrid scenario and less than the cost of the grey scenario, however the cost differences between the three are slim. It also employs more technologies with positive water quality effects and has significantly more co-benefits associated with it. Overall, it seems as though this scenario is the most beneficial for implantation in the Slaughter Creek Watershed, although the implementation of traditional features in highly developed areas when above ground space is limited may be worthwhile.

Land Availability

Space is an important consideration and could be a limiting factor with a green infrastructure dominant approach to stormwater management. In this study, a green infrastructure approach used roughly ten times as much land within the watershed. Based on the CLASIC model results, I estimated that 1 hectare of built technology averages 1,400 cubic meters of runoff captured by GI practices and 6,300 cubic meters of runoff captured by traditional infrastructure features. However, on a watershed-wide scale green infrastructure was able to treat twice as much runoff.

It is important to account for available public space and private space to implement these practices. Based on the 2019 NLCD data, the land use intensity classifications of the various subunits in the watershed are an average of 28% “other” and 15% “developed, open space” (Figure 12). “Other” is a combination of shrub/scrub, grassland/herbaceous, and evergreen forest. “Developed, open space” is defined by the NLCD as areas with a mixture of some constructed materials, but mostly vegetation in the form of grasses. These areas commonly include large-lot single family housing, parks, golf courses, and vegetation planted for recreation, erosion control, or aesthetics. These would be the two easiest land classifications areas to implement large scale bioretention features, as many parks are publicly-owned and privately-owned ranches may be easily persuaded to dedicate portions of their land to stormwater management.

Single-family housing units comprise both the “developed, low intensity” and “developed, medium intensity” classification areas which together comprise 49% of the watershed. These are also good areas to target with incentivized or city subsidized programs for neighborhood scale green infrastructure features. If results from the city of Austin’s Rain Catcher Pilot Program in north Austin can be recreated, then approximately half of the homeowners might be interested in participating. As the model only required 80 hectares to be dedicated to the features, this should be achievable out of the watershed’s total 8,000 hectares.

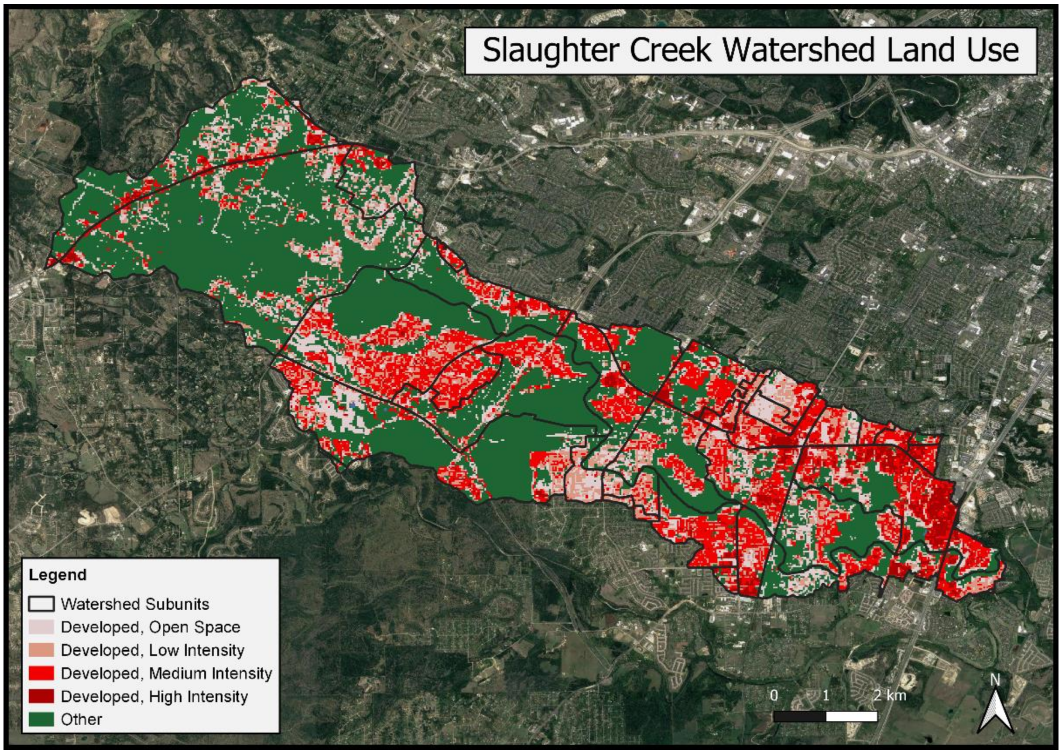

Figure 12. Land Use Intensity Classifications for the Slaughter Creek Watershed based off 2019 NLCD data from the Multi-Resolution Land Characteristics Consortium.

Study Limitations

I acquired the historical water quality data for untreated stormwater from a monitoring location in central Austin. Although the watershed is considered representative, this could result in slightly different pollutant concentration values than if water quality data was gathered directly from the Slaughter Creek Watershed's runoff. There was not a reliable, complete dataset available for a monitoring location along Slaughter Creek. The historical precipitation data I used in this model may also not be the most accurate, as they do not account for hydrologic non-stationarity. Storms are not the same as they have been in the past due to climate change, which leads to an element of uncertainty (Bayazit, 2015). The calculated two-year storm event precipitation amount may not be representative of the two-year storm event over the 30-year lifetime of the proposed stormwater management features. This could result in higher pollutant levels and runoff volumes than accounted for in this study. It is also crucial for green infrastructure features to be installed properly and protected from sediment runoff during the construction phase. If they are not, they may not perform as designed for water quality treatment or volume reduction.

The CLASIC program I used to model the various stormwater management scenarios was only able to integrate 2016 national land cover data. There was not a way to upload the most recent 2019 version of the data, so I extrapolated land use intensity and impervious cover percentages in QGIS. Consequently, percentages may not be as accurate as if interpreted directly by the program. The CLASIC model also does not factor in obtaining funding for subsidies or acquiring citizen approval for use of private property before installing the prescribed stormwater features. This could result in the three scenarios capturing less stormwater volume than the model stated.

CONCLUSION

Water quality benefits for effluent runoff were higher overall when the green infrastructure stormwater management features were used. The pollutants of concern for the Slaughter Creek Watershed would also be best addressed by permeable pavers, one of the GI technologies focused on in this case study. Modeled life cycle costs were lowest for the hybrid model, which utilized both green and grey infrastructure features throughout the watershed. However, there was not a large difference among the costs of the three scenarios. Treated stormwater runoff volumes were also largest for the hybrid scenario, closely followed by the green infrastructure scenario. Co-benefits were significantly highest for the green infrastructure model. As a result, the information in this study appears to indicate that the Slaughter Creek Watershed will benefit most from a revised hybrid approach. This approach will feature primarily green infrastructure practices where feasible, yet also incorporate traditional features where more practicable.

Additional data on land use available for green infrastructure implementation and funding sources will increase the feasibility of this watershed management strategy. The information in this case study helps municipal entities better understand the benefits and drawbacks of the three main stormwater management strategies available. These findings can be used to minimize localized flooding, while also improving water quality, recreational opportunities, and protecting the ecosystems within the Slaughter Creek Watershed. It is critical to address stormwater management due to the increasingly frequent extreme rain events in Texas resulting from climate change.

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APPENDICES

APPENDIX A

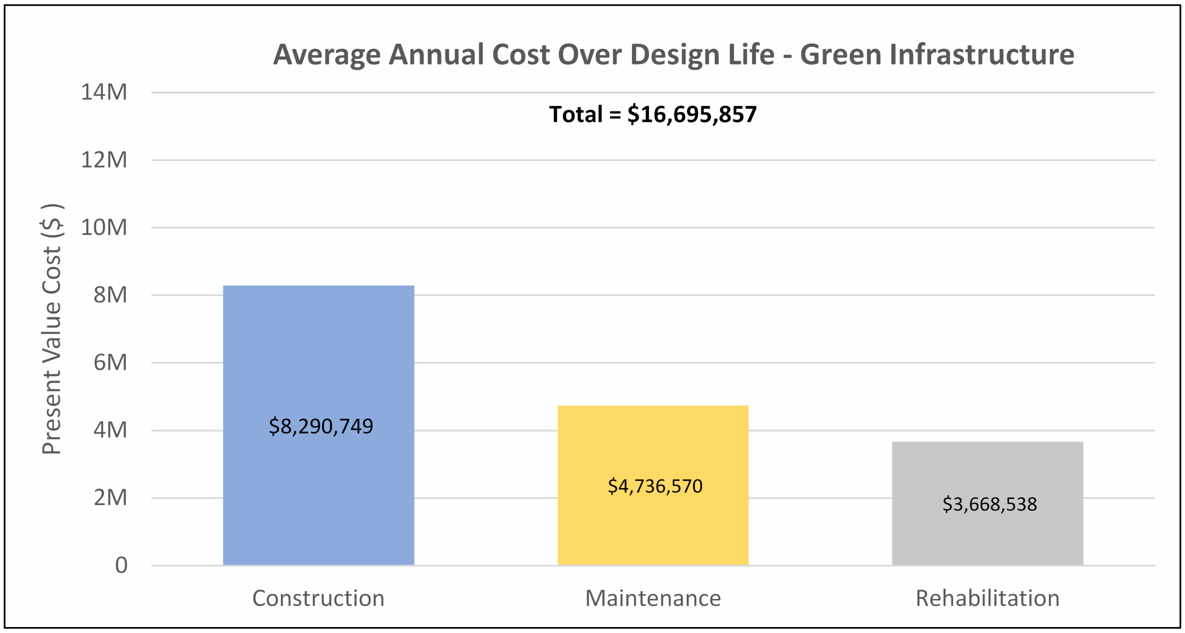
UNTREATED STORM WATER QUALITY DATA

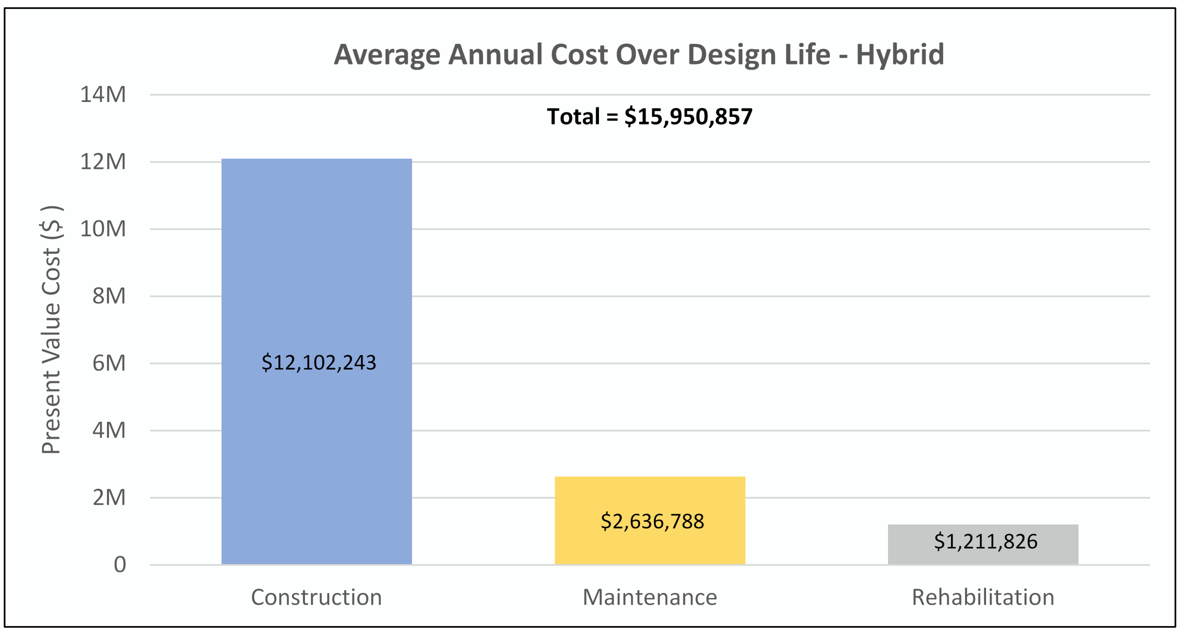
Sample Date	Parameter *TSS (mg/l)*	*Total N (mg/l)*	*Total P (mg/l)*	*Fecal Coliform/ E-Coli (MPN/100ml)*	*Precipitation (in.)*
10/1/99	133.0	10.12	1.18	20,000	0
1/27/00	64.0	4.53	0.529	76,000	0.91
4/12/00	74.0	2.21	0.296	53,000	0.39
9/13/00	110.0	4.07	0.703	20,000	0.63
10/7/00	44.0	3.2	0.468	23,600	0.32
3/8/01	128.0	3.9	0.492	11,500	0.15
5/26/01	24.0	2.1	0.188	53,000	0.15
9/21/01	14.0	1.3	0.139	34,850	0.03
11/28/01	95.0	1.54	0.21	34,850	1.91
6/16/02	43.0	2.84	0.33	16,700	1.4
8/8/02	31.0	4.58	0.29	20,000	0.11
10/9/02	40.0	2.71	0.43	17,750	0.74
12/16/02	26.0	2.56	0.26	15,500	0
7/8/03	73.0	4.39	0.4	38,400	0.45
12/12/03	34.0	2.66	0.26	10,500	0.39
2/4/04	146.0	4.37	0.39	2,200	0.94
6/8/04	38.0	1.92	0.23	2,000	1.39
8/11/04	506.0	9.26	0.963	2,200	0.26
3/16/05	73.0	1.03	0.155	8,300	0.07
8/3/05	122.0	3.41	0.48	144,000	0
11/26/05	464.0	3.54	0.728	1,300	0.33
3/19/06	13.0	3.54	0.182	11,300	0.53
5/19/06	22.0	2.65	0.247	3,040	0
9/12/06	-	-	-	22,000	0
10/10/06	256.0	5.86	0.732	13,700	1.42
1/3/07	100.0	0.72	0.177	3,600	0.84
4/30/07	39.0	1.45	0.236	89,000	0.2
8/16/07	110.0	2.26	0.419	38,000	0.89
10/22/07	18.0	2.01	0.3	53,000	1.02
3/6/08	-	-	-	14,000	0.21
4/4/08	70.0	2.71	0.423	62,000	0.14
7/24/08	20.0	3.75	0.65	5,100	0.3
10/15/08	20.0	3.59	0.336	88,000	1.03
1/27/09	37.0	3.71	0.385	19,500	0.05
4/17/09	70.3	1.51	0.217	35,000	1.24
9/10/09	35.7	2.82	0.364	47,000	0.22

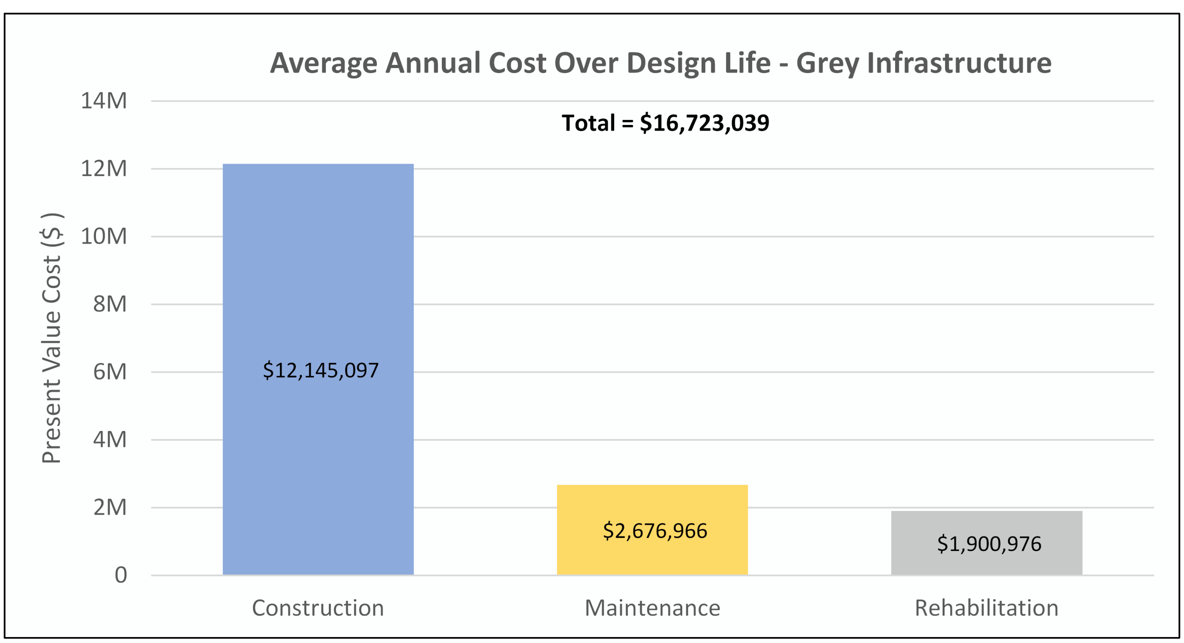
Sample Date	Parameter *TSS (mg/l)*	*Total N (mg/l)*	*Total P (mg/l)*	*Fecal Coliform/ E-Coli (MPN/100ml)*	*Precipitation (in.)*
12/17/09	74.4	0.89	0.166	13,500	0.5
2/3/10	33.6	0.9	0.112	8,550	0.86
5/14/10	50.7	4.68	0.335	75,000	0.22
7/8/10	16.0	1.62	0.136	27,600	0.93
2/24/11	45.7	3.18	0.173	20,000	0.06
5/12/11	120.0	3.51	0.473	11,200	2.96
11/15/11	54.3	1.91	0.312	56,000	0.68
2/17/12	55.9	2.41	0.133	6,130	0.53
9/13/12	48.0	5.78	0.560	38,700	0.38
3/8/13	29.7	4.32	0.322	9,210	0.16
4/18/13	16.0	3.19	0.256	98,000	0.36
11/4/13	30.0	4.81	0.365	81,600	0.04
4/14/14	44.0	2.98	0.313	9,460	0
11/4/14	19.6	1.57	0.141	11,000	0.56
2/3/15	6.7	0.815	0.0694	5,790	0.26
5/28/15	128.0	1.3	0.198	173,000	0.2
8/20/15	9.8	2.46	0.188	>2420	0.35
10/22/15	54.5	9.53	0.974	19,900	0.13
3/8/16	123.0	3.92	0.384	92,100	0.22
8/29/16	33.4	1.72	0.317	81,600	0.06
9/23/16	58.5	1.3	0.55	18,700	0.03
1/13/17	67.3	1.26	0.241	120,000	0.65
3/24/17	349	1.54	0.318	43,500	0.05
8/7/17	60.2	0.84	0.288	25,000	2.41
2/20/18	32.8	2.12	0.065	4,720	0.2
5/4/18	53	1.23	0.177	>24200	3.67
6/19/18	27.8	2.22	0.309	>48,400	0.38
2/19/19	67	4.93	0.281	120000	0.17
3/13/19	121	2.02	0.239	579000	0.34
6/24/19	93	1.69	0.136	11200	0.38
11/14/19	53	1.38	0.23	105000	0.1
12/10/19	50	1.87	0.259	32,600	0.37
4/9/20	45.00	2.65	0.241	72,700	0.19
6/23/20	34.0	0.7	0.1	92,100	0.58
9/3/20	92	1.86	0.197	387,000	1.43
4/23/21	152	4.03	0.467	>242,000	0.83

APPENDIX B

CLASIC OUTPUT: AVERAGE ANNUAL COST OVER DESIGN LIFE


Average Annual Cost Over Design Life - Green Infrastructure
Total = $16,695,857
Present Value Cost ($)
14M
12M
10M
8M
6M
4M
2M
0
$8,290,749
$4,736,570
$3,668,538
Construction
Maintenance
Rehabilitation


Average Annual Cost Over Design Life - Hybrid
Total = $15,950,857
Present Value Cost ($)
14M
12M
10M
8M
6M
4M
2M
0
$12,102,243
$2,636,788
$1,211,826
Construction
Maintenance
Rehabilitation

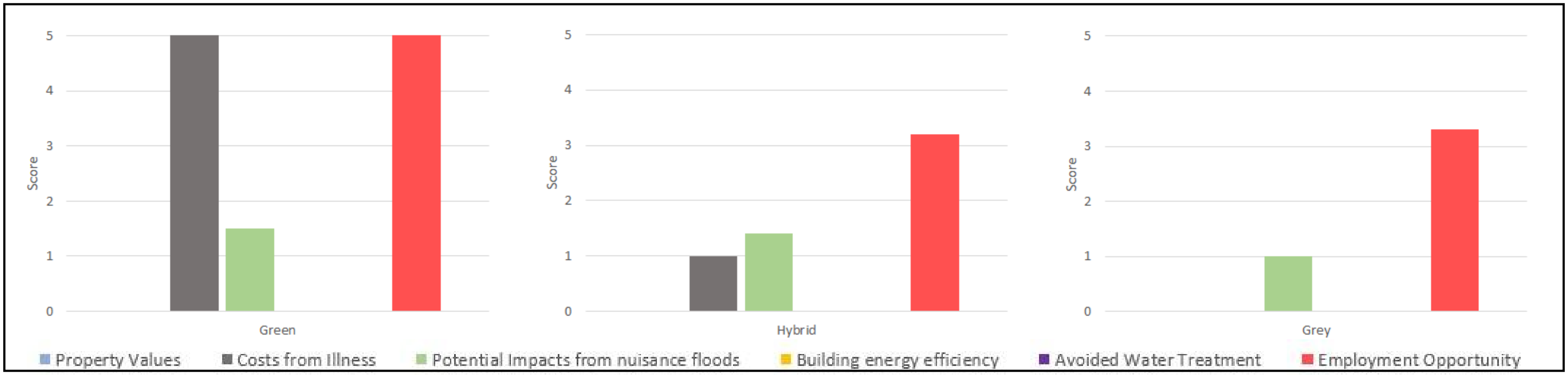

Average Annual Cost Over Design Life - Grey Infrastructure
Total = $16,723,039
Present Value Cost ($)
14M
12M
10M
8M
6M
4M
2M
0
$12,145,097
$2,676,966
$1,900,976
Construction
Maintenance
Rehabilitation

APPENDIX C

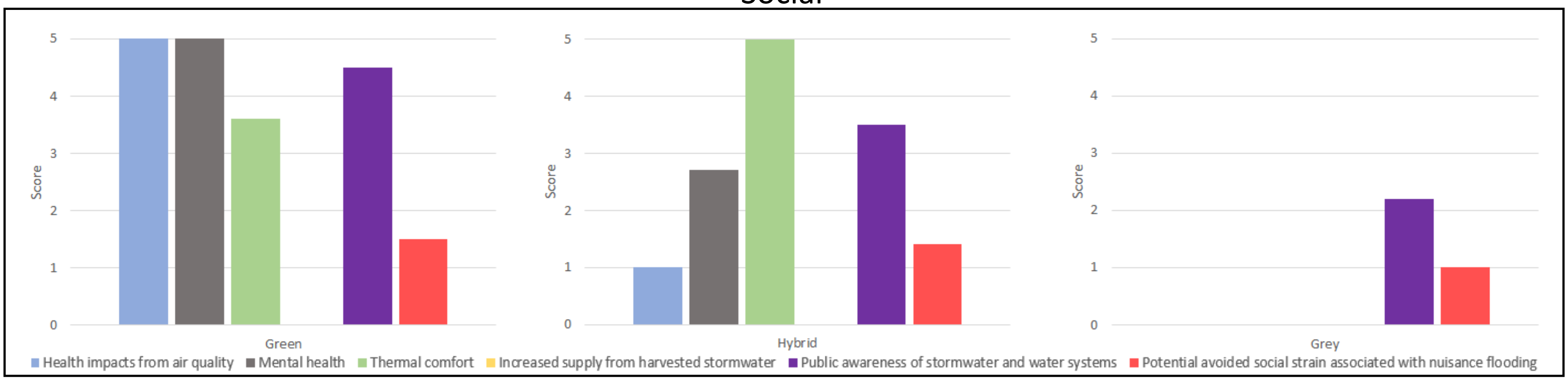
CLASIC OUTPUT: CO-BENEFIT INDICATORS SCENARIO RESULTS

Score for individual indicators in Environmental, Economic, and Social Categories (Maximum is 5*)

Economic



Social



Environmental