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Green Stormwater Infrastructure Assessments in Santa Clara County, CA: An In-Situ Analysis of Select Bioretention Projects

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GREEN STORMWATER INFRASTRUCTURE ASSESSMENTS IN SANTA CLARA COUNTY, CA: AN IN-SITU ANALYSIS OF SELECT BIORETENTION PROJECTS

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Laura M. Bates
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GREEN STORMWATER INFRASTRUCTURE ASSESSMENTS IN SANTA CLARA COUNTY, CA: AN IN-SITU ANALYSIS OF SELECT BIORETENTION PROJECTS

by

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APPROVED FOR THE DEPARTMENT OF ENVIRONMENTAL STUDIES

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May, 2019

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ABSTRACT

GREEN STORMWATER INFRASTRUCTURE ASSESSMENTS IN SANTA CLARA COUNTY, CA: AN IN-SITU ANALYSIS OF SELECT BIORETENTION PROJECTS

by Laura M. Bates

Stormwater runoff, defined as rainwater that flows over impervious surfaces, is both an under-harnessed groundwater resource and the leading contributor to water body impairments due to the number of pollutants it can transport. One widely successful strategy to capture and treat stormwater runoff is to implement Green Stormwater Infrastructure (GSI): engineered green spaces to enhance the overall environmental quality of an urban landscape. GSI projects, particularly bioretention systems, capture and treat stormwater runoff through infiltration and plant absorption before it reaches receiving bodies of water. In order to operate efficiently, GSI systems require specific maintenance procedures. The purpose of this study is to evaluate the performance and maintenance processes of approximately fifty bioretention areas in Santa Clara County. The bioretention areas in this study were evaluated by observing current site conditions and measuring infiltration rates, as well as conducting interviews of municipal and facilities staff to determine the processes and challenges for GSI design, inspection, and maintenance. The results of this study showed that 26% of sites fell within the acceptable range of 5 to 10 inches per hour. Additionally, larger site designs and California native perennial bunch grasses were positively associated with acceptable infiltration rates. This research will help contribute to future GSI design and maintenance considerations for local municipal and facilities staff, such as the use of larger bioretention ponds over smaller designs, and planting more bunch grass vegetation.

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LIST OF ABBREVIATIONS

C.3 – Provision C.3 New Development and Redevelopment of the MRP

CWA – Clean Water Act

GSI – Green Stormwater Infrastructure

MRP – Municipal Regional Stormwater Permit

NPDES – National Pollutant Discharge Elimination System

SCVURPPP – Santa Clara Valley Urban Runoff Pollution Prevention Program

SFEI – San Francisco Estuary Institute

SFPUC – San Francisco Public Utilities Commission

SWRCB – State Water Resources Control Board

US EPA – United States Environmental Protection Agency

Introduction

Stormwater runoff, which is considered rainfall that runs off impervious surfaces after rainfall or snowmelt events (Minnesota Pollution Control Agency, 2017), collects numerous pollutants including car oils, fertilizers, and heavy metals, depositing them into vital ecosystems that support aquatic and riparian habits, as well as urban landscapes (SCVURPPP, 2012). Often, including in Santa Clara County, California, this stormwater runoff is not treated prior to being discharged into receiving waters (Bicknell et al., 2016). Dr. John Snow, considered one of the founding fathers of epidemiology, proved that water was a vector for the spread of the major 1850's cholera outbreak in Soho, London when he discovered that the source of the cholera bacteria was in a municipal well (Johnson, 2006). Since 1948, over half of documented waterborne disease outbreaks, such as cholera and *giardia*, have been linked to post-rainfall events in the United States (Gaffield et al., 2003). Southern Californian surfers, for example, have experienced illnesses while being exposed to near-shore seawater following major rain events (Arnold et al., 2017). Stormwater runoff is recognized as one of the major threats to water quality in the United States (Coutts and Hahn, 2015; Gaffield et al., 2003; US EPA, 2017). The lack of vegetated landscape barriers in urban environments aids the spread of diseases in human, domestic animal, and wildlife populations (Coutts and Hahn, 2015). Additionally, stormwater runoff is an often under-harnessed resource, with the potential to generate 0.6 billion gallons of water with one inch of rain over an 800 square kilometer area comprised of seventy percent impervious surfaces (Lozefski et al., 2017). It is highly beneficial for a society to implement an effective integrated strategy to protect public and environmental health. One common and widely successful strategy to treat stormwater runoff is to implement Green Stormwater Infrastructure into urban landscapes.

Green Stormwater Infrastructure (GSI) is a term to describe engineered systems that mimic natural processes to provide ecosystem services and to enhance the overall environmental quality of an urban landscape (Lozefski et al., 2017; US EPA, 2017; US EPA, 2011; Vermont Agency of Natural Resources, 2018). GSI uses sustainable, best management practices to manage stormwater, including treatment, storage, and flood protection (US EPA, 2017). Examples of this type of infrastructure include bioretention areas (also called bioswales), rain gardens, pervious pavements, and green roofs (California Department of Public Health, 2012; Schultze-Allen, 2015). According to Lindholm (2017), GSI is often defined as an interconnected network of green space infrastructure that conserves natural ecosystem values and functions and provides associated benefits to human populations (Benedict and McMahon, 2001; Coutts and Hahn, 2015; Lindholm, 2017). Some of the social benefits of GSI include improvements in physical activity and health, improving mental health, and encouraging a positive, active and inclusive community (Lozefski et al., 2017; Molla, 2015). While the term Green Stormwater Infrastructure is relatively new, starting in the mid-1990s as “green structure” (Lindholm, 2017), its concepts date back to approximately 150 years ago to link separate green structures as one large ecosystem, rather than having isolated parks within an urban landscape (Benedict & McMahon, 2001). As global populations increase, urban sprawl impedes on existing ecosystems, which negatively affects critical ecosystem services resulting in an unsustainable environment (Artmann, Bastian & Grunewald, 2017).

Bioretention areas, a component of GSI (also referred to as bioswales or bioretention ponds), are vegetated depressions that capture and treat stormwater runoff from impervious surfaces (Cahill et al., 2013; Schultze-Allen, 2015; US EPA, 2017). Stormwater runoff flows into bioretention areas, where vegetation and engineered soil media filters and absorbs pollutants in the runoff before it is diverted into a storm drain or infiltrated into the groundwater aquifer (Cahill et al., 2013). This technique was developed in 1992 by the Department of Environmental Resources, Prince George's County, Maryland (Guo, 2013). Many municipalities are implementing GSI practices in their new development plans. The Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP), an association of fifteen agencies in the Santa Clara Valley, helps local agencies manage stormwater discharge into the South San Francisco Bay, and comply with the Municipal Regional Stormwater permit (MRP) requirements that new development and redevelopment projects implement GSI in their project designs (SCVURPPP, 2012).

Problem Statement

Humans depend on various ecosystem services to have a better quality of life, such as clean air, water, and exposure to nature. GSI in urban environments helps to provide some of these necessary ecosystem services with vegetation transpiration, stormwater treatment, flood control, increased pedestrian safety, and aesthetic appearances (Artmann, Bastian & Grunewald, 2017; Lozefski et al., 2017). In order to operate efficiently, GSI systems need to be inspected and maintained on a regular basis (City and County of Denver, 2015). Bioretention systems may not be maintained properly in the South San Francisco Bay Area to ensure maximum effectiveness, as there could be evidence of trash, erosion, and structural integrity or design concerns.

Implementing and inspecting GSI with development is a requirement in Santa Clara County under MRP provision C.3; however, GSI systems such as bioretention areas (bioswales), rain gardens and pervious pavements are very expensive to design, construct and maintain. Despite challenges associated with bioretention area designs, costs and long-term maintenance, these vegetated depressions can help protect local waterways by treating stormwater runoff (City and County of Denver, 2015; Xiao, 2011). In addition, bioretention areas provide a myriad of social, environmental, and health benefits to society (US EPA, 2011), and it is important to ensure that the cost of implementing and maintaining bioswales is met with the benefits they could potentially provide. Research indicates that frequent inspection and long-term maintenance would benefit bioretention area functioning (City and County of Denver, 2015; Schweitzer, 2013). Municipalities that are part of SCVURPPP implement an inspection process and enforce maintenance requirements under the C.3 Stormwater Permit provision, although some cities will have stricter regulations and policies regarding GSI maintenance (SCVURPPP, 2012). For example, under the permit, it is required that all bioretention systems be inspected every five years, but some cities inspect structures in their jurisdiction every year due to either the abundance of GSI systems or available finances and personnel to conduct the inspections (Municipal Staff 1, 2018; Municipal Staff 3, 2018; Municipal Staff 6, 2018; SCVURPPP, 2012). Despite extensive and frequent inspections in the first few years of implementation, there is no evidence of long-term effectiveness of bioretention systems in Santa Clara County, and observations may not be followed up with evaluations of overall improvements.

Municipal stormwater management guides and reports outline specific design and maintenance parameters to ensure GSI effectiveness, such as one field guide from the Oregon State University Stormwater Solutions, which details what bioswales should look like when conducting inspections (Cahill et al., 2013). This guide mentions field inspection criteria that can affect bioretention performance, such as evidence of erosion, trash, sediment buildup, and dead vegetation (Cahill et al., 2013). The State of Oregon Department of Environmental Quality has a guidance that includes specific design parameters and bioswale performance expectations such as sizing, grading, water velocity and flow volume (Jurries, 2003). While these design parameters are useful for developers, there is missing information for maintenance staff on how to properly maintain bioswales to ensure that these performance expectations are met. There is not a lot of communicated information about how these GSI structures are performing years after they have been implemented. For example, since some of these GSI designs are aging, it would be useful to know when the soil media would need to be replaced or cleaned out to get rid of accumulated sediment and heavy metals. Each municipality within SCVURPPP's jurisdiction conducts their own inspection and maintenance processes, and there is not any knowledge of which processes are most effective and why. Perhaps a higher priority is placed on the construction and immediate performance of GSI structures, as municipalities are required under the MRP to meet long-term inspection requirements. There also may be concerns regarding responsible parties' knowledge of how to properly maintain their GSI structures over time, and disconnects between initial developers and current owners, or on the knowledge of inspectors and maintenance staff of GSI purposes and functions.

The purposes of this study are to evaluate Santa Clara County bioretention systems, with an observational study to determine their effectiveness in capturing and filtering stormwater runoff, and to compare and contrast observation results between each city to determine the value of the inspection process. Inspection processes will be documented from the GSI project site approval to the ongoing operations and maintenance procedures. Infiltration rates will be documented, because soil infiltration is one of the main factors affecting the performance of a bioretention area (Kazemi, 2014; Minnesota Pollution Control Agency, 2017), and ensuring appropriate drainage of a bioretention area is a necessary component of a GSI project (US EPA, 2011). The objective is to evaluate site conditions and infiltration rates, determine conclusions in different inspection processes based on overall site conditions, and evaluate which inspection criteria has the greatest correlation to the stormwater runoff's ability to flow or infiltrate into the site.

Previous research has proven the effectiveness of GSI in reducing stormwater runoff volume, reducing pollutant concentrations, and enhancing urban communities (Bachmann, 2007; Chen, 2014; David et al., 2011; Schweitzer, 2013; Xiao, 2011; Yang et al., 2013). GSI design considerations can vary depending on geographic regions, but they consist of the same basic components with system shape, inlet and outlet structures, and underdrain systems. Many studies have evaluated GSI performance shortly following their construction or in comparison to control systems (David et al., 2011; McKee & Gilbreath, 2016; Xiao, 2011), however only a few studies evaluate the infiltration rate and long-term performance of GSI systems (Kazemi, 2014; Lozefski et al., 2013). Only one study assessing GSI performance has been conducted in the San Francisco Bay Area (David et al., 2011), but no other studies have been conducted in Santa Clara County. Since different geographic regions in the United States, and even within the San Francisco Bay Area, have different climates or stormwater management policies, it would be important to accumulate further research that assesses GSI performance in different regions to optimize their design and local maintenance practices.

Related Research

Green Stormwater Infrastructure

As rainfall pours over the urban landscape, pattering on rooftops, creating a wet sheet across pavements, it flows directly into hydrologically engineering storm sewer systems through gutters in the streets, and eventually flows into creeks and the San Francisco Bay. This water runoff, also known as stormwater, collects various pollutants on its journey to the sea, including but not limited to: car oil, dirt, pet waste, trash, heavy metals, PCBs, pesticides, and fertilizers (State Water Resources Control Board, 2017). Stormwater is often not treated for these harmful pollutants before it reaches its final destination, nor is it likely being used as a vital water resource in California (SCVURPPP, 2012). Stormwater greatly raises the need for water pollution control efforts, as it is the leading contributor to water quality impairment in nationwide water bodies (National Research Council, 2008), and is heavily linked to waterborne diseases such as *Giardia* and *Cryptosporidium* (Gaffield et al., 2003). To address these water quality concerns, the United States Congress, under amendments to the Clean Water Act (CWA) in 1987, mandated the U.S. Environmental Protection Agency (EPA) to manage and monitor stormwater discharges under the National Pollutant Discharge Elimination System (NPDES) (National Research Council, 2008). Under the CWA and the Porter Cologne Act, cities in California are now required to obtain permits before they can discharge runoff from storm drains to receiving waters (SWRCB, 2017). The San Francisco Bay Area in particular is under the jurisdiction of the Municipal Regional Stormwater Permit (MRP), which seeks to prevent stormwater pollutants from entering into the Bay

(SWRCB, 2017). The MRP requires, as of 2012, that for all new development in the Bay Area cities, Green Stormwater Infrastructure (GSI) designs must be implemented for every new or redeveloped ten thousand square feet of impervious surfaces and five thousand square feet of impervious surfaces for parking lots, restaurants and gas stations (SWRCB, 2017). The southern part of the Bay Area, known as the South Bay and within Santa Clara County, is part of the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP), which includes 13 municipalities, including the cities of Campbell, Cupertino, Los Altos, Los Altos Hills, Los Gatos, Milpitas, Monte Sereno, Mountain View, Palo Alto, San Jose, Santa Clara, Saratoga, and Sunnyvale, as well as the County of Santa Clara and the Santa Clara Valley Water District (SCVURPPP, 2012). These municipal agencies are managing stormwater discharge into the South San Francisco Bay, and are requiring the implementation of GSI in new development and more recently, working to also retrofit GSI in the Public Right of Way.

GSI is a term used to describe an array of products, technologies, and practices that use natural systems - or engineered systems that mimic natural processes - to enhance overall environmental quality and provide utility services (Lozefski et al., 2017; US EPA, 2017; US EPA, 2011; Vermont Agency of Natural Resources, 2018). GSI techniques use soils and vegetation for the infiltration, evapotranspiration, and/or recycling of stormwater runoff (Schultze-Allen, 2015; US EPA, 2017). Modern day discussions of GSI began in the mid-1990s, and continue to incorporate integration between natural ecosystems and the urban environment for human benefits (Lindholm, 2017). The term “GSI” was at one point interchangeable with the term “Low Impact Development (LID)”, but with recent broadening of stormwater management, they are now used as separate distinct terms (Vermont Agency of Natural Resources, 2018). LID refers to land planning and site design that tries to prevent or minimize environmental degradation, whereas GSI refers to the physical elements of the landscape when addressing or minimizing impacts from stormwater runoff (Vermont Agency of Natural Resources, 2018). Strategic placement of various GSI structures, such as bioretention areas (bioswales) and rain gardens, throughout the urban landscape allows for natural ecosystem connections and effective stormwater management practices.

Green spaces, such as parks and open spaces, improve the overall environmental quality of a landscape by connecting ecosystems rather than isolating them (Benedict and McMahon, 2001; Coutts and Hahn, 2015; Lindholm, 2017). GSI mimics connecting concepts of these green spaces in urban environments on a smaller scale, such as a small rain garden or tree landscaping. Some economic benefits of GSI include improving a region's image, attracting high-value industries, fostering environmentally friendly living and working environments, creating jobs, reducing property costs by reducing flooding events, and by reducing operational costs regarding energy and gas (Molla, 2015). Aside from the myriad of social and health benefits, GSI can also restore vital environmental ecosystems (Artmann, Bastian & Grunewald, 2017; Coutts & Hahn, 2015), and help to effectively manage stormwater runoff. An example of an engineered mini-ecosystem for stormwater management would be bioretention systems, including bioretention areas.

Bioretention System Components

Bioretention areas assist in the filtration of stormwater pollutants by capturing and treating stormwater runoff in urban landscapes (Cahill et al., 2013; Guo, 2013). The dense vegetation and engineered soil media in the bioretention area are used to absorb and filter harmful pollutants and heavy metals that would otherwise be transported directly into the San Francisco Bay (SWRCB, 2017). Figure 1 shows a basic diagram of a bioretention area and its components. Stormwater runoff can flow into the bioretention system through overflow from the surface or through channel systems that run off of rooftops.

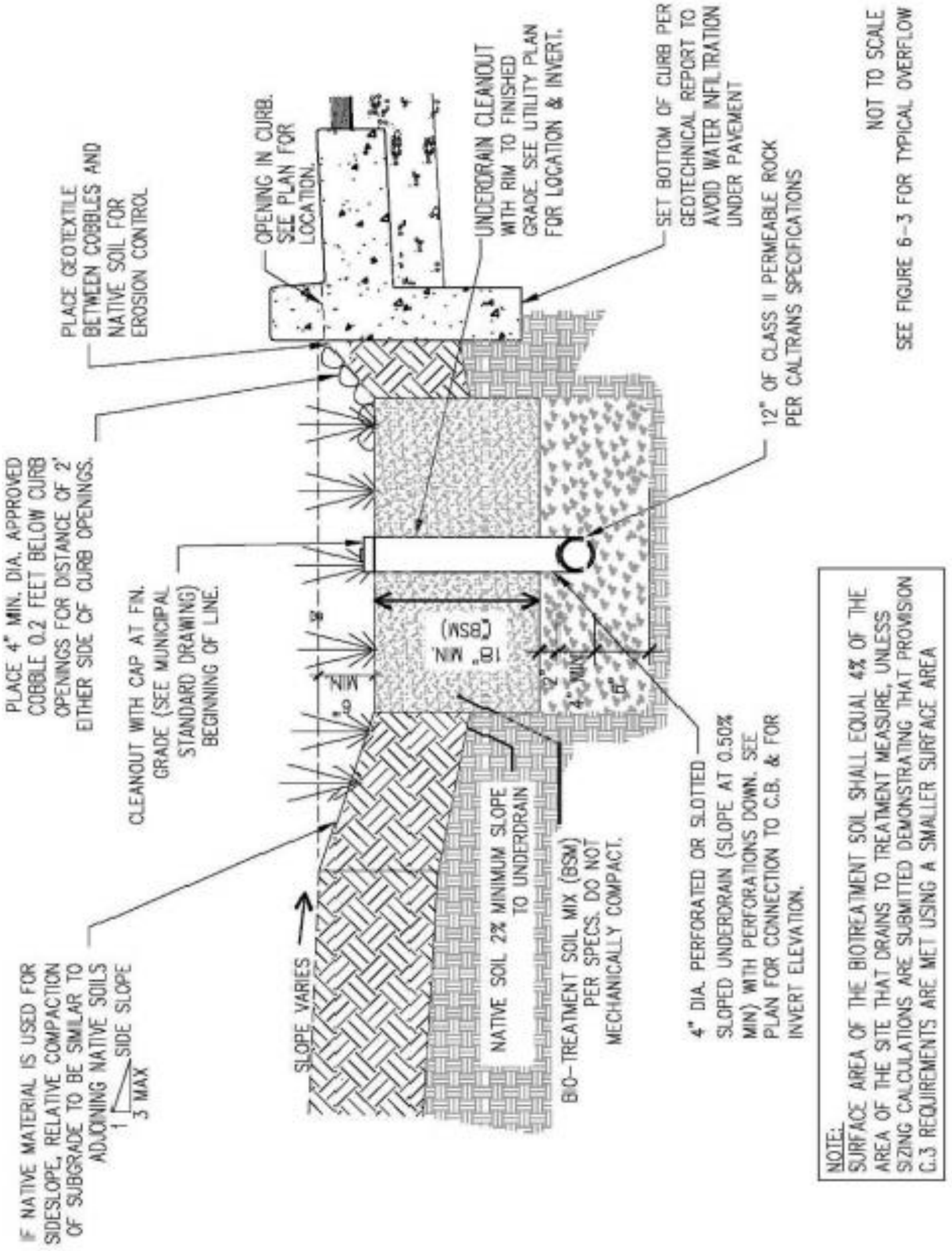

Figure 1. Bioretention area cross section, with design specifications for plant and soil usage (Bicknell et al., 2016).

The bioretention area structure has a bed of various soil media that holds generally larger, drought tolerant plants on the middle and outer or highest zones, and smaller and more flood tolerant plants in the middle to lowest zone, as this is where stormwater runoff will temporarily pond during a rain event (Philadelphia Water, 2015). Underdrain systems can be used to collect and drain filtered stormwater runoff from beneath the bioretention media (City and County of Denver, 2015) and redirect it to the storm drainage system. Bioretention systems consist of multiple different smaller-scale GSI structures, such as rain gardens and bioswales. Rain gardens are densely vegetated landscapes that are designed to absorb stormwater runoff to reduce runoff loads on urban storm sewer systems (StormTech, 2016; US EPA, 2017). Benefits of rain gardens include bioretention, pollutant removal, groundwater recharge, prevention of standing water, efficient land use, preservation of the pre-development hydrologic cycle, and aesthetics (StormTech, 2016). Figure 2 shows an example of a rain garden in Elk Grove, California.

Figure 2. Rain garden in Elk Grove, California (Zane, 2015). Reprinted with permission.

Bioswales are smaller versions of bioretention areas that are designed to filter heavy metals, harmful nutrients and pollution from stormwater runoff (Natural Resources Conservation Service, 2005). Figure 3 below shows an image of a typical bioswale in California. Maintenance of bioretention systems includes weeding and watering as the basin vegetation grows, removing trash and dead plant materials, and conducting regular inspections and cleaning of overflow structures (StormTech, 2016). Design considerations for bioretention systems include soil infiltration rate, proximity to buildings, and the use of native, drought-tolerant plants (StormTech, 2016).

Figure 3. Bioswale along a city street in California (Mackie, 2017). Reprinted with permission.

Collectively, bioretention systems have effectively trapped, filtered, and treated stormwater runoff nationwide, including California (Cahill et al., 2013; Guo, 2013; SWRCB, 2017). For more information on the benefits of GSI, see Appendix D.

The use of GSI practices in California, particularly in the Bay Area, is relatively new, with the oldest projects having been established within the last fifteen years (SCVURPPP, 2017). SCVURPPP uses existing GSI projects in other cities such as Seattle, New York, Portland, Philadelphia, and Washington D.C., as models for projects and maintenance processes within the local South San Francisco Bay Area (SCVURPPP, 2017). Unlike these other cities, which have wet or cooler climates, California has a semi-arid Mediterranean climate, which may affect how GSI projects are designed and maintained in California versus other regions over time. While there are many local and nationwide case studies which prove bioretention effectiveness through water quality monitoring and testing after implementation (Bachmann, 2007; Chen, 2014; David et al., 2011; McKee and Gilbreath, 2016; Schweitzer, 2013; Xiao, 2009; Yang et al., 2013), there is not much empirical evidence suggesting that GSI projects are effective in the long term in California, as many of these systems are fairly new. Two notable studies, however, have evaluated the long-term performance of GSI structures by assessing infiltration rates in Louisville, Kentucky (Kazemi, 2014) and New York City, New York (Lozefski et al., 2017).

Long-Term GSI Performance Studies

In New York's Jamaica Bay watershed, researchers investigated the variability of infiltration rates of stormwater within about a dozen GSI bioretention sites, and compared their values to data collected since 2011 for trends (Lozefski et al., 2017). Infiltration rate is identified as a critical indicator of the potential stormwater capturing efficiency of a bioretention system, and its parameters in this study include soil texture, soil compaction, vegetation health and type, and correct applications of topsoil (Lozefski et al., 2017). Results of this study concluded a high variability in infiltration rates among different sites at different locations, and infiltration rates remained the same order of magnitude after five years since the completion of the bioretention construction (Lozefski et al., 2017). While the infiltration rates had high variability, the study recommended further infiltration rate testing at a larger number of sites over a longer time period, and there was no clear evidence to explain the high variability (Lozefski et al., 2017).

Another study, conducted in Louisville, Kentucky, evaluated the hydrological performance, which included infiltration rate, of two permeable pavement systems over a two-year study period (Kazemi, 2014). Infiltration rate was observed to be the key indicator of the permeable pavement system's hydrological performance, and the system's infiltration capacity was limited by clogging formed on the surface over time (Kazemi, 2014), which suggests a need for better long-term maintenance treatment. About 2.6 million gallons of overflow volumes were eliminated from the combined sewer system during the second half of the study, and the tests that were completed both before and after routine maintenance treatment showed an increase in runoff volume reduction post-maintenance (Kazemi, 2014). This study also concluded that infiltration rates in the permeable pavement system were greatly affected by rainfall intensities (Kazemi, 2014).

Long-term maintenance processes are critical to maintain GSI performance (City and County of Denver, 2015; Kazemi, 2014; Minnesota Pollution Control Agency, 2017). Many variables, however, including the specific design and implementation of the GSI structure (StormTech, 2016; US EPA, 2011; Vermont Agency of Natural Resources, 2018), can affect infiltration rates and other indicators of site performance (Lozefski et al., 2017; US EPA, 2011), and these variables can potentially change based on the bioretention site's geographic location. As the following case studies in the Eastern, Midwestern United States and the Western United States demonstrate, bioretention systems can perform well in short time periods, but more research is needed to determine the long-term performance of bioretention systems.

Effective GSI in the Eastern and Midwestern United States

Bachmann conducted a study on a stormwater management system to evaluate its hydrologic performance in Gainesville, Virginia (Bachmann, 2007). Bachmann's study used a comprehensive monitoring system of rainfall amounts and flow rates into and out of the stormwater management system, which includes pervious pavements, green roofs, rain gardens, and bioswales (Bachmann, 2007). This study determined that the types of soil media used or the types of vegetation planted can have a significant effect on hydrologic performance, and ongoing maintenance is needed for long-term performance (Bachmann, 2007). Over the one-year study period, this study concluded that the GSI system overall reduced runoff volume by 17%, and increased water retention by 24% (Bachmann, 2007). Recommendations for future research included an understanding of physical characteristics that maximize hydrologic performance, as well as studies that facilitate long-term analysis to inform GSI design lifetime (Bachmann, 2007).

Chen used computer simulated hydraulic models to test the hydrologic performance of a bioswale and catchment system for approximately 692 square meters of drainage area on Carroll Street and Denton Place near Drexel University in Brooklyn, New York (Chen, 2014). Data was collected over a one-year period from 2013 to 2014 (Chen, 2014). Soil quality and evidence of erosion were noted as key criteria that affected hydrologic performance (Chen, 2014). The system in this study reduced runoff volume by 6 to 7% during a 1-inch rain event (Chen, 2014).

Yang et al. conducted a field evaluation in the United States Midwest of a new biphasic rain garden for stormwater flow management and pollutant removal at Ohio

State University (Yang et al., 2013). Two biphasic (saturated to unsaturated water) rain gardens were constructed at Ohio State in 2008 and 6 native plant species were planted within each of them (Yan et al., 2013). Rainwater and agricultural runoff were used to calculate the total runoff in the rain garden over 5-day intervals (Yang et al., 2013). The biphasic rain garden effectively removed ~91% of nitrate and ~99% of phosphate under high levels of pollution loading with simulated runoff events (Yang et al., 2013). The initial water conditions of the agricultural runoff versus the rainwater runoff, as well as soil saturation levels, were considered the key criteria in determining the rain garden system performance at reducing pollutant loads (Yang et al., 2013). Table 1 summarizes the three studies conducted in Virginia, New York, and Ohio.

Table 1

Summary of the three Eastern and Midwestern United States studies

Researcher	**Location**	**Type of GSI Studied**	**Number of Sites**	**Methods and Results**	**Conclusions on Performance**
Bachmann, 2007	Gainesville, Virginia	Pervious pavements, green roofs, rain gardens, bioswales	One	Monitoring with hydrologic flow lab and testing methods; harmful pollutants have successfully been removed. Runoff volume decreased by 16.7% and water retention increased by 24% on the 4-acre site.	The components of the structures, such as the type of soil media used or the types of vegetation planted, can have a significant effect on hydrologic performance; need effective stakeholder communication and ongoing maintenance to ensure long-term effectiveness.
Chen, 2014	Drexel University, Brooklyn, New York	Bioswale and catchment system	One	Computer simulated hydrologic models (MODFLOW) and Piezometric Head for continuous time-series measurements of water flow and infiltration rates; Flooding was reduced by catching 6 to 7% of runoff during a 1 inch rain event.	Further consideration is needed for infiltration rates over a longer period of time based on the soil medium quality, and whether or not there was evidence of erosion within the bioswale that might affect long-term effectiveness.
Yang et al., 2013	Ohio State University, Columbus, Ohio	Rain Garden	Two	Calculated the total runoff in the rain garden over 5-day intervals, measured initial and final pollutant concentrations; effective at removing about 90% of all pollutants of concern under high levels of pollution loading with simulated storm events.	Hydrologic performance of the rain garden is affected by initial water conditions (i.e. agricultural runoff versus rainwater).

The studies conducted by Bachmann in Gainesville, Chen in Brooklyn, and Yang et al. at Ohio State University have shown examples of GSI influence and success in the eastern and mid-western United States regions with a mixture of municipal project locations and university project locations. While all of these systems have proven to be successful, all researchers collectively conclude that a well-performing GSI project needs to have effective designs and ongoing maintenance practices. Factors that can negatively affect project performance include erosion, the types of vegetation and soil media used, and soil quality over time. GSI has also made a positive stormwater management impact in the western region of the United States.

Effective GSI in the Western United States

Schweitzer, from Pomona College in Claremont, California, tested for pollutant retention effectiveness of bioswales in Portland, Oregon and Los Angeles, California (Schweitzer, 2013). Of the three different systems studied, the average pollutant concentration reduction for total metals was 85-97.2%, and for dissolved metals was 88-88.5%, however sediment accumulation was considered a concerning factor at all sites over time (Schweitzer, 2013). Ideal soil conditions for infiltration rates were determined to be mostly sandy loam with about 1/3 compost material, and infiltration depended on the pollutant particle size (Schweitzer, 2013).

Also on the West Coast, researchers David et al. evaluated four rain gardens and one bioswale located at a library in Daly City, California for their effectiveness at reducing and treating runoff flow (David et al., 2011). These bioretention structures were located on either a parking lot or a recreation area. Trash accumulation clogged some inlets into the system, which was identified as potential criteria for affecting site performance (David et al., 2011). The infiltration rate at the library site was 7.8 inches per hour, which falls within the optimal 5 to 10 inches per hour (Bicknell et al., 2016; David et al., 2011). Following large rain events, the site was able to reduce sediment loads by 84%, but only reduced runoff volume by 10% due to the soil maintaining its saturation over time (David et al., 2011).

Another successful GSI project in California is the Hacienda Avenue bioretention area in Campbell. Newly constructed bioswales along a 1.5 km stretch of Hacienda Avenue were assessed on their ability to reduce flow volume, as well as capture and treat stormwater runoff. This project has captured and filtered 100% of the 1.5 km street runoff volume (McKee and Gilbreath, 2016). More assessments should be made as the project ages over time to determine its long-term site performance. The Hacienda Avenue project is included as one of the site locations in this research project. Table 2 summarizes the methods, results and conclusions from the studies in Portland, Los Angeles, Daly City, Campbell, and Davis.

Table 2

Summary of the four western United States studies

Researcher	**Location**	**Type of GI Studied**	**Number of Sites**	**Methods and Results**	**Conclusions on Performance**
Schweitzer, 2013	Portland, Oregon and Los Angeles, California	Bioswales	Three	Fire hydrant simulated storm events, collected water and soil samples; both city bioswales effectively removed heavy metals/other pollutants- removed on average 85-97.2% of total metals, and on average 88-88.5% of dissolved metals.	Some bioswales demonstrated a need for long-term maintenance, sediment accumulation harmful to human/animal health, and can hinder ability to infiltrate runoff
David et al., 2011	Daly City, California	Rain Gardens and Bioswale	One	Water flow and pollutant concentrations measured before and after construction; Significant reduction in pollutants after construction, but evidence of trash at inlets. There was a 10% decrease in runoff volume after large storm events in a 16,200 square meter drainage area, and sediment loads were reduced by 84%.	No evidence of long-term pollutant removal, as study was conducted immediately following project completion
McKee and Gilbreath, 2016	Campbell, California	Bioretention Area	Two	Rain gauge and data logger used to record precipitation, flow rates/volume, and pollutant concentrations; successfully captured and treated 100% of runoff since completion in 2015	Need further evaluations of how project handles larger/more frequent storm events over time; researchers acknowledge need to observe evidence of trash, erosion, and pet manure over time
Xiao, 2011	UC-Davis, Davis, California	Bioswale	Two	Constructed bioswale and a controlled site, monitored tree growth, nutrient loading and runoff volume in each after 50 rain events; significant reduction in nutrient loading, increase in tree growth rate, and 88% reduced runoff in bioswale compared to control site, as well as a 95.4% reduction in pollutant loading	Measurements taken in one year time-span, and it would be useful to monitor the sites over time to determine maintenance needs, performance factors, etc.

Lastly, Xiao conducted a study on a parking lot in the University of California-Davis campus to compare and contrast the effectiveness of a constructed bioswale site and a control site without a bioswale within the same parking lot (Xiao, 2011). Both the control site and the constructed bioswale site had a tree planted, and rain events and tree growth were monitored over 50 rain events from February, 2007 to October, 2008 (Xiao, 2011). The bioswale outperformed the control site with an 88% reduction in runoff volume and a 95.4% reduction in pollutant loads (Xiao, 2011). In addition, tree growth was higher in the bioswale site than in the control site (Xiao, 2011). Noted parameters to indicate system performance included tree and vegetation growth, runoff volume, and pollutant concentration reductions.

The case studies in the western United States monitor GSI projects in both municipal and university locations, with most studies being conducted within the first couple years of GSI construction. All studies conclude that ongoing evaluations of long-term GSI project performance would be necessary, including sediment accumulation, soil quality, and maintenance needs.

Barriers to GSI Implementation and Solutions

The implementation of GSI is a critical, but very expensive, public investment for projects which have done a retrofit on the urban landscape (Benedict and McMahon, 2001; McKee and Gilbreath, 2016). The Hacienda Avenue bio-infiltration basin in Campbell, California, which spans about 1.1 miles of road, cost $6.7 million for its design, implementation, and post-construction maintenance, in addition to some conflicts in working around existing utilities (McKee and Gilbreath, 2016; SCVURPPP, 2017).

This project was funded by using city funds and grants (SCVURPPP, 2017). The Southgate Neighborhood biotreatment project in Palo Alto, California, covers a surface area of approximately 3,200 square feet, and cost about $1.8 million with funding directly from the City of Palo Alto Stormwater Management Fees (SCVURPPP, 2017). While all of these GSI retrofit projects have brought many environmental, human health and stormwater management benefits to their communities, they are still expensive investments that require time to obtain the necessary funding to implement them. The South Bay Area under the MRP's C.3 Stormwater Permit provision is required to implement GSI with new development, and now requires retrofits on public parcels and Right of Way as part of the GSI Planning portion of this provision (SCVURPPP, 2012); however there are still barriers for designing GSI systems and strategically utilizing them to maximize their benefits.

GSI is very complex, with the intention to treat stormwater using systems that attempt to mimic natural environments (Benedict and McMahon, 2001). However, unlike natural linkages that allow for biological connectivity, GSI systems are generally individualized and isolated from one another, leaving each system to operate independently (Benedict and McMahon, 2001; Lindholm, 2017; Pataki, 2015). Engineered components of constructed ecosystems, such as soil media on the bottom of a green roof or catchment basins in a bioswale, are essential for the proper functioning of these ecosystems, and human designs are much simpler than their natural and more complex counterparts (Lundholm, 2015; Pataki, 2015). One challenge faced by municipalities is urbanization resulted in many unanticipated consequences; by trying to fix previous problems, humans have created new problems (Pataki, 2015). For example, human health concerns regarding horse manure in urban streets and waterways lead to combustion engines, cars, and more people in hospitals as a result of air pollution (Pataki, 2015). Another example relating to GSI: implementing bioretention areas that can calm car traffic on residential streets lead to some parked cars accidentally having a tire get stuck in the bioretention inlet (SCVURPPP, 2017). Constructed ecosystems have distinct spatial boundaries, such as buildings, curbs and pavements; natural ecosystems do not (Lundholm, 2015). Further ecological insight would help improve GSI practices and functionality in an urbanized setting (Lundholm, 2015).

It is critical to consider the piece of land on which the GSI is constructed, as well as the surrounding landscape, as ecosystems function as a whole connected system of operations (Lindholm, 2017). Because of the complexity of GSI, multiple departments and disciplines are involved in the design construction process, and linkage between stakeholders is the key to successful GSI implementation (Benedict and McMahon, 2001). Many barriers to this linkage include a lack of design standards and codes, a lack of rules and regulations with construction and maintenance, political differences, and a lack of community awareness and education on GSI and stormwater management (Geberemariam, 2016). Land use conflicts and long-term operating costs can prevent some GSI from delivering all of its possible ecosystem services (Lindholm, 2017). Some solutions for these barriers include collection of technical data for a better understanding of GSI purposes and optimal locations, developing design standards, and raising public awareness (Tian, 2011). Other barrier solutions include clearly defined rules and regulations regarding GSI development and permits, providing educational workshops for communities, encouraging inter-agency cooperation, and developing a clear and consistent operations and maintenance plan to ensure long-term GSI viability (Geberemariam, 2016). An example of this is SCVURPPP's *C.3 Stormwater Handbook*, and workshops to ensure consistent implementation practices in the South Bay Area.

Although the MRP requires cities to conduct operations and maintenance inspections on the C.3 installations in their cities (SCVURPPP, 2012), there is insufficient information on long-term operation and maintenance costs for post-construction of GSI structures (Geberemariam, 2016). The MRP requires that stormwater runoff from undeveloped hydromodification sites cannot exceed the stormwater runoff of the same site before construction was implemented (SCVURPPP, 2012), and the change in hydrology from a pre-construction site to a post-construction site needs to be monitored over time (Bicknell, Beyerlein, and Feng, 2006). One of the common obstructions to GSI in the southern Bay Area are trash buildup and pedestrian traffic through them; this could be where public education and outreach could help to bring awareness to what GSI is, what it does, and how the public can help to keep it properly maintained and functioning (Marin County, 2015). Long-term maintenance of GSI is often referred to as maintenance of bioretention system vegetation (NRCS, 2005), but not necessarily of maintenance to ensure bioretention system long-term effectiveness.

Performance Tests and Guidelines

Many studies evaluate the effectiveness of bioretention areas in general, as well as site specific performance either following construction or by using controlled simulation experiments. Tables 1 and 2 summarize the findings from each of the GSI project effectiveness studies, including conclusions relating to ongoing project performance. Bachmann's research in Gainesville, Virginia measured hydrologic performance as a parameter for the effectiveness of various GI structures (Bachmann, 2007). Chen at the Drexel University bioswale study evaluated stormwater runoff influence on groundwater (Chen, 2014). David et al. found that the bioretention system at the Daly City library performed effectively in terms of reducing peak flow and treating stormwater runoff, but there was evidence of trash clogging inlets and compromising the capacity of the system, and there was no mention as to what extent this affected the bioretention system performance (David et al., 2011). Gilbreath and McKee mention all of the benefits of the Hacienda Avenue bio-infiltration system in Campbell in the first year it was built, but they did not evaluate long-term effectiveness of the system or its ability to tolerate larger storm events (McKee and Gilbreath, 2016). The comparison study by Schweitzer of the bioretention systems in Portland and Los Angeles concluded that while both systems in both cities were effective at removing pollutants, there was still evidence of heavy metal accumulation, which can be a threat to plant, animal and human health, and can also leach into the groundwater aquifers and hinder infiltration rates (Schweitzer, 2013). This demonstrates that maintenance and monitoring of bioswales are necessary for them to operate at full capacity and as effectively as possible (Schweitzer, 2013).

Research Questions

This study addresses the following research questions:

1. What is the process for bioretention project planning, implementation, and ongoing inspection and maintenance across multiple jurisdictions in Santa Clara County, California?
    - What are general challenges to this overall process?
2. Which major inspection criteria (i.e., trash, dead vegetation, erosion, mulch, or infrastructure damage) are associated with high performance (i.e., an infiltration rate of 5 to 10 inches per hour)?
    - What might be other sources of variability for site performance, measured in terms of infiltration rate?
3. Does bioretention project performance vary by site location (i.e., campuses versus municipalities)?

Methods

Study Site and Description

This study was conducted in the South San Francisco Bay area in Santa Clara County, California, at approximately fifty bioretention areas. Each bioretention area was sampled once during the data collection period. These systems represent a range of GSI sizes, designs, and locations, as well as a diverse mixture of maintenance and inspection processes and procedures per their designated jurisdiction. Bioretention systems are located on select college campuses, and within cities that are part of the Santa Clara Valley Urban Runoff Pollution Prevention Program (SCVURPPP), which comprises fifteen associated agencies or cities that manage stormwater discharge into the southern San Francisco Bay. The fifteen agencies and cities are Campbell, Cupertino, Los Altos, Los Altos Hills, Los Gatos, Milpitas, Monte Sereno, Mountain View, Palo Alto, San José, Santa Clara, Saratoga, and Sunnyvale, as well as the County of Santa Clara and the Santa Clara Valley Water District.

This region in California has a drought-prone Mediterranean climate, with the dry season occurring in the summer and the rainy season occurring in the autumn and winter. California often goes through drought cycles with minimal rain during the autumn and winter months, or may have particularly rainy seasons that last through the spring season. Temperatures are moderate, ranging from 50 to 80 degrees Fahrenheit throughout the year. Bioretention systems in California are designed to be drought tolerant, but can sustain major storm events and periods of flooding. Since bioretention system effectiveness is largely dependent on runoff flow and infiltration, all site observations occurred during the rainy season and into the summer, starting in February through August of Calendar Year 2018.

In November of 2015, the Municipal Regional Stormwater National Pollutant Discharge Elimination System Permit (MRP NPDES) was adopted under the federal Clean Water Act to regulate pollutants in stormwater discharge before they flow into the Bay (CALEPA, 2017). This permit is shared by all partnering agencies within SCVURPPP, and governs the requirement that all new development above a threshold of impervious area created and/or replaced implement the use of Green Infrastructure post-construction to mitigate stormwater pollutants in runoff (SCVURPPP, 2012).

The South Bay has over two thousand bioretention systems spread throughout the region that are operational (SCVURPPP, 2012). Since GSI is very expensive to design and develop, it is critical that its structures function properly to maximize potential benefits, so it is useful to observe its effectiveness based on an operations and maintenance criteria list.

Target Locations

This study evaluated GSI effectiveness by observing bioretention area site conditions and infiltration rates from February through August of Calendar Year 2018. The study examined approximately fifty bioretention area sites located on four college campuses: San José State University, Santa Clara University, Foothill College, and West Valley College, as well as five cities: Los Altos, Campbell, San José, Mountain View, and Palo Alto. Each of these campuses and cities was chosen because they all are located within SCVURPPP's program area, with the *C.3 Stormwater Handbook* being used as the guideline for GSI design, construction and maintenance for this area. These college campuses include a mixture of community colleges and public and private universities to ensure diversity in campus jurisdiction size and type, as well as a mixture of bioretention area sizes. Each campus varies in size with regards to acreage and student enrollment: San José State University has an area of 154 acres with approximately 33,000 students (SJSU, 2017); Santa Clara University is 106 acres with approximately 9,000 students (SCU, 2017); Foothill College is 122 acres with approximately 14,000 students (Foothill College, 2017); and West Valley College is 143 acres with approximately 14,500 students (West Valley College, 2016). It is important to note that the size of the campus does not necessarily indicate the number of bioretention areas present on campus, or their overall performance. Each of the cities also varies in size and economic status to potentially provide a better understanding of how the various factors may influence the effectiveness of bioretention systems among each type of city. In addition to college campuses, cities were also added as study locations to compare and contrast bioretention system performance and inspection and maintenance processes with the college campuses. The cities within the study area include Los Altos, with a population of 30, 288 and a median household income of over $200,000 (City-Data.com, 2016), Campbell, with a population of 42,584 and a median household income of $108,912 (City of Campbell, 2017), San José, with a population of 1,046,079 and a median household income of $87,210 (City of San Jose, 2017), Mountain View, with a population of 81,438 and a median household income of $120,351 (United States Census Bureau, 2015), and Palo Alto with a population of 64,403 and a median household income of $160,000

(Pisillo, 2012). The size and median household incomes of each city may not necessarily correlate with the number of bioretention areas within each city or their overall performance. The individual campuses and cities were chosen among other campuses and cities partnering with SCVURPPP because permission to conduct the research study has been granted at each of these locations by facilities personnel and/or city staff. Sites were identified with the help of an appointed expert, where the researcher identified and counted sites while walking through each campus or identifying sites on a city map. Appointed experts included faculty members, facilities directors, city staff, or resource managers. Permission has been granted by designated facilities and city staff for each site to conduct this research; signed letters of approval are included in the appendix. All available bioretention area sites for each college campus and university were chosen for this study. For site selection in each municipality, bioretention areas were chosen at the discretion of the representative for the city, which includes all available bioretention areas managed by the municipality, excluding individual bioswales and rain gardens as those projects do not have infiltration rate requirements. Table 3 summarizes the site locations and basic details of each site.

Table 3

Site locations and their details

Location	**Description**	**Number of Sites**	**Size Category(s)**	**Site Type(s)**
San José State University	Campus in San Jose, CA	5	Small	Parking Lot/Campus
Santa Clara University	Campus in Santa Clara, CA	3	Small and Large	Parking Lot/Campus and Large Bioretention Area
Foothill College	Campus in Los Altos Hills, CA	4	Small and Large	Parking Lot/Campus and Large Bioretention Area
West Valley College	Campus in Saratoga, CA	5	Small and Large	Parking Log/Campus and Large Bioretention Area
City of Campbell	Municipality	7	Small	Public Street and Residential Street
City of Mountain View	Municipality	12	Small and Large	Large Bioretention Area, Private Street, Public Street, and Parking Lot/Campus
City of Palo Alto	Municipality	6	Small	Residential Street
City of San José	Municipality	2	Small	Parking Lot/Campus
City of Los Altos	Municipality	8	Small	Public Street, Parking Lot/Campus, and Residential Street
TOTAL		**52**		

Figure 4 shows an example of the site locations on Foothill College's campus. See Appendix F to view the site maps of the remaining sites per location. Four bioretention areas were studied on Foothill College's campus in Los Altos Hills. Three of the bioretention areas are located in Parking Lot 4, and one is located between Parking Lot 5 and the Physical Science Engineering Complex building (Figure 4).

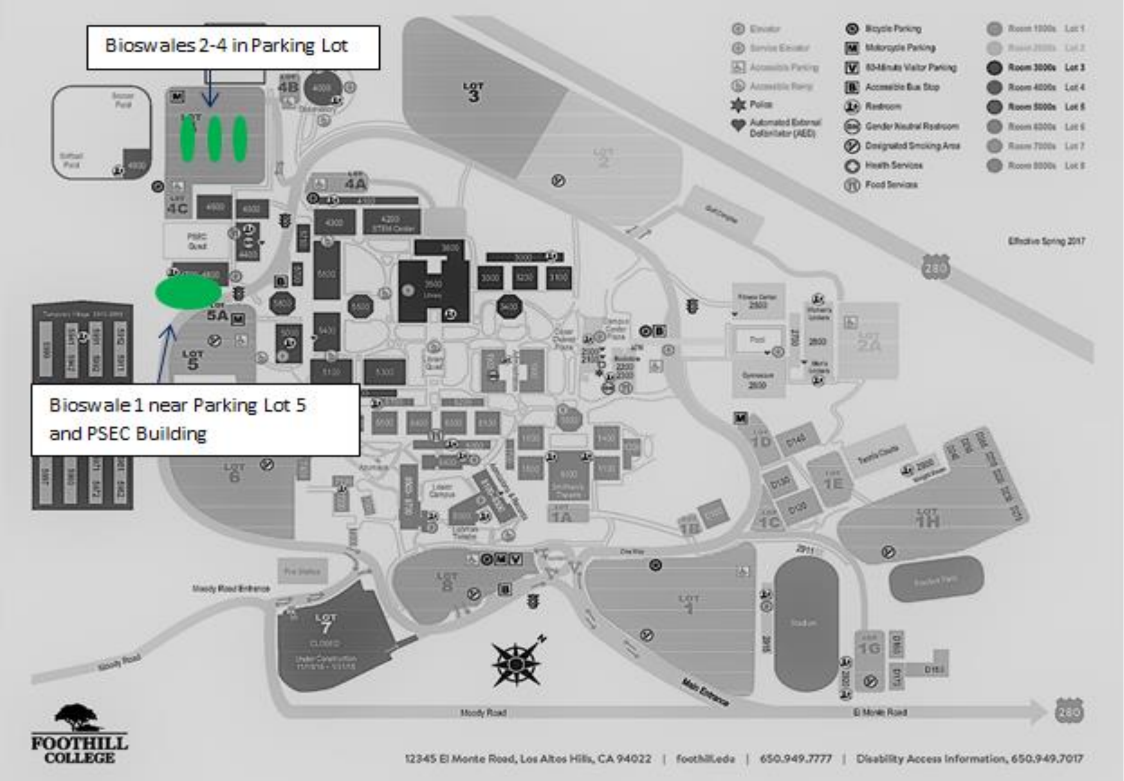

Figure 4. Site map of Foothill College's campus (Foothill Community College, 2017).

Three bioretention areas were studied on Santa Clara University's campus in Santa Clara, located near the North Parking Garage on Benton Street, near the Admissions Building and Palm Drive, and near the Schott Baseball Stadium. Five bioretention areas were studied on San José State University's campus, which are located in front of the Student Wellness Center, the Spartan Annex building, and near Washington Square Hall. Five bioretention areas were studied on West Valley College's campus, which are located on Admissions Way (between parking lots 4 and 5), within the Central Campus complex, near the VTA bus station on Allendale and Fruitvale Avenue, and near the Cilker School of Art and Design Building.

Seven bioretention area sites were studied in the City of Campbell, and are located along Hacienda Avenue, between Burrows Road and Winchester Boulevard, as well as within the Jasmine Court neighborhood. Six bioretention area sites were studied in the City of Palo Alto. They are located in the Southgate Neighborhood near Serra Street and bordered by El Camino Real and Alma Street. Twelve bioretention area sites were studied in the City of Mountain View. They are located at the Shoreline Athletic Field and Fire Station, in the Colony Condominium Complex, on Ada Street, in front of the Sierra Vista Body Shop, near office buildings on National Avenue, and near the Franklin Street Apartments by the Mountain View Police Station. Eight bioretention area sites were studied in the City of Los Altos. They are located near the Packard Foundation on Second Street and Rosita Park on Rosita Avenue. Two bioretention area sites were studied in the City of San José. They are located in the parking lot of Steinbeck Elementary School.

Out of the approximately fifty bioretention area sites in total, about half of them are considered a small size category (about the distance between two neighborhood driveways, or 0.01 to 0.1 miles in length), and about half of them are considered a large size category (about a city block, or 0.2 to 0.4 miles in length). The size of the bioretention area is important because it determines the drainage area treated for stormwater runoff at the site. At least ten large size category bioretention areas were on college campuses, and at least ten within the municipalities. There will also be at least ten small size category bioretention areas in the college campuses as well as the municipalities. To account for the age in each structure in regards to making future recommendations for long-term bioretention area performance, this study defines "newer" bioretention area systems as having been constructed within the last five years. At least ten sites representing both, campuses and municipalities are considered "newer" sites. Alternately, "older" sites are defined as constructed five years ago or more and this study has at least ten sites of "older" status represented from campuses and municipalities.

Study Design

The bioretention systems for this study are all located in or near parking lots, campuses, city streets, or residential streets. Infiltration is a critical parameter in assessing the potential stormwater capturing efficiency of a bioretention area (Lozefski et al., 2017). The results from the observational study and the infiltration test were used as evidence of current bioretention system conditions and performance in the South Bay Area. The researcher conducted an observational study and basic inspection of these bioretention systems by using a specific criteria list, compiled from criteria lists used by the City of San José, SCVURPPP, the San Francisco Estuary Institute, and the San Francisco Public Utilities Commission (SFPUC), to evaluate bioswale site conditions (See Appendix B) (Gilbreath et al., 2012). Fifty-two individual sites were evaluated based on the criteria list (California Water Boards, 2017; City of San José, 2017; San Francisco Estuary Institute, 2017; SCVURPPP, 2012; SFPUC, 2017), where the researcher first observed general site conditions that may potentially affect long-term performance (Gilbreath et al., 2012), and then measured their infiltration rates (FAO Corporate Document Repository, 2017; SFPWS, 2017) and collected soil samples for analysis (Simon & Nardozzi, 2018; Sprinkler Warehouse, 2007; UV, 2018).

Infiltration rate is defined as the rate at which water flows through a soil medium (FAO Corporate Document Repository, 2017; Minnesota Pollution Control Agency, 2017; SFPWS, 2017). Stormwater infiltration helps to reduce runoff volume and reduce pollutant loading to surface waters (Minnesota Pollution Control Agency, 2017; Xiao, 2017). Infiltration tests, which measure the bioretention system's infiltration rate (Figure 5), help to determine the health of the soil media, and if there is any heavy metal or sediment accumulation negatively affecting the structure performance that needs to be addressed (Minnesota Pollution Control Agency, 2017).

Figure 5. Basic infiltration test (Catchment Management Authority, 2012).

It also helps determine if water is infiltrating at a minimum of five inches per hour and a maximum of ten inches per hour, as recommended by the *C.3. Stormwater Handbook* (SCVURPPP, 2012).

One approach to determining infiltration rate is to use a double ring infiltrometer, which is designed to measure infiltration at the soil surface after initial wetting of the subsurface soil within the outer ring (Lozefski et al., 2017). The methodology for the double ring infiltration test was adopted from the San Francisco Public Utilities Commission (SFPUC) Water, Power and Sewer services, and the FAO Corporate Document Repository. Previous performance test studies used the double ring infiltrometer to assess infiltration rates of pervious pavements in Louisville (Kazemi, 2014) and various bioretention areas in New York (Lozefski et al., 2017). Infiltration tests used by the SFPUC include the simple infiltration test and the double ring infiltration test (SFPWS, 2017). The double ring infiltration test method was used because it is designated for small-scale projects of less than 2,000 square feet of stormwater drainage area, as recommended by the SFPUC, and it minimizes data error by creating a buffer for lateral water flow in the soil media (FAO Corporate Document Repository, 2017; SFPWS, 2017). This methodology by SFPUC is similar to the methodology by the FAO Corporate Document Repository, so a combination of both methods will be used. Only one infiltration test was necessary per site, because the sample dates fall within SFPUC's requirement, which is the months of October through April (SFWPS, 2017). To be consistent, infiltration tests at each site were conducted at a minimum of five days following a rainfall event, as the *C.3 Stormwater Handbook* requires that all bioretention areas infiltrate completely in seventy-two hours or less following a rain event (SCVURPPP, 2012). Because California can potentially experience an exceptionally wet rainy season, and because there are approximately fifty sites to sample, infiltration testing may need to continue into the summer months to ensure that all sites are tested five or more days following a rain event. If sampling needs to continue into the summer dry season months, due to unforeseen weather events, two tests were required within two days from May through September (SFPWS, 2017).

Concurrent with gathering observational data on projects, the researcher evaluated municipal inspection processes for each of the cities and organizations within the study area. Documenting the inspection and maintenance processes from each city was performed because cities may have different requirements and expectations for bioretention system performance, including the frequency of inspections, how inefficiencies are handled, and who is responsible for inspections and maintenance (Schweitzer, 2013). Inspection and maintenance processes were documented by reviewing public municipal reports, and by conducting twelve interviews with municipal staff and facilities staff (Schweitzer, 2013). These interviews are intended to review the inspection, maintenance, design and implementation of GSI processes for each campus or jurisdiction, determine if there are any gaps in knowledge regarding what the GSI systems do and how they should be maintained or designed, and identifying the responsible parties for conducting maintenance practices and inspections on these systems. The interview questions for the municipal staff and for the facilities staff are in Appendix A. Thematic analysis was used to determine local challenge themes in the county to compare to national challenges in GSI design, construction, implementation, and ongoing maintenance (Thomas & Harden, 2008).

Techniques for Measurement and Data Collection

To determine the general processes of the design, implementation and on-going maintenance of GI structures, the researcher reviewed public reports, design drawings, and other relevant documentation, as well as conducted interviews with municipal, facilities and maintenance staff for each jurisdiction or campus. Municipal documents that were reviewed included SCVURPPP's annual C.3 handbook (Bicknell et al., 2016), inspection sheets for the cities of Los Altos, Mountain View, and San José, and site drawings of bioretention areas at San José State University and in Campbell. Interview questions were open-ended to gather information that is direct and concise, and interviews were conducted verbally in-person. Interviewees were contacted first by email, then by phone if there was not an email response within five business days. There were twelve total thirty-minute in-person interviews, which included seven municipal staff and five facilities staff. The municipal staff interviews were located at the respective office locations of each interviewee in the cities of Mountain View, Los Altos, Palo Alto, San José, and Campbell. Each interviewee in the municipal interviews was given a basic flow chart of events that follow GSI design, implementation, and inspection processes, adapted from briefly reviewing SCVURPPP's annual C.3 handbook, and asked to edit or add further detail to the chart. A revised flow chart was created based on municipal staff edits and comments in their interviews, which shows the general process for GSI design, construction, implementation, and ongoing maintenance. Facilities staff interviews were held on each campus (San José State University, West Valley College, and Foothill College) either in the staff offices or in a common meeting area such as a cafeteria. Due to scheduling conflicts, no interviews of facilities staff at Santa Clara University were conducted. These interviews were intended to be a maximum of thirty minutes in length, however some interviews voluntarily went longer and others voluntarily went shorter. Specific interview questions are found in Appendix A. All interviews of facilities and maintenance staff asked about current challenges with designing, implementing and maintaining GSI systems within their jurisdiction. To synthesize the common challenges within Santa Clara County for GSI design, implementation and maintenance, thematic analysis was used to determine common themes in local challenges (Thomas & Harden, 2008). Thematic analysis was conducted in three stages, which included coding the interview responses by line, developing descriptive themes by listing each challenge mentioned and tallying the number of responses per challenge, and the generation of analytical themes by determining the top mentioned local challenges and comparing them to national challenges (Thomas & Harden, 2008).

For the general site conditions observations, the researcher brought the compiled criteria list (Appendix C) for every site visited, as well as a camera to document the site as well as factors that may be significant in affecting infiltration rates, such as extreme structural damage, dead vegetation or debris blocking water flow at the inlet (Gilbreath et al., 2012; US EPA, 2011). Inspection criteria were gathered from inspection logs from the San Francisco Public Utilities Commission, the City of San José, and SCVURPPP’s C.3 guidelines (Bicknell et al., 2016; City of San José, 2017; SFPUC, 2017). Using inspection guidelines as a means for assessing site conditions and to indicate bioretention area performance was derived from a SCVURPPP workshop presentation titled *GI Landscape Design and Maintenance Considerations* (Schultze-Allen, 2017). This presentation used inspection criteria and photographs to help make recommendations for long-term bioretention area maintenance, and included criteria such as plant health, trash, sediment accumulation, irrigation, sand composition, and infiltration rates (Schultze-Allen, 2017). These inspection observations occurred at the same time at which the infiltration test was conducted, and each site was visited at a later date for soil sampling. It is not necessary to inspect bioretention system sites during rain events (Gilbreath et al., 2012; SCVURPPP, 2012); however, if it is possible to do so, water flow into the site will be observable. At the top of each criteria list, the name or location of the site was recorded, along with the time, date, and current weather conditions. Each of the criteria was scored on a three-point scale based on the inspection, with the score indicating the site condition with respect to the variable of interest. Table 4 shows the details for scoring each criterion in the inspection observations.

Table 4

Scoring mechanism for inspection Criteria (1=Poor, 2=Average, 3=Good)

Criteria	**1**	**2**	**3**
Obstructions/Trash	Greater than 30% cover of trash or leaves, or clogging inlets	Between 30% cover and 5% cover of trash and leaves	No trash or leaves
Ponded Water Exceeding 12 inches	>16 inches of ponding	Between 12 and 16 inches of ponding	<12 inches of ponding
Evidence of Erosion	Major erosion throughout entire area	Some erosion at inlet	No erosion
Sediment Accumulation	Thick	Some accumulation	No accumulation
Vegetation Health	No vegetation or all vegetation is dead	Mostly healthy plants with some dead plants	All vegetation is healthy
Functioning Irrigation Systems	Dead vegetation, visible pipes, damage to structure	Vegetation is healthy, but some pipes visible to surface	Healthy vegetation, no visible pipes
Overall Structural Integrity/Evidence of Vandalism or Damage	Major evidence of damage	Some evidence of damage	No evidence of damage
Vegetation Obstructing Sight on Roads	Complete obstruction for vehicular traffic	Minor obstructions	No obstructions
Rodent Damage/Burrows/Animal Feces	Major evidence	Some evidence	No evidence

Note. Adapted from the City of San José (2017), Schultze-Allen (2017), SCVURPPP (2016), and SFPUC (2017); edited by the researcher.

One objective of this research is to determine if a higher criteria “score” indicates a better performing bioretention area than one with a lower criteria “score”. For example, excess sediment accumulation (i.e., a criteria score of 1) could be associated with a slow infiltration rate (i.e., a rate that is less than five inches per hour), or poor erosion (i.e., a criteria score of 1) might be associated with a high infiltration rate (i.e., greater than ten inches per hour). Once a criterion’s scores are matched with the infiltration rates, the resulting dataset will be used to assess correlation between the variables. Table 5 shows an example of a hypothetical field observation, using the criteria list and the scoring method.

Table 5

Completed field inspection sheet example

Criteria	**Score**	**Comments**
Obstructions/Trash	2	Paper, plastic bag, and a straw wrapper; about 15% cover
Ponded Water Exceeding 12 inches	3	No ponding water
Evidence of Erosion	3	No evidence of erosion
Sediment Accumulation	2	Some evidence of sediment accumulation
Approved Vegetation Health	3	Vegetation seems well watered
Functioning Irrigation Systems	2	Vegetation is healthy, but some pipes visible to surface
Overall Structural Integrity/Evidence of Vandalism or Damage	3	No damage or vandalism
Vegetation Obstructing Site on Roads	3	No vegetation obstructions
Rodent Damage/Burrows/Animal Feces	3	No damage or feces from animals
TOTAL	24	

Note. Adapted from the City of San José (2017), SCVURPPP (2012), and SFPUC (2017); edited by the researcher.

Ideally, all sites would have higher criteria scores. For this example (Table 5), there is evidence of some trash at about fifteen percent cover, which gives it a score of 2. Comments were noted about any details regarding the criteria list. For example, if there is excessive trash and debris, the comments would note the locations within the site of the trash and debris, and the types of trash or debris present. Some examples of trash or debris could include leaf piles, bottles and cans, plastic bags, or dead plant matter. Weather conditions were recorded to indicate wind speeds, cloud cover, outdoor temperature, and the most recent precipitation event.

In addition to conducting the field observations, infiltration tests were implemented at each site February through May, to compare and contrast the results with the inspection observations throughout this time period. To run the infiltration test, two cylinders were inserted into the ground towards the center of the bioretention area. The center cylinder was marked in one-inch increments, and water was poured into the cylinder as a timer starts. The researcher noted the time it takes for the water level to drop each inch, and refilled the cylinder before it infiltrated all the way into the ground. This process continued until the drop in water level was the same over the same time interval (FAO Corporate Document Repository, 2017), and the average time was noted as the bioretention area's infiltration rate. For detailed instructions on implementing the infiltration rate test, see Appendix B.

Lastly, soil samples were taken from each site to ensure that the proper engineered soil was used in the bioretention area (i.e., 70% sand material, 30% organic matter (Bicknell et al., 2016; Lozefski et al., 2017)), and to rule out any discrepancies of infiltration rate results based on the type of soil used. Stormwater infiltration can be greatly influenced by soil characteristics (Minnesota Pollution Control Agency, 2017). Soil samples were taken by shoveling down to three inches into the ground and filling a marked brown lunch bag about halfway (UV, 2018). To identify the soil type, quart-sized mason jars were marked by site name and filled about one-third to halfway with the corresponding soil sample (Simon & Nardozzi, 2018). Sticks, rocks, leaves, and other large debris matter were removed from the soil sample prior to adding it to the jar (UV, 2018). Each jar was filled with tap water with a dash of salt to break up the soil particles, shaken vigorously, then set to settle for six to twelve hours (Simon & Nardozzi, 2018; Sprinkler Warehouse, 2007). Photos were taken of each sample to document the soil layers (Sprinkler Warehouse, 2007) and the researcher used a ruler to measure the proportions of each soil layer within the whole jar sample (Simon & Nardozzi, 2018). For example, if a sample had 0.75 inches of bottom layer and 0.25 inches of top layer, the sample is about 75% sand and 25% compost material. The scoring classification for soil type was "High Sand" for samples that were 80-100% sand, "Mostly Sand" for 60-79%, "Medium Sand" for 45-59%, and "Low Sand" for 0-44%. Ideally, the engineered soil composition for bioretention areas in Santa Clara County should be about 70% sand and 30% compost material (Bicknell et al., 2016), which falls into the "Mostly Sand" category.

Data Analysis

To answer the first research question, twelve interviews of seven municipal staff and five facilities staff within Santa Clara County were conducted. Most of the thirty-minute in-person interviews were recorded for continued reference. Research question one (What is the process for bioretention project planning, implementation, and ongoing inspection and maintenance across multiple jurisdictions in the South San Francisco Bay Area, California) was addressed using inductive coding and organizing responses from interviews. To answer the second part of research question 1 (What are general challenges to this overall process), the researcher used a qualitative thematic analysis of common themes based on a review of public reports, design plans, and in-person interviews with facilities and municipal staff. Each of the challenges mentioned in interviews were listed and tallied to determine the most pressing local concerns for the municipalities and campuses in this study.

All statistical analysis was conducted using R Studio software to answer research questions 2 and 3. Kruskal-Wallis rank sum tests were used to answer research question 2 (which major inspection criteria are associated with high performance) because there are multiple categories and independent variables for comparison, but only one dependent variable. Project performance is defined as a site having an infiltration rate of five to ten inches per hour, and the inspection criteria refers to the criteria list for the observational study, such as trash and vegetation health. For instance, three groups: Trash1, Trash2, and Trash3, which correspond with the different score results for the trash criteria in the observational study, will be tested against the infiltration rate as the dependent variable. This determined if there is any positive or negative correlation between each of the inspection criteria as independent variables and the infiltration rate as the dependent variable. For example, the analysis assumption for trash is that little or no presence of trash (i.e., criteria score of 3) is associated with better site performance (i.e., infiltration rate of 5 to 10 inches per hour).

In conjunction with the Kruskal-Wallis rank sum test results used to answer the first part of research question 2, the second part (What other factors account for variability in site performance, measured in terms of infiltration rate), was answered based on a thematic analysis among how each site was constructed, designed, maintained, and its overall performance results, and on the soil sampling analysis results. Photographs of each site revealed common themes of site performance, including side design and the presence of California native perennial bunch grass vegetation, which as analyzed using Pearson's chi-squared contingency test and the Wilcoxon rank sum test to determine if the individual site design or the presence of bunch grass vegetation affects whether the site falls within the recommended infiltration rate range of 5 to 10 inches per hour. The Kruskal-Wallis rank sum test was used to determine if different site designs affected whether the site fell within the recommended infiltration rate range.

In answering research question 3 (Does bioretention area performance vary by site type), a Wilcoxon rank sum test/Mann-Whitney U test was used, with infiltration rate as the dependent variable and bioretention area location/type as the independent variable. The two different categories of site locations are college campuses and municipalities. This helped determine if there was any positive or negative correlation of each location category to infiltration rate. Research Question 1 will be answered by conducting twelve in-person, thirty-minute interviews of five facilities and seven municipal staff, and by utilizing photographs, municipal reports and site design drawings. Thematic analysis will be used to analyze common themes regarding top bioretention challenges within each municipality or campus. To summarize the remaining analysis, Table 6 shows the research questions with their associated independent variables, dependent variables, and proposed statistical analysis tests to answer these questions.

Table 6

Research questions with associated variables and statistical tests

Research Question	Independent Variable(s)	Dependent Variable	Analysis Test
Question 2: Which major inspection criteria (i.e. trash, dead vegetation, erosion, mulch, or infrastructure damage) are associated with high performance (i.e. an infiltration rate of 5 to 10 inches per hour)? -What other factors account for variability in site performance, measured in terms of infiltration rate?	Inspection criteria	Infiltration Rate	Kruskal-Wallis rank sum test and Pearson's chi-square contingency test; Thematic analysis
Question 3: Does bioretention area performance vary by site type?	Bioretention area location (i.e. campuses and municipalities)	Infiltration Rate	Wilcoxon rank sum test/Mann-Whitney U-test

Study Limitations

While all sites were observed at face value without the presence of natural stormwater flow, it is beneficial to observe the sites during a rain event if water flow is to be observed. Because California has a Mediterranean climate with a tendency for long drought periods, storm events were a limiting factor in being able to observe all sites during a rain event. Another limitation is that some campuses and municipalities have more bioretention areas than others, as well as an unequal distribution of different sizes in bioretention areas, which lead to biased results in the overall design, maintenance and inspection processes of each campus and/or municipality. Infiltration tests were only able to be completed once at each site, which yielded a lower sample size. Lastly, not all reports and documentation for the bioretention areas were available, and they are not able to be tested for definitive reasoning for bioretention area infiltration rates, but can be useful to make recommendations on future research projects.

Results

This study examined 52 bioretention areas throughout the South San Francisco Bay Area. These bioretention areas were located in four campuses (West Valley College, Foothill College, San José State University, and Santa Clara University) as well as five municipalities (Los Altos, Palo Alto, San José, Campbell, and Mountain View). Seventeen sites were sampled on the campuses, and thirty-six sites were sampled in municipalities. Although these sites were widely dispersed throughout Santa Clara County, not all of them were randomly selected, because campuses generally did not have as many bioretention sites as municipalities, and some municipal sites required an escort by a staff member.

Overall, the municipal staff interview results revealed that all municipalities in the study followed the same general process for GSI design, implementation, and inspection, as required by the MRP and recommended by the C.3 handbook. Based on the thematic analysis from municipal and facilities staff interviews, the top challenges for implementing and maintaining this process are concerns with trash, plant health, functioning irrigation, growing demand strains in terms of maintenance and development, the technical design of the GSI systems, communication between facilities and municipal staff, and public or owner awareness of GSI purposes and functions.

The average infiltration rate across all sites was 23.3 inches/hour, the median infiltration rate was 15.4 inches/hour, the mode infiltration rate was 40.0 inches/hour, and the range of infiltration rates was 2.7 inches/hour to 62.1 inches/hour. Twenty-six percent of sites had infiltration rates within the recommended range of five to ten inches per hour, with sixty-six percent of sites exceeding the maximum ten inches per hour, and about seven percent of sites had infiltration rates that were below the minimum five inches per hour. The Kruskal-Wallis rank sum test was used to determine if the score levels of each observational criteria affected infiltration rates. This test was used in lieu of Analysis of Variance (ANOVA) because the infiltration rate data did not have a normal distribution, but exhibited homogeneity of variances with each observational criterion. Additionally, Pearson's chi-squared contingency test was used to determine if each observational criteria score was independent of sites falling within the recommended five to ten inches per hour range.

The site observations revealed that about sixty-six percent of sites had some concerns with trash/obstructions and sediment accumulation, sixty-two percent of sites had poor vegetation health, which often means dead or dry vegetation and can include the presence of weeds, thirty-eight percent had irrigation concerns (exposed irrigation pipes, lack of irrigation, damaged sprinkler heads), twenty-five percent had erosion concerns, and twenty-three percent of sites had evidence of animal damage due to burrowing or feces droppings from household pets. Table 7 shows the results for each site. The sites highlighted in green are sites that fell within the recommended range of five to ten inches per hour (Bicknell et al., 2016).

Table 7

Site observation and infiltration test results

Score 3= 'Excellent Condition', Score 2= 'Fair Condition', Score 1= 'Poor Condition'

Site Name	Infiltration Rate (in/hr.)	Soil Type	Trash	Erosion	Sediment Accumulation	Vegetation Health	Irrigation	Animal Damage	Total Score
M17	2.7	High Sand*	2	3	2	2	3	3	24
C16	3.6	Mostly Sand	2	3	3	3	3	3	26
M19	3.9	Medium Sand	3	3	2	3	3	3	26
C14	4.2	Mostly Sand	2	3	2	3	3	3	25
M1	4.8	Mostly Sand	2	3	3	3	3	3	26
C13**	5.5	High Sand	1	3	2	2	3	3	23
M11	5.7	High Sand	3	3	3	2	3	3	26
M5	6.5	High Sand	2	3	2	3	2	2	23
M26	6.5	Mostly Sand	2	3	2	2	3	2	23
M2	7.3	High Sand	3	3	3	2	3	3	26
M35	7.8	Mostly Sand	2	2	2	2	2	2	21
M6	8.2	Mostly Sand	3	2	2	3	2	3	24
C9	8.8	Mostly Sand	2	3	2	2	2	3	23
M24	9	Mostly Sand	2	3	2	2	3	2	23
M27	10	Medium Sand	2	3	2	2	3	3	23
M36	10	Mostly Sand	2	2	2	2	2	1	20
M23	10.1	High Sand	2	3	2	2	2	3	23
C17	10.4	Mostly Sand	2	3	3	2	2	3	24
M22	13.3	High Sand	2	3	2	2	2	3	23
M31	13.3	Medium Sand	2	1	3	1	1	1	17
C7	14	High Sand	3	2	2	2	1	3	21
M16	14.3	High Sand	2	3	1	3	3	3	24
M34	14.8	High Sand	3	3	3	2	3	3	26
C4	15.1	High Sand	2	3	3	2	3	2	24
M15	15.2	High Sand	3	2	2	3	3	3	25

Site Name	Infiltration Rate (in/hr.)	Soil Type	Trash	Erosion	Sediment Accumulation	Vegetation Health	Irrigation	Animal Damage	Total Score
M28	15.4	High Sand	2	2	3	3	2	3	23
M9	16.7	Medium Sand	2	3	2	3	3	3	25
M20	17.7	Mostly Sand	2	3	2	2	3	3	23
C15	17.9	High Sand	3	3	3	3	3	3	27
M21	18.2	High Sand	2	3	2	2	2	3	23
C12	19.1	Mostly Sand	1	3	1	2	3	3	22
C8	19.7	Mostly Sand	3	2	3	2	2	3	24
C6	19.8	Mostly Sand	2	3	3	3	3	3	26
M30	23.4	High Sand	2	3	3	2	2	3	24
M33	25	Mostly Sand	3	3	3	2	3	3	26
M7	25.9	Mostly Sand	3	3	2	2	2	3	24
M18	26.7	High Sand	3	3	2	2	3	3	25
M8	27.1	Low Sand	3	2	2	3	2	3	24
M14	27.5	Mostly Sand	3	3	1	3	3	3	25
M32	27.5	Mostly Sand	3	3	3	2	3	3	26
C5	27.7	Mostly Sand	3	3	3	3	3	3	27
M29	28.1	High Sand	3	1	3	2	2	3	23
C1	29.3	Mostly Sand	1	3	2	2	3	2	22
C10	37.9	Medium Sand	2	3	2	2	3	3	23
C3	38.3	High Sand	2	1	2	2	3	2	21
M3	40	Mostly Sand	2	3	3	3	2	3	25
M10	40	High Sand	2	2	2	1	3	3	22
C11	52.9	High Sand	3	3	2	1	1	2	21
M13	60	High Sand	2	3	2	3	2	3	24
M12	61	High Sand	2	3	2	3	3	3	25
C2	62.1	High Sand	2	2	2	2	3	2	22
		Average	**2.3**	**2.7**	**2.3**	**2.3**	**2.6**	**2.7**	**23.7**
		Mode	**2**	**3**	**2**	**2**	**3**	**3**	**23**

Note. Soil Type Code: High Sand (80-100% Sand); Mostly Sand (60-79% Sand); Medium Sand (45-59% Sand); Low Sand (0-44% Sand). The twelve sites that are shaded are sites that had infiltration rates within the recommended range. The recommended infiltration rate range 5 to 10 inches per hour, and recommended soil composition 70% sand, 30% compost material. Copyright 2016 by SCVURPPP.

There was no statistical significance in each criteria score affecting infiltration rates or affecting whether sites fell within the recommended infiltration rate range, based on the results from the Kruskal-Wallis rank sum test and Pearson’s chi-squared contingency test, nor was there a statistical significance of the site’s overall scores in affecting infiltration rates or the site falling within the recommended range. Other factors that were identified as affecting infiltration rates include site design and the use of California native perennial bunch grasses.

Since the data set meets the assumption of homogeneity of variances but not normality, the Wilcoxon rank sum test was used to compare the infiltration rate means of municipalities versus campuses, and it was determined that there is no significant difference in site performance, measured in terms of infiltration rates, between municipalities or campuses.

Research Question 1: GSI Design, Implementation and Maintenance Process and Challenges

GSI Design, Implementation and Maintenance Process

Seven municipal staff members were interviewed to help determine the general design, implementation, and maintenance process for bioretention areas in Santa Clara County. Figure 6 illustrates the general bioretention area implementation process for the county, and summarizes the general timeline to the GSI implementation and maintenance process.

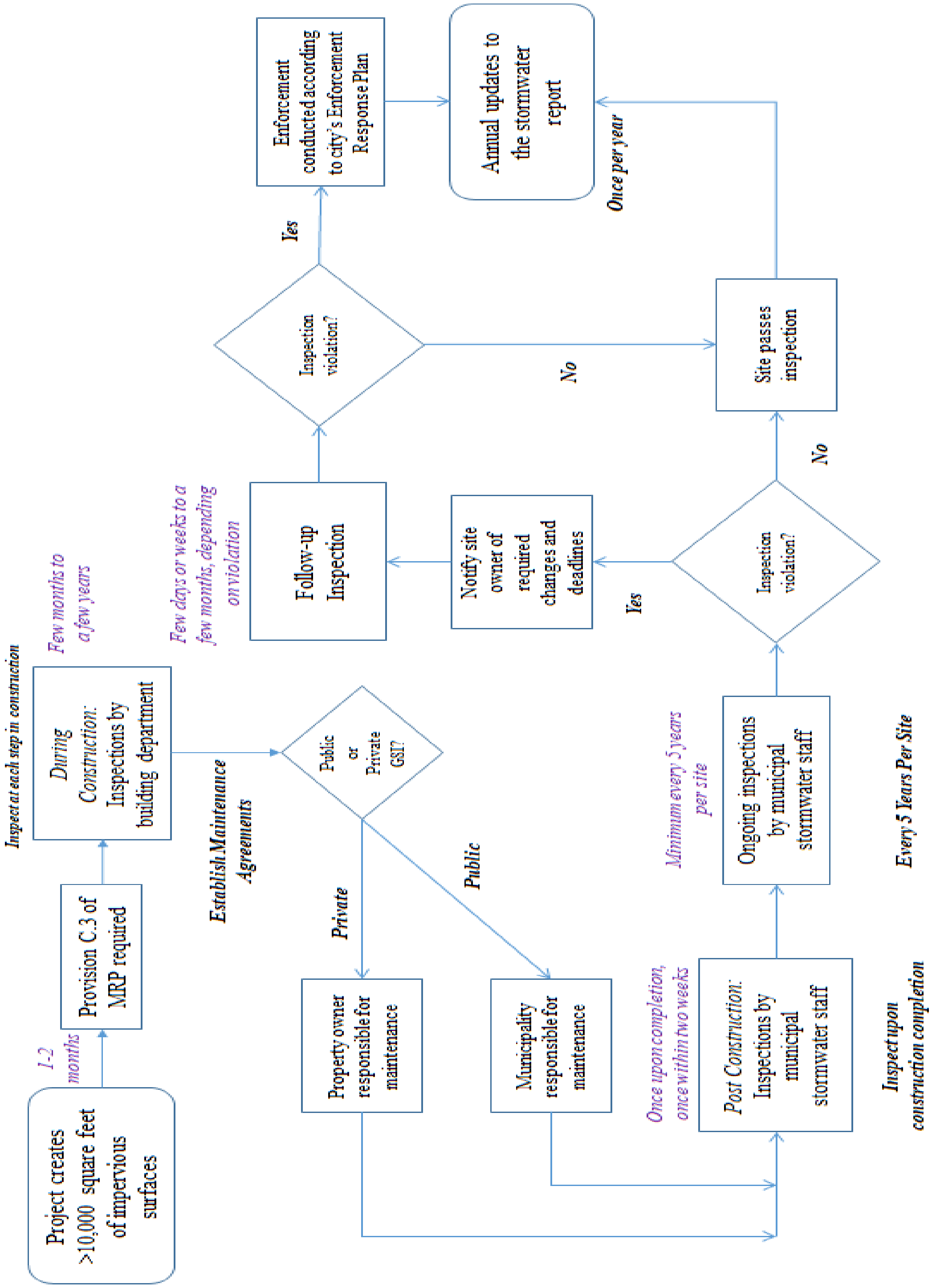

Figure 6. GSI process and timeline for Santa Clara County (Bicknell et al., 2016; City of Campbell, 2018; City of Los Altos, 2018; City of Mountain View, 2018; City of Palo Alto, 2018; City of San José, 2018).

Provision C.3 of the *Stormwater Permit* requires that for all proposed projects that replace or create greater than 10,000 square feet of impervious surfaces, GSI must be implemented to mitigate for stormwater runoff (Bicknell et al., 2016; Municipal Staff 3, 2018; Municipal Staff 6, 2018). Developers propose their initial project ideas to the municipality in which the project will reside, and the stormwater permit determines if the site will require GSI features (Municipal Staff 6, 2018). In the design phase, the project awaits approval from municipal staff engineers, which can take up to several months (Municipal Staff 6, 2018). The GSI project needs to consider current and future repairs and replacement of utilities in the site area, and investigation of these utilities' concerns should be within the project design phase (City and County of Denver, 2015). The above figure shows the implementation process after a municipality has determined that the site requires GSI features.

During the construction phase of the GSI project, inspections are typically handled by building department inspectors, and city staff will likely check each step of the process to ensure it was constructed correctly (Municipal Staff 1, 2018). The City of Palo Alto, however, requires the project proponent to hire a third party to sign off on the construction of their GSI projects (Municipal Staff 7, 2018). Examples of design specifications include making sure the site uses the required engineered soil (approximately 70% sand, 30% compost material) (Bicknell et al., 2016; Municipal Staff 1, 2018), and that the soil depth is 18 inches (Municipal Staff 4, 2018). Construction observation and coordination with the contractor by the project designer and owner is recommended to ensure the functionality of the GSI system (City and County of Denver, 2015). Upon construction completion, as required by Provision C.3 of the MRP, site inspections are under the responsibility of municipal stormwater staff (Municipal Staff 1, 2018; Municipal Staff 2, 2018; Municipal Staff 3, 2018; Municipal Staff 6, 2018). Maintenance agreements typically require the owners or operators of the site to inspect more frequently throughout the construction process (Facilities and Maintenance Staff 4, 2018). Upon construction completion, a third party (usually an outside contractor) will also inspect the site to certify that the feature meets all of the design specifications (Municipal Staff 7, 2018).

Different maintenance agreements are established following construction for private GSI projects and public GSI projects (Municipal Staff 1, 2018; Municipal Staff 3, 2018; Municipal Staff 5, 2018). Under private projects, for example in residential development (Homeowner’s Association) or some business parking lots, the owner of the property is responsible for ongoing maintenance of the GSI structure (City and County of Denver, 2015; Municipal Staff 1, 2018). For public projects, which include structures located along city streets and public right-of-ways, the municipality in which the site resides is responsible for ongoing maintenance (Municipal Staff 1, 2018; Municipal Staff 3, 2018). For sites located on college campuses, grounds keepers or facilities staff is responsible for ongoing maintenance of GSI structures (Facilities and Maintenance Staff 2, 2018; Facilities and Maintenance Staff 4, 2018; Facilities and Maintenance Staff 5, 2018). For an example comparison, the City of Denver, Colorado allocates similar maintenance responsibilities for public and private GSI projects, however, they require site inspections yearly instead of every five years, and maintenance agreements are determined in the planning and design phase of the GSI project, before it has been approved or constructed (City and County of Denver, 2015). This is also consistent with Santa Clara County (Municipal Staff 1, 2018; Municipal Staff 3, 2018).

Municipalities in Santa Clara County are responsible for inspecting all sites at least once every five years, although some cities may inspect more frequently (Municipal Staff 2, 2018; Municipal Staff 3, 2018; Municipal Staff 6, 2018). Inspection logs are kept with the municipality in their database, and any significant comments are reported publicly in the annual SCVURPPP stormwater report (Municipal Staff 2, 2018; Municipal Staff 6, 2018; Municipal Staff 7, 2018). If there are any concerns in the inspection process, city staff are responsible for contacting the respective site owner with a list of what needs to be addressed in a variable amount of days, depending on the type or extent of the issue (City and County of Denver, 2015; Municipal Staff 1, 2018; Municipal Staff 6, 2018). Common concerns can be plant replacement or erosion repairs; whereas routine maintenance involves sediment and trash removal and weed control (City and County of Denver, 2015). Should any issues fail to be addressed within the specified time frame, the city can issue a ticket to the site owner that requires a fee (Municipal Staff 1, 2018; Municipal Staff 6, 2018; Municipal Staff 7, 2018). Cities are required to have an Enforcement Response Plan for C.3 permit inspections, which often includes a verbal or written warning, and generally does not result in issuing a ticket right away (Municipal Staff 3, 2018; Municipal Staff 5, 2018). Maintenance activities can vary by site, and are dependent on runoff volume, pollutant loads, seasonal weather variations, and adjacent land uses (City and County of Denver, 2015). Generally, plants should be monitored every ten to fourteen days for watering needs while they are in their early stages of growth (City and County of Denver, 2015), but should be relatively maintenance-free once they reach maturity (Facilities and Maintenance Staff 1, 2018; Facilities and Maintenance Staff 3, 2018). Weed control must involve physically extracting the roots and removing the plant from the site; they should not be sprayed or pulled and left onsite to spread seeds or create debris buildup (City and County of Denver, 2015; Facilities and Maintenance Staff 3, 2018).

Meeting the MRP requirements is a minimum, and some cities may choose to expand upon these requirements and enforce stricter specifications (Municipal Staff 7, 2018). For example, the City of Palo Alto potentially plans to implement GSI structures that are tailored to the City's needs, such as connecting different individual sites into one system rather than having single sites within each new development (Municipal Staff 7, 2018). If this strategy is implemented in the future, the City would require third party inspectors to base their inspections off of the tailored GSI specifications and criteria, which would include all MRP requirements as well as additional requirements as determined by Palo Alto (Municipal Staff 7, 2018).

GSI Challenges

Thematic analysis was used to determine the top challenges for GSI implementation and maintenance in the study area, based on challenges listed in municipal and facilities staff interviews (Thomas & Harden, 2008). Figure 7 shows the common challenge themes as mentioned by each interviewee, which include soil loss, plant overgrowth, irrigation (in terms of their function or integrity), public/owner awareness (with respect to what these systems are and their purpose), ponding, growing demand strains (unable to keep up with increased projects, or in need of funding, maintenance personnel or equipment), and trash. These bioretention challenges correlate with some of the field observations, as shown in the following subsections.

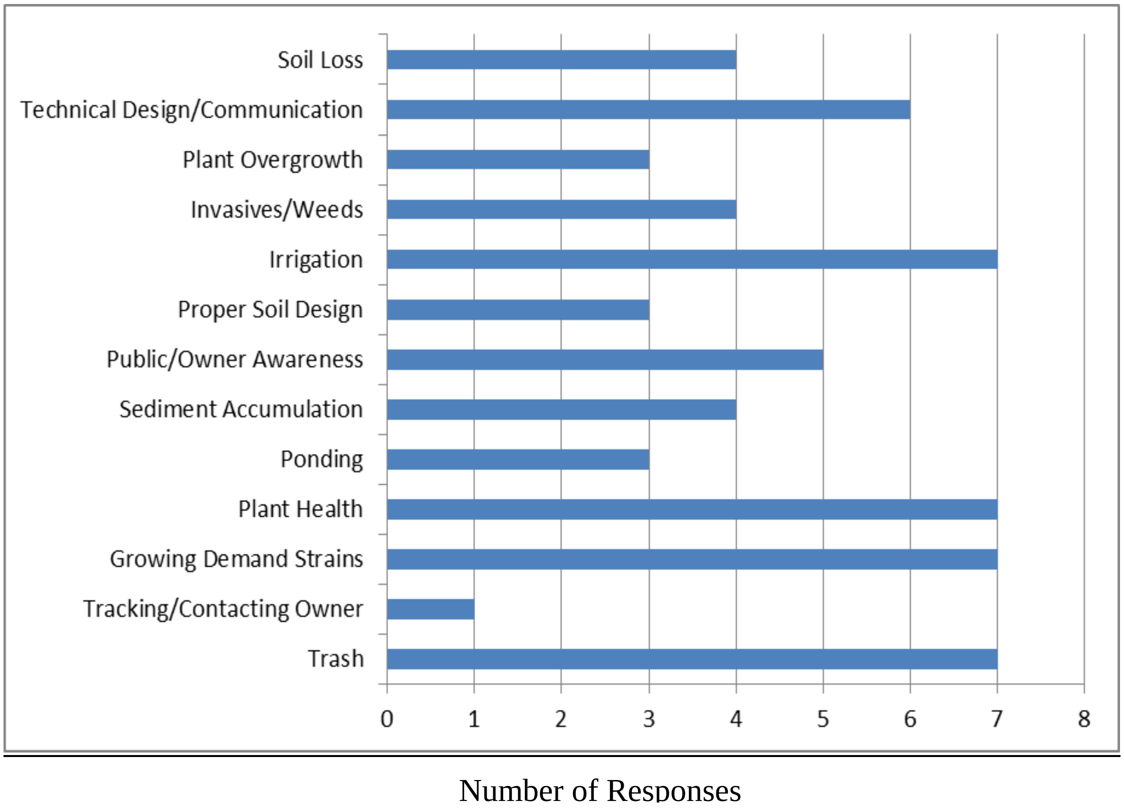

Figure 7. Common bioretention challenges derived from research interviews. Histogram by researcher.

Sediment accumulation. Over half of the sites were observed to have lower scores of sediment accumulation and trash. For some sites, sediment accumulation was highly variable, even if they were located on the same intersection as shown in Figure 8.

Figure 8. Municipal Site 14 on the left (Infiltration Rate: 27.5 in/hr.) and Municipal Site 15 on the right (Infiltration Rate: 15.2 in/hr.) (Photo by author).

Municipal Site 14 (M14) on the left has much more sediment accumulation and buildup on its rocks than Municipal Site 15 (M15) does on the right, although they are on the same corner of the same residential property. M14, however, is closer to a busy road than M15, and even though both sites were only meant to drain the street and rooftop runoff, M14 might also be taking on runoff from this busy road. Another possible explanation could be that M14 receives more runoff than M15 due to the shape of the grading and system design. This is important to note because it can indicate that soil replacement should be dependent on site location or design, in addition to how much runoff or the type of runoff, rather than an arbitrary standard number of years.

Sites that were on residential streets and campuses had less trash than sites that were near parking lots and on city streets, likely due to the fact that residents may take more care to remove trash that is on or near their property (Municipal Staff 3, 2018). Campuses have facilities grounds crew that maintain and clean their properties routinely (Facilities and Maintenance Staff 4, 2018; Facilities and Maintenance Staff 5, 2018). More public locations may have more trash simply because there is more pedestrian traffic, contaminants or opportunities for trash nearby (US EPA, 2011), and because there are more sites with less available and constant monitoring from maintenance staff.

Technical design and implementation. Common design and implementation errors include placing the outlet drain right at or near the site inlet (Figure 9), which prevents most of the runoff from entering into the bioretention area to be treated before entering into the storm sewer system.

Figure 9. Municipal Site 3 storm sewer drain (Infiltration Rate: 40.0 in/hr.) (Photo by author).

Figure 10 also shows another example of a storm drain being placed right in front of a bioretention area. Other examples are Campus Sites 12 (C12), which has an excess number of sprinkler heads right next to each other (Figure 11).

Figure 10. Municipal Site 11 storm drain (Infiltration Rate: 5.7 in/hr.) (Photo by author).

Figure 11. Site C12 sprinkler heads (Infiltration Rate: 19.1 in/hr.) (Photo by author).

Other noted technical design challenges were determining the catchment size of runoff into the bioretention area, and navigating different sizes of bioretention areas within one project (Municipal Staff 4, 2018). Another technical design challenge previously mentioned was the type of trees used in and around the bioretention area

(Facilities and Maintenance Staff 3, 2018). For example, trees that seasonally shed their leaves can clog the bioretention areas, as well as trees that shed small seeds or pine needles (Figure 12).

Figure 12. Municipal Site 22 seed accumulation (Infiltration Rate: 13.3 in/hr.) (Photo by author).

This buildup of plant matter can clog bioretention area outlets (Minnesota Pollution Control Agency, 2017), and cannot be as easily removed as larger substances such as trash (Facilities and Maintenance Staff 3, 2018). In addition to avoiding the proximity to certain tree and shrub species, GSI projects should not be implemented in brownfields (i.e., sites with known pollution issues) or locations with the potential for high loads of certain pollutants, such as vehicle fueling areas (Minnesota Pollution Control Agency, 2017).

Selection and design of GSI bioretention areas is dependent on the physical characteristics of the location, including drainage areas, groundwater table levels, surrounding land use, and soil composition (City and County of Denver, 2015). Determining engineered soil mixtures can be challenging, as the soil must be permeable enough to infiltrate water, but should also be able to retain some water to support native drought-tolerant plant life (US EPA, 2011).

Vegetation health and irrigation. Sixty-two percent of sites had concerns with vegetation health, which includes dry or dead vegetation, overgrown vegetation, or not enough vegetation. Figure 13 shows a site with not enough vegetation, and Figure 14 shows a site with overgrown vegetation.

Figure 13. Campus Site 17 bare vegetation (Infiltration Rate: 10.4 in/hr.) (Photo by author).

Figure 14. Municipal Site 30 overgrown grasses (Infiltration Rate: 23.4 in/hr.) (Photo by author).

Exposed irrigation pipes were a common concern among many sites because they can leave irrigation systems vulnerable to damage, and can be an indication of soil loss. Figure 15 shows an example of an exposed irrigation pipe at Municipal Site 21.

Figure 15. Exposed drip irrigation pipe at Municipal Site 21 (Infiltration Rate: 18.2 in/hr.) (Photo by author).

Other leading challenges from the interviews included communication between stakeholders, as well as handling public or site owner awareness of what these bioretention areas are and how they should be maintained. One site had concerns with pet feces and personal trash in the bioretention area (Figure 16).

Figure 16. Evidence of pet feces and an empty cigarette package at Municipal Site 31 (Infiltration Rate: 13.3 in/hr.) (Photo by author).

This site was particularly dry and dominantly covered in dead vegetation. This could lead local residents or pedestrian passerby's to assume the system is a dead and useless plot of land, and not see that it was built as a bioretention area or give incentive to keep the area aesthetically pleasing. Several sites had mulch landscaping surrounding the bioretention area, particularly in sites located on residential streets (Figures 17 and 18).

Figure 17. Municipal Site 17 surrounding landscape mulch (Infiltration Rate: 2.7 in/hr.) (Photo by author).

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Figure 18. Municipal Site 6 surrounding landscape mulch (Infiltration Rate: 8.2 in/hr.) (Photo by author).

Even if mulch was not placed directly into the bioretention area, it can leak into the system by runoff or pedestrian traffic if it is placed adjacent to the area, which can negatively affect infiltration rates or clog outlet pipes after heavy rainfall events (Bicknell et al., 2016). Campus facilities interviewees mentioned their efforts to keep pedestrians out of their bioretention areas, which can be challenging depending on placement of the bioretention area in proximity to high pedestrian traffic. For example, bioretention areas that border recreational fields, or areas in parking lots that block pedestrian access to the front doorway from their automobile can be susceptible to pedestrian traffic. Some sites did take measures to address public awareness concerns with the use of informational signage, such as Campus Sites 12 and 13 (Figure 19).

Figure 19. Campus Site 12 (Infiltration Rate: 19.1 in/hr.) informational signage “Stormwater Returns to Earth” (left) and “To biofilter” (right) (Photo by author).

Research Question 2: Criteria that are Associated with Infiltration Rates

Summary

Thirteen out of fifty-two sites fell within the recommended infiltration rate range of 5 to 10 inches per hour. As shown in Figure 20, while most of the sites did not fall within the recommended range, they are generally skewed towards that range rather than away from it. Twenty sites had infiltration rates that were greater than 20 inches per hour, and thirteen sites had infiltration rates that were either just below the recommended range (0 to 4.5 inches per hour) or just above the recommended range (10.6 to 15.5 inches per hour). Infiltration rates were organized in different range categories for representation (Figure 20), with a rectangle encircling the number of sites that fell within the recommended range of five to ten inches per hour. The total overall criteria scores for the sites are shown in Figure 21.

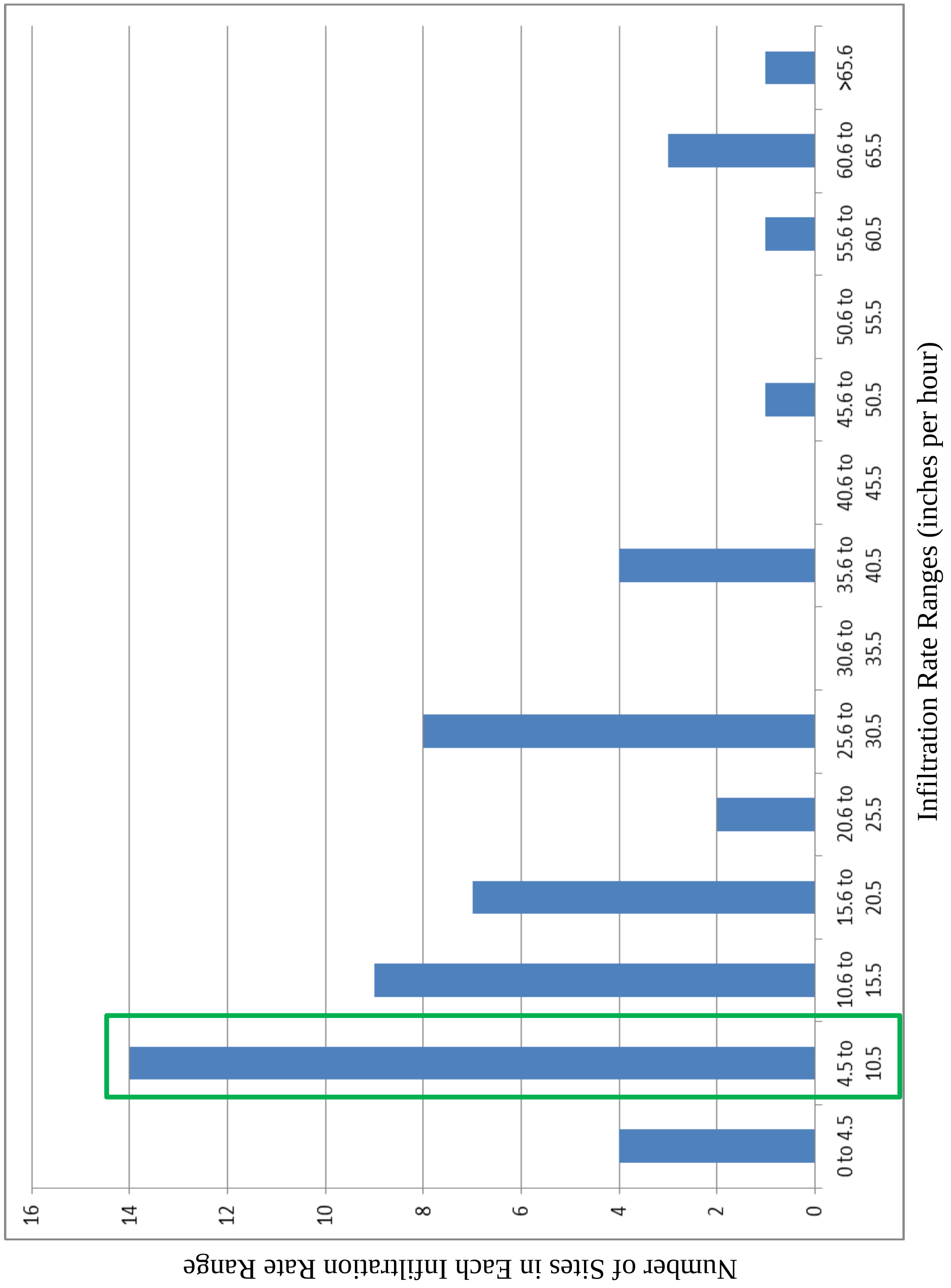

Figure 20. Histogram of the number of sites within each infiltration rate range. The recommended range, as noted by the rectangle, is between 5 and 10 inches per hour (Bicknell et al., 2016). Most sites did not fall within the recommended range. Histogram by author.

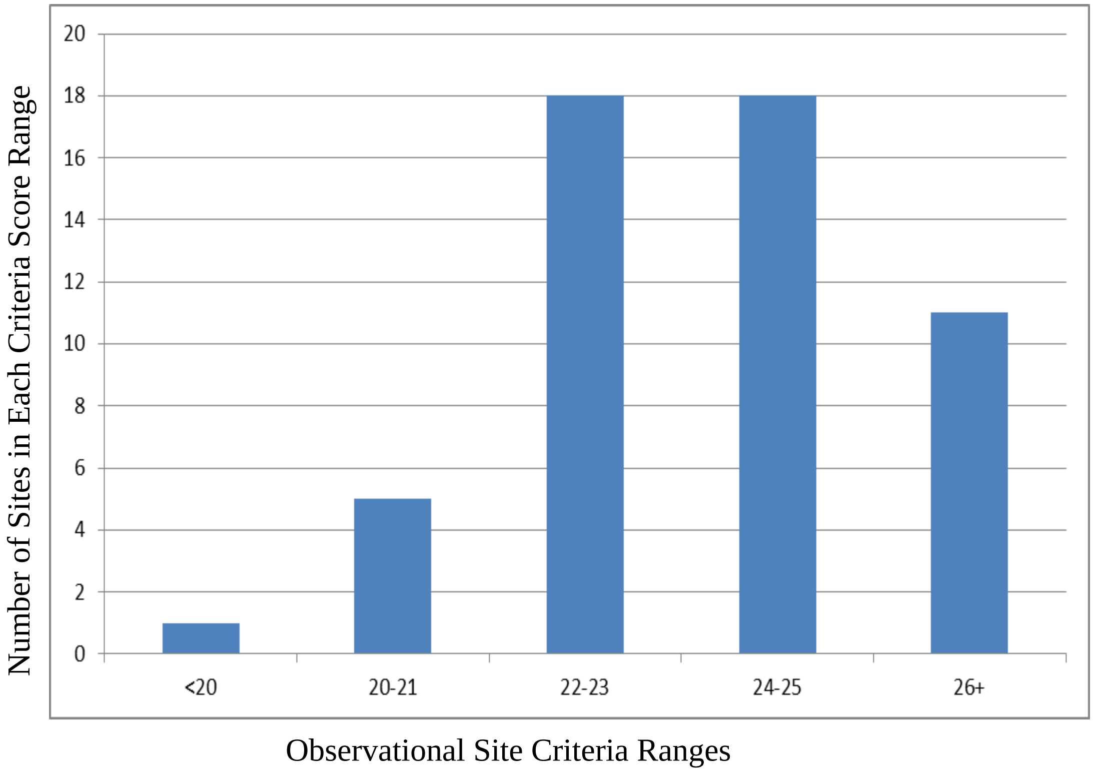

Figure 21. Histogram of the number of sites within each criteria score range. Histogram by author.

These criteria were grouped by ranges, with the lowest criteria score at 17 and the highest criteria score at 27. Most sites fell within the criteria scores of greater than or equal to 24, which shows that overall, the sites are well maintained and in good condition. Each of the criteria that could affect infiltration rate were statistically analyzed using R Software. These criteria include Soil Classification, Obstructions/Trash, Sediment Accumulation, Vegetation Health, Erosion, Animal Damage/Feces, and Functioning Irrigation.

Observational Site Criteria

Soil classification. For the purposes of this study, soils refer to “engineered” soil, which is defined as mineral or organic material that has been graded, moved or compacted over time (US EPA, 2011) and specifically designed to support native plant growth and allow for optimal infiltration rates. This soil is typically a mixture of topsoil, sand and compost (Schweitzer, 2013; US EPA, 2011). The recommended soil composition for Santa Clara County is approximately 70% sand and 30% compost materials (Bicknell et al., 2016), which in this study is considered to fall into the “Mostly Sand” classification. This ratio is comparable to the engineered soil mix of 70-85% sand, 10-15% silt, and 5-15% clay in New York City (Lozefski et al., 2017), and soils that fall into Hydrologic Soil Groups A and B (i.e., soils with high permeability) are best for infiltration, or soils with 80-90% sand (City and County of Denver, 2015). Based on the results of the Fligner-Killeen test, the data meet the assumption of homogeneity of variances (df=3, p-value=0.4723>0.05), and fail to reject the null hypothesis of homogeneity of variances. Using the Shapiro-Wilk normality test (p-value<0.05), the data set rejects the null hypothesis of normality and the Kruskal-Wallis rank sum test was used to compare the different sand classifications to infiltration rates. Based on the results (Kruskal-Wallis chi-squared = 2.1472, df = 3, p-value = 0.5424), the data set fails to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on soil classification. Figure 22 shows the boxplot analysis of infiltration rates with respect to soil classification, as identified in this study.

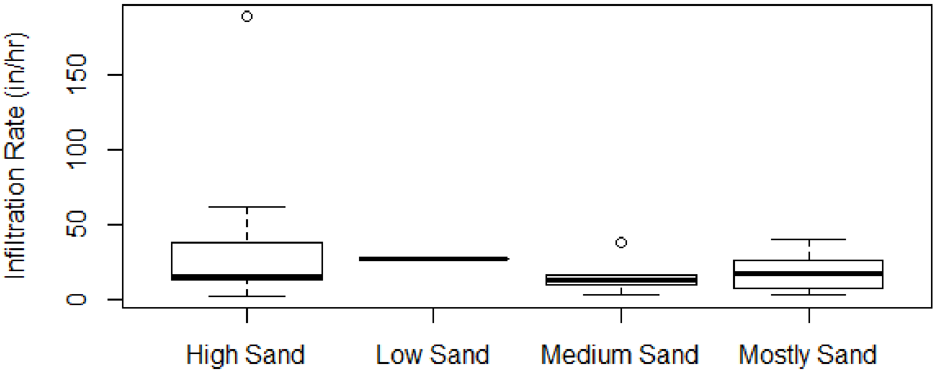

Figure 22. Boxplot of the four different soil classifications and their infiltration rates.

Figure 22 shows a larger range of infiltration rates with high sand soil classification than the other classifications, and almost no range in infiltration rates for the low sand classification. To determine if soil composition is independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=1.4567, df=1, p-value=0.2275>0.05), soil composition was independent of whether sites fell within the recommended infiltration rate range.

Research indicates that soil condition is critical in determining the development location of bioretention areas, as poor soil conditions can impede GSI success and infiltration rates (Bachmann, 2007; Chen, 2014; US EPA, 2011; Vermont Agency of Natural Resources, 2018). Particle size distribution, infiltration capacity, nutrient content and soil chemistry are all factors that determine soil health (Schweitzer, 2013; US EPA, 2011). Long-term soil maintenance and management is pertinent to ensuring adequate organic matter for plant growth and that the soil is not filled with debris or heavily compacted (Bachmann, 2007; US EPA, 2011). Over time, natural soil health declines during and after bioretention site construction, leading to heavy compaction, which can exhibit similar stormwater runoff characteristics as impervious surfaces (US EPA, 2011), because compaction leads to decreased aeration, drainage, root penetration and water-holding capacity. This demonstrates the necessity of engineered soils added to the sites, and for the health of the engineered soils to be monitored over time. This study only examined soil composition, not soil health, which can explain the unexpected insignificance in soil composition affecting infiltration rates in contrast with previous studies on soil condition being critical to bioretention performance. Further study on soil composition concurrent with soil condition could indicate a statistical significance in affecting infiltration rates.

Obstructions and trash. While bioretention areas can clean stormwater runoff by collecting trash during rain events, long-term trash accumulation can clog outlet drains, block runoff from entering inlets, and create a loss of aesthetic appeal for the site (City and County of Denver, 2015; David et al., 2011). The results of the Fligner-Killeen test shows that the data meet the assumption of homogeneity of variances (df=2, p-value=0.8.752>0.05), and the Shapiro-Wilk normality test results (p-value<0.05), shows a non-normal distribution. Analysis will proceed with Kruskal-Wallis rank sum test, with results showing that there is no significant difference in infiltration rate based on the criteria scoring for Obstructions/Trash (Kruskal-Wallis chi-squared = 0.70181, df = 2, p-value = 0.7041). Figure 23 shows a boxplot of the Obstructions and Trash criteria scores with infiltration rates.

Figure 23. Boxplot of the Obstructions/Trash criteria levels infiltration rates.

To determine if obstructions and trash criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=0.95022, df=2, p-value=0.6218>0.05), the obstructions/trash criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Sediment accumulation. If bioretention areas are susceptible to clogging by sediment or other debris accumulation over time, they will require a greater amount of long-term maintenance, and can cause the site to fail and achieving optimal infiltration rates (Minnesota Pollution Control Agency, 2017). The results of the Fligner-Killeen test meet the assumption of homogeneity of variances (df=2, p-value=0.1533>0.05), and the Shapiro-Wilk normality test (p-value<0.05), shows a non-normal distribution. Proceeding with the Kruskal-Wallis rank sum test (Kruskal-Wallis chi-squared = 0.2779, df = 2, p-value = 0.8703), the data fails to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the scoring for Sediment Accumulation. Figure 24 shows a boxplot of the Sediment Accumulation criteria scores and infiltration rates.

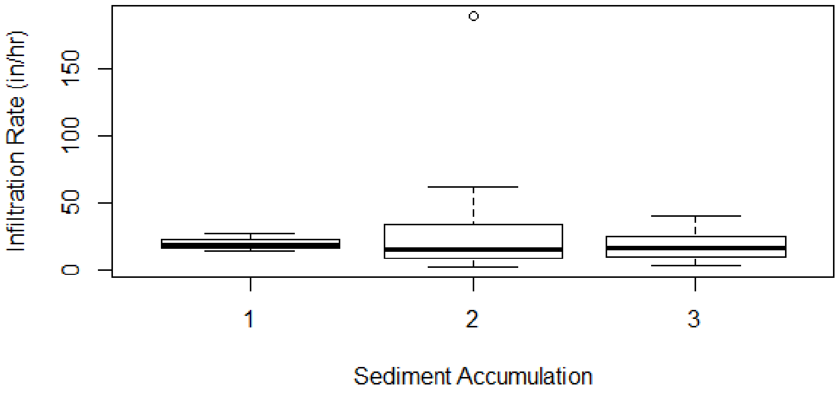

Figure 24. Boxplot of the Sediment Accumulation levels infiltration rates.

To determine if sediment accumulation criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=2.357, df=2, p-value=0.3077>0.05), the sediment accumulation criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Vegetation health. Plants are known to greatly improve infiltration rates, as well as improve water quality through pollutant uptake and biological processes (Bachmann, 2007; City and County of Denver, 2015). These natural processes generate necessary organic soil material, but are often disturbed in urban environments, which ultimately harm plant health (US EPA, 2011). Ideal bioretention areas should have dense and tightly spaced vegetation to reduce areas for weed growth, ensure maximum pollutant uptake, create a neat appearance, and facilitate the ease of maintenance (Bicknell et al., 2016; City and County of Denver, 2015). For the purposes of this study, the density of plants within the bioretention area, and the absence of dead or dying vegetation determine vegetation health. The Fligner-Killeen test shows a homogeneity of variances (df=2, p-value=0.08827>0.05), and the Shapiro-Wilk normality test shows a non-normal distribution (p-value<0.05). Proceeding with the Kruskal-Wallis rank sum test (Kruskal-Wallis chi-squared = 0.93522, df = 2, p-value = 0.6265), the data fail to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the scoring for Vegetation Health (Figure 25).

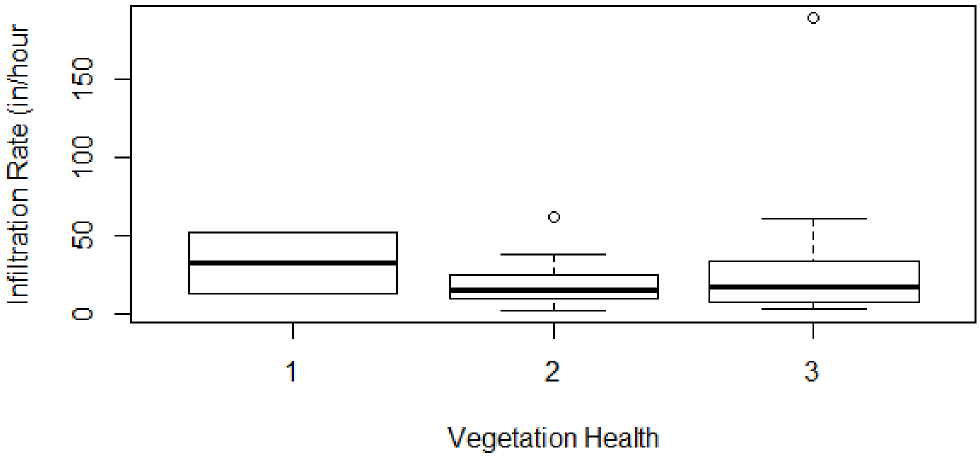

Figure 25. Boxplot of the Vegetation Health criteria levels infiltration rates.

To determine if vegetation health criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=2.6314, df=2, p-value=0.2603>0.05), the vegetation health criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Erosion. Erosion is one of the critical factors to look out for during site inspections, as well as locations of concentrated flow and drainage areas (Chen, 2014; US EPA, 2011). Erosion can cause soil loss, plant damage, and expose irrigation pipes to external vulnerabilities such as pedestrian traffic or maintenance vehicles (Facilities and Maintenance Staff 3, 2018; Municipal Staff 3, 2018; Municipal Staff 7, 2018). The Fligner-Killeen test shows a homogeneity of variances (df=2, p-value=0.8646>0.05), and the Shapiro-Wilk normality test shows a non-normal distribution (p-value<0.05). Proceeding with the Kruskal-Wallis rank sum test, (Kruskal-Wallis chi-squared = 1.3099, df = 2, p-value = 0.5195), the data fail to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the scoring for Erosion (Figure 26).

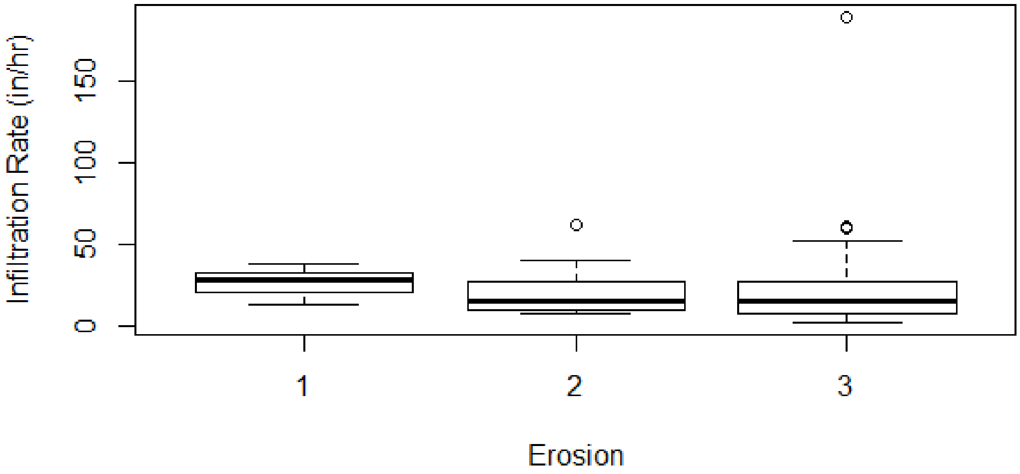

Figure 26. Boxplot of the Erosion criteria levels infiltration rates.

To determine if erosion criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=1.1415, df=2, p-value=0.5651>0.05), the erosion criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Animal damage and feces. The Fligner-Killeen test shows a homogeneity of variances (df=2, p-value=0.2776>0.05) and the Shapiro-Wilk normality test shows a non-normal distribution (p-value<0.05). Proceeding with the Kruskal-Wallis rank sum test (Kruskal-Wallis chi-squared = 0.82685, df = 2, p-value = 0.6614), the data fail to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the scoring for Animal Damage/Feces (Figure 27).

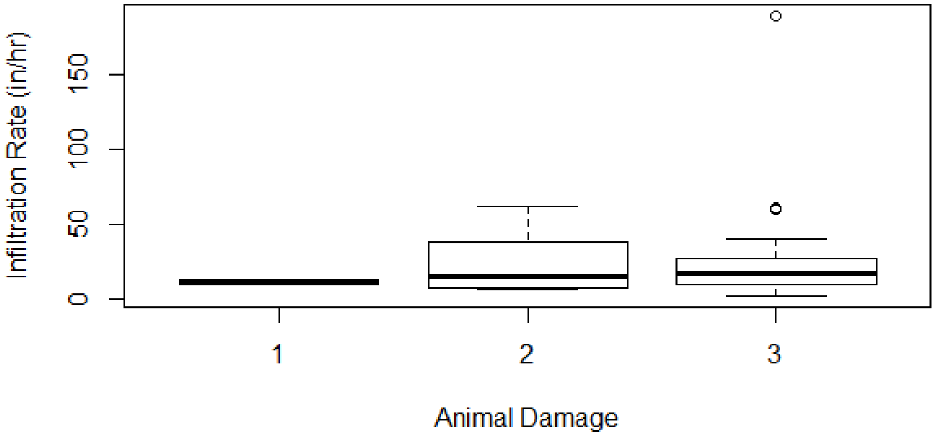

Figure 27. Boxplot of the Animal Damage criteria levels infiltration rates.

To determine if animal damage criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=2.5513, df=2, p-value=0.2792>0.05), the animal damage criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Functioning irrigation. The Fligner-Killeen test shows a homogeneity of variances (df=2, p-value=0.5327>0.05), and the Shapiro-Wilk normality test shows a non-normal distribution (p-value<0.05). Proceeding with the Kruskal-Wallis rank sum test, (Kruskal-Wallis chi-squared = 0.10736, df = 2, p-value = 0.9477), the data fail to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the scoring for Functioning Irrigation systems (Figure 28).

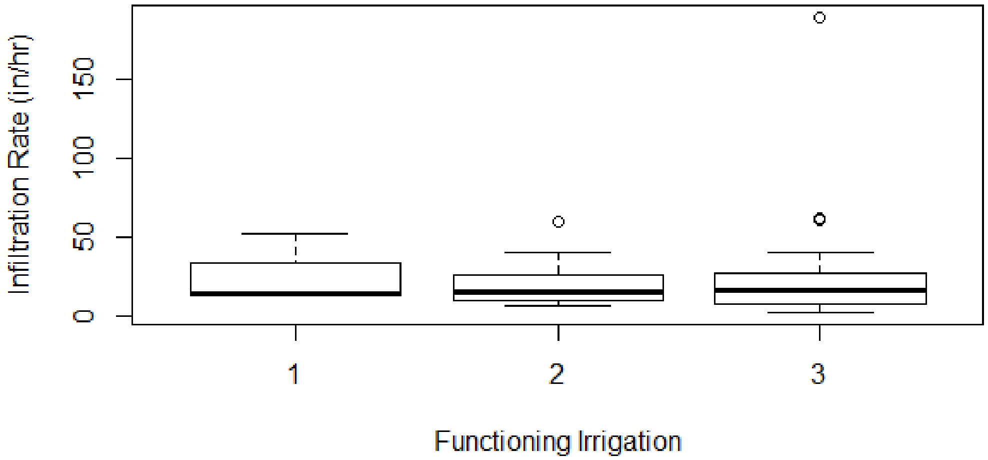

Figure 28. Boxplot of the Functioning Irrigation criteria levels infiltration rates.

To determine if functioning irrigation criteria scores are independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. Based on the chi-square results (Chi-Square=2.2354, df=2, p-value=0.3279>0.05), the functioning irrigation criteria scores were independent of whether sites fell within the recommended infiltration rate range.

Highest criteria scoring sites. Campus Site 15 had a total criteria score of 27 with an infiltration rate of 17.9 inches per hour. Campus Site 5 also had a total criteria score of 27, with an infiltration rate of 27.7 inches per hour. Both of these sites were located within campus borders, in the “Parking Lot/Campus” project typology category. Below are images of the top two criteria score sites (Figures 29 and 30).

Figure 29. Campus Site 15 (2013), with a total criteria score of 27 and an infiltration rate of 17.9 in/hr. (Photo by author).

Figure 30. Campus Site 5, with a total criteria score of 27, and an infiltration rate of 27.7 in/hr. (Photo by author).

Lowest criteria scoring sites. Municipal Site 31 (Figure 31) had a criteria score of 17, but an infiltration rate of 13.3 inches per hour, which falls within the "good" infiltration rate range of 2.5 to 16.0 inches per hour.

Figure 31. Municipal Site 31 (2015), with a criteria score of 17, and an infiltration rate of 13.3 in/hr. (Photo by author).

This site had less dense and dead or dying vegetation, evidence of animal feces, weed growth, and trash, and erosion in some locations. Municipal Site 36 (Figure 32) had a criteria score of 20, with an excellent infiltration rate of 10.0 inches per hour.

Figure 32. Municipal Site 36 (2014), with a criteria score of 20, and an infiltration rate of 10 in/hr. (Photo by author).

These four sites support the statistical insignificance of the total site criteria affecting infiltration rates, as the sites with the two lowest criteria scores had good infiltration rates, and the sites with the highest criteria scores had poor infiltration rates. To determine if there were any similar characteristics between sites with good infiltration rates and poor infiltration rates, the five lowest performing infiltration rates were identified (i.e., sites with infiltration rates greater than or equal to 40 inches per hour). Additionally, the top nine performing infiltration rate sites (i.e., sites that fell within the optimal range of 5 to 10 inches per hour) were analyzed for site-specific similarities.

Lowest performing infiltration rate sites. The five lowest performing infiltration rate sites (campus sites 2 and 11, and municipal sites 10, 12 and 13) are listed in Table 9, followed by their photos. Lowest performing infiltration rate sites were characterized as sites that have infiltration rates that are greater than 40 inches per hour. Campus Site 2 had a lot of leaf buildup throughout the basin, as well as dirt buildup at the basin inlets, which can block water flow (Figure 33).

Table 8

The four lowest performing infiltration rate sites

Site Name	**Infiltration Rate (inches per hour)**	**Soil Type**	**Total Criteria Score**	**Project Type**
C2	62.1	High Sand	22	Parking Lot/Campus
C11	52.9	High Sand	21	Large Bioretention
M10	40	High Sand	22	Public Street
M12	61	High Sand	25	Public Street
M13	60	High Sand	24	Public Street

Note. (Highest Possible Criteria Score: 27; Recommended Infiltration Rate Range: 5-10 in/hr.). Copyright 2016 by SCVURPPP.

Figure 33. Campus Site 2 (2014) with an infiltration rate of 62.1 in/hr., and total criteria score of 22 (Photo by author).

Leaf buildup can clog outlet drains over time, and may negatively affect the growth of native vegetation. This site has many trees, however not dense enough vegetation to remove pollutants through transpiration and absorption. Evidence of animal burrowing can also be an indicator for a lack of vegetation, because burrowing can damage roots and soil compaction that retains moisture. Campus Site 11 has minimal vegetation, with the little present vegetation being dry and small (Figure 34).

Figure 34. Campus Site 11 (2013) with an infiltration rate of 52.9 in/hr., and a total criteria score of 21 (Photo by author).

This site has a lot of gravel materials at the surface and did not seem to have much compost materials to support native plant growth. There was also evidence of animal feces towards the perimeter of the site, likely from pets that are walked along the bordering sidewalk. Municipal Site 10 had a lot of sediment buildup with leaves, trash and dirt at the basin inlets, and had some evidence of erosion that may have been caused by the removal of invasive weed species present in the site (Figure 35).

Figure 35. Municipal Site 10 (2015) with a infiltration rate of 40 in/hr., and a total criteria score of 22 (Photo by author).

Weeds dominate the basin over native vegetation, with only some native grasses in the center of the basin. It should be noted, however, that this site was cleaned out and replaced with lawn rolls a few months after the site visit (Municipal Staff 1, 2018). Municipal Sites 12 and 13 (Figures 36 and 37) both had mulch covering their surfaces and minor bits of trash.

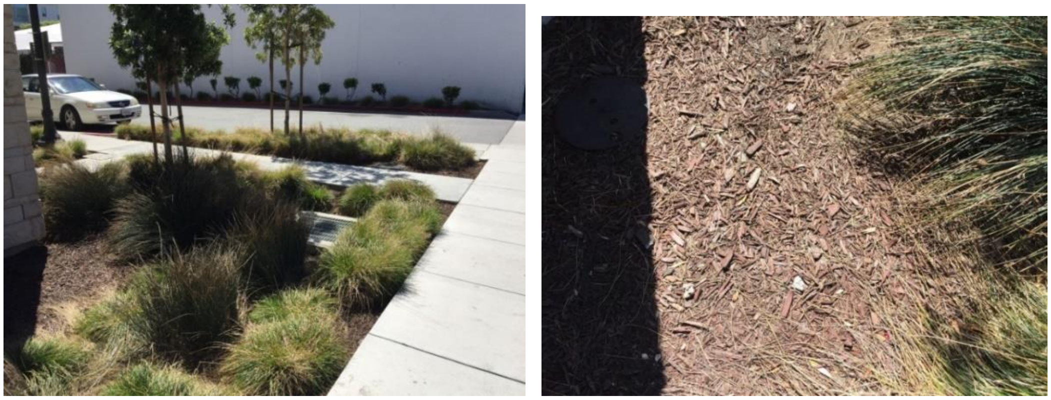

Figure 36. Municipal Site 12 (2013) with an infiltration rate of 61 in/hr., and a total criteria score of 25 (Photo by author).

Figure 37. Municipal Site 13 (2013) with an infiltration rate of 60 in/hr., and a total criteria score of 24 (Photo by author).

Municipal Site 12 has a bit more native vegetation that Municipal Site 13, but Municipal Site 13 has some trees in the basin. Based on the above photos and their criteria scores, all five sites were constructed in either 2013, 2014 or 2015, had a high sand content (80-100% sand material), and had lower criteria scores for sediment accumulation. Four out of the five sites had lower scores for obstructions/trash, three out of five had lower scores for vegetation health/density, and two out of five sites had lower scores for either irrigation concerns or animal damage. None of these five sites consisted of California native perennial bunch grasses, which is a common trait among most of the sites that had infiltration rates between five to ten inches per hour.

Highest performing infiltration rate sites. This infiltration rate range is similar to suggested ranges in other geographic regions of the United States, including Vermont which has 0.5 to 8 inches per hour (Vermont Agency of Natural Resources, 2018). Nine out of twelve sites had California native perennial bunch grass vegetation in their basins, whereas none of the highest infiltration rate sites had these bunch grasses. These sites were constructed between 2011 and 2016, and seven out of the twelve sites had medium (45-59% sand material) to mostly sand (60-79% sand material), whereas five out of twelve sites still had high sand (80-100% sand material). Ten out of twelve sites had lower criteria scores (score 2 or 1) for vegetation health and sediment accumulation, and nine out of twelve sites had lower criteria scores for obstructions/trash. Below is a table and photos of the twelve sites that had infiltration rates within the recommended range of five to ten inches per hour, which is the optimal infiltration rate for Santa Clara County (Bicknell et al., 2016).

Table 9

The twelve highest performing infiltration rate sites

Site Name	**Infiltration Rate (inches per hour)**	**Total Criteria Score**	**Soil Type**	**Project Type**
C9	8.8	23	Mostly Sand	Parking Lot/Campus
C13	5.5	23	High Sand	Parking Lot/Campus
M2	7.3	26	High Sand	Parking Lot/Campus
M5	6.5	23	High Sand	Public Street
M6	8.2	24	Mostly Sand	Parking Lot/Campus
M11	5.7	26	High Sand	Residential Street
M23	10.1	23	High Sand	Public Street
M24	9.0	23	Mostly Sand	Parking Lot/Campus
M26	6.5	23	Mostly Sand	Parking Lot/Campus
M27	10.0	23	Medium Sand	Residential Street
M35	7.8	21	Mostly Sand	Parking Lot/Campus
M36	10.0	20	Mostly Sand	Parking Lot/Campus

Note. (Highest Possible Criteria Score: 27; Recommended Infiltration Rate Range: 5-10 in/hr.). Copyright 2016 by SCVURPPP.

Campus Site 9 consists entirely of thick California native perennial bunch grass vegetation, which is overgrown in most areas but otherwise green and healthy. Mulch landscaping surrounds the site, and there was evidence of Redwood tree needles or branches within the basin (Figure 38).

Figure 38. Campus Site 9 (2015) with an infiltration rate of 8.8 in/hr., and a total criteria score of 23 (Photo by author).

Campus Site 13 had evidence of trash, sediment accumulation and a low density of vegetation, with excess sprinkler heads within the area. The shrubs in the site were healthy (Figure 39).

Figure 39. Campus Site 13 (2012) with an infiltration rate of 5.5 in/hr., and a total criteria score of 23 (Photo by author).

Municipal Site 2 has California native perennial bunch grass vegetation, but much of it is overgrown and there are some brown patches within the basin. This site is otherwise in good condition with respect to the site observation criteria (Figure 40).

Figure 40. Municipal Site 2 (2012) with an infiltration rate of 7.3 in/hr., and a total criteria score of 26 (Photo by author).

Municipal Site 5 had thick and healthy California native perennial bunch grass vegetation, however, there was evidence of trash, animal damage (including rodent poison), sediment accumulation, and exposed irrigation pipes (Figure 41). Municipal Site 6 has newly installed grass vegetation, with some exposed irrigation pipes and sediment accumulation from surrounding landscape mulch that has leaked into the basin (Figure 42). Municipal Site 11 has developing grass vegetation and an overall high criteria score with respect to the site observational criteria (Figure 43).

Figure 41. Municipal Site 5 (2016) with an infiltration rate of 6.5 in/hr., and a total criteria score of 23 (Photo by author).

Figure 42. Municipal Site 6 (2016) with an infiltration rate of 8.2 in/hr., and a total criteria score of 24 (Photo by author).

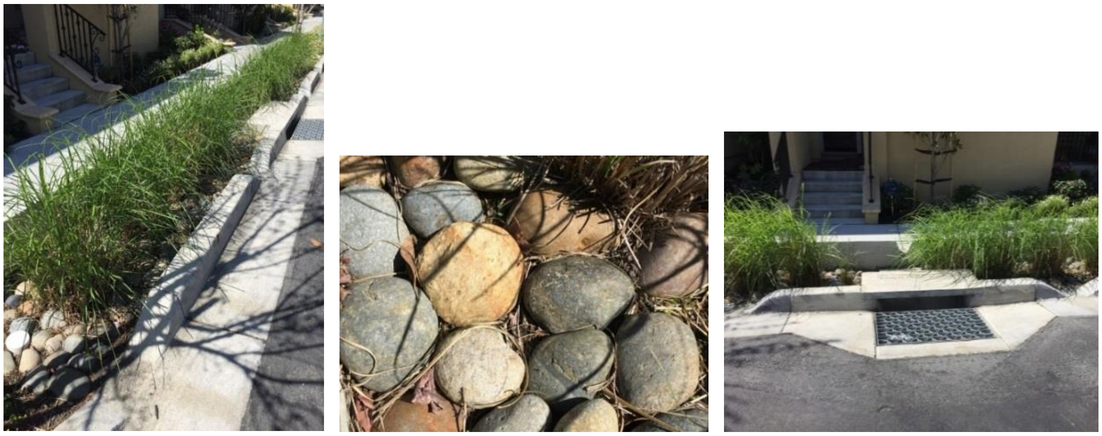

Figure 43. Municipal Site 11 (2015) with an infiltration rate of 5.7 in/hr., and a total criteria score of 26 (Photo by author).

Municipal Site 23 had minimal existing vegetation, exposed irrigation pipes, clogged inlets, and accumulation of plant debris, but an otherwise excellent infiltration rate (Figure 44). Municipal Sites 24 and 26 each had evidence of animal burrowing, surrounding mulch leakage, and some bits of trash, but they both had excellent infiltration rates and exhibited healthy, California native perennial bunch grass vegetation (Figures 45 and 46). Municipal Site 27 had an excellent infiltration rate, but less dense vegetation, bits of sediment accumulation, and trash debris including a couple broken wooden boards (Figure 47).

Figure 44. Municipal Site 23 (2012) with an infiltration rate of 10.1 in/hr., and a total criteria score of 23 (Photo by author).

Figure 45. Municipal Site 24 (2011) with an infiltration rate of 9 in/hr., and a total criteria score of 23 (Photo by author).

Figure 46. Municipal Site 26 (2011) with an infiltration rate of 6.5 in/hr., and a total criteria score of 23 (Photo by author).

Figure 47. Municipal Site 27 (2011) with an infiltration rate of 10.0 in/hr., and a total criteria score of 23 (Photo by author).

Municipal Sites 35 and 36 each had large evidence of animal burrowing and weed growth, as well as erosion spots and dry vegetation. Groundhogs live in the surrounding landscape, and they often travel over the parking lot to each of the two bioretention basins (Facilities and Maintenance Staff 1, 2018). These sites are shown in Figures 48 and 49.

Figure 48. Municipal Site 35 (2014) with an infiltration rate of 7.8 in/hr., and a total criteria score of 21 (Photo by author).

Figure 49. Municipal Site 36 (2014) with an infiltration rate of 10.0 in/hr., and a total criteria score of 20 Total Criteria Score 20 (Photo by author).

Even though all of these sites fell within the recommended 5 to 10 inches per hour infiltration rates, they each had some lower criteria scores, which is evidence that individual criteria scores in this study do not have a significant effect on infiltration rate performance. To determine if there was any statistical significance in each of the combined criteria, the total scores were added and compared to infiltration rates. For example, Campus Site 1 had the following criteria scores: Obstructions/Trash-1, Ponded Water-3, Erosion-3, Sediment Accumulation-2, Vegetation Density/Health-2, Functioning Irrigation-3, Structural Integrity-3, Vegetation Obstructing Road Visibility-3, and Animal Damage/Feces-2, adding up to a total criteria score of 22. For all sites, the range of total criteria scores was 17 to 27, the average criteria score was 23.8, and the most common score was 23 (Figure 50).

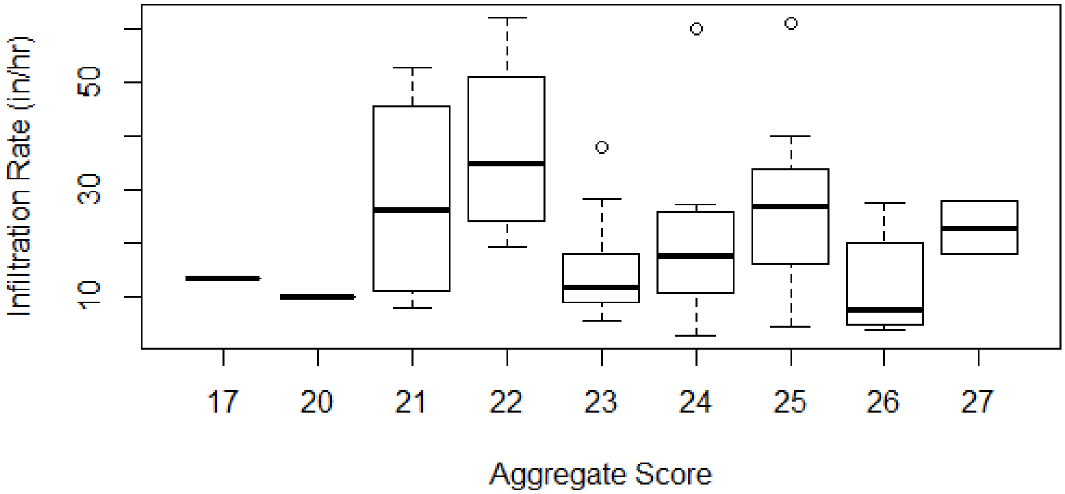

Figure 50. Boxplot of the total criteria scores and their infiltration rates.

Based on the results of the Fligner-Killeen test, the data meet the assumption of homogeneity of variances (df=8, p-value=0.1746>0.05), and the data fails to reject the null hypothesis of homogeneity of variances. Using the Shapiro-Wilk normality test (p-value<0.05), the data rejects the null hypothesis of normality and will proceed with Kruskal-Wallis rank sum test. Based on the results (Kruskal-Wallis chi-squared = 13.179, df = 8, p-value = 0.1058), the data fails to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the total criteria scores. Each of the individual criteria scores as well as the total criteria scores are not enough to strongly affect infiltration rates in each site. To determine if a different score scale made a significant difference in affecting infiltration rate, each of the criteria scores (i.e., 1, 2 and 3) were increased by multiplying by 3. The new scores thus become 3 (poor sites), 6 (fair sites) and 9 (good sites). The Kruskal-Wallis rank sum test was used in lieu of ANOVA due to homogeneity of variances but not a normal distribution (Fligner-Killeen p-value=0.4604, Shapiro-Wilk p-value<0.05). The results of the Kruskal-Wallis rank sum test (Chi-Squared=19.212, df=15, p-value=0.2043>0.05), there is still not a significant affect on infiltration rate with increased criteria score values (Figure 51).

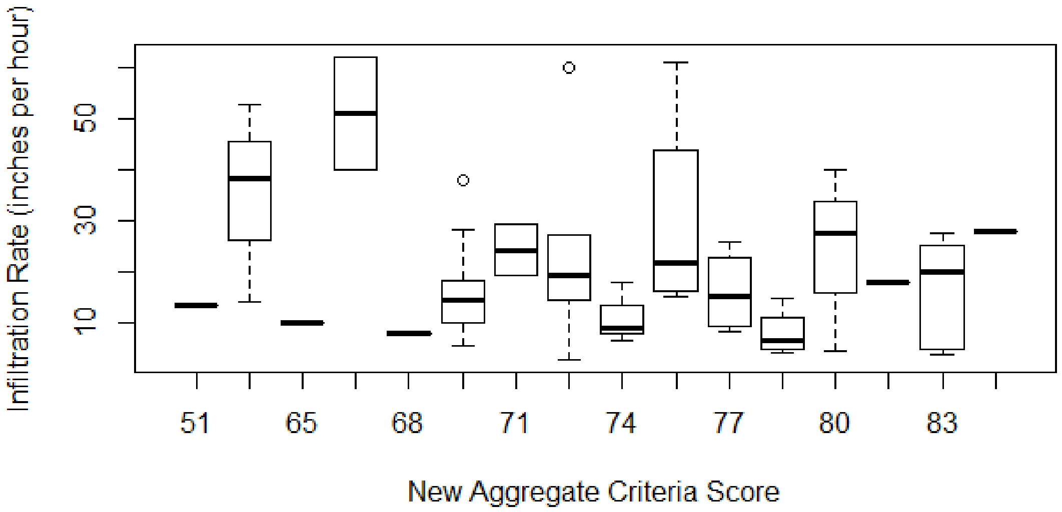

Figure 51. Boxplot of the new total criteria scores with increased score values and their infiltration rates.

To determine if the total criteria score is independent of sites falling within the recommended range of 5 to 10 inches per hour, Pearson's chi-squared contingency test was used. The criteria scores were organized by three levels: Low (scores less than or equal to 21), Medium (scores of 22 to 23), and High (scores greater than or equal to 24). The results of the test (Chi-Square=4.2195, df=2, p-value=0.1213>0.05), it is determined that the total criteria score levels are independent of whether sites fall within the recommended criteria range.

Although the total criteria scores do not indicate whether sites fall within the recommended infiltration rate range, a larger sample size might yield more significant results. In testing this theory, the number of sites within each chi-square matrix category was increased by multiplying by three to simulate a larger sample size. This resulted in the criteria score ranges having a significant dependence on whether sites fell within the recommended infiltration rate range (Chi-Square=12.659, df=2, p-value=0.001783<0.05). This is a strong indicator that criteria scores may have a significant effect on infiltration rates and sites falling within their recommended range if the sample size was increased, although the bar plots in Figures 52 and 53 still show that a medium range criteria score yields more sites within the recommended range than a low or high criteria range score.

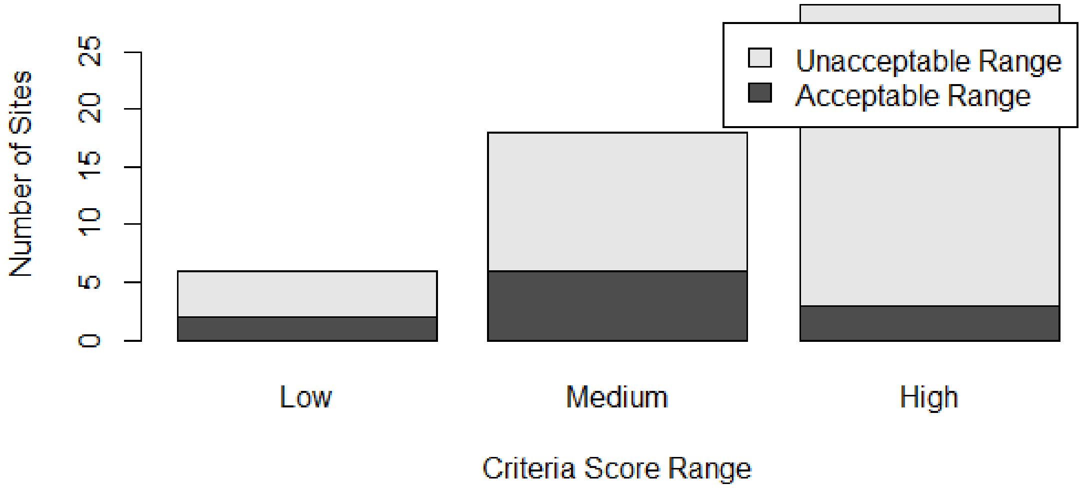

Figure 52. Bar plot of the three criteria score ranges and whether the sites fall in the acceptable range of infiltration rates.

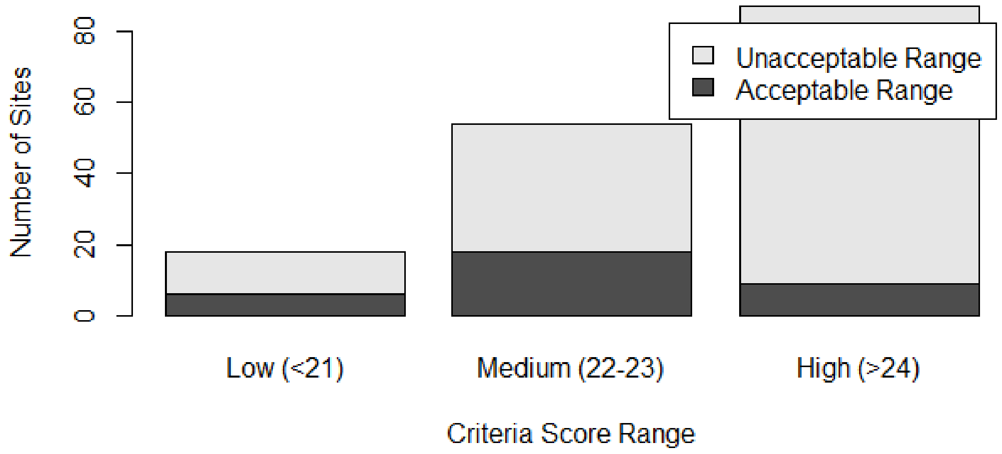

Figure 53. Bar plot of the three criteria score ranges with the simulated larger sample size analysis.

The total overall scores include the total criteria score, plus the soil classification score. For soil classification, five points were added to the total criteria score if the site had a “Mostly Sand” classification, or 60-79% sand material, which meets the recommended sand composition by SCVURPPP. If the site had any other sand classification (i.e., High Sand [80-100%], Medium Sand [45-59%], or Low Sand [0-44%]), no points were added. Table 10 summarizes an example of the total scoring for three sites.

Table 10

Total overall score calculation example

Site Name	**Total Criteria Score**	**Soil Classification**	**Total Overall Score**
Campus Site 9	23	Mostly Sand: +5	*28*
Municipal Site 3	25	Mostly Sand: +5	*30*
Municipal Site 16	24	High Sand: +0	*24*

Based on the results of the Fligner-Killeen test, the data meet the assumption of homogeneity of variances (df=15, p-value=0.4604>0.05). The data fails to reject the null hypothesis of homogeneity of variances. Using the Shapiro-Wilk normality test (p-value<0.05), the data rejects the null hypothesis of normality and will proceed with Kruskal-Wallis rank sum test. Based on the results (Kruskal-Wallis chi-squared = 19.212, df = 15, p-value = 0.2043>0.05), the data fails to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the total scoring, which includes the total criteria scores and soil type scores. This means that with the addition of using the additional points for the recommended soil composition (70% sand, 30% compost material), the total scores still do not significantly affect infiltration rates. Figure 54 summarizes the statistical means of the total overall scores and their infiltration rates.

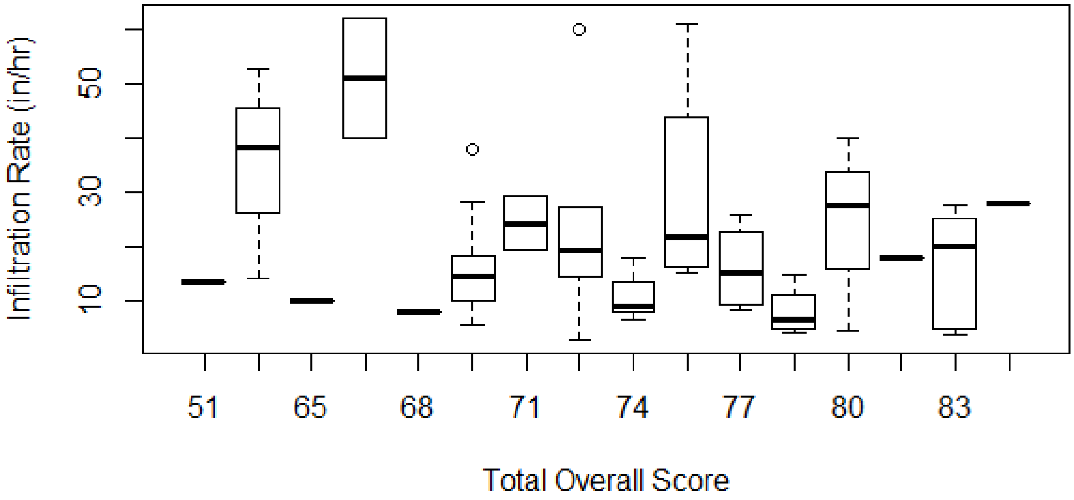

Figure 54. Boxplot of the total overall scores and their infiltration rates.

The criteria score sheet for this study, adapted from municipal inspection logs (Bicknell et al., 2016; City of San José, 2017; SFPUC, 2017) and used as a means to assess bioretention area performance (Schultze-Allen, 2017), was not associated with infiltration rates, either as individual criteria scores or as a total criteria score. Considering the addition of different criteria or other factors may improve the association between inspection criteria and infiltration rates.

Other Factors That Can Affect Infiltration Rate

To further investigate factors that affect site infiltration rates, the researcher examined the presence or absence of trees or California native perennial bunch grass vegetation on the site, the year the sites were each completed, and patterns associated with project typology. In addition to these factors, it should be noted that infiltration rates are also affected by rainfall intensities (Kazemi, 2014), which were not monitored in this study. Additionally, infiltration rates tend to decrease as temperature decreases due to an increase in stormwater runoff viscosity (Minnesota Pollution Control Agency, 2017). Other factors not included in this study that can affect infiltration rates are soil compaction, soil condition, pollution concentrations, and disturbance by human activity (Lozefski et al., 2017).

Tree presence. Existing trees at or near bioretention sites are often excellent long-term indicators of soil condition (US EPA, 2011). This is because trees support the decay of plant materials and growth of microorganisms to generate organic soil matter (US EPA, 2011). Trees can help improve infiltration rates in bioretention areas (City and County of Denver, 2015) by penetrating the soil to create flow paths (Schultze-Allen, 2017), and tree canopies prove a large surface area for evaporation and intercepting rainwater before it hits the ground (Vermont Agency of Natural Resources, 2018). Based on the results of the Fligner-Killeen test, the data meet the assumption of homogeneity of variances (df=1, p-value=0.3874>0.05). Using the Shapiro-Wilk normality test (p-value<0.05), the data reject the null hypothesis of normality and will proceed with Kruskal-Wallis rank sum test. Based on the results (Kruskal-Wallis chi-squared = 0.0069486, df = 1, p-value = 0.9336), it is determined that there is no significant difference in infiltration rate based on the presence or absence of trees in the basin. Although the presence or absence of a tree is not statistically significant in how it affects infiltration rate, the Figure 55 shows a much higher range of infiltration rates for sites that do not have a tree in their basin, which can indicate that the trees help to slow down infiltration rates. This may be different over time as trees mature and further develop their roots underground or their canopies above the basin, since the oldest site within the study frame is only seven years old.

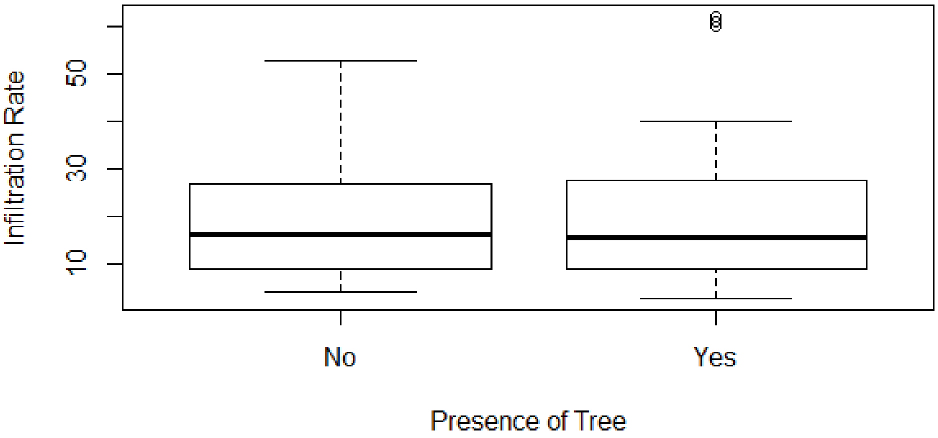

Figure 55. Boxplot comparing the presence or absence of trees and infiltration rates.

To further assess tree presence as a factor affecting infiltration rate, Pearson's chi-squared contingency test was performed to determine if tree presence was independent of sites falling within the recommended 5 to 10 inches per hour range and sites that do not fall in this range. This test did not result in a significant difference in sites falling in the recommended range based on the presence or absence of trees (Chi-Squared= 0.43348, df=1, p-value= 0.5103). In Figure 56, more sites with a tree have "Poor" (i.e., not in range) infiltration rates than sites with a tree that have "Good" (i.e., within 5 to 10 inches per hour) infiltration rates.

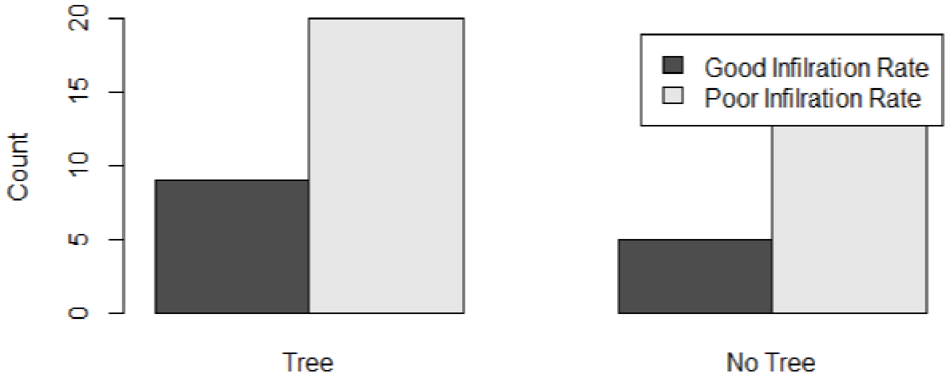

Figure 56. Bar chart comparing the frequencies of acceptable infiltration rates (i.e., 5 to 10 inches per hour) and “Poor” infiltration rates (i.e., >10 inches per hour or <5 inches per hour) with tree presence.

This could be affected by the low frequency of “Good” infiltration rates in general among all sites with or without trees. Many of the trees within each site are also young and have not yet reached maturity, which can also affect the statistical significance. Adding a section in municipal inspection logs and this study’s criteria sheet for tree presence might show an association over time with infiltration rates based on the presence or absence of trees and even individual tree species.

California native perennial bunch grass vegetation. The site observations and analysis of top performing bioretention areas and bottom performing bioretention areas suggest the use of California native perennial bunch grass vegetation as a factor that positively affects infiltration rate. In using Pearson’s chi-squared contingency test, it was determined that bunch grass vegetation presence on site is independent of sites falling within the recommended 5 to 10 inches per hour range or not (Chi-Square=2.9, df=1, p-value=0.089), however the p-value is low enough to suggest that perhaps a larger sample size might yield a higher dependence on bunch grass to indicate sites falling within 5 to 10 inches per hour. Figure 57 shows a histogram comparing the presence or absence of bunch grass vegetation to infiltration rates, organized by range categories.

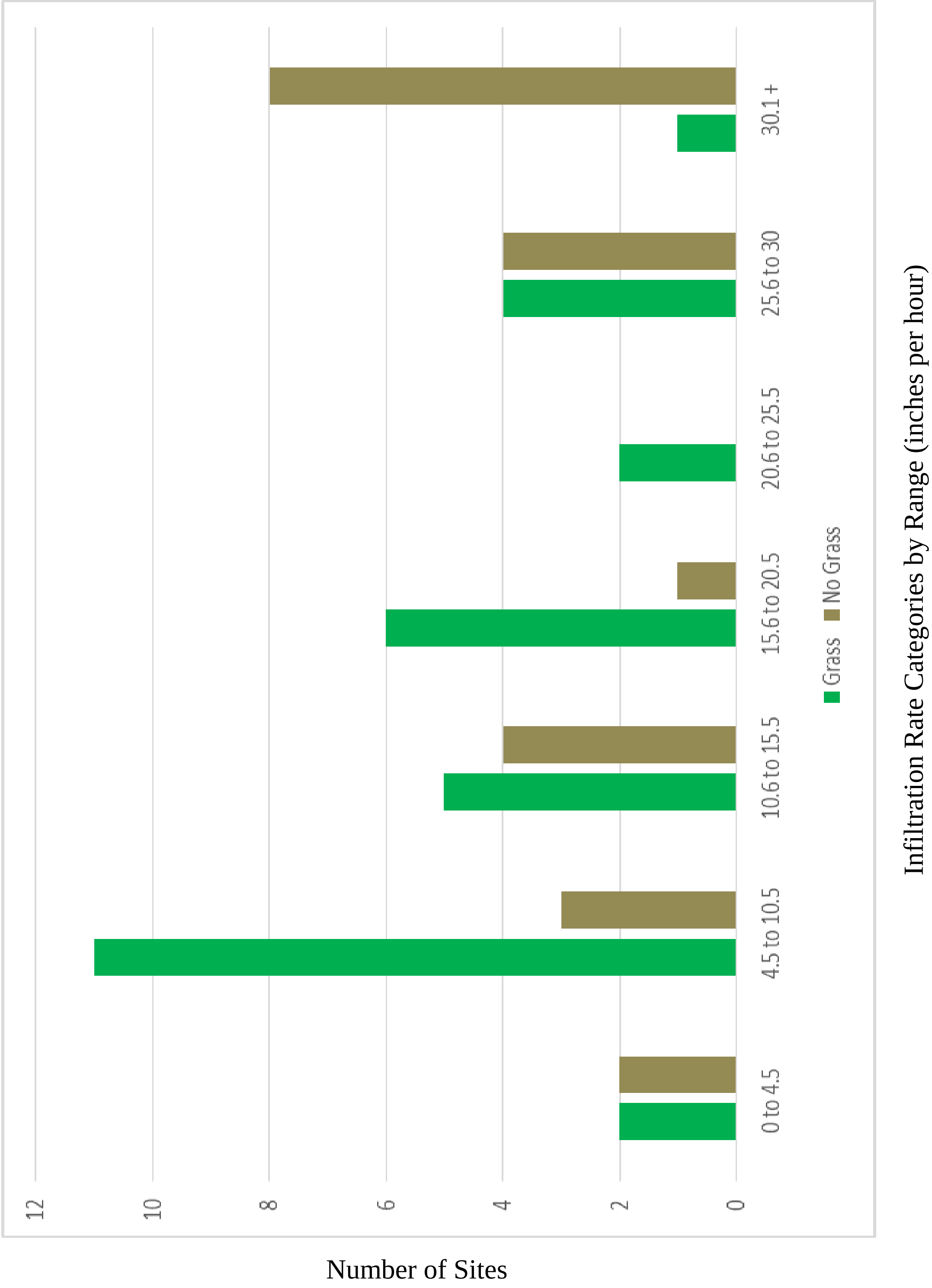

Figure 57. Histogram comparing the number of sites with or without California native perennial bunch grass vegetation in each infiltration rate range category.

As shown in Figure 57, almost all sites within the recommended range of 5 to 10 inches per hour had the bunch grass vegetation, and almost all of the lowest performing sites (i.e., greater than 30 inches per hour) did not have the bunch grass vegetation. This suggests a correlation to the presence of bunch grass vegetation indicating better infiltration rates, and a larger sample size may create a statistical significance.

To compare the infiltration rate means of sites with the presence or absence of bunch grass vegetation, Wilcoxon rank sum test was used, which yielded a significant result (W=462, df=50, p-value=0.03653<0.05). These results determined that infiltration rates in general were closer to the recommended range of 5 to 10 inches per hour if bunch grass vegetation is present, based on the statistical significance of the Wilcoxon rank sum test. This test was used in lieu of the two sample t-test because the data did not meet the assumption of homogeneity of variances (Fligner-Killeen p-value<0.05) or normality (Shapiro-Wilk normality test p-value<0.05). The mean of infiltration rates for sites that did not have the bunch grass was 26.44 inches per hour, and the mean of infiltration rates for sites that do have bunch grass was 15.45 inches per hour, which is much closer to the recommended 5 to 10 inches per hour range. While the presence of California native perennial bunch grass vegetation significantly affects infiltration rate, further research would be needed to determine which specific species of bunch grasses help to improve infiltration rates, as this study did not examine specific bunch grass species (Figure 58).

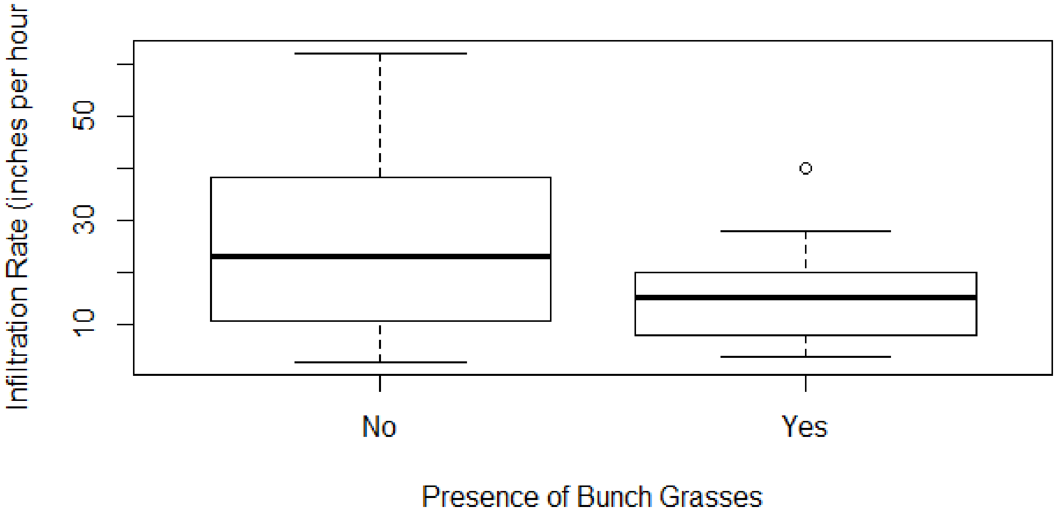

Figure 58. Boxplot comparing the infiltration rates of sites with and without bunch grass vegetation.

In future inspection and criteria sheets for municipal inspections or continued research, noting the presence or absence of bunch grass vegetation may indicate an association between bunch grass species and types with infiltration rates.

Year of completion. The Calendar Year of completion was recorded for each of the sites in the study area. Based on the results of the Fligner-Killeen test, the data meet the assumption of homogeneity of variances (df=6, p-value=0.05052>0.05). The data fail to reject the null hypothesis of homogeneity of variances. Using the Shapiro-Wilk normality test (p-value<0.05), the data reject the null hypothesis of normality and the Kruskal-Wallis rank sum test was used. Based on the results (Kruskal-Wallis chi-squared = 12.286, df = 6, p-value = 0.05589), the data fail to reject the null hypothesis and it is determined that there is no significant difference in infiltration rate based on the year the bioretention project was completed. Since the p-value is so close to 0.05, a larger sample size might yield a statistically significant value. As shown in the figure above, sites built in 2013 had much higher infiltration rates than all other years of completion, sites built in year 2014 had the largest range of infiltration rates, and sites built in 2011 and 2017 had infiltration rates closest to 5-10 inches per hour (Figure 59).

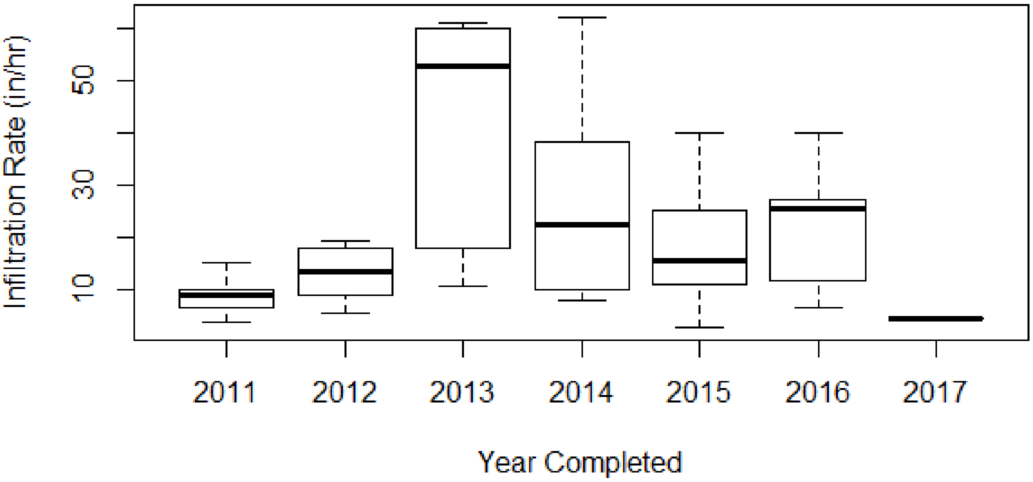

Figure 59. Boxplot comparing the year of completion and infiltration rates.

Project typology. To determine if there is a pattern of acceptable performing sites (sites with infiltration rates of 5 to 10 inches per hour), each bioretention area was grouped into one of four categories: Residential Bioswale, Public Bioswale, Parking Lot/On Campus Bioretention, and Large Bioretention Pond. Bioretention areas that were along neighborhoods and adjacent to residential properties were considered to be in the Residential Bioswale category, whereas sites that were along public roads were considered to be in the Public Bioswale category. Sites that were within parking lots or within campus borders and not along streets were in the Parking Lot/On Campus Bioretention category, and exceptionally large sites that covered large areas fell into the Large Bioretention Pond category. As shown in Table 11, Large Bioretention Pond category sites had the highest frequency of acceptable performing sites at 67%, followed by Parking Lot/On Campus Bioretention at 24%, Public Bioswales at 17%, and Residential Bioswales at 14%. This suggests that larger bioretention ponds may be the best design to achieve an ideal infiltration rate. Parking Lot/On Campus Bioretention sites are also slightly larger than Residential and Public Street Bioswales, which can be another indicator that larger site designs perform better in terms of infiltration rate than smaller site designs. A slightly smaller percentage of Residential Bioswale sites fell within the recommended range than Public Bioswales, which is not consistent with other studies. Residential vegetated areas tend to have less soil compaction, lower levels of contamination, and higher organic matter content than vegetated areas located in more urbanized settings (US EPA, 2011).

Table 11

Four different project types

Project Type	**Number of Sites**	**Percent with acceptable infiltration rates (5 to 10 inches per hour)**
Residential Bioswale	14	14%
Public Bioswale	12	17%
Parking Lot/On Campus Bioretention	21	24%
Large Bioretention Pond	6	67%

To determine if there was any statistical significance in each of the site designs affecting infiltration rates, the Kruskal-Wallis rank sum test was used since the data had homogeneity of variances (Fligner-Killeen p-value=0.53) but not a normal distribution. The results of the Kruskal-Wallis rank sum test (Kruskal-Wallis test=9.2962, p-value=0.054), it is determined that site typology does affect infiltration rate (Figure 60).

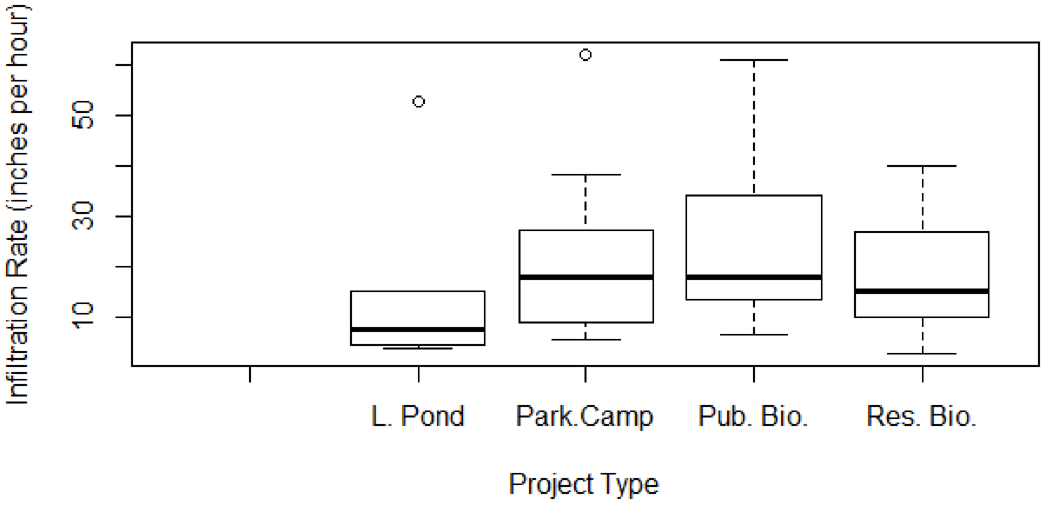

Figure 60. Boxplot of the four different project typologies and infiltration rates in inches per hour.

Based on the boxplot of Figure 60, it can be visually observed that most of the sites in the Large Bioretention Pond category fell within the 5 to 10 inches per hour range, and the Public Bioswales had the highest variability of infiltration rates. Project design type should be considered for inspection criteria in future research or municipal inspections to improve the association between design and infiltration rates.

Research Question 3: Campuses versus Municipalities Site Performances

The Wilcoxon rank sum test/Mann-Whitney U test was used to compare the means of infiltration rates on campuses versus municipalities. Based on the results from the Wilcoxon rank sum test (W=342, p-value=0.4987), the data fail to reject the null hypothesis that bioretention infiltration rates do not have a difference in means based on site location. The Wilcoxon rank sum test/Mann-Whitney U test was used due to the data not meeting the assumption of normality (Shapiro-Wilk normality test W=0.89969, p-value=0.06712) and homogeneity of variances (F-test for variances, F=0.28255, num df=16, denom df=35, p-value=0.009136). Infiltration rate performance does not differ based on its location on a campus or within a municipality. This can indicate that bioretention areas have similar maintenance and inspection procedures in both locations, as well as similar design techniques. Eleven out of the thirteen sites within the acceptable infiltration rate range, however, were municipal sites, and only two campus sites fell within the acceptable range (Figure 61).

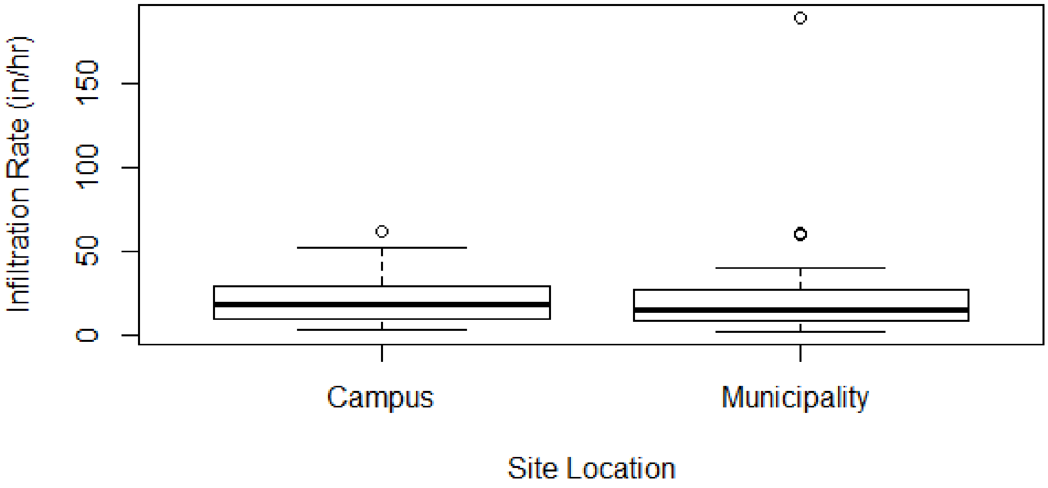

Figure 61. Boxplot of the Campus and Municipality overall infiltration rates.

To test whether site location is independent of sites falling within the acceptable infiltration rate range, Pearson's chi-squared contingency test was used to compare campuses and municipalities with being in the acceptable range and not being in the acceptable range. Based on the results of the chi-square test (Chi-Square=1.4275, df=1, p-value=0.2322>0.05), site location is independent of whether sites fall within the acceptable infiltration rate range. This may be affected by the fact that there were twice as many municipal sites in the study as campus sites, and a larger sample size might yield significant results (Figure 62).

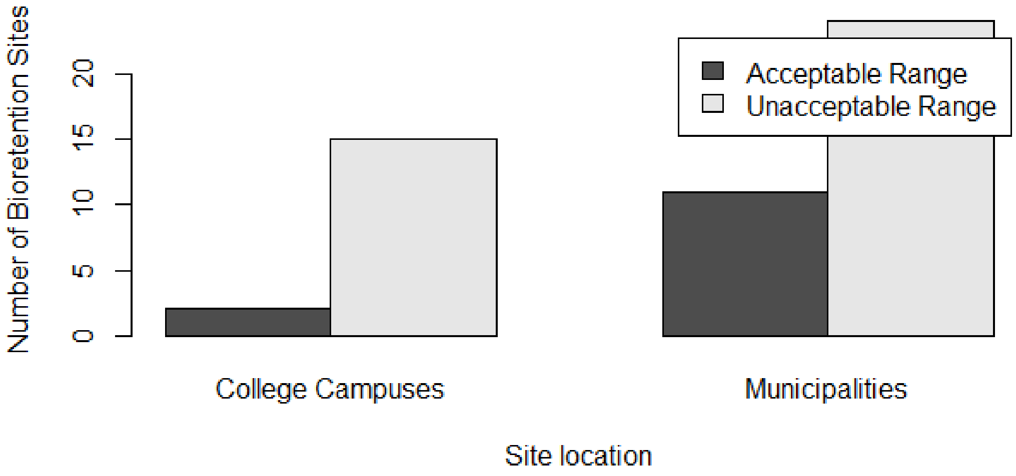

Figure 62. Bar plot of the site locations and whether sites fell within the acceptable infiltration rate range based on location.

Discussion

This section discusses findings from this study and how they relate to the study's research questions, and contextualizes this work relative to prior research on bioretention system long-term performance. It also includes a discussion on implications of the results of this study, the limitations of this study, and how this study design could be changed, and provides directions for further research and GSI development.

GSI Design and Implementation Process

In all seven interviews with municipal staff, the general process for the initial design, construction, implementation and maintenance of GSI projects in Santa Clara County were consistent with guidelines set forth by SCVURPPP to meet MRP requirements. Despite this process being consistent across all of the municipalities in the county with MRP requirements, infiltration rates in this study still had high variability, ranging from 2.7 to 62.1 inches per hour, and 74% of sites did not fall within the recommended range of 5 to 10 inches per hour.

Each of the municipal staff in the interviews mentioned liberal communication among each other within the county and with jurisdictions outside of the county; however there may be a disconnect in information with facilities staff for how and why these sites should be maintained differently than general landscape designs. Facilities staff on campuses frequently maintained their bioretention area sites, but largely maintained them in the same way that other landscape designs on campus were maintained, and did not know or understand why they would have distinct maintenance requirements. There may also be a disconnect between what is being designed in the planning and design phase of the process and what is actually being built in the construction phase of the process. All municipal staff mentioned that the GSI sites were inspected by stormwater staff or third party contractors at each step in the construction phase, but these sites were being inspected to ensure that they meet MRP requirements and recommendations, and not to see if the constructed product matches the original design. Further research that compares original site design drawings to the actual finished bioretention system could be useful to determine any potential discrepancies or confusion.

Although cities are required under the MRP to inspect each site at least once every five years, some cities inspected more frequently (Bicknell et al., 2016). The cities that inspected more frequently tended to have fewer sites than cities that inspect each site only once every five years. Municipal inspectors varied by city in terms of who was responsible for conducting the inspections. Generally, cities with many sites (100 or more) have specific inspection personnel that are responsible for checking the sites. Cities with fewer sites generally have specific individuals that inspect sites in addition to their other municipal responsibilities. All municipalities indicated collaboration with other municipalities, particularly at SCVURPPP monthly meetings and workshops.

Infiltration Rates

There was no significant difference in infiltration rates based on the site observation criteria or soil classification, but the range of infiltration rates was highly variable from 2.7 inches/hour to 62.1 inches/hour. Additionally, the average infiltration rate across all sites was 23.3 inches/hour, the median infiltration rate was 15.4 inches/hour, and the mode infiltration rate was 40.0 inches/hour; none of which fall within the recommended 5 to 10 inches per hour (Bicknell et al., 2016). This suggests a high variability of infiltration rates, despite this lack of statistical significance. One study performed in New York City found similar results with a high variability of infiltration rates among different sites at different locations, also using a double-ring infiltrometer system to measure infiltration rates (Lozefski et al., 2017). The range of infiltration rates with the NYC study was from 0.8 inches per hour to 163 inches per hour (Lozefski et al., 2017). In the NYC study, infiltration rate was considered the critical parameter of the potential stormwater capturing efficiency of a bioretention system, and results were also used to inform design and maintenance practices for optimal infiltration rates (Lozefski et al., 2017).

Only twenty-six percent of sites in this study had infiltration rates within the recommended range of five to ten inches per hour, the requirement under Provision C.3 of the MRP (Bicknell et al., 2016), which leaves seventy-four percent of sites outside of this range. This suggests that the bioretention area was either not designed correctly, or that there are other external factors affecting infiltration rates that project planners and engineers may be able to anticipate (City and County of Denver, 2015; Kazemi, 2014; Lozefski et al., 2017; Minnesota Pollution Control Agency, 2017; US EPA, 2011). About forty percent of all sites consisted of the required seventy percent sand and thirty percent compost material (Bicknell et al., 2016). This indicates that about sixty percent of all sites did not consist of the recommended proportions of engineered soil, which should consist of around 70% sand and 30% organic materials (Bicknell et al., 2016; City and County of Denver, 2015; Lozefski et al., 2017). It is unclear that the sites that currently do not have the MRP recommended soil did not have it in the past, as organic matter could break down over time. About forty-nine percent of all sites consisted of eighty percent or more sand, which is not optimal due to the soil's lack of ability to retain water, which can lead to dry plants, excessive irrigation, and faster infiltration rates. While soil type is necessary as per the MRP recommendations (Bicknell et al., 2016), it was not sufficient in this study to determine a correlation with infiltration rate performance. With a larger sample size, this could correlate with the sixty-six percent of sites that had infiltration rates that exceeded the maximum ten inches per hour, and only about seven percent of sites had infiltration rates that were below the minimum five inches per hour.

Although there was not a statistical significance, erosion criteria scores of "1" had a slightly higher mean infiltration rate than erosion criteria scores of "2" and "3" indicating that a larger sample size might yield statistically significant results for higher infiltration rates in correlation with lower scores for erosion. As stated in some interviews, erosion indicates soil loss, which will speed up infiltration rates to less optimal levels (Municipal Staff 1, 2018; Municipal Staff 2, 2018). Similarly, vegetation health scores of "1" had a slightly higher mean infiltration rate than those with scores of "2" or "3" which could also indicate that with a larger sample size, there may be a statistical significance with infiltration rates and vegetation health. For the purposes of this study, vegetation health generally meant identifying dead or dry vegetation, as well as vegetation density (overgrown or not dense enough). Plants can improve infiltration rates by helping to maintain healthy soils and providing water uptake through their roots (US EPA, 2011;

City and County of Denver, 2015). Sites that do not have healthy vegetation may not be able to support optimal infiltration rates over time.

Site Observations

Site observations included criteria scoring, photographs, soil sampling, and recording notes on surrounding conditions and weather (US EPA, 2011). None of the individual criteria on the inspection sheet or compiled criteria had a statistical significance affecting infiltration rates despite this criteria being used by municipalities in the Bay Area to assess site conditions (Bicknell et al., 2016; City of San José, 2017; SFPUC, 2017) or as an assessment of site performance (Schultze-Allen, 2017). One possible explanation is that only one infiltration test was taken at each site. This study did not analyze results from pH measurements, however further research should use pH as a possible inspection criteria that can be associated with infiltration rate. The optimal pH for the engineered soil on each site is between 6.0 or 6.8 and 7.5 (City and County of Denver, 2015; US EPA, 2011), which will help support plant growth. If the soil pH is too high, chemicals and pollutants that are meant to be treated by the bioretention system will be unable to enter into the plants through absorption, and if the pH is too low, certain pollutants can remain concentrated in the soil (US EPA, 2011). Soil moisture is also an important factor for infiltration rates and plant health (US EPA, 2011), as soil saturation causes lower infiltration rates, and it ensures enough water retention to support plant growth (Minnesota Pollution Control Agency, 2017). Given the results of this study indicating that the inspection criteria did not have an association with infiltration rates, it would be useful to add additional criteria to inspection and site observation sheets to help determine any patterns or correlations. In addition to adding data analysis on pH and soil moisture parameters, inspection criteria sheets should also consider noting the site design (e.g., large bioretention pond, street bioswale, etc.), the presence or absence of bunch grass vegetation or trees, and the types of vegetation or trees (perennial, annual), or species (e.g., deer grass).

Bioretention Design, Implementation, and Maintenance Challenges

Twelve individuals were interviewed, including seven municipal staff and five facilities/maintenance staff members. All individuals were asked what the common challenges were with respect to designing, implementing, and maintaining GSI systems within their municipality or campus. The most common challenges indicated were trash, growing demand strains, irrigation, and plant health. Trash was the most commonly mentioned criteria among interviewees when sites are being maintained and inspected. All interviewees indicated that trash in their campus or municipality should be picked up regularly by site owners; however, it is a culminating and ongoing concern, as bioretention areas are meant to capture and treat runoff pollutants, including trash. Sixty-six percent of the sites in the researcher’s observational study had lower criteria scores for trash (i.e. score “2” or “1”). With an ongoing increase in GSI projects, some cities and maintenance staff are struggling to keep up with the demand. Cities often lack funding availability to implement new projects, or the personnel and equipment needed to properly maintain these systems over time (Meadows, 2017). For example, bioretention areas cannot be treated with pesticides or covered in mulch to ward off invasive plants, which must be picked by hand (Bicknell et al., 2016; City and County of Denver, 2015).

Many municipalities and campuses reported concerns with functioning irrigation systems, and a preference for sprinkler head irrigation over drip irrigation. Almost forty percent of sites had irrigation concerns, mainly including exposed pipes (Figure 29), which can indicate a loss of soil, and leaves drip irrigation pipes vulnerable to damage. As a consequence for many sites having higher soil content and lacking functioning irrigation systems, vegetation health was another concern among municipal and facilities staff. Dry or dead vegetation was present in 62% of sites, including sites within each of the four campuses and five municipalities. Dense, grass vegetation was commonly used among the highest performing infiltration rate sites, and can ease maintenance responsibilities and reduces area available for weed growth (City and County of Denver, 2015).

Bioretention Performance in Campuses Versus Municipalities

There was no statistically significant difference in infiltration rates between the bioretention areas on campuses and the bioretention areas in municipalities. Based on the interview results, most facilities staff understood the functional purpose of bioretention areas on their campuses, but many of them maintain them the same way that general landscaping areas are maintained. Campus bioretention areas generally had much less amounts of trash than municipal bioretention areas, likely because campus facilities and grounds crew are cleaning up all campus green areas daily, including picking up any trash in all landscaping and bioretention areas. Three facilities staff members described bioretention areas as “self-maintaining systems”, meaning they do not expect to have to perform much long-term maintenance. Municipal staff members were much more knowledgeable on the design of bioretention areas, as well as how to properly inspect and maintain them over time. Most municipal staff members interviewed, however, are not the same individuals that perform maintenance tasks. Based on the general inspection and maintenance process of bioretention areas, municipal staff will notify site owners and/or individuals who are responsible for site maintenance of what needs to be done in order to complete the inspection process. Interviews with both municipal and facilities staff revealed that there is still little communication with respect to municipal staff understanding the maintenance demands placed on facilities staff, and facilities staff understanding the importance of addressing “A” and “B” concerns within the bioretention areas. For example, one city has hundreds of bioretention areas to maintain and inspect each year. When there is a concern raised from a site inspection, such as removal of invasive plant species, facilities and maintenance staff are notified to fix the concern by a specified date. Often, according to a facilities staff member, the municipality does not provide enough time to resolve the inspection concern, or enough prior notification, which can catch facilities staff “off-guard” and force them to rearrange their work orders and staff members to resolve the concern. On the other hand, according to a facilities interviewee, this city’s facilities staff would prefer to use pesticides to aide in the removal of invasive species rather than pick by manual labor, as this would be more efficient and allow the concern to be addressed without putting too much of a strain on staff members. The use of pesticides in bioretention areas is not permitted, however, because it can affect the site’s ability to treat stormwater runoff (Bicknell et al., 2016). Further communication between municipal and facilities/maintenance staff could help alleviate high maintenance demands or provide clarity of how bioretention areas need to be maintained.

Applications and Recommendations

There has been extensive research done on the benefits and effectiveness of bioretention systems nationwide, including one in Daly City, California (David et al., 2011), yet only a select few studies evaluate infiltration rate performance of these systems (Kazemi, 2014; Lozefski et al., 2017). This study is the first that assesses the infiltration rate performance of select bioretention areas in the South San Francisco Bay Area, specifically in Santa Clara County. It is useful to conduct further research in the San Francisco Bay area and within the county, as there are few studies that assess infiltration rate performance, and of the studies that do, they are located in other states including New York (Lozefski et al., 2017) and Kentucky (Kazemi, 2014). These regions have different weather climates and local policies governing stormwater management than in California. Further research would need to be developed to cover other geographic areas in the United States, as well as more areas in California and in the San Francisco Bay, in order to assess overall long-term GSI performance and make recommendations for improving future designs or maintenance practices. Below are recommendations for further research that would benefit the current body of literature on the long-term performance and effectiveness of bioretention areas.

Recommendation 1: Conduct Further Study on Other Indicators of Bioretention Area Performance

This study uses infiltration rates as an indicator for bioretention system performance; however other indicators include the system's ability to capture, treat and absorb stormwater runoff. Further research would be needed to test other performance parameters, such as observing bioretention areas during major rainfall events, collecting and testing water samples both prior to entering into the bioretention area and after it has been filtered through, testing different plants to determine their effectiveness of absorbing pollutants over time, and collecting soil samples for lab analysis on particular pollutants that get filtered out. The San Francisco Estuary Institute has started monitoring water quality results in the Bay Area to help assess local GSI effectiveness (SFEI, 2018). Past studies have compared the site performance between an engineered bioswale and a control site by monitoring tree growth, nutrient loading and runoff volume in each site (Xiao, 2011), and have shown significant results in nutrient load reduction and tree growth in the engineered bioswale as opposed to the control site. It would be useful to understand other physical characteristics to maximize long-term performance (Bachmann, 2007).

Recommendation 2: Incorporate Different Observational Criteria and a Larger Sample Size

While there was no significant correlation between infiltration rates and the observation criteria, infiltration rates still had a large range with variable rates outside of the intended five to ten inches per hour, which was similar to the results of the related study conducted in New York (Lozefski et al., 2017). Further research would be useful to include a larger sample size of bioretention areas, or to include different criteria that could be a factor in infiltration rates and bioretention area performance. Other criteria may include pollution concentrations (Lozefski et al., 2017), surrounding land usage, soil compaction (Lozefski et al., 2017; US EPA, 2011), plant/tree growth (Xiao, 2011), drainage areas (US EPA, 2011), runoff volume (Xiao, 2011), soil temperature and disturbance by human activity (Lozefski et al., 2017). Additionally, it would be useful to include criteria on the factors that were statistically associated with infiltration rates, such as the use of bunch grass vegetation, site design, and tree presence. Table 12 shows an example section to add to the existing criteria sheet from this study.

Table 12

Additional criteria for site inspections

Criteria	**Presence (Yes/No)**	**Comments**
Bunch Grass Vegetation		○ Perennial Species Name: ○ Annual ○ Native ○ Non-Native
Trees		○ Perennial Species Name: ○ Annual ○ Native ○ Non-Native
Site Design		Site Type: [Large bioretention pond, street bioswale, private bioswale, rain garden, etc.]

Recommendation 3: Improve Communication Between Technical Staff and the General Public

Municipalities and campuses could benefit from increasing awareness of bioretention areas by better informing the general public and site owners of their purpose and function, as human activity (such as walking in basins or allowing pets to defecate in basins) can negatively affect system performance (Lozefski et al., 2017). More informational signage and labels could aide in public understanding. Municipalities collaborate liberally across the San Francisco Bay Area through the Bay Area Stormwater Management Agencies Association as well as throughout Santa Clara County, however cities could benefit from further extending communication to cities from other regions of

California or the United States, as well as by strengthening communication between municipal employees and facilities staff members. In increasing communication between cities in other nationwide regions, ideas for better maintenance can spread, such as the City of Denver's use of sediment collection pads and forebays used to facilitate proactive and routine maintenance as part of their street sweeping program (City and County of Denver, 2015). Another example is to learn different methods for infiltration testing, such as using the Cornell Sprinkle Infiltrometer that is used in New York, which simulates rainfall by wetting the soil surface more naturally to create a realistic surface condition with minimal disturbances (Lozefski et al., 2017). Further studies and communication can facilitate long-term analysis to inform GSI design lifetime (Bachmann, 2007). Using additional inspection criteria, such as labeling the design type (e.g., large bioretention pond, street bioswale), noting the use of California native perennial bunch grasses, and monitoring tree growth over time may also expand upon the existing criteria used in this research.

Recommendation 4: Further Examine the Relationship Between Site Planning, Design, What's Actually Built, and Subsequent Operations and Inspections

Forty-one out of fifty-two sites (78%) in this study did not fall in the recommended infiltration rate range of five to ten inches per hour and therefore appear to not be functioning optimally, yet an examination of the twelve sites that fell within range indicates that a wide variety of site designs can work well. Further research that compares the original site design drawings with the site that was actually built could be helpful in determining if there was a disconnect between the design and construction phase. Additionally, the site design and inspections at each stage of the construction in the GSI design, construction, implementation and maintenance process could merit further investigation and could help explain variances in infiltration rates.

Conclusion

Implementing GSI systems in urban landscapes is an effective way of capturing and treating stormwater runoff before it reaches local waterways. Without treatment, rainwater picks up harmful pollutants, such as fertilizers, pesticides, car oils, and trash, as it runs off impervious pavements. This can create water quality concerns for the San Francisco Bay, as well as human health concerns with respect to the transport of disease bacteria. Cities across the United States, such as Seattle, New York, Denver, Los Angeles, Washington D.C., and San Francisco, to name a few, are taking action to prevent the transport of harmful pollutants by requiring the implementation of GSI systems with new development projects. While there is plenty of evidence that demonstrates the effectiveness of GSI systems at treating stormwater runoff, it is important to ensure that these systems are designed and built correctly, are maintained properly over time, and are inspected regularly to assess their long-term performance.

The studied bioretention sites in Santa Clara County showed that the use of California native perennial bunch grasses and tree plantings can have a positive effect on infiltration rate, which is defined as a critical parameter to assess bioretention area performance. Additionally, the type of bioretention area (Parking Lot/Campus, Residential Street, Public Street, Large Bioretention Area) has an effect on performance, as sites that were in the “Large Bioretention Area” category had the highest performance, followed by sites in the “Parking Lot/Campus” category, and sites in the “Public Street” category had the lowest performance. Further research would determine bioretention area performance based on other parameters, such as pollutant concentration reduction and runoff volume reduction. Lastly, while individual inspection criteria did not have a significant effect on infiltration rates, several criteria were mentioned as concerns among local municipal and facilities staff, including sediment accumulation, trash, healthy vegetation, and erosion. Further research with a larger sample size, longer time period, or with comparisons between other counties would be needed to determine more effective maintenance strategies and other criteria that affect site performance.

Overall, the bioretention sites in Santa Clara County were generally consistent between each campus and municipality with respect to their design and observed site conditions, however there was a large variability in infiltration rates. Bioretention systems can still be a highly effective method for capturing and treating stormwater runoff, but further research would be needed to facilitate their long-term performance to establish the most efficient design and maintenance strategy. This study can help to contribute to further research to assess the use of California native perennial bunch grass vegetation and larger bioretention pond designs as factors that positively affect infiltration rates. By continuing research on factors that affect infiltration rates and other parameters of site performance, design, construction, and maintenance practices can further be improved to help increase the long-term effectiveness of bioretention areas for protecting local waterways and replenishing potable groundwater supplies.

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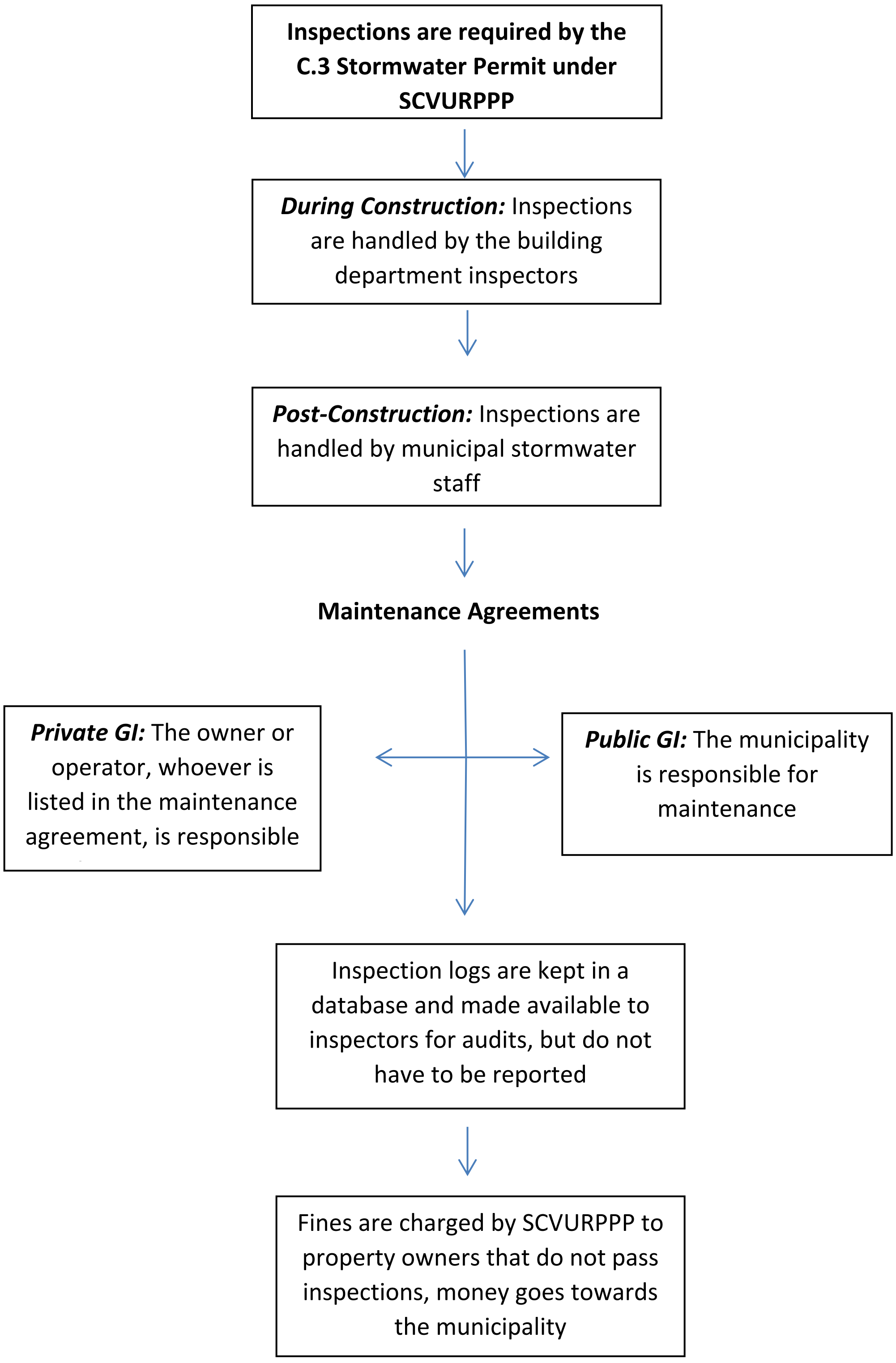
Appendices

Appendix A: Interview Questions

For Municipal Staff Interviews

1. What is the general process for the initial design, construction, and implementation of stormwater permit C.3 provision/Green Stormwater Infrastructure in new development projects in the South Bay Area? *(Use diagram below as a starting point)*
    - Who is the responsible party for each step in the process as it relates to GI?
    - How are these steps monitored to ensure they are followed correctly?
    - How long does each step in the process last?
    - Can you provide any documentation that helps to describe this process, such as memos, reports, forms, inspection logs, etc.?



Inspections are required by the C.3 Stormwater Permit under SCVURPPP

During Construction: Inspections are handled by the building department inspectors

Post-Construction: Inspections are handled by municipal stormwater staff

Maintenance Agreements

Private GI: The owner or operator, whoever is listed in the maintenance agreement, is responsible

Public GI: The municipality is responsible for maintenance

Inspection logs are kept in a database and made available to inspectors for audits, but do not have to be reported

Fines are charged by SCVURPPP to property owners that do not pass inspections, money goes towards the municipality

2. How does the process you described earlier drive the day-to-day planning and implementation of GI for your municipality? Are there any challenges with implementing these policies as written?
3. To what extent do you share your general GI design, implementation, and maintenance processes with other institutions and/or municipalities?
4. Taking a look at my own site inspection form, do you have a similar process for site inspections of bioretention areas, particularly following construction and within the first two years of implementation? What are some differences? What do you do with the inspection data after inspections? Is any of the data available publicly?
5. How does the on-going inspection and maintenance process for GI structures, particularly bioretention areas that have been implemented in the last five or more years, work in your municipality?
    - Who is responsible for conducting the inspection?
    - Who is responsible for maintaining the GI structure?
6. What constitutes a "passing grade" or "approval" of GI condition and maintenance during an inspection process?
    - What are the consequences for not "passing" the inspection process?
7. What are some challenges with respect to on-going maintenance and GI implementation? What are some challenges in ensuring that all sites "pass" inspection processes?

For Facilities and Maintenance Staff Interviews

1. What is the purpose of the GI bioretention systems on your campus/within your municipality?
    - How many GI structures, particularly bioretention areas, are on your campus/in your municipality?
2. What is the general process or procedure for conducting maintenance on the GI systems in your campus/municipality? If you use a contractor, are they trained on GI system maintenance?
3. How often are these GI systems inspected and maintained? How is this determined?
4. What are some criteria that you look for or that are cause for concern when conducting maintenance operations on these GI structures? (i.e. trash, vandalism, etc.)
5. How many staff members are in charge of maintaining GI structures?

Appendix B: Infiltration Test Details

To measure the infiltration rate, the researcher will identify a section towards the center of the bioretention system that has no cracks in the soil, and use a wooden block and hammer to push a cylinder into the soil (Figure A1) to a depth of about fifteen centimeters (SFWPS, 2017).

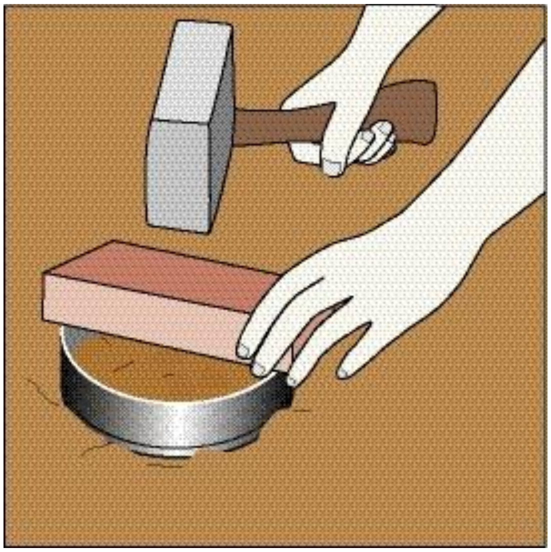


Figure B1. This is a cartoon image demonstrating the insertion of the cylinder into the ground using a wooden brick and a hammer (Philadelphia Water Department, 2017).

The cylinder will be a PVC pipe with an inside diameter of twelve inches, which is approximately thirty centimeters, and a length of fourteen inches, and will serve as the exterior buffer for the infiltration test. A second PVC pipe with a diameter of six inches and a length of fourteen inches will be inserted in the middle of the larger PVC pipe using the same method with the brick and hammer (Figure A2).

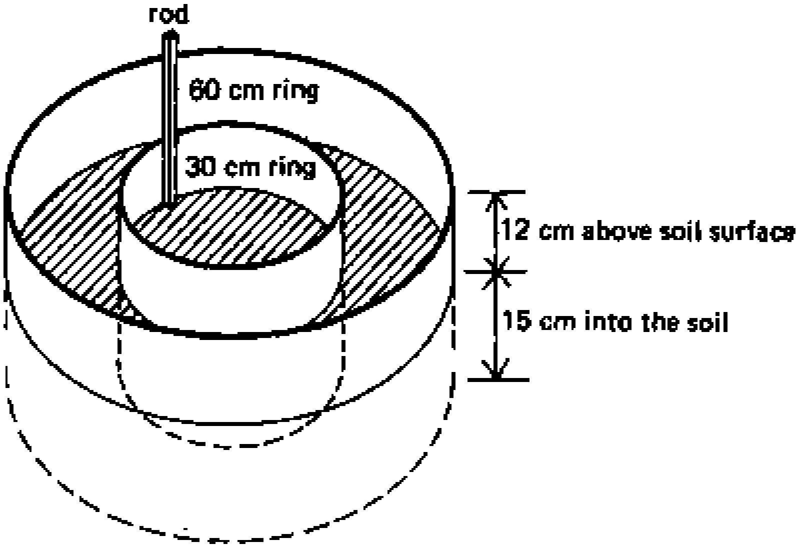
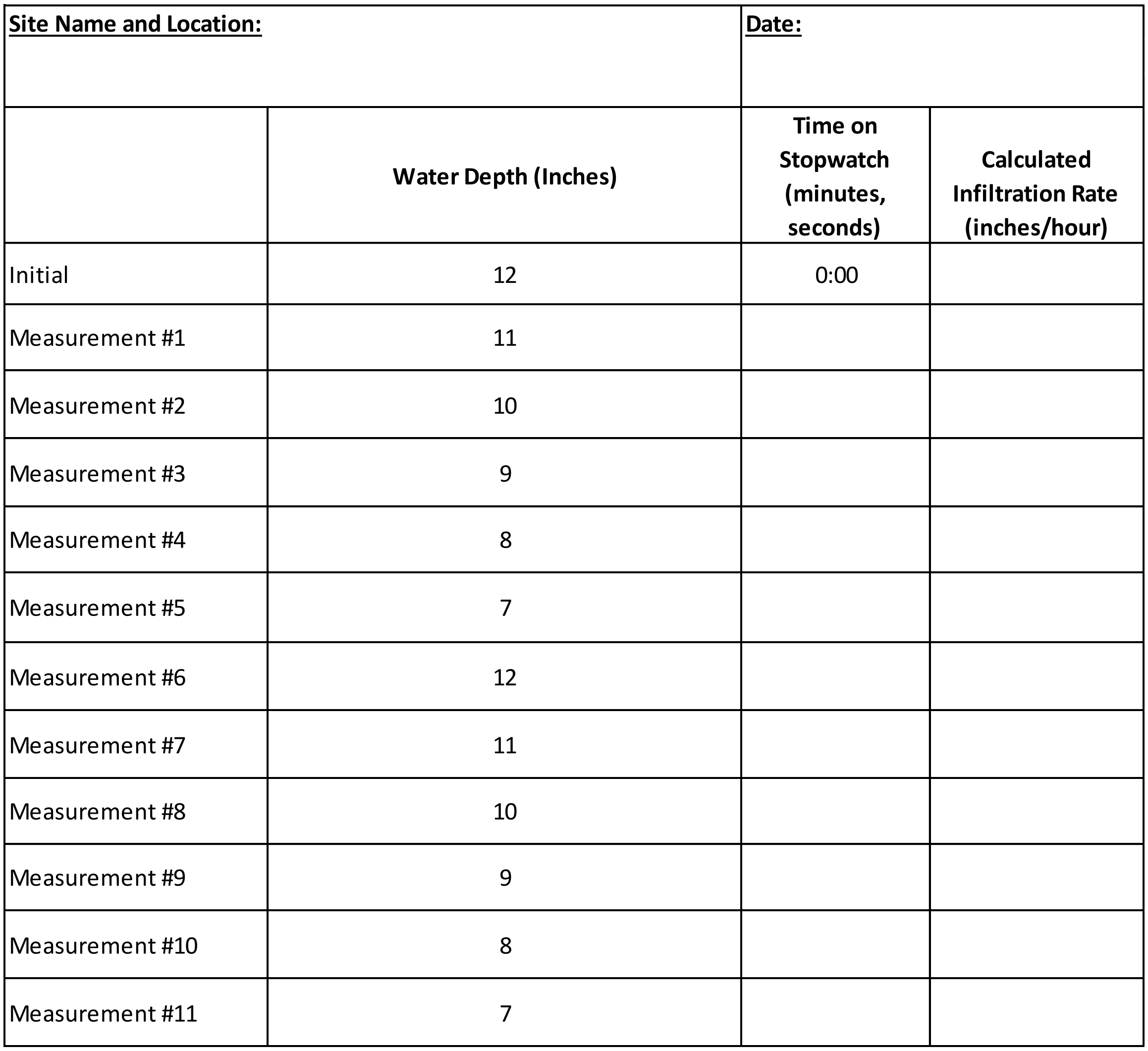


Figure B2. This diagram illustrates the use of two cylinders for the infiltration test, and their diameters and depths both above and below the soil media (FAO Corporate Document Repository, 2017).

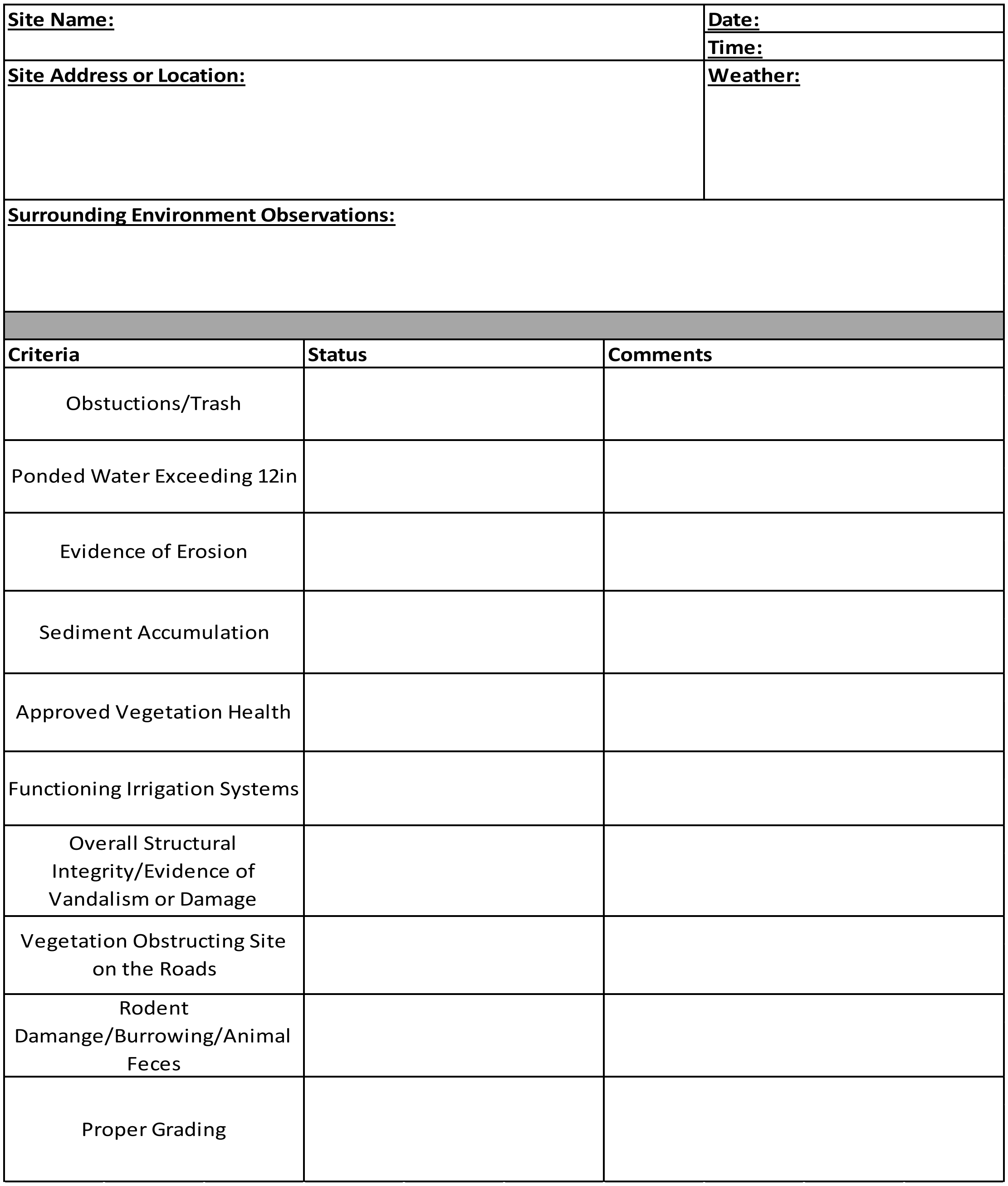
PVC pipes will be used because they can be easily marked, cut, and replaced if damaged or lost. Part of the cylinder will remain exposed to the air above ground, by about six to eight inches, or about fifteen to twenty centimeters (SFWPS, 2017). SFPUC suggests a hole with a diameter of twenty-four inches, approximately sixty centimeters (Figure A2), for municipal infiltration tests (SFPWS, 2017); however the researcher has determined that a smaller hole with a diameter of six inches will be sufficient and less invasive to the bioretention systems for this study. The length of the PVC pipes will remain the same as Figure A2 at fourteen inches, or about twenty-seven centimeters. For the sections of the smaller cylinder exposed to the air, there will be markings on the interior of the pipe using a black marker to indicate each unit of measurement. For example, there will be a mark at the top indicating fourteen inches and a mark below that indicating thirteen inches, and so forth until the six inch mark at the ground level. The researcher will use a full one gallon pitcher to carefully pour potable water into the smaller cylinder ring without splashing or altering the smooth ground surface until the water level reaches the twelve inch mark, as well as pour water into the outer cylinder ring, and then start a timer (FAO Corporate Document Repository, 2017). The water level in the outer ring will not be measured by time, as it is only used to buffer lateral flow out of the interior ring for better accuracy (FAO Corporate Document Repository, 2017). The original water level will be recorded at time zero on the data sheet (Figure A3). As the water level drops by one inch, the time that has passed in seconds will be recorded. Once the water level reaches the seven inch mark, the water in the cylinder will be replenished using the pitcher back up to the original level at twelve inches, and continue recording the time for the drop in water level at each inch mark (FAO Corporate Document Repository, 2017). This process will continue until the drop in water level is the same over the same time interval (FAO Corporate Document Repository, 2017). The time will be measured in minutes and seconds, and data will be recorded on the data infiltration sheet (FAO Corporate Document Repository, 2017; SFWPS, 2017).



Site Name and Location:		**Date:**	
	Water Depth (Inches)	**Time on Stopwatch (minutes, seconds)**	**Calculated Infiltration Rate (inches/hour)**
Initial	12	0:00	
Measurement #1	11		
Measurement #2	10		
Measurement #3	9		
Measurement #4	8		
Measurement #5	7		
Measurement #6	12		
Measurement #7	11		
Measurement #8	10		
Measurement #9	9		
Measurement #10	8		
Measurement #11	7		

Figure B3. This is the example data sheet for the infiltration rate testing, including the number of measurements, water depth, time, and infiltration rate. Adapted from "Determination of Design Infiltration Rates for the Sizing of Infiltration-based Green Infrastructure Facilities", San Francisco Water, Power, Sewer, 2017, San Francisco Public Utilities Commission.

Appendix C: Observational Study Inspection Criteria Field Sheet



Site Name:		**Date:** **Time:**
Site Address or Location:		**Weather:**
Surrounding Environment Observations:		
Criteria	**Status**	**Comments**
Obstuctions/Trash		
Ponded Water Exceeding 12in		
Evidence of Erosion		
Sediment Accumulation		
Approved Vegetation Health		
Functioning Irrigation Systems		
Overall Structural Integrity/Evidence of Vandalism or Damage		
Vegetation Obstructing Site on the Roads		
Rodent Damange/Burrowing/Animal Feces		
Proper Grading		

Figure C4. This is the inspection list the researcher will use while conducting the observational study of water flow into GI systems, which is a compilation of multiple sources, including SFPUC, the City of San José, and SCVURPPP. Adapted and edited from the researcher.

Appendix D: Benefits of Using GSI Systems in Urban Environments

Stormwater management benefits of GSI. GSI, particularly bioretention systems, can reduce soil erosion, help to recharge groundwater aquifers, reduce recharge loads on municipal storm drains, minimize flooding, and improve the water quality of stormwater runoff before it reaches the San Francisco Bay (Chen, 2014; David et al., 2011; Gilbreath, Pearce and McKee, 2012). Local and regional water quality is protected by reduced sediment and nutrient loads from GSI (Natural Resource Conservation Service, 2005). Bioretention systems, bioswales in particular, replenish groundwater aquifers, reduce streambank and channel erosion due to high flows, and reduce infrastructure costs on streets, curbs, gutters and sidewalks (NRCS, 2005; US EPA, 2017). Urbanization has caused serious negative effects to the quality of downstream aquatic ecosystems (Pavlowsky, 2016). With the lack of GSI implementation, city environments show a higher level of pollutants and harmful nutrients in local waterways (Pavlowsky, 2016).

Other benefits of GSI. Along with stormwater management, GSI provides a myriad of other environmental, economical, industrial, and human health benefits. Urban sprawl has a negative effect on the environment and various ecosystems due to the decline in biodiverse habitats (Artmann, Bastian and Grunewald, 2017). Humans depend on various ecosystem services to survive, and the implementation of GI in urban settings will help to provide some of these necessary ecosystem services (Artmann, Bastian and Grunewald, 2017). GSI can balance urban growth needs with environmental protection (NRCS, 2005). The concept of ecosystem services can support urban landscape planning by reflecting the human perspective and its dependence on the environment (Artmann, Bastian and Grunewald, 2017). Environmental protection and GSI implementation can lead to human health benefits (Coutts and Hahn, 2015).

Perhaps the most impactful way that GSI protects human health is that it prevents the spread of infectious diseases through contaminated stormwater runoff (California Department of Public Health, 2012; Coutts and Hahn, 2015; Johnson, 2006). Stormwater runoff, a nonpoint source of pollution when it collects various surface pollutants, threatens the water quality of creeks, rivers, lakes, and ocean bays in the United States (Coutts and Hahn, 2015; Gaffield et al., 2003; US EPA, 2017). More than half of the documented waterborne disease outbreaks in the United States since 1948 have followed extreme rainfall events (Gaffield et al., 2003). Bioretention systems absorb and filter out harmful bacteria, nutrients and pollutants (Natural Resource Conservation Service, 2005; US EPA, 2017) that can cause common diseases (Coutts and Hahn, 2015; Gaffield et al., 2003).

Kondo et al. conducted a study in Philadelphia, Pennsylvania, to investigate the health and safety effects of installed GSI systems by using regression analysis of blood pressure, cholesterol levels, and stress levels for health measurements, and felonies, property crimes and nuisance crimes for safety measurements (Kondo et al., 2015). Kondo et al. found that there were significant reductions in narcotics treatments over time due to the installation of GSI, which improves overall human health, and there were reductions in crimes such as vandalism and graffiti, but not necessarily significant enough to credit the GSI exclusively (Kondo et al., 2015).

The Hacienda Avenue bio-infiltration basin in Campbell, California, has been proven to increase public safety and overall community health (McKee and Gilbreath, 2016). Since completion of the bio-infiltration basin, aside from stormwater management benefits, other proven benefits include boosting community morale by adding an aesthetic appeal to the street; increasing pedestrian and bike safety by reducing the number of lanes on the road and creating a vegetated barrier between the sidewalk and the road; reducing the heat island effect by removing pavement that radiates heat from the sun and replacing it with vegetation that absorbs the heat; and improving air quality with the addition of trees and shrubs for transpiration (McKee and Gilbreath, 2016). Nature has the ability to combat mental fatigue, and urban planning would benefit from ensuring that communities have adequate access to nature (Molla, 2015).

Many social benefits of GSI include improvements in physical activity and health, promotion of psychological health and mental well-being, and facilitation of social interaction, inclusion and community involvement (Molla, 2015). Economic benefits of GSI include improvement in a region’s image, attract high-value industries, foster environmentally friendly living and work environments, create jobs, reduce operational costs regarding energy and gas, increase property values with added appeal and lower flood risks (Molla, 2015). Despite the potential drawback of a reduction in parking spaces in some locations, GSI is pedestrian-friendly by creating barriers between roads and sidewalks, which can help to improve the overall quality of life for urban residents, and increases community character (NRCS, 2005).

Because GSI can balance urban growth needs with environmental protection, it consequently provides many benefits to environmental ecosystems as well as humans (NRCS, 2005). GSI protects sensitive areas, increases habitat for wildlife by preserving trees and vegetation, protects local and regional water quality (US EPA, 2017) by reducing sediment and nutrient loads, reduces the potential for flooding, and reduces streambank and channel erosion by minimizing frequent surges and bounces of higher flows from storm sewer discharges (NRCS, 2005). The myriad of stormwater, human health and safety, ecosystem services, and environmental health benefits from GSI are well-known among many municipalities across the nation (SCVURPPP, 2012).

Appendix E: Site Location Maps

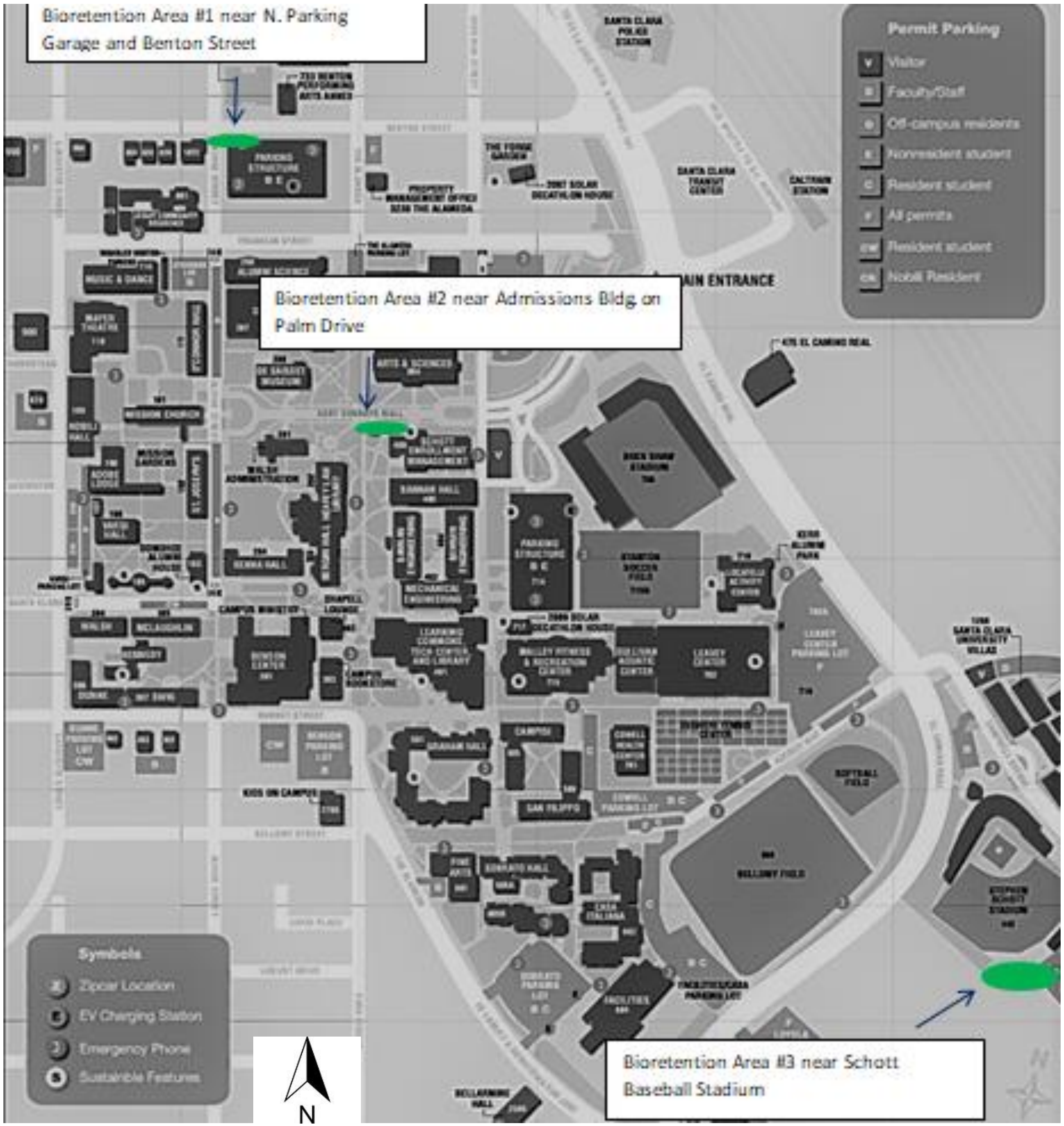


Figure E1. This is a site map of Santa Clara University's campus, where the labeled bioretention areas of study are indicated by the green ovals edited in by the researcher (Santa Clara University, 2017).

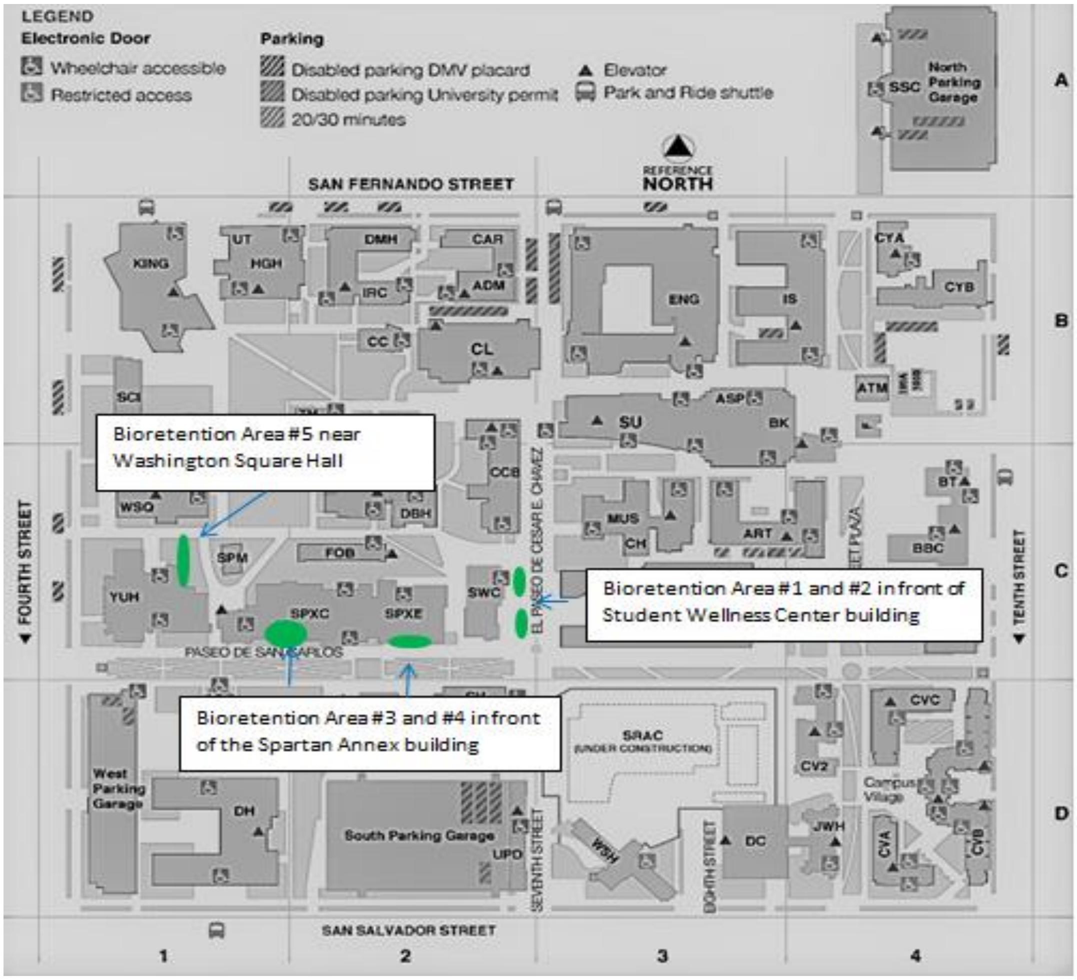


Figure E2. This is a map of San José State University's campus, with the study sites indicated by the green ovals (San José State University, 2017).

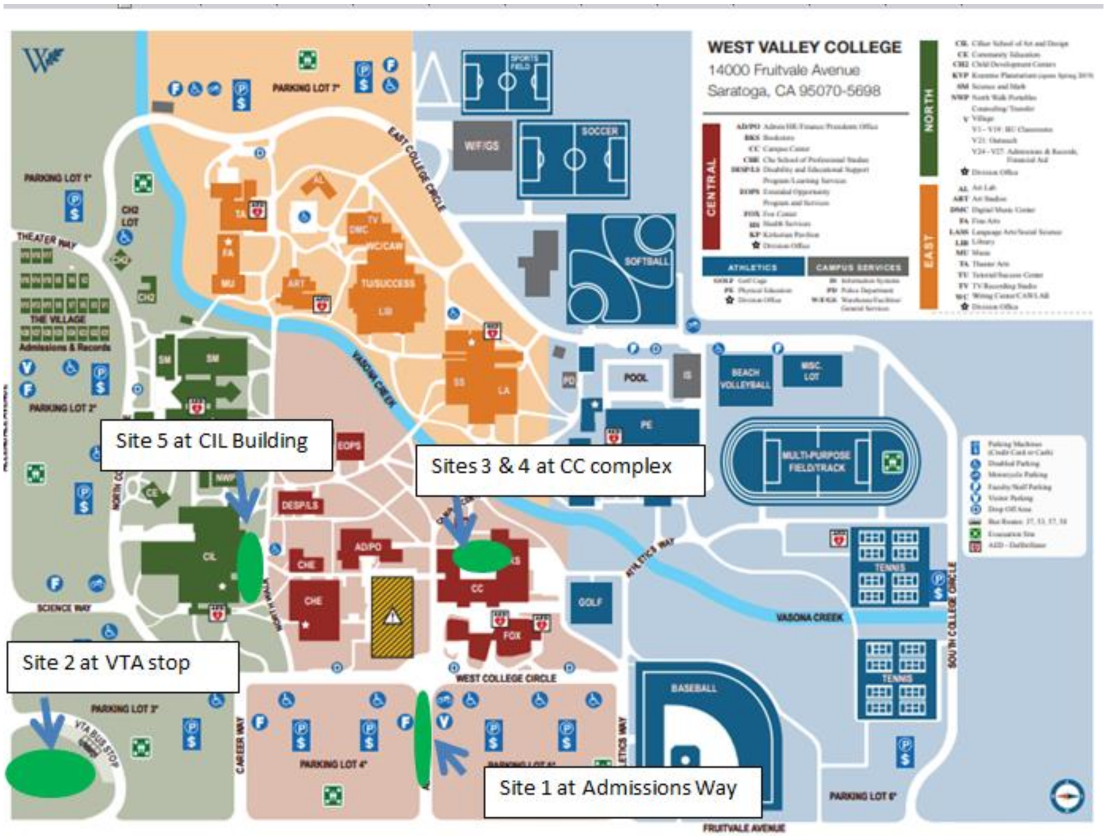


Figure E3. This is an image of the West Valley College campus map, with the study sites indicated by the green ovals and labeled with the text boxes (West Valley College, 2017).

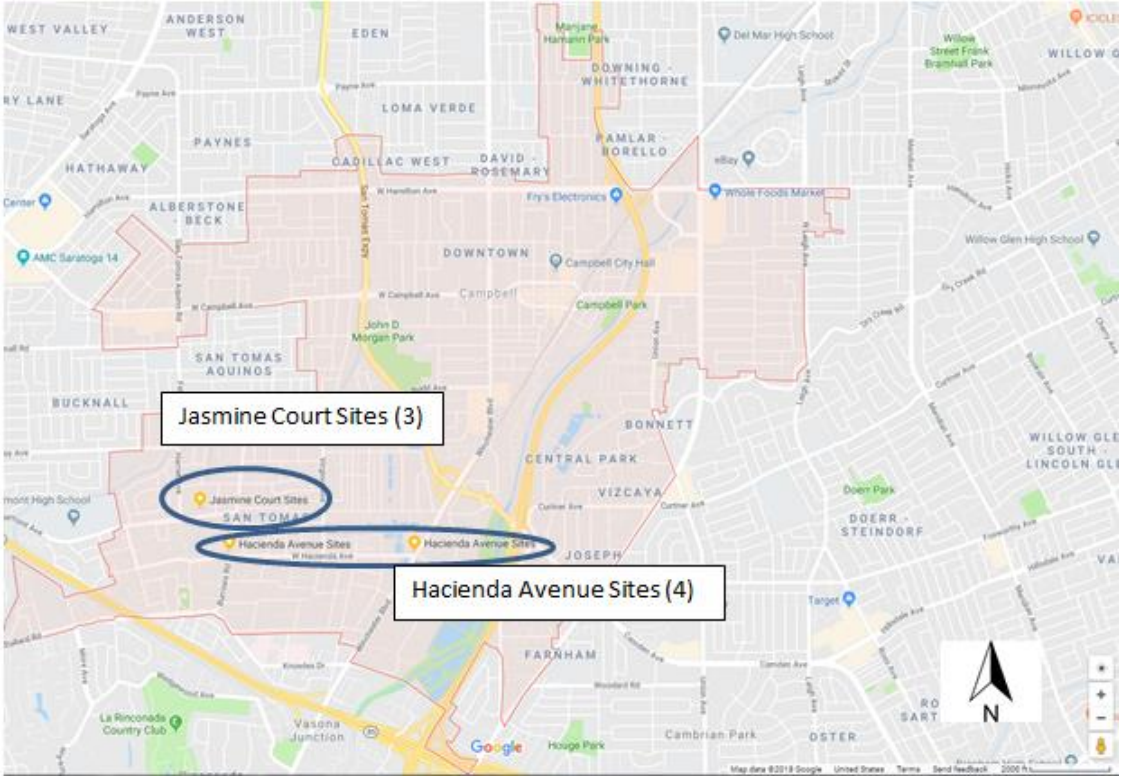


Figure E4. This is an image of the study area in the City of Campbell, including a blue circle edited by the researcher to indicate the locations of the bioretention areas (Google Maps, 2017).

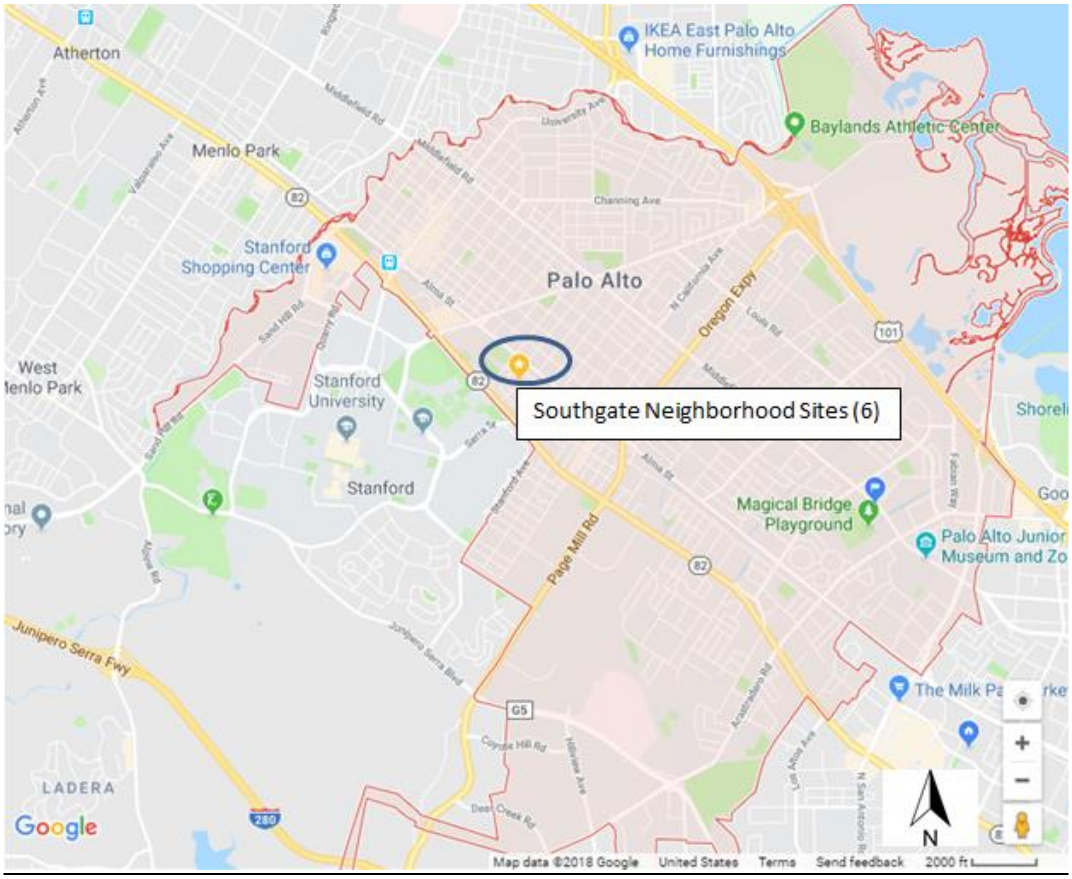


Figure E5. This is an image of the study areas in the City of Palo Alto, located in the Southgate Neighborhood near Serra Street and El Camino Real, just northeast of Stanford University (Google Maps, 2018).

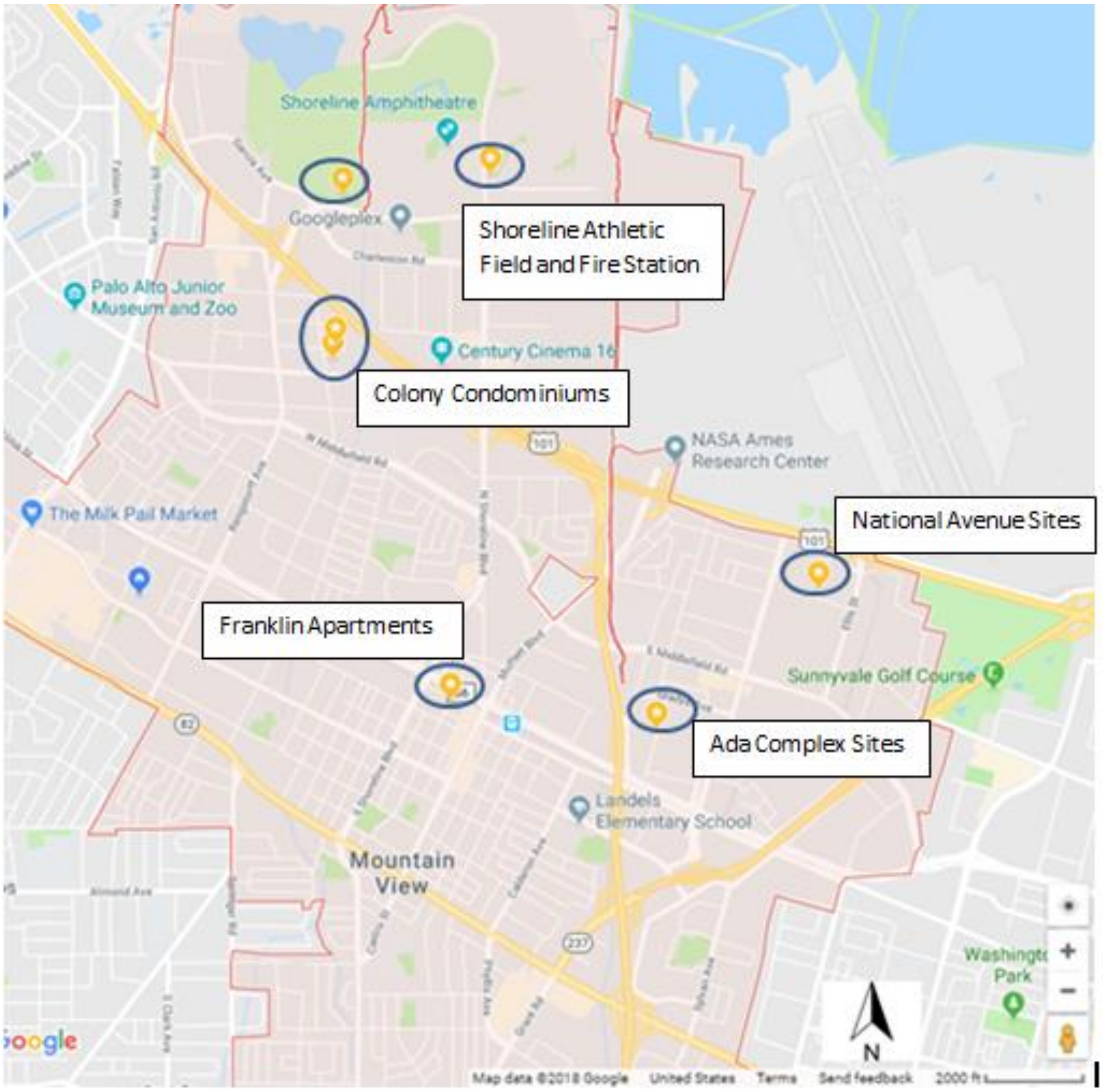


Figure E6. This is an image of the study areas in the City of Mountain View, located throughout the north and eastern areas within the city border (Google Maps, 2018).

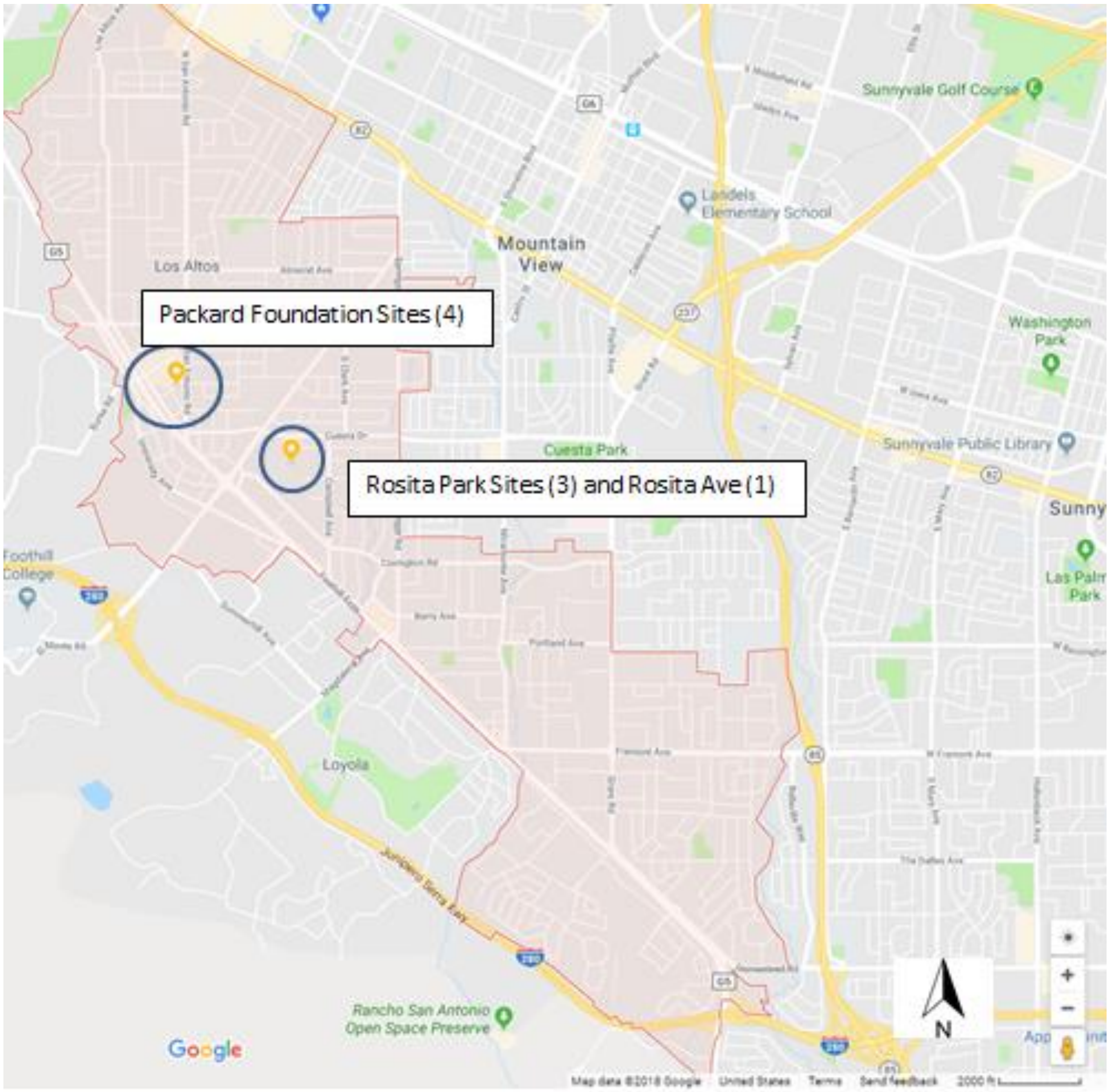


Figure E7. This is an image of the study areas in the City of Los Altos, located northeast from Foothill College (Google Maps, 2018).

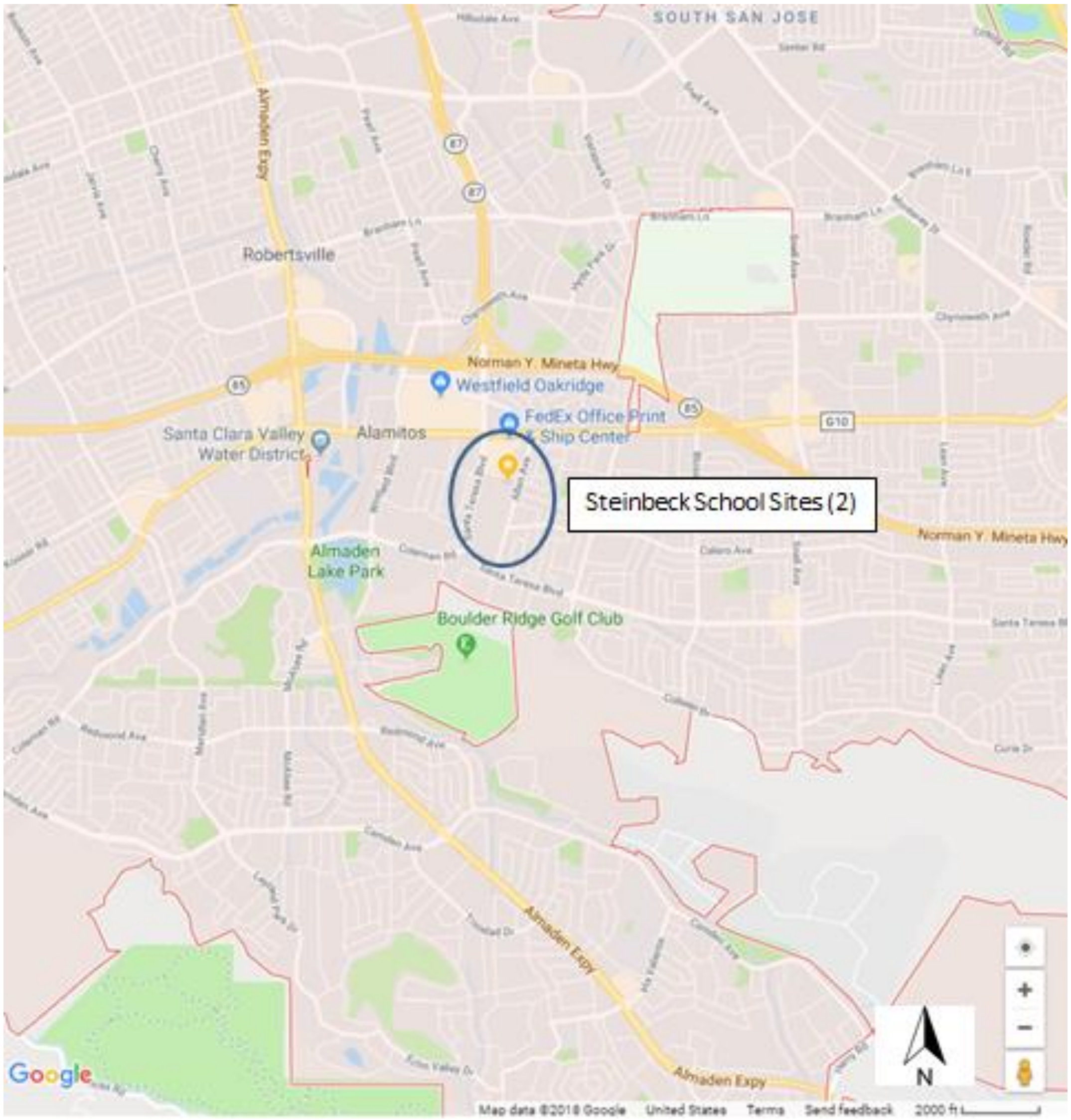


Figure E8. This is an image of the study areas in the City of San José, located in the parking lot of Steinbeck Elementary School off Santa Theresa Street in South San José (Google Maps, 2018).

Appendix F: Permission Letters

CITY OF CAMPBELL
Public Works Department

December 5, 2017

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems within the City of Campbell during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens in the city. System sites for your research will be identified with the help of myself and our CIP Manager Fred Ho. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at each site in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. The City of Campbell is not responsible or liable for any damaged or lost equipment or vehicles during this project time period, or for the health and safety of you as the researcher or any assistants involved in conducting this project. It will be your responsibility to ensure your safety by abiding by all laws, regulations and best practices.

Please contact me if you have any questions.

Regards,

Roger K. Storz, PE
Senior Civil Engineer
Public Works Department
(408) 866-2190
rogers@cityofcampbell.com

Roger K. Storz, P.E.
Senior Civil Engineer
Public Works

70 North First Street • Campbell, CA 95008-1423
TEL 408.866.2190 • FAX 408.376.0958
Email: rogers@cityofcampbell.com

Department of Public Works
Engineering Division
One North San Antonio Road
Los Altos, California 94022-3087
Tel: (650) 947-2780
Fax (650) 947-2732

June 4, 2018

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems within the City of Los Altos during the designated data collection period. These Green Infrastructure systems include bioretention systems. System sites for your research will be identified with the help of City Staff. The time frame for data collection will commence from May through June of Calendar Year 2018, with a possible extension into July if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about two inches. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.
- Soil sampling at each site, which involves a minimally invasive cylinder sample.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection. The City of Los Altos is not responsible or liable for any damaged or lost equipment or vehicles during this project time period, or for the health and safety of you as the researcher or any assistants involved in conducting this project. It will be your responsibility to ensure your safety by abiding by all laws, regulations and best practices.

Regards,

Aida Fairman, P.E., QSD/QSP, M. ASCE
Senior Civil Engineer
City of Los Altos
afairman@losaltosca.gov
(650)-947-2603

CITY OF MOUNTAIN VIEW

April 18, 2018

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems within the City of Mountain View during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens in the city. System sites for your research will be identified and inspected with the help of Eric Anderson or Carrie Sandahl. The time frame for data collection will commence from February through May of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about six inches and a circumference of twelve and six inches. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection. The City of Mountain View is not responsible or liable for any damaged or lost equipment or vehicles during this project time period, or for the health and safety of you as the researcher or any assistants involved in conducting this project. It will be your responsibility to ensure your safety by abiding by all laws, regulations and best practices.

Regards,

4/18/18

Carrie Sandahl
Water Environment Specialist
City of Mountain View
carrie.sandahl@mountainview.gov
650-903-6224

CITY OF
SAN JOSE
CAPITAL OF SILICON VALLEY

May 2, 2018

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at the Steinbeck School Soccer Fields Green Infrastructure systems within the City of San Jose during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens in the city. System sites for your research will be identified with the help of Adriel Castro. The time frame for data collection will commence from May through June of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal/parks staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection. The City of San Jose is not responsible or liable for any damaged or lost equipment or vehicles during this project time period, or for the health and safety of you as the researcher or any assistants involved in conducting this project. It will be your responsibility to ensure your safety by abiding by all laws, regulations and best practices.

Regards,

Adriel Castro
Senior Maintenance Worker
Parks, Recreation and Neighborhood Services
adrielcastro@sanjoseca.gov
408-390-8639

FOOTHILL
COLLEGE

December 1st, 2017

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems on Foothill College's campus during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens on campus. System sites for your research will be identified with the help of Brenda Visas, Director of Foothill. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated by you as the researcher. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes digging two small holes per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters, and inserting a cylinder in each hole. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at each site in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. Foothill College is not responsible for any damaged or lost rain gauges during the data collection period.

Sincerely,

Brenda Davis Visas
Director, Facilities and Special Projects
Foothill College
650-949-7033
davisvisasbrenda@foothill.edu

December 4, 2017

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems on Santa Clara University's campus during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens on campus. System sites for your research will be identified with the help of Chris Young. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff (Christ Young) closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes digging two small holes per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters, and inserting a cylinder in each hole. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at each site in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. Santa Clara University is not responsible for any damaged or lost rain gauges during the data collection period.

Sincerely,

Chris Young
Assistant Director, Facilities
Santa Clara University
cyoung@scu.edu
408-554-4875

January 26, 2018

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems within the City of Palo Alto during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens in the city. System sites for your research will be identified with the help of Shari Carlet. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at each site in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. The City of Palo Alto is not responsible or liable for any damaged or lost equipment or vehicles during this project time period, or for the health and safety of you as the researcher or any assistants involved in conducting this project. It will be your responsibility to ensure your safety by abiding by all laws, regulations and best practices.

Regards,

Shari Carlet, MSCE
Project Engineer
City of Palo Alto
Shari.Carlet@cityofpaloalto.org
408-205-8261

San José State
UNIVERSITY

December 12, 2017

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research under Dr. Katherine Cushing, your thesis advisor in the Environmental Studies Department, at select Green Infrastructure systems on San Jose State University's campus during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens on campus. System sites for your research will be identified with the help of Debbie Andres and Brian Bagley. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at an approved location on campus in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for contacting SJSU facilities ahead of time to let us know what day you plan to conduct the infiltration tests, as well as restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. San Jose State University is not responsible for any damaged or lost rain gauges during the data collection period, or for the health, safety and well-being of you as the researcher or any people who may assist you. You are responsible for abiding by all SJSU and City of San Jose laws and policies during your research.

Sincerely,

Adam Salvadalena

West Valley
College

December 8, 2017

Dear Laura Bates,

I am writing to confirm that you may conduct your thesis research at select Green Infrastructure systems on West Valley Community College's campus during the designated data collection period. These Green Infrastructure systems may include bioswales, bioretention systems, and/or rain gardens on campus. System sites for your research will be identified with the help of Leticia Gallardo. The time frame for data collection will commence from January through April of Calendar Year 2018, with a possible extension into the summer season if needed. The specific date of data collection for the infiltration test will be communicated between you as the researcher and municipal staff closer to the collection period. The research that this institution allows from you is as follows:

- Infiltration tests to be conducted at each site, which includes inserting two small cylinders per site to a depth of about fifteen centimeters and a circumference of up to ten to fifteen centimeters. Water will be poured into the cylinders, and the researcher will time the infiltration rate. This experiment will only be conducted once at each system location.
- Inserting a rain gauge at each site in January of 2018, and periodically checking in through the end of April to record rainfall amounts after rain events.
- Observations of the overall site, which includes visually observing site conditions, taking photographs, and recording current weather data.

You, as the researcher, are responsible for re-filling the holes for the infiltration test and restoring the system back to its original condition upon completion of data collection, which also includes removing the rain gauges at the end of April. West Valley Community College is not responsible for any damaged or lost rain gauges during the data collection period. WVC is also not responsible for the health, safety and well-being of the researcher or any assistants during this project. You are responsible for abiding by all laws and regulations for your own safety.

Sincerely,

Leticia Gallardo
Instructor of Biology
Biology Department
West Valley College
408-741-2416
Leticia.gallardo@westvalley.edu