ASSESSING THE IMPACTS OF POST-CONSTRUCTION BEST MANAGEMENT PRACTICES ON STORMWATER RUNOFF IN AN ULTRA URBAN ENVIRONMENT

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ABSTRACT

ASSESSING THE IMPACTS OF POST-CONSTRUCTION BEST MANAGEMENT PRACTICES ON STORMWATER RUNOFF IN AN ULTRA URBAN ENVIRONMENT

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The effects of urbanization on water resources in the United States and around the world have been well documented by scientists and engineers. Traditional storm sewer systems coupled with detention basins have historically been implemented to mitigate the increased stormwater runoff volume and peak flow rates from urbanized areas. However, this solution has been found to exacerbate the problems associated with increased peak flow rates and runoff volumes in the receiving streams. Future effectiveness of addressing urbanization must seek to mimic the natural hydrologic processes that occurred prior to urbanization. Low Impact Development is an alternative approach to sewer systems that has been implemented to promote the natural hydrologic processes including evaporation, infiltration, and transpiration. However, detailed full-scale water quantity performance data is scarce. To address this knowledge gap, the following research objectives were developed: (1) evaluate the influential factors that impact infiltration rate in engineered soils, (2) determine the relation between the percentage of unfilled pore space, soil compaction, and plant health, (3) analyze the overall health of the planted community, and (4) evaluate how the bioretention systems have modified the surface runoff hydrograph with respect to change in total volume, the time to peak, the peak flow rate and the overall shape of the runoff hydrograph. An EPA SWMM model was developed and results indicate that a viable alternative exists to the conventional stormwater drainage system that provides substantial reductions in runoff volume, peak flow rates, and increase the time of concentration while changing the overall shape of the runoff hydrograph. Additionally, improvements in data collection and performance testing were provided.

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KEY TO ABBREVIATIONS

BMP	Best Management Practice
cfs	cubic feet per second
CN	Curve Number
CPD	Condition Prior to Development
CSDS	City Stormwater Drainage System
EPA	Environmental Protection Agency
ESD	Environmental Services Department
FEMA	Federal Emergency Management Agency
FHWA	Federal Highway Administration
GIS	Geographic Information Systems
LID	Low Impact Development
L-THIA	Long-Term Hydrological Impact Analysis
MDEQ	Michigan Department of Environmental Quality
MDOT	Michigan Department of Transportation
MS4	Municipal Separate Storm Sewer System
NCDC	National Climatic Data Center
NPDES	National Pollutant Discharge Elimination System
NPS	Non-Point Source
NRCS	Natural Resources Conservation Service (formerly Soil Conservation Service, SCS)
O&M	Operations and Maintenance
R^2	Coefficient of Determination
RCP	Reinforced Concrete Pipe
SCM	Stormwater Control Measure

SCS	Soil Conservation Service (now the NRCS)
SDST	Site Development Stormwater Tool
SESC	Soil Erosion and Sedimentation Control
SWAT	Soil and Water Assessment Tool
SWMM	Stormwater Management Model
TN	Total Nitrogen
TP	Total Phosphorous
TR-55	NRCS Technical Release No. 55 of June 1986. Urban Hydrology for Small Watersheds
USDA	United States Department of Agriculture
USDOT	United States Department of Transportation
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey

1. INTRODUCTION

Worldwide, there is a well-documented decline in habitat and water quality of urban streams. Runoff from urban areas is one of the leading causes of the decline in surface waters (EPA, 2000). Urbanization is typically accompanied by increases in impervious surfaces such as roofs and roads, construction of hydraulically efficient drainage systems, compaction of soils, and modifications to vegetation. This results in a variety of impacts that are not easy to separate including increased intensity and frequency of flood flows, stream erosion and the potential for decreased baseflows. Urbanization also leads to water pollution from suspended sediments, heavy metals, hydrocarbons, nutrients and pathogens (Hatt et al., 2004; Jacobson, 2011; Walsh et al., 2012).

Despite an increasing awareness and knowledge of these issues and potential solutions, the transition to more sustainable urban stormwater management that mimics the natural hydrologic process has been slow. This may reflect, among other factors, the lack of field scale performance data for Low Impact Development (LID) practices. Meanwhile, the availability of LID modeling software is increasing. Models can make design and application of LID more efficient and demonstrate water quality and water quantity benefits when implementing LID practices that can be used for stormwater management in the future. The challenge is to translate complex and highly variable natural processes through LID modeling that can provide meaningful performance metrics and design considerations to address urban stormwater.

Based on the lack of field scale performance data for LID practices, the goal of this project is to determine the impacts of one of these practices called bioretention facilities on the surface runoff hydrograph in the ultra-urban corridor of Michigan Avenue in Lansing, Michigan. Additionally, the project will investigate the link between unfilled pore space, soil compaction and plant health and evaluate the factors that impact infiltration rates in the engineered soils.

There are three specific knowledge gaps that must be addressed when designing LID practices to mitigate urban stormwater runoff.

- *Impact of media material on infiltration rates*: It is known that media material used in a bioretention system will affect infiltration rates. Current research suggests that a higher percentage of sand in the media will provide the best infiltration performance. Infiltration rates with media materials in bioretention systems that contain higher clay content are poorly understood and research should be performed. (Brown et al, 2009; Li et al., 2009, Brown and Hunt, 2011a, Liu et al, 2014).

- *Effects of soil porosity and field capacity on system performance and plant health*: Two of the principal components of bioretention systems are plants and soil, which remain largely untested. Additional research must be performed to understand how soil compaction and porosity affect system performance (Johnston, 2011).

- *Effectiveness of bioretention on hydrograph modification:* In evaluating the effects bioretention systems on hydrograph modification, the capture efficiency must be addressed. The capture efficiency of a bioretention system is defined as the fraction of total stormwater volume captured by the system and can be used to demonstrate the water quantity and water quality performance of the system. The capture efficiency is highly dependent on the design of the bioretention (Li et al., 2009; Davis et al. 2012) and climatological conditions (Emerson and Traver 2008). In order to ensure that bioretention systems are designed for optimal performance based on design goals, accurate methods are needed to estimate the actual performance of the system (Davis et al. 2009).

Therefore, the specific objectives of this project located in the ultra-urban corridor of Michigan Avenue in Lansing are as follows:

1. Infiltration Capacity: What are the influential factors that impact infiltration rate in engineered soils?

2. Porosity and Field Capacity: What is the percentage of unfilled pore space in the engineered soil? Is there a correlation between the percentage of unfilled pore space, soil compaction, and plant health?

3. Plant and Garden Health: What is the overall health of the planted community? What are the trends in plant species survival/health? What is recommended for replanting specific gardens? Is there any correlation between condition of the soil, the thickness of the mulch, the presence of weeds, and the presence of trash/debris and the health of the plants?

4. Surface Runoff Hydrograph Modification with Bioretention: How have the bioretention systems modified the surface runoff hydrograph with the gardens in place?

5. Quantification of Hydrologic Changes: What is the change in total runoff volume, time to peak, peak flow rate and overall shape of the hydrograph with the implementation of bioretention facilities?

2. LITERATURE REVIEW

2.1. OVERVIEW

This literature review focuses on three key areas of research associated with stormwater: the stormwater impacts from urbanization, types of solutions used to treat the stormwater impacts, and hydrologic modeling for hydrograph modification assessment studies. The first section examines the changes (water quantity and quality) in streams and waterways from urbanization. The next section describes the methods to mitigate the negative effects of urbanization on water resources including an in-depth review of bioretention practices. Finally, hydrologic models and their applications in respect to determining the mitigation effects of best management practices are reviewed.

2.2. URBANIZATION

2.2.1. Water Quantity Aspects of Urbanization

Urbanization alters the hydrology of our lakes, rivers and streams by increasing impervious surfaces resulting in an increase in overland flow runoff (Burns et al. 2012). As urbanization and impervious cover increase, the ability for precipitation to be intercepted by vegetation and either infiltrate into the ground, be stored in the soil column or evapotranspiration significantly decreases (Paul et al., 2001). Pre-urbanization conditions are characterized by pervious land cover that allows precipitation to infiltrate into the ground, including a substantial amount that deeply infiltrates replenishing groundwater and streams. A very small percent of precipitation that falls onto pervious land is actually converted to runoff, typically less than 20% (Paul and Meyer 2001; CWP 2003; EPA 2012,). Conversely, watersheds characterized with a majority of impervious surfaces, experience approximately 75-100% runoff and 0-15% infiltration with only a small percentage of that deeply infiltrating (CWP 2003; Burns et al., 2012;). A study conducted by Simmons and Reynolds (1982) assessing annual baseflow discharges for two streams on Long Island, New York found that discharge volumes were reduced by more than 40% following urban development (Konrad and Booth, 2002).

As urbanization and stormwater runoff increase, the risk of flooding increases, which threatens the public welfare and surrounding infrastructure (Brown et al., 2009; Burns et al., 2012; EPA 2012). Many cities in North America constructed extensive sewer systems initially to help control the outbreak of disease (Staley and Pearson, 1899). Most sewage collection systems collected both sewage and urban runoff (combined sewer) incorporating relief structures that allowed flow to be discharged into a nearby river or stream when the capacity of the collection system was exceeded (combined sewer overflow, CSO) (Burrian, 1999; EPA, 2004). As urbanization exploded, the quantity of combined sewer discharges increased causing serious water pollution problems. Cities and communities were forced by the United States Environmental Protection Agency (USEPA) to reduce or eliminate CSO related pollution problems (EPA, 1994). A solution to the CSO problem was to implement sewer separation constructing a separate sewer for stormwater runoff from wastewater.

Researchers have found that changes to peak flow rates (specifically increases) and stormwater runoff volumes have a strong correlation to the increase in impervious cover (Konrad and Booth, 2002; CWP, 2003; EPA, 2012; Burns et al., 2012). Increases in peak flow rates exacerbate the problems of erosive velocities and scour by extending the duration of higher flows (Fongers et al., 2001, Baker et al., 2008). The more frequent high peak flow rates occur in a stream, the greater the risk of producing simple trophic structures with low taxonomic diversity (Rabeni and Wallace, 1998; Konrad and Booth, 2002). Another result is the increase in the frequency and duration of bankfull flow events. The Center for Watershed Protection cites that these events expose the stream channel to more shear stress above the critical threshold needed to maintain bank and bed sediment loads. As a consequence, the stream channel adjusts by expanding its cross-sectional area (CWP, 2003).

2.2.2. Water Quality Aspects of Urbanization

Runoff from urban areas is one of the leading sources of water quality degradation in surface waters. Increased loads of pollutants and at higher concentrations enter urban streams as a result of urbanization. The quantity of pollutant loads conveyed to receiving streams through stormwater runoff is directly proportional to the quantity of impervious cover (CWP, 2003). These pollutants include sediment, nutrients, metals, hydrocarbons, bacteria and pathogens, organic carbon, methyl tertiary butyl-ether (MTBE) pesticides and deicers (CWP, 2003). Further, studies have documented that degradation from pollutants occurs even at low levels of catchment urbanization (Booth et al., 2004; Hatt et al., 2004; Walsh et al., 2005).

Increased sediment loads in stormwater runoff cause sediment to deposit in receiving streams, covering benthic organisms, including aquatic insects and freshwater mussels. Suspended sediments in stormwater runoff are the major carriers of other pollutants into receiving streams like heavy metals and hydrocarbons (CWP, 2003). Nutrients, while essential for aquatic systems, cause negative impacts on receiving waters in excessive concentrations. Many studies have indicated that nutrient concentrations are directly linked to land use type, with urban and agricultural watersheds producing the highest nutrient loads (Chessman et al., 1992; Wernick et al., 1998; Paul et al., 2001; USGS, 2001; CWP, 2003)

The decrease in quality of stream biotic health has been directly linked to the increase in percent of impervious cover (EPA, 2000; Walsh et al., 2001; Stephnuck et al., 2002; Morse et al., 2003, Hatt et al., 2004)). Faulkner (2004) identified habitat fragmentation and biochemical and physical changes to streams as specific results of urban stormwater due to urbanization. Other studies have documented that increases in peak flow rates from urbanization produces bank instability, undercut banks, exposed roots, and channel incision (Bragg et al., 2005; Bunn & Arthington, 2002; Roy et al., 2005). The bed-scouring and channel-erosive effects include reduced periphyton biomass, reduced macrophyte and fish populations and low diversity in lotic assemblages (Konrad and Booth, 2002, EPA 2012). In particular, high peak flow rates causing streambed scour directly affect stream biota by killing organisms or dislodging them and transporting them downstream.

Prolonged periods of low flows have been documented to pull the water out of the stream floodplain and vegetation changing the riparian corridor species to more drought-tolerant species (Poff et al., 2009). Low flow conditions can also result in changes to nutrient uptake and cycling, creating a potential source of nitrate rather than a sink for nitrate (EPA, 2012).However, several studies have not found any conclusive evidence that impervious cover is responsible for lower baseflows during certain times of the year (Hollis, 1975; Evett et al., 1994). For example, Konrad and Booth found that stream baseflows actually increased during the summer months (Konrad and Booth, 2002). Increased infiltration from lawn watering, leaking water supply systems, inputs from wastewater treatment plants and septic systems are common sources for the increased baseflow (Brandes et al., 2005; Price, 2011; Burns et al., 2012). In either scenario, the result is extremes in stream baseflows. Researchers have found that these extremes are a direct impact to lotic communities often resulting in mortality and decreases in macroinvertebrate community composition, density and/or diversity (Coleman et al. 2008).

Walsh et al. (2005) assessed that aquatic ecosystem damage is quite common where the urban stream syndrome is present, which is characterized by flashy hydrographs, higher pollutant levels, highly modified channel geomorphology, and decreased biotic richness.

It is evident that the water quality impacts realized from urbanization are a result of the increased runoff that carry the pollutants into nearby stream and rivers, along with the higher peak flows which contribute to the channel erosion and bank-instability. It is hypothesized then, that a reduction in the quantity of stormwater runoff, will have a direct impact on improved water quality and reduced pollutant loads.

2.3. SOLUTIONS TO IMPACTS OF URBANIZATION

Urban stormwater managers are challenged to provide a solution to the water quality and water quantity problems that have been created by urbanization resulting in an increase in impervious surfaces. The traditional approach of collecting stormwater in a traditional storm water collection system, of catch basins and underground storm sewer pipes that discharge to a detention basin and is slowly released to the local waterbody was discussed above. This approach does not fully address the problems caused by CSO's or flooding risks (Walsh et al. 2005).

Low impact development (LID) is an alternative approach that reduces peak flow rates, stormwater runoff volumes, provides water quality treatment, and minimizes exposure of the stream channel to erosive flows (EPA, 2000; Davis, 2007; Davis, 2008; USGS, 2010). LID is a widely used term that has been used interchangeably with the term Green Infrastructure. For the purposes of this research, the term LID is referred to as an approach to land development or re-development that use or mimic natural processes to store, infiltrate, evaporate, transpire, or reuse stormwater on the site as close to its source as possible. Weinstein (The Executive Director of the LID Center) remarks in a 10th anniversary of the LID Center letter that any successful LID project requires the use of hydrology and hydrologic processes as the framework for design, micromanagement techniques, a focus on controlling stormwater at the source, incorporating simplistic, non-structural methods and creating a multi-functional landscape and infrastructure (Weinstein, 2008). LID provides benefits beyond just water quality and water quantity benefits including reduced energy use, reduced CO_2 emissions, air quality improvements, and reductions in urban heat island effect (Weinstein, 2008; CNT, 2010; EPA, 2013; EPA, 2014). From a community livability perspective, the benefits of LID include recreation, reduced noise pollution, improved human health, beautification and adding aesthetic value (Weinstein, 2008; CNT, 2010; EPA, 2013; EPA, 2014).

Specific examples of LID practices include bioretention facilities (rain gardens), vegetated bioswales, green roofs, water harvesting (rain barrels and cisterns), and permeable (porous) pavement (SEMCOG, 2008). All of these practices focus on intercepting the stormwater runoff before it enters the conventional stormwater drainage system and is conveyed to the nearby stream and allowing the water a chance to infiltrate into the ground, and promote evapotranspiration (SEMCOG, 2008; Burns et al., 2012).

2.4. BIORETENTION FACILITIES

Bioretention has been used as a stormwater LID practice since 1992 and is very common in communities across Michigan and the United States (EPA, 1999; Hunt, 2006; Davis et al., 2009, Hunt et al., 2012). Bioretention facilities are more than just infiltration practices. They are designed to mimic all aspects of the natural site hydrology, including interception, infiltration, soil storage, detention and evapotranspiration to retain and treat stormwater runoff (Weinstein, 2008; Trowsdale 2011). Bioretention systems are composed of an excavation area backfilled with engineered soil over an aggregate storage layer and a shallow area above the soil for surface storage. The systems are typically planted with native vegetation such as trees, shrubs and grasses to remove pollutants from stormwater runoff. A mulch layer is incorporated to protect the soil and retain water. An underdrain is provided when the native underlying soils lack the capacity to infiltrate water effectively (Thompson et al., 2008).

2.4.1. Design Criteria

A wide variety of design guidelines exist including recommendations for soil media mixtures, aggregate storage layer stone size, vegetation options, drawdown time, and infiltration rates (Carpenter & Hallam, 2010; Hunt et al., 2012). Design guidelines for soil media mixtures and aggregate storage layers are based on specific design goals (i.e. water quality treatment versus water quantity) and geographic region. Guidelines for drawdown time and infiltration rates are applicable regardless of the design goal; however, vary based on the geographic region. Due to the fact that designs are specific to geographic location, the variability in the design guidelines is expected.

Research suggests that the ability of water to move into and through a bioretention system determines its effectiveness (Thompson et al., 2008; Li et al., 2009; Hunt et al., 2012). Water quality treatment efficiencies are directly related to the ability of a bioretention system to reduce outflow volumes. Hunt et al. (2012) advised that in many cases, the single reason pollutants loads are less at the outflow than at the inflow is due to the hydrologic modifications and water balance in the bioretention system. Further, the effectiveness of bioretention systems to provide water quality treatment and water quantity reductions is predominantly controlled by the soil particle arrangement and stability (Thompson et al., 2008). Therefore, it is important to understand treatment mechanisms as well as hydrologic modification mechanisms to allow effective design of bioretention systems.

2.4.1.1. Vegetation Options

Vegetation used in bioretention facilities varies by geographic location, the necessary level of care, the land use environment, and aesthetic and functional goals. A variety of studies have documented that vegetation is an important system component for enhancing the function of bioretention systems (Denman et al., 2007; Henderson et al., 2007; Lucas and Greenway 2008; Read et al. 2008; Bratieres et al. 2008 from Barrett 2013). Plants directly contribute to treatment efficiency by degradation of organic pollutants, uptake of macronutrients and heavy metals (Breen, 1990; Schnoor et al., 1995; Cunningham and Ow, 1996) and maintenance of longer-term soil porosity (Read et al., 2008). Plants also make direct use of nitrogen and phosphorous.

Additionally, research indicates that pollutant removal and system functionality can be affected by the type of vegetation selected (Read et al., 2008; Bratieres et al., 2008). Read et al (2008) observed that the large variation in reported pollutant removal efficiencies in bioretention systems, is directly affected by the choice of plants. The study concluded that the type of plant species selected, could have a measurable impact on the bioretention system effectiveness. As an example, certain plants have a high number of microscopic root hairs that greatly increase the area of soil accessible to plants (Read et al., 2008). Limited research is available evaluating how particular plants, both native and non-native, influence pollutant removal for bioretention systems in the state of Michigan. The choice of plants needs to be based not only on their treatment ability but also on their capacity to survive in stressful growing and environmental condition (Read et al. 2008).

2.4.1.2. Bioretention Soil Media

The soil media used in bioretention systems directly influences the stormwater treatment effectiveness as well as overall system performance (Hunt et al., 2009). It must be able to effectively treat stormwater and maintain the ability to drain the storm event while surviving and providing aesthetic benefits in the environmental conditions it resides in.

Bioretention soil media typically consists of a mix of sand, soil, and compost. Current literature regarding the content of soil media varies widely. It does not characterize soil media properties and fail to evaluate it based on its treatment capacity and functionality (Ermilio and Traver, 2006; Hunt et al., 2008; Read et al., 2008; Barrett et al., 2013). In general, studies provide information on the percentages of the various soil media components but do not provide quantitative information about organic matter content and type of organic matter, permeability, water holding capacity, and particle size distribution among others.

Organic matter in bioretention systems provides enhance aggregate stability, water holding capacity, hydraulic conductivity, and decreases bulk density (Albiach et al., 2001; Thompson et al., 2008). However, the incorporation of organic matter also increases the potential for compaction, increasing the bulk density, which can result in a reduction in the infiltration capacity (Gregory et al., 2006; Thompson et al., 2008). Current research indicates that organic matter present in addition to a soil component provide a more stable structure to increase the longevity of the bioretention system. Although compost will eventually degrade and lose its performance enhancing effects, it provides a structure for plant roots and macrospores to mature so that the impact is sustained (Olson et al., 2013).

2.4.2. Water Quality Treatment

The evaluation of water quality treatment performance of bioretention systems has predominantly been in the laboratory (Davis et al., 2001; 2003, Trowsdale, 2011). These studies suggest that bioretention systems are effective at reducing stormwater contaminants including sediments, heavy metals and phosphorous (Sun and Davis, 2007; Bratieres et al., 2008; Lucas and Greenway, 2008; Trowsdale, 2011). Limited measurements at field scale applications of bioretention systems supported the laboratory findings of high removal efficiencies for sediments and heavy metals (Hatt et al., 2009; Trowsdale, 2011). Full-scale bioretention water quality and quantity performances data is scarce and further research of pollutant removal efficiencies in field applications to provide more conclusive results is necessary.

This section will discuss reported treatment efficiencies of bioretention systems for nutrients, total suspended solids and heavy metals. Typically these are quantified by reporting the percent removal from the influent to the effluent. However, the use of fractional removal (percent) can be misleading and inaccurate for effective treatment systems when the input pollutant concentration is very low (Davis, 2007). Event mean concentrations (EMCs) prove a better way to represent performance but can be misrepresentative because they do not consider the size of the runoff event. Therefore, total pollutant mass removal is a more representative measure of bioretention system efficiency for water quality performance. Limited studies are available that report pollutant mass removal efficiencies so EMCs or fractional removal will be presented in cases where mass removal is not reported.

2.4.2.1. Nutrient Removal

Total nitrogen and total phosphorous load reductions have been documented at both the laboratory scale and field scale applications. Nitrogen removal has been reported between 30 and 95 percent (Hunt, 2006; Davis et al., 2009; Liu et al., 2014). On a total pollutant mass removal basis, nitrogen rates range between 90 and 95% (Davis, 2007). Increases in nitrogen removal can be realized by retaining water in the bioretention system for longer periods of time. This ca be achieved by changes to the bioretention system design.

Researchers have found good phosphorous removal in bioretention systems (Davis et al., 2006; Hseih et al., 2007; Lucas and Greenway, 2008) while significant variations were noted in a study by Hsieh and Davis (2005a). More recently, phosphorous mass removals in bioretention facilities have been noted between 77-79% (Davis, 2007). Dietz and Clausen (2005) noted a net export of phosphorous from bioretention systems. A review of the temporal data; however, suggested that higher concentrations occurred in newer facilities due to phosphorous being washed from the original soil media. Hunt et al. (2006 and 2012) noted that phosphorous performance was highly dependent on the soil composition in the bioretention system while nitrogen removal efficiencies are linked to plant selection (Lucas and Greenway, 2008).

2.4.2.2. Suspended Solids

Suspended solids and particulate matter are removed in bioretention systems through sedimentation and filtration. As water passes through the soil media in a bioretention system, it is filtered allowing fine particles to be captured. Larger particles are strained out at the surface of the media (Hunt et al., 2012). Davis (2007) reported total suspended solids (TSS) mass removal was between 54-59% while a study by the University of New Hampshire reported TSS removal as high as 97% for a bioretention system (UNHSC, 2006).

A more recent study by Trowsdale (2011) supported the observation that total suspended solid concentrations are significantly reduced through the use of bioretention systems, with median and maximum concentrations measured in the outflow were 3 and 42 mg/L, respectively as comparted to the inflow values (median 30 mg/L, max 375 mg/L). Bioretention systems that have been in place for several years provide for greater filtration and sedimentation of TSS with improved TSS removal efficacy (Liu et al., 2014).

Removal efficiencies can be modestly improved with the addition of vegetation as it slows the water velocity, allowing more settling time for sediment (Emerson and Traver, 2008; Hatt et al., 2009a). Additionally, protection of the bioretention area from construction sediment will reduce the chance of system failure from large inflows of sediment before practice establishment.

2.4.2.3. Metals

Heavy metals wash from tires, automobile exhausts, road asphalt, parking dust and recreational land into urban stormwater runoff (Reddy et al., 2014) and are a major contributor to the degradation of many urban streams and rivers (NRDC, 1999). The primary treatment mechanism for these pollutants is adsorption by the engineered soil media and overlaying mulch layer (Hunt et al., 2012). Overall, high removal rates of heavy metals have been documented for bioretention systems (Davis et al., 2003; Hunt et al., 2008; Hatt et al., 2009b). In order to ensure that the adsorbed heavy metals do not become re-suspended and transported through the effluent, the periodic removal of the top 10-cm (4-inches) of soil media is necessary (Li and Davis, 2008; Hunt et al., 2012)

Copper mass removal efficiencies range between 77 and 99% and lead mass removal efficiencies have been reported between 84 and 93% (Clark et al, 2004; Davis, 2007;WaDOT, 2007). The wide range of removal efficiencies could be affected by the overall runoff volume reduction observed in the bioretention system.

Reported concentrations of total dissolved zinc inflow values had a median concentration of 659 (total) and 355 (dissolved) µg/L, respectively. Effluent values show bioretention systems remove much of the Zn from the water, reducing the median total concentration to 29 µg/L and the dissolved to 24 µg/L. Studies done by Clark et al. (2004) reported zinc mass percent removal varies between 54 and 69%.

Further, metal adsorption can be increased at higher pH levels, with effective adsorption occurring within a pH range of 6-7 (Hunt et al., 2012). Therefore, it is necessary to ensure design of the bioretention system to maintain a pH between 6-7 in the engineered soil media.

2.4.3. Water Quantity Benefits

Sources of runoff are diverted into bioretention systems directly as overland flow or through a stormwater drainage system as close to the source as possible. Reductions in stormwater volumes occur within bioretention systems through evapotranspiration, vegetation uptake and infiltration into the native underlying soils. Numerous studies have documented bioretention performance in improving watershed hydrology (Davis et al, 2001; 2003; Dietz and Clausen, 2005; 2006; Hunt et al., 2006 and 2008; Davis 2007 and 2008). In general, bioretention systems have been found to be effective in reducing runoff volume and in treating the first flush (first one-half inch) of stormwater runoff. However, bioretention systems are less effective at reducing runoff volume for larger storm events (EPA, 2000; Williams and Wise 2006). However, still limited quantitative information on hydrologic impacts of LID, specifically bioretention is available (Davis, 2008). Actual volume removal efficiencies vary largely, ranging from 40% to 97%, due to differences in design and climatic conditions (Ahiablame et al., 2012a; Zhang and Guo, 2013).

Rates of runoff volume reduction have been examined as they relate to evapotranspiration. Research has found that evapotranspiration (ET) loss from a bioretention facility may account for approximately 10% to 19% of total inflow (Li et al., 2009; Liu et al., 2014). These rates of ET are substantial and support a goal of bioretention in mimicking predevelopment hydrology. A further increase in ET loss can be realized with larger bioretention surface areas but also cost more. Additional studies have shown that increasing the root zone volume provides a greater opportunity for inter-event storage and for increased vegetation update of stormwater (Hunt et al., 2012).

Runoff volume reduction that is attributed to infiltration (or exfiltration from the bioretention system) was determined by Li et al (2009) to be around 8%. The study documents that deeper storage media depths promote increased infiltration as well as increased ET. The incorporation of an internal storage zone shows the ability to appreciably increase the volume reduction for small storms in bioretention systems (Li et al., 2009).

2.4.4. Costs

The USEPA (1999) documents that construction cost estimates for a bioretention facility are slightly greater than those for traditional landscaping for new development sites. The increased cost is typically offset by the decreased cost for stormwater conveyance at the site. Typical construction costs vary widely depending on the cross-section, vegetation, and environmental constraints and site restrictions. Ballestero (2013) published costs of $12,000 per impervious acre for a retrofit situation and $25,000 per impervious acre for a non-retrofit application. Prince George's County (2007) summarizes that a net reduction of between 15% and 50% of the site development costs can be realized with the integration of bioretention facilities.

2.4.5. Limitations

The use of bioretention facilities have few limitations. For example, bioretention facilities are not appropriate in locations where the water table is within 6 feet of the ground surface or 2 feet the bottom of the bioretention practice (EPA 2000). One of the principal components of a bioretention system in terms of water quality and water quantity treatment benefits is the vegetation. As such, the long-term performance of the bioretention depends on the survival and maintenance of the vegetation.

Another factor is installation of bioretention in areas with highly contaminated runoff. In this case, impermeable liners must be installed at the bottom of the bioretention facility to prevent migration of contaminated water (Prince George's County, 2007).

2.5. PERMEABLE PAVEMENT

Permeable pavements are comprised of a surface that allows stormwater to pass through it, along with a filter and reservoir layer for capturing the stormwater runoff from the tributary drainage area. These pavement systems have been installed since the early 1980's throughout the United States and are now well established stormwater management practices (Ferguson, 2005; Gilbert and Clausen, 2006; Schaus, 2007; Horst et al., 2011; Welker et al., 2012). There are a variety of different types of permeable pavement including modular paving systems (e.g. concrete pavers, articulating concrete blocks, grass pavers) or poured in place solutions (e.g. pervious concrete, porous asphalt, glass porous paving) (EPA, 1999). Schaus (2007) reported that the design of the pavement mix is the key to the effectiveness of the system to adequately control stormwater runoff.

The benefits of permeable pavement systems include runoff volume reduction, groundwater recharge, and pollutant removal capacity, among others (Legret and Colandini, 1999; Kwiatkowski et al., 2007; Haselbach et al., 2011; Nemirovsky et al., 2013). These benefits are achieved primarily through infiltration and adsorption of stormwater pollutants to the pavement system.

2.5.1. Design Criteria

Permeable pavement systems are comprised of three main components including a surface course, a filter course, and a reservoir course. The surface course consists of an open graded asphalt or concrete mix approximately 50-100 mm (2-6 inches) thick depending on the structural strength necessary (FHWA, 2004; Schaus, 2007). The air void percentage of the surface course is the critical component to ensuring the pavement system functions for stormwater management. Air void percentages ranging from 16 to 22% (or greater) have been recommended by NAPA (2003) as well as other studies (Backstrom, 2000; FHWA, 2004). The filter course consists of a crushed aggregate, which filters the stormwater runoff before infiltrating into the reservoir layer and native soil. The depth ranges between 25-50 mm (1-2 inches) (FHWA, 2004; Schaus, 2007). The third component is a reservoir course that provides storage volume for stormwater until the water can infiltrate into the native soil. The depth of this layer depends on the quantity of stormwater that is to be stored (FHWA, 2004). The air void percentage of the reservoir layer should be at approximately 40% (Cahill, 2003; Schaus, 2007).

2.5.2. Water Quality Treatment

2.5.2.1. Nutrient Removal

Two long term permeable pavement studies in Maryland and Virginia provided an estimate of permeable asphalt’s pollutant removal efficiency. The studies observed phosphorous removal efficiency to be 65% and 80% to 85% for total nitrogen (EPA, 1999). Pollutant removal efficiencies for phosphorous are further supported by Ballestero (2013) who reported 60% removal of phosphorous.

2.5.2.2. Suspended Solids

The two long term permeable pavement studies performed in Maryland and Virginia observed that 82% to 95% of suspended solids removal through a permeable pavement system (EPA 1999). More recent pollutant removal efficiencies reported by Ballestero (2013) and the Asphalt Paving Association of Michigan (2014), indicate suspended solids removal efficiency near 100% for permeable pavement systems.

2.5.2.3. Metals

An early study of permeable pavement systems reported heavy metal reductions of 79% for lead, and 75% for zinc (Legret et al., 1996). Published data from the Asphalt Paving Association of Michigan reports metals removal of 85% (2014). Another recent study by Zhao and Zhao (2014) documented reductions in lead concentrations above 95%. However, the study reported zinc levels increased in the short-term. This was noted to potentially be caused by the aggregate material used in the reservoir storage layer not being cleaned prior to installation. Lead reductions were observed only long time after the rain event. The study suggests that future research is needed to better quantify the pollutant removal efficiencies of metals in permeable pavement systems (Zhao and Zhao, 2014).

2.5.3. Water Quantity Benefits

There are two approaches to permeable pavement design for stormwater runoff capture and volume reduction. The first approach considers sizing the reservoir course to hold the calculated runoff volume from a design storm event. The second approach is to design the pavement system for a percent reduction in stormwater runoff compared against the rainfall total (Field et al., 2004; Tennis et al., 2004; Martin and Kaye, 2014). This approach has reported stormwater runoff volume reductions ranging from 90% to 100% for smaller, more frequent storm events (Pratt et al., 1989; Dreelin et al., 2006; Collins et al., 2008; Martin and Kaye, 2014). Martin and Kaye (2014) discuss the lack of published data on quantifying the stormwater runoff volume reductions over a broad range of storm events.

2.5.4. Costs

The costs of permeable pavement systems tend to be approximately 35% to 40% higher than traditional pavement systems (APAM, 2014). Costs vary with location and installation conditions (Ballestero, 2013). Additionally, concrete pavers and articulating concrete blocks are typically more expensive than porous asphalt or pervious concrete. Ballestero (2013) reports a cost per impervious acre of $58,000 for porous asphalt and $174,000 for porous concrete.

2.5.5. Limitations

Permeable pavements are most successful at sites that have an underlying soil permeability of greater than 13 mm per hour (ACI, 2006; Schaus, 2007). As such, sites with poor infiltration capacity should incorporate an underdrain into the system design. The EPA (1999) reported that there is a risk of contaminating groundwater by pollutants not easily trapped, adsorbed, or reduced in the pavement system that migrate through to the soil and groundwater.

2.6. VEGETATED BIOSWALES

Bioswales are defined as linear planted areas that allow for collection, conveyance, filtration and infiltration of stormwater (SUNY 2015). Bioswales are composed of a shallow area for surface storage above a vegetated layer. They often contain amended soils to promote infiltration. While vegetated swales have been widely used as a stormwater LID practice, there are certain properties that have not been quantified. These aspects include whether pollutant removal rates decline over time, the effect of the slope of the bioswales on the filtration capacity, and design factors that enhance the pollutant removal efficiency (EPA 1999).

2.6.1. Design Criteria

The design of vegetated bioswales depends on the intended function, either as an infiltration practice, water quality practice or a combination of the two. Bioswale dimensions are typically long and narrow with widths between 0.6 and 2.5 meters with a maximum ponding depth of 0.5 meters (Dorman et al., 2013). The soil media mix components are identical to bioretention facilities based on the pollutant of concern and hydrologic goals. A bioswale includes a longitudinal slope to allow for stormwater runoff conveyance to a downstream LID practice or a storm sewer system. As such, flow velocity is a major design component to allow adequate settling time for suspended solids. Flow velocity should not exceed the permissible shear stress of the bioswales bed materials (TxDOT, 2011; Dorman et al., 2013). Mulch and vegetation are critical design components for hydrologic, water quality, and aesthetic perspectives. Design and selection of these components should meet the criteria for bioretention facilities.

2.6.2. Water Quality Treatment

Bioswales are intended to provide similar pollutant removal capacity as a bioretention facility with a narrower configuration. Limited research shows that bioswales can achieve up to 92% pollutant removal efficiency for stormwater runoff (DEQ NWR, 2003; Aklaku, 2014). Bioswales can achieve much higher levels of suspended solids removal compared to the removal efficiency of metals and nutrients. Increased levels of suspended solids removal can be achieved with the incorporation of check dams and ensuring the longitudinal slope provides for adequate settling time (Dorman et al., 2013).

2.6.2.1. Nutrient Removal

Bioswales can achieve a moderate percentage of nutrients removal in runoff (OR DEQ, 2013). Horner and Chapman (2007) report removal efficiencies for total phosphorous in the range of 49% to 74% and nitrate removal in the range of 39% to 89%.

2.6.2.2. Suspended Solids

Ballestero (2013) published data on pollutant removal efficiencies for various LID practices. The study reports a suspended solids removal efficiency ranging from 50% for a stone-lined bioswales to 57% removal for a vegetated swale. Other studies report pollutant removal efficiencies for bioswales ranging from 83% to 92% (DEQ NWR, 2003; Aklaku, 2014). The suspended solids removal is achieved through settling as the vegetation in the bioswales slows the stormwater runoff down.

2.6.2.3. Metals

Bioswales have been documented to achieve a moderate percentage removal of metals in stormwater runoff, ranging from 20% to 60% (OR DEQ, 2003). A study by Aklaku (2014) published overall metal removal efficiencies for bioswales systems ranging from 30% to 90%. Removal efficiencies for lead were between 67% and 90%, between 30% and 55% for dissolved zinc, and between 63% and 76% for total zinc.

This relatively lower level of removal compared to sediment is due partly to the large percentage of metals and nutrients that appear in dissolved form in runoff. Since most bioswales infiltrate only a portion of their flow, removal rates for pollutants in dissolved form are lower than those for sediment (Aklaku, 2014).

2.6.3. Water Quantity Benefits

Vegetated bioswales can be designed as infiltration practices or as water quality treatment devices. The narrow configuration of a vegetated bioswales system and its intended use along narrow spaces at the edges of parking lots and roads, require restrictions on infiltration to prevent undermining surrounding infrastructure and foundations (Dorman et al., 2013).

2.6.4. Costs

Costs of vegetated bioswales vary greatly depending on size, plant material, and site considerations. However, they are generally less expensive when used in place of underground storm sewer piping. Ballestero (2013) reported costs of vegetated bioswales at $13,000 per impervious acre.

2.6.5. Limitations

Vegetated bioswales are versatile and can be designed to provide the same hydrologic and water quality benefits of a bioretention facility with similar limitations. Compared to a bioretention facility, bioswales are typically incorporated into space limited locations and as such, typically provide less hydrologic and water quality benefits than a bioretention facility (Dorman et al., 2013).

2.7. GREEN ROOFS

Green roofs are rooftops that have a growing medium and vegetation. In general, there are two types of green roofs, intensive and extensive (Long et al., 2006; Cresswell, 2007; Molineux et al., 2009; and Castleton et al., 2010). Intensive green roof systems have a deep growing medium layer to support trees, bushes, shrubs, perennials or succulents. Intensive roof systems require structural support, along with a waterproofing membrane to prevent building leaks, insulation, drainage cups to provide aeriation, water and a barrier to roots (Bengtsson et al., 2005; Aziz and Ismail, 2007). These types of green roofs require more structural support and as such, can support loads from human traffic as well. Extensive green roofs have a shallow soil with hardy succulents that grow horizontally. These systems require little or no additional structural support and are designed only for occasional maintenance foot traffic (Bengtsson et al., 2005; Aziz and Ismail, 2007)

Green roof systems have been installed for a relatively short period of time (Voorhies, 2012). Limited research suggests that green roofs offer value by providing stormwater retention (Bengtsson et al., 2005; Aziz and Ismail, 2007; Voorhies, 2012).

2.7.1. Design Criteria

The two major design components for green roofs that provide hydrologic and water quality treatment benefits are the soil growth medium and vegetation.

2.7.1.1. Growing Medium

The growing medium is typically made up of a mineral based mixture of sand, gravel, crushed brick, leca, pea, organic matter and some soil, depending on the type of system (Peck and Kuhn, 2014).

2.7.1.2. Vegetation

Location, wind, rainfall, air pollution, building height, shade, and soil depth are all factors in determining what plants can be grown and where. Since green roofs, by definition, are placed on top of an impermeable system, the root growth of vegetation used is limited to the depth and horizontal width of the green roof system. Vegetation incorporated into an extensive system often consists of hardy, dryland species, such as sedum, grasses, mosses, festucias, irises and wildflowers (Peck and Kuhn, 2014). The type of vegetation for an intensive roof system is more diverse, and with a few exceptions, are limitless.

2.7.2. Water Quality Treatment

Improvement of water quality is one of the main stated benefits of green roofs through vegetation and the growing media. However, these benefits are not properly understood and it is still uncertain whether or not green roofs improve or degrade local runoff water quality. Several studies and reports indicate that green roofs act as sources of pollutants (Moran, 2005; Vijayaraghavan et al., 2012; Razzaghmanesh et al., 2014; Speak et al., 2014).

2.7.3. Water Quantity Benefits

Stormwater runoff volume is reduced through green roof systems via plant evapotranspiration and water retention in the soil and plant system. Runoff volume reductions of up to 50% have been reported by several studies (Bengtsson et al. 2005; Musa et al, 2008; Berghage et al., 2009; Aziz and Ismail, 2011).

Another study by Moran et al., (2005) reported stormwater runoff volume reductions between 55% and 67% for two sites in North Carolina. Other studies have reported less substantial reductions in stormwater runoff of between 11 to 15% (Beckman et al., 1997)

2.7.4. Costs

Green roofs are more expensive to install than traditional roofs. A study by Wong et al. (2003) reported green roof installation costs ranged from three to six times the cost of a conventional roof system. However, the study stated that the green roof system was projected to have three-times the life expectancy of the conventional roof systems. Specific installation costs for an extensive green roof system are between $108 to $217 per square meter (Dunnett and Kingsbury, 2004).

2.7.5. Limitations

The widespread use of green roofs is limited by high installation costs and extra structural load requirements. Green roofs require a roofing membranes to hold the (dry) system in place to prevent wind blow off. In many cases, the amount of material required to hold the system down in a high wind event is greater (when the system is wet) than the capacity of the structural system to support this weight (Voorhies, 2012).

2.8. RAINWATER HARVESTING SYSTEMS

Water harvesting techniques have a long history throughout the world (EPA, 2008; Beatty and McLindin, 2012). The practice includes capturing, storing and using rainwater runoff at the place it occurs. Rainwater harvesting can include systems such as a rain barrel that captures residential rooftop runoff and is used for garden irrigation or a more complex system such as a cistern that provides for multiple end-uses (TWDB, 2005). The residential application where the end use is garden irrigation does not require treatment and are typically less than 380 liters (100 gallons) of storage. The more complex system used for non-potable indoor use requires treatment (EPA, 2008) and allow for storage of more than 380 liters (100 gallons) of rainwater (Dorman et al., 2013).

2.8.1. Design Criteria

Currently there is no uniform national guidance for the design or use of rainwater harvesting systems for both a residential garden irrigation use or commercial non-potable water use system (EPA, 2008). System design is therefore the responsibility of the system owner. Design of individual systems is based on the water demand for the targeted end use of the system.

2.8.2. Water Quality Treatment

While the runoff that is captured from rainwater harvesting practices is often considered clean runoff, pollutants generated from the rooftop itself are present in the water but are generally in low concentrations (EPA 2008). These include metals or hydrocarbons from roofing materials, nutrients from atmospheric deposition and bacteria from bird droppings. When rainwater harvesting systems are implemented, these pollutants are captured and prevented from being conveyed to the conventional storm sewer system. However, the treatment is typically insignificant and is ultimately provided by a downstream LID practice (Dorman et al., 2013)

The pollutant removal mechanisms of cisterns are poorly understood (Dorman et al., 2013). Despite this, rainwater harvesting can greatly reduce pollutant loads to waterways if stored rainwater is infiltrated into surrounding soils or conveyed to a downstream LID practice. Additional pollutant removal can be seen with the implementation of solids screening mechanisms and other filtration systems.

2.8.3. Water Quantity Benefits

One of the major functions of a rainwater harvesting system is the storage or flow attenuation (Dorman et al., 2013). Residential rain barrels,; however, do not typically provide substantial hydrologic benefits because they tend to be undersized relative to their contributing drainage area.

2.8.4. Costs

The cost for a residential rain barrel between 208 to 380 liters (55 to 100 gallons) is typically around $100. This equates to approximately $0.26 to $0.48 per liter ($1.00 to $1.80 per gallon) of rainwater captured (TWDB, 2005).

Costs for a cistern vary widely depending on the size, material and intended end use of the system. Costs range from approximately $0.13 per liter up to approximately $1.05 per liter ($0.50 to $4.00 per gallon) (TWDB, 2005). It should be noted that as the tank size increases, the cost per gallon of rainwater decreases.

2.8.5. Limitations

Rainwater harvesting systems are most beneficial when the storage system is adequately sized for the tributary drainage area. The system must be drained between rain events to achieve hydrologic and treatment benefits after each rainfall event (Jones and Hunt, 2010; Dorman et al., 2013).

Plumbing codes have been recognized as a barrier to implementing rainwater harvesting systems (EPA, 2008). Many codes across the country require roof downspouts to be connected to the storm sewer system or make no provisions for rainwater reuse. In the western part of the United States, water rights and the doctrine of "first in time, first in line" causes an additional barrier to rainwater harvesting as many western states view this doctrine as a prohibition to rainwater harvesting (EPA, 2008).

2.9. HYDROLOGIC MODELING FOR HYDROGRAPH MODIFICATION

Many factors influence the performance of bioretention systems, including type of vegetation, type and depth of soil media, surface area, total storage volume, and the presence or absence of an underdrain. Design of bioretention systems must simultaneously account for these factors to achieve maximum effectiveness over the long-term. To determine the effects that bioretention systems have on urban stormwater hydrographs, a hydrologic model is necessary because of the predictive capabilities and the ability for models to account for interactions of all bioretention system components.

Many hydrologic models can predict the water quality and water quantity impacts of LID practices (EPA, 2014). In general, LID practices are represented in models in two ways. The first is process representation (e.g. infiltration, sedimentation, adsorption, and ET) occurring within the LID practice. The second is practice representation that entails combining all the complex processes that the LID practice can perform into one parameter (e.g. representing the effects of bioretention with curve number values), (Ahiablame et al., 2012a). Elliott and Trowsdale (2007) cite that all of the models lack components of modeling the effects of LID practices. For example, none of the models include temperature, despite this being an important stressor in urban streams. Very few include dissolved oxygen depletion calculations and most have limited or no ability to predict pathogenic micro-organisms or bacterial indicators.

The following models are commonly used for modeling the effectiveness of bioretention systems and illustrate the two representative approaches to modeling LID practices. The models discussed below are currently available and have not been superseded by a newer version of the model or replaced.

2.9.1. USEPA Stormwater Management Model with LID Controls (SWMM)

SWMM is a physically based, spatially distributed, watershed-scale model that operates on a continuous daily or sub-hourly time step. The SWMM model was developed by the United States Environmental Protection Agency – Water Supply and Water Resources Division (EPA, 2014) and is public domain. This model is used to simulate both water quality and quantity of urban stormwater runoff. SWMM allows modeling of a discrete storm event as well as long-term continuous simulations. EPA SWMM is suitable for a wide range of uses but is too complex to be used by the general public or non-modeling planners (Elliott & Trowsdale, 2007).

2.9.1.1. SWMM Model Components

SWMM model components include hydrology, weather, soil, temperature, depression storage, and watershed characteristics (EPA, 2010). The model uses subcatchments to define land area that accumulates precipitation and provides for infiltration and surface runoff to a specific node, other subcatchment or to a stormwater management practice.

Surface runoff is simulated using a simple nonlinear reservoir routing process, which includes rainfall intensities and antecedent moisture conditions, depression storage, land use and topography. Subsurface flow (routing) is modeled using either steady flow routing, kinematic wave routing and dynamic wave routing and assumes complete mixing. The model generates a complete runoff hydrograph, including flow rate and flow depth and routes it through a user-defined network of links and nodes. Several studies have documented that the SWMM model is most sensitive to the percent impervious and depression storage parameters with regards to the effects on peak flow and total stormwater runoff (Tsihrintzis et al., 1998; Barco et al., 2008).

2.9.1.2. SWMM Model Applications

Various studies have used SWMM to study the impacts of urbanization on water resources. A study performed by Boeley (2008) evaluated urban stormwater drainage for a large parking lot at the edge of a university campus. Jang et al. (2007) used SWMM to model both pre- and post-development conditions of four planned development areas. The study evaluated methods to improve irrationalities in modeling to improve accountability of the hydrologic impacts from planned development areas. Cambez et al. (2008) used SWMM 5 to model selected urban areas and found limitations in the catchment hydrological description and found no relevant benefits to the water quality model tool. Krebs et al. (2013) present the setupand results of a parameter sensitivity analysis using LID practices in a highly urbanized small catchment. Guan et al. (2014) use SWMM to model the effects of land cover changes on hydrological response to storms and change in distribution of peak and low flows. The study then incorporated LID practices and analyzed their effects on catchment hydrology. Tobio et al. (2015) performed a study to optimize the design of LID practices using SWMM rather than modeling the hydrologic changes of an LID practice already implemented.

The introduction of LID routines into SWMM is fairly recent. The following limited studies have modeled LID practices on a watershed scale using SWMM. Bosely (2008) analyzed the hydrologic changes with the implementation of swales, bioretention, rain barrels and vegetated roofs using SWMM. The study concluded that more tests are required to identify parameter sensitivity to model results. Additionally, the study determined that although SWMM has weaknesses in peak flow and timing predictions, those can be overcome by considering relative, rather than absolute differences between model results. Abi Aad et al. (2010) studied rain gardens and rain barrels using SWMM to estimate the percentage runoff volume reduction, peak flow reduction time delay of the runoff hydrograph and any potential reduction in runoff due to infiltration from a very small site. Eichenwald et al. (2010) developed a SWMM model for a multiyear project that modeled LID practices and provided final recommendations for LID practices to maximize the reduction of stormwater runoff volume and pollutant loads. This study focused on using SWMM for design recommendations rather than post-construction assessments. Tate (2010) modeled a combination of distributed infiltration trenches and underground storage vaults, vegetated swales and porous pavement. This study found that SWMM consistently predicted larger peak flows than other models. Rosa et al. (2015) setup a SWMM model to evaluate the impacts on stormwater runoff hydrology and nutrient export with the incorporation of LID practices in a watershed. The study results suggest that calibration is needed to improve predictions for watershed with LID practice incorporated.

2.9.2. RECARGA

RECARGA is a design tool for evaluating the performance of bioretention facilities, rain garden facilities, and infiltration basins. It is a MATLAB based application that can simulate continuous rainfall, a single discrete event, or a user specified volume. The model was developed by the University of Wisconsin – Madison, Civil and Environmental Engineering Department.

2.9.2.1. RECARGA Model Components

RECARGA model parameters include hydrology, weather, LID practice characteristics, and watershed (tributary area) characteristics. The model breaks hourly precipitation data into smaller time steps and calculates runoff from the tributary area by performing a water budget calculation and utilizing the SCS Curve-Number Method and initial abstraction methods (Atchison and Severson, 2004).

Model output information includes the depth of water for each water budget term (i.e. runoff, infiltration, ET), recorded at hourly time steps, and relative water content in each layer (root zone, storage zone and native soil layer) of the LID practice. This is expressed as a fraction of the overall soil volume utilized by the runoff generated. The model uses Green-Ampt infiltration for initial infiltration and the van Genuchten relations for drainage between soil layers (Dussaillant et al., 2004). Another feature of the RECARGA model is the capability to calculate the facility to tributary area ratio required to meet a certain target “stay on” volume. This allows the user to design the LID practice for a specific tributary area.

2.9.2.2. RECARGA Model Applications

Bioretention facility impact assessments have been performed using RECARGA in multiple studies such as Shuster et al. (2007), Neilson & Turney (2010) and Sun et al. (2011) These studies focused on the sensitivity of design elements and model parameters to the hydrologic performance metrics rather than evaluating the effects that LID practices have on stormwater runoff hydrographs.

2.9.3. Long-Term Hydrologic Impact Assessment Model (L-THIA)

The L-THIA model was developed by the College of Engineering at Purdue University. It is a web-enabled screening level tool that quantifies the impact of land use change on water quantity and water quality at both a site and watershed scale.

2.9.3.1. L-THIA Model Components

L-THIA model parameters include precipitation data, soils, event mean concentrations for pollutant loading estimation, watershed characteristics and LID practice characteristics (Park et al., 2013). Model output data includes both graphical and tabular runoff volumes, depths and associated pollutant loads for the modeled watershed and LID practices.

2.9.3.2. L-THIA Model Applications

L-THIA has historically been used to evaluate the impacts of land use changes (e.g. from open space to urbanized areas) in watersheds (Park et al., 2013). The ability to incorporate LID practices in the evaluation was incorporated in 2012. Therefore, limited studies are available that evaluate the effects of proposed land use changes with the incorporation of LID practices. These documented studies include: Ahiablame et al. (2012b and 2013). Study results indicate the need for enhancing metrics and modeling techniques for evaluating the performance of LID practices.

2.10. SUMMARY

Low Impact Development practices have been implemented across the country since the early 2000's. Water quality and water quantity performance evaluation of bioretention systems has predominantly been in the laboratory (Davis et al., 2001; 2003, Trowsdale, 2011). Limited measurements at field scale applications of bioretention systems supported the laboratory findings of high removal efficiencies for sediments and heavy metals (Hatt et al., 2009; Trowsdale, 2011). Full-scale bioretention water quality and quantity performances data is scarce and further research of pollutant removal efficiencies in field applications to provide more conclusive results is necessary.

In recent years, there has been a growing interest in modeling LID practices to evaluate their performance (Elliott and Trowsdale, 2007; Bosely, 2008). However, most modeling efforts focus on relative comparisons of LID effectiveness between scenarios. Ahiablame et al. (2012b) suggests that modeling approaches need to account for design considerations and guidelines to represent actual ground conditions. The study also recommends the need to standardize modeling techniques when evaluation and reporting the effectiveness of LID practices. Many studies have been performed using SWMM and other modeling programs to evaluate land use changes on stormwater runoff volumes and peak flow rates. In more recent years, SWMM has been used to model LID practices. However, limited studies have been performed using the LID routines in SWMM to evaluate ability of bioretention facilities to modify the surface runoff hydrograph.

3. INTRODUCTION TO METHODOLOGY AND RESULTS

This thesis is in the form of two research papers. The first paper, entitled "Michigan Avenue Bioretention Three Years Later: The Monitoring Results Are In", aims to evaluate how well the constructed bioretention facilities in an ultra-urban environment are performing. The infiltration capacity, porosity and field capacity, and plant and garden health were all evaluated to determine the influential factors of infiltration rate in engineered soils, the correlation between percentage of unfilled pore space, soil compaction and plant health. Soil samples were taken of the engineered soil and evaluated in the laboratory for porosity and field capacity. Additionally, infiltration testing was performed along with an overall plant and health qualitative assessment.

The objective of the second paper, entitled, "Determining the Effectiveness of Bioretention Facilities for Hydrograph Modification" is to quantify the impacts of bioretention on water quantity in the Michigan Avenue corridor. Bioretention facilities were physically represented within the EPA SWMM model to quantify the modifications to the surface runoff hydrograph with and without the LID practices. The EPA SWMM model was calibrated for peak flow rate, total runoff volume, and time to peak using observed water quantity and precipitation data. Forty seven years of precipitation data from the rain gauge at the Capital City airport was used in the model to perform a continuous simulation with the bioretention facilities in place.

4. BIORETENTION THREE YEARS LATER: THE MONITORING RESULTS ARE IN

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4.1. ABSTRACT

The Great Lakes are the largest group of freshwater lakes on Earth. Therefore, preserving the freshwater resources of the Great Lakes is of the utmost environmental and economic importance. Four out of the five Great Lakes border Michigan and water resources are so important to the state that water quality status was identified as one of the indicators to measure Quality of Life. As the capital of Michigan, the City of Lansing is committed to improving water quality. In 2007, the City began its Go Green! Go Lansing! Initiative, which focuses on bringing together and promoting various local environmental programs. At the same time, the city began construction of bioretention gardens along a busy downtown corridor leading to Michigan's Capitol to treat stormwater runoff from the sidewalk and road. A total of 34 bioretention gardens with just over 706 square meters (7,600 square feet) were constructed along a four-block stretch. The objective of this study was to monitor and determine how well the bioretention gardens were performing in terms of overall plant health, infiltration capacity, and porosity and field capacity of the engineered soil. Selecting the plants are crucial to the bioretention system performance. Twenty seven types of native trees, shrubs, grasses and perennials were used including the following six plants that performed the best *Eupatorium maculatum* (Joe-Pye Weed),

Eupatorium perfoliatum, (Boneset), *Hibiscus moscheutos* (Rose Mallow), *Iris virginica* (Southern Blue Flag), *Panicum virgatum* (Switch Grass), and *Vernonia missurica* (Ironweed). Each bioretention garden was thoroughly assessed to document the health of the plants, structural integrity of the bioretention areas, and any erosion and trash problems. Using a 24-inch double ring infiltrometer, a Turf-Tec infiltrometer, and a mini-disk infiltrometer, the infiltration rate of the engineered soil was measured. Nine soil samples were obtained and sent to a laboratory for analysis to determine the porosity and field capacity of the engineered soil.

The bioretention garden assessment indicated that ninety percent of the gardens had good overall plant health. This indicates that bioretention systems are able to survive in this challenging environment. The infiltration results showed highly variable infiltration rates, ranging from 0 - 63.5 cm/hr (0 - 25 in/hr). Porosity varied from 43.2% to 62.5% and field capacity values range from 25.8% to 40.5%.. Finally, low compactions were observed in bioretention sites with the ability to store 5.9 cubic meters (210 cubic feet) of water for every 28.3 cubic meters (1,000 cubic feet) of soil.

KEYWORDS: Low impact development, bioretention, post-construction monitoring, infiltration testing, soil analysis, plant health assessment

4.2. INTRODUCTION

Healthy rivers, streams and lakes are an important part of a thriving state, country and planet; as humans and ecosystems depend on clean water for survival. The world is rapidly becoming more urbanized and the harmful effects on streams draining urban land are consistently observed. It has been well documented that stormwater runoff from the urban environment contains many pollutants that are harmful to the environment and the nations waterways. These pollutants include sediment, heavy metals, nitrogen, phosphorous, oil and grease, chlorides, and pathogens (Davis et al., 2009, Collier et al., 2011, Walsh et al., 2012, Hatt et al., 2004). As urbanization expands, the quantity of evaporation and infiltration into the native landscape decreases and stormwater runoff volumes increase (Vicars-Groening and

Williams, 2007, Carter et al., 2009). Larger stormwater volumes can carry more pollutants than before that have many environmental consequences. In addition, this results in lower groundwater recharge, increased flood frequency and volume, and higher pollutant loads to our nearby lakes, rivers and streams.

To address these negative effects of urbanization, stormwater engineers have been implementing stormwater best management practices (BMPs) in order to capture, treat, and store stormwater runoff close to its source. Common stormwater BMPs include extended detention basins, permeable pavement, green or blue roofs, bioretention facilities, rain gardens, constructed wetlands, and vegetated swales. Bioretention is known to be the most widely implemented and effective urban BMP (Woods-Ballard et al., 2007; Davis et al., 2009). Bioretention systems provide filtration and treatment through a shallow surface layer, a soil layer, an aggregate storage layer and plants. In bioretention, stormwater runoff is generally stored in a shallow surface layer, within the soil layer and/or in an aggregate/stone layer. The soil layer provides the opportunity for contaminants to sorb to the soil particles, filtered or biologically degraded. Evapotranspiration is achieved by plant uptake and through release back into the atmosphere and infiltration occurs through the bottom of the system into the native soil layer (Denich and Bradford, 2010; Trowsdale and Simcock, 2011; Zhang and Guo, 2012; Zhang and Guo, 2014)

Despite the widespread use of bioretention systems throughout the country, detailed performance information is not available for many regions (Davis et al, 2009). In addition, in planning and designing bioretention systems, the following knowledge gaps must be addressed:

- *Impact of media material on infiltration rates*: It is known that media material used in a bioretention system will affect infiltration rates. Current research suggests that a higher percentage of sand in the media will provide the best infiltration performance. Infiltration rates with media materials in bioretention systems that contain higher clay content are poorly understood and research should be performed. (Brown et al, 2009; Li et al., 2009, Brown and Hunt, 2011a, Liu et al, 2014).

- *Effects of soil porosity and field capacity on system performance and plant health*: Two of the principal components of bioretention systems are plants and soil, which remain largely untested. Additional research must be performed to understand how soil compaction and porosity affect system performance (Johnston, 2011).

Post-construction monitoring sought to evaluate how well the constructed bioretention areas were performing. The overall goal is to evaluate how the bioretention facilities perform in relation to the design elements, construction constraints and the long-term survivability. Specifically, the following questions or objectives were to be addressed:

1. Infiltration Capacity: What are the influential factors that impact infiltration rate in engineered soils?
2. Porosity and Field Capacity: What is the percentage of unfilled pore space in the engineered soil? Is there a correlation between the percentage of unfilled pore space, soil compaction, and plant health?
3. Plant and Garden Health: What is the overall health of the planted community? What are the trends in plant species survival/health? What is recommended for replanting specific gardens? Is there any correlation between condition of the soil, the thickness of the mulch, the presence of weeds, and the presence of trash/debris and the health of the plants?

4.3. MATERIALS AND METHODS

4.3.1. Study Area

Michigan Avenue, in the heart of downtown Lansing, contributes to the ultra-urban environment with four driving lanes, a center turn lane and additional roadside parking on both sides of the street (Figure 4-1). An extra wide sidewalk lines the corridor between the back of the curb and the building faces.

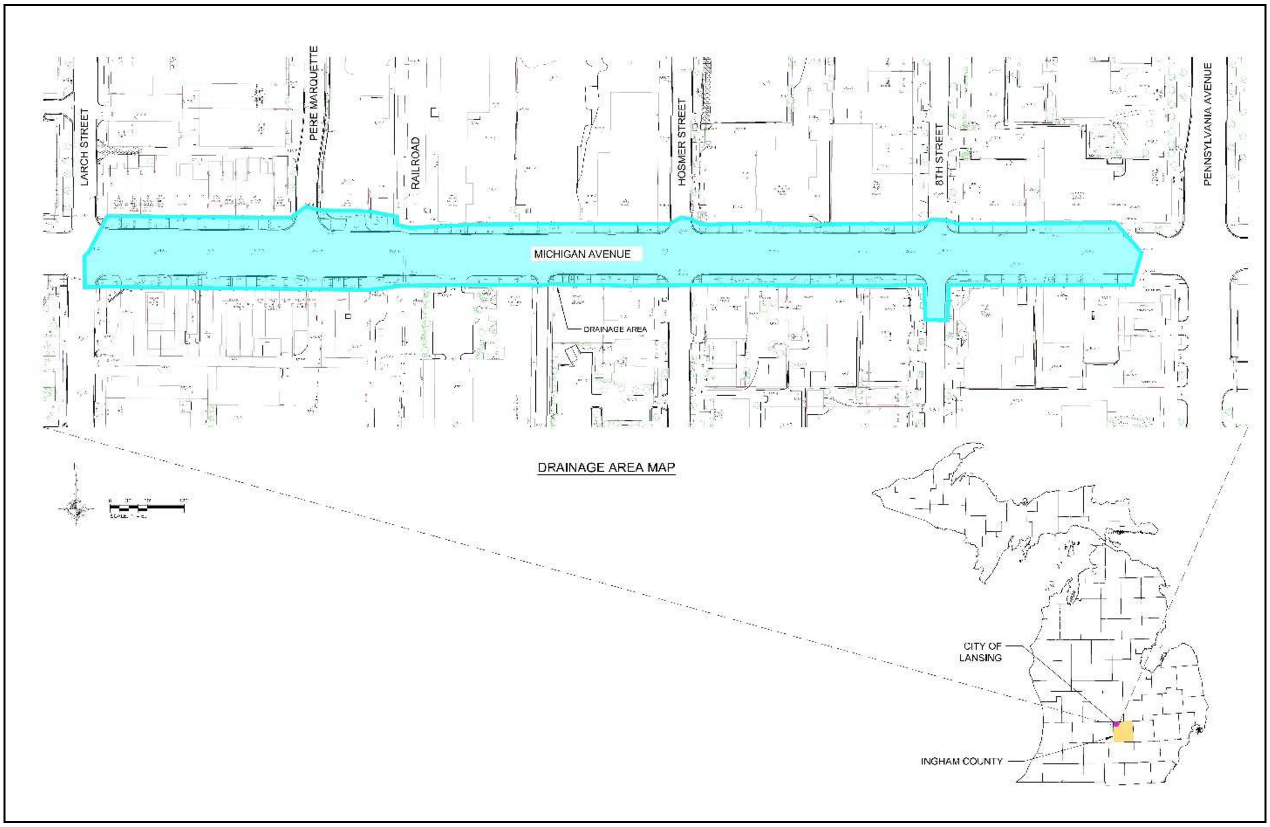

Figure 4-1. Study Area.

With a nearly 100% impervious surface and a traditional curb and gutter drainage system that discharges directly to the Grand River only two blocks away, there is little to no opportunity for stormwater to infiltrate. The Grand River is listed as an impaired water body in the State of Michigan's 2004 Section 303(d) list (MDEQ, 2014). The impairments are for combined sewer overflow (CSO) discharges (pathogens), and water quality exceedances for dissolved oxygen.

The Michigan Avenue bioretention system has a total tributary drainage area of 16,592 m^2 (4.1 acres) of mostly transportation and commercial land use. The City of Lansing installed over 30 bioretention systems along a busy avenue in the downtown corridor. Construction was completed on the bioretention facilities installed along Michigan Avenue in spring 2008 and is one of a few facilities in the country successfully installed in an ultra-urban environment. The combined surface area of the gardens are 709 m^2 (7,631 square feet), or approximately 4% of the contributing area. This comparable to what is typically required using a traditional detention pond system (USEPA, 2014).

4.3.2. Overview of the Michigan Avenue Bioretention Facility Design

Planning for the Michigan Avenue bioretention project began in January 2004 with the formation of a Mayoral Task Force. The Task Force's recommendation called for "Greening Up" the corridor to the Capitol Building along with creating an attractive walkable area. In 2005, a meeting of commercial businesses was held to discuss the bioretention idea. Design began shortly after.

The Michigan Avenue bioretention gardens were designed to address stormwater runoff and provide an educational opportunity for the general public of the water quality benefits of a stormwater BMP project in the City of Lansing. The location of this project along the main corridor leading up to the State Capital building harmonizes with the recommendation of the task force to beautify the corridor (Figure 4-2). The bioretention gardens were designed to capture and treat, at a minimum, 2.54 cm (one inch) of runoff according to the Michigan LID manual (2009) .

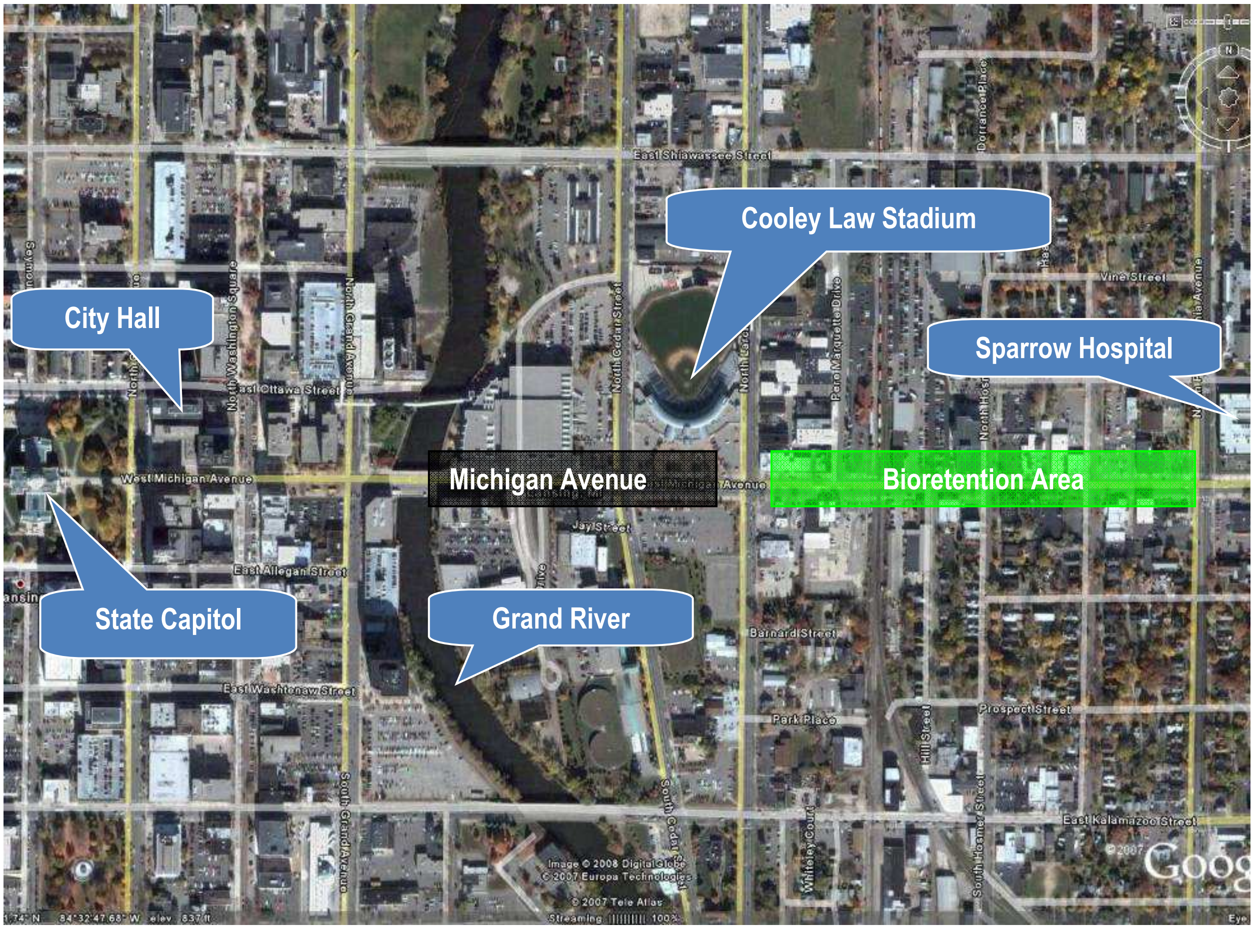

Figure 4-2. Michigan Avenue bioretention project location and surrounding area.

Stormwater enters the bioretention garden areas from the street by curb cuts. Curb cuts direct runoff to a sediment forebay before spilling into the bioretention areas (

Figure 4-3). Bioretention is incorporated as a depressed 1.52 m (5 feet) wide trench designed to hold 54.6 equivalent cm (21.5 inches) of water in the cross section before forcing excess stormwater down the traditional curb and gutter system. The soil mixture used for this project was selected to retain enough water to sustain the tall floral plants chosen for this application while providing a slower infiltration rate of about 0.83 cm/hr (0.33 inches per hour). Research suggests that the extensive root system of native plants, maintains and even enhances soil permeability (Wolverton, 1986; USEPA, 2014).The soil mix was engineered with a mixture of 30% Michigan Department of Transportation (MDOT) 2NS sand, 30% topsoil (10% sand, 40% silt, 40% clay, 10% organic matter), 10% coconut coir fiber, and 30% municipal compost 0.76 to 0.91 meters deep (2.5 to 3 inches). Below the soil mix is a 38.1 centimeter (15 inches) deep aggregate storage layer (34R Aggregate). Underdrains located 30.5 centimeters (12 inches) above the bottom of the gardens allow excess water to leave the system and protect the adjacent businesses and roadway. Metal grates were provided to allow pedestrians to traverse the expanse of vegetation from their cars to the sidewalk.

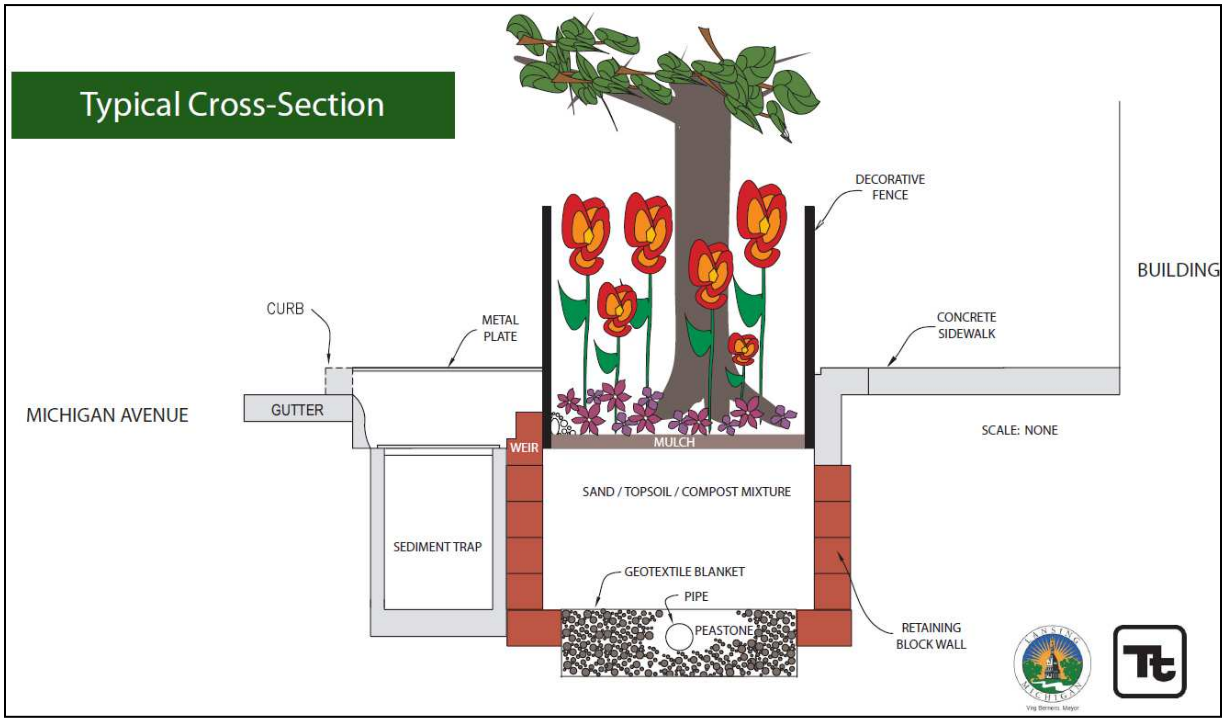

Figure 4-3. Typical Bioretention cross-section

Specially chosen trees, and native perennials and shrubs within the bioretention areas provide nutrient and water uptake. Plants were chosen for their tolerance to road salt, drought, flooding, height, and showiness. The native perennials and shrub plants include Joe-Pye Weed (*Eupatorium maculatum*), Boneset (*Eupatorium perfoliatum*), Rose Mallow (*Hibiscus moscheutos*), Southern Blue Flag (*Iris virginica*), Switch Grass (*Panicum virgatum*), Ironweed (*Vernonia missurica*), Nodding Wild Onion *(Allium cernuum)*, Swamp Milkweed *(Asclepias incarnata)*, Tall Tickseed *(Coreopsis tripteris)*, Alum Root *(Heuchera)*, Giant St. Johns Wort *(Hypericum ascyron)*, Rough Blazing Star *(Liatris aspera)*, Marsh

Blazing Star *Liatris spicata)*, Beardtongue *(Penstemon)*, Yellow Coneflower *(Rudbeckia hirta)*, Three Lobed Coneflower *(Rudbeckia triloba)*, and Stiff Goldenrod *(Solidago rigida)*.

Construction of the bioretention system began in the spring of 2007 and was completed in spring 2008. The bioretention project was included as part of an overall streetscape enhancement project that had a total construction cost of approximately $2 million, of which approximately $931,000 was for the bioretention facilities. This cost equates to approximately $1,315 per square meter ($122 per square foot) of bioretention, which is in line with projects around the country with similar ultra-urban constraints (Perry, 2009).

The photos in figure 4 chronicle the construction process. The construction process began by digging trenches for the locations of the bioretention facilities (Figure 4-4(a)), then forms were placed (Figure 4-4(b)) to build the concrete block retaining walls. Concrete block retaining walls were selected to work around large utility pipes, such as a fiber-optic duct, that traversed the bioretention areas (Figure 4-4(c)). Each bioretention area was then backfilled with aggregate stone for the storage reservoir (Figure 4-4(d)), an engineered soil mixture (figure 4(e)) and finally planted with the specially chosen plants (Figure 4-4(f)).

Figure 4-4. Photos that chronicle the construction process for the bioretention project along Michigan Avenue

4.3.3. Post Construction Monitoring

Post-construction monitoring included an evaluation of the infiltration capacity of the engineered soil, measuring the porosity and field capacity of the engineered soil, performing an overall plant and health qualitative assessment and evaluating how the bioretention systems modified the surface runoff hydrograph.

4.3.3.1. Infiltration

The infiltration capacity of the bioretention gardens was measured using three different infiltrometers, a 24-inch double-ring infiltrometer, a Turf-Tec infiltrometer, and a mini-disk infiltrometer. All three infiltrometers estimate the vertical movement through the bottom of the test area (surface of the bioretention facility); however the surface area used to perform the measurement differs between them. The 24-inch double ring infiltrometer provides the largest surface area for testing the infiltration, comparted to the Turf-Tec and mini-disk infiltrometers. All three infiltrometers were used to measure the infiltration capacity. It was later determined that the mini-disk infiltrometer is unable to obtain accurate infiltration readings and was discarded from the analysis. Infiltration capacity was measured in one of the bioretention gardens at three separate locations. Infiltration was measured both at the surface (through the mulch) and in the same location after removing the mulch layer and the top 5.1 centimeters (2 inches) of soil per specifications in the standard testing methodology. Testing was performed with and without the mulch to determine if the mulch layer was limiting the vertical infiltration of the bioretention system. Hence, a total of six infiltration tests were conducted with one infiltrometer.

While it is understood that many factors affect infiltration rate and tests taken at the same site are not likely to give identical results (ASTM, 2009), the design team wanted to ensure some level of accuracy of the test data. If any one of the three locations produced a result greater than 20 percent different from any of the other locations during the infiltration testing, an additional location/reading was taken by the double-ring infiltrometer (Tetra Tech 2010).

4.3.3.2. Porosity and Field Capacity

The percentage of unfilled pore space in the soil of the bioretention gardens was determined by taking the difference between porosity and field capacity of the soil. Porosity and field capacity were measured in three of the bioretention gardens; 1) the same garden as the flow monitoring, 2) the garden with frequent standing surface water, and 3) a garden with notably prosperous vegetation and good drainage. Porosity and field capacity was measured at three separate locations (a total of nine tests) by scooping two cups of soil into a sampling container and sending the samples to the laboratory for analysis, (Fetter, 1994).

More detailed descriptions of laboratory tests are included in Appendix A. Porosity was measured following the *United States Golf Association (USGA) Putting Green Method, 1997*. Field capacity was analyzed using an approach described at *Methods of Soil Analysis, Part I (*Black, 1965).

4.3.3.3. Plant and Garden Health

A plant and garden health assessment was conducted in September 2009 of each individual garden that began on the northwest corner of Pennsylvania Avenue and Michigan Avenue and continued along the north side of Michigan Avenue, returning on the south side. An assessment form was created to meet the study design objectives that included the following (Tetra Tech, 2011):

1. Photographs
2. Quantification of each grass, forb, and tree species present
3. Qualitative assessment of each plant species (robust, average, unhealthy)
4. Pervasiveness of weeds (absent, few present, excessive)
5. Condition of the soil (good, excessively dry, excessively wet)
6. Degree of erosion (none, some, excessive)
7. Degree of soil compaction (normal, excessive)
8. Thickness of mulch (good, too thick, too thin)
9. Pervasiveness of trash/litter (absent, normal, excessive)
10. Overall aesthetics

At the time the assessment was conducted, the grasses and forbs had gone dormant making it easier to count species than if all was flourishing. The trees still had their leaves and could be assessed qualitatively (Tetra Tech, 2011).

4.4. RESULTS AND DISCUSSION

The results and discussion section details the infiltration, porosity and field capacity results, and the plant and garden health assessment results.

4.4.1. Infiltration

Infiltration testing was performed to understand what factors influence or affect infiltration rates. Infiltration testing was initially performed in August and September of 2010 to analyze the factors that impact infiltration rates. After observing scattered data results with no consistent pattern, additional testing was performed again in June of 2011. The measured infiltration rates for each location using 24-inch Double Ring and Turf Tec instruments are shown below in Table 4-1. Summary of infiltration testing results. The mini-disk infiltrometer was originally planned as a third test method, however, water readily seeped horizontally away from the infiltrometer and hence accurate readings could not be obtained. The use of the mini-disk infiltrometer was abandoned after several attempts. The final infiltration rate was determined by averaging the last three measurements for each test. Infiltration rates ranged from 0 to 54.6 cm/hr. Figure 4-5 displays the raw infiltration test results of tests performed at bioretention garden A located on the south side of Michigan Avenue, west of Hill Street, in front Young Bros & Daley business.

Table 4-1. Summary of infiltration testing results

Garden ID	Location within Garden	Equipment	Date	Mulch and top 5.0-cm soil	Infiltration (cm/hr)
A; south side west of Hill St (Young Bros & Daley)	East	24-inch	8/13/2010	Removed	22.1
			6/1/2011	In Place	0.5
				Removed	0.3
		Turf-Tec	6/1/2011	In Place	5.6
				Removed	5.6
	Middle	24-inch	9/28/2010	Removed	7.4
			6/2/2011	In Place	4.8
				Removed	3.0
		Turf-Tec	9/28/2010	Removed	54.6
			6/2/2011	In Place	50.5
				Removed	0.0
	Middle-West	24-inch	6/3/2011	In Place	36.6
				Removed	13.5
		Turf-Tec	6/3/2011	In Place	32.5
				Removed	12.4
	West	24-inch	8/13/2010	Removed	18.3
			6/3/2011	In Place	27.7
				Removed	4.6
		Turf-Tec	8/13/2010	Removed	9.1
			6/3/2011	In Place	17.5
				Removed	0.0
B; north side west of Hosmer St (MSHDA)	Middle	24-inch	9/27/2010	Removed	10.2
		Turf-Tec	9/27/2010	Removed	1.5

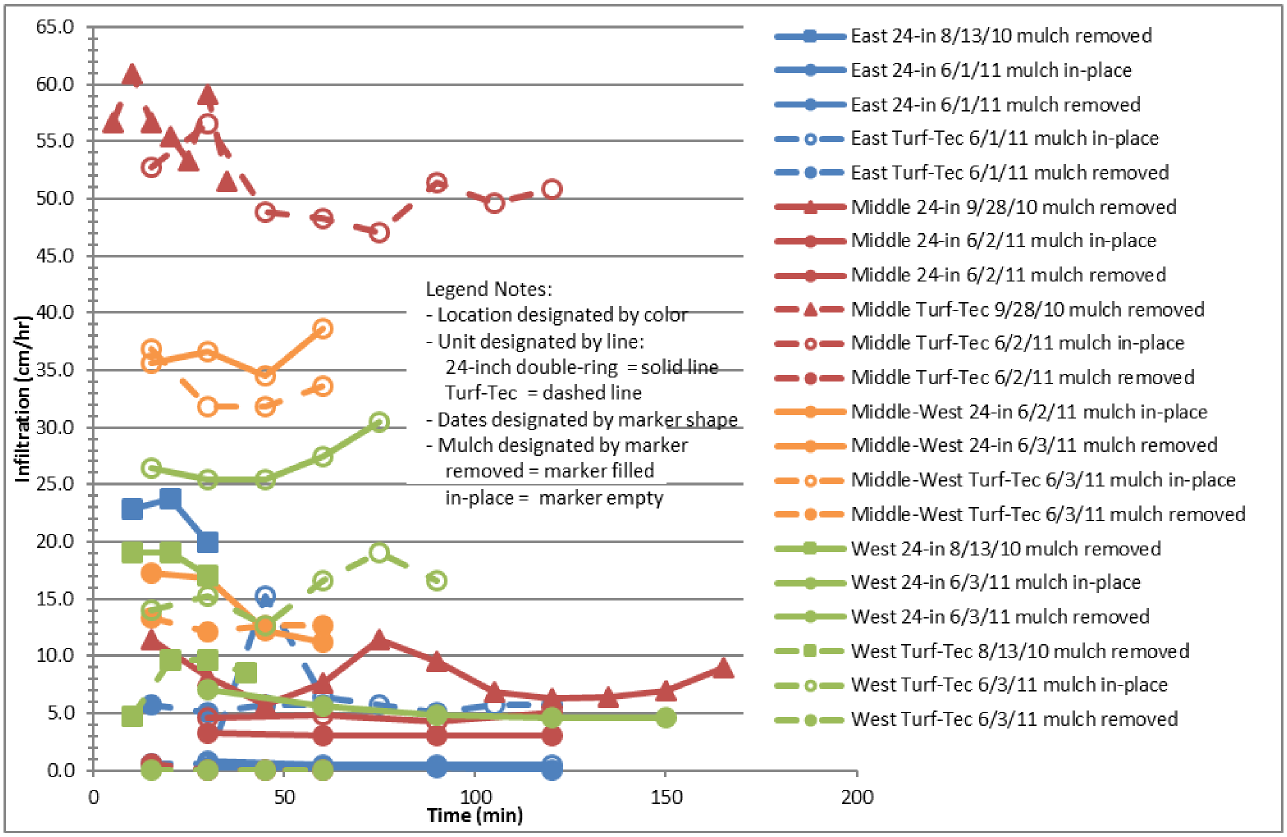

Figure 4-5. Garden A infiltration testing

As evident from the summary table (Table 4-1) and Figure 4-5, a wide range of infiltration values was recorded. The variation was observed with time, between test equipment, with and without the mulch layer, and between locations within the bioretention garden. See Appendix B for infiltration testing results from garden B. Infiltration rates using the 24-inch Double Ring infiltrometer were between 0.13 cm/hr and 36.6 cm/hr with an average of 12.4 cm/hr. The range of infiltration rates using the Turf-Tec infiltrometer was 0.0 cm/hr to 54.7 cm/hr with an average of 17.2 cm/hr. The calculated p-value from performing a two sample t-test is 0.013, which is less than 0.05 (or 5 percent) suggesting that infiltration rate is dependent on the test equipment used,

Installing the infiltrometer equipment through the mulch layer proved to be problematic; the mulch itself limited the ability to drive the infiltrometer through it. Additionally, the mulch often floated during the test and complicated the measurement process. Evidence of horizontal seepage through the mulch layer was visually observed in many of the tests. The purpose of trying to measure the infiltration through the mulch was to determine if the mulch layer was limiting the infiltration. Infiltration results with the mulch in place range between 0.2 and 6.0 cm/hr and infiltration with the mulch removed ranges between 0.0 and 9.4 cm/hr. A simple t-test was performed to determine whether the samples are significantly different. Since the calculated p-value was 0.178, greater than 0.05 (or 5 percent) it can be concluded that there is no difference between the means of the data sets with and without the mulch in place. Based on the test results and observations it was determined that the mulch layer is not limiting the infiltration rate. Removal of the mulch and the top layer of soil, as called for in the standard testing methodology (Schueler, 2009) are recommended for any future infiltration tests.

One of the lessons learned through this project was that measuring infiltration within a small area is challenging based on the heterogeneous nature of the system and the interaction between plants and the soil. Future infiltration measurements are suggested to be accomplished by flooding the entire garden area and measuring the time required to drain.

4.4.2. Porosity and Field Capacity

Soil testing was performed to measure for porosity and field capacity on the 700 block and 800 block of Michigan Avenue. Results of the porosity and field capacity soil testing are summarized in Table 4-2. The readings from the three locations were averaged together to describe the porosity and field capacity of the garden.

Table 4-2. Soil analysis results

Garden Location	Location within the garden	Lab No.	Bulk Density (g/cm3)	Capillary Pore Space (%)	Non-Capillary Pore Space (%)	Porosity (%) *sum of the pore space*	Water Holding Capacity @ 1/3 Bar (%) *field capacity*	Temporary Storage Volume (Porosity - Field Capacity)
700 block south side (#1) *flow monitoring*	East	31452	1.06	45.3%	7.2%	52.4%	31.3%	21.1%
	Center	31453	1.18	43.1%	5.5%	48.6%	29.7%	18.9%
	West	31454	1.20	39.2%	4.0%	43.2%	27.5%	15.7%
		Average	***1.15***	***42.5%***	***5.5%***	***48.1%***	***29.5%***	***18.6%***
800 block south side (#2) *good vegetation*	East	31455	1.17	44.2%	5.1%	49.2%	25.8%	23.5%
	Center	31456	1.25	41.8%	4.7%	46.5%	25.8%	20.7%
	West	31457	1.29	40.9%	4.8%	45.7%	25.8%	19.9%
		Average	***1.24***	***42.3%***	***4.9%***	***47.2%***	***25.8%***	***21.4%***
700 block north side (#3) *poor draining*	East	31458	1.08	49.6%	8.2%	57.8%	27.9%	29.8%
	Center	31459	0.89	52.2%	10.3%	62.5%	40.5%	22.1%
	West	31460	1.05	42.9%	6.4%	49.2%	31.6%	17.6%
		Average	***1.01***	***48.2%***	***8.3%***	***56.5%***	***33.3%***	***23.2%***
		Overall Average	**1.13**	**44.3%**	**6.2%**	**50.6%**	**29.5%**	**21.0%**

The difference between the porosity and the field capacity is the percentage of unfilled pore space in the engineered soil or the temporary storage volume available for stormwater storage in the soil. The soil test results indicate this ranged from 18.4% to 21.6%, or an average of 21.0%. This means that given 28.3 cubic meters (1,000 cubic feet) of soil, the garden can temporarily store 5.9 m^3 (210 cubic feet) of stormwater runoff.

Soil compaction can be directly quantified using a variety of compaction measuring devices, such as a penetrometer. Compaction can also be indirectly quantified by measuring the bulk density of the soil. Research suggests (Daddow, 1983) that at a bulk density of approximately 1.65 g/cm^3 root growth begins to be limited for the type of soil in the garden. The average bulk density of the soil mix in the three gardens tested ranged from 1.01 to 1.24 g/cm^3. Since the measured bulk density is well below the suggested value at which root growth becomes limited, the level of compaction in the gardens is not limiting the vegetation growth or the rate of infiltration.

A discussion on the correlation between unfilled pore space, soil compaction and plant health is further discussed in Section 4.4.3.

4.4.3. Plant and Garden Health Assessment

The plant and garden health assessment was conducted in September 2009 to evaluate the overall health of the plants and assess any trends in species survival or correlations between soil conditions, garden conditions and health of the plants. A separate assessment form was filled out for each bioretention system along with photo documentation. All assessments were completed on the same day to provide an equal comparison between gardens and plants.

Example photos that were taken as part of the assessment are provided in Figure 4-6. Photo (a) depicts field crews documenting the condition of the plants, presence of trash and debris and performing a count of each plant. Photo (b) provides a longitudinal view of the conditions of one of the bioretention facilities at the time of the plant and garden health assessment. This garden exhibits good overall plant health and aesthetics, has few weeds present and minimal trash and debris. Photo (c) shows an example of a sump cover in poor structural condition in need of repair. Photo (d) demonstrates a garden that had a fair amount of sediment accumulation and trash and debris.

Figure 4-6. Plant and garden health assessment photos

During installation of the bioretention facilities a total of 37 trees, 28 shrubs, 212 grasses and 3,134 perennials were planted. The quantitative assessment performed in September 2009 (one and half years later), identified 32 trees, 21 shrubs, 139 grasses and 1,863 perennials. This results in an average overall plant survival rate of 72%. Research suggests that this plant survival rate is within the acceptable range of plant survival rates in the urban environment (Schneider, 2011). The loss experienced with the perennial plants of approximately 40% is higher than expected. The higher loss is attributed to two bioretention gardens in particular that had little to no vegetation remaining, including being void of weeds. It is assumed that vandalism was a contributing factor.

The plant and garden health assessment included a qualitative ranking of each plant species in each garden; indicated by checking either robust, average or unhealthy for each plant. Then, based on the health of each plant species, a determination was made on the overall health of each garden (indicated as either good, fair or poor). Upon review of the qualitative scoring it was concluded that qualitatively, ninety percent (90%) of the gardens were rated as having good overall plant health. The overall good performing plants include: Joe-Pye Weed, Boneset, Rose Mallow, Southern Blue Flag, Switch Grass, and Ironweed.

The assessment found that no immediate action was needed on any gardens, and no erosion, compaction, or structural issues were found. In general, few weeds were found in a majority of the gardens, a small amount had excessively wet soils, and only a small amount had excessive trash. In any ultra-urban downtown environment, street trash is a concern. Since the Michigan Avenue bioretention gardens are depressed trenches, most of the street trash does end up in the gardens. For future design projects, a trash rack or other filter system should be considered to capture the trash before entering the gardens and to concentrate it in one location for easy cleaning and aesthetics.

Mulch was found to be placed too thick in almost 75 percent of the gardens, 22.9 centimeters (9 inches) thick in some areas. Overall, the aesthetics were rated as 64 percent ‘good’, 21 percent ‘fair’ and 15 percent ‘poor’.

Replanting of the perennials that did not survive was done in June 2011. The replacement perennials were selected from both the original planting list as well as three new trial plants. Fifty-percent of the replacement perennials were selected from the list of good performers (Joe-Pye Weed, Boneset, Rose Mallow, Southern Blue Flag, Switch Grass, and Ironweed). The other half of the plants included: Nodding Wild Onion, Swamp Milkweed, Tall Tickseed, Alum Root, Giant St. Johns Wort, Rough Blazing Star, Marsh Blazing Star, Beardtongue, Yellow Coneflower, Three Lobed Coneflower, and Stiff

Goldenrod all from the original planting list; plus the following three trial plants were selected: Purple Coneflower, Queen of the Prairie and the Obedient Plant.

A few gardens are not draining sufficiently to support the originally selected species as evidenced by the absence of planted species and the growth of cattails. The cattails are thriving, unique and attractive, and are working to improve the garden drainage so a decision was made to leave the cattails in place and supplement with new species including: Tall Sunflower (*Helianthus giganteus*), Three-Square (*Schoenoplectus pungens (Scirpus americanus*)), and Softstem Bulrush *(Schoenoplectus tabernaemontani (Scirpus validus))*.

4.5. CONCLUSION

The Michigan Avenue bioretention project was constructed to beautify the corridor, treat the "first flush" of runoff, and provide a pedestrian friendly environment. Post construction monitoring was performed in 2009 and 2010 to evaluate the performance of the bioretention systems. Quantitative measurements have been recorded for infiltration, porosity and field capacity, and quantification of plants. Qualitative observations were made regarding the plant and garden health. Replanting efforts of plants that did not survive have been completed. As the data shows, the Michigan Avenue bioretention gardens are a success, meeting the project objectives. While measured infiltration rates range from 0 to 63.5 cm/hr, several important conclusions were made. First, it was revealed, using a two sample t-test that the infiltration rate is dependent on the type of infiltrometer used. Based on conversations with soil scientists and a review of literature, future infiltration testing should be performed by flooding the entire area of the bioretention practice. Additionally, it was determined that with a p-value above 0.05 (or 5 percent), infiltration is not dependent on whether mulch remains in place or is removed. However, because of the difficulty with properly installing the test equipment with the mulch in place, future infiltration testing using infiltrometers should be conducted with the mulch layer removed. Porosity and field capacity measured values indicate the bioretention gardens are able to capture and store approximately 2.54 cm (1 inch) of runoff from the project drainage area. Post construction monitoring indicates the gardens have optimal soil conditions, with bulk density values below that which is considered to be soil limiting. These soil conditions provide an environment that is able to support the healthy plant growth quantified during the plant and garden health assessment.

The results of this study demonstrate that a viable alternative exists to the conventional stormwater drainage system that supports stormwater runoff capture and storage, and provides added benefits of community beautification.

5. DETERMINING THE EFFECTIVENESS OF BIORETENTION FACILITIES FOR HYDROGRAPH MODIFICATION

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5.1. ABSTRACT

Urbanization has seen a steady increase over the past several decades and has caused the overall approach to stormwater runoff dramatically change. In general, stormwater management system facilities help with mitigating the effects that stormwater runoff. However, the effectiveness of these systems varies by the magnitude and frequency of stormwater runoff. Therefore, accurate methods are needed to estimate the actual performance of the system. The objective of this project was to evaluate the effectiveness of one of these systems called bioretention gardens in terms of their ability to change the surface runoff hydrograph. Bioretention gardens were installed along a busy corridor in the ultra-urban downtown city of Lansing, Michigan. Post-construction continuous flow monitoring was conducted in May 2010 through November 2010. A flow meter was installed in the inlet sump at the upstream end of one bioretention garden and one flow meter at the downstream end of the garden in the outlet pipe. A computer model was developed using Stormwater Management Model to simulate hydrologic and hydraulic characteristics of flow in the garden. Results from the flow meters were used to calibrate the computer model. Model simulations for different rainfall events revealed the effectiveness of the bioretention on reducing surface runoff volume and peak flow rates between 5% and 27% and between 33% and 87%, respectively. In

addition, the time of concentrations were improved after bioretention implementation between 8% and 729%.

KEYWORDS: Low impact development, bioretention, post-construction monitoring, SWMM, stormwater runoff, peak flow rate, urbanization

5.2. INTRODUCTION

Currently, more than 50 percent of the world's population lives in urban areas and it is expected that this number will increase by 67 percent by the year 2050 (UN-Habitat, 2012). From a water resources perspective, change in natural runoff is one of the biggest issues with urbanization. Urbanization increases the impervious surfaces within a watershed and; therefore, altering both surface runoff and the flow regime of stream networks. The impact of impervious surfaces on runoff and water quality has been extensively studied (Ayers et al., 1985; Bannerman et al., 1996; Benke et al., 1981; Walsh et al., 2005; Walsh et al., 2012). In general, as urban area develops, the amount of precipitation that runs off the land surface as overland flow surges, which significantly increases the risk of flooding (Brown et al., 2009; Burns et al., 2012; EPA, 2012). As urbanization increases, the natural hydrologic cycle experiences a shift from an infiltration-based system to a predominantly runoff-based system with a deterioration in water quality and minimal ground water recharge (Walsh et al, 2012).

The expansion of impervious surfaces coupled with the implementation of conventional stormwater drainage systems significantly affects the watershed and receiving stream hydrology by increasing the volume, frequency and peak flow rates of stormwater flows; reducing infiltration and evapotranspiration resulting in a reduction in groundwater recharge and baseflow (Burns et al., 2012; Kauffman et al., 2009) and winter (Konrad et al., 2002). Figure 5-2 is a graphic representation of the altered stream hydrology from urbanization comparing a pre-urban hydrograph (i.e. forest and meadow land areas) and an urban hydrograph. The pre-urban hydrograph has a much lower peak flow rate, and the recession limb (tail) of the hydrograph persists for an extended period of time because precipitation that is infiltrated slowly enters streams through subsurface flows (baseflow). The urban hydrograph is characterized by a very high peak flow rate that happens very quickly ("flashy") with little to no recession limb as a result of the small amount of infiltration/evaporation occurring.

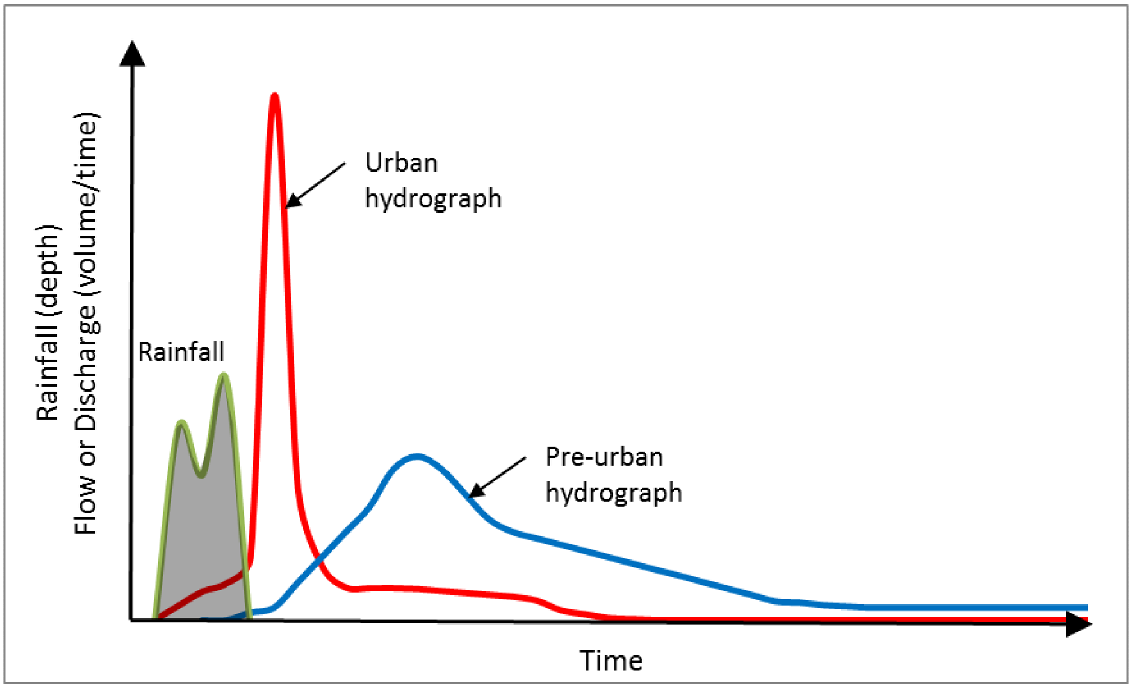


Figure 5-1. Comparison of pre- and post-urbanization hydrographs (Graph modified from data from this thesis)

The challenge for urban stormwater managers is to mimic the natural hydrology, which was presented before urbanization, so that impervious surface runoff is conveyed to streams with similar hydrologic characteristics of the condition prior to development (Konrad et al., 2002). There are several approaches to address this issue. The traditional approach entails collecting stormwater in a collection system, such as catch basins and underground storm sewer pipes, that discharge to a detention basin and is slowly released to the local waterbody (Burns et al., 2012). This approach focuses on water quantity and does not address water quality and is generally ineffective at removing pollutants as adequate time for solids to settle is not provided (Dauphin County, 2014). However, research has shown that detention basins actually exacerbate the problem of erosive velocities in streams by extending the duration of higher flows (Fongers et al., 2001; Baker et al., 2008) as the basins release the water at a constant rate for a longer period of time.

A modern approach to mimic the natural hydrology is low impact development (LID). LID techniques have been shown to reduce peak flow rates, stormwater runoff volumes, provide water quality treatment, and minimizes exposure of the stream channel to erosive flows through a combination of extended detention and a reduction of runoff, (USGS, 2010; Davis, 2007; Davis, 2008; EPA, 2000). LID is a flexible term that has been used interchangeably with the term Green Infrastructure and used differently in different contexts. For the purposes of this study, we used a more comprehensive term for LID as an approach to land development or re-development that use or mimic natural processes to store, infiltrate, evaporate, transpire, or reuse stormwater on the site as close to its source as possible. In the LID practices, stormwater is managed in small, cost-effective landscape features located on-site, where the runoff is generated, rather than being conveyed to and managed in large detention facilities that provide little to no benefit to the natural system. Examples of LID practices include bioretention facilities, bioswales, rain gardens, blue and green roofs, rain barrels and cisterns, and permeable (porous) pavement. Bioretention was selected for this study because the City Lansing requested a stormwater management practice that provided aesthetic benefits with the addition of vegetation and trees as well as the hydrologic benefits provided.

Bioretention is a practice that uses filtration to treat stormwater runoff (Davis et al., 2009). Bioretention systems are shallow depressions of engineered soil that are typically planted with vegetation, such as trees, shrubs, and grasses, to remove pollutants from stormwater runoff. Sources of runoff are diverted into bioretention systems directly as overland flow or through a stormwater drainage system as close to the source as possible. In general, bioretention systems have been found to be effective in reducing runoff volume and in treating the first flush (first one-half inch) of stormwater (EPA, 1999). However, they are less effective at reducing runoff volume for larger storm events and have been found to export nutrients to downstream systems, (EPA, 2000).

In evaluating the effects of bioretention systems on hydrograph modification, the issue of capture efficiency of bioretention must be addressed. The capture efficiency of a bioretention system is defined as the fraction of total stormwater volume captured by the system and can be used to demonstrate the water quantity and water quality performance of the system. The capture efficiency is highly dependent on the design of the bioretention (Li et al., 2009; Davis et al. 2012) and climatological conditions (Emerson and Traver, 2008). In order to ensure that bioretention systems are designed for optimal performance based on design goals, accurate methods are needed to estimate the actual performance of the system (Davis et al., 2009).

This study is unique because it evaluates the effectiveness of bioretention system performance beyond the few observed conditions using a calibrated hydrologic model, which is the goal of this study. Specifically, the following questions will be addressed:

- How have the bioretention systems modified the surface runoff hydrograph?
- How does the surface runoff hydrograph compare with and without the gardens in place?
- What is the change in total volume, the time to peak, the peak flow and the overall shape of the hydrograph?

5.3. MATERIALS AND METHODS

5.3.1. Study Area

The bioretention project is located in Lansing, MI along Michigan Avenue between Larch Street and Pennsylvania Avenue on both sides of the street (Figure 5-2). The area tributary to the bioretention facilities is 16,592 square meters (4.1-acres) and with 7 lanes of street pavement, sidewalk from the back of curb to building face, is nearly 100% impervious. Stormwater runoff drains via overland flow to the curb and gutter where it enters the bioretention facilities through curb-cut inlets (Figure 5-3).

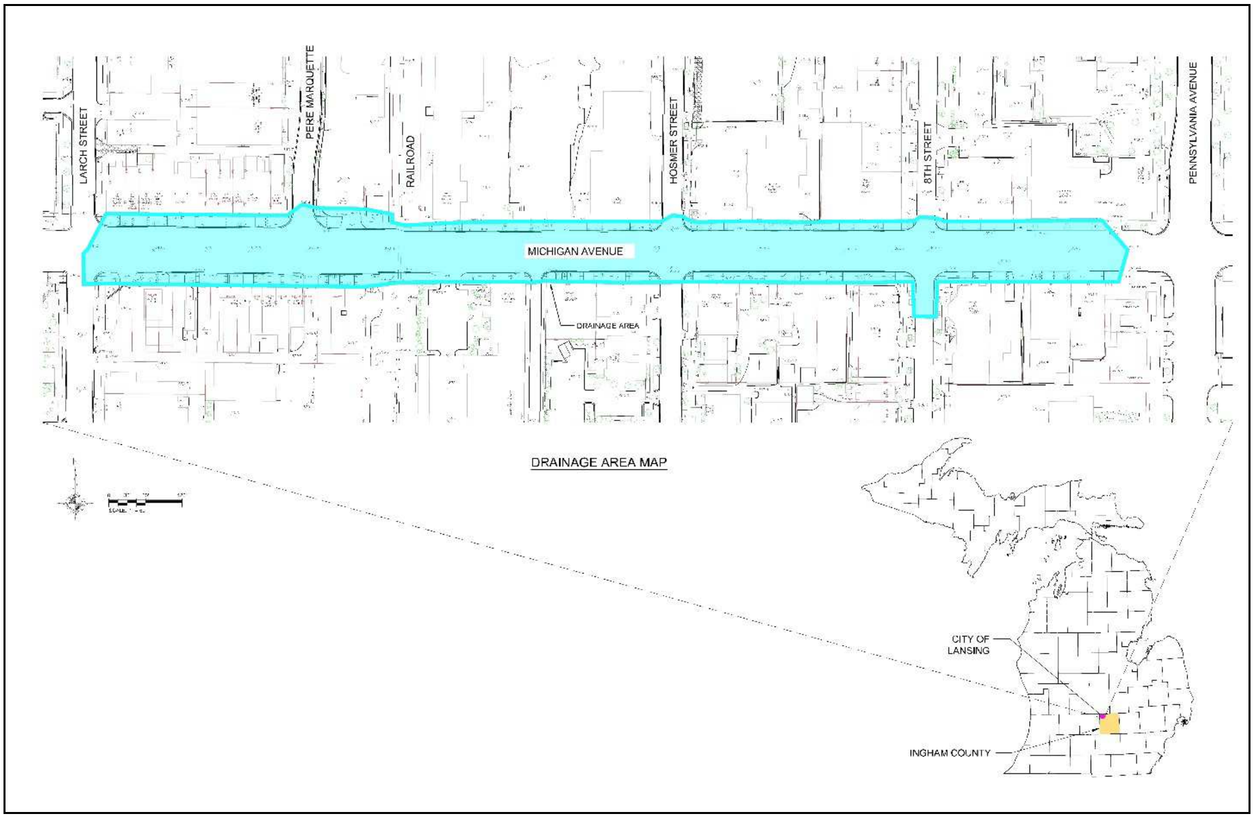


Figure 5-2. Michigan Avenue bioretention study area

Figure 5-3. Curb-cut inlet from street (curb and gutter) into pre-treatment sump and bioretention facility

Continuously recording flow monitoring equipment, (ISCO 2150 Area Velocity Flow Module, specification provided in Appendix C) was installed in a storm sewer downstream of the bioretention area, in the sump inlet and outlet pipe of the bioretention area, and also in a storm sewer downstream of a representative surrogate area not containing bioretention facilities. Rainfall information was collected from a nearby rain gauge (ISCO 674 Rain Gauge with an ISCO 4150 Flow Logger, specifications provided in Appendix C).

5.3.2. Flow Monitoring Sample Collection

Flow monitoring for the surrogate site was conducted May 2008 - November 2008, and in the bioretention project area May 2010 – November 2010 using ISCO 2150 flow meters in both locations.

Figure 5-4 shows the tributary area and flow meter location for the surrogate site, which was located immediately west of the project area along Michigan Avenue at Cedar Street. The surrogate site was used as the "pre" bioretention conditions and was selected based on having similar site characteristics as the bioretention project area. Data was not collected during the winter months due to the problems associated with accounting for the snow pack.

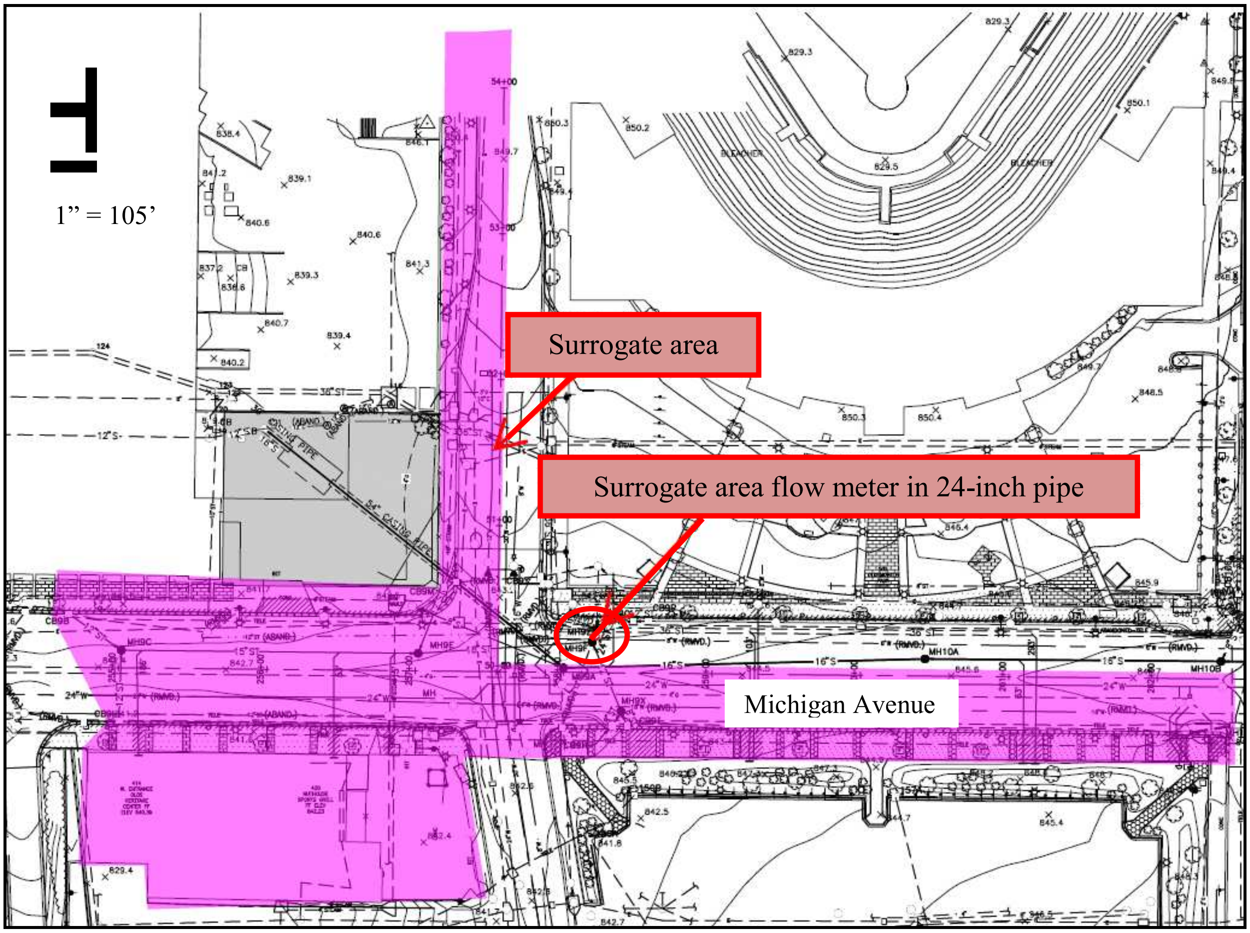


Figure 5-4. Surrogate area and flow meter location

During the monitoring period, field crews visit each monitoring location periodically to retrieve data, verify proper monitor operation and document field conditions. Upon successful initial installation of the monitoring equipment and sensors and during routine site visits, one field staff member enters the manhole to perform check measurements of flow rate, depth and velocity. This is done to ensure the manual measurements match the monitor. During each site visit, field crews measure and record the power level, which is supplied by a dry cell battery pack and compare the clock time to the meter time for accuracy. Data collected by the flow monitoring is downloaded to a computer and reviewed to check for consistency and identify any deviations in the flow pattern, depth or velocity readings. Deviations may indicate equipment failure or required maintenance of the equipment, such as removing dirt and debris from the probe.

Monitoring of the surrogate area was done with an ISCO 2150 Area Velocity Module located in the 24-inch circular storm sewer discharge pipe from the tributary area. The meter probe measured the velocity and depth of the water in the pipe at 15-minute intervals. The flow rate was then computed based on the pipe cross-sectional area (of flow) times the measured velocity.

In addition to monitoring in the storm sewer downstream from the bioretention facilities, ISCO 2150 flow meters were installed at a bioretention (sump) inlet and in the underdrain discharge pipe. Bioretention garden #33, located on the south side of Michigan Avenue just west of 720 Michigan Avenue (Young Brothers and Daly), was chosen as the representative bioretention facility for the post-construction flow monitoring. Selection of the specific bioretention facility to be monitored depended on accessibility for equipment placement, overall perceived function of the bioretention gardens, the ability to isolate the underdrain, having a minimal number of inlet points, and the overall suitability of the site characteristics to obtain accurate depth and velocity measurements. Figure 5-5 shows where bioretention facility #33 (flow monitoring location #1) was located within the project area as well as the relative location of the surrogate site flow monitoring location (location #2). Figure 5-6 shows details of where the flow meters were installed within garden #33 (flow monitoring location #1).

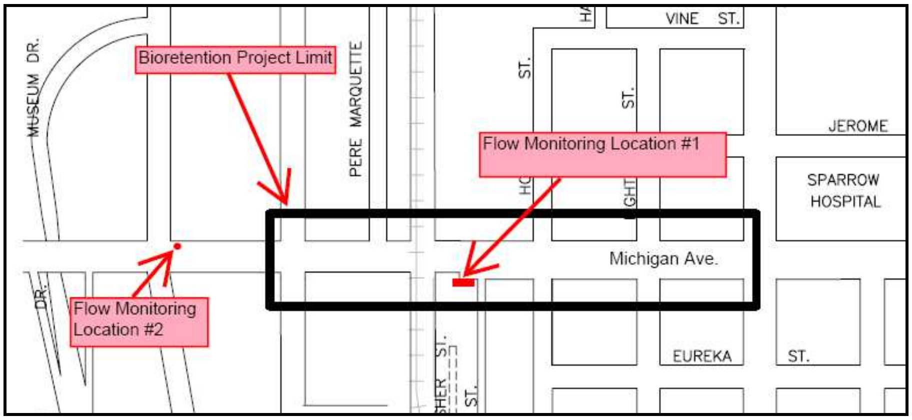


Figure 5-5. Bioretention facility #33 and flow monitoring locations

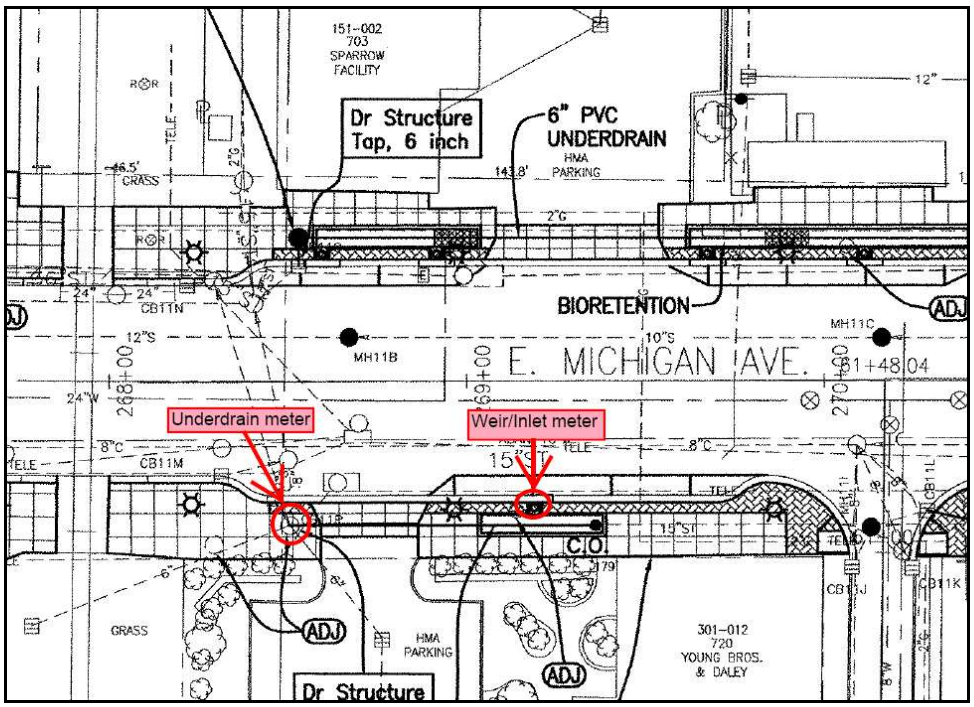


Figure 5-6. Detailed bioretention monitoring, location #1 (720 E. Michigan Avenue)

Influent flow depth to the bioretention garden was measured using a pressure transducer mounted on the wall of the weir between the sediment sump and the entrance to the garden at 15-minute intervals. The flow was then computed using the standard weir equation with the head over the weir being the depth recorded by the pressure transducer. The standard weir equation method is shown in equation 1 (Chow, 1958).

$$Q = c \times L \times H^{(3/2)} \tag{1}$$

Where, Q is the flow rate, c is the discharge constant for the weir, L is the length of the weir, and H is the head on the weir. The value for c was selected from the weir manual (Chow, 1958), the weir length was measured in the field and the head was measured by the pressure transducer.

Figure 5-7. Pressure transducer mounted to the wall of the sump at bioretention facility #33

The effluent flows from the bioretention garden #33 were measured by an ISCO 2150 area velocity module located in the underdrain discharge pipe from the garden. The area velocity meter measures depth and velocity at 15-minute intervals. The discharge flow rate was calculated based on the area times the velocity. Flow monitoring data was reviewed for data quality. Any bad data due to meter failure or data measurements outside of the meter accuracy would be considered unusable for model calibration.

5.3.3. Rain Gauge Locations

The rain gauges used for this study were located on the roofs of Bingham Elementary School and the City of Lansing Harton Street Pump Station. Figure 5-8 shows the rain gauge locations in relation to the project study area. The rain gauge was a non-heated tipping bucket gauge totalizing rainfall information on 5-minute intervals. The distance from the Bingham Elementary School rain gauge to the project site is less than 800 meters (0.5 miles). The distance from the City of Lansing Harton Street Pump Station to the project site is approximately 1,930 meters (1.2 miles). The two rain gauges were compared but the Bingham Elementary School rain gauge took precedence.

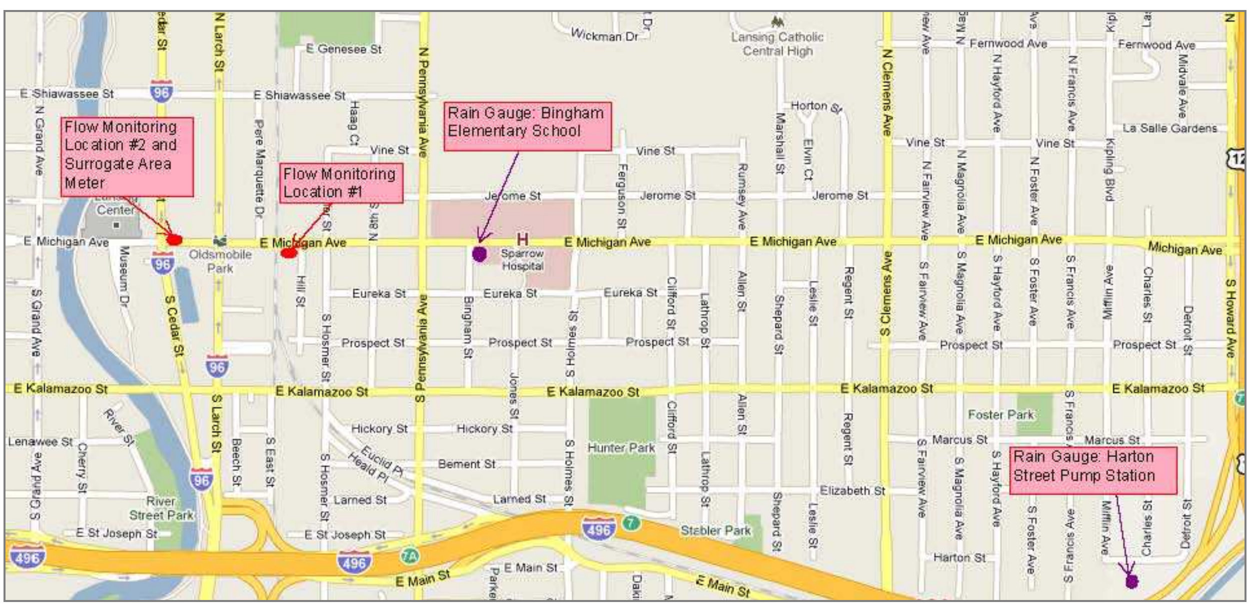


Figure 5-8. Rain gauge locations

In addition to the natural rain events monitored, a man-made rainfall event was simulated utilizing a water source from a nearby fire hydrant. The rainfall simulation approximated a 3.3-centimeter (1.3-inch) rainfall event over 4-hours using a 1st quartile Huff rainfall distribution.

Figure 5-9. Rainfall simulation test

During the simulated rainfall event, the rate of flow entering the gardens was monitored by using a hydrant flow meter. Check measurements of the flow rate were done by timing the duration to fill a bucket, and the depth (converted to flow) over the weir monitor (Tetra Tech, 2010). The flow was regulated such that the only flow leaving the garden was through the underdrain or infiltration, that is to say water was not allowed to bypass the garden and the garden was not overfilled. The flow meter in the underdrain pipe was used to record the discharge through the underdrain.

5.3.4. Model Setup

A hydrologic and hydraulic computer model was developed for the monitored area and used to normalize and compare the hydrograph modification data. A range of rainfall events, from the 90-percent non-exceedance event through the 100-year, 24-hour storm, was considered in the analysis.

The Storm Water Management Model (SWMM) is a dynamic rainfall-runoff simulation model developed by the United States Environmental Protection Agency (EPA) – Water Supply and Water

Resources Division (EPA, 2014). The model is used for discrete event or continuous (long-term) simulations of runoff quality and quantity. EPA SWMM uses subcatchments to represent a land area that collects precipitation and allows infiltration and drainage to a specific node, other subcatchment or to a stormwater management practice. The model can account for infiltration and evaporation losses, and depression storage, allowing water to pond on pervious and impervious surfaces, depending on the user input. The model generates a complete runoff hydrograph and routes it through a user-defined network of links and nodes.

The model requires various datasets for model setup including subcatchment properties, precipitation data, soils data, infiltration parameters and evaporation rates. A list of the user-defined input parameters for each subcatchment is detailed in Table 5-1.

Table 5-1. EPA SWMM subcatchment input parameters

Subcatchment Property	**Description**	**Unit**
Area	The physical area of the subcatchment	acres
Width	Width of the overland flow path	feet
% Slope	Average slope of the ground surface	%
% Impervious	Percent of Subcatchment area that is impervious	%
N-Imperv	Manning's N value for impervious area of subcatchment	None
N-Perv	Manning's N value for pervious area of subcatchment	None
Dstore-Imperv	Depth of depression storage on impervious area	inches
Dstore-Perv	Depth of depression storage on pervious area	inches
%Zero-Imperv	Percent of impervious area that has no depression storage	%
Subarea Routing	Selection of internal routing of stormwater runoff in the Subcatchment. Either discharges to an outlet, pervious or impervious area.	None
Percent Routed	Percentage of runoff that is routed between sub-areas	%
Infiltration	Section to enter in the infiltration parameters for the infiltration method selected.	Infiltration Rate Decay Constant Drying Time Max. Volume
Groundwater	Groundwater flow patterns including surface elevation, GW flow coefficient, GW exponent, surface water flow coefficient, surface water flow exponent, surface-GW interaction coefficient, fixed surface water depth and threshold GW elevation	Various
Snow Pack	Name of snow pack parameter set	Name
LID Controls	Pop-up of adding low impact development controls	Various

Table 5-1 (cont'd)

Subcatchment Property	Description	Unit
Land Uses	Assignment of land uses to Subcatchment, used for water quality modeling.	Various
Initial Buildup	Initial pollutant buildup on Subcatchment, used for water quality modeling	Various
Curb Length	Length of curb (if needed for pollutant buildup functions), used for water quality modeling	feet

Physical characteristics of the tributary drainage area (subcatchment) were obtained using topographic information gathered during survey work for the construction of the bioretention facilities, and land use maps. As-built drawings and laboratory results of soil testing of the bioretention facilities were used to set up the LID controls.

Version 5.0.022 of EPA SWMM was used for the model analysis of both the surrogate site and the bioretention area.

5.3.5. Model Calibration

Model calibration is the process of varying input parameters that are used to represent a physical system to best match actual field conditions. The parameters used in model calibration for this project were the measured field conditions of the bioretention facilities, including soil conductivity, bulk density, infiltration rate and the physical dimensions of the facility. These parameters were adjusted to present a model that best fits the actual data to the model results.

The surrogate site (pre-bioretention condition) model was calibrated to flow monitoring data and physical dimensions and conditions of the tributary drainage area. The calibrated coefficients from the surrogate site model were used to set up the model of the bioretention facility. The bioretention facility model was calibrated using the surrogate model data and to collected monitoring data and soil testing values.

5.4. RESULTS AND DISCUSSION

The results and discussion section details the flow monitoring, model calibration process and the hydrograph modification results calculated from the calibrated model.

5.4.1. Flow and Precipitation Data Collections

The flow monitoring data collected for the surrogate site and the bioretention facility was analyzed for completeness and validity to identify any anomalies in the measured data. This section includes discussion of data collected from the flow meters as well as data collected from the rain gauges.

5.4.2. Surrogate Site

The flow meter for the surrogate site was installed early May 2008 and removed at the end of October 2008. Flow monitoring results for the months of May, June and July showed several data collection errors that indicate large sections of the flow monitoring data should not be used for calibration. Flow depth measurements were recording negative values; a depth adjustment was made to account for meter drift; however, depth values were still recording negative following the adjustment. Velocity measurements were recorded as zero values in several cases. A scattergraph was generated for each month displaying the relationship between flow depth and velocity under actual conditions versus expected conditions (Manning's formula values). The R^2 values for the trend line of this data relationship ranged between 0.28 and 0.52, indicating a very poor correlation between flow depth and velocity (see scattergraph plots (a), (b) and (c) in Figure 5-10). The hydrograph in Figure 5-11 shows the flow monitoring data from the surrogate site meter location during the month of May. The green line shows flow depth, the red line shows velocity, the dark blue line displays flow rate and the light blue line on the secondary axis displays rainfall depth. It can be seen from the depth and velocity measurements that the meter is not functioning properly. The flow depth does respond to rainfall events; however, in several cases, the depth reading is negative and does not show a direct relationship to the velocity readings (see scattergraph plots (a) and (c) in Figure 5-10).

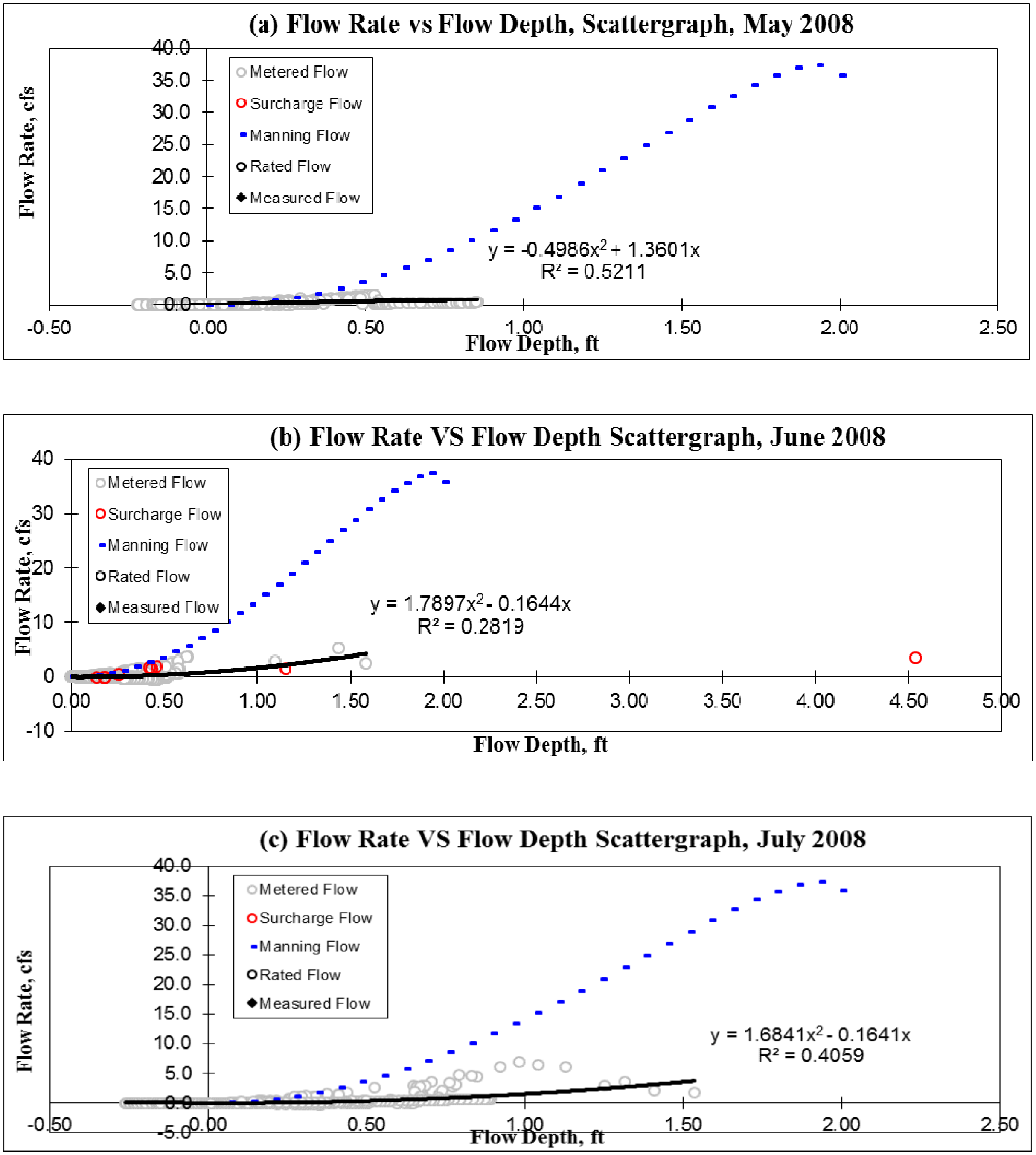


Figure 5-10. Scattergraph plots of flow rate versus flow depth for the surrogate site

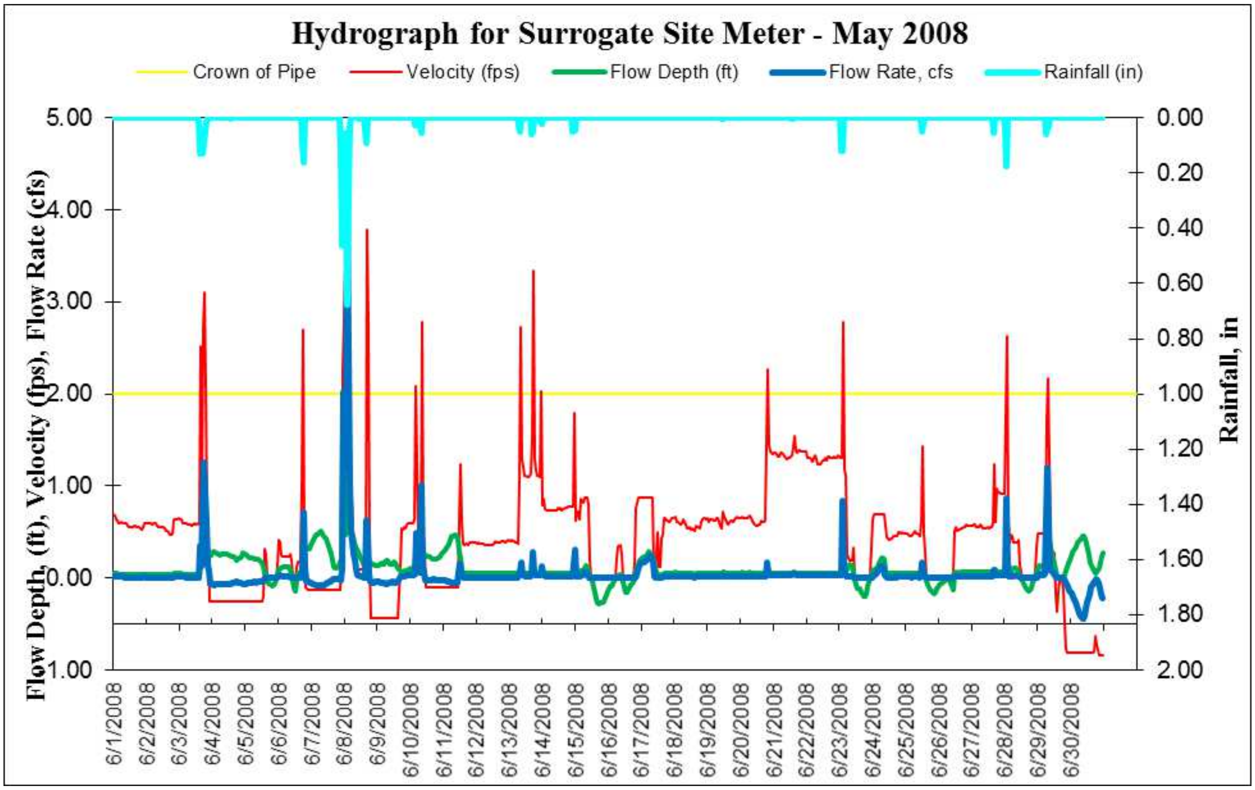


Figure 5-11. Flow depth and velocity vs time and hydrograph for the surrogate site meter

5.4.3. Rainfall

Rainfall data for the flow monitoring analysis was recorded using a rain gauge installed at Bingham Elementary School and checked against an existing rain gauge at Harton Street Pump Station. Because of the localized nature of rainfall events and the relative proximity to tall buildings that may obstruct rainfall measurements, existing rain gauges across the region were analyzed to determine spatial variability of each rainfall event. Table 5-2 shows eight different rain gauge locations, RG1-RG8 and the summary of rainfall events measured for the storm events that occurred during the surrogate site flow monitoring period. RG1 (highlighted in green) is the rain gauge at Bingham Elementary School. RG2-RG8 are regional rain gauges with precipitation data available either through the National Oceanic and Atmospheric Administration (NOAA) or through the Global Historical Climatology Network (GHCN).

Table 5-2. Rainfall depth recorded at regional rain gauges, September 2008-October 2008

Storm Date	RG1	National Oceanic and Atmospheric Association (NOAA) Rainfall (cm)					Global Historical Climatology Network Rainfall (cm)			Total Overall Average Rainfall (cm)	Average RG2, RG6 Rainfall (cm)
		RG2	RG3	RG4	RG5	RG2-RG5 Average	RG6	RG7	RG8		
8/23/2008	0.64	0.25	0.18	0.18	0.15	**0.19**	0.18	0.18	1.60	0.42	0.22
9/4/2008	1.42	1.27	1.40	1.47	1.45	**1.40**	1.57	1.32	1.83	1.47	1.42
9/29/2008	2.11	2.51	1.75	2.62	2.41	**2.32**	2.16	1.68	2.11	2.17	2.34
10/8/2008	1.04	1.17	0.91	1.04	1.24	**1.09**	--	1.12	1.35	1.12	1.17
10/15/2008	0.69	0.91	0.86	0.86	0.94	**0.90**	--	0.69	0.97	0.85	0.91
10/20/2008	0.43	0.56	0.51	0.46	0.64	**0.54**	0.58	0.51	0.53	0.53	0.57
10/24/2008	0.89	1.78	1.52	1.68	1.57	**1.64**	--	1.07	1.07	1.37	1.78

— indicates rainfall data was not available for that particular storm event

As illustrated in the table, uneven rainfall distribution is common throughout the region. A comparison was performed with the rainfall depth recorded at the Bingham Elementary School rain gauge (RG1) with RG2 and RG6 as these three rain gauges are all within 800 meters of the surrogate site monitoring location. From the comparison in Table 5-3, it can be seen that even within close distances to the monitoring location, spatial variability in the recorded rainfall depth is present. In some cases, the rainfall variability was as much as 100% difference between the Bingham Elementary School rain gauge and, in this case, RG2. It was also observed that the larger rainfall events had less spatial variability than the smaller rainfall events.

Table 5-3. Rainfall depth comparison at three rain gauges closest to monitoring site

Storm Date	Rainfall Depth (cm)			Average RG2, RG6 Rainfall (in)	% Change from RG1
	RG1	RG2	RG6		
8/23/2008	0.64	0.25	0.18	0.22	-66
9/4/2008	1.42	1.27	1.57	1.42	0
9/29/2008	2.11	2.51	2.16	2.34	11
10/8/2008	1.04	1.17	--	1.17	12
10/15/2008	0.69	0.91	--	0.91	33
10/20/2008	0.43	0.56	0.58	0.57	32
10/24/2008	0.89	1.78	--	1.78	100

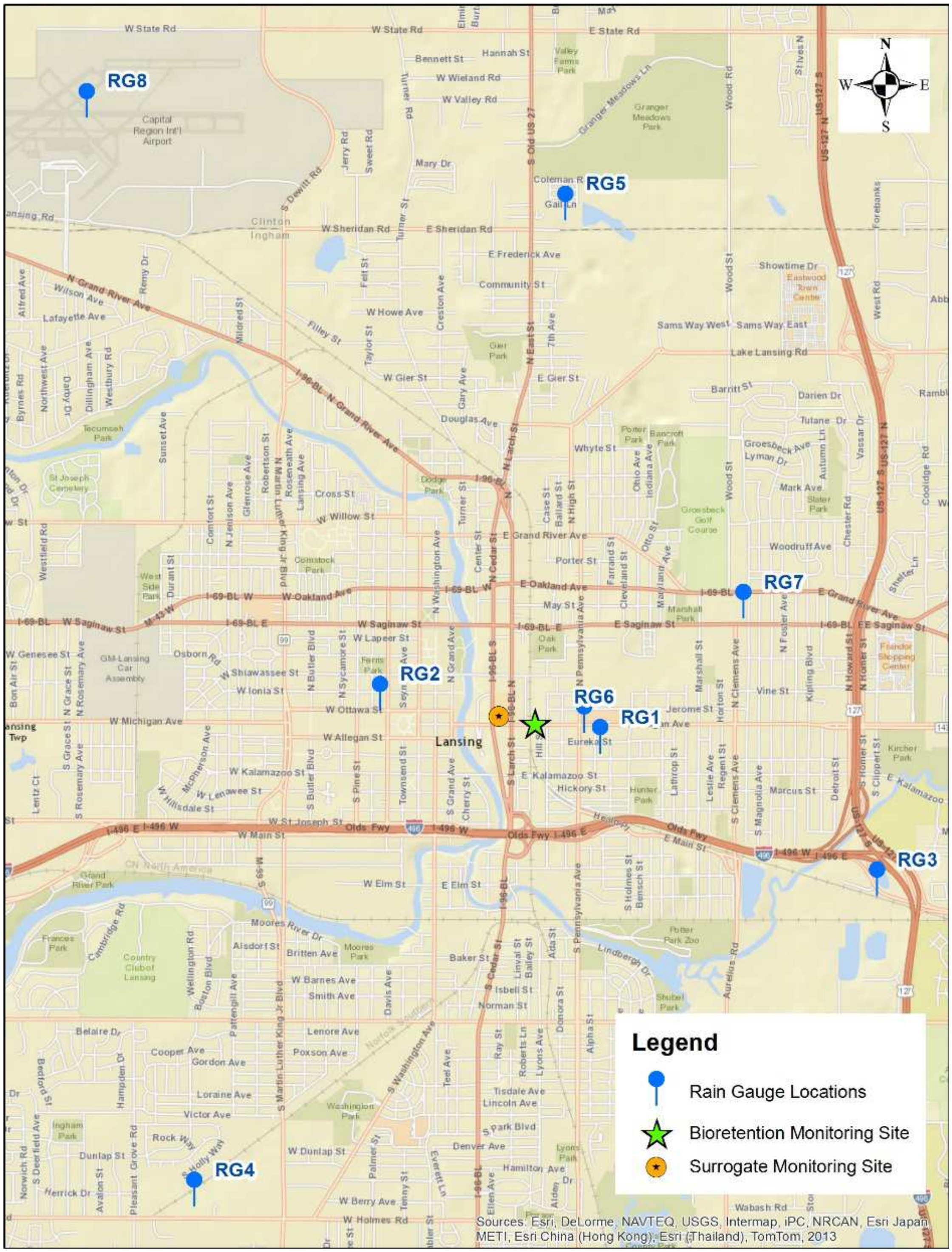


Figure 5-12. Rain gauge locations

The spatial variability observed in rainfall for the storm events during the monitoring period proved to be a limitation for model calibration. Future post-construction monitoring should consider the spatial distance of the system to be analyzed and the rainfall measuring device. It is recommended that a rain gauge be installed within the facility to be evaluated when possible. Obstructions that may affect the accuracy of measuring rainfall should be considered when selecting the install location for the rain gauge.

5.4.4. Bioretention Facility

The flow meters for the bioretention facility, both at the inlet and downstream discharge pipe, were installed at the end of May 2010 and removed at the beginning of November 2010. Initial review of the flow monitoring data for the bioretention facilities indicated that the meters were responding to the flow in a manner that is expected (The measured flow depth had a correlation to the rainfall and began tapering off after the rain event). The hydrograph in Figure 5-13 displays the flow rate entering the bioretention facility and the flow depth in the inlet sump measured by the meter probe. The green line represents the flow depth, the dark blue line displays flow rate and the light blue line on the secondary axis displays rainfall depth from RG 1. The measured flow depth shows an immediate response to rainfall events, following by a slow decrease in the depth over time. Many factors affect the bioretention systems ability to capture and infiltrate rain events (antecedent moisture conditions, time between rainfall events, temperature, etc.) The flow rate hydrograph shows a reasonable correlation between the size of the rainfall event and the height of the spike for flow rate, with an R^2 value of 0.72 given the high variability in environmental conditions at the onset of each rainfall event.

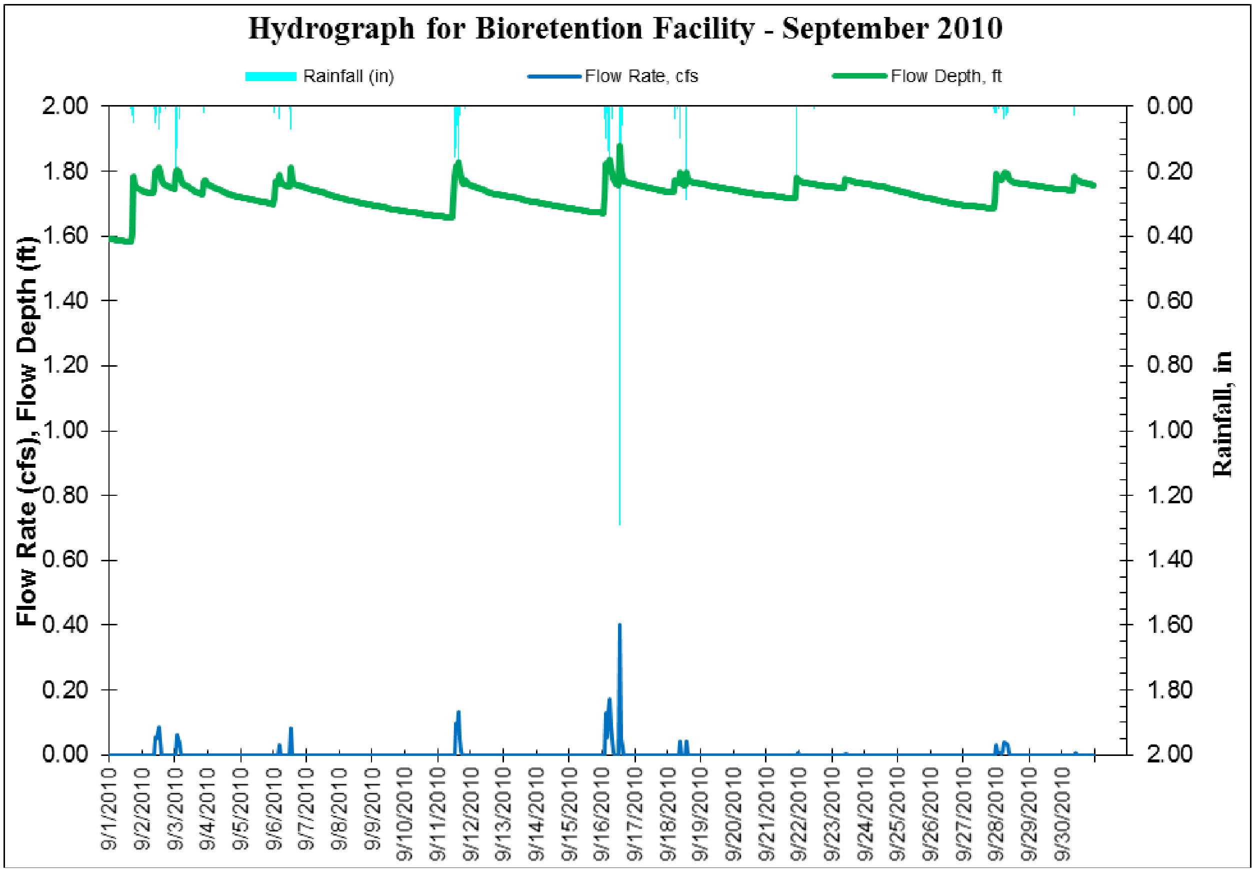


Figure 5-13. Hydrograph and flow depth for bioretention facility flow meter

Review of the flow monitoring data for the meter located in the discharge pipe downstream of the bioretention facility indicated that there was a problem with several of the data points. Figure 5-14 displays the flow hydrograph, velocity and flow depth in relation to rainfall for the meter in the discharge pipe downstream of the bioretention facility. The red line displays velocity, the dark blue line shows the flow rate, the green line represents flow depth, and the light blue line on the secondary axis displays rainfall depth. The velocity measurements show no pattern or consistent response to rainfall and are constantly fluctuating. On July 13, 2010, the velocity flat-lined and indicated no response to the rain events that occurred. The manufacturer's specification for the ISCO 2150 Area Velocity Sensor indicate that the level measurement range is 0.010 to 3.05 meters with an accuracy of ±0.003 meters from 0.01 to 3.05 meters (see Appendix C for specification sheet from manufacturer). Based on reviewing the flow monitoring data and the specifications of the equipment, it was determined that the flow monitoring data for the meter in the discharge pipe downstream of the bioretention facility is unreliable.

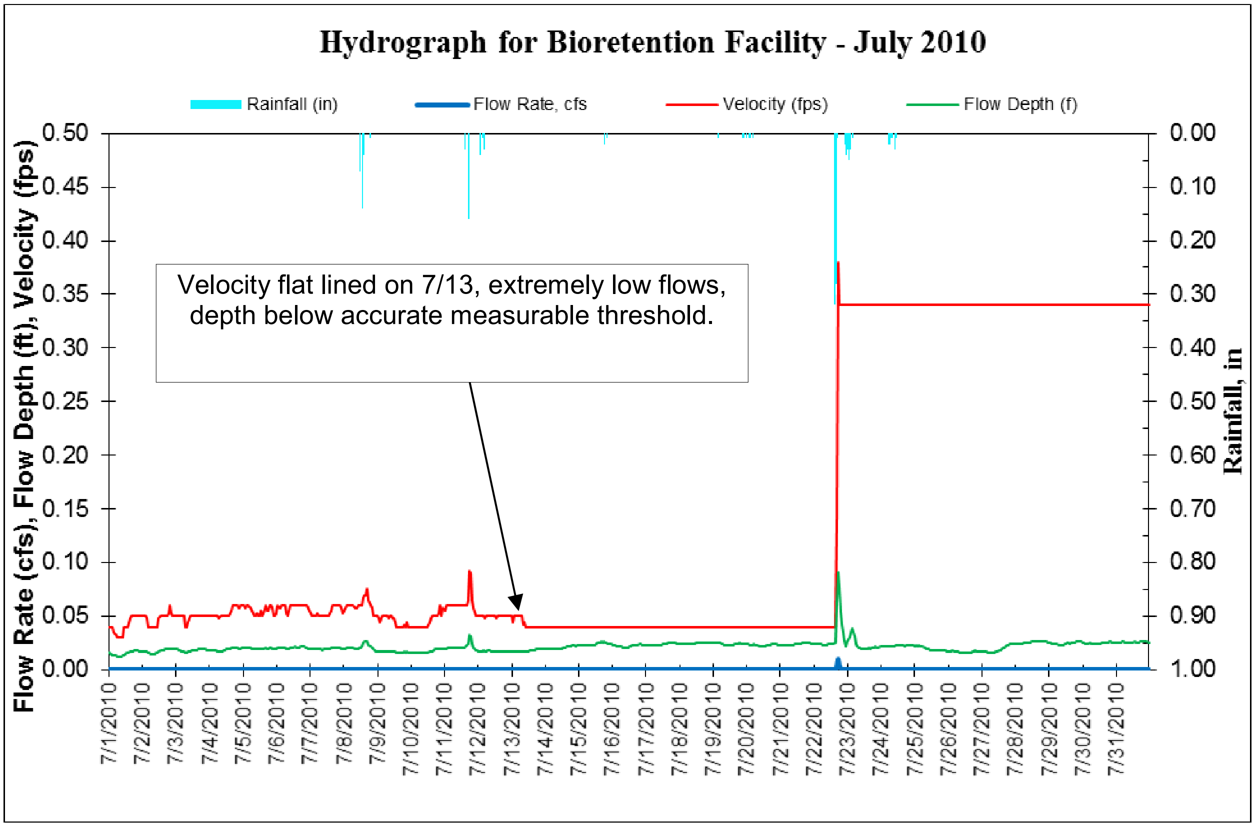


Figure 5-14. Flow monitoring data – flow depth and velocity versus time at outlet

Due to a lack of reliable rainfall data and insufficient flow monitoring for the bioretention facility, a man-made rainfall event was simulated using a water source from a nearby fire hydrant and hydrant metering equipment. The man-made rainfall event provided for more accurate rainfall measurements as all of the water discharging from the fire hydrant, was captured in the bioretention facility. Table 5-4 displays the simulated rainfall event, which recorded approximately a 3.3 centimeter (1.3 inch) rainfall event over 4-hours using a 1st quartile Huff rainfall distribution.

Table 5-4 Field measurement data for simulated rainfall event – November 1, 2010

Δ Time	Field Measurement Data (Simulation performed on 11/1/2010)					
	Meter Reading (ft^3)		ΔVol	ΔVol	Flow Rate (cms)	Flow Rate (cfs)
(min)	Start	End	(ft^3)	(m^3)	(ΔVol/720 sec)	(ΔVol/720 sec)
0	4442580					
12[a]	4442513	4442580	67.5	1.91	0.0027	0.094
24	4442580	4442715	67.5	1.91	0.0027	0.094
36	4442715	4442770	55	1.56	0.0022	0.076
48	4442770	4442807	37	1.05	0.0015	0.051
60	4442807	4442843	36	1.02	0.0014	0.050
72	4442843	4442873	30	0.85	0.0012	0.042
84	4442873	4442898	25	0.71	0.0010	0.035
96	4442898	4442913	15	0.42	0.0006	0.021
108	4442913	4442928	15	0.42	0.0006	0.021
120	4442928	4442938	10	0.28	0.0004	0.014
132	4442938	4442941	3	0.08	0.0001	0.004
144	4442941	4442944	3	0.08	0.0001	0.004
156[a]	4442944	4442951	6	0.17	0.0002	0.008
168	4442951	4442956	6	0.17	0.0002	0.008
180	4442956	4442966	10	0.28	0.0004	0.014
192	4442966	4442976	10	0.28	0.0004	0.014
204	4442976	4442987	11	0.31	0.0004	0.015
216[b]	4442987		6.4	0.18	0.0003	0.009
228[b]			6.4	0.18	0.0003	0.009
240[b]		4442987	6.4	0.18	0.0003	0.009
Total			**426.3**	**12.1**		

[a]Estimated - The meter reading for this time interval was not recorded. Therefore, the meter reading at the next time interval was divided evenly between the two time intervals as the flow rate was kept constant over the entire 24 minutes.
[b]Flow rates for the last three measurements were determined using a bucket test as the hydrant flow meter was unable to measure such small flow quantities.

Flow measurements for the man-made simulated rainfall event were collected by the previously installed flow meters for model calibration. The inflow hydrograph includes the flow measurements recorded by the fire hydrant flow meter, which are presented in tabular format in Table 5-4. The outflow hydrograph was recorded using the flow meter located in the outlet discharge pipe downstream of the bioretention facility. Figure 5-15 displays the measured flow depth (depicted by the green line) and velocity (depicted by the red line), along with the calculated flow rate, shown in blue, during the rain simulation event.

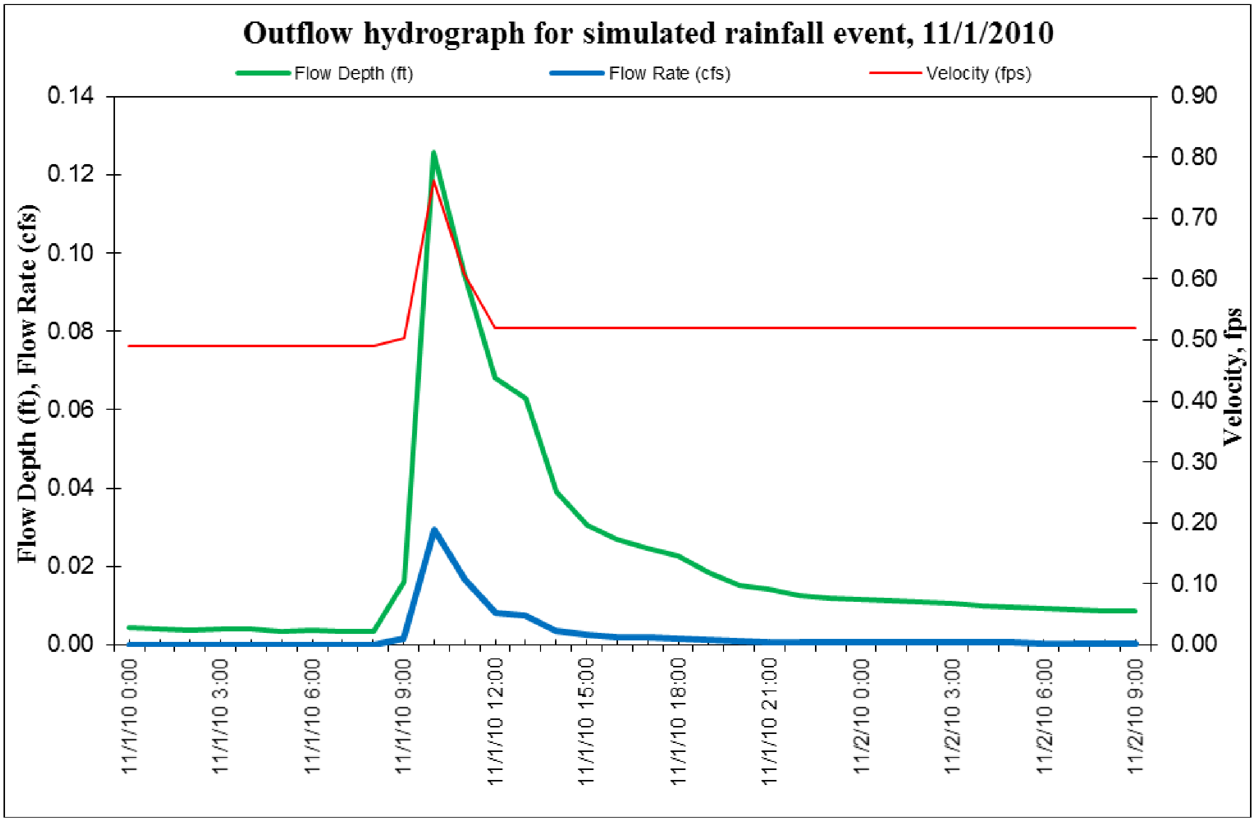


Figure 5-15. Flow meter measurements for simulated rainfall event – November 1, 2010

Review of the flow monitoring results for the simulated rainfall event indicate that the meter responded to the flow in a manner that is expected. The simulated event began at 09:00 on November 1st and the effluent flow depth exhibited a quick response to the rainfall event starting at 10:00. The simulated event ended at 13:00 and as is expected, the flow in the effluent pipe lags behind as water slowly percolates through the garden.

The simulated rainfall event provided a more accurate rainfall event to use for model calibration than the surrounding rain gauges and flow monitoring equipment techniques. Therefore, future post-construction monitoring work should consider the use of several man-made simulated rainfall events, combined with flow monitoring equipment that has the ability to more accurately measure small flow rates.

5.4.5. Model Calibration

The surrogate site flow monitoring and rainfall data was intended to provide a calibrated pre-bioretention condition. The calibrated parameters, including width, depression storage values and percent impervious cover, would be used in the bioretention facility model condition. However, based on the poor rainfall data due to large spatial variability and erroneous flow monitoring data from the flow meters, the surrogate site model condition was rejected. Although the calibration parameters for the surrogate site were unsatisfactory, relative comparisons can be made between a pre-bioretention condition and post-bioretention condition.

The post-bioretention condition model was calibrated. The flow and rainfall observations from the man-made simulated rainfall event was used for the model calibration. Figure 5-16 shows the inflow and outflow hydrographs for the simulated rainfall event measured by the flow meters at the inlet and outlet of the bioretention facility. The red line with square points represents the inflow hydrograph and the blue line with diamond point represents the outflow hydrograph.

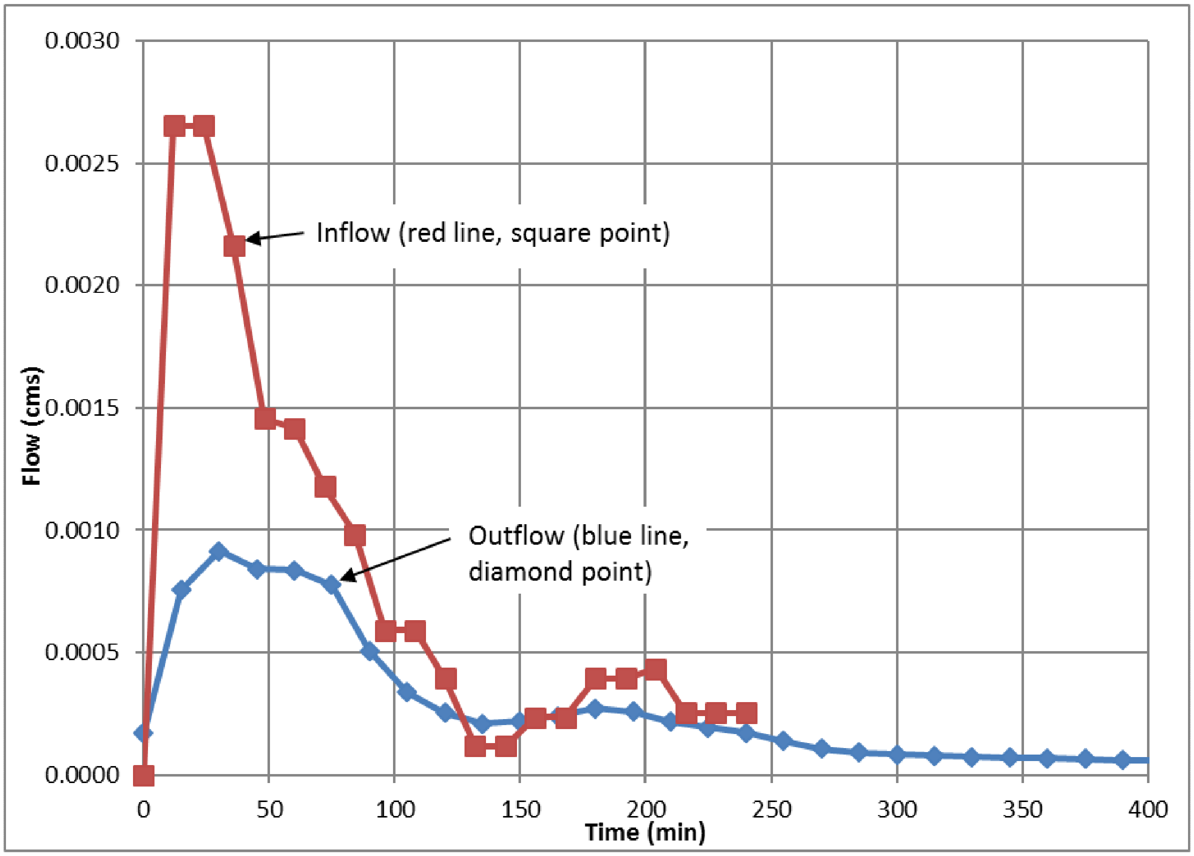


Figure 5-16. Inflow and outflow hydrographs from flow meters for simulated rainfall event

The bioretention facility model was calibrated to the inflow and outflow hydrographs. The R^2 value between the observed and predicted flow rate is 0.94, which indicates that the model is performing satisfactory in predicting flows. Adjustments were made to the subcatchment width, depression storage, and percent impervious cover to match the inflow hydrograph in the model to the metered data. Table 5-5 and Figure 5-17 summarize the results of the inflow hydrograph calibration. The model performed well in replicating the monitoring results for the man-made simulation event, indicating a range of 5.4% to 5.6% difference between the data sets.

Table 5-5. Calibration results

	Monitored	Modeled	% Difference
Volume (cubic meter)	12.1	11.4	-5.4
Peak Flow (cms)	0.0027	0.0028	5.6

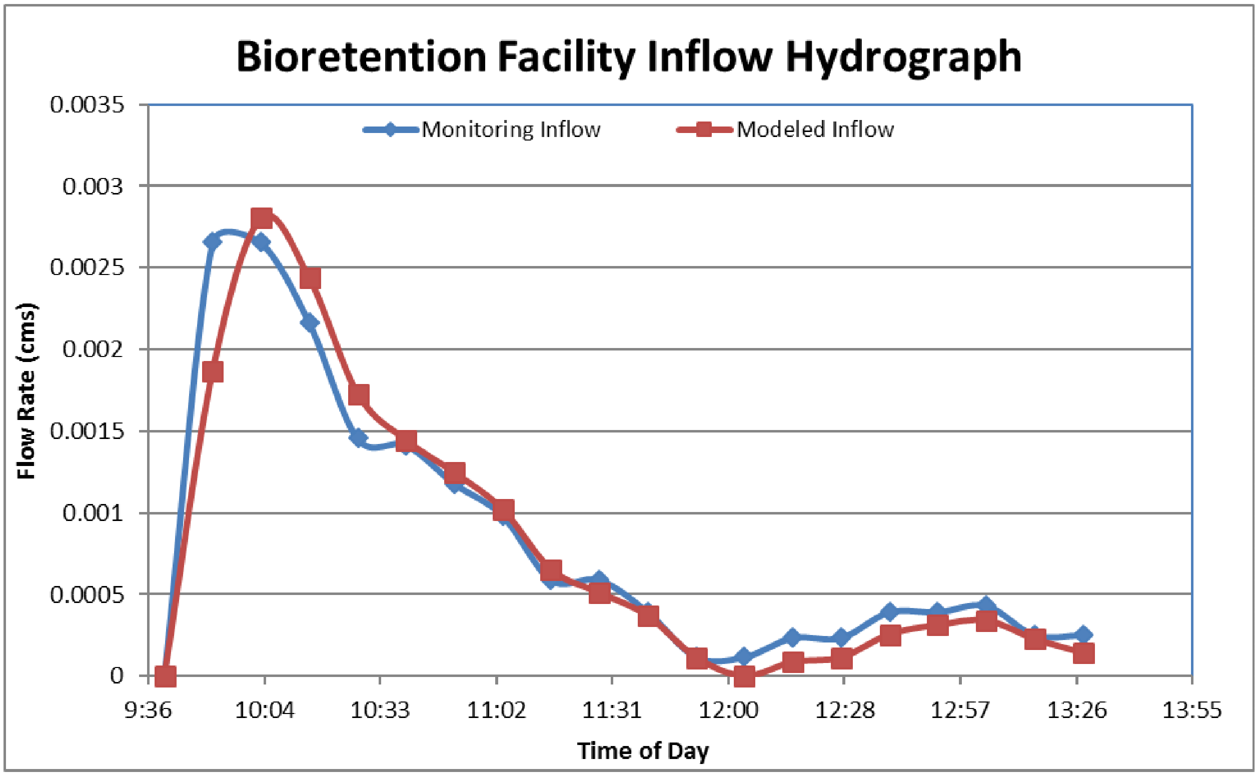


Figure 5-17. Calibration hydrograph results

Calibration for the outflow hydrograph was performed by populating the design components of the bioretention facility from the as-built drawings and soil testing results. Addiitonal model parameters for the bioretention facility (LID controls), including vegetation volume, hydraulic conductivity, storage void ratio, and underdrain coefficients were then adjusted to calibrate the effluent flow hydrograph in the model to the flow meter outflow hydrograph. Table 5-6 provides a list of the model parameters and the calibrated values for the bioretention facility. The first set of calibrated model parameters (area, width, percent slope, % impervious, Manning's n and depression storage) displayed in Table 5-6 were used in the model for the bioretetion facility before LID controls were implemented.

Table 5-6. Calibrated model parameters

Parameter	**Calibrated Value**
Area (acres)	0.11
Width (ft)	50
Percent Slope	2.58
% Impervious	100
Manning's n Impervious	0.014
Manning's n Pervious	0.3
D-Store Impervious	0.05
D-Store Pervious	0.05
Surface	
Storage Depth (in)	14
Vegetation Volume Fraction	0.03
Surface Roughness (Manning's n)	0.024
Surface Slope (%)	0
Soil	
Thickness (in)	36
Porosity (volume fraction)	0.506
Field Capacity (volume fraction)	0.295
Wilting point (volume fraction)	0.055
Conductivity (in/hr)	13
Conductivity Slope	20
Suction Head (in)	5
Storage	
Height (in)	12
Void Ration (voids/solids)	0.35
Conductivity (in/hr)	13
Clogging Factor	0
Underdrain	
Drain Coefficient (in/hr)	1.8
Drain Exponent	0.8
Drain Offset Height (in)	3

A model calibration hydrograph comparing the underdrain discharge rate from the monitored data and the model prediction is shown in Figure 5-18.

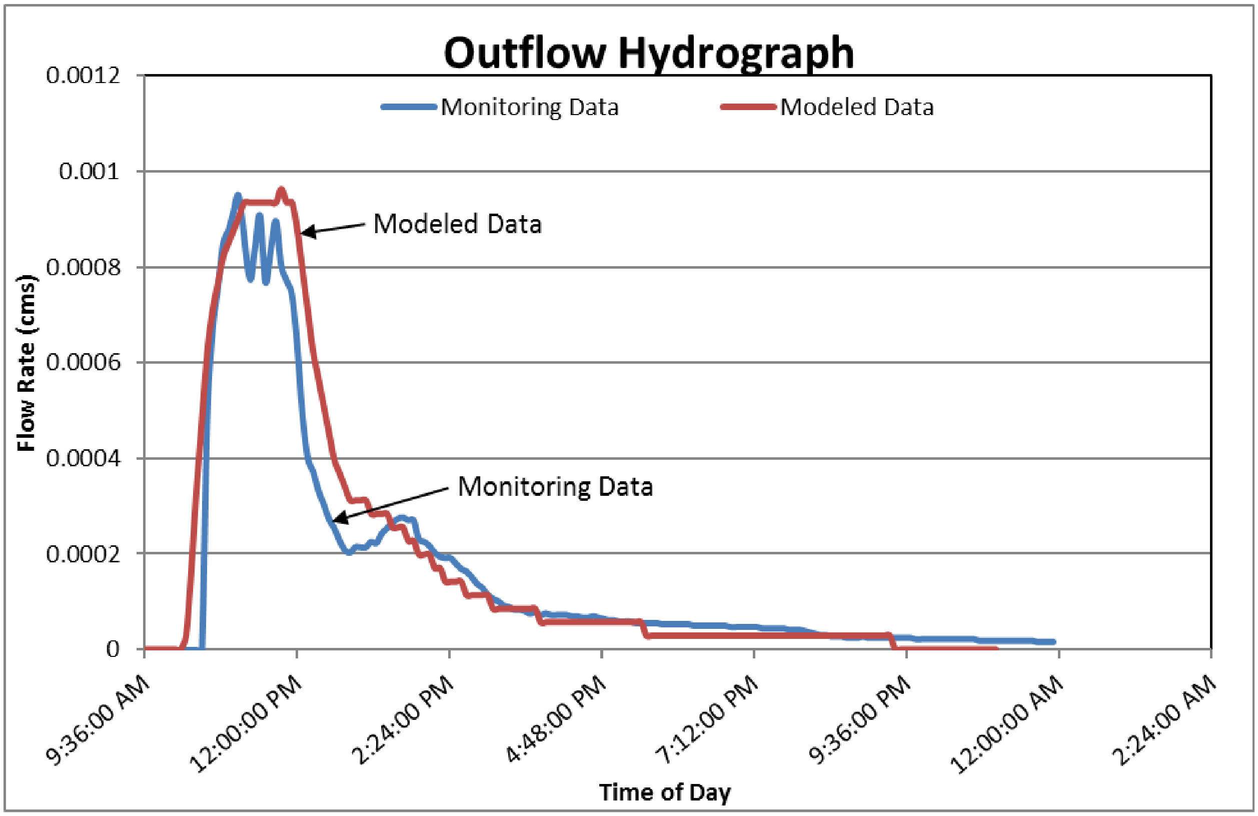


Figure 5-18. Outflow hydrograph - model calibration plot

Overall, the results show that the calibrated model is slightly over predicting the volume by 14% and predicting the flow rate very well, within 1% of the monitored data. The R^2 value between the observed and predicted flow is 0.91, indicating that the model is satisfactorily predicting the flows. The model performs well at predicting the timing of the peak flow. As the model is over predicting the outflow volume compared to what was measured, the calculated effectiveness of the bioretention facilities for volume reduction will be conservative (under-predicted).

5.4.6. Effectiveness of Bioretention Facilities on Hydrograph Modification

The calibrated models for the bioretention facility were solved for a range of storm events simulating both the site without ("pre") and with ("post") the bioretention facilities. Numerical results were obtained for total volume, time to peak, and peak flow for a range of rainfall recurrence intervals and storm durations as well as a continuous simulation utilizing forty-seven years of rainfall records.

Recurrence intervals ranging between the 1- and 10-year and between 1- to 24-hour rainfall durations were simulated. Table 5-7 provides a summary of the model analysis for both pre- and post-conditions for the range of events. Example runoff hydrograph comparisons are shown in Figure 5-19 for the 1- and 10-year recurrence intervals and the 1- and 24-hour rainfall durations.

Results indicate that the reduction in surface runoff volume ranges between 5 percent and 27 percent. The larger changes occurred for the smaller storm recurrence intervals with the shorter durations. These results are in line with the design criteria as the bioretention facilities were designed to manage the stormwater runoff from a 2.54-cm rainfall event (between a 1- and 2-year, one hour event).

A similar pattern is demonstrated from the change in peak flow rate from the pre- to post-conditions. Results indicate that the reduction in peak flow rate ranges between 33 percent and 89 percent, with the largest reductions occurring during the smaller recurrence interval storm during the shorter duration events. The longer duration storm event results correlate to the engineered soil in the bioretention facility having time to reach saturation and consequently allows more water to percolate through the soil medium to the underdrain. Results for the change in time to peak show that the bioretention facilities are significantly slowing the water down before it reaches the underdrain discharge pipe. Time to peak reductions range between 8 percent and 729 percent. The greatest reductions occur during the one hour storm event. These results support the occurrence that the bioretention facilities have time to reach saturated conditions for the larger storm events. These results in more water reaching the underdrain at a faster rate than for the shorter duration storms.

Table 5-7. Hydrology Change Summary

Rainfall			Pre- Condition (no bioretention)			Post- Condition (with bioretention)			Change from Pre- to Post- Conditions		
Recurrence Interval	Duration (hr)	Total (cm)	SRO (cm)	Qp (cms)	Tp (hr)	SRO (cm)	Qp (cms)	Tp (hr)	SRO (%)	Qp (%)	Tp (%)
2-month	1	1.32	1.30	0.004	0.17	0.94	0.001	1.08	-27%	-87%	535%
6-month	1	1.96	1.93	0.006	0.17	1.55	0.001	1.33	-20%	-84%	682%
1-year	1	2.41	2.39	0.008	0.17	2.01	0.001	1.41	-16%	-87%	729%
2-year	1	2.90	2.90	0.010	0.17	2.49	0.001	1.41	-14%	-89%	729%
10-year	1	4.09	4.09	0.016	0.17	3.66	0.006	0.33	-11%	-64%	94%
25-year	1	4.88	4.88	0.019	0.17	4.45	0.008	0.25	-9%	-56%	47%
100-year	1	6.20	6.17	0.025	0.17	5.79	0.016	0.2	-6%	-33%	18%
2-month	24	2.84	2.34	0.001	12	1.91	0.000	20	-18%	-82%	67%
6-month	24	4.17	3.66	0.002	12	3.18	0.000	19	-13%	-81%	58%
1-year	24	5.16	4.65	0.003	12	4.11	0.001	13	-11%	-56%	8%
2-year	24	6.15	5.64	0.003	12	5.13	0.002	13	-9%	-38%	8%
10-year	24	8.71	8.26	0.005	12	7.65	0.003	13	-7%	-40%	8%
25-year	24	10.39	9.88	0.005	12	9.30	0.003	13	-6%	-38%	8%
100-year	24	13.21	12.70	0.007	12	12.07	0.004	13	-5%	-34%	8%
90%	24	2.29	1.78	0.001	12	1.37	0.001	16	-23%	-50%	33%

SRO: Surface Runoff; Qp: Peak Flow; Tp: Time to Peak

These hydrograph modifications are principally a function of the soil matrix slowing the water down (the soil permeability), providing storage (the porosity of the soil) and capture capacity (the soil field capacity). This is reiterated with the results in Figure 18 showing that the hydrograph modifications are more substantial for the lower precipitation events. During the larger storm events, the bioretention system reaches capacity either volumetrically or through the soil permeability rate. Once the system capacity is exceeded, the surface runoff is allowed to bypass the bioretention system and is continues to flow to the traditional catch basin/sewer system where no further hydrograph modification takes place.

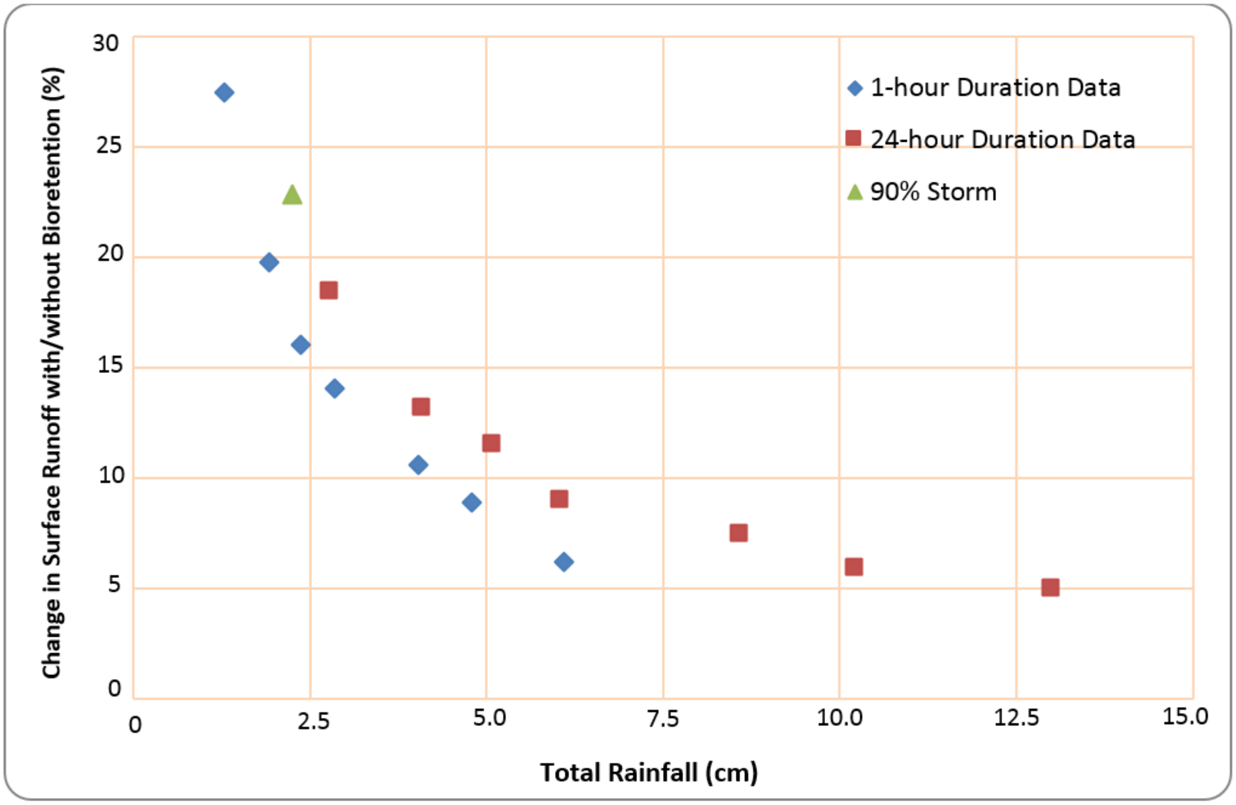
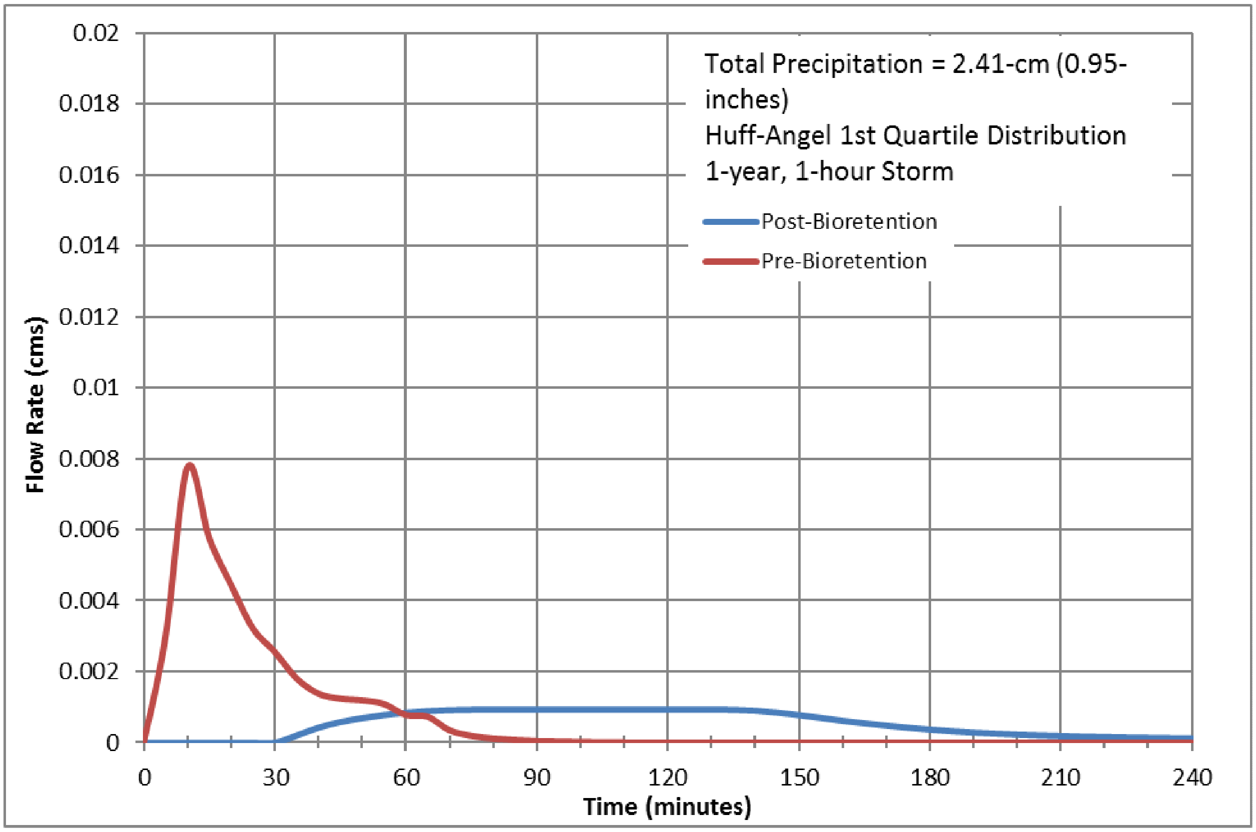


Figure 5-19. Runoff change as a function of total rainfall

Hydrograph results for a 1-year and 10-year recurrence interval 1-hour and 24-hour duration storm events during the "pre" and "post" biorentetion conditions are graphically displayed in Figure . As the figure shows, the 1-hour duration storms provide a greater reduction in the surface runoff volume, peak flow, and time to peak than the 24-hour duration storms.



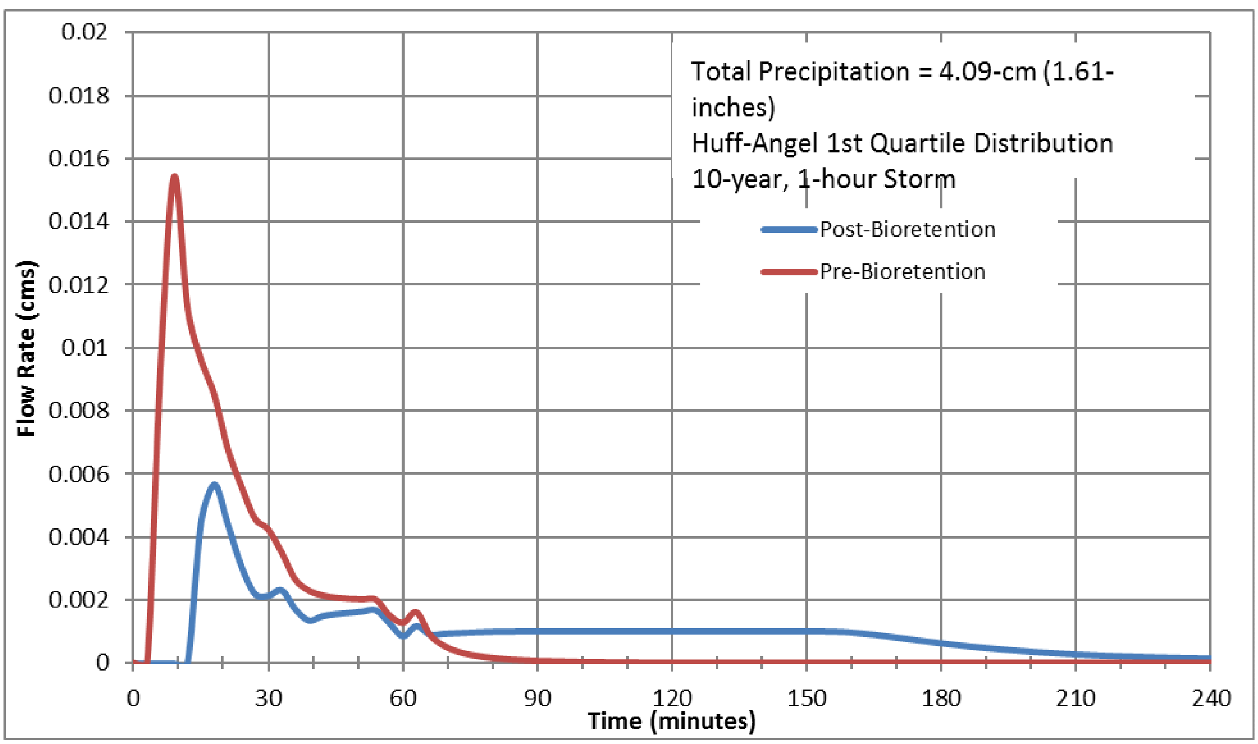
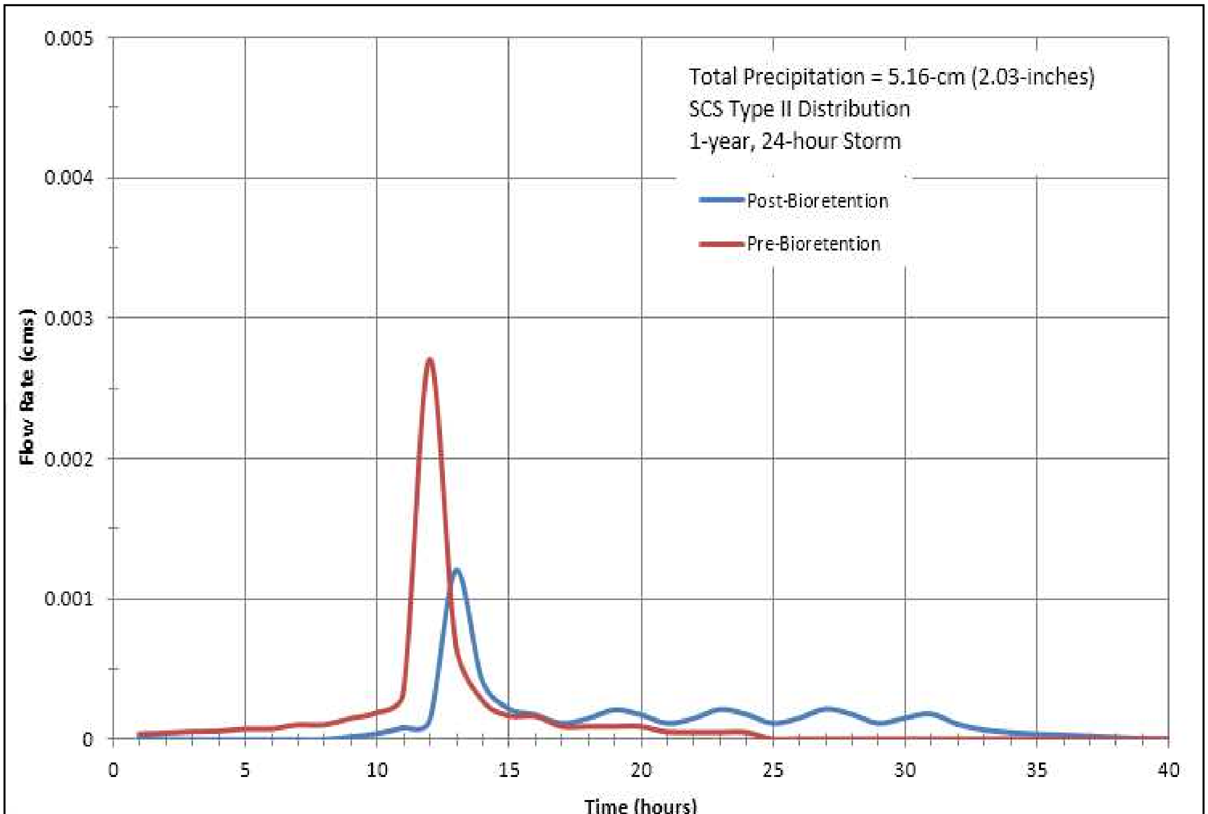
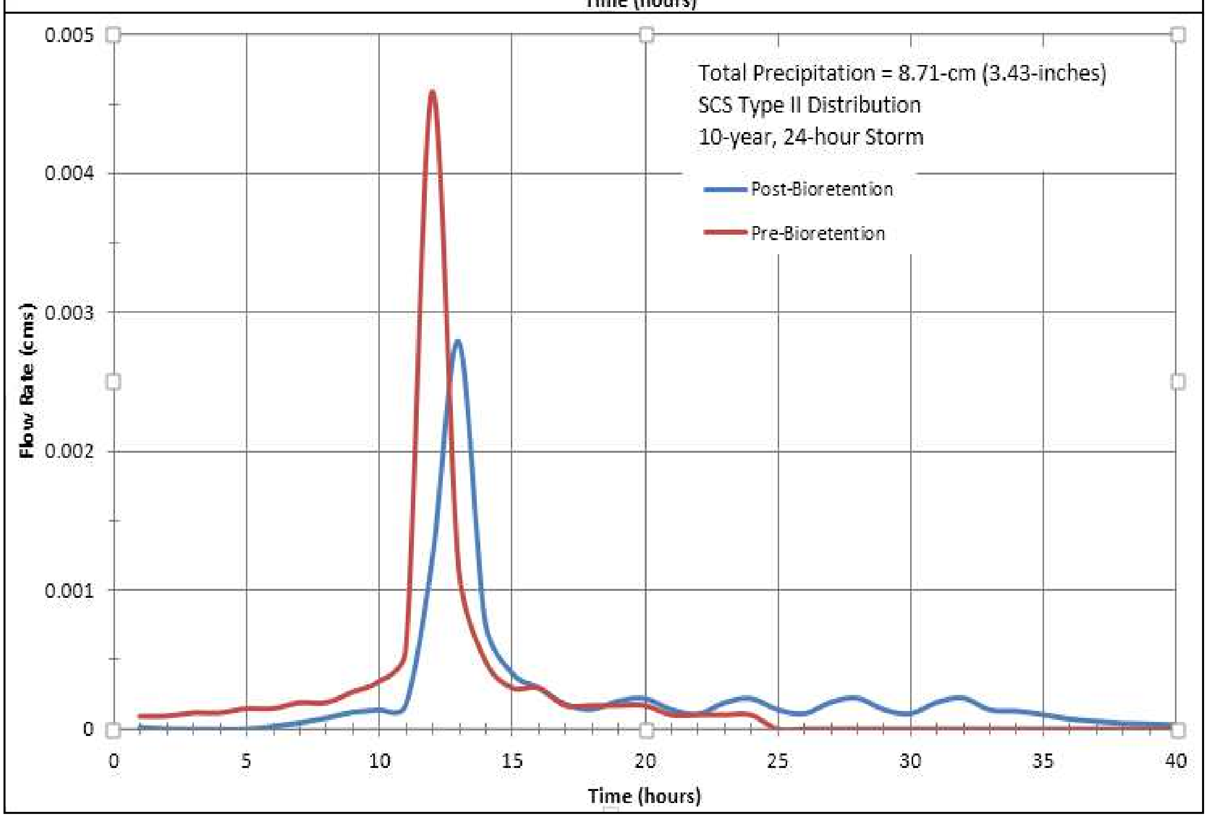


Figure 5-20. Runoff Comparison for 1-yr 1-hour, 10-yr 1-hour, 1-yr 24-hour, and 10-yr 24-hour

Figure 5-20 (cont'd)





A long term continous simulation utilizing forty-seven years of rainfall records from the Capital City Airport was performed. Over the forty-seven year period of record from 1957 through 2008, there were a total of 6,234 events totaling 3,693-centimeters (1,454-inches) of precipitation with a mean annual average of 78-centimeters (31-inches) of precipitation. Table 5-8 summarizes the frequency analysis of preciptation events for the forty-seven years. During the 47-year period, there were 288 precipitation events greater than 2.54 centimeters (1-inch) with most of those event depths between 2.54-centimeters (1-inch) and 5.15-centimeters (2.03-inches). Two large storm events greater than a 25-year storm occurred but no flood events (100-year) occurred during the forty-seven year period.

Table 5-8. Frequency analysis of precipitation events for forty-seven year record

Recurrence Interval	**# of Events**	**Rainfall Depth (cm)**
Total number of events greater than 2.54-cm (1-inch) rainfall	288	> 2.54
Number of events between a 1 and 1.99 year return	31	5.16-6.12
Number of events between a 2 and 4 year return	17	6.15-7.54
Number of events between a 5 and 9 year return	6	7.57-8.69
Number of events between a 10 and 24 year return	4	8.71-10.36
Number of events between a 25 and 49 year return	1	10.39-11.73
Number of events between a 50 and 99 year return	1	11.76-13.18
Number of 100 year return events	0	13.21

Results from the forty-seven year continuous simulation demonstrate a significant change is observed with the inclusion of the bioretention facility in the flow stream. The results calculate a 75 percent decrease in overall surface runoff volume with the bioretention gardens in place over the entire forty-seven years of record. Figure 5-21 depicts the model output results.

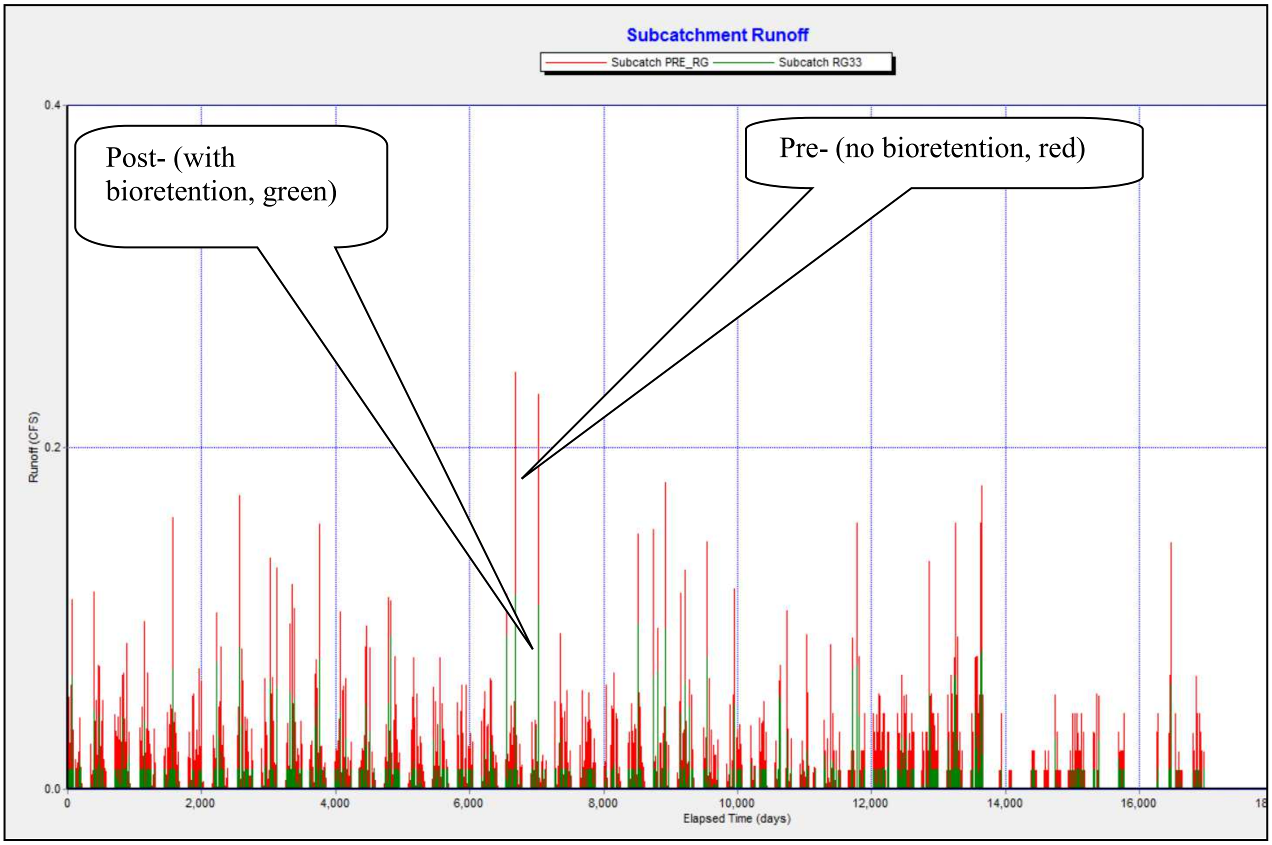


Figure 5-21. Continuous simulation of flow events for pre and post bioretention implementation over 47 years of rainfall records

5.5. CONCLUSION

The bioretention facilities on Michigan Avenue were constructed as part of a Go Green! Go Lansing! Initiative. The objective of post-construction monitoring was to assess how the bioretention systems have modified the surface runoff hydrograph. Specifically, the study objectives were to evaluate how the bioretention systems modified the surface runoff hydrograph, perform a comparison of the surface runoff hydrograph with and without the bioretention gardens in place, and evaluate what the change in total volume, peak flow rate, time to peak and overall shape of the hydrograph is.

Post-construction monitoring was performed in the bioretention project area starting in May 2010 and concluding in November 2010. Flow measurements at the inlet to the bioretention facility as well as the effluent discharge pipe have been recorded using ISCO 2150 Area Velocity Modules. Rainfall was recorded using an ISCO 674 rain gauge with an ISCO 4150 flow logger. The inlet flow was recorded using a depth probe located in the catch basin sump at the inlet of the bioretention facility. The effluent flow was recorded using a depth and velocity probe installed on the bottom of the underdrain pipe in a manhole immediately downstream of the bioretention facility.

The surrogate site that was originally designed to be the “pre” bioretention condition was rejected after review of the rainfall data and flow monitoring data. The rainfall demonstrated a high rate of spatial variability while the flow monitoring data indicated that the equipment was not responding to the flow in an accurate manner.

The flow monitoring data from the bioretention facility was analyzed. This study concluded that the flow monitoring equipment was not able to measure the small flow rates present in the outlet pipe of the bioretention facility. However, comparisons between the “pre” and “post” bioretention model scenarios were able to be made based on the implementation of a man-made simulated rainfall event. Results indicate that peak flow rates were reduced from “pre” to “post” conditions by a range of 33% to 89%. The larger flow reductions occurred for the smaller storm events. Similar patterns were observed for the total volume, with reductions ranging from 5% to 27%. Increases in time to peak ranged from 8% for the larger events to 729% for the smaller storm events. A review of the overall shape of the surface runoff hydrograph indicates that the shape changed from a flashy, quick peak with minimal to no event tail to one with a smaller, delayed peak (increase in time to peak) and a more extensive tail on the hydrograph. The resulting hydrograph correlates to a system that responds to the bioretention facilities by shifting to an infiltration-dominated, pre-development system.

Lessons learned from the post-construction monitoring work were discussed with the goal of improving the ability to more accurately assess the effects of bioretention facilities on the surface runoff hydrology, including peak flow rate, volume and time to peak. Ensuring an accurate method to collect rainfall data and monitor small flow rates into and out of the bioretention system is critical when performing post-construction monitoring. While bioretention facilities have been implemented for years in the stormwater management community, this study provides valuable information to the design community. Over the course of this research work, preliminary findings and recommendations have been implemented on new projects. Flow monitoring equipment suitable for extremely low flows is being used and rain gauges are being installed at the LID practice locations rather than somewhere offsite. Manmade rainfall events are increasing being utilized as well for quicker, more accurate flow monitoring data collection.

Future analysis of the effects that bioretention systems have on the surface runoff hydrograph with the recommended data collection methods is necessary. This will provide verification that the recommended improvements prove effective.

6. CONCLUSION

This research examined the effects that implementing bioretention facilities on the surface runoff hydrograph in terms of total runoff volume, peak flow rate, time to peak, and shape of the surface runoff hydrograph. The study area is located in the ultra-urban downtown corridor along Michigan Avenue leading to the state capital in Lansing, Michigan. Post construction flow monitoring was conducted at the upstream and downstream ends of a selected bioretention facility. Rainfall data was collected from a nearby rain gauge. Soil samples of the engineered soil mixture were taken, infiltration testing was performed and an overall plant and garden health assessment was completed. The following general conclusions were made:

- Infiltration capacity of the engineered soil is dependent on the type of infiltrometer used but is not dependent on whether the mulch layer remains in place or is removed.
- Porosity and field capacity measured values indicate the bioretention gardens are able to capture and store approximately 2.54 cm (1 inch) of runoff from the project drainage area with an average measured value for temporary storage volume of 21%.
- Post construction qualitative monitoring indicates the gardens have optimal soil conditions, with bulk density values below which is considered to be soil limiting. These soil conditions provide an environment that is able to support the healthy plant growth quantified during the plant and garden health assessment.
- The overall plant survival rate, at 72%, was within the acceptable range of plant survival rates in the urban environment. Replanting recommendations for the 28% that did not survive, include using the top six performing plants for 50% of the replacements and a mix from the complete original list for the other 50% of the replacements.

- The flow monitoring equipment used was not able to measure the small flow rates present in the outlet pipe of the bioretention facility. However, comparisons between the "pre" and "post" bioretention model scenarios were able to be made based on the implementation of a man-made simulated rainfall event.
- Results indicate that peak flow rates were reduced from "pre" to "post" conditions by a range of 33% to 89%. The larger flow reductions occurred for the smaller storm events. Similar patterns were observed for the total volume, with reductions ranging from 5% to 27%. Increases in time to peak ranged from 8% for the larger events to 729% for the smaller storm events.
- A review of the overall shape of the surface runoff hydrograph indicates that the shape changed from a flashy, quick peak with minimal to no event tail to one with a smaller, delayed peak (increase in time to peak) and a more extensive tail on the hydrograph.
- The resulting hydrograph correlates to a system that responds to the bioretention facilities by shifting to an infiltration-dominated, pre-development system.

7. FUTURE RESEARCH

This study provides valuable insight into the performance of bioretention facilities and design considerations for optimal performance. The relationships between bulk density, porosity, field capacity, infiltration rate and plant and garden health were defined. The impacts of the implementation of bioretention facilities on the surface runoff hydrograph were determined. However, there is need to further enhance our understanding of the performance of bioretention practices along with other types of LID practices. Suggestions for future research include:

- Evaluation of the effect on infiltration results of flooding the entire LID practice area.
- Perform infiltration testing at strategic locations within the LID practice facility. Suggested locations include immediately adjacent to the flow inlet, adjacent to plant roots and in areas where no plants are present, further away from the flow inlet. This will allow a determination of whether infiltration is consistent across a given LID practice or if certain physical components affect infiltration rates.
- Evaluate alternate flow monitoring methods. This may include completing several man-made rainfall simulations by setting up an automated rainfall apparatus for different durations and total rainfall depths. Due to the relative low cost of performing man-made rainfall simulations, this should be done both short-term and long-term over the life of the LID practice to evaluate the lifetime performance of the system.

APPENDICES

APPENDIX A – INFILTRATION TESTING METHODS

Methodology for double-ring infiltrometer field test

A double-ring infiltrometer consists of two concentric metal rings. The rings are driven into the ground and filled with water. The outer ring helps to prevent divergent flow. The drop-in water level or volume in the inner ring is used to calculate an infiltration rate. The infiltration rate is the amount of water per surface area and time unit which penetrates the soils. The diameter of the inner ring should be approximately 50-70 percent of the diameter of the outer ring, with a minimum inner ring size of four inches. Double-ring infiltrometer testing equipment designed specifically for that purpose may be purchased. However, field testing for stormwater BMP design may also be conducted with readily available materials.

Equipment for double-ring infiltrometer test:
Two concentric cylinder rings six inches or greater in height. Inner ring diameter equal to 50-70 percent of outer ring diameter (i.e., an eight-inch ring and a 12-inch ring). Material typically available at a hardware store may be acceptable.

- Water supply,
- Stopwatch or timer,
- Ruler or metal measuring tape,
- Flat wooden board for driving cylinders uniformly into soil,
- Rubber mallet, and
- Log sheets for recording data.

Procedure for double-ring infiltrometer test

- Prepare level testing area.
- Place outer ring in place; place flat board on ring and drive ring into soil to a minimum depth of two inches.
- Place inner ring in center of outer ring; place flat board on ring and drive ring into soil a minimum of two inches. The bottom rim of both rings should be at the same level.
- The test area should be presoaked immediately prior to testing. Fill both rings with water to water level indicator mark or rim at 30-minute intervals for one hour. The minimum water depth should be four inches. The drop in the water level during the last 30 minutes of the presoaking period should be applied to the following standard to determine the time interval between readings:
  - If water level drop is two inches or more, use 10-minute measurement intervals.
  - If water level drop is less than two inches, use 30-minute measurement intervals.
- Obtain a reading of the drop in water level in the center ring at appropriate time intervals. After each reading, refill both rings to water level indicator mark or rim. Measurement to the water level in the center ring should be made from a fixed reference point and should continue at the interval determined until a minimum of eight readings are completed or until a stabilized rate of drop is obtained, whichever occurs first. A stabilized rate of drop means a difference of ¼ inch or less of drop between the highest and lowest readings of four consecutive readings.
- The drop that occurs in the center ring during the final period or the average stabilized rate, expressed as inches per hour, should represent the infiltration rate for that test location.

Methodology for percolation test
Equipment for percolation test

- Post hole digger or auger,
- Water supply,
- Stopwatch or timer,
- Ruler or metal measuring tape,
- Log sheets for recording data,
- Knife blade or sharp-pointed instrument (for soil scarification),
- Course sand or fine gravel, and
- Object for fixed-reference point during measurement (nail, toothpick, etc.).

Operating Instrucions

1. SETTING THE TIMER:
   A) PRESS THE STOP / RESET BUTTON ONCE TO RESET THE TIMER TO READ "00 00".
   B) SET THE TIMER FOR 15 MINUTES BY PRESSING MINUTES 15 TIMES UNTIL 15:00 IS DISPLAYED.

2. PLACE DOUBLE RING CUTTING BLADES ON THE AREA TO BE TESTED. SILICONE SPRAY MAY BE APPLIED TO THE CUTTER EDGES TO ALLOW EASIER AND CLEANER REMOVAL OF TOOL.

3. PUSH DOWN ON HANDLE GRIPS WHILE SLIGHTLY TURNING INSTRUNENT BACK AND FORTH* UNTIL THE SATURN RING IS AGAINST THE SOIL SURFACE.**
   *(ON TURF AREAS, EXCESSIVE TWISTING CAN ALSO CAUSE ROOTS TO TEAR AND A PLUG TO BE PULLED UPON REMOVAL OF TOOL).
   ** (DO NOT MOVE THE INSTRUMENT SIDE TO SIDE WHILE TURNING)

4. FILL BOTH THE OUTER AND INNER RING WITH CLEAN WATER UNTIL THEY SLIGHTLY OVERFLOW. (THIS IS ACCOMPLISHED EASIEST BY FILLING THE INNER RING FIRST AND ALLOWING IT TO SPILL OVER AND FILL THE OUTER RING TO THE EDGE).

5. WHEN THE POINTER REACHES THE BEGINNING OF THE INCH SCALE START THE TIMER IMMEDIATELY BY PRESSING THE START BUTTON.

6. AS THE WATER SEEPS INTO THE SOIL, THE PLASTIC BALL ATTACHED TO THE TUBE WILL MEASURE THE WATER IN INCHES AND REGISTER IT ON THE SCALE WITH THE POINTER LOCATED JUST BELOW THE TIMER.

7. AT FIFTEEN MINUTES, THE TIMER WILL START BEEPING.

8. STOP THE BEEPER BY DEPRESSING THE STOP / RESET BUTTON ON THE TIMER

9. NOTE THE POSITION OF THE POINTER ON THE SCALE. RECORD THIS NUMBER ON THE MONITORING RECORD. THIS SCALE IS IN INCHES. MULTIPLY THE INCHES REGISTERED ON THE SCALE BY FOUR TO GIVE YOU THE WATER INFILTRATION IN ONE HOUR.

10. ALSO RECORD THIS INFORMATION ON THE RECORD CHART.

Continued on next page

11. TO REMOVE THE INSTRUMENT FROM THE SOIL, USE THE HAND GRIPS TO ROTATE THE CUPS IN A TWISTING MOTION

12. THE HANDLES MAY ALSO REQUIRE A SLIGHT BUT CONSTANT TURNING WHILE LIFTING THE TOOL OUT OF THE GROUND. EXTRACT THE TOOL SLOWLY IN ORDER NOT TO DISTURB THE SOIL SURFACE.

13. IF ANY SOIL IS REMOVED USE THE PLUG PUSHER THAT IS PROVIDED WITH THE TURF-TEC INFILTROMETER TO REMOVE THE PLUG IN ONE PIECE.

14. TO START TIMER AGAIN REPEAT STEP # 1. IT IS BEST TO GET SEVERAL READINGS ON AN AREA TO GET THE AVERAGE INFILTRATION RATE.

15. IF THE INFILTRATION RATE IS SLOW, A THIRTY MINUTE OR AN HOUR LONG TEST MAY BE DESIRED, IF THE INFILTRATION RATE IS FAST (IN NEW SAND CONSTRUCTION), A FIVE MINUTE TEST MAY BE SUFFICIENT.

16. AFTER USING YOUR TURF-TEC INFILTROMETER, WASH THE CUTTER BLADES, DRY, AND SPRAY WITH SILICONE (THIS WILL HELP THE INFILTROMETER TO REMOVE A CLEAN PLUG AND PREVENT RUST).

NOTE: TIMER OPERATES ON AN A 1.5 VOLT "AAA" BATTERY AND IS GOOD FOR A LONG PERIOD. TO REPLACE BATTERY REMOVE TIMER BY LOOSINING TWO SCREWS LOCATED ON THE BACK SIDE OF THE FACE PLATE AND THEN REMOVING TIMER. REPLACE BATTERY LOCATED INSIDE TIMER BODY UNDER BATTERY COVER. BE SURE TO REPLACE BATTERY COVER WHEN NEW BATTERY IS INSTALLED AND THEN RE-ATTACH TIMER TO INFILTROMETER FACE PLATE.

APPENDIX B – GARDEN B INFILTRATION RESULTS

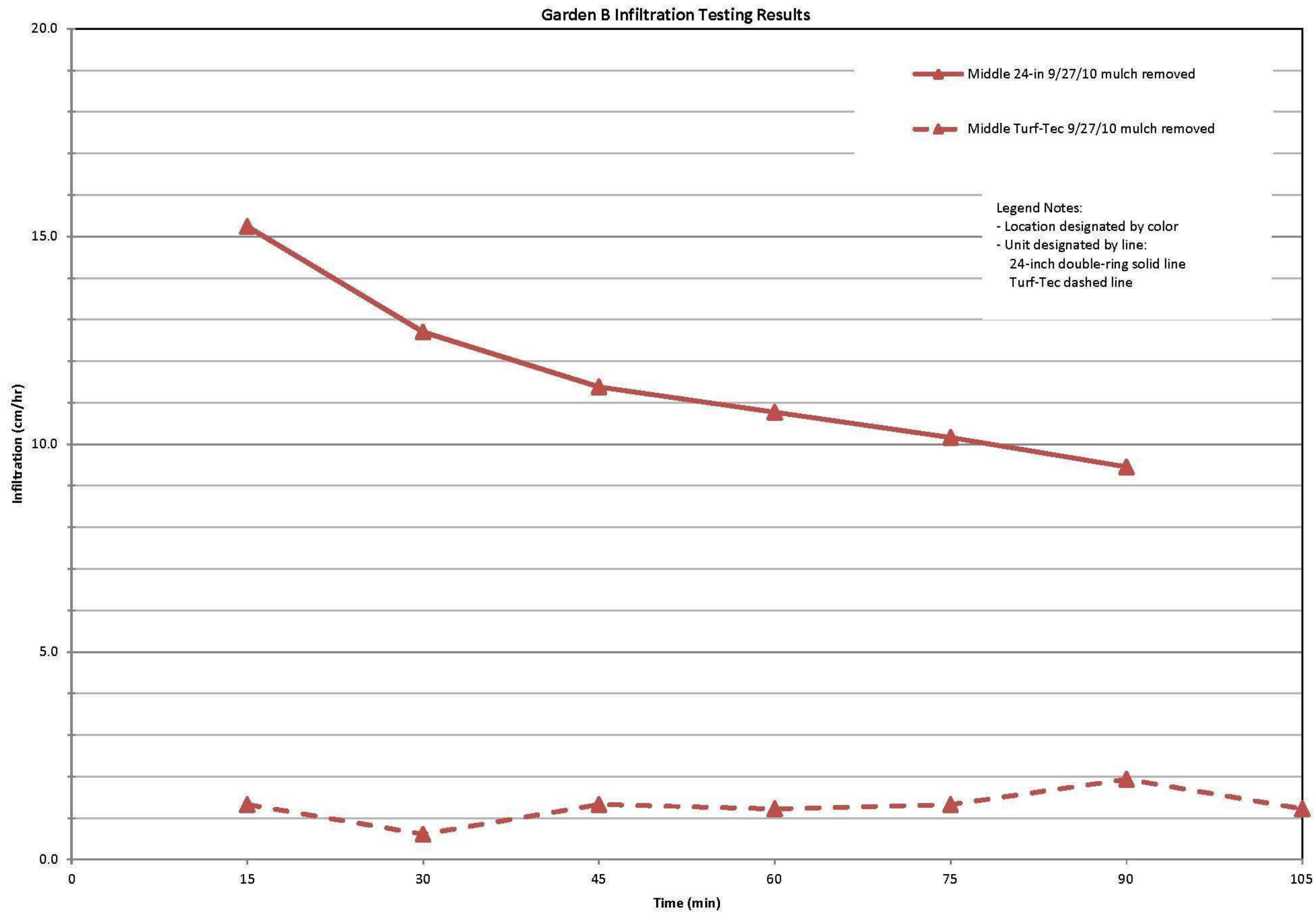


Figure B-1 Garden B infiltration testing results

APPENDIX C – MONITORING EQUIPMENT MANUFACTURER SPECIFICATIONS

Specifications

2150 Flow Module	
Size (HxWxD):	2.9 x 11.3 x 7.5 in (74 x 287 x 191 mm)
Weight:	2.0 lb (0.9 kg)
Materials of construction:	High-impact polystyrene, stainless steel
Enclosure (self-certified):	NEMA 4X, 6P (IP68)
Temperature Range:	-40° to 140° F (-40° to 60° C) operating and storage
Power Required:	12 VDC nominal (7.0 to 16.6 VDC), 100 mA typical, 1 mA standby
Power Source:	Typically, an Isco 2191 Battery Module, containing 2 alkaline or 2 rechargeable lead-acid batteries. (Other power options are available; ask for details.)
Typical Battery Life:	Using 15-minute data storage interval Energizer® Model 529 alkaline - 15 months Isco rechargeable lead-acid - 2.5 months
Program Memory:	Non-volatile programmable flash; can be updated using PC without opening enclosure; retains user program after updating.
Built-in Conversions	
Flow Rate Conversions:	Up to 2 independent level-to-area conversions and/or level-to-flow rate conversions.
Level-to-Area Conversions:	Channel Shapes - round, U-shaped, rectangular, trapezoidal, elliptical, with silt correction; Data Points - Up to 50 level-area points.
Level-to-Flow Conversions:	Most common weirs and flumes; Manning Formula; Data Points (up to 50 level-flow points); 2-term polynomial equation
Total Flow Calculations:	Up to 2 independent, net, positive or negative, based on either flow rate conversion
Data Handling and Communications	
Data Storage:	Non-volatile flash; retains stored data during program updates. Capacity 395,000 bytes (up to 79,000 readings, equal to over 270 days of level and velocity readings at 15-minute intervals, plus total flow and input voltage readings at 24-hour intervals)
Data Types:	Level, velocity, flow rate 1, flow rate 2, total flow 1, total flow 2, input voltage, temperature
Storage Mode:	Rollover; 5 bytes per reading.
Storage Interval:	15 or 30 seconds; 1, 2, 5, 15, or 30 minutes; or 1, 2, 4, 12, or 24 hours Storage rate variable based on level, velocity, flow rate, total flow, or input voltage
Data Retrieval:	Serial connection to PC or optional 2101 Field Wizard module; optional modules for spread spectrum radio; land-line or cellular modem; 1xRTT. Modbus and 4-20 mA analog available.
Software:	Isco Flowlink for setup, data retrieval, editing, analysis, and reporting
Multi-module networking:	Up to four 2100 Series Flow Modules, stacked and/or remotely connected. Max distance between modules 3300 ft (1000 m).
Serial Communication Speed:	38,400 bps

2150 Area Velocity Sensor	
Size (HxWxD):	0.75 x 1.3 x 6.0 in (19 x 33 x 152 mm)
Cable (Length x Diameter):	33 ft x 0.37 in (10 m x 9 mm) standard. Custom lengths available on request.
Weight (including cable):	2.2 lbs (1 kg)
Materials of construction:	Sensor - Epoxy, chlorinated polyvinyl chloride (CPVC), stainless steel Cable - Polyvinyl chloride (PVC), chlorinated polyvinyl chloride (CPVC)
Operating Temperature:	32° to 140° F (0° to 60° C)
Level Measurement:	Method - Submerged pressure transducer mounted in the flow stream Transducer Type - Differential linear integrated circuit pressure transducer Range (standard) 0.033 to 10 ft (0.010 to 3.05 m); (optional) up to 30 ft (9.15 m). Maximum Allowable Level 34 ft (10.5 m) Accuracy ±0.01 ft from 0.033 to 10 ft, (±0.003 m from 0.01 to 3.05 m,) Long-Term Stability ±0.023 ft/yr (±0.007 m/yr) Compensated Range 32° to 122°F (0° to 50°C)
Velocity Measurement:	Method - Doppler ultrasonic, frequency 500 kHz Typical Minimum Depth 0.08 ft (25 mm) Range -5 to +20 ft/s (-1.5 to +6.1 m/s) Accuracy (in water with uniform velocity profile, speed of sound = 4850 ft/s, for indicated velocity range) ±0.1 ft/s from -5 to 5 ft/s (±0.03 m/s from -1.5 to +1.5 m/s) ±2% of reading from 5 to 20 ft/s (1.5 to 6.1 m/s)
Temperature Measurement:	Accuracy ±3.6° F (±2° C)

2191 Battery Module	
Size (HxWxD):	6.0 x 9.6 x 7.6 in (152 x 244 x 193 mm)
Weight (without batteries):	3.2 lb (1.4 kg)
Materials of construction:	High-impact polystyrene, stainless steel
Enclosure (self certified):	NEMA 4X, 6P, (IP68)
Batteries:	Two 6-volt Energizer Model 529* alkaline (25 Ahrs capacity) or Isco Rechargeable Lead-acid (5 Ahrs capacity) recommended. *Note – Energizer 529 ER does not give specified life.

2150 Ordering Information

Contact your Teledyne Isco representative for complete ordering details and information on other 2100 Series Modules.

Description	Part No.
2150 with AV sensor, 2191 Battery Module, and Handle	68-2050-002
2150 Module with AV sensor (only)	68-2050-001
Isco Flowlink® 5 Software	68-2540-200
Energizer® Model 529 Alkaline Lantern Battery (2 required)	340-2006-02
Isco Rechargeable Lead-acid Battery (2 required)	60-2004-041
Charger for Lead-acid Batteries (holds 2 batteries)	60-2004-040

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Isco Product Data

Isco 2150 Area Velocity Flow Module

The 2150 Flow Module uses continuous wave Doppler technology to measure mean velocity. The sensor transmits a continuous ultrasonic wave, then measures the frequency shift of returned echoes reflected by air bubbles or particles in the flow.

The 2150's "smart" area velocity probe is built on digital electronics, so the analog level is digitized in the sensor itself to overcome electromagnetic interference. The probe is also factory-calibrated for 10-foot (3 meter) span at different temperatures. This built-in calibration eliminates drift in the level signal, providing long-term level stability that reduces recalibration frequency and completely eliminates span recalibration.

In field use, the 2150 is typically powered either by two alkaline, or Isco Rechargeable Lead-acid batteries, within a 2191 Battery Module. Highly efficient power management extends battery life up to 15 months at 15-minute data storage intervals. Other power options (including solar) are available.

Applications

- Portable and permanent-site AV flow monitoring for inflow and infiltration, capacity assessment, sewer overflow, and other sewer studies.
- Measuring shallow flows in small pipes. Our low-profile area velocity sensor minimizes flow stream obstruction and senses velocity in flows down to 1 inch (25 mm) in depth.

Standard Features

- Rugged, submersible enclosure meets NEMA 4X, 6P (IP68) environmental specs.
- Chemically resistant epoxy-encapsulated sensor withstands abuse, resists oil and grease fouling, and eliminates the need for frequent cleaning.
- Replaceable high-capacity internal desiccant cartridge and hydrophobic filter protect sensor reference from water entry and internal moisture.
- Pressure transducer vent system automatically compensates for atmospheric pressure changes to maintain accuracy.
- The quick-connect sensor can be easily removed and interchanged in the field without requiring recalibration.
- Up to four 2100 Series flow modules can be networked by stacking and/or extension cables.

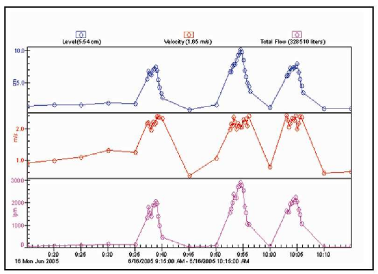
Above left: Additional modules can be added for redundant or multi-stream measuring (Isco 2110 Ultrasonic Module shown). Right: Optional mounting rings provide quick, secure sensor installation in round pipes from 6 to 80 inches (150 to 2000 mm).

Figure C-1. ISCO 2150 Area Velocity Flow Module technical specifications

Figure C-1 (cont'd)

Software Features

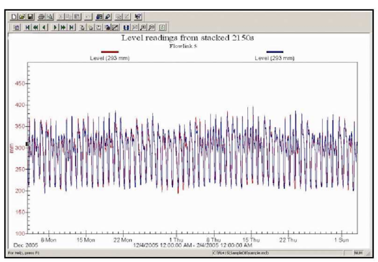
- Secure data storage. All data are continuously stored in flash memory to protect against loss in case of power failure
- Easy to upgrade. New operating software can be downloaded into non-volatile flash memory, without affecting stored program and data.
- Records and stores input voltage and temperature data.
- Variable rate data storage lets you change the data storage interval when programmed conditions occur. This feature assures maximum information about an exceptional event – such as an overflow – while conserving power and data capacity during normal conditions.
- 38,400 bps communication provides speedy setup and data retrieval.



Variable rate data storage

The 2150 flow module has the ability to automatically switch data storage rates based on varying conditions.

In the example at left, the 5-minute data storage rate automatically changed to 30 seconds when the flow rose above a programmed level.



Level stability

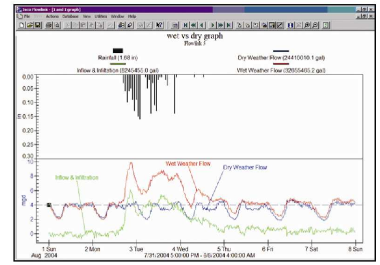
Frequent multipoint level recalibration is a requirement with other area velocity flow meters. Isco's exclusive "smart" sensor design in the area velocity probe yields exceptionally low drift in the level signal.

The 2150's factory-calibrated 3-meter span totally eliminates the need for cumbersome span recalibration in the field.

In the example at left, two area velocity probes were installed at the same site. The level readings from both sensors track closely without any drift, over an 8-week period.

Flowlink® Data Analysis

Isco Flowlink® Software is a powerful tool for analyzing flow and water quality data. It provides site setup, data retrieval, and comprehensive data analysis, as well as advanced reporting and graphing. See separate datasheets for details on Flowlink and Flowlink Pro software.



The Flowlink screen shown above gives a comparison of dry and wet weather flows, plus rainfall typical of an inflow & infiltration study

Information Delivery

Isco 2100 Series Flow Modules offer a wide variety of communication and retrieval options, to minimize the need for expensive on-site visits and confined space entry. These include:

Isco 2103 Land-line Modem Module
Reliable two-way dial-up communication between down-hole 2100 Flow Modules and your desktop computer, equipped with Isco Flowlink Software. A dial-out feature enables the system to transmit a text message alarm to your digital cell phone or pager.

Isco 2103c Cellular Modem Module
All the features of the 2103 Modem with the convenience of cell phone access. And the 2103c can automatically send data via the Internet to a designated server running Flowlink Pro software, using economical 1xRTT packet-switched data transmission.

Isco 2108 Analog Output Module
Provides current outputs for use with Isco 2100 Series Area Velocity and Ultrasonic Flow Modules. It allows easy interface with SCADA/DCS or other secondary instrument systems.

Modbus
2100 Series Flow Modules provide digital RS 232 Modbus output that can be used to interface with external communication modules, SCADA systems, or other devices.

On-site Data Retrieval

Isco Flowlink Software
Download and process data on-site. Enjoy unmatched data management capability, advanced data editing and analysis, powerful reporting and presentation choices, and a variety of downloading and data handling options.

Isco 2101 Field Wizard
A durable, weatherproof module for on-site data retrieval. Don't risk damage to your fragile notebook PC. The 2101 Field Wizard provides on-site display of current readings, information about stored data, diagnostics, and more.

Interrogate all 2100 Series Flow Modules in the stack at one time, and store more than 14 days' data from up to 20 modules!

Isco 2102 Communication Module
Connect with your Isco 2100 Series Flow Modules from the safety and convenience of your vehicle.

Digital spread-spectrum radio signals enable "drive-up" data retrieval, system configuration, and level calibration, with minimum power consumption. "Plug and Play" setup – no interfacing needed.

1.6 Technical Specifications

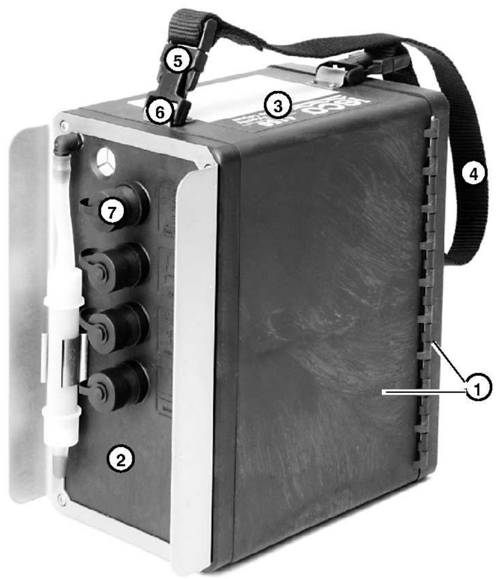


Figure 1-2 4150 Replaceable Parts

1. **Case and battery compartment door:** polystyrene.
2. **Connector panel:** Noryl
3. **Labels:** polyester
4. **Strap:** nylon
5. **Strap latches:** acetyl plastic
6. **Strap-latch retainer:** stainless steel
7. **Connector cap:** (acetyl plastic)
8. **Suspension hook:** stainless steel (not shown)

Table 1-1 4150 Flow Logger Technical Specifications	
Size	10.5 x 9.0 x 6.0 inches (26.7 x 22.9 x 15.2 centimeters)
Weight	8 pounds (3.6 kilograms), without batteries
Operating Temperature	0• to 140• F (-18• to 60• C)
Storage Temperature	-40• to 140• F (-40• to 60• C)
Enclosure	Self-certified NEMA 4X, 6
Power	Two 6-volt alkaline lantern batteries, or one 12-volt Isco 947 Lead-Acid Battery
Alkaline Battery Life	3 months with minimum level-reading intervals of 15 minutes

Figure C-2. ISCO 4150 flow logger technical specifications

Figure C-2 (Cont'd)

Table 1-2 Standard/Extended Range AV Probe Technical Specifications	
Sensor Size	$1^{3}/_{16}$" High x $1^{5}/_{8}$" Wide x $6^{5}/_{8}$" Long (3.0 x 4.1 x 16.8 cm)
Sensor Weight	Standard sensor: 2.1 pounds (0.96 kilograms) (includes 25-foot cable and connector) Extended range sensor: 3.9 pounds (1.8 kilograms) (includes 50-foot cable and connector)
Wetted Sensor Material	Polybutadiene-based polyurethane, stainless steel
Cable Length	Standard sensor: 25 feet (7.6 meters) Extended range sensor: 50 feet (15.2 meters)
Maximum Distance: (Between area velocity sensor and Flow Logger)	Standard Sensor: 75 feet (22.8 meters) with optional extension cables. Extended Range Sensor: 100 feet (30.5 meters) with optional extension cables. The distance can be extended up to 1000 feet (304.8 meters) with the optional Quick Disconnect Box.
Cable Material	PVC (polyvinyl chloride), CPVC (chlorinated polyvinyl chloride)
Operating Temperature	32• to 160• F (0• to 71• C)
Storage Temperature	-40• to 160• F (-40• to 71• C)
Level Specifications	
Level-Measurement Range	Standard sensor: 0.05 to 10.0 feet (0.015 to 3.05 meters) Extended range sensor: 0.05 to 30.0 feet (0.015 to 9.14 meters)
Maximum Allowable Level	Standard sensor: 20.0 feet (6.10 meters) Extended range sensor: 40.0 feet (12.19 meters)
Level Measurement Accuracy	Standard sensor (25• C): 0.033 to 5.0 ft: ± 0.008 ft/ft (0.01 to 1.52 m: ± 0.008 m/m) >5.0 ft: ± 0.012 ft/ft (>1.52 m: ± 0.012 m/m) Extended range sensor (25• C): Head change of 0.05 to 15.0 feet (0.015 to 4.57 meter): ± 0.03 foot (0.009 meter) Head change of 0.05 to 21.0 feet (0.015 to 6.40 meter): ± 0.09 foot (0.027 meter) Head change of 0.05 to 30.0 feet (0.015 to 9.14 meter): ± 0.30 foot (0.091 meter) (*Specifications include nonlinearity, repeatability, and hysteresis, but do not include a temperature coefficient.*)
Compensated-Temperature Range	32• to 100• F (0• to 38•C)
Temperature Error (over-compensated-temperature range, per degree of temperature change)	Standard sensor: 0.05 to 4.0 ft (0.015 to 1.22 m): ± 0.005 ft/•F (± 0.0027 m/•C) 4.0 to 10.0 ft (1.22 to 3.05 m): ± 0.007 ft/•F (± 0.0038 m/•C) Extended range sensor: 0.05 to 30.0 ft (0.015 to 9.14 m): ± 0.008 ft/•F (± 0.0044 m/•C)

Figure C-2 (cont'd)

Table 1-2 Standard/Extended Range AV Probe Technical Specifications (Continued)	
Velocity Measurement	
Minimum Depth for Velocity Measurement	2, 3, 4 inches (50, 75, 100 mm) Selected during programming
Range	-5 to +20 feet per second (-1.5 to +6.1 meters per second)
Accuracy	-5 to +5 ft/s (-1.5 to +1.5 m/s): ± 0.1 ft/s (± 0.03 m/s) 5 to 20 ft/s (1.5 to +6.1 m/s): 2% of reading
Resolution	± 0.024 feet per second (± 0.0073 meters per second)
Frequency	500KHz
Nose Angle	35 degrees from horizontal

Table 1-3 Low Profile AV Probe Technical Specifications	
Weight	2.1 lbs (.95 kg) including cable and connector
Sensor Dimensions	Length: 6.00 inches (15.2 cm) Width: 1.31 inches (3.3 cm) Height: 0.75 inches (1.9 cm)
Nose Angle	110° from horizontal
Wetted Sensor Material	Epoxy, chlorinated polyvinyl chloride (CPVC), Stainless-steel
Cable Material	Polyvinyl chloride (PVC) Chlorinated polyvinyl chloride (CPVC)
Cable Length	25 ft (7.6 m)
Maximum Distance (between sensor and module)	75 ft (22.8 m) with optional extension cables. The distance can be extended up to 1000 ft (300 m) with the optional Quick Disconnect Box.
Operating Temperature	32° to 122°F (0° to 50°C)
Storage Temperature	-40° to 160°F (-40° to 71°)
Level Specifications	
Level Measurement Range	0.033 to 10.0 ft (0.01 to 3.05 m)
Maximum Allowable level	20 ft (6.1 m)
Level Measurement Accuracy	0.033 to 5.0 ft: ± 0.008 ft/ft (0.01 to 1.52 m: ± 0.008 m/m) >5.0 ft: ± 0.012 ft/ft (>1.52 m: ± 0.012 m/m) Accuracy per foot of change from calibrated depth @77°F (25°C). Includes non-linearity and hysteresis.
Temperature Coefficient	± 0.0023 ft/°F (± 0.0013 m/°C) Maximum error within operating temperature range at zero pressure (per degree of change from calibration temperature).
Maximum Long-term Drift	0.033 ft (± 0.010 m)

Figure C-2 (cont'd)

Table 1-3 Low Profile AV Probe Technical Specifications (Continued)	
Velocity Measurement	
Velocity Measurement Method	Doppler Ultrasonic
Frequency	500 kHz
Transmission Angle	20° from horizontal
Typical minimum depth for velocity measurement	1 inch (25 mm)
Range	-5 to +20 ft/s (-1.5 to +6.1 m/s)
Velocity Accuracy	-5 to +5 ft/s (-1.5 to +1.5 m/s): ± 0.1 ft/s (± 0.03 m/s) 5 to 20 ft/s (1.5 to 6.1 m/s): 2% of reading Velocity accuracy for a uniform velocity profile in water with a speed-of-sound of 4850 ft/s.

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674 Rain Gauge

Connects directly to 6712 and Avalanche Samplers, 4200 Flow Meters, and 4100 Flow Loggers

The Isco 674 Rain Gauge is a precision instrument that uses a tipping bucket design for accurate rainfall measurement. It has an 8 inch diameter orifice and is factory-calibrated to tip at either 0.01 inch or 0.1 mm of rainfall. With a 674 Rain Gauge connected, an Isco flow meter or sampler will:

- Plot graphs and print reports of rainfall data on the flow meter's built-in printer
- Store rainfall data in internal memory for retrieval and analysis with Isco Flowlink® Software
- Activate sampling based on rainfall

Standard Features

- Three-point leveling and integral bubble level make it easy to align the rain gauge for maximum accuracy.
- Sapphire jewel bearings on the tipping bucket are spring-loaded to prevent damage to the bearings and ensure consistent operation over a wide temperature range.
- Screens cover all openings to prevent leaves, insects, and other debris from clogging the gauge.
- Included 50-foot cable connects directly to compatible Isco flow meters and samplers.

Applications

- Stormwater runoff monitoring
- Inflow and infiltration studies
- Combined sewer overflow monitoring
- cMOM and CSO/SSO programs (Sewer overflow monitoring and prevention)
- General rainfall measurement

Options and Accessories

- English units - tips every 0.01 in. of rainfall
- Metric units - tips every 0.1 mm of rainfall

Specifications

Type:	Tipping bucket
Compatible equipment:	Isco 6700, 6712, and Avalanche Samplers, 4200 Series Flow Meters, 4100 Series Flow Loggers
Connect cable:	50 ft. (15.2 m), 2 conductor with 4-pin plug
Bearings:	Spring-loaded sapphire jewel
Orifice Diameter:	8 in. (20 cm)
Sensitivity:	English - 0.01 inch; Metric 0.1 mm
Accuracy:	English - ±1% at 2 in/hour; +3%/-4% up to 5 in/hour. Metric - ±1.5% at 5 cm/hour; +3.5%/-9% up to 13 cm/hour
Capacity:	English – 22 inches/hour; Metric – 38 cm/hour
Output Signal:	Contact closure of at least 50 millisecond duration
Switch Type:	Normally open, encapsulated reed; 10 watts, 200V DC, 0.5 A maximum
Height:	13 in. (33 cm)
Diameter:	9.5 in. (24 cm) (at mounting base)
Weight:	10 lbs. (4.5 kg)
Operating Temperature:	32° to 140°F (0° to 60°C)
Storage Temperature:	-40° to 140°F (-40° to 60°C)

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Figure C-3. ISCO 674 Rain Gauge technical specifications

REFERENCES

REFERENCES

Abi Aad, M.P., Suidan, M.T., & Shuster, W.D. (2010). Modeling techniques of best management practices: rain barrels and rain gardens using EPA SWMM-5. J. Hydrol. Eng. 15, SPECIAL ISSUE: Low Impact Development, Sustainability Science, and Hydrological Cycle, 434-443.

Ahiablame, L.M., Engel, B.A., & Chaubey, I. (2012a). Effectiveness of low impact development practices: literature review and suggestions for future research. Water Air Soil Pollut. 223:4253-4273. doi: 10.1007/s11270-012-1189-2.

Ahiablame, L.M., Engel, B.A., & Chaubrey, I. (2012b). Representation and evaluation of low impact development practices with L-THIA-LID: An example for site planning. Environment and Pollution, Volume 1(2). doi: 10.5539/ep.v1n2p1

Ahiablame, L.M., Engel, B.A., & Chaubrey, I. (2013). Effectiveness of low impact development practices in two urbanized watersheds: retrofitting with rain barrel/cistern and porous pavement. Journal of Environmental Management, 119, 151-161.

Albiach, R., Canet, R., Pomares, F., & Ingelmo, F. (2001). Organic matter components and aggregate stability after the application of different amendments to a horticultural soi. Biores. Tech. 76(2): 125-129.

Ayers, M., Brown, R., & Oberts, G., (1985). Runoff and Chemical Loading in Small Watersheds in the Twin Cities Metropolitan Area, Minnesota. U.S. Geological Survey Water Resources Investigations Report 85-4122.

Bannerman, R.A., Legg A., & Greb, S., (1996). Quality of Wisconsin Stormwater 1989-1994. U.S. Geological Survey. Reston, VA. Open File Report 96-458.

Barco, J., Wong, K.M., & Stenstrom, M.K. (2008). Automatic calibration of the U.S. EPA SWMM Model for large urban catchment. Journal of Hydrologic Engineering 134(4), 466-474.

Barrett, M.E., Limouzin, M. & Lawler, D.F. (2013). Effects of media and plant selection on biofiltration performance. J. Environ. Eng. 139:462-470.

Beatty, R., & McLindin, M. (2012). Rainwater Harvesting and Urban Design in Australia. Conference proceedings from Water Environment Federation’s Annual Technical Exhibition and Conference, 2012.

Beckman, S., Jones, S., Liburdy, K., & Peters, C. (1997). Greening our Cities: An Analysis of the Benefits and Barriers Associated with Green Roofs. Portland State University, Planning Workshop, 1997.

Benke, A., Willeke, E., Parrish, F., & Stites, D., (1981). Effects of Urbanization on Stream Ecosystems. Office of Water Research and Technology. US Department of the Interior. Completion Report Project No. A-055-GA.

Booth, D.B., Karr, J.R., Schauman, S., Konrad, C.P., Morley, S.A., Larson, M.G, & Burges, S. J. (2004). Reviving urban streams: land use, hydrology, biology, and human behavior. Journal of the American Water Resources Association 40:1351-1364.

Bouwer, Herman. (1986). Chapter 32, Intake Rate: Cylinder Infiltrometer of the Methods of Soil Analysis Part 1 Physical and Mineralogical Methods Second Edition. Number 9 (Part 1) in the series Agronomy by American Society of Agronomy, Inc. and Soil Science Society of America, Inc. 1986.

Bragg, O.M., Black A.R., Duck, R.W., & Rowan, J.S., (2005). Approaching the Physical-Biological Interface in Rivers: a Review of Methods for Ecological Evaluation of Flow Regimes. Progress in Physical Geography 29(4): 506-531.

Brandes, D., Cavallo, G.J., & Nilson, M.L., (2005). Base Flow Trends in Urbanizing Watersheds of the Delaware River Basin. Journal of the American Water Resources Association, 41: 1377-1391.

Bratieres, K., Fletcher, T.D., Deletic, A., Zinger, Y. (2008). Nutrient and sediment removal by stormwater biofilters: a large-scale design optimization study. Water Research 42, 3930-3940.

Brown, R.A., & Hunt, W.F., (2011a). Impacts of media depth on effluent water quality and hydrologic performance of under-sized bioretention cells. Journal of Irrigation and Drainage Engineering. 137 (3), 132-143.

Brown, R.A., & Hunt, W.F., (2011b). Underdrain configuration to enhance bioretention infiltration to reduce pollutant loads. Journal of Environmental Engineering. 137 (11), 1082-1091.Breen, P.F. (1990). A mass balance method for assessing the potential of artificial wetlands for wastewater treatment. Water Res. 24, 689-697.

Brown, R.A., Skaggs, R.W., & Hunt, W.F., (2013). Calibration and validation of DRAINMOD to model bioretention hydrology. Journal of Hydrology. 486 (2013) 403-442.

Brown, R.R., Keath, N, & Wong, T.H.F., (2009). Urban Water Management in Cities: Historical, Current and Future Regimes. Water Science and Technology, 59 (5): 847-855.

Bunn, S.E., & Arthington, A.H., (2002). Basic Principes and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity. Environmental Management 30(4): 492-507.

Burns, M.J., Fletcher, T.D., Walsh C.J., Ladson A.R., & Hatt, B.E, (2012). Hydrologic Shortcomings of Conventional Urban Stormwater Management and Opportunities for Reform. Landscape and Urban Planning 106: 230-240.

Burrian, Steven J., et al. (1999). "The Historical Development of Wet-Weather Flow Management." EPA, National Risk Management Research Laboratory, Cincinnati, OH. Document No. EPA/600/JA-99/275.

Cady, S., & Pierson, G. S., (1899). The Separate System of Sewerage, Its Theory and Construction. New York: Van Nostrand.

Cambez, M.J., Pinho, J., & David, L.M. (2008). Using SWMM 5 in the continuous modeling of stormwater hydraulics and quality. 11th International Conference on Urban Drainage, Edinburgh, Scotland, UK. 2008

Carpenter, D.D., & Hallam, L. (2010). Influence of Planting Soil Mix Characteristics on Bioretention Cell Design and Performance. Journal of Hydrologic Engineering, 15(6), 404-416. doi: 10.1061/(asce)he.1943-5584.0000131

Carter, T. et al. (2009). Beyond the urban gradient: barriers and opportunities for timely studies of urbanization effects on aquatic ecosystems. Journal of the North American Benthological Society, 28(4): 1038-1050.

Castleton et al. (2010). Green roofs, building energy savings and the potential for retrofit. Energy and Buildings, vol. 1582-1591, 2010.

Center for Watershed Protection, (2003). Watershed Protection Research Monograph No. 1: Impacts of Impervious Cover on Aquatic Ecosystems. Center for Watershed Protection.

Chessman, B., Hutton, P, & Burch, J. (1992). Limiting nutrients for periphyton growth in sub-alpine forest, agricultural and urban streams. Freshwater Biology 28: 349-361.

Chow, V.T. (1958). Open-Channel Hydraulics. McGraw Hill Book Company. Library of Congress Catalog Card Number 58-13860.

Coleman, J.C., Miller, M.C., & Mink, F.L., (2008). Hydrologic Disturbance Reduced Biological Integrity in Urban Streams. Environmental Monit. Assess, Published in 2010 172: 663-687.

Collier, K. et al. (2011). Influences of catchment and corridor imperviousness on urban stream macroinvertebrate communities at multiple spatial scales. Hydrobiologia, 664: 35-50.

Cresswell, D. (2007). Characterisation of Mineral Wastes, Resources and Processing technologies – Integrated waste management for the production of construction material. University of Sheffield, 2007.

Cunningham, S.D., & Ow, D.W. (1996). Promises and prospects of phytoremediation. Plant Physiol. 110, 715-719.

Davis, A.P. (2007). Environmental Engineering Science. October 2007, 24(8): 1048-1064. Doi:10.1089/ees.2006.0190.

Davis, A. P. (2007). Field performance of bioretention: Water quality. Environ. Eng. Sci., 24(8), 1048-1063.

Davis, A.P. (2008). Field performance of bioretention: Hydrology impacts. Journal of Hydrol. Eng., 13(2), 90-95.

Davis, A.P., Hunt, W.F., Traver, R.G., & Clar, M., (2009). Bioretention Technology: Overview of Current Practice and Future Needs. Journal of Environmental Engineering, 2009, 135:109-117.

Davis, A.P., Shokouhian, M., Sharma, H., & Minami, C. (2001). Laboratory study of biological retention for urban stormwater management. Water Environment Research, 73(1), 5-14.

Davis, A.P., Shokouhian, M., Sharma, H., Minami, C. & Winogradoff, D. (2003). Water quality improvements through bioretention: Lead, copper and zinc removal. Water Environment Research, 75(1), 73-82.

Davis, A.P., Shokouhian, M., Sharma, H., and Minami, C. (2006). Water quality improvements through bioretention: nitrogen and phosphorous remomval. Water Environ. Res. 78(3), 284.

Davis, A.P., Traver, R.G., Hunt, W.F., Lee, R., Brown, R.A., & Olszewski, J.O., (2012). Hydrologic performance of bioretention stormwater control measures. Journal of Hydrologic Engineering 17(5):604-614.

Daddow, R.L., & Warrington, G.E., (1983). Growth-Limiting Soil Bulk Densities as Influenced by Soil Texture. Watershed Systems Development Group Report WSGN-TN-005, USDA Forest Service. January 1983.

Denich, C., & Bradford, A. (2010). Estimation of evaportranspiration from bioretention areas using weighing lysimeters. Journal of Hydrologic Engineering 15(6):522-530.

Denman, L., May, P., & Breen, P.F. (2007). An investigation of the potential to use street trees and their root zone soils to remove nitrogen from urban stormwater. Aust. J. Water Resour. 10, 303-311.

Dietz, M.E. & Clausen, J.C. (2005). A field evaluation of rain garden flow and pollutant treatment. Water, Air, Soil Pollut., 167, 123-138.

Dietz, M.E. & Clausen, J.C. (2006). Saturation to improve pollutant retention in a rain garden. Environ. Sci. Technol., 40, 1335-1340.

Dorman, T., M. Frey, J. Wright, B. Wardynski, J. Smith, B. Tucker, J. Riverson, A. Teague, & K. Bishop. (2013). San Antonio River Basin Low Impact Development Technical Design Guidance Manual, v1. San Antonio River Authority, San Antonio, TX.

Dussaillant, A.R., Wu, C.H., & Potter, K.W. (2004). Richards equation model of a rain garden. Journal of Hydrologic Engineering, ASCE, 9(3), 219.

Eichenwald, Z. & McGarity, A. (2010) Watershed-Based Optimal Stormwater Management: Part 2—Hydrologic Modeling of LID/BMP Sites on Little Crum Creek in Suburban Philadelphia. World Environmental and Water Resources Congress 2010: pp. 2522-2530. doi: 10.1061/41114(371)260

Emerson, C.H., & Traver, R.G., (2008). Multi-year and seasonal variation of infiltration from stormwater best management practices. Journal of Irrigation and Drainage Engineering 134(5): 598-605.

EPA, (1994). Combined Sewer Overflow (CSO) Control Policy. Federal Register, 59 FR 18688. April 19, 1994.

EPA, (1999). United States Environmental Protection Agency Storm Water Technology Fact Sheet, Bioretention. USEPA, Office of Water, September 1999. EPA 832-F-99-01.

EPA, (2004)."Report to Congress: Impacts and Control of CSOs and SSOs." August 2004. Document No. EPA-833-R-04-001.

EPA, (2008). Managing Wet Weather with Green Infrastructure Municipal Handbook, Rainwater Harvesting Policies. December 2008. Document number: EPA-833-F-08-010.

EPA, (2012). http://www.epa.gov/caddis/ssr_flow_int.html. Last Accessed December 6, 2012.

EPA, (2014). United States Environmental Protection Agency Stormwater Management Model Users Manual. Last accessed online: November 2014.)

Ermilio, J.R. & Traver, R.G. (2006). Hydrologic and pollutant removal performance of a bio-infiltration BMP. Proc. World Environmental and Water Resources Congress, ASCE. Reston, VA.

Evett, J., Love, M., & Gordon, J., (1994). Effects of Urbanization and Land use Changes on Low Stream Flow. North Carolina Water Resources Research Institute. Report No. 284.

Fetter, C.W., 1994. Applied Hydrogeology, 3rd Edition.

Gregory, J.M., Dukes, M.D., Jones, P.H., & Miller, G.L. (2006). Effect of urban soil compaction on infiltration rate. J. Soil and Water Cons. 61(3): 117-124.

Guan, M., Sillanpaa, N., & Koivusalo, H. (2014). Modeling and assessment of hydrological changes in a developing urban catchment. Hydrological Processes, 10.1002/hyp.10410.

Hatt, B.E., Fletcher, T.D., Walsh, C.J., & Taylor, S.L. (2004). The influence of urban density and drainage infrastructure on the concentrations and loads of pollutants in small streams. Environmental Management 34:112-124.

Hatt, B.E., Fletcher, T.D., & Deletic, A. (2009a). Hydrologic and pollutant removal performance of stormwater biofiltration systems at field scale. Journal of Hydrology 365, 310-321.

Hatt, B.E., Fletcher, T.D., & Deletic, A. (2009b).Pollutant removal performance of field-scale stormwater biofiltration systems. Water Sci. Technol., 59(8), 1567-1576.

Henderson, C., Greenway, M. & Phillips, I. (2007). Removal of dissolved nitrogen, phosphorous and carbon from stormwater by biofiltration mesocosms. Water Sci. Technol. 55, 183-191.

Hollis, F., (1975). The Effects of Urbanization on Floods of Different Recurrence Intervals. Water Resources Research 11: 431-435.

Hsieh, C.H., Davis, A.P., & Needleman, B.A. (2007). Bioretention column studies of phosphorous removal from urban stormwater runoff. Water Environ. Res., 79(2), 177-184.

Hsieh, C.H., & Davis, A.P. (2005a). Evaluation and optimization of bioretention media for treatement of urban storm water runoff. J. Environ. Eng. 131(11), 1521.

Hunt, W.F., Jarrett, A.R., Smith, J.T., & Sharkey, L.J. (2006). Evaluating bioretention hydrology and nutrient removal at three field sites in North Carolina. Journal of Irrigation and Drainage Engineering-Asce, 132(6), 600-608. doi: 10.1061/(asce)0733-9437(2006)132:6(600).

Hunt, W.F., Smith, J.T., Jadlocki, S.J., Hathaway, J.M. & Eubanks, P.R. (2008). Pollutant removal and peak flow mitigation by a bioretention cell in urban Charlotte, NC. Journal of Environmental Engineering, 134(5), 403-408.

Jang, S., Cho, M., Yoon, J., Yoon, Y., Kim, S., Kim, G., Kim, L., & Aksoy, H. (2007). Using SWMM as a tool for hydrologic impact assessment. Desalination 212(1-3), 344-356.

Kauffman, G.J., Belden, A.C., Vonck, K.J., & Homsey, A.R., (2009). Link between Impervious Cover and Base Flow in the White Clay Creek Wild and Scenic Watershed in Deleware. Journal of Hydrologic Engineering 14: 324-334.

Konrad, C.P., & Booth, D.B., (2002). Hydrologic Changes in Urban Streams and their Ecological Significance. American Fisheries Society Symposium. American Fisheries Society, 47: 157-177.

Krebs, G., Kokkonen, T., Valtanen, M., Koivusalo, H., & Setala, H., (2013). A high resolution application of stormwater management model (SWMM) using genetic parameter optimization. Urban Water Journal, 10.1080/1573062X.2012.739631, 394-410.

Li, H., & Davis, A.P., (2008). Urban particle capture in bioretention media I: laboratory and field studies. Journal of Environmental Engineering 134(6), 409-418.

Li, H., Sharkey, L.J., Hunt, W.F., Davis, A.P., (2009). Mitigation of impervious surface hydrology using bioretention in North Carolina and Maryland. Journal of Hydrologic Engineering, 14:407-415.

Liu, J., Sample, D.J., Bell, C., & Guan, Y., (2014). Review and research needs of bioretention used for the treatment of urban stormwater. Water 2014, 6, 1069-1099; doi: 10.3390/w6041069.

Long et al., (2006). Green Roof Media Selection for the Minimization of Pollutant Loadings in Roof Runoff. Penn State University, Penn State Harrisburg, 2006.

Lucas, W.C., & Greenway, M., (2008). Nutrient retention in vegetated and nonvegetated bioretention mesocosms. J. Irrig. Drain. Eng., 134(5), 613-623.

MDEQ, (2014). Water Quality and Pollution Control in Michigan 2014 Sections 303(d), 305(b) and 314 Integrated Report. Michigan Department of Environmental Quality Water Resources Division. March 2014; WRD-14/001.

Molineux et al. (2009). Characterising alternative recycled waste materials for use as green roof growing media in the U.K. Ecological Engineering, vol. 35, pp. 1507-1513, 2009.

Morse, C.C., Horyn, A.D., & Cronan, C., (2003). Impervious Surfaces Area as a Predictor of the Effects of Urbanization on Stream Insect Communities in Maine, U.S.A. Environmental Monitoring and Assessment 89: 95-127.

Neilson, I. & Turney, D., (2010). Green Infrastructure Optimization Analyses for Combined Sewer Overflow (CSO) Control. Low Impact Development 2010: pp. 1533-1541. doi: 10.1061/41099(367)132

NRDC. (1999). Stormwater Strategies: Community Responses to Runoff Pollution. National Resources Defense Council. www.igc.apc.org/nrdc/nrdcpro/storm/stoinx.html.

Olson, N.C., Gulliver, J.S., Nieber, J.L., & Kayhanian, M. (2013). Remediation to improve infiltration into compact soils. Journal of Environmental Management 117: 85-95.

Passeport, E., Hunt, W.F., Line, D.E., Smith, R.A., & Brown, R.A., (2009). Field study of the ability of two grassed bioretention cells to reduce storm-water runoff pollution. Journal of Irrigation and Drainage Engineering. 135 (4), 505-510.

Paul, M.J., & Meyer, J.L., (2001). The ecology of urban streams. Annual Review of Ecology and Systematics 32: 333-365.

Paul, M., Leigh, D., & Lo, C. (2001b). Urbanization in the Etowwah River Basin: effects on stream temperature and chemistry. Proceedings of the 2001 Georgia Water Resources Conference. University of Georgia, Athens, GA.

Peck, S., & Kuhn, M., (2014). Design Guidelines for Green Roofs. Web access via: http://www.cmhc-schl.gc.ca/en/inpr/bude/himu/coedar/upload/Design-Guidelines-for-Green-Roofs.pdf. Last accessed April, 2015.

Perry, Kevin. (2009). Presentation at Managing Wet Weather with Green Infrastructure. A Workshop for Technical, Regulatory, Planning and Design Professionals. Hartford, CT. July 8, 2009.

Poff, et al., (2009). The Ecological Limits of Hydrologic Alteration (ELOHA): a New Framework for Developing Regional Environmental Flow Standards. Freshwater Biology, J.1365-2427.2009.02204.

Price, K., (2011). Effects of Watershed Topography, Soils, Land Use, and Climate on Baseflow Hydrology in Humid Regions: A Review. Progress in Physical Geography, 35: 465-492.

Prince George's County, (2007). Bioretention Manual. Environmental Services Division, Department of Environmental Resources, Revised December 2007.

Rabeni, C.F., & Wallace, G.S., (1998). The Influence of Flow Variation on the Ability to Evaluate the Biologocical Health of Headwater Streams. Hydrology, Water Resources and Ecology in Headwaters. International Association of Hydrological Sciences Press, IAHS Publication 248, Wallingford, Oxfordshire, UK.

Razzaghmanesh, M., Beecham, S., & Kazemi, F. (2014). Impact of green roofs on stormwater quality in a south Australian urban environment. Sci. Total Environ. 470-471, 651-659.

Read, J., Wevill, T., Fletcher, T., and Deletic, A. (2008). Variation among plant species in pollutant removal from stormwater in bioinfiltration systems. Water Res., 42(4-5), 893-902.

Reddy, K.R., Xie, T., & Dastgheibi, S., (2014). Removal of heavy metals from urban stormwater runoff using different filter materials. Journal of Environmental Chemnical Engineering, Vol 2(1): 282-292.

Rosa, D., Clausen, J., & Dietz, M., (2015). Calibration and verification of SWMM for low impact development. JAWRA Journal of the American Water Resources Association, 10.1111/jawr.12272.

Roy, A.H., Freeman, M.C., Freeman, B.J., Wenger, S.J., Ensign, W.E., & Meyer, J.L., (2005). Investigating Hydrologic Alteration as a Mechanism of Fish Assemblage Shifts in

Schneider, Bill., (2006). Personal conversation with Bill Schneider with Wildtype Design, Native Plants and Seeds LTD.

Schnoor, J.L., Licht, L.A., McCutcheon, S.C., Woolfe, N.L. & Carreira, L.H., (1995). Phytoremediation of organic and nutrient contaminants. Environ. Sci. Technol. 29(7), 318A-323A.

Schueler, T., & Claytor, R., (2000). 2000 Maryland Stormwater Design Manual Volumes I and II. Center for Watershed Protection and Maryland Department of the Environment. Ellicott City, Maryland.

SEMCOG, (2008). Low Impact Development Manual for Michigan: A Design Guide for Implementers and Reviewers. SEMCOG information Center, 535 Griswold Street, Suite 300, Detroit, MI. 48226.Management and Opportunities for Reform. Landscape and Urban Planning 106: 230-240.

Shuster, W.D., Gehring, R., & Gerken, J., (2007). Prospects for enhanced groundwater recharge via infiltration of urban storm water runoff: a case study. Journal of Soil and Water Conservation 62.3; 129-137.

Simmons, D.L., & Reynolds, R. J., (1982). Effects of urbanization on base flow of selected south-shore streams, Long Island, New York. Water Resources Bulletin; 18:797-805.

Speak, A.F., Rothwell, J.J., Lindley, S.J., & Smith, C.L., (2014). Metal and nutrient dynamics on an aged intensive green roof. Environ. Pollut. 184, 33-43.

Stephnuck, K., Crunkilton, R., & Wang, L., (2002). Impacts of Urban Landuse on Macroinvertebrate Communities in Southeastern Wisconsin Streams. Journal of the American Water Resources Association 38: 1041-1051.

Sun, N., Hall, M., Hong, B., & Zhang, L., (2012). Impact of SWMM catchment discretization: case study in Syracuse, New York. Journal of Hydrologic Engineering, 10.1061/(ASCE)HE.1943-5584.0000777, 223-234.

Sun, X., & Davis, A.P., (2007). Heavy metal fates in laboratory bioretention systems. Chemosphere 66, 1601-1609.

Sun, Y., Wei, X., & Pomeroy, C.A., (2011). Global analysis of sensitivity of bioretention cell design elements to hydrologic performance. Water Science and Engineering 4(3), 246-257SUNY, 2015. The SUNY College of Environmental Science and Forestry (ESF) Department of Environmental Resources Engineering. Website: http://www.esf.edu/ere/endreny/GICalculator/Acknowledgements.html. Last accessed March 2015.

Tetra Tech, (2010). Michigan Avenue Bioretention Quality Assurance Project Plan for Hydrologic and Environmental Monitoring.

Tetra Tech, (2011). Michigan Avenue Bioretention Facilities Final Project Report. June 2011.

Thompson, A.M., Paul, A.C., & Balster, N.J., (2008). Physical and Hydraulic Properties of Engineered Soil Media for Bioretention Basins. Transactions of the ASABE, 2008 American Society of Agricultural and Biological Engineers. Vol 51(2) 499-514.

Tobio, J., Maniquiz-Redillas, M., & Kim, L. (2015). Optimization of the design of an urban runoff treatment system using stormwater management model (SWMM). Desalination and Water Treatment, 10.1080/19443994.2014.922288, 3134-3141.

Trowdale, SA, & Simcock, R. (2011). Urban stormwater treatment using bioretention. Journal of Hydrology 397:167-174.

Tsihrintzis, V.A. & Hamid, R. (1998). Runoff quality prediction from small urban catchments using SWMM. Hydrologic Processes 12(2), 311-329.

TWDB., (2005). The Texas Manual on Rainwater Harvesting. Texas Water Development Board, Third Edition, 2005.Vijayaraghavan, K., Joshi, U.M. & Balasubramanian, R. (2012). A field study to evaluate runoff quality from green roofs. Water Res. 46, 1337-1345.

UN-Habitat, (2012). website: http://www.unhabitat.org/cdrom/docs/WUF1.pdf. Last Accessed December 6, 2012.

UNHSC, (University of New Hampshire Stormwater Center) (2006). 2005 Data Report, Durham, NH: CICEET.

USGS, (2001). The Quality of our Nation's Waters: Nutrients and Pesticides. USGS. FS-047-01.

USEPA, (2014). Website: http://water.epa.gov/polwaste/npdes/swbmp/Dry-Detention-Ponds.cfm. Last accessed August 2014.

US Environmental Protection Agency, (2012). website http://www.epa.gov/caddis/ssr_flow_int.html. Last Accessed December 6, 2012.

Vicars-Groening, J., & Williams, H.F., (2007). Impact of urbanization on storm response of White Rock Creek, Dallas, TX. Environmental Geology, 51: 1263-1269.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., & Morgan II, R.P., (2005). The urban stream syndrome: current knowledge and the search for a cure. Journal of North American Benthological Society, 2005, 24(3); 706-723.

Walsh, C.J., Fletcher, T.D., & Burns, M.J., (2012). Urban Stormwater Runoff: A New Class of Environmental Flow Problem. Last accessed via: www.plosone.org in November 2014.

Walsh, C.J., Sharpe, A.K., Breen, P.F., & Sonneman, J.A., (2001). Effects of Urbanization on Streams in the Melbourne Region. Victoria, Australia. I. Benthic Macroinvertebrate Communities. Freshwater Biology 46: 535-551.

Weinstein, N., (2008). Tenth Anniversary Letter from the Executive Director. Low Impact Development Center. May 2008.

Wernick, B.G., Cook, K.E., & Schreier, H. (1998). Land Use and Streamwater Nitrate-N Dynamics in an Urban-rural Fringe Watershed. Journal of the American Water Resources Association 34(3): 639-650.

Williams, E.S. & Wise, W.R., (2006). Hydrologic impacts of alternative approaches to storm water management and land development. J. Am. Water Resour. Assoc., 42(2), 433-455.

Woods-Ballard, B.K., et al. (2007). The SUDS Manual. CIRIA (C697), London and Dundee.

Wolverton, B.C., & McDonald-McCaleb, R.C., (1986). Biotransformation of Priority Pollutants Using Biofilms and Vascular Plants. Journal of the Mississippi Academy of Sciences. Vol XXXI, pp. 79-89.

Zhang, S., & Guo, Y., (2012). An explicit equation for estimating the stormwater capture efficiency of rain gardens. Journal of Hydrologic Engineering 18(12): 1739-1748.

Zhang, S. & Guo, Y., (2014). Stormwater capture efficiency of bioretention systems. Water Resour. Manage. 28:149-168. doi: 10.1007/s11269-013-0477-y.

Zimmerman, M.J., Barbaro, J.R., Sorenson, J.R., & Waldron, M.C., (2010). Effects of selected low-impact-development (LID) techniques on water quality and quantity in the Ipswich River Basin, Massachusetts—Field and modeling studies: U.S. Geological Survey Scientific Investigations Report 2010–5007, 113 p.