December 2020

Retrospective Analysis of Hydrologic Performance of Green Infrastructure Systems of the Save The Rain (STR) Program in Syracuse, New York

Priyanka Rajashekar
Syracuse University

Recommended Citation

Rajashekar, Priyanka, "Retrospective Analysis of Hydrologic Performance of Green Infrastructure Systems of the Save The Rain (STR) Program in Syracuse, New York" (2020). *Theses - ALL*. 458.
https://surface.syr.edu/thesis/458

Abstract

Combined sewer systems and urbanization are significant concerns confronted by many aging cities, including the City of Syracuse, New York. This study addresses the role of impervious surfaces in the direct discharge of surface runoff, domestic and industrial wastewaters into Onondaga Lake and tributaries during wet weather events. Onondaga County addressed the combined surface overflow (CSO) problem in 2009 through a stormwater management program known as "Save the Rain" (STR)." This strategy involved adopting a combination of constructed (gray) and plant-soil-atmosphere based (green) infrastructure (GI) practices to address the CSO issue. GI practices are a proven viable option for stormwater management, however clear empirical evidence of in-field hydrologic performance at meaningful spatial and temporal scales is uncommon. Despite many successes, widespread adoption of these systems remains slow. This may reflect the limited availability of long-term empirical data to corroborate the claims of hydrologic benefits, and substantial variability in the performance data. There remains considerable discussion in the research literature regarding standard methods and metrics for quantifying the GI performance.

This study aims to clarify the performance characteristics of GI retrofit structures installed in Onondaga County NY over the period 2014-2015. The goal is to understand the hydrologic performance of three different types of green infrastructure retrofits through in-situ measurements of fluxes and any changes in structure performance over the period 2014-2019. The stormwater capture structures include rain gardens, infiltration trenches, and permeable pavements. The catch basins of 13 monitoring sites were instrumented with in-situ water-level sensors. Local precipitation data and areal extent of the contributing area for each GI contributing area were collected to estimate inflow and outflow volumes for each structure. Changes in catch basin stage relative to overflow drain to storm sewers were used to determine the infiltration rates and the percent runoff capture within the soil and gravel layers of these systems. The analysis also compares the percent runoff reduction and percent runoff capture.

The findings from these analyses indicated that site performance decreased in the order of permeable pavements, rain gardens and infiltration trenches. The regression analysis of infiltration rates and precipitation depth showed a positive increasing trend for all the sites. The infiltration rates provided by porous pavements ranged from 20 to 80 cm/hr, the infiltration rate provided by rain gardens ranged from 0.5 to 120 cm/hr, and the infiltration rate provided by infiltration trenches ranged from 0.05 to 25 cm/hr. The percent runoff capture varied from 40 to100% for rain gardens, 20 to 30% for infiltration trenches, and 80 to 100% for porous pavements. The percent runoff reduction ranged from 64 to 100% for Barker Park rain garden, 50 to 80% for the rain garden at the city parking lot 4, and 100% for all other rain gardens. The percent runoff reduction ranged from 90 to 100% at the Zoo parking lot, 80 to 100% at the Lewis basketball court, and 22 to 100% at Hughes Magnet School parking lot. The outflow from Barker Park rain garden showed a strong dependence on precipitation depth but the City Parking lot 4 rain garden showed a weaker relationship with precipitation depth. The percent runoff reduction at Barker Park showed a strong decreasing trend with precipitation depth whereas a weak trend was observed for City Parking Lot 4 rain garden.

The findings from the field evaluation of the green infrastructure controls helped identify the factors that were the cause for the variability of the hydrologic performance across and within structure types.

Retrospective Analysis of Hydrologic Performance of Green Infrastructure Systems of the Save The Rain (STR) Program in Syracuse, New York

By

Priyanka Rajashekar

B.E., Visvesvaraya Technological University, 2013

M.Tech., National Institute of Technology Karnataka, 2015

Thesis

Submitted in partial fulfillment of the requirements for the degree of

Master of Science in Environmental Engineering

Syracuse University

December 2020

Acknowledgments

I would like to express my sincere gratitude to my mentor and advisor, Dr. David Chandler, for providing me with the opportunity to conduct this research. His valuable guidance has helped me grow as an individual, researcher, writer, and presenter. His encouragement has helped me step out of my comfort zones and take on new challenges. This research would not have been possible without his guidance and patience. This has been a priceless learning experience.

I would also like to thank the committee members - Dr. Baris Salman, Dr. Cliff Ian Davidson, Dr. Teng Zeng, and Dr. Svetoslava Todorova for their comprehensive review, valuable insights, and constructive feedback.

I would also like to thank Syracuse University and the Department of Civil and Environmental Engineering, for supporting me through graduate research and teaching assistantship programs.

A special thanks is owed to my parents and husband, who provided constant support during this journey's challenging times.

Table of Contents

Appendix

Appendix A: Site plans for STR GI study sites

Appendix B: Hydrographs for study sites for 2014, 2015, 2019

Appendix C: Precipitation records for 2014, 2015, 2019

Appendix D: Estimates of infiltration rates of rain gardens, infiltration trenches & porous pavements for all selected storm events

Appendix E: Number of overflow events and estimates of overflow volumes at the study sites during the study periods

List of Tables

List of Figures

Chapter 1: Introduction

1.1. Background and Problem Statement

The first sections of this chapter describe historic environmental concerns associated with Onondaga Lake, the effects of urbanization on the hydrological cycle, combined sewer systems, combined sewer overflows, and Green Infrastructure (GI) stormwater control measures employed by the County to achieve CSO mitigation. The sections following that include the motivation to understand hydrologic performance of GI systems, a brief literature review of prior studies, and the research questions for this study.

Onondaga Lake is a dimictic lake situated in Central New York, along the northern side of the City of Syracuse, NY, USA which receives water from a 285 square mile watershed. The drainage basin encompasses the City of Syracuse, and much of the surrounding Onondaga County (Figure 1).

Nine-mile Creek and Onondaga Creek are major tributaries that contribute approximately 70% of the Onondaga Lake's annual hydrologic input. The Metropolitan Syracuse Wastewater Treatment Plant (Metro WWTP) is located on the southern shore of Onondaga Lake. This facility discharges wastewater effluent into the lake's southeastern end, which accounts for about 20% of the Lake's annual inflow. The smaller tributary sources including Ley Creek, Harbor Brook, Sawmill Creek, and Bloody Brook represent the remaining 10% of the total surface influx received by the lake in a year. The Lake discharges northwest into Seneca river, joining the Oneida river to form the Oswego river, and subsequently into Lake Ontario.

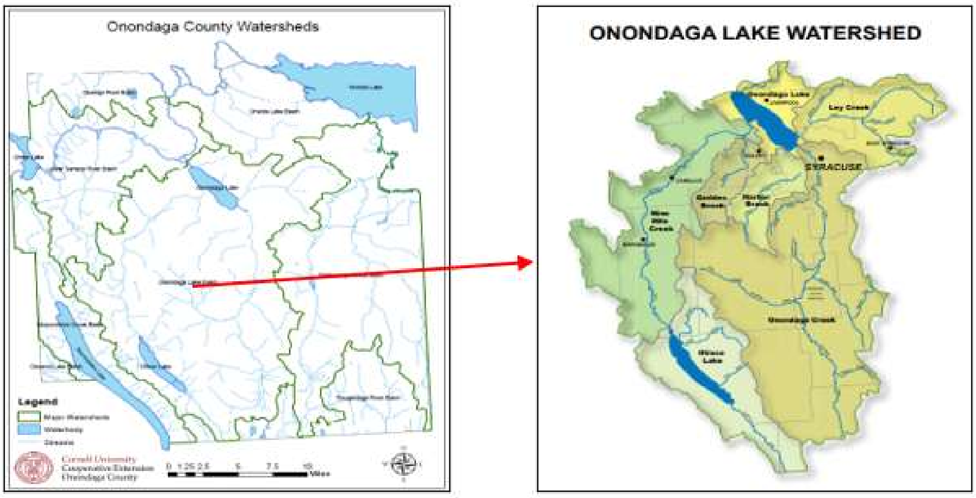


Figure 1: Hydrologic inputs to lake. The figure to the left shows the map of Onondaga county watersheds (Cornell University) and the figure to the right shows the Onondaga lake watershed (Onondaga Lake Partnership)

Environmental Concerns

Onondaga Lake has experienced a history of pollution from industrial processes, municipal wastewater discharges, and runoff due to increased industrialization and urbanization from the 18th century to the early 20th century. While the city thrived from industrial development for over a century, the release of massive amounts of wastes from these industries led to severe impairment of the Lake's water quality by the late 19th Century (Rowell 1996; Effler et al., 1996). A myriad of pollutants contributed to the degradation of the surface water and the sediments of the lake. Due to the profound contamination, EPA added Onondaga Lake and some of its tributaries to the federal superfund National Priority List (NPL) in 1994.

Combined Sewer Systems (CSS)

Combined sewer overflow (CSO) discharges to the Lake were identified as a primary contributing source of pollution in Onondaga Lake. During the late 19th and early 20th centuries, Syracuse built combined sewer systems (CSS), a type of wastewater collection system that collects and conveys residential sewage, industrial wastewater, and stormwater runoff through a single, conventional pipeline system (New York State Comptroller, P Dinapoli, 2018). Figure 2 shows the working mechanism of the combined sewer systems for dry and wet weather conditions.

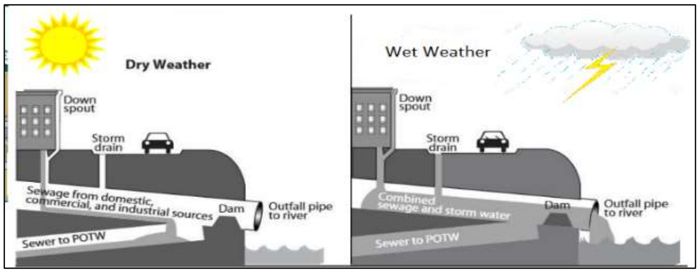


Figure 2**:** Working mechanisms of combined sewer systems (USEPA 2004)

During dry weather conditions, wastewater, combined with stormwater runoff, is directed through the CSS to Metro WWTP before release into the Lake. However, during wet weather conditions, the hydraulic loads from combined sewers exceed the capacity of the sewers and wastewater treatment systems. Under such circumstances, surplus flow is directly discharged into the Lake and its tributaries through CSO outfalls (Gao & Sage, 2015). The contaminants in the untreated sewage discharges pose a threat to the environment and public health (Office of Water Programs, 2008).

Hydrological Impacts Due to Urbanization

Typically, precipitation incident on the Earth surface moves between land, atmosphere, and water bodies through the processes of infiltration, evaporation, and surface runoff. However, the expansion of urban areas is attended by increased conversion of natural land covers to impervious landscapes. These urban features significantly modify the watershed's natural surface & subsurface hydrodynamics and runoff generating processes, thereby rising challenges associated with stormwater quantity and quality (Center for Watershed Protection, 2003). The volumetric runoff coefficient (R_v) increases as a function of site imperviousness.

Thus, the increased impermeable surfaces no longer allow rainfall to infiltrate into the ground and, as a result, generate large volumes of runoff (Figure 3).

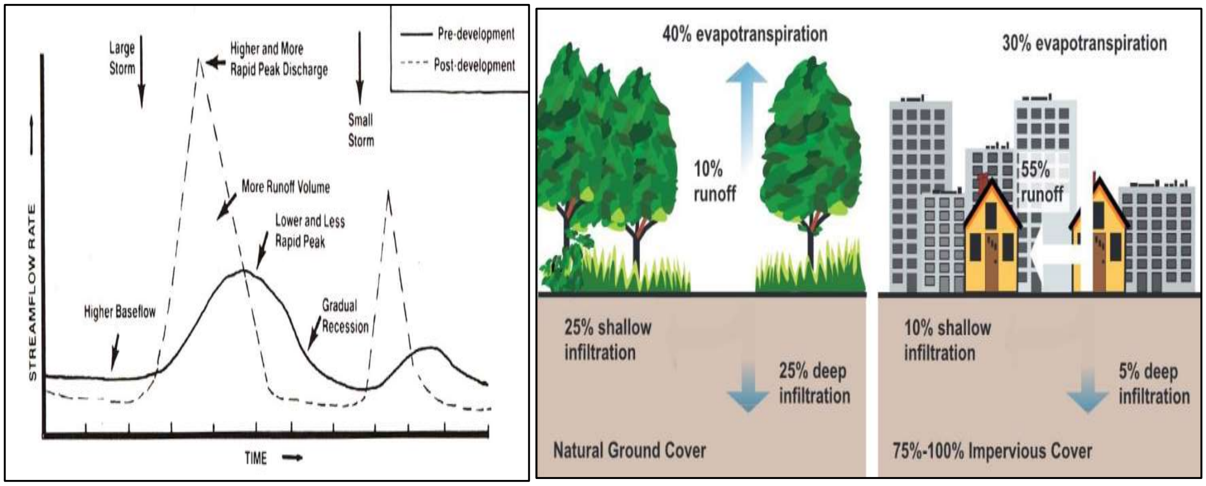
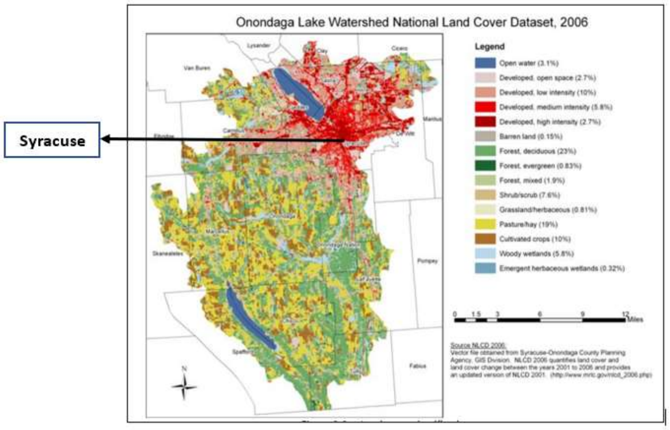


Figure 3: Hydrographs and hydrology of pre-and post-development conditions (USDA)

In such a scenario, the conventional conveyance-based infrastructure becomes inadequate for addressing stormwater management needs. The areas with combined sewer drainage systems are unable to handle such vast volumes of the combined flow from large runoff events, and as a result, stormwater mixed with untreated sewage flows into the receiving water bodies via overflow structures as combined sewer overflows. Figure 4 indicates the fractional landcover distribution in the Onondaga Lake watershed. The city of Syracuse and the Lake are in a highly urbanized region.



Source NLCD 2006:
Vector file obtained from Syracuse-Onondaga County Planning Agency, GIS Division. NLCD 2006 quantifies land cover and land cover change between the years 2001 to 2006 and provides an updated version of NLCD 2001. (http://www.mrlc.gov/nlcd_2006.php)

Figure 4: Onondaga lake watershed landcover (NLCD, 2006)

The quantitative and qualitative impacts of urban developments are increase in runoff rates and runoff volumes, shorter flood return periods, greater peak discharges, increased pollutant loads and decreased runoff lag times, infiltration, groundwater recharge, evapotranspiration (US EPA 1997; Hatt et al., 2009). An increase in the urbanization of cities with CSS can lead to an increase in runoff volume, which can further increase the frequencies and durations of CSOs.

A solution to Mitigate CSO Issues: Green Infrastructure

GI practices are decentralized control measures intended to emulate pre-urbanization hydrologic characteristics. These practices enhance stormwater capture and retain stormwater generated from impermeable landscapes that would otherwise run off the site. These techniques aim at attenuating peak flows, total stormwater runoff volumes, and pollutant loads at the source by facilitating natural ecological phenomena, namely infiltration, groundwater recharge, and evapotranspiration (DeBusk et al., 2011; Fletcher et al., 2015; USEPA 2017b; Eger, Chandler, & Driscoll, 2017).

GI retrofits are designed to effectively detain most of the runoff volume generated from more frequent and smaller storm events, leading to a substantial reduction in discharge volumes. The two broad categories of stormwater management technologies are infiltration-based techniques and retention-based technologies (Fletcher et al., 2015). These systems include a wide array of structural measures such as rain gardens, infiltration trenches, porous pavements, bioretention cells, tree trenches, bioswales, rain barrels/cisterns, green roofs, and constructed wetlands. These systems, combined with CSS, decrease the total surface runoff volume, and reduce the occurrence and magnitude of CSOs.

Widespread application of these engineered systems can dramatically reduce overflow events, alleviate the stress on stormwater and wastewater infrastructure, and restore the health of surrounding waterways by exhibiting a hydrologic response similar to a natural system. This stormwater management strategy has gained extensive attention due to growing interest in the potential ecological, economic, and social services.

The benefits of GI at macro and micro scales are reduced stormwater runoff volume, peak flows, occurrence of combined sewer overflows, salt use, and pollutant loads, increased infiltration, evapotranspiration, and time to peak, decreased frequency and magnitude of flooding, reduced energy consumption, urban heat island effect, and carbon emissions, improved air quality, aesthetics, habitat, and community livability (Ahiablame et al., 2012, 2013; Chen et al., 2019; Dietz, 2007; Emerson et al., 2010; Liu et al., 2015; Wright et al., 2016; Drake et al., 2014)

Onondaga County’s Action Plan

In 1988, Atlantic States Legal Foundation (ASLF) and the New York State Department of Environmental Conservation (NYSDEC), filed a legal suit against Onondaga county under the federal Clean Water Act (CWA), claiming County's violations by discharging insufficiently treated sewage into the Lake and its tributaries from Metro and CSO outfalls. As per the fourth stipulation of the Amended Consent Judgement (ACJ) from 2009, Onondaga County Department of Water Environment Protection (OCDWEP) established the County's CSO management program known as the "Save The Rain (STR)" program to combat CSO issues, and this entailed implementing a decentralized, integrated approach that involved the use of GI technologies in combination with conventional gray infrastructure for sustainable urban stormwater runoff management and CSO abatement. This solution to mitigate the effects of the urban watershed and CSOs primarily focuses on controlling urban rainfall and stormwater runoff at the source through green infrastructure, CSO storage with conveyance to Metro, and eliminating the number of operational CSO discharge points.

The County hired the engineering firm CH2MHILL, to plan, design, and construct green and gray infrastructure to replace combined sewer systems on both public and private properties in Onondaga county. Under the STR initiative, the County built more than 220 green infrastructure projects and several large detention ‘gray’ infrastructure projects, namely Clinton, Erie Boulevard, and Harbor Brook storage facilities in the past ten years. Green infrastructure approaches employed by the County include rain barrels, rain gardens, bioretention basins, infiltration trenches, tree trenches, porous pavements, green roofs, bioswales, and cisterns. Rain gardens, infiltration trenches and porous pavement are the most commonly used approaches in the STR program. The court order mandated the County's CSO program to reduce the total volume of CSOs by 95% during wet weather events by the end of 2018. The County reported 97.7% system-wide CSO capture, ahead of the mandated deadline (OCDWEP, 2018).

1.2. Motivation for This Research

Despite numerous studies confirming the potential of GI measures to attenuate stormwater surface runoff by promoting infiltration and evapotranspiration, many cities remain reluctant to adopt the GI approach. Most of the stated concerns are related to:

a) Lack of detailed quantitative information on its short and long-term hydrologic performance (Davis, 2014; Eckart et al., 2017).

b) No unanimity on standard performance metrics and monitoring guidelines to evaluate the efficacy of these systems.

c) Long-term field studies conducted to evaluate their hydrology impacts are sparse and challenging due to the high costs of monitoring efforts (Dietz, 2007).

d) Whereas some studies found a decline in hydrologic response across spatial and temporal scales (Hunt et al., 2006) the other studies, however, indicated no apparent changes in their hydrologic performance (Emerson et al., 2010).

e) Some studies found differences in GI efficiencies of based on type. However, the range of performance reported for the same GI type also varied dramatically from one study to another. Thus, drawing comparisons and generalizing conclusions about these systems' efficiencies is difficult as the site-specific design and field variables differ. (Jaffe et al., 2010).

f) Large-scale studies (watershed scale) investigating the cumulative impacts of these systems are few. Most of these experimental efforts are at micro-scales (individual stormwater facilities) (Davis, 2008), whereas data regarding the collective effects of these practices at larger scales (Dietz 2007) is also vital.

There is a crucial need for continued in-depth empirical research over different spatial and temporal scales to resolve these questions and concerns. Sufficient field data representing the actual ground conditions is necessary to enhance and advance simulation modeling efforts. Such efforts would provide valuable insights into the cumulative assessment of the hydrologic functionality across different spatial (lot scale to a watershed scale) and temporal (single event to long-term simulations) scales (Ahiablame et al., 2012, 2013; Eckart et al., 2017). As a result, the number and types of modeling techniques used to assess GI practices efficiencies have grown rapidly. The findings from field-based and model-based studies (Not covered in this study) can help stakeholders, and decision-makers support the extensive implementation of this approach for stormwater management.

1.3. Literature Review

To date, numerous field-based studies have demonstrated that GI practices are effective at managing surface runoff volume significantly or potentially eliminating surface runoff (Alsubih et al., 2017; Ball & Rankin, 2010; Bean et al., 2007; Bergman et al., 2011; Booth & Leavitt, 1999; Cording et al., 2017; Davis, 2014; Debusk & Wynn, 2011; Brattebo and Booth 2003; Fassman and Blackbourn 2010;).

The degree of hydrologic performance varies based on the following factors: media composition, depth, drainage configuration, surface storage capture volume, drainage area to GI area ratio, type of GI technology, vegetation type, climatic and geographical conditions (Davis et al., 2012; Dietz 2007; Hatt et al., 2009; Hunt et al., 2006, 2008; Roseen et al., 2012).

Brattebo and Booth (2003) studied four different types of permeable pavement systems (PPS) and found that no surface runoff occurred for any of the 15 monitored events at two sites, and minimum surface runoff occurred for six of the 15 events at the other two sites. In a study by Pratt et al. (1995), the hydrologic performance of four PPS was investigated, and they found that all four sites discharged on average between 34% and 47% of the rainfall depth. They attributed the variability in runoff reduction between events to varying antecedent hydrologic conditions. Table 1 highlights a few short and long-term empirical studies that have explored the effectiveness of GI practices on hydrology.

Table 1**:** List of short and long-term empirical studies on hydrologic performance

Literature Citation	Intended Objectives	Type of GI studied & Location	Monitoring Period	Results
Brattebo & Booth, 2003	Runoff reduction	Permeable Pavement system (Renton, Washington)	Four months	96 – 100%

Gruber, 2013	Runoff Reduction	PPS (Fort Collins, Colorado)	2 years	55-65%
Tamkin, 2019	Runoff Reduction	Bioretention Cells	2011	28-78%
			2012	22-79%
			2015-2016	55-81%
Bean et al., 2007	Runoff reduction	Permeable Pavement system (Eastern North Carolina)	10 – 26 months	13-100%
				1-100%
				100%
Davis, 2014	To quantify the reduction of hydrologic volume, flow peaks, and delay in peak timing	Bioretention cells (University of Maryland campus)	2 Years (49 runoff events)	The entire inflow volume was captured for 18% of the monitored events, and no outflow was observed. Mean peak reductions of 49 and 58% were noted. Flow peaks were significantly delayed as well, usually by a factor of 2 or more.
Tang et al., 2016	Runoff reduction	Rain garden	4-year study	77 to 94%
Shuster et al., 2017	Stormwater retention capacity, time to peak	Rain garden	4-year study	Achieved more than 50% overall volume retention capacity. 90% of all rainfall events were fully detained.

				Delayed off-peak for an average of 5.5 h
Chapman and Horner 2010	Percent runoff reduction	Bioretention (Washington, USA)	2.5 years	48-74%
DeBusk and Wynn 2011	Percent runoff reduction	Bioretention (Virginia, USA)	2007-2008	97-99%
Hunt et al., 2006	Runoff reduction	Bioretention cell (North Carolina, USA)	2 years	46-93%
Roseen et al., 2012	Percent runoff reduction	Permeable pavement systems	2004-2008	90-100%
Huang et al., 2016	Percent runoff reduction	Permeable pavement systems	2011-2013	19-64%
Alsubih et al., 2017	Percent runoff reduction	Permeable pavement systems	2-years	40-92%
Brown and Hunt 2011	Percent runoff reduction	Bioretention Cells	2008-2009	28-35%
Winston et al., 2016	Percent runoff reduction	Bioretention Cells	2013-2014	27-50%

Previous studies have found that the infiltration rate depends on the site design, size of the GI, ratio of GI area to total capture area, soil media depth, available storage capacity, and antecedent moisture conditions (Le Coustumer et al., 2007; Leming and Malcom., 2007; Tennis et al., 2004; Davis et al., 2004).

Several studies have indicated that permeable pavement systems experience clogging from sediment deposits over time, due to which the infiltration and exfiltration rates, which are key components influencing its hydrologic functioning, are reduced (Bean et al., 2007). Other studies show that the clogging rate depends on site-specific, intrinsic parameters such as surface slope, pavement type, sediment load in the stormwater, cumulative captured runoff volume since its installation, capture ratio, surface openings and gaps (Abbott and Comino-Mateos 2003; Al-Rubaei et al., 2013).

1.4. Research Questions

Few field-based studies are available to assess the long-term hydrologic behavior of GI stormwater controls in a working city. Thus, there is insufficient data to gain insight into the efficacy of GI retrofits at large scale and for long-term field study.

This thesis focuses on assessment of the changes in hydrologic function of three common GI technologies over time, specifically: infiltration trenches, permeable pavements, and rain gardens. The study period is summer 2014-2015 and 2019.

The observations from this monitoring effort will support interrogation of the following questions:

1: How does the GI structure performance vary across GI types?

2: Are the current GI systems adequate for storm events typical of Onondaga County?

3: Has system performance changed over time since installation?

Chapter 2: Case Studies - STR Green Infrastructure Study Sites

The study sites selected are dispersed across the city of Syracuse. These were chosen for the study due to their significant variability in terms of structure type, size, and drainage characteristics. This research evaluates seven rain gardens, three permeable pavements, and three infiltration trenches (Figure 5). The outflows from these systems are routed towards either the Clinton, Midland, Franklin, or Harbor Brook sewersheds.

Figure 5: Location map of study sites

Site plans for each study site are provided in Appendix A. Details of its design features are provided in Tables 2, 3, and 4.

1.1. Description of Rain Gardens

A rain garden is a constructed depression in the landscape filled with a natural or engineered soil mix of high hydraulic conductivity with a vegetated surface. It captures stormwater runoff from nearby impervious urban spaces including driveways, lawns, street curb cuts and parking lots to promote recharge at the source where the stormwater is generated. It has a ponding layer with native plants at the surface in which excess runoff pools up as temporary detention. STR rain gardens consist of a planting soil bed consisting primarily of sand and compost (S1), a structural soil layer with a greater proportion of sand (S3), and a gravel layer of variable depth. A portion of the stormwater captured in the depression storage and vegetative capture in the unsaturated zone of the soil layers is lost through evapotranspiration.

The runoff retained within the gravel layer either percolates into the native subsoil or the gravel layer is equipped with a lateral perforated underdrain pipe connected to a catch basin and an outlet weir. The catch basin is constructed of a PVC standpipe that controls surface stage in the rain garden to a preset stage. Water input in excess of the ponding layer, direct rainfall and stormwater input from storm drains and direct precipitation contribute to the storage volume. Excess stormwater storage passes over a weir in the standpipe and drains to the sewer system. (Figure 6)

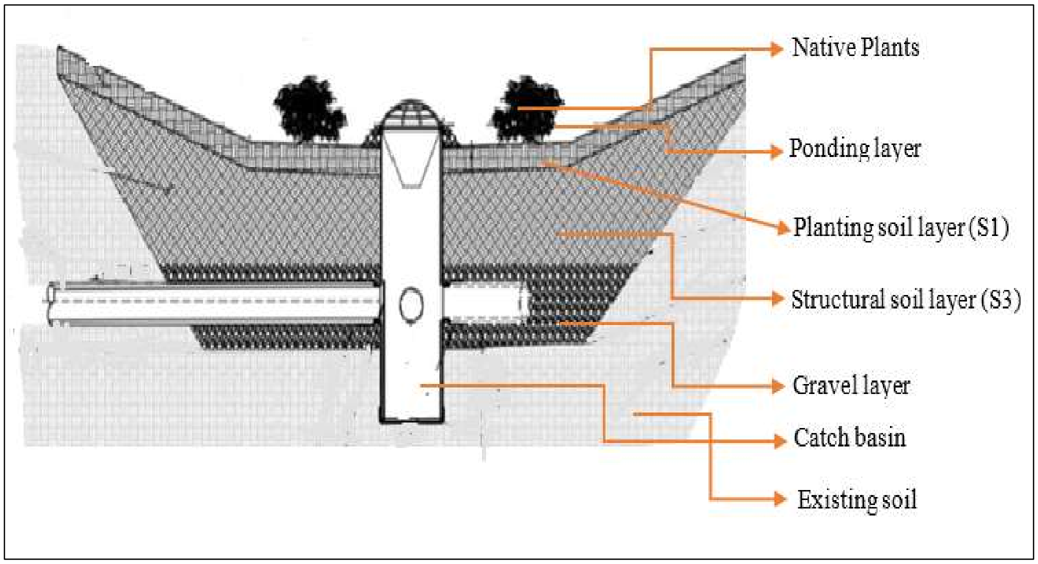


Figure 6: Schematic diagram of a typical STR rain garden (CH2MHILL)

1.1.1. Barker Park

Figure 7: Barker Park rain garden

The Barker Park rain garden captures stormwater runoff from Barker Avenue, Wilkinson, and Tracy streets. It has a surface area of 132 m^2, impervious cover is 22% and a catchment area of 4908 m^2. The GI area to total impervious area ratio is 0.12. The excess runoff infiltrated through the GI is drained into the combined sewer system located on Wilkinson Street via the domed outlet riser structure. (Design drawing - Appendix-A, Figure A-1)

1.1.2. 1344 W Onondaga Street Vacant Lot

Figure 8: 1344 W. Onondaga vacant lot rain garden

The rain on the vacant lot receives stormwater runoff from the impervious West Onondaga Street and the vacant lot itself. It has a surface retention area of 148 m^2, with a catchment area of 1885 m^2 and an impervious area of 87 m^2. The ratio of the GI area to the total capture area is 1.71. (Design drawing - Appendix-A, Figure A-3)

1.1.3. Pass Arboretum North

Figure 9**:** Pass Arboretum North rain garden

The site collects surface runoff from Avery Avenue, Tennyson Avenue, the outflow from the rain garden on the south side, and the precipitation falling directly on it. It has a surface area of 292 m^2, with a catchment area of 4676 m^2. It has an impervious cover of 12%. The ratio of the GI area to the capture area is 0.53. This green infrastructure's outlet pipe is connected to a combined sewer system located on South Avery Avenue. (Design drawing - Appendix-A, Figure A-2)

1.1.4. Pass Arboretum South

Figure 10: Pass Arboretum south rain garden

The inflows to this rain garden are the surface runoff from Avery Avenue and Bryant Street and direct precipitation. The site surface area is 613 m^2, with a catchment area of 6451 m^2, including an impervious area of 1142 m^2. The ratio of the GI area to the capture area is 0.54. (Design drawing - Appendix-A, Figure A-2)

1.1.5. Wadsworth South

Figure 11: Wadsworth south rain garden

The rain garden receives stormwater runoff from Glenwood Avenue. It has a surface area of 106 m^2, with a catchment area of 2241 m^2 and an impervious cover of 24%. The ratio of the GI area to the capture area is 0.2. It discharges the excess into a combined sewer drain. (Design drawing - Appendix-A, Figure A-4)

1.1.6. Wadsworth West

The site captures surface runoff from Wolcott Terrace and Wolcott Avenue. The site has a surface retention area of 139 m^2, a catchment area of 4837 m^2, and an impervious area of 1204 m^2. The ratio of the GI area to the capture area is 0.12. It drains the excess runoff into a combined sewer drain located on Wolcott Avenue. (Appendix-A, Figure A-5)

1.1.7. City Parking Lot #4

Figure 12: City parking lot 4 rain garden

A rain garden of a surface area of 134 m^2 is installed to capture stormwater runoff from the I-81 NB ramp and portions of N. State Street. The catchment area is 3067 m^2. The total fraction of impervious cover is 82%. The ratio of the GI area to the capture area is 0.05. The rain garden receives runoff from the porous City Lot 4, from an 80' by 5' roadside infiltration trench, and a curbside stormwater inlet. The site drains excess runoff into a storm drain located on N. State St. (Design drawing - Appendix-A, Figure A-6)

Table 2: Design specifications of selected rain gardens

Site Name	Sewershed	Ponding Depth (cm)	S1 Soil Depth (cm)	S3 Soil Depth (cm)	Gravel Depth (cm)	Catch Basin Diameter (cm)	Weir Height (cm)
Pass Arboretum North	Harbor Brook	15	15	46	101	46	87
Pass Arboretum South	Harbor Brook	15	15	46	86	46	50
Leavenworth Barker Park	Clinton	15	15	46	31	61	61
1344-50 W Onondaga Street Vacant Lot	Harbor Brook	15	15	63	31	61	121
Wadsworth South	Harbor Brook	8	15	56	86	61	30
Wadsworth West	Harbor Brook	8	15	46	56	61	51
City Parking Lot #4 Avalon	Franklin	15	15	46	31	61	110

1.2. Description of Infiltration Trenches

An infiltration trench is a long, shallow, excavated storage zone with porous soils on the top and backfilled with granular stone to form a temporary subsurface reservoir and lined with non-woven geotextile fabric. These structures receive sheetflow stormwater directed from adjacent impervious surfaces such as rooftops, paved driveways, and parking lots. The stormwater runoff entering the trench seeps through the vegetated porous soils and collects in the voids between the stones. The stormwater slowly percolates into the underlying native soil matrix from the trench base and sides to recharge the local groundwater table. Excess runoff tends to pond the surface of the trench before discharging over an overflow control structure (NYSDEC, 2015) (Figure 13)

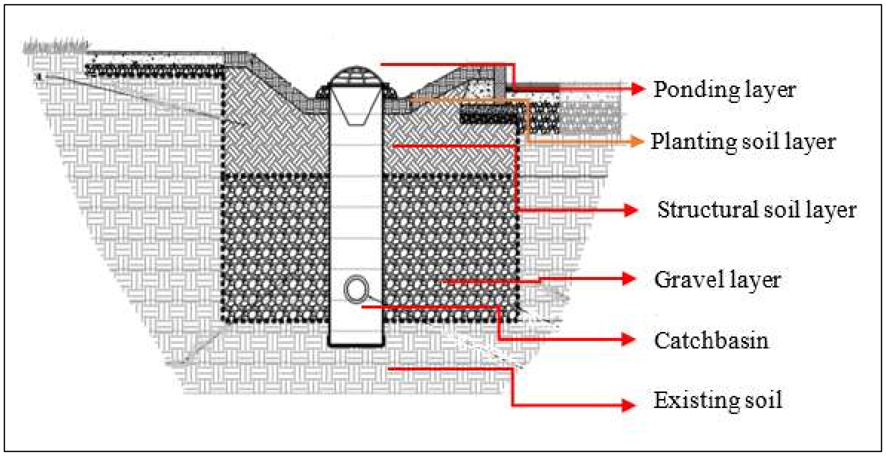


Figure 13: Schematic diagram of a typical STR infiltration trench (CH2MHILL)

1.2.1. White Library

Figure 14: White library infiltration trench

The infiltration trench collects runoff from Peters Street and the impervious parking facility. It has a surface area of 52 m^2 and a catchment area of 986 m^2, resulting in a GI area to capture area ratio of 0.06. (Design drawing - Appendix-A, Figure A-7)

1.2.2. S. Townsend Street Trench

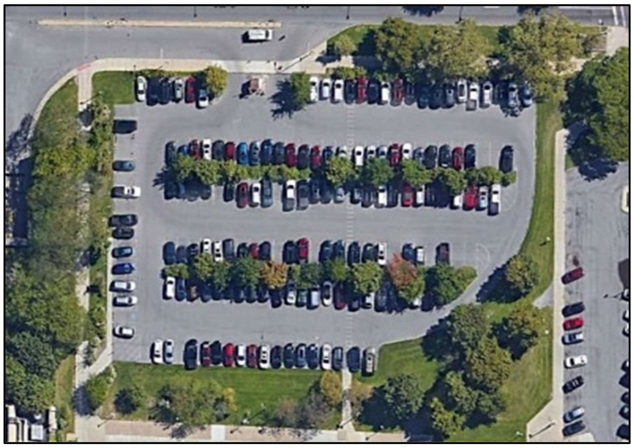


Figure 15: S. Townsend St infiltration trench

The infiltration trench captures upslope runoff from a repaved asphalt parking lot with a series of runoff collection ditches. The capture zone surface area is 49 m^2 for a catchment area of 4983 m^2. The GI area to total capture area ratio is 0.01. It releases the excess runoff into a storm drain situated on S. Townsend Street. (Design drawing - Appendix-A, Figure A-8)

1.2.3. Mundy Library

Figure 16: Mundy library infiltration trench

The infiltration trench installed along Rowland Street diverts street surface runoff to the curbside stormwater drains. The trench capture area is 59 m^2. The total catchment area is 1136

m^2. Thus, the contributing area to capture area ratio is 0.09. Flows in excess of the structure capacity discharges into the municipal sewer. (Design drawing - Appendix-A, Figure A-9)

Table 3**:** Design specifications of selected infiltration trenches

Site Name	Sewershed	Ponding Depth (cm)	S2 Soil Depth (cm)	S3 Soil Depth (cm)	Gravel Depth (cm)	Catch Basin Diameter (cm)
White Library	Franklin	--	46	--	76	61
S. Townsend Street Trench	Clinton	8	--	69	37	46
Mundy Library	Harbor Brook	--	91	--	91	61

1.3. Description of Permeable Pavements

Conventional parking lots, roadways, and walkways are built from materials with very low porosity. This paving is an impermeable surface that does not allow the rainfall to infiltrate into the ground below to recharge groundwater. Thus, porous pavements have become an alternative to traditional pavements as they can resist the stress of vehicles while allowing the rain that falls on the surface to pass through the soil below.

Permeable pavement is a highly porous urban surface composed of concrete, open-pore pavers, or asphalt with a gravel underlayment and a non-woven geotextile fabric lining. It is commonly used to provide a stable surface with internal drainage for low-traffic roads, parking lots, sidewalks, low-traffic areas, and driveways. Examples of porous pavements include plastic grid pavers with flexible joints, rigid or rolled plastic pavers, interlocking concrete grids, permeable concrete, and asphalt pavement. (Figure 17)

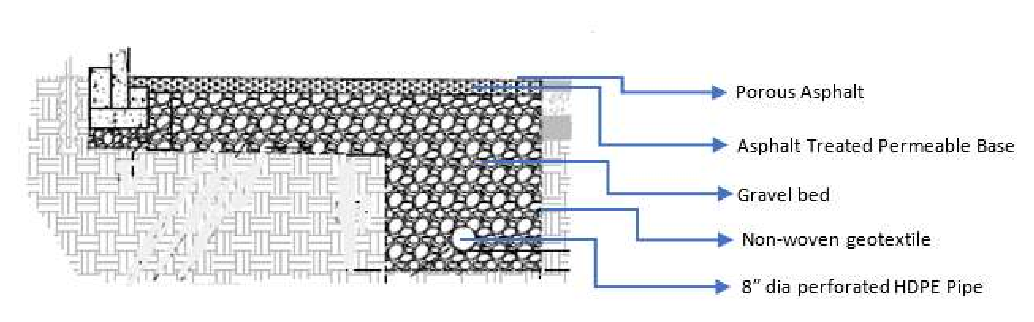


Figure 17**:** Schematic diagram of a typical STR permeable pavement (CH2MHILL)

These pavers are designed to capture precipitation and surface runoff, detain it in a gravel-base subsurface reservoir to promote infiltration into gravel base and native soil. Drainage is to the aggregate layer underdrain system via perforated tile drain.

1.3.1. Lewis Basketball Court

Figure 18**:** Lewis Basketball Court permeable pavement

Lewis Basketball Court is constructed of porous asphalt collects stormwater runoff from Lewis Street to the north, Milton Ave to the east, walkways within the park, and the court itself. The excess flow is directed to the combined sewer system located on Lewis Street. It has a surface area of 819 m^2 and a catchment area of 2762 m^2. The percentage of impervious cover is 31.1. The ratio of GI to capture area is 0.95. (Design drawing - Appendix-A, Figure A-10)

1.3.2. Rosamond Gifford Zoo Elephant Parking Lot

Figure 19: Zoo elephant parking lot permeable pavement

The zoo has a porous asphalt parking lot on the northeast side. The permeable pavement captures runoff from the 2/3rd of the parking lot. It has a surface area of 1222 m^2. The catchment area is 610,577 m^2, and the percentage of impervious area is 80.0. The ratio of GI to capture area is 0.25. The excess flow is drained into combined sewer systems. (Design drawing - Appendix-A, Figure A-11)

1.3.3. Hughes Magnet School Parking Lot

Figure 20: Hughes Magnet School parking lot permeable pavement

The new parking facility constructed from porous asphalt captures surface runoff from the existing adjacent parking lot, school roof, Jamesville Ave, and the parking lot itself. It has a surface area of 323 m^2, a catchment area of 5478 m^2, and an impervious area of 3977 m^2. The GI to impervious area ratio is 0.08. (Design drawing - Appendix-A, Figure A-12)

Table 4**:** Design specifications of selected permeable pavements

Site Name	Sewershed	Asphalt depth (cm)	Asphalt treated base depth (cm)	Gravel Depth (cm)	Catch Basin Diameter (cm)
Lewis Basketball Court	Harbor Brook	4	8	91	61
Zoo Elephant Parking Lot NE	Harbor Brook	6	9	152	61
Hughes Magnet School Parking lot	Midland	6	8	98	61

Chapter 3: Methods of Data Collection

The empirical data required for this analysis are precipitation and stage data in the catch basins of the GI controls. The methods used to collect this data are described below in detail.

3.1. Precipitation Data

Syracuse, NY, lies in the humid continental climate region, with precipitation relatively well distributed year-round. Since precipitation cannot be measured at all the 13 monitored sites, precipitation data from gages located nearby were collected to compute the areal average rainfall. Precipitation data for the year 2019 were obtained from gages operated by NOAA at the Hancock International Airport, Syracuse 2.7 S, and Dewitt 1.4 WSW. Additional data was collected from MOST Armory Square, SU carrier dome, from the weather underground website (https://www.wunderground.com/). Supplemental records were measured with the Hobo data loggers placed inside the gages located at Syracuse Center of Excellence, Rosamond Gifford Zoo, and Sunny Crest Golf Course Parking lot. Data for 2014 and 2015 were obtained from the gages at the Hancock International airport, Metro WWTP, and the SUNY-ESF (Zulfiqar 2016).

The Thiessen polygon tool in ARCGIS was utilized to estimate the areal mean rainfall from the system of point rain gauge measurements at the locations mentioned above. This is a weighted-average technique that divides the city of Syracuse into polygons, with each rain gage serving as a centroid. The Thiessen weights are obtained by dividing the gage's polygon area by the area of the entire city. The average rainfall across the entire city is computed by multiplying the rainfall value for each gauge station by the corresponding polygon area and summing up all the individual weighted precipitation.

$$P = \frac{P_1 * A_1 + P_2 * A_2 + P_3 * A_3 + \cdots \ldots\ldots + P_n * A_n}{A_1 + A_2 + A_3 + \cdots \ldots + A_n} = \sum_1^n P_i * \frac{A_i}{A} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 3.1}$$

Figure 21 illustrates the Thiessen polygons delineated around these precipitation gages in ArcGIS.

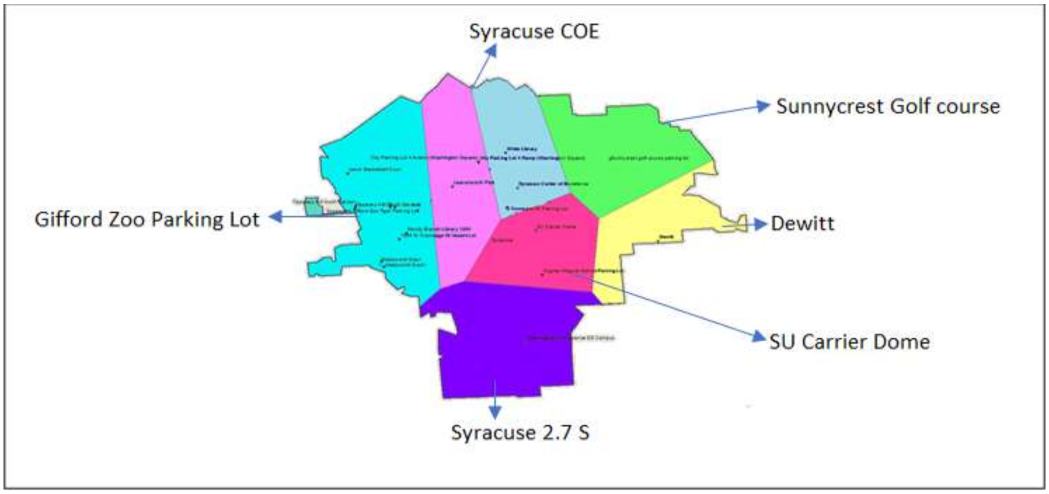


Figure 21: Thiessen polygons delineation for the precipitation gages

For this study, a storm event was defined as a distinct event if the precipitation were equal to or greater than 0.5" (1.27 cm) and if the antecedent dry period was greater than 6 hours. Precipitation record data analysis showed a threshold to runoff 0.5”. The storm events for which all the study sites showed responses were considered for the analysis (5 days in 2014, 11 days in 2015, and 9 days in 2019). Only discrete events were analyzed. Appendix C shows the rainfall records of the significant events for the monitoring periods during 2019, 2014, and 2015.

3.2. Catch basin stage data

The experimental procedure involved a field-based approach to monitor water level and temperature data continuously at 15-minute intervals by deploying the research-grade, autonomous, integrated water level data sensors & loggers (HOBO U20L-04) for the duration of the monitoring period within the catch basins connected to the base of each of the GI structures (Figure 22) (Winston et al., 2016, Ma 2016, Zulfiqar 2016). The catch basins are considered as the monitoring chambers of the GI because the continuously changing water depths provide insights into the outflow volume and the total volume captured by the GI control in response to real-time storm events.

All sensors were programmed with the HOBOware software (www.onsetcomp.com) to collect pressure data at 15-minute intervals. The level data sensor was suspended in each catch basin by securing it to the domed-riser with a lanyard of sufficient length for the sensor to remain submerged at the base of the catch basin. The logger features a pressure sensor with an on-board Wheatstone bridge that measures the absolute pressure (0 to 145 kPa), including atmospheric pressure and water head, and a thermistor that records water temperature (-20° to 50°C). The measured data is stored in the sensor's memory of 64K bytes. The HOBO Optic USB- Base Station and the HOBOware software were used to read out the data from the loggers. An additional HOBO U20L, water level logger, placed at Link Hall, Syracuse University, was used as a barometric reference to continuously record atmospheric pressure at 15-minute intervals to compensate for the barometric pressure changes. Since barometric pressure readings are regionally relatively consistent, data measured at the reference sensor was used to compensate for all other water level loggers.

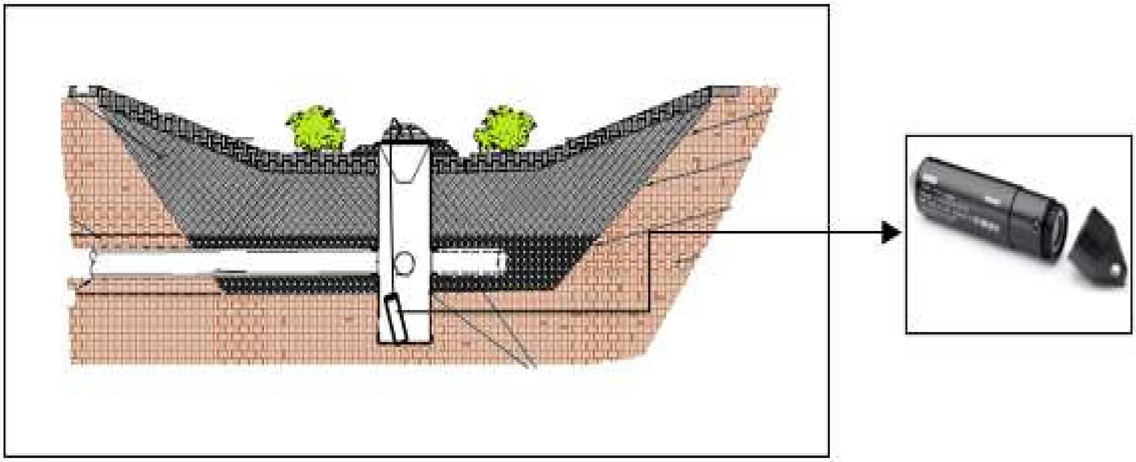


Figure 22**:** Drainage stage monitoring set-up

Each structure is connected to a catch basin with an outlet weir to control the maximum storage volume and weep pores to drain the catch basin between events. The conversion from absolute pressure (psi) to water depth (cm) was calculated by using the equations 3.2 and 3.3.

$Actual\ water\ pressure(psi) = Absolute\ pressure\ (psi) - Atmospheric\ pressure\ (psi)$ Equation 3.2

$$Water\ Depth\ (cm) = \frac{Actual\ water\ pressure * \left(\frac{6894.7\ (Pa)}{1\ (psi)}\right)}{[1000\ (kg\quad ^{-3})] * [9.81\ (ms^{-2})] * [0.01\ \left(\frac{m}{cm}\right)]}$$ ……………….. Equation 1.3

Hydrographs from collected data for each GI site for the period of record. Supplemental measurement and calculations of the base head, peak head, time to peak, and overflow were extracted from these data. The generated data plots clearly show the storm sewer hydrographs during precipitation, increase in stage during the event, occasional overflow in the GI structure and stormwater stage recession in the GI as surrounding native soils absorb the stormwater. Hydrographs for each study site are provided for all the study periods in Appendix B.

Chapter 4: Data Analysis

The field data collected during the study periods were analyzed to determine changes in their hydrologic behavior over time and across structures. As depicted in figure 23, the physical fluxes associated with this system are Inflow, Infiltration, percolation, discharge, evapotranspiration, and infiltration to the native soil.

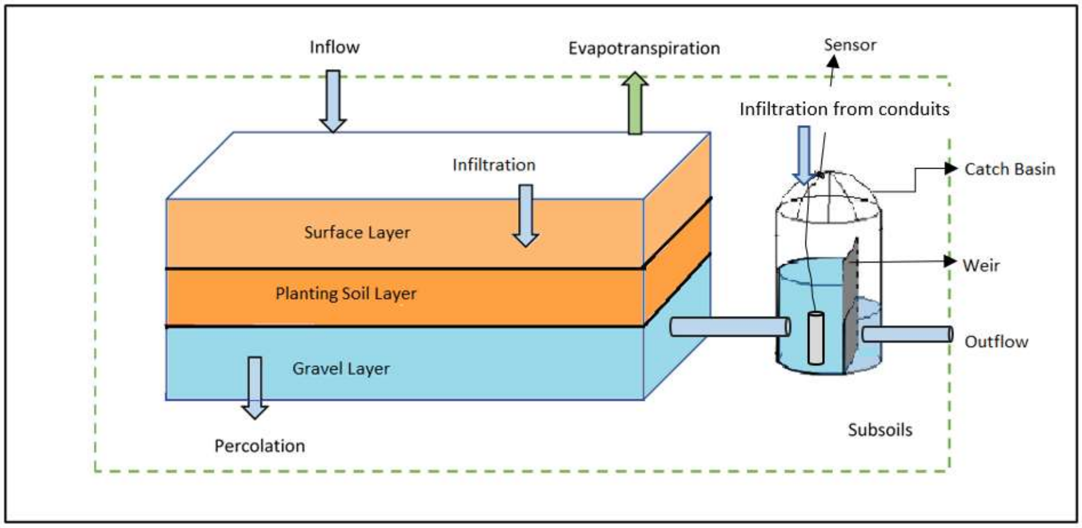


Figure 23 : Schematic diagram of processes associated with GI.

The surface layer receives runoff and direct precipitation. The engineering soil media layers beneath receives infiltration from the surface layer. A portion of the water stored in the depression storage and vegetative capture in the unsaturated zone is lost through evapotranspiration. The water in the gravel layer either percolates into the underlying native soil or flows out to the combined sewer system through a perforated pipe underdrain system. Field evaluation of structure performance in response to the chosen precipitation events during the 4-month monitoring period in the years- 2014, 2015, and 2019 include the inflow resulting from the stormwater runoff generated from the contributing area, infiltration rates, resultant overflow volumes, percent runoff reduction, and percent runoff capture. The methods used for these analyses are described in detail in the following sections.

4.1. Inflow Volume

The inflow to the GI control is equivalent to the stormwater runoff generated from the contributing area and the direct rainfall over the GI site area. Thus, the total inflow volume received by GI control depends upon the magnitude of the local Spatio-temporal precipitation, contributing area, percentage of impervious area, and the area of the GI control.

The Soil Conservation Service (SCS-CN) approach developed by the Natural Resources Conservation Service of the United States Department of Agriculture (NRCS, USDA) was used to estimate the approximate amount of stormwater runoff generated for the selected storm events at each study site. Based on the literature, a value of 99 was considered for the curve number under urban conditions and a value of 70 for permeable pavements (Schlea et al., 2014; Tamkin 2019; Schwartz 2010). The surface runoff volume was calculated for each day during the monitoring period based on the curve-number and the 5-day antecedent moisture condition. Potential retention (S) which is a function of the curve number (CN) was estimated using equation 4.1. Stormwater runoff depth and stormwater runoff volumes were calculated using equations 4.2 and 4.3.

$S = \left(\frac{2540}{CN}\right) - 25.4$ ……………………………………………………………………… … Equation 2.1

Stormwater runoff depth $= \left(\frac{(P - (0.2*S)^2}{(P + (0.8*S)}\right)$ ……………………………………… … Equation 4.2

Stormwater runoff volume, Q = Stormwater runoff depth * contributing area …... Equation 4.3

4.2. Infiltration Rate

Infiltration is the process by which the stormwater runoff from the drainage area and the direct rainfall on the GI site on the ground surface enter the underlying soil and gravel layers of the system. For the infiltration analysis, the rate is determined by the time difference for the water level in the structure to decline from peak stage to the base head in the structure. (Kazemi 2014, Zulfiqar 2016).

$$\mathrm{I_t} = \frac{\text{Peak head} - \text{Base head}}{\text{Time to peak}} \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 4.4}$$

4.3. Outflow Volume

Each GI retrofit is connected to a Nyloplast catch basin with an outlet control structure that regulates the system's maximum storage volume and releases the excess stormwater to the combined sewer systems. Types of overflow structures implemented in these GI practices include domed risers in conjunction with sharp-crested, suppressed Cipolletti or trapezoidal weir or circular orifices. These are responsible for controlling the ponding elevation and discharge rate from the stormwater management practice during various storm events. The flow rate over the weir is a function of the vertical head above its crest, and thus these flow-regulating structures can be used as a flow-measuring device.

The outflow was determined through the analysis of stage records and the measured outlet weir height. When the water level in the catch basins exceeds the weir height, all the water beyond this point flows out of the system. The downward blue columns of the hyetograph and saw-toothed orange stormwater hydrograph traces show the impulse and response for each storm event. Traces that cross the horizontal line stormwater volume discharge from the weir into the combined sewer systems (Figure 24).

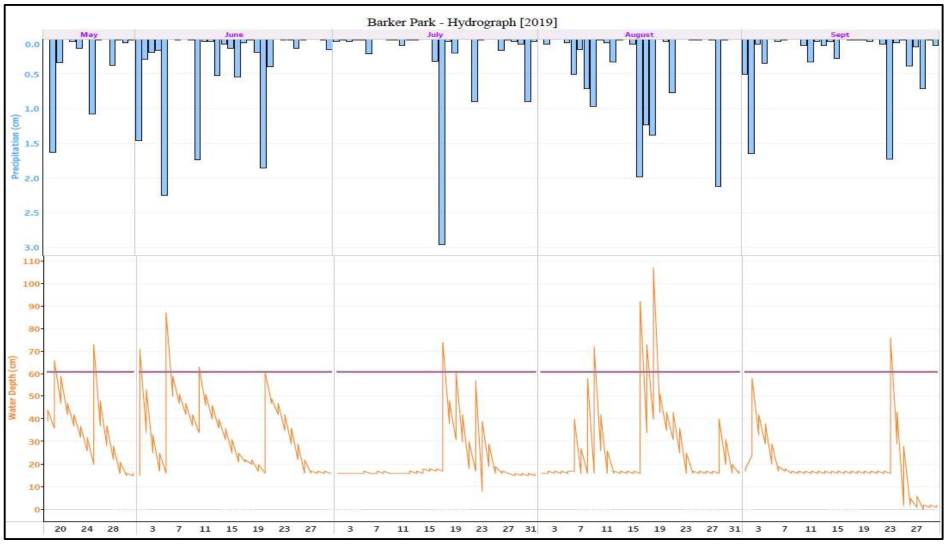


Figure 24: Hydrograph with the outlet weir height.

The purple line on the hydrograph indicates the outlet weir height for the rain garden at Barker Park.

The equations based on the Bernoulli equation principles can represent the stage-discharge relations for these various outlet controls. With the empirical elevation head collected, the hydraulic equations 4.5 and 4.7 were used to determine discharge for these various configurations. Coefficients of discharge were determined for each weir using equation 4.6 to account for errors in estimating the flow rate.

a) For a trapezoidal/ Cipolletti weir (Figure 25)

The discharge equation for the trapezoidal weir is given by the following equation (Kindsvater and Carter, 1980),

$$\mathrm{Q} = \mathrm{C_e} * \left(\frac{2}{3}\right) * \sqrt{2 * \mathrm{g}} * \mathrm{b} * \mathrm{H}^{3/2} \qquad \text{………………………………. Equation 4.5}$$

$$\mathrm{C_e} = 0.602 + 0.075 * \left(\frac{\mathrm{H}}{\mathrm{P}}\right) \qquad \text{………………………………. Equation 4.6}$$

Where Q = flow rate (cm^3/s); b = effective weir width (cm); H = elevation head on the weir (cm); g = gravitational constant; Ce = discharge coefficient, P = height of weir from base to catch basin (cm)

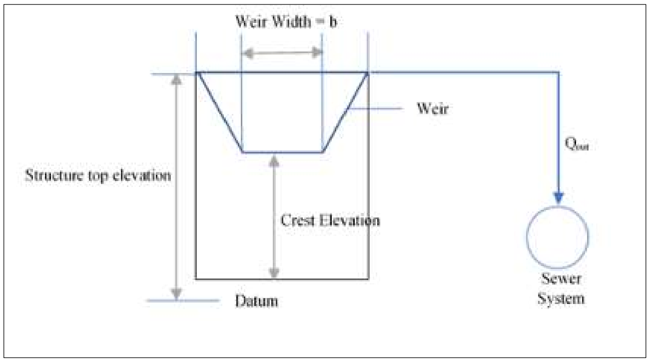


Figure 25: Cipolletti weir

a) For an orifice

The discharge equation for an orifice is given by,

$Q = 0.92 * A * 2 * g * H$ ……………………… Equation 4.7

Where:

Q = the orifice flow discharge (ft^3/s); A = cross-sectional area of orifice (ft^2); g = acceleration due to gravity (32.2 ft/s^2); H = effective head on the orifice, from the center of orifice to the water surface.

Outflow volume was determined by numerically integrating the hydrograph in R using the trapezoid method (trapz from package pracma).

4.4. Percent Runoff Capture

The change in stormwater storage in each of the layers in the structure is a function of antecedent moisture conditions, soil characteristics, contributing area, the impervious area, and the GI area. The actual volume of runoff capture can differ from the theoretical runoff capture volume for the GI control since design as well as field variables influence this parameter. Hence, this is an important measure that aids in understanding the performance of this system with respect to this flux in response to real-time events.

The total stormwater runoff volume captured within the GI retrofit was calculated as the product of total event equivalent storage depth ($h_{eq)}$ and GI plan area (A) (Equation 4.10) (Ma and Chandler 2016). h_{eq} was calculated over multiple depths of saturated and unsaturated layers within the system. This method was based on the following assumptions:

- In each of the soil layers, the storage may occur at volumetric water content (ϴ) that ranges between 0 to aggregate porosity (ϕ).
- The assumed values of ϴ at saturation for the gravel layer and soil layers are 0.4 and 0.35 (McWhorter and Sunada, 1977). The assumed values of field capacity and wilting point for the soil layers are 0.2 and 0.05 (Walker, 1989).
- Based on the 5-day antecedent moisture (AM-5) content calculated, it was determined whether the unsaturated soil layers' volumetric water content was at field capacity or wilting point. If the GI had not received rainfall for five days prior to the event, then the initial volumetric water content in the aggregate was considered close to the wilting point. If the Gi had received rainfall in the past 5 days, then the initial volumetric content was considered to be close to the field capacity.

The unsaturated and saturated event equivalent depth (D_{eq}) for each layer was calculated using equation 4.8. The total event equivalent depth (h_{eq}) was calculated as the summation of the surface storage depth (D_P), saturated and unsaturated storage depth in the soil layers (D_S), and the storage depth in the gravel layer (D_G) was determined for the days with significant storm events using equation 4.9.

$$D_{eq} = \theta i * Zi$$ …………………………… Equation 4.8

Where Θ_i is the volumetric water content in the layer, Z_i is the depth of the layer.

$$h_{eq} = D_p + D_S + D_G$$ …..…………………… Equation 4.9

The total volume of actual stormwater runoff capture (Vss) in the structure was calculated as

$$V_{ss} = A * h_{eq}$$ ……..………………… Equation 4.10

Where V: total volume of runoff capture (cm^3); A: area of the GI control (cm^2); h_e: event equivalent saturated depth (cm)

Percent of runoff capture was determined by using equation 4.11.

$$\% \text{ Runoff capture} = \left(\frac{\text{Actual Volume of runoff stored within the GI for the event)}}{\text{Inflow}}\right) * 100 \qquad \ldots\ldots \text{ Equation 4.11}$$

4.5. Percent Runoff Reduction

The runoff reduction was calculated as the ratio of the difference between inflow and resultant outflow to the inflow to the GI control for all the significant events at each site.

$$\text{Runoff Reduction} = \frac{(\text{Inflow volume} - \text{Outflo} \quad \text{Volume})}{\text{Inflow Volume}} * 100 \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ Equation 4.12}$$

Chapter 5: Results

Hydrologic performance for each study site was assessed in terms of three metrics: infiltration rate, percent runoff capture, and percent runoff reduction. The objective of the analyses was to compare response behavior in 2014/2015 to behavior in 2019. The magnitude and duration of the precipitation events varied during the three monitoring periods (Table 5).

Table 5: Overview of storm events analyzed in this study

Year	Number of rain event days	Number of discrete events > 1.27 cm	Mean value of event depth (cm)	Range of precipitation depth of selected storm events (cm)
2014 (May to September)	49	5	2.87	1.63 – 3.83
2015 (May to September)	42	11	4.75	2.09 – 9.33
2019 (May to September)	104	9	2.00	1.63 - 2.97

5.1. Infiltration Rate Analysis

The system's ability to infiltrate stormwater entering it, is considered a critical measure of its functionality. Thus, this measure was used as one of the performance indicators to assess its hydrologic behavior. For every time step, the infiltration rate was calculated as the ratio of the difference between the peak head and base head to the time taken for the base head to reach the peak head in response to a storm event.

$$\mathrm{I_t} = \frac{\text{Peak head} - \text{Base head}}{\text{Time to peak}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 5.1}$$

Infiltration rates for the selected storm events were considered for this analysis. The estimates of infiltration rates of these sites are provided in Appendix D.

Comparison of infiltration rates over time and across structure types.

The purpose of this analysis is to compare the infiltration capacity for the GI controls in 2014/2015 to that in 2019. Previous studies have suggested that precipitation depth is one of the factors that influences the infiltration rate. Thus, a univariate linear regression analysis was applied to assess if the variability in the infiltration rates is dependent on the precipitation depth and if the trends were similar or different during monitoring periods of this study. However, infiltration rate is also driven by a set of other variables such as antecedent moisture, slope of contributing area, the percentage of impervious area, and the ratio of impervious to GI area, level of ground water at the study site. Thus, a multivariate regression analysis would have given a more holistic picture of the magnitude of influence that the other factors are having on infiltration rates at the sites.

Regression analysis was done with the 2014 data, 2014 and 2015 data collectively, and 2019 data for each study site. Two statistics namely the R-squared and the slope in the model output were analyzed in detail. R-squared is a statistical measure which represents the proportion of the variation in the infiltration rate that can be attributed to precipitation depth. Slope indicates the ratio of change in infiltration per change in precipitation depth and this measure will be used to explain how the infiltration rates varied across structures. The statistical results from regression analysis of data from 2014 alone was found to be inconclusive for some sites due to the fewer number of events (5 data points). Since the objective of the study is to compare the earlier performance (2014+2015) of GI controls to their recent performance (2019), 2014 and 2015 records were analyzed collectively. Henceforth the 2014 and 2015 jointly will be referred to as period 1. All the 13 study sites showed a positive relationship between infiltration rates and precipitation depth. However, the strength of the relationship varied among the sites. The details are discussed in detail in the following sections.

Rain gardens

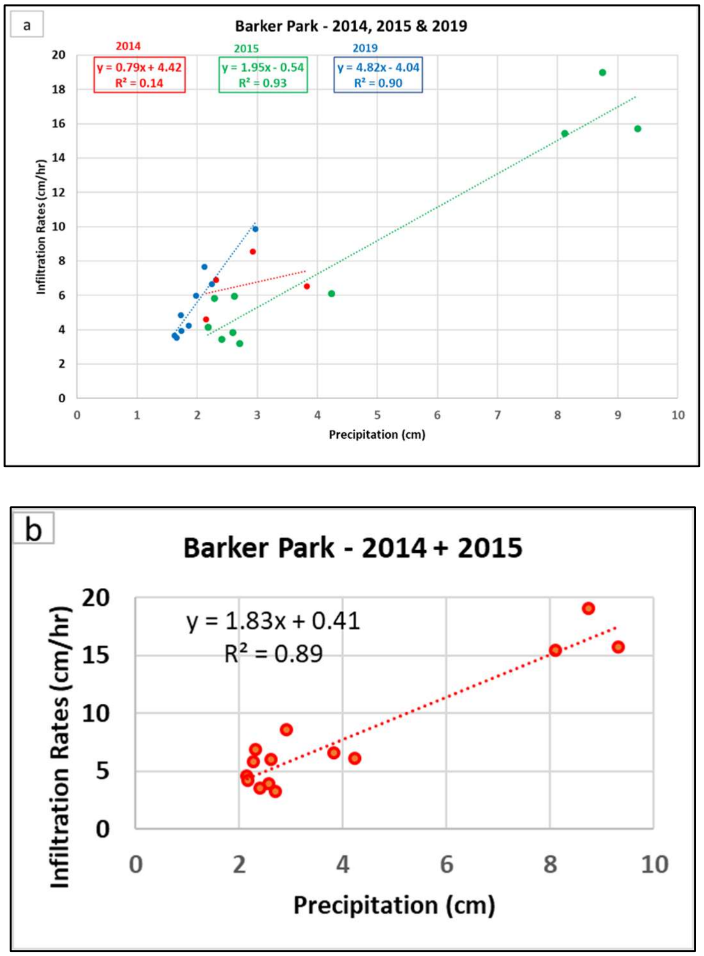


Figure 26: Regression analysis charts for Barker Park rain garden

Barker Park rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 10 days in 2015 with a range of 2.09 – 9.33 cm and 9 days in 2019 with a range of 1.63 – 2.97 cm. The corresponding infiltration rates ranged from 3.89 to 8.53 cm/hr in 2014, 3.2 to 19 cm/hr in 2015, and 3.53 to 9.85 cm/hr in 2019. The 2014 records (red) show no significant trend, but the 2015 (green) and 2019 (blue) show a strong positive trend

(Figure 26a). Similarly, the aggregated data for 2014-2015 also shows a strong positive trend (Figure 26b)

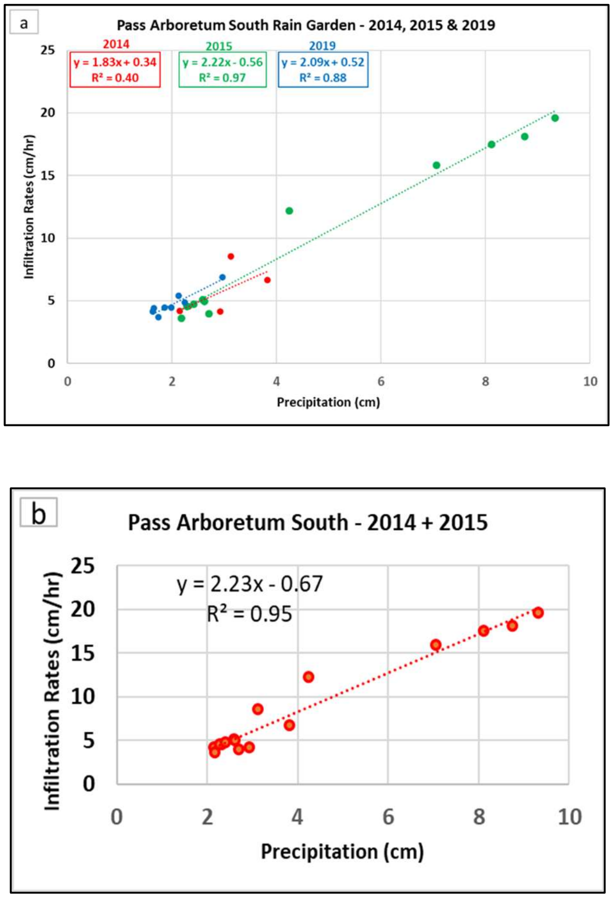


Figure 27: Regression analysis charts for Pass Arboretum south rain garden

Pass Arboretum south rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 11 days in 2015 with a range of 2.09 – 9.33 cm and 9 days in 2019 with a range of 1.63 – 2.97 cm. The corresponding infiltration rates ranged from 4.12 to 8.5 cm/hr in 2014, 3.61 to 19.59 cm/hr in 2015, and 3.68 to 6.84 cm/hr in 2019. The 2014 records (red) show a weak trend, but the 2015 (green) and 2019 (blue) show a strong positive trend (Figure 27a). Similarly, the aggregated data for 2014-2015 also shows a strong positive trend (Figure 27b)

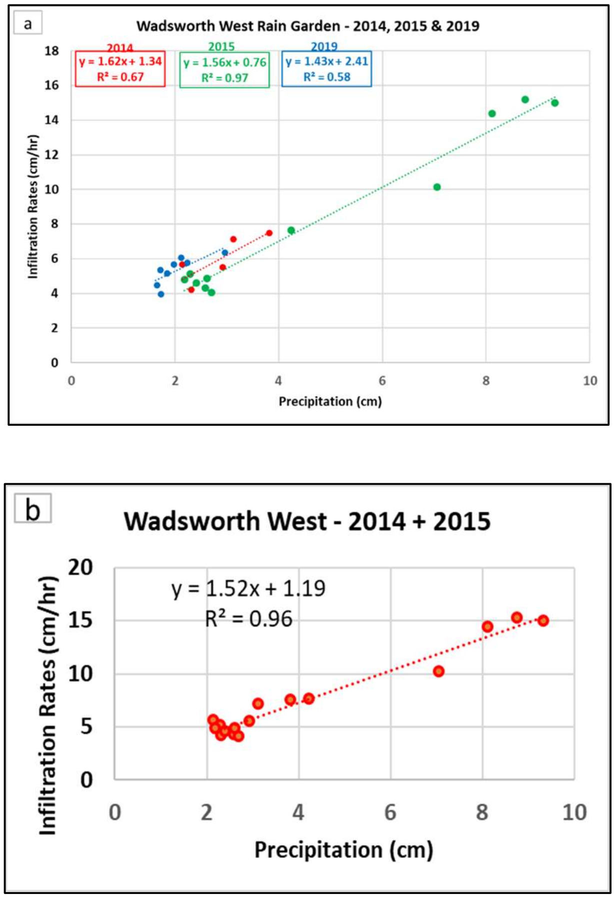


Figure 28: Regression analysis charts for Wadsworth west rain garden

Wadsworth west rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 11 days in 2015 with a range of 2.09 – 9.33 cm and 8 days in 2019 with a range of 1.66 – 2.97 cm. The corresponding infiltration rates ranged from 4.2 to 7.48 cm/hr in 2014, 4.05 to 15.2 cm/hr in 2015, and 3.95 to 6.32 cm/hr in 2019. The 2014 records (red) and 2019 records (blue) show moderate identical trends, but the 2015 (green) shows a strong positive trend (Figure 28a). However, the aggregated data for 2014-2015 also shows a strong positive trend (Figure 28b)

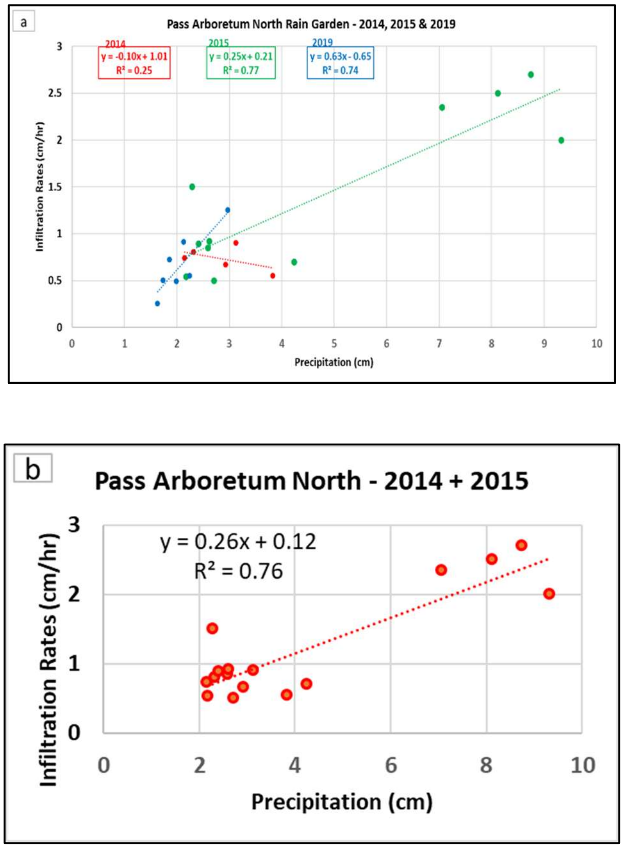


Figure 29.: Regression analysis charts for Pass Arboretum north rain garden

Pass Arboretum north rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 11 days in 2015 with a range of 2.09 – 9.33 cm and 7 days in 2019 with a range of 1.66 – 2.97 cm. The corresponding infiltration rates ranged from 0.55 to 0.9 cm/hr in 2014, 0.5 to 2.7 cm/hr in 2015, and 0.17 to 1.25 cm/hr in 2019. The 2014 records (red) show a weak decreasing trend, but the 2015 (green) and 2019 (blue) records show a strong increasing trend (Figure 29a). The aggregated data for 2014-2015 also shows a similar strong positive trend (Figure 29b)

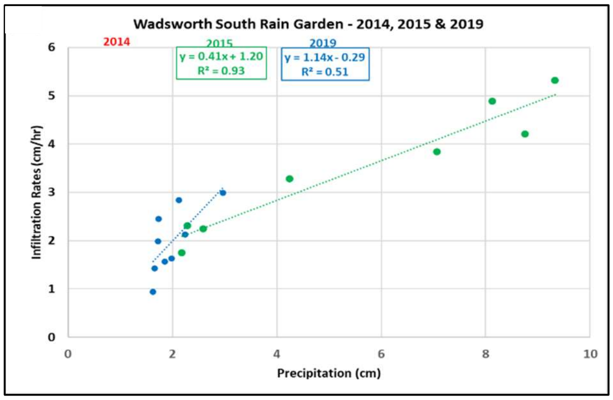


Figure 30.: Regression analysis charts for Wadsworth south rain garden

Wadsworth south rain garden showed response to precipitation on 8 days in 2015 with a range of 2.09 – 9.33 cm and 9 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 1.75 to 5.32 cm/hr in 2015 and 0.93 to 2.98 cm/hr in 2019. There was no data for this site for 2014. The 2015 records (green) show a strong increasing trend whereas 2019 records (blue) show a moderate increasing trend (Figure 30).

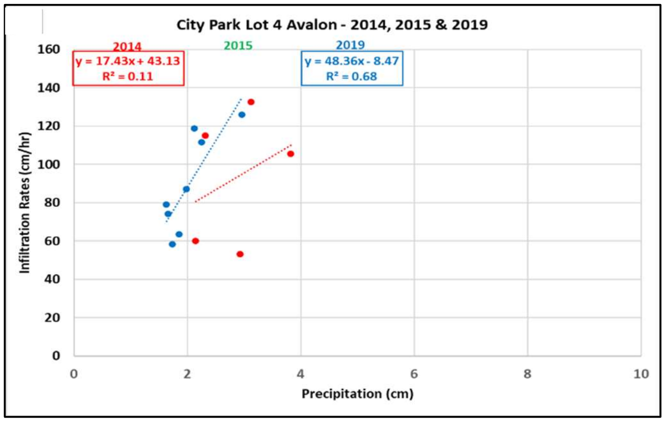


Figure 31: Regression analysis charts for City parking lot 4 rain garden

City Parking lot 4 rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm and 8 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 53 to 132.5 cm/hr in 2014 and 58.15 to 125.76 cm/hr in 2019.

There was no data for this site for 2015. The 2014 records (red) show a weak increasing trend whereas 2019 records (blue) show a moderate increasing trend (Figure 31).

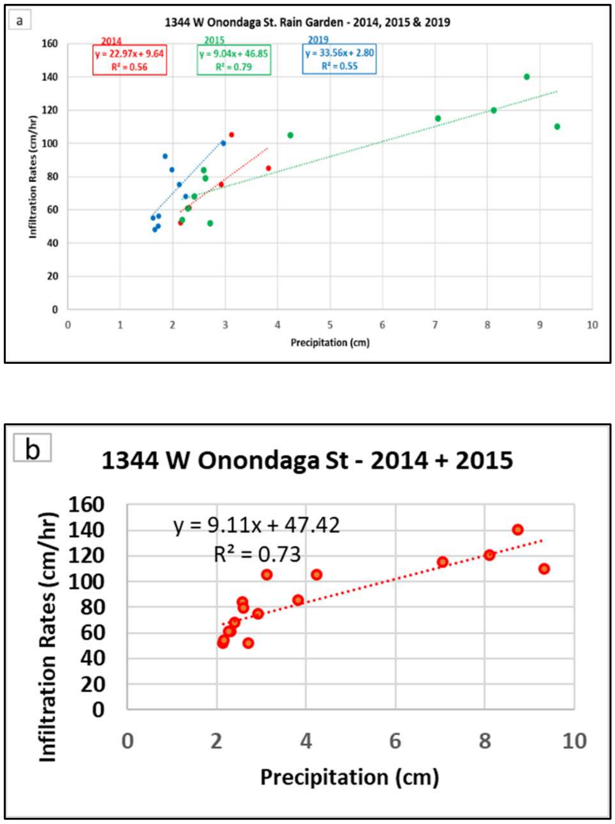


Figure 32: Regression analysis charts for 1344 W Onondaga St rain garden

1344 W. Onondaga vacant lot rain garden showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 11 days in 2015 with a range of 2.18 – 9.33 cm, and 9 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 52 to 105 cm/hr in 2014, 52 to 140 cm/hr in 2015, and 48 to 100 cm/hr in 2019. The 2014 (red) and 2019 records (blue) show moderate increasing trend whereas 2015 records (green) show a strong increasing trend (Figure 32a). Similarly, the aggregate data shows a similar strong increasing trend (Figure 32b).

Summary of results for rain gardens:

The infiltration rates at Barker park, Pass Arboretum south, and Wadsworth west show a strong positive relationship with precipitation depth and their slope values (greater than 1), indicate that the increase in infiltration rate is high per unit increase in precipitation. The weak regression statistics for 2014 records at Barker park and Pass Arboretum south indicates that these sites may have behaved differently in that year due to other factors that cannot be analyzed from this current study. Since the strength of the regression remained approximately close for 2015 and 2019, it may be inferred that there was no apparent change in the behavior of these rain gardens over time. However, Wadsworth west rain garden behaved similarly in 2014 and 2019. A higher R-squared value indicates that the proportion of variability in infiltration rate was strongly attributed to the precipitation depth during 2015.

The Pass Arboretum north rain garden showed a significant variability in infiltration rate as a function of precipitation depth. Since the strength of the relationship remained almost the same for 2015 and 2019, it may be concluded that their behavior did not change over time. The results for Wadsworth south rain garden showed a slightly stronger response in 2015 than in 2019.

Pass Arboretum north and Wadsworth south rain gardens have slopes less than 1. This indicates that there is less change in infiltration rate per unit increase in precipitation. This may be attributed to the high groundwater level at these sites.

City parking lot showed better response in 2019 than 2014. The rain garden at this study site is designed to receive inflow from overland flow from steeply sloped surfaces as well as inlet storm drains. It receives inflow from a large impervious area. Thus, a multivariate regression analysis may be helpful for understanding the behavior of this GI retrofit. The high slope values imply that the change in infiltration rates due to a unit increase in precipitation depth is high.

The rain garden on the W. Onondaga street showed similar behavior in 2014 and 2019, but it showed a stronger dependence on precipitation depth in 2015. Similar to the rain garden on City parking lot 4, this rain garden also receives inflow from inlet storm drains and overland runoff. Since there are other factors driving infiltration at this site, a multiple regression analysis may be more useful for this site as well. A high slope value indicates that the change in infiltration rate is very high with a unit increase in precipitation.

Infiltration Trenches

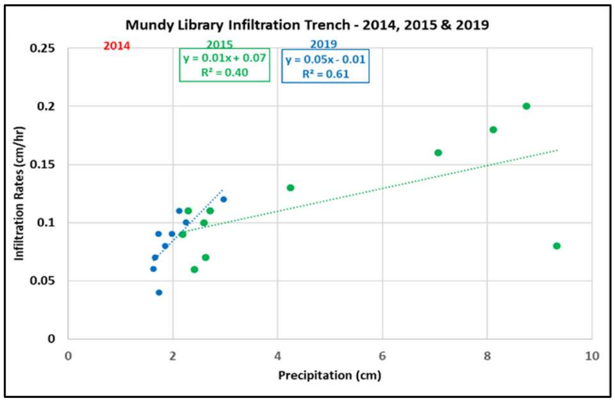


Figure 33: Regression analysis charts for Mundy library infiltration trench

Mundy Library infiltration trench showed response to precipitation on 11 days in 2015 with a range of 2.18 – 9.33 cm, and 9 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 0.06 to 0.2 cm/hr in 2015 and 0.04 to 0.12 cm/hr in 2019. This site was not monitored in 2014. The 2015 (green) and 2019 records (blue) show moderate increasing trend (Figure 33).

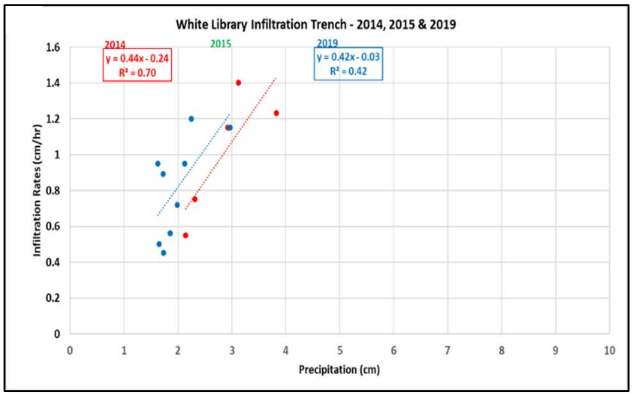


Figure 34: Regression analysis charts for White library infiltration trench

White Library infiltration trench showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, and 9 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 0.55 to 1.4 cm/hr in 2014 and 0.45 to 1.2 cm/hr in 2019. This site was not monitored in 2015. The 2014 records (red) show a strong increasing trend and 2019 records (blue) show moderate increasing trend (Figure 34).

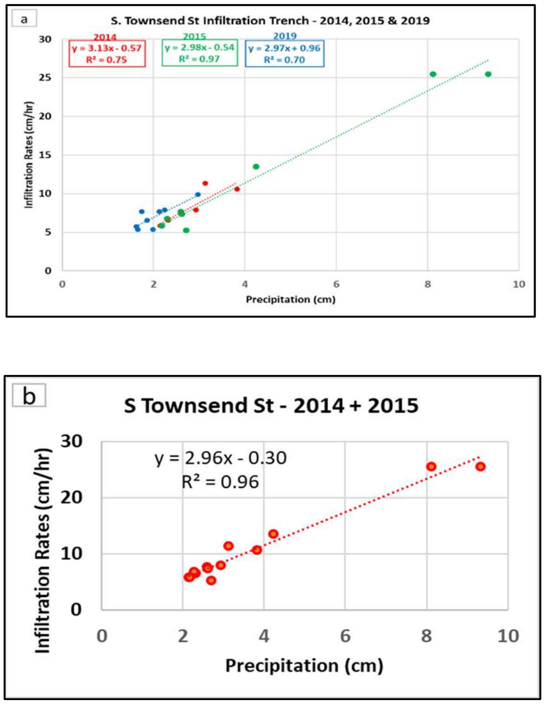


Figure 35: Regression analysis charts for S. Townsend St infiltration trench

S. Townsend St. infiltration trench showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 8 days in 2015 with a range of 2.18 – 9.33 cm and 8 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 5.83 to 11.34 cm/hr in 2014, 5.23 to 25.5 in 2015, and 5.31 to 9.86 1.2 cm/hr in 2019. The 2014 records (red) and 2019 records (blue) show a strong increasing trend, but 2015 records (green) show a stronger increasing trend (Figure 35a).

Summary of results for infiltration trenches

The infiltration trenches at Mundy library and White library shows moderate relationship with the precipitation depth. This may be because these two sites lie in low wetland areas due to which the stage in these GI controls is controlled by the groundwater stage. The infiltration trench at Mundy library showed similar responses in 2015 and 2019. The infiltration trench at White library showed better response in 2014 than 2019. It was observed that this site was poorly maintained. The infiltration performance of infiltration trench at S. Townsend St seems to have decreased from 2015 to 2019.

Permeable Pavements

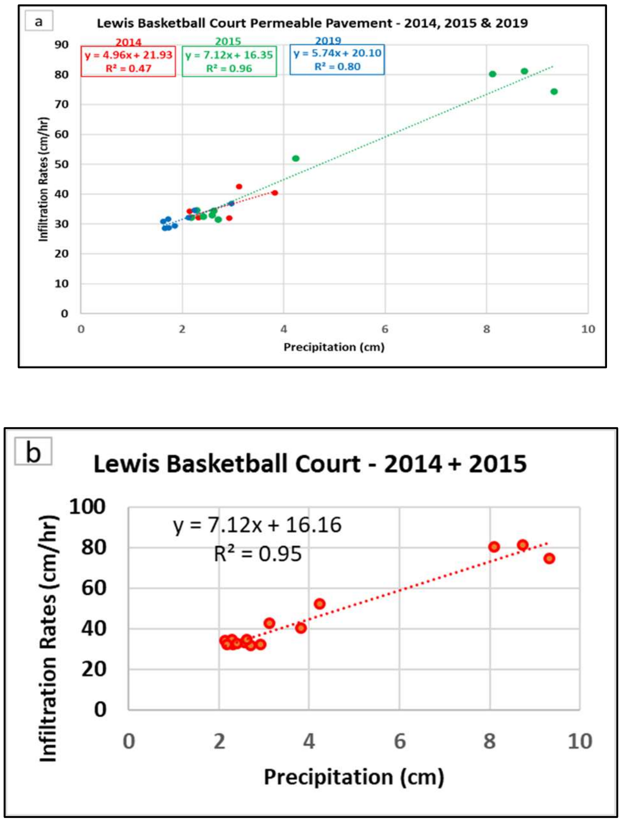


Figure 36: Regression analysis charts for Lewis basketball court permeable pavement

Lewis Basketball Court permeable pavement showed response to precipitation on 5 days in 2014 with a range of 2.15 – 3.83 cm, 10 days in 2015 with a range of 2.18 – 9.33 cm and 8 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 31.89 to 42.4 cm/hr in 2014, 31.45 to 81.25 cm/hr in 2015, and 28.49 to 36.78 cm/hr in 2019. The 2014 records (red) show a weak trend, but 2015 records (green) and 2019 records (blue) show a strong increasing trend (Figure 36a). The aggregate data shows a similar strong increasing trend (Figure 36b).

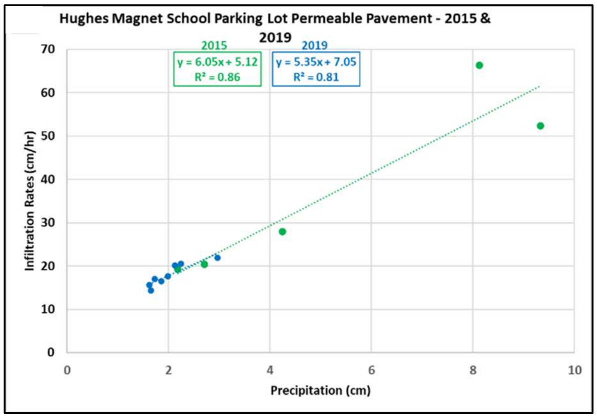


Figure 37: Regression analysis charts for Hughes Magnet School parking lot permeable pavement

Hughes Magnet School permeable pavement showed response to precipitation on 5 days in 2015 with a range of 2.18 – 9.33 cm and 8 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 19.25 to 66.40 in 2015 and 14.35 to 21.83 cm/hr in 2019. This site was not monitored in 2014. The 2015 records (green) and 2019 records (blue) show a strong increasing trend (Figure 37).

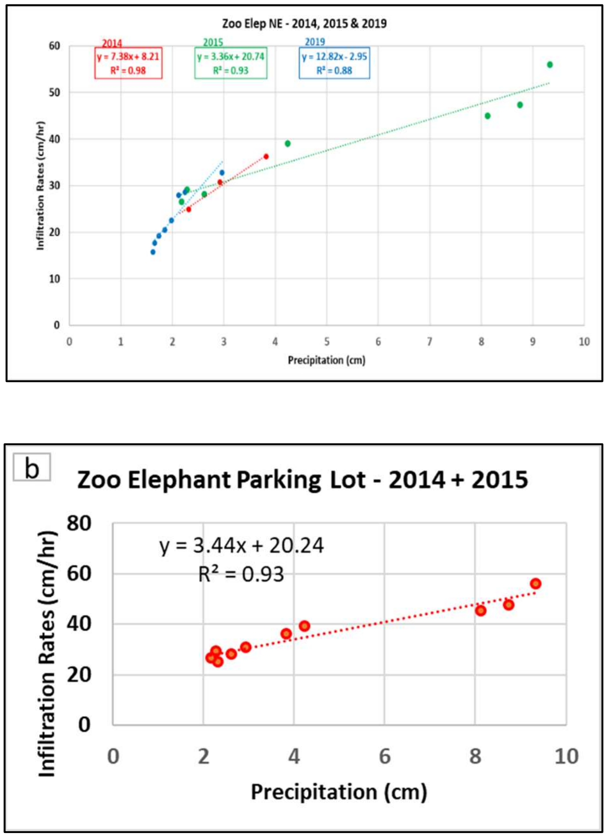


Figure 38: Regression analysis charts for Zoo Elephant parking lot permeable pavement

Zoo Elephant parking lot permeable pavement showed response to precipitation on 3 days in 2014 with a range of 2.32 – 3.83 cm, 7 days in 2015 with a range of 2.18 – 9.33 cm and 8 days in 2019 with a range of 1.66 - 2.97 cm. The corresponding infiltration rates ranged from 24.85 to 36.15 cm/hr in 2014, 26.53 to 56 cm/hr in 2015, and 15.71 to 32.73 cm/hr in 2019. The 2014 (red), 2015 (green), and 2019 (blue) records show a strong positive trend (Figure 38a). The aggregate data also shows a similar strong increasing trend (Figure 38b).

Summary of results for permeable pavements

The three permeable pavements showed strong regression statistics. All the three sites show a strong relationship with precipitation depth and have slope values greater than 1. The strength of the relationship remained almost the same across the study periods. This indicates that their hydrologic behavior remained the same.

5.2. Percent Runoff Capture Analysis

Percent runoff capture is another critical measure that indicates how effective GI systems are at capturing the stormwater runoff inflow. It represents the percentage of runoff volume collected by the system for a given storm event.

Rain Gardens

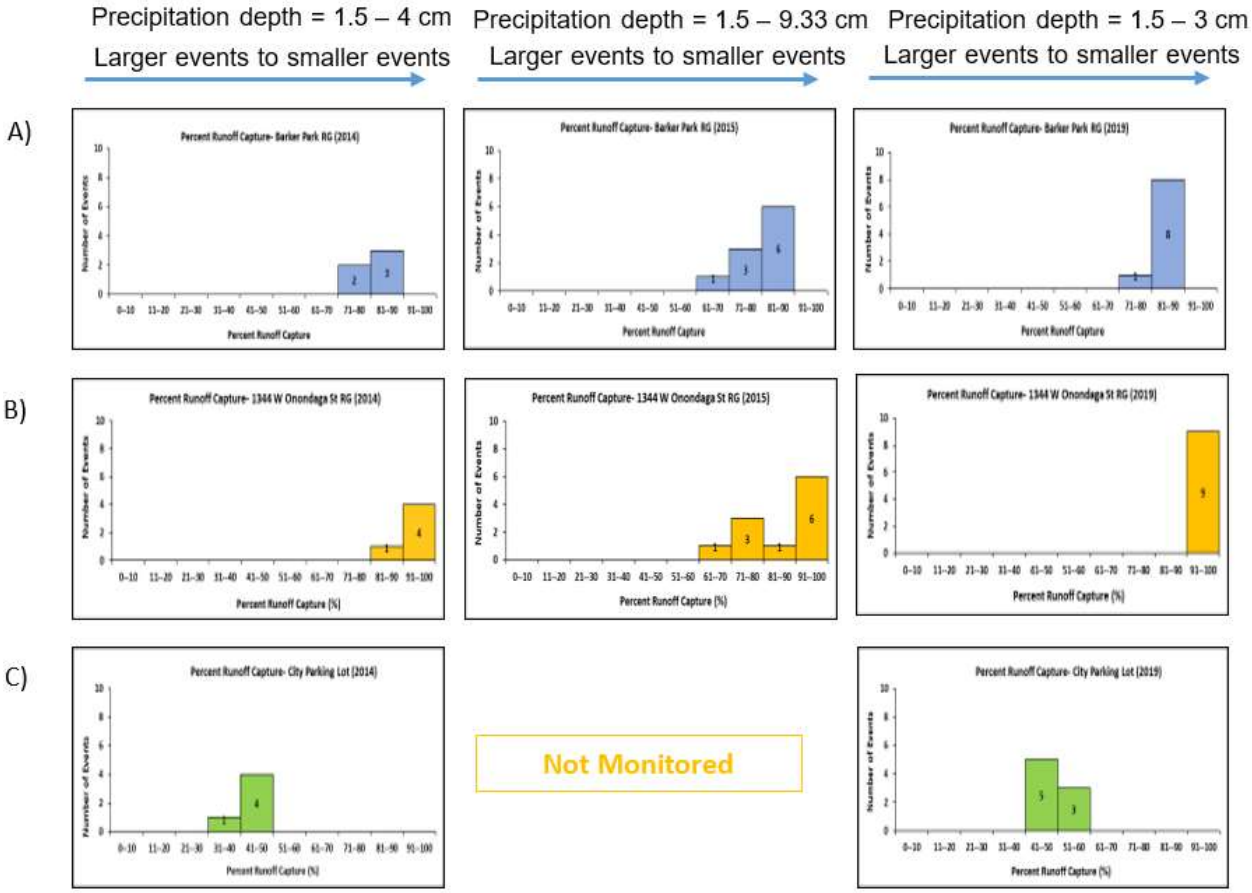


Figure 39: Frequency-analyses plots for percent runoff capture A) Barker Park rain garden B) 1344 W Onondaga St. rain garden C) City parking lot 4 rain garden.

The percent runoff capture were in the range of 70 to 90 in 2014, 60 to 90 in 2015, and 70 to 90 in 2019 for the rain garden at the Barker Park. The runoff capture by the rain garden on the W. Onondaga street was 80-100 percent of the stormwater runoff in 2014, 60 – 100 percent in 2015, and 90-100 percent in 2019. The rain garden on the city parking lot 4 was able to capture 30-50 percent of the stormwater runoff in 2014, and 40-60 percent in 2019.

Although these rain gardens are similarly sized, the percentage of stormwater runoff that they can capture varies. The city parking lot 4 rain garden receives large exogenous overflow from the highways and from the inlet storm drains. The percentage of impervious area contributing runoff to this rain garden is large when compared to these other two rain gardens. The size of the rain garden is small relative to the impervious area.

The rain garden on the W. Onondaga street shows the highest percent runoff capture among the three rain gardens and this may be attributed to its larger plan area and lower ratio of impervious to GI area. Also, from the recession limbs on the hydrographs, it can be observed that the W. Onondaga lot rain garden has shorter recession times and greater soil storage depth, whereas the city Parking lot 4 rain garden shows slower recession. This may explain the greater storage capacity for runoff capture at W. Onondaga lot rain garden when compared to the City Parking lot that has reduced storage capacity.

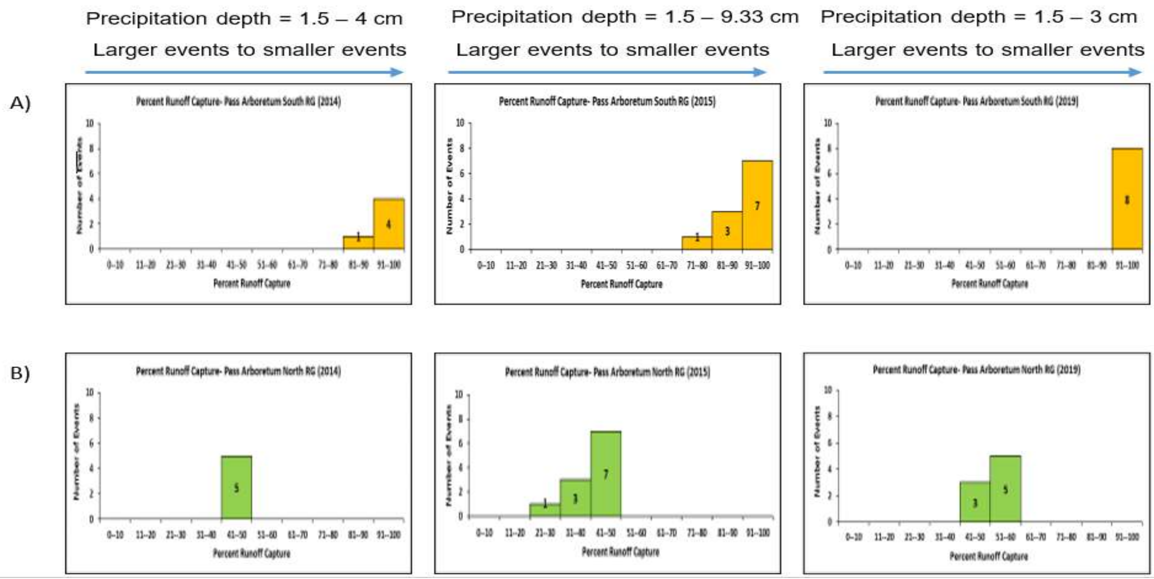


Figure 40: Frequency-analyses plots for percent runoff capture A) Pass Arboretum south rain garden B) Pass Arboretum north rain garden

The two gardens in located in the Pass Arboretum performed differently. The percent runoff capture varied from 80-100 in 2014, 70-100 in 2015, 90-100 in 2019 for Pass Arboretum south rain garden, whereas the Pass Arboretum South rain garden was able to capture 40-50 percent of the stormwater runoff in 2014, 20-50 percent in 2015, and 40-60 percent in 2019.

Pass Arboretum south rain garden shows the highest percent runoff capture compared to all the other sites and this may be attributed to its design features. It is the largest in size among all the 7 rain gardens but receives lesser runoff volumes when compared to the other smaller sized rain gardens with approximately the same catchment areas but higher impervious areas (Barker Park and Wadsworth west).

On the other hand, the rain garden on the north of Pass Arboretum almost always had an elevated base head due to which it may have had reduced infiltration, storage capacity, and runoff capture.

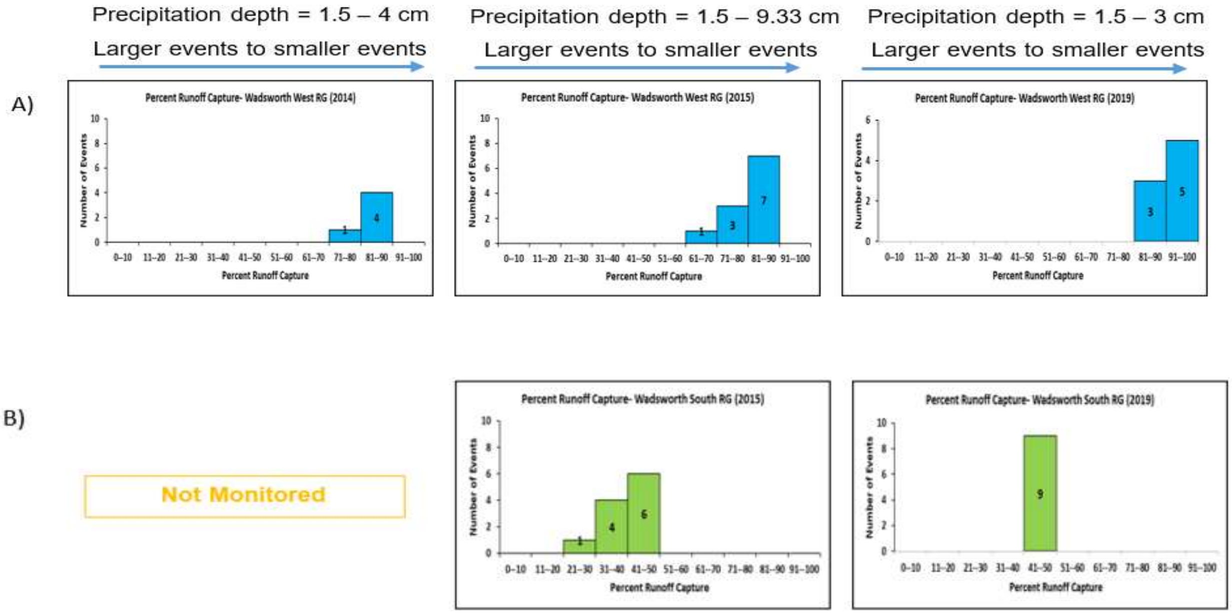


Figure 41: Frequency-analyses plots for percent runoff capture A) Wadsworth west rain garden B) Wadsworth south rain garden

The data shows that the rain garden on the West performed better than the rain garden on the South of Wadsworth Park. The percent runoff capture ranged from 70-90 in 2014, 60-90 in 2015, and 80-100 in 2019 for Wadsworth West rain garden. The rain garden on the south was able to capture 20-50 percent of the stormwater runoff in 2015 and 40-50 percent in 2019.

The Wadsworth South rain garden always showed an elevated base head which may be due to the high groundwater level at the site. This site also has a high impervious to GI area ratio. The groundwater controls the stage in the GI control. Thus, the rain garden remained constantly saturated and this may have led to reduced runoff capture.

The percent runoff capture at the Wadsworth West rain garden was high and similar to the Barker Park rain garden. This may be due to the similarities in GI areas, impervious to GI area ratios, and total catchment areas.

Infiltration Trenches

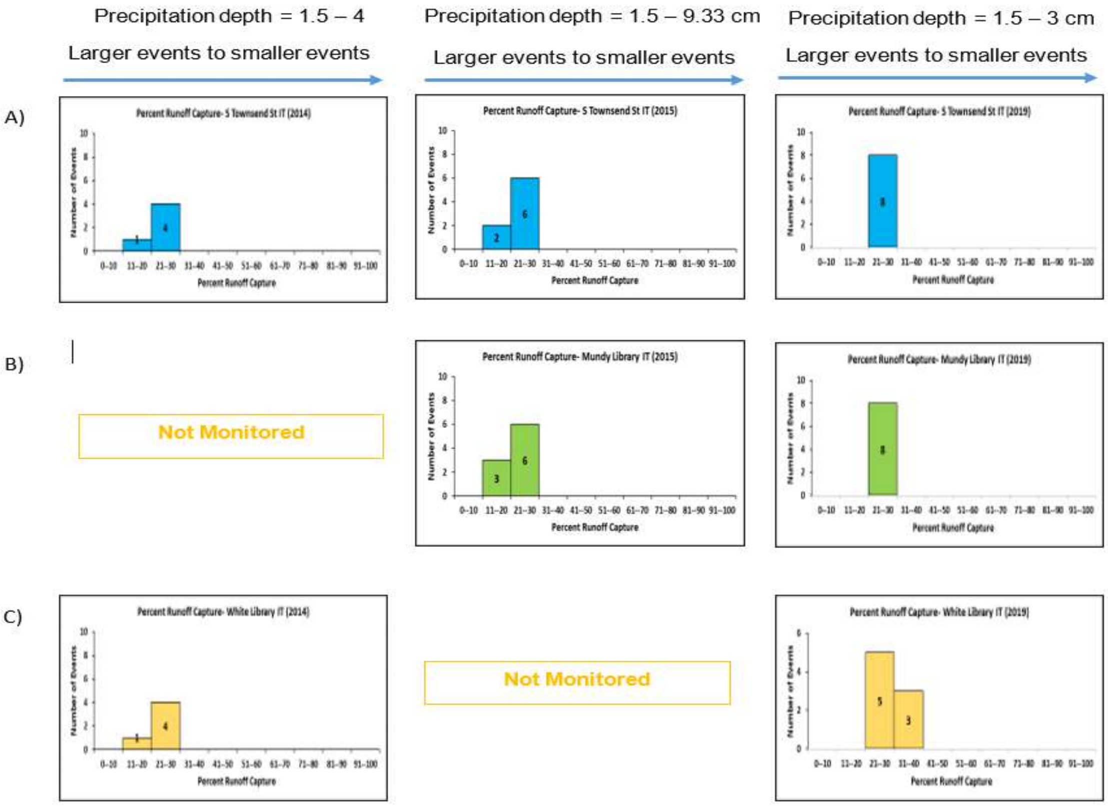


Figure 42: Frequency-analyses plots for percent runoff capture A) S. Townsend St B) Mundy Library C) White library

All three infiltration trenches showed reduced runoff capture when compared to the rain gardens that had nearly the same percentage of impervious areas and high groundwater levels (Wadsworth south and Pass Arboretum north). This may be due to smaller plan areas with reduced storage capacity. In addition to this, these infiltration trenches are built in areas with high groundwater levels. As a result, the wetland stage is controlling the stage in the GI control. Also, the infiltration trench was poorly maintained. The infiltration trench on S. Townsend St. parking lot showed less runoff capture. This may be due to the smaller plan area relative to the runoff volumes that it receives from large contributing areas.

Permeable Pavements

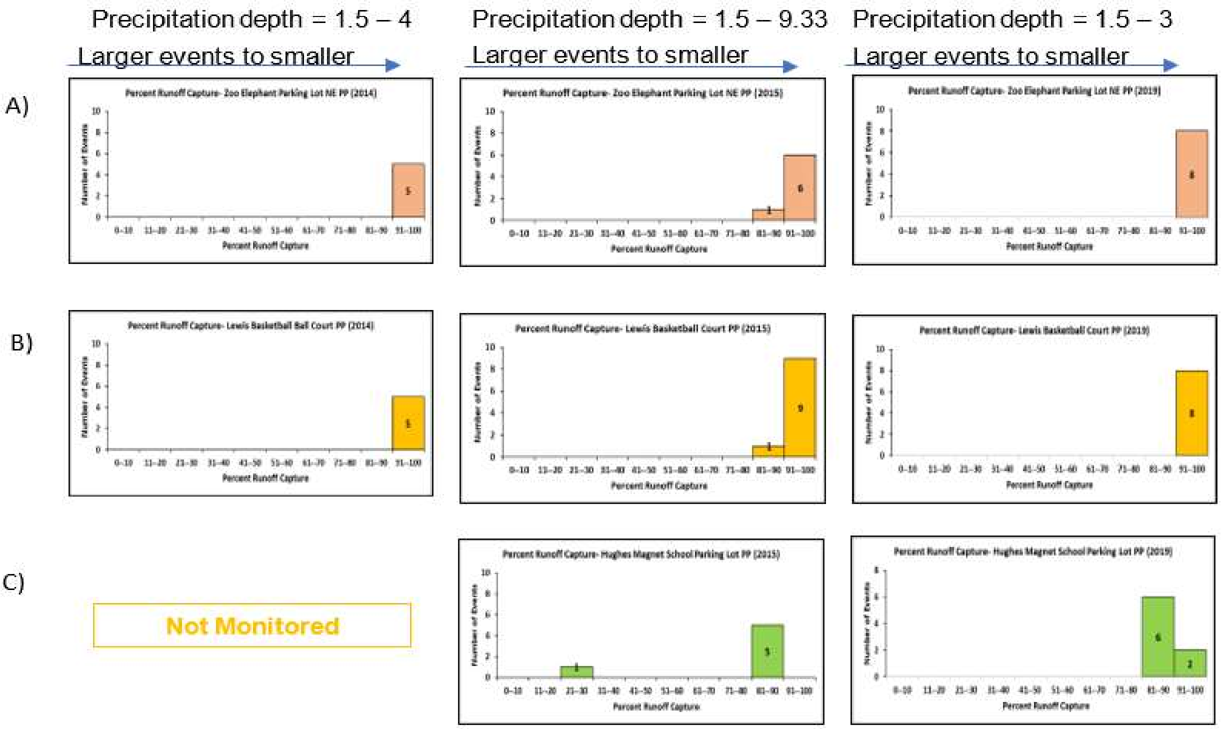


Figure 43: Frequency-analyses plots for percent runoff capture A) Zoo Elephant parking lot NE B) Lewis basketball court C) Hughes Magnet school parking lot

Permeable pavements showed the highest runoff capture compared to the other two GI types. The percent runoff capture ranged from 90 to 100 in 2014, 80 – 100 in 2015, and 90 – 100 in 2019 at both the Lewis basketball court and the zoo elephant parking lot. At Hughes Magnet school parking lot, it ranged from 20-90 percent in 2015, 80-100 percent in 2019. The large volume of runoff capture at these sites is likely related to the greater storage capacities and infiltration rates, and lower impervious to GI area ratios. Again, the hydrographs showed faster recession rates for the porous pavement sites than for the other technologies. The void spaces in the porous asphalt layer allows precipitation to infiltrate quickly, and the void spaces in the gravel layer provides temporary storage for large runoff volumes. The lower percent runoff capture at Hughes magnet school parking lot may be due to its smaller plan area with a higher impervious area.

5.3. Overflow Analysis and Percent Runoff Reduction

The number of overflow events and overflow volumes that occurred at the study sites during the monitoring periods are provided in Appendix E.

Measurable outflows occurred only at 2 of the rain gardens (Barker Park & City Parking lot 4 Avalon). The rainfall depth for which outflows occurred ranged from 0.97 cm to 9.33 cm for Barker Park rain garden and 1.08 cm to 3.13 cm for the rain garden at the City Parking lot 4.

A rainfall depth of 9.33 cm (5-year design storm event) resulted in overflow from the permeable pavements (Zoo Elephant Parking Lot NE, Lewis Basketball Court, & Hughes Magnet School) in 2015. There were no overflow events at any of the three infiltration trenches. The infiltration trenches at the Mundy Library and White Library are built in low wetland areas and the runoff captured by these sites may be recharging the wetland. The absence of occurrence of overflow events at this site may be attributed to the reason mentioned above.

The storm hydrographs show that the at Barker Park rain garden had slower recession rates than other sites. As a result of slower recession, the drainage between successive rain events may have been incomplete, leading to frequent small overflows at this site. The rain garden at City Parking lot 4 receives a greater volume of stormwater runoff than other rain gardens of similar sizes. The reduced storage capacity may explain the incidence of overflow events at this site.

The high R-squared values and p-values (<0.05) from the regression analysis for both the sites indicate that outflow from these GI controls was significantly dependent on the precipitation depth. However the City Parking lot 4 rain garden showed a slightly lesser dependence on precipitation depth when compared to the Barker Park rain garden. This analysis supports the premise that extenuating circumstances occasionally influence the performance of this site (Figure 44).

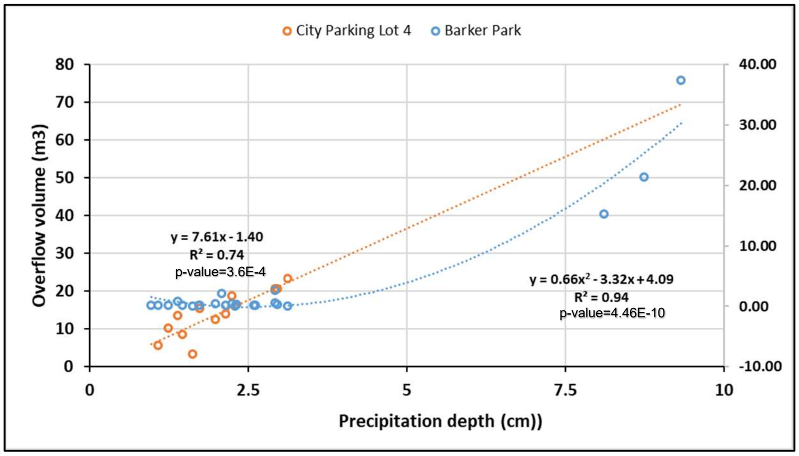


Figure 44: Regression analysis chart for overflow volume and precipitation depth

The percent runoff reduction ranged from 64 to 100 at Barker Park rain garden, 50 to 80 at the City Parking lot 4 rain garden, and 100 for all the other rain gardens (Figure 45). The regression analysis between precipitation depth and percent runoff reduction shows that the runoff reduction is significantly dependent (high R-squared and low p-value) on the precipitation depth at Barker Park rain garden whereas the percent runoff reduction at the City Parking lot 4 rain garden shows an insignificant relationship with precipitation depth (low R-squared and high p-value). This indicates that there may be other factors that are strongly influencing the runoff reduction at City Parking lot 4 rain garden.

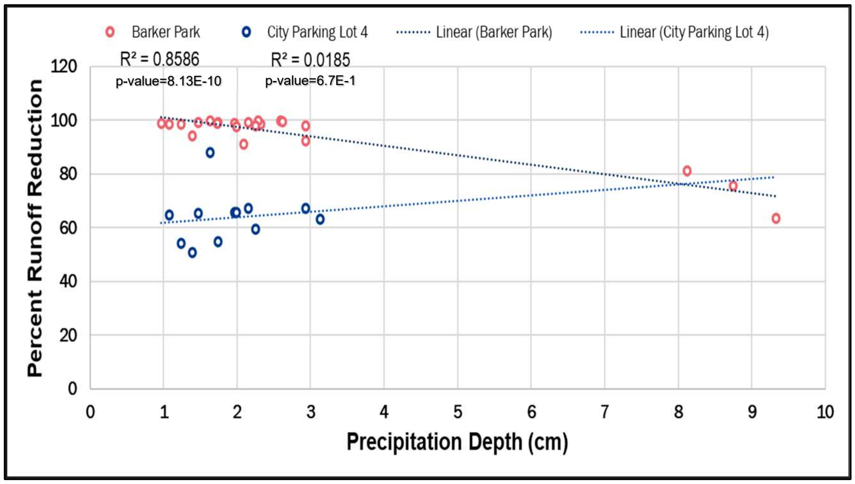


Figure 45: Regression analysis chart for percent runoff reduction and precipitation depth

Permeable pavements reduced the runoff by 100 % in response to all the storm events except for an event measuring 9.33 cm (5-year design storm event) in 2015. This runoff reduction for this event was 91% at the Zoo Elephant parking lot, 88% at the Lewis Basketball court, and 22 % at Hughes Magnet School parking lot. However, the permeable pavement at Hughes Magnet parking lot responded differently compared to the other two. This site receives larger volumes of runoff although this is smaller than the other two sites.

Chapter 6: Discussion

The findings from the analysis of three different types of GI controls presented in this study indicates that their performance decreases in the order of permeable pavements, rain gardens, and infiltration trenches. An assessment of probable causes for the variability in infiltration rates, percent runoff capture and runoff reduction within and across structures was done.

Some earlier studies have provided evidence that the factors that influence the hydrologic performance are structure type, media depth, storage capacity, drainage area to GI area ratio, geographical conditions, and vegetation type (Dietz 2007; Hatt et al., 2009; Hunt et al., 2006, 2008; Roseen et al., 2012).

Similar to previous studies the findings from this study indicated that the variations in behavior within the same type of GI structure seems to be due to the differences in design, drainage configuration, and geomorphology characteristics among the sites. We found that the two rain gardens which are similarly sized (Barker park and City parking lot 4) showed different responses because of the differences in the slopes of their drainage areas and the impervious to GI area ratio. The other two rain gardens (Wadsworth south and Pass arboretum north) showed decreased performances due to their geomorphology characteristics.

Similarly, infiltration trenches (Mundy library and White library) showed decreased performance. These sites maintained an elevated saturated head as these are located in areas of low topographic relief. The reduced performance of the infiltration trench at S. Townsend St can be explained by the high impervious to GI area ratio. Based on anecdotal evidence, there was poor maintenance of some sites (White library infiltration trench, Wadsworth south rain garden, city parking lot, and Pass Arboretum North rain garden).

In addition to the factors that were considered in earlier literature, this study showed that the groundwater level also maybe one of the controlling factors of their hydrologic response. A detailed analysis to corroborate this finding would be necessary as investigating this was not the purpose of this study.

Previous studies reported that the infiltration rate depends on the precipitation depth, site design, size of the GI, ratio of GI area to total capture area, soil media depth, available storage capacity, and antecedent moisture conditions (Le Coustumer et al., 2007; Leming and Malcom., 2007; Tennis et al., 2004; Davis et al., 2004).

The regression analysis performed on the rate of infiltration, overflow volumes and percent runoff reduction demonstrated strong dependence on precipitation depth. Although the infiltration performance at all the study sites showed an increasing trend with precipitation depth, the proportion of variability in infiltration rate with increase in precipitation differed at all the GI controls. However, sites where other factors like groundwater level, slope of the contributing area, and percentage of impervious area generating runoff may be the drivers of their hydrologic performance showed weaker trends (City Parking lot, Pass Arboretum North, Wadsworth south, Mundy library, white library). Thus, the findings of this study emphasize the importance of multivariate regression analysis.

The regression analysis of infiltration rate and frequency analyses of percent runoff capture for all the sites indicated that the hydrologic functioning seemed to have remained the same across the study periods for many of the sites-Barker Park rain garden, Pass Arboretum South rain garden, Wadsworth West rain garden, 1344 W Onondaga Lot rain garden, zoo elephant parking lot permeable pavement, Lewis basketball court, and Hughes Magnet School parking lot. From these analyses, it was clear that the slight variations in their performance over the study periods were a function of precipitation depth.

Overall, most of the rain gardens and all the three permeable pavements exhibited the desired performance.

Chapter 7: Conclusions

The hydrologic performance of the three types of GI controls were evaluated in terms of three metrics; infiltration rate, percent runoff capture, and percent runoff reduction. Infiltration rates were highest for City Parking Lot 4, 1344 W. Onondaga St, Zoo Elephant Parking Lot, Lewis Basketball Court, and Hughes Magnet School Parking Lot. The infiltration rates were lower for Barker Park, Pass Arboretum South, Wadsworth West, and S. Townsend Infiltration Trench. Mundy library, White library, Pass Arboretum north, and Wadsworth South showed the lowest infiltration rates. Regression analysis of infiltration rates showed positive relationships with precipitation depth for all study sites. The difference in the regression statistics among sites is related to the range of depth for the rainfall events. Sites with weaker trends, appear to be due to the local influence of topography, drainage configuration and storage capacity.

GI controls with the highest percent runoff capture include Barker Park (60% – 90%), Pass Arboretum south (70% - 100%), 1344 W. Onondaga (60%-100%), Wadsworth west (60% - 100%), Zoo elephant parking lot (80% - 100%), Hughes Magnet school (80% - 100%), and Lewis basketball court (80% to 100%). GI controls that provided lowest percent runoff capture are City parking lot 4 (30% - 60%), Pass Arboretum north (20% - 60%), Wadsworth south (20% - 50%), Mundy library (11% - 30%), White library (11% - 40%), and S. Townsend St. (11% to 30%).

Overflow events occurred regularly only at Barker Park rain garden and City Parking Lot 4 rain garden. Regression analysis showed that the overflow volume increased with increase in precipitation depth. A 5-year design storm event of 9.33 cm with a 5-day antecedent moisture of 7.57 cm resulted in outflows at all the three permeable pavements.

The percent runoff reduction varied from 64 to 100% for Barker Park, 50 to 80 % for City Parking Lot 4 and 100 % for all other rain gardens. The percent runoff reduction ranged from 90 – 100 % for Zoo Elephant parking lot, 80 – 100 % for Lewis Basketball Court, and 22-100% for Hughes Magnet School parking lot.

The study suggests that the variability in the behavior of these sites across study periods was a function of precipitation depth and poor maintenance at some sites.

The findings revealed that design and field variables have a collective effect on the hydrologic performance of GI retrofits. The magnitude of their influence may vary from one study site to another. Thus, it is essential to perform field evaluations of their behavior post-installation and explore long-term trends at these sites to gain insights on all the contributing factors. This information would provide basis for selecting their plan area, drainage characteristics, and placement.

The limitations of this study were the limited number of datasets for detailed statistical analysis. Also, the comparison over the years is challenging due to the differences in the rain events across the study periods.

A recommendation for future studies is to perform a multivariate regression analysis on a larger dataset with all the influential factors included in the analyses.

As shown in this study, the infiltration rate, percent runoff capture, and percent runoff reduction could be used as a simple diagnostic tool to assess structure performance.

Appendices

Appendix-A

Fig. A-1 Plan view for Barker park rain garden

Fig. A-2 Plan view for Pass Arboretum north and south rain gardens

Fig. A-3 Plan view for 1344 W. Onondaga St. rain garden

Fig. A-4 Plan view for Wadsworth south rain garden

Fig. A-5 Plan view for Wadsworth west rain garden

Fig. A-6 Plan view for city parking lot 4 rain garden

Fig. A-7 Plan view for white library infiltration trench

Fig. A-8 Plan view for S. Townsend Street parking lot infiltration trench

Fig. A-9 Plan view for Mundy library infiltration trench

Fig. A-10 Plan view for Lewis basketball court permeable pavement

Fig. A-11 Plan view for zoo elephant lot NE permeable pavement

Fig. A-12 Plan view for Hughes magnet school parking lot permeable pavement

Appendix-B

Fig. B-1 (a) Hydrograph for Barker park rain garden (2014)

Fig. B-1 (b) Hydrograph for Barker park rain garden (2015)

Fig. B-1 (c) Hydrograph for Barker park rain garden (2019)

Fig. B-2 (a) Hydrograph for 1344 W. Onondaga St. rain garden (2014)

Fig. B-2 (b) Hydrograph for 1344 W. Onondaga St. rain garden (2015)

Fig. B-2 (c) Hydrograph for 1344 W. Onondaga St. rain garden (2019)

Fig. B-3 (a) Hydrograph for Pass Arboretum north rain garden (2014)

Fig. B-3 (b) Hydrograph for Pass Arboretum north rain garden (2015)

Fig. B-3 (c) Hydrograph for Pass Arboretum north rain garden (2019)

Fig. B-13 (b) Hydrograph for Hughes Magnet school parking lot permeable pavement (2019)

Appendix C

Table C-1 Precipitation records for 2014, 2015, and 2019

Appendix D: Estimates of Infiltration Rates of Rain Gardens, Infiltration Trenches, and Permeable Pavements

Appendix E: Number of overflow events and estimates of outflows for the study sites during the study periods

Appendix-A: Site Plans

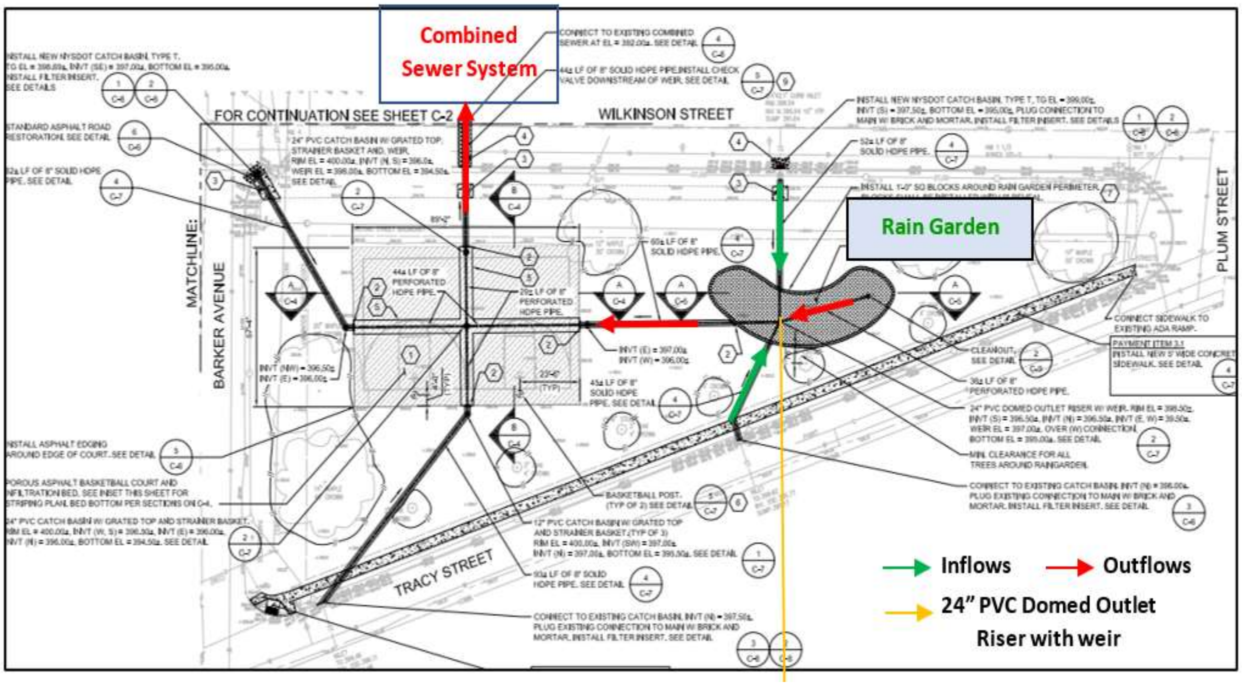


Fig. A-1 Plan View for Barker Park Rain Garden

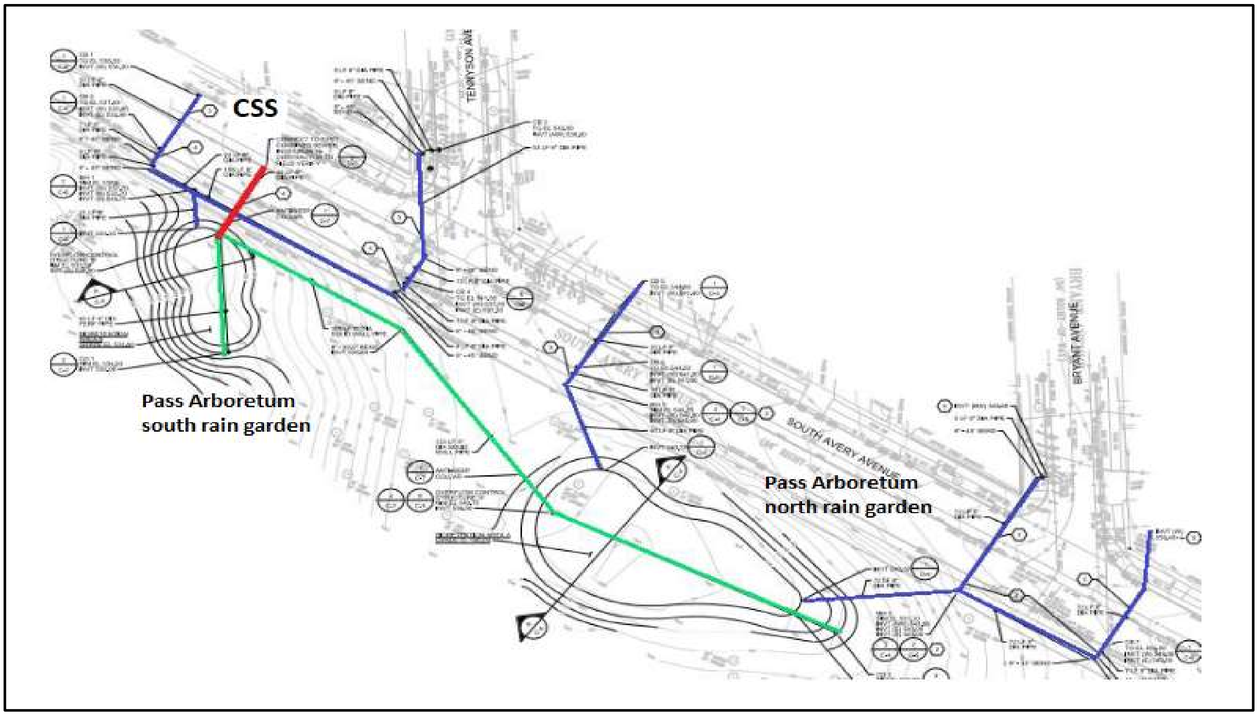


Fig. A-1 Plan View for Pass Arboretum North and South Rain Garden

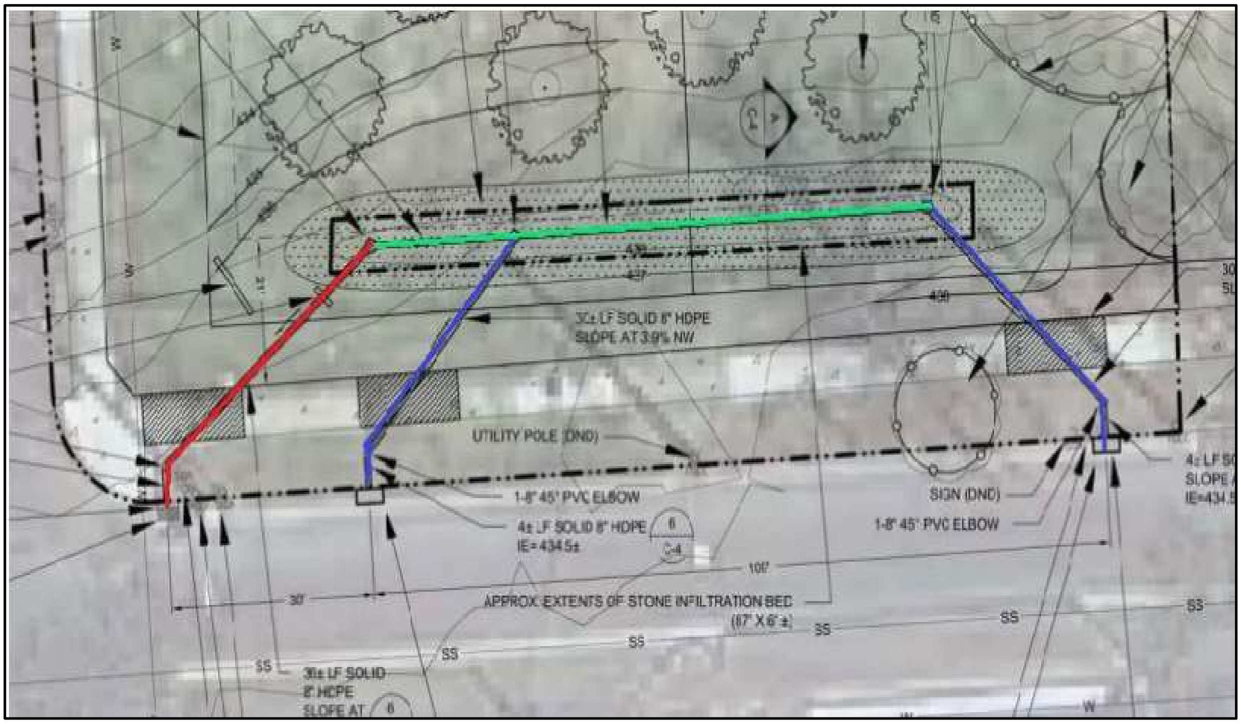


Fig. A-3 Plan View for 1344 W. Onondaga St. Rain Garden

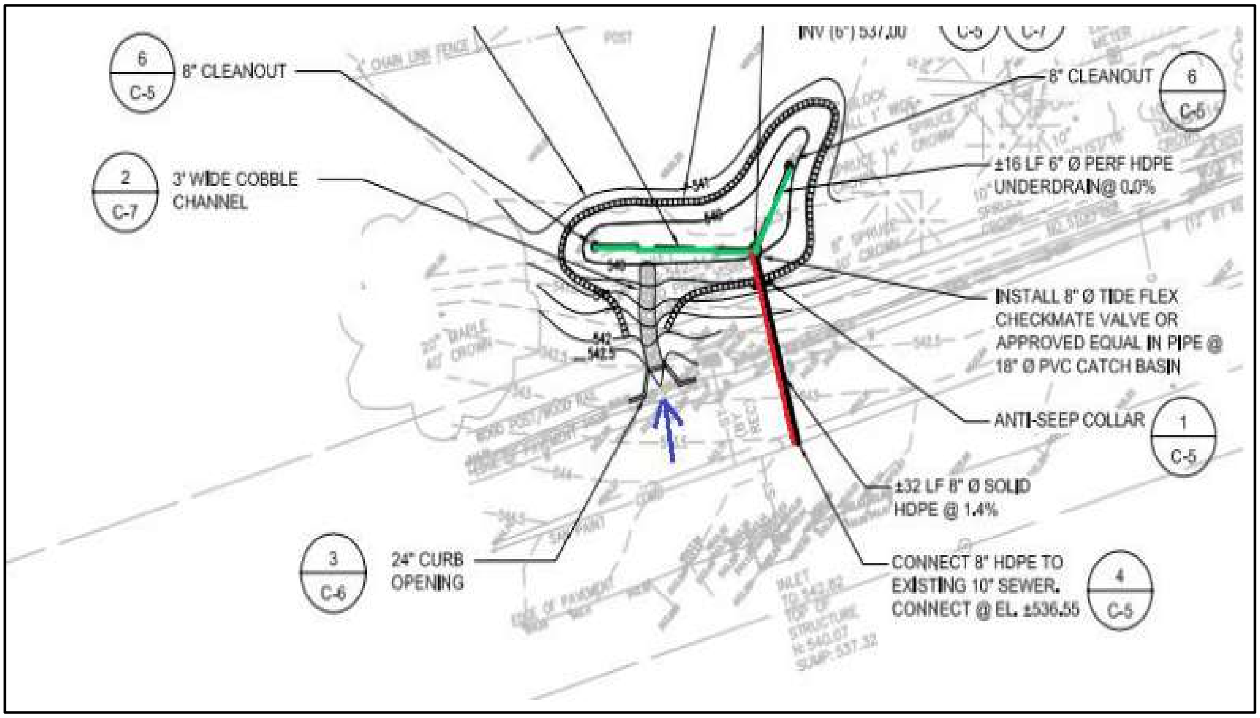


Fig. A-4 Plan View for Wadsworth South Rain Garden

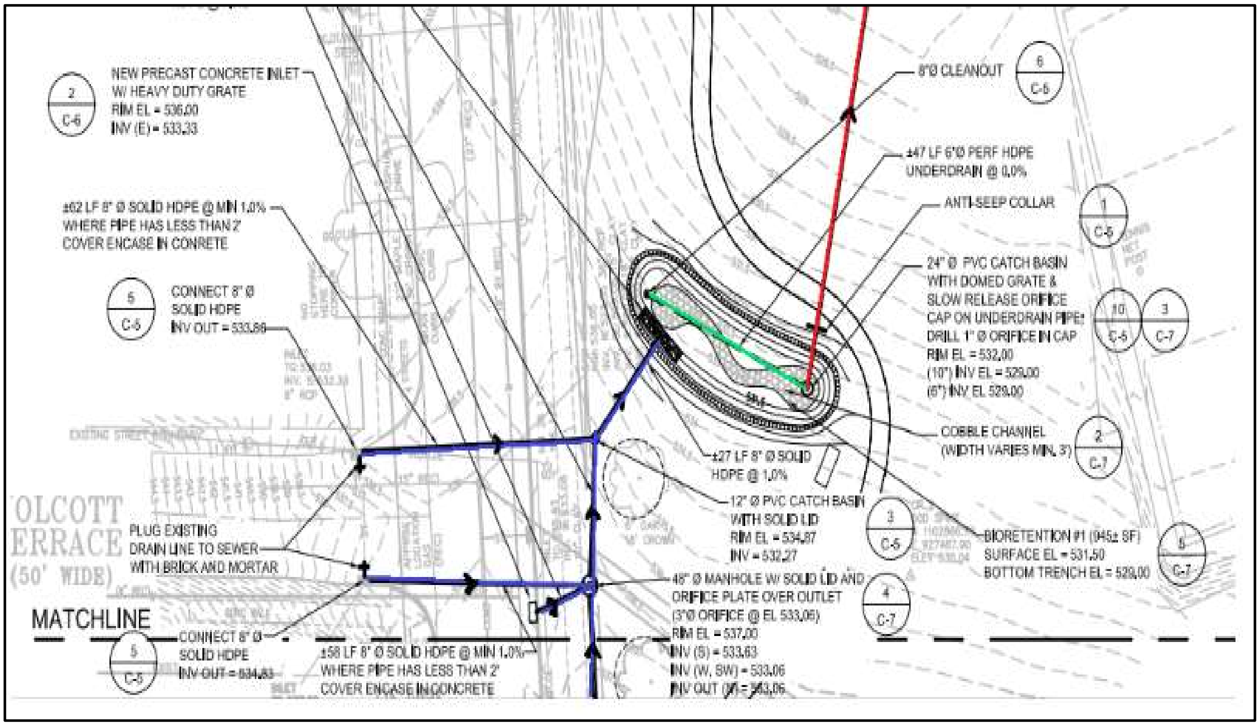


Fig. A-5 Plan View for Wadsworth West Rain Garden

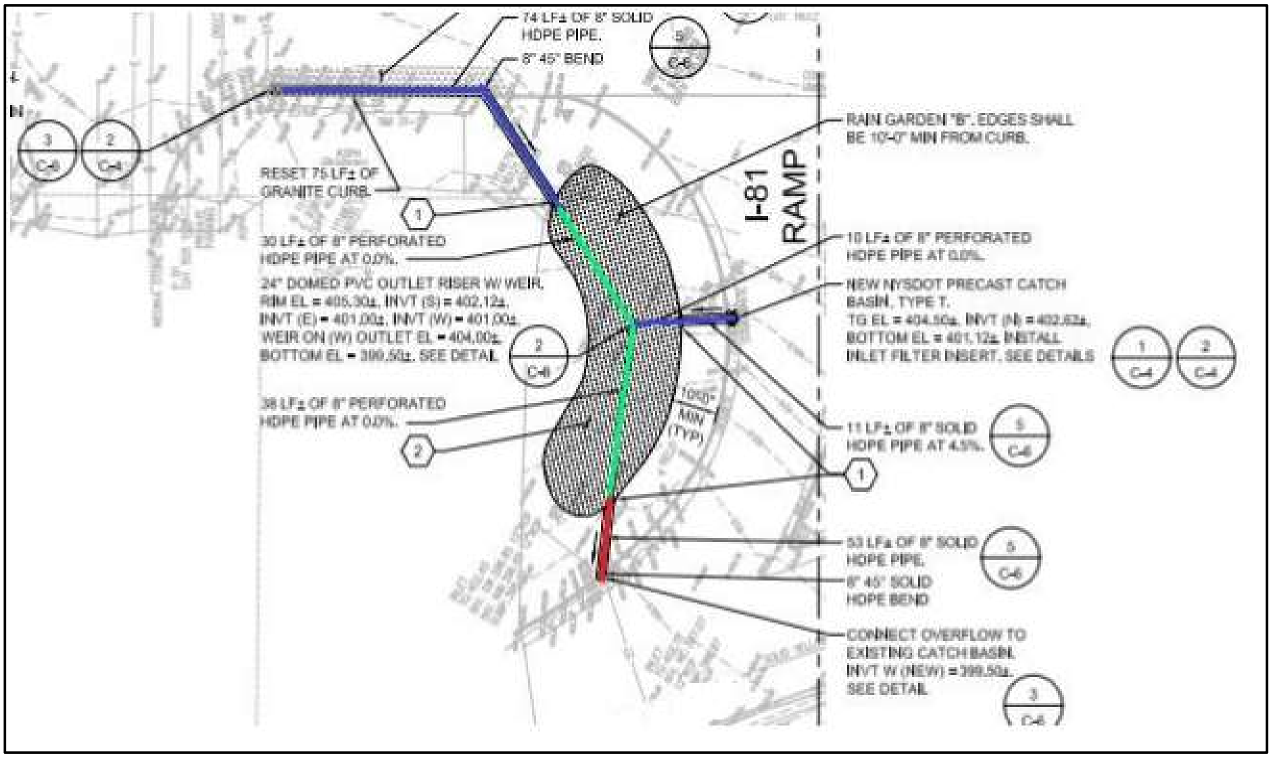


Fig. A-6 Plan View for City Parking Lot 4 Rain Garden

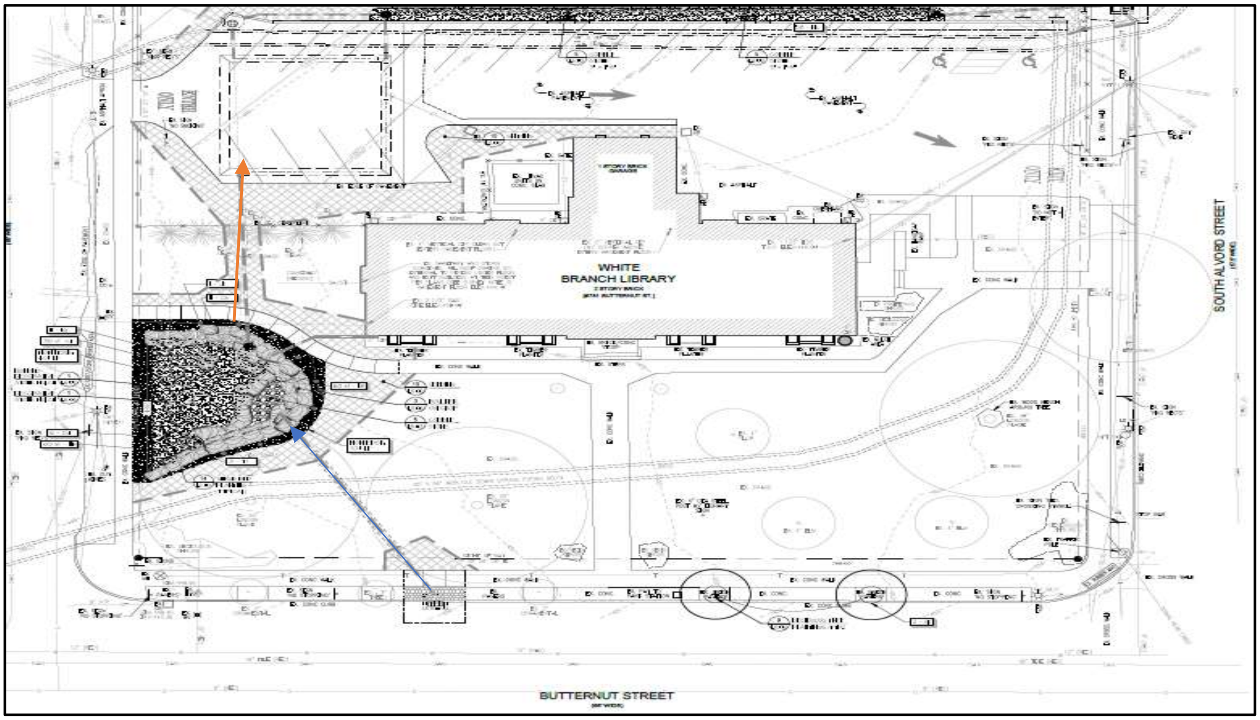


Fig. A-7 Plan View for White Library Infiltration Trench

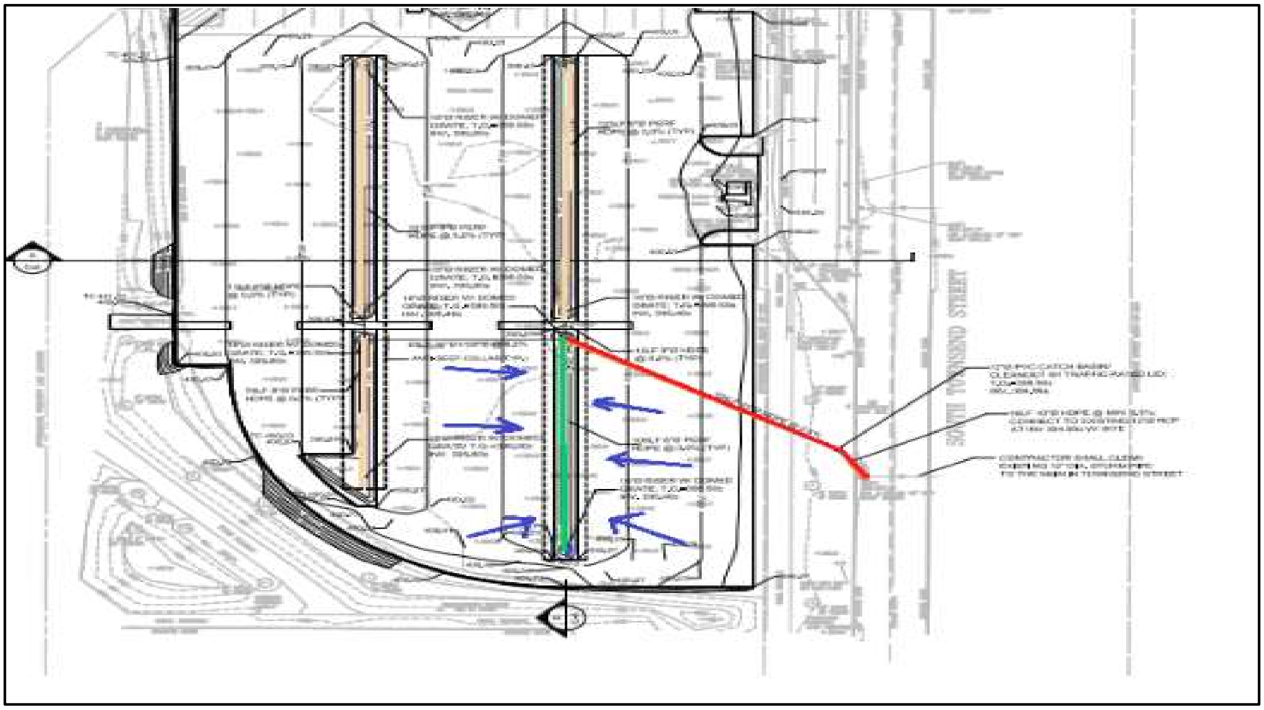


Fig. A-8 Plan View for S. Townsend Street Parking Lot Infiltration Trench

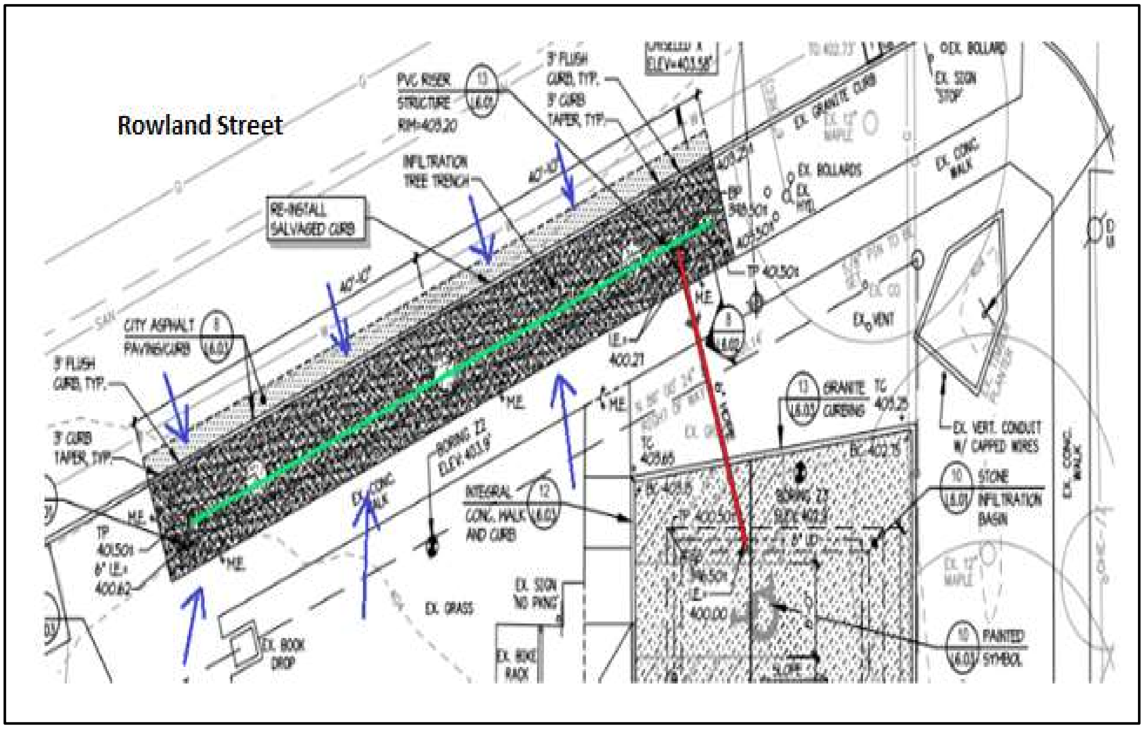


Fig. A-9 Plan View for Mundy Library Infiltration Trench

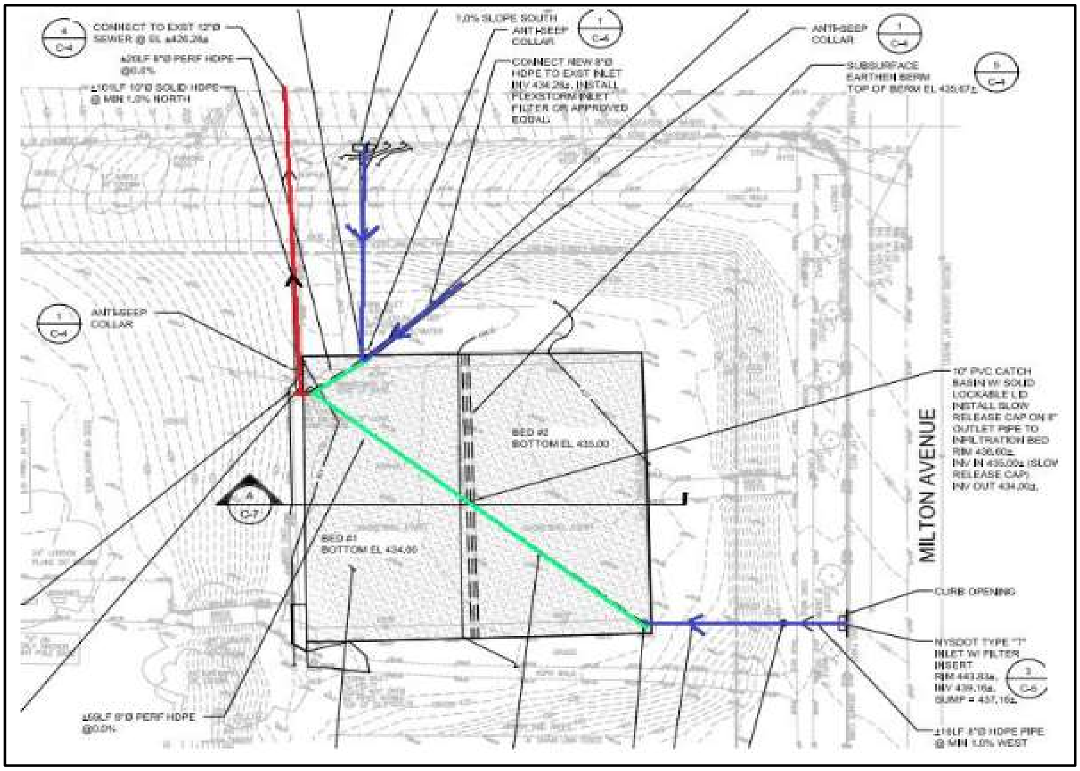


Fig. A-10 Plan View for Lewis Basketball court Permeable Pavement

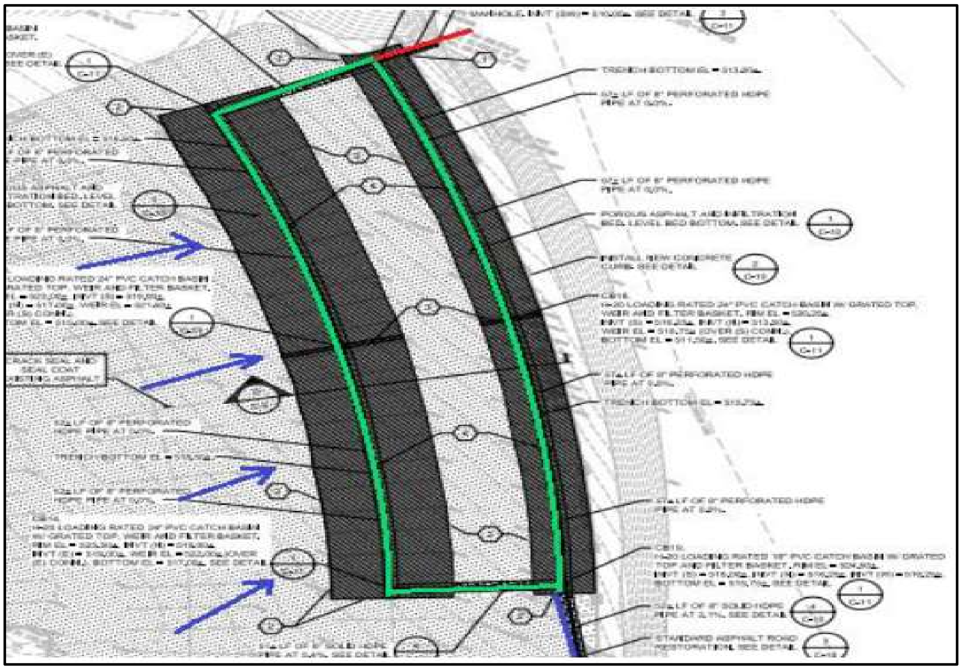


Fig. A-11 Plan View for Zoo Elephant Lot NE Permeable Pavement

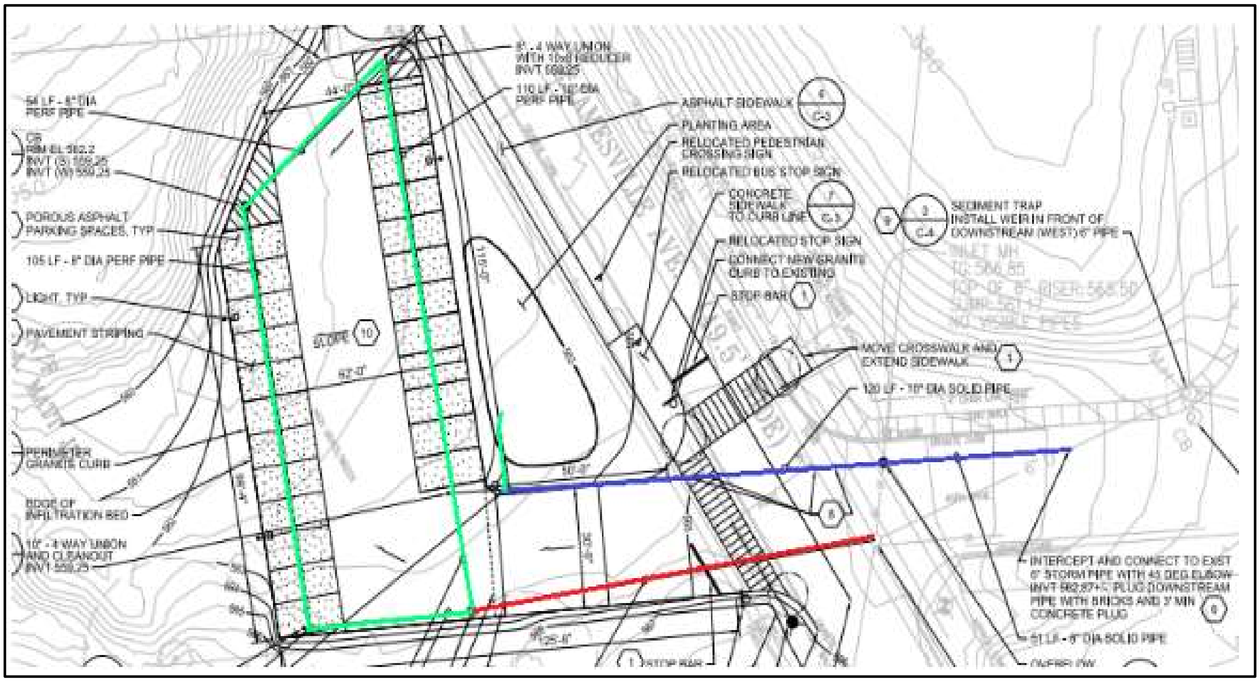


Fig. A-12 Plan View for Hughes Magnet School Parking Lot Permeable Pavement

Appendix-B: Hydrographs

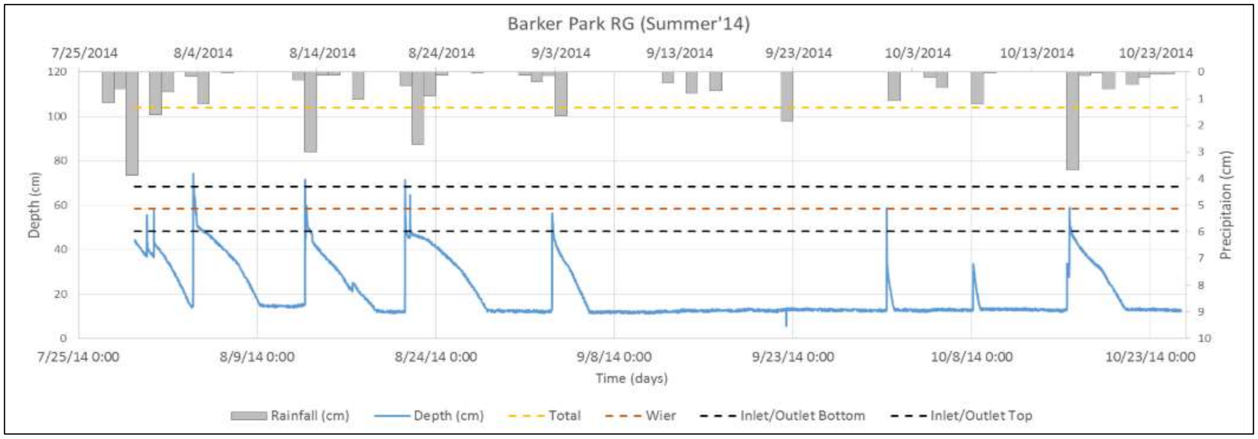


Fig. B-1 (a) Hydrograph for Barker Park Rain Garden (2014)

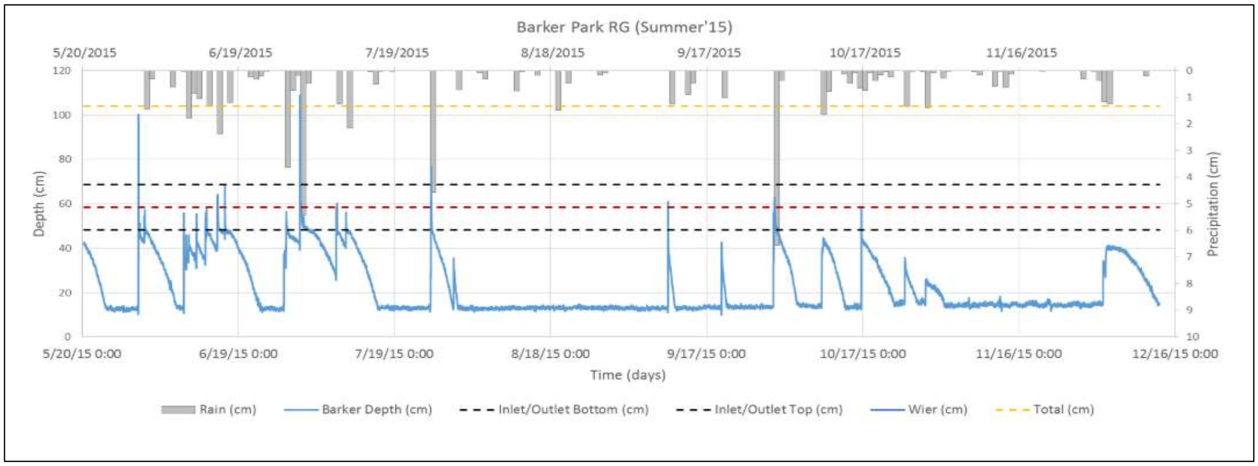


Fig. B-1 (b) Hydrograph for Barker Park Rain Garden (2015)

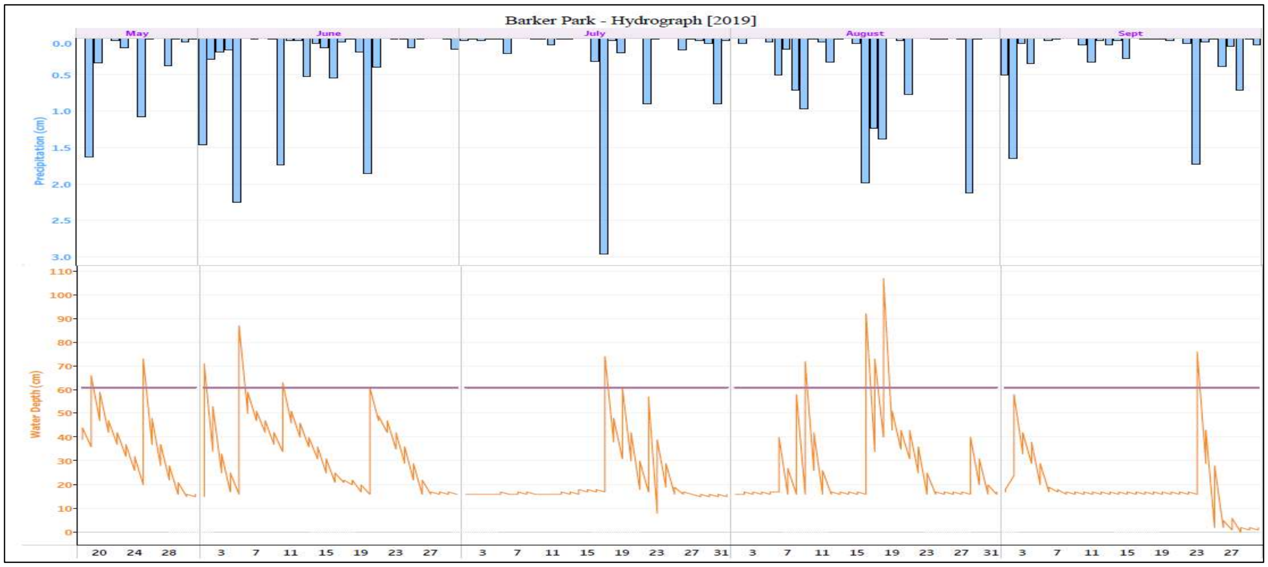


Fig. B-1 (c) Hydrograph for Barker Park Rain Garden (2019)

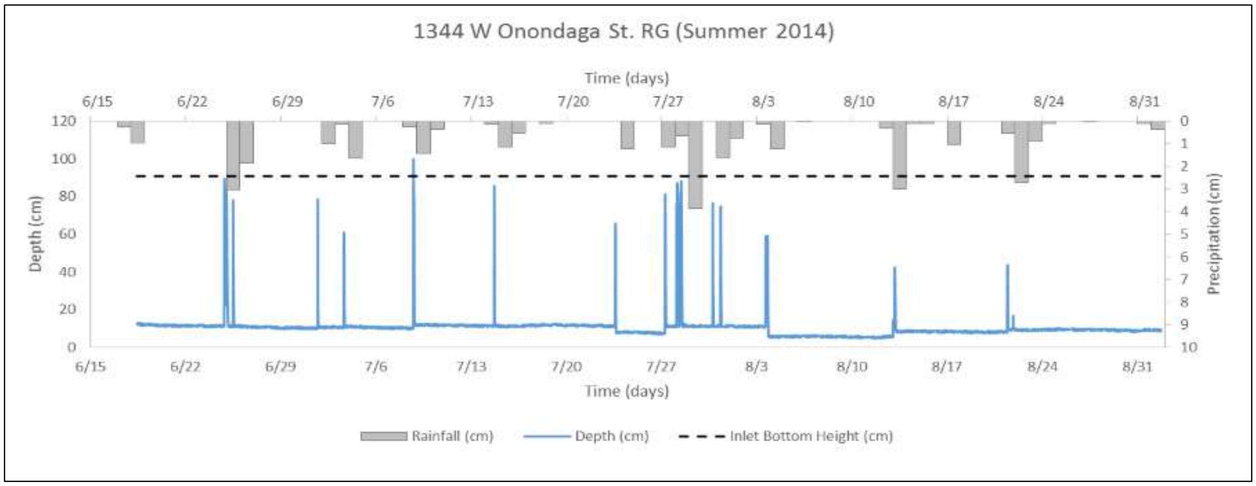


Fig. B-2 (a) Hydrograph for 1344 W. Onondaga St. Rain Garden (2014)

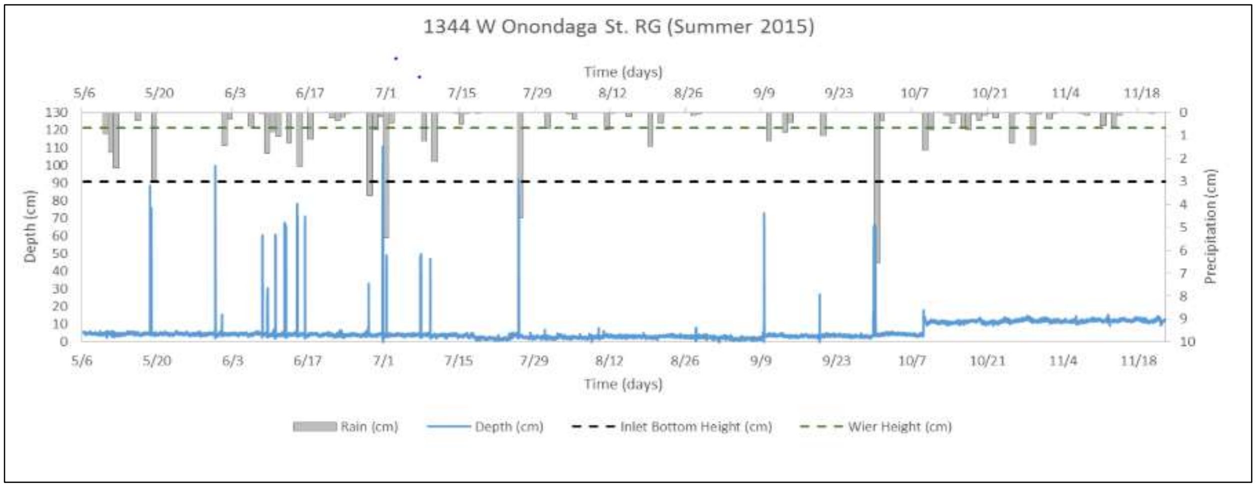


Fig. B-2 (b) Hydrograph for 1344 W. Onondaga St. Rain Garden (2015)

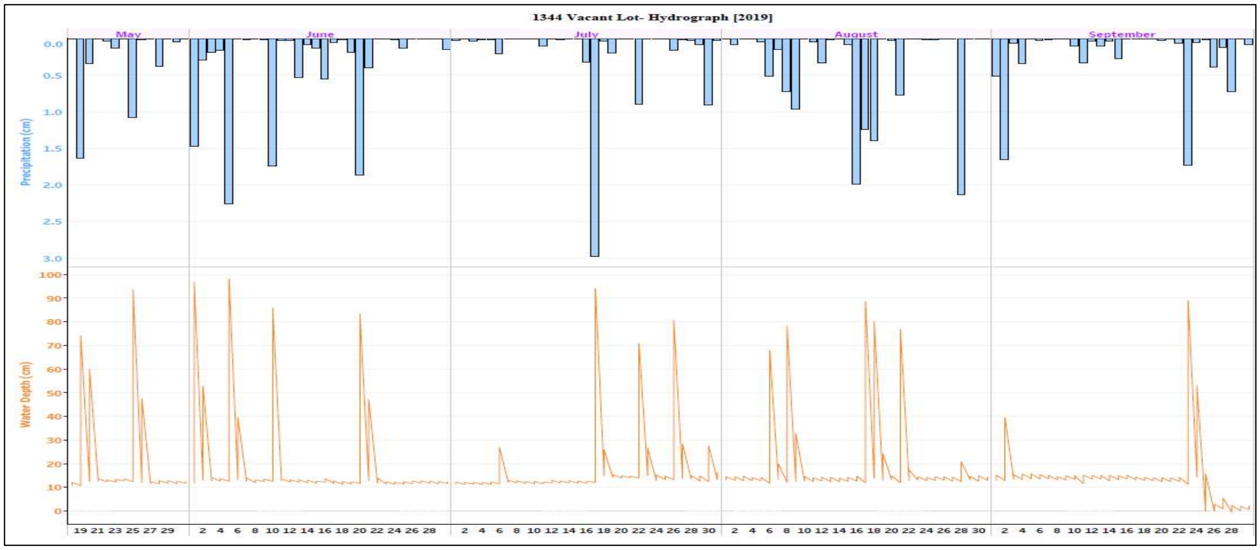


Fig. B-2 (c) Hydrograph for 1344 W. Onondaga St. Rain Garden (2019)

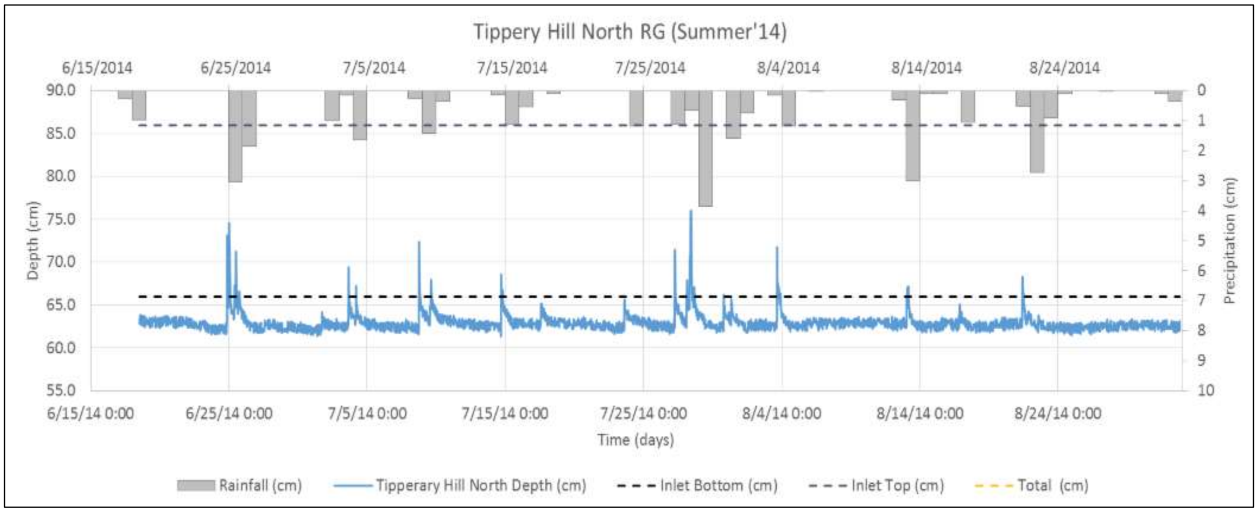


Fig. B-3 (a) Hydrograph for Pass Arboretum North Rain Garden (2014)

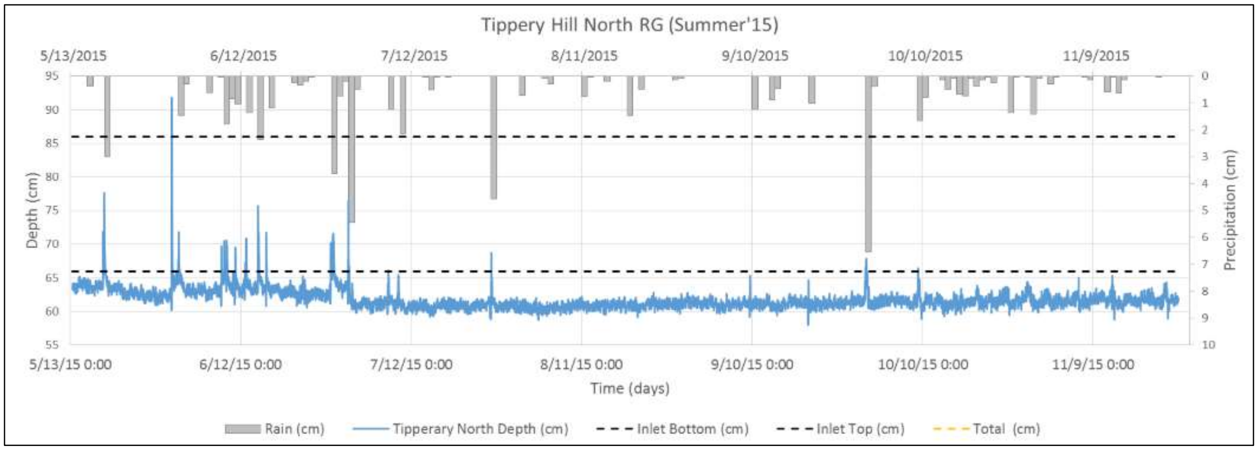


Fig. B-3 (b) Hydrograph for Pass Arboretum North Rain Garden (2015)

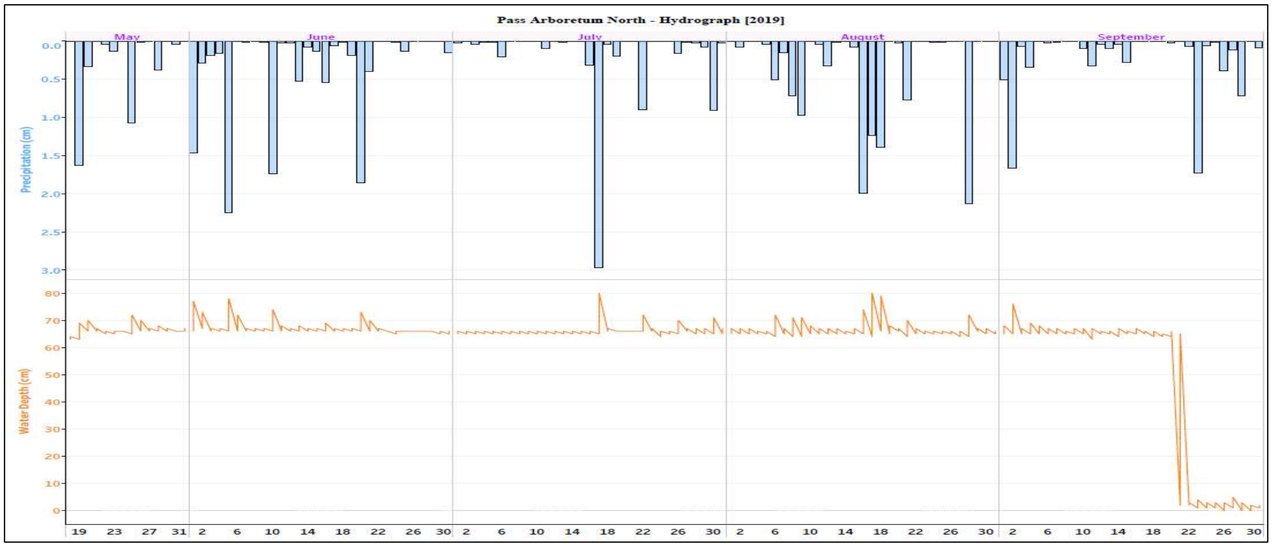


Fig. B-3 (c) Hydrograph for Pass Arboretum North Rain Garden (2019)

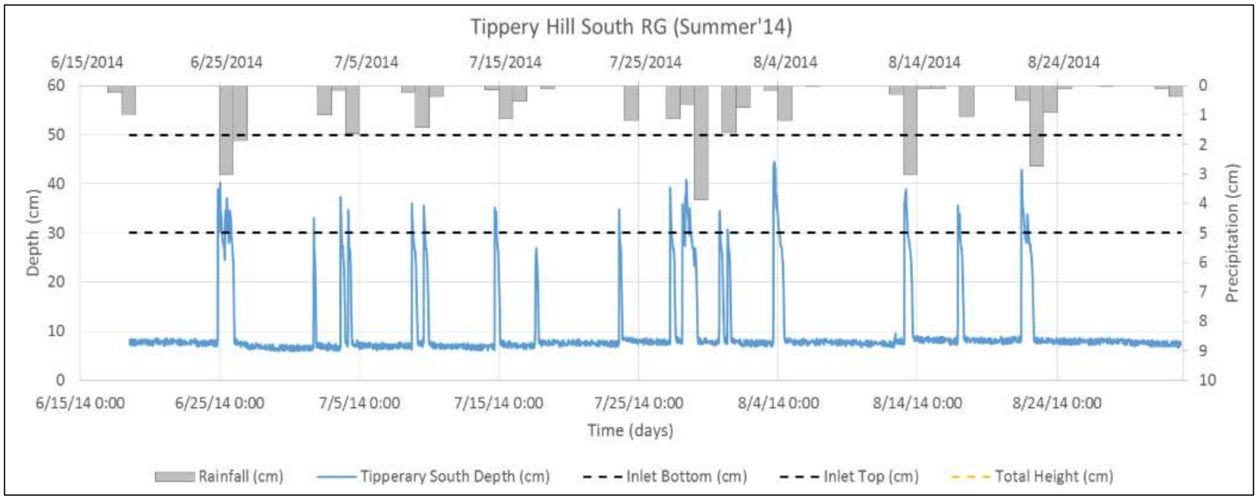


Fig. B-4 (a) Hydrograph for Pass Arboretum South Rain Garden (2014)

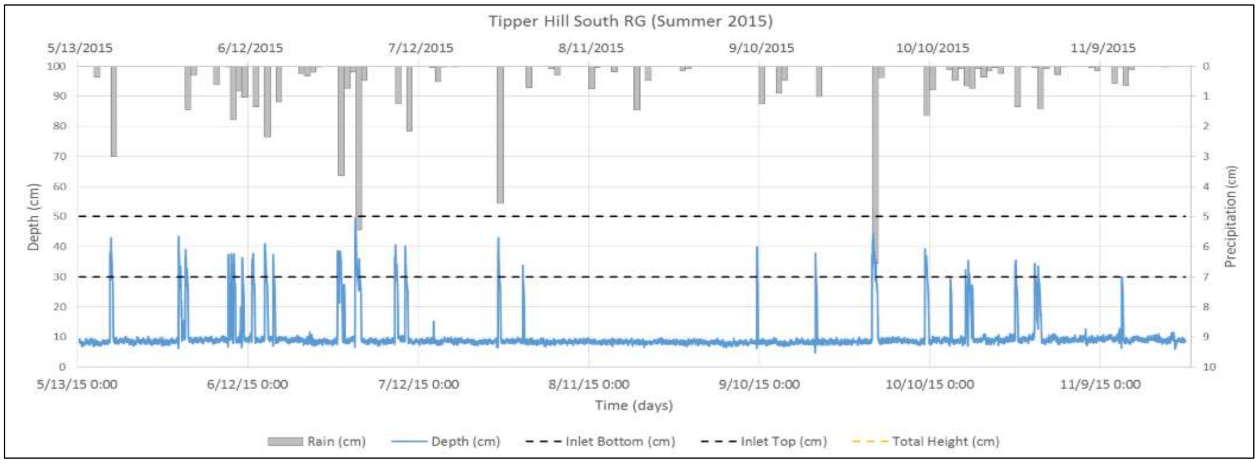


Fig. B-4 (b) Hydrograph for Pass Arboretum South Rain Garden (2015)

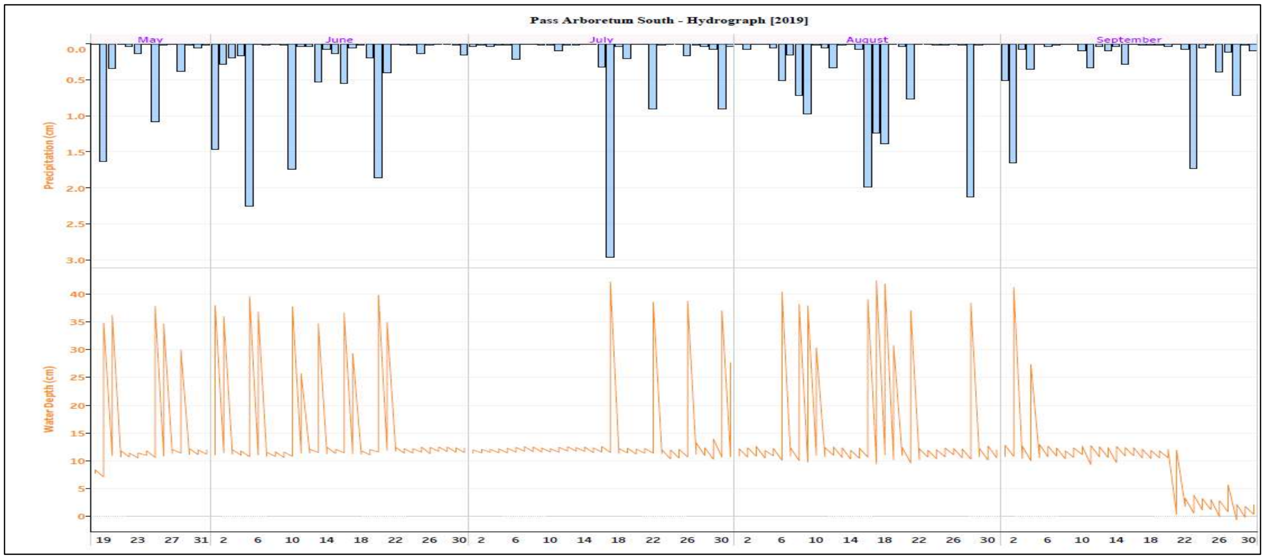


Fig. B-4 (c) Hydrograph for Pass Arboretum South Rain Garden (2019)

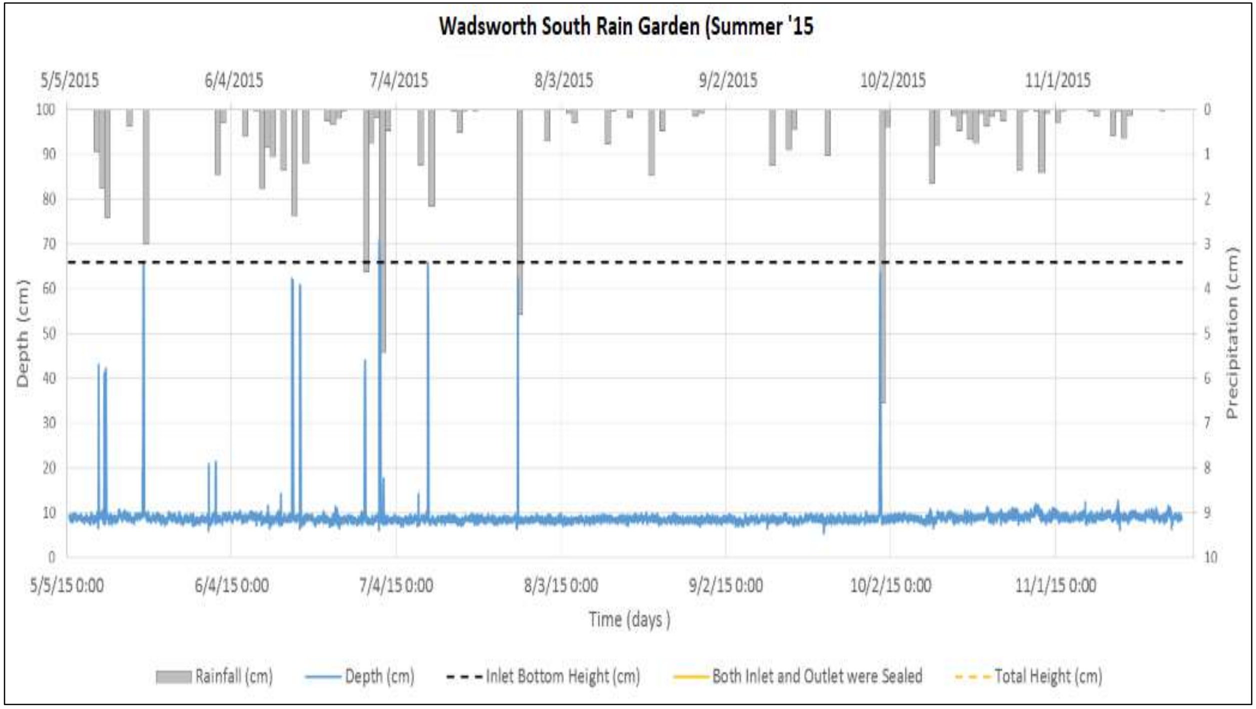


Fig. B-5 (a) Hydrograph for Wadsworth South Rain Garden (2015)

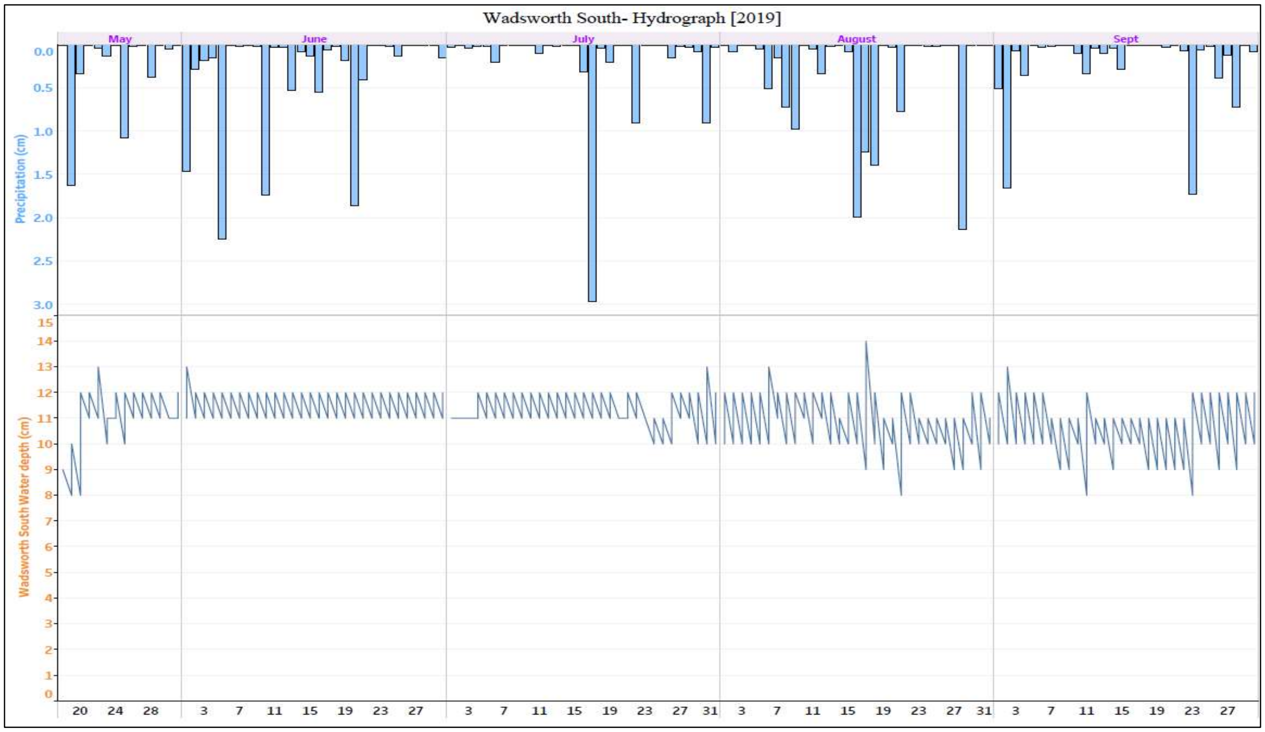


Fig. B-5 (b) Hydrograph for Wadsworth South Rain Garden (2019)

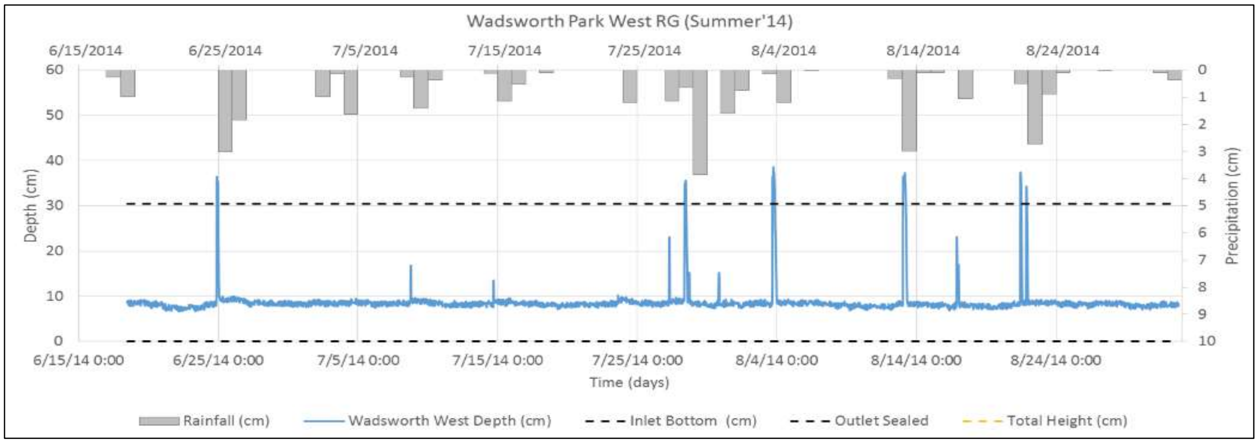


Fig. B-6 (a) Hydrograph for Wadsworth West Rain Garden (2014)

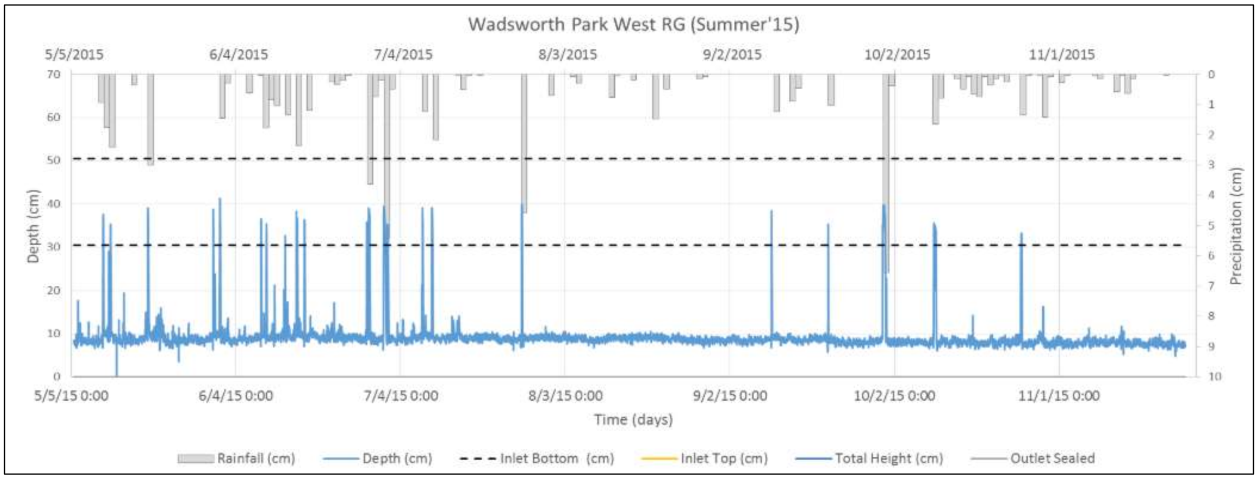


Fig. B-6 (b) Hydrograph for Wadsworth West Rain Garden (2015)

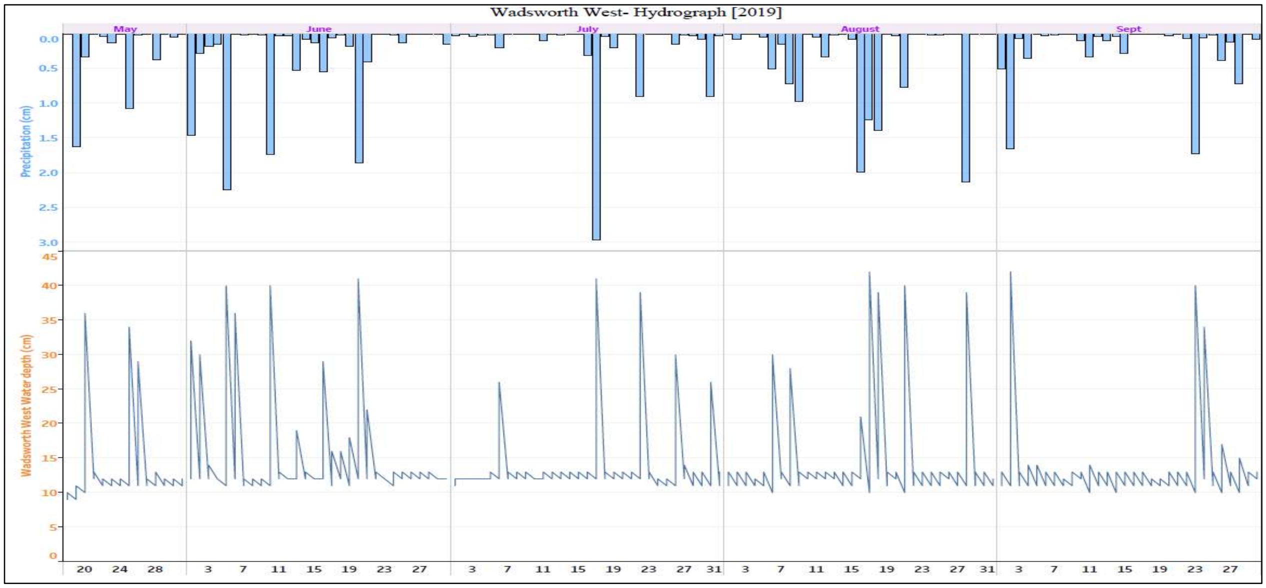


Fig. B-6 (c) Hydrograph for Wadsworth West Rain Garden (2019)

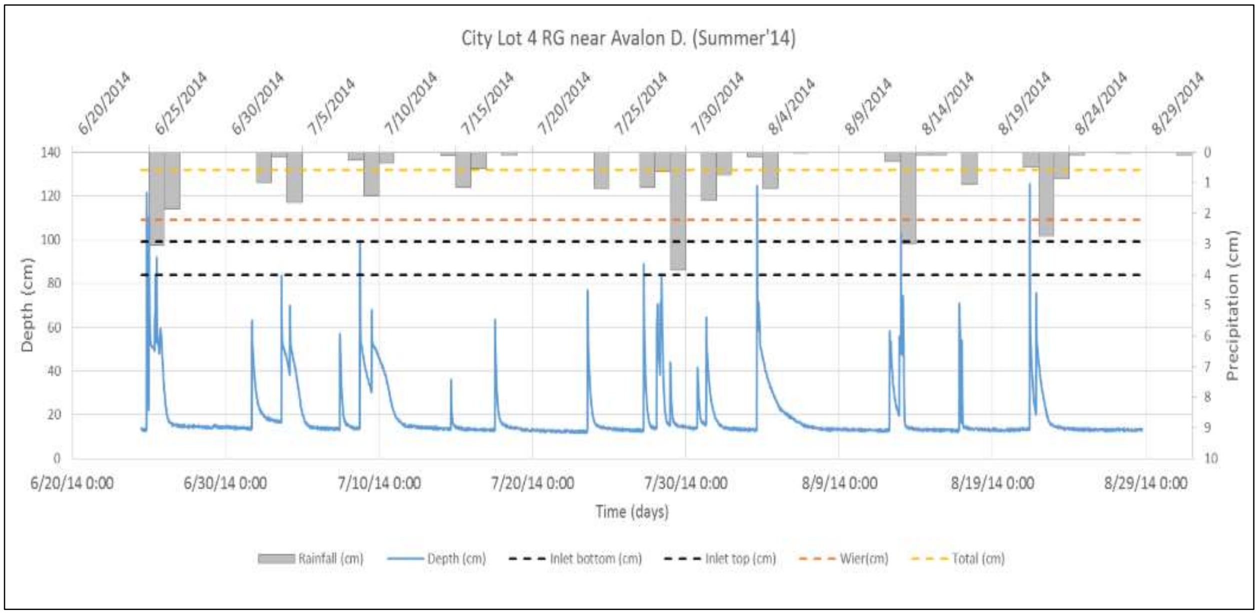


Fig. B-7 (a) Hydrograph for City Parking Lot 4 Rain Garden (2014)

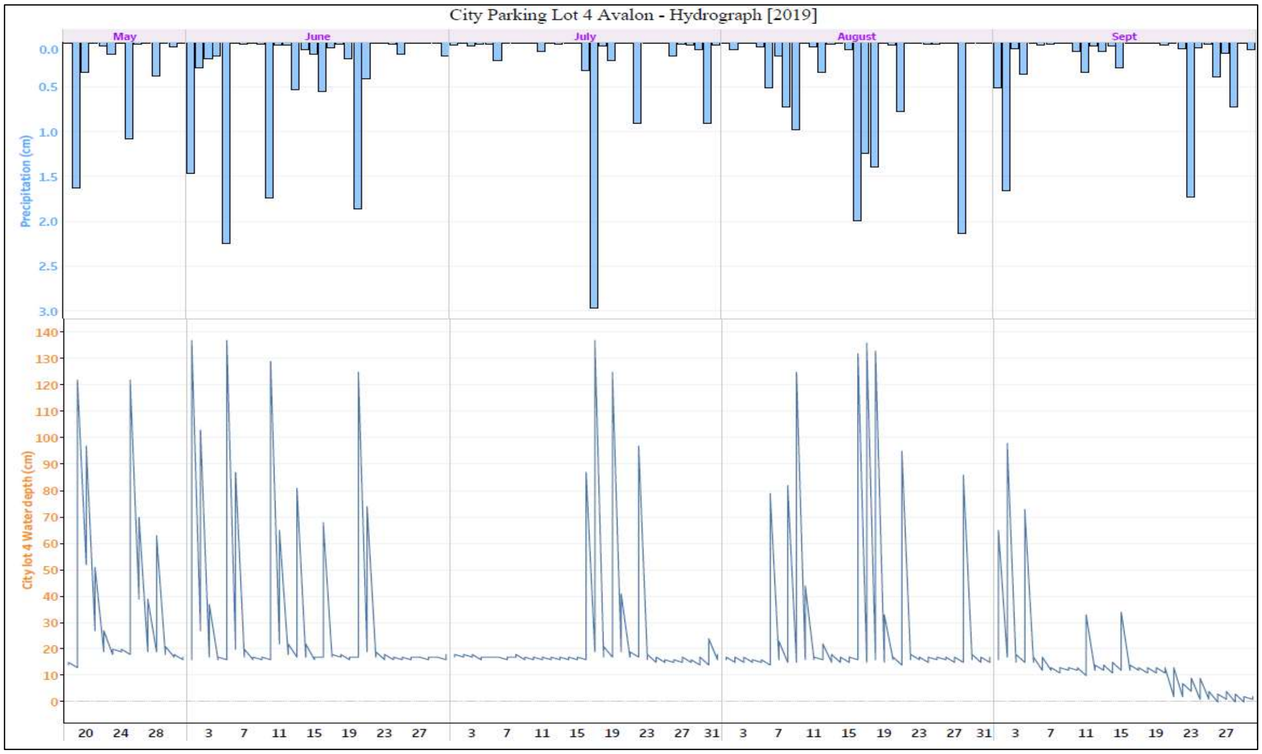


Fig. B-7 (b) Hydrograph for City Parking Lot 4 Rain Garden (2019)

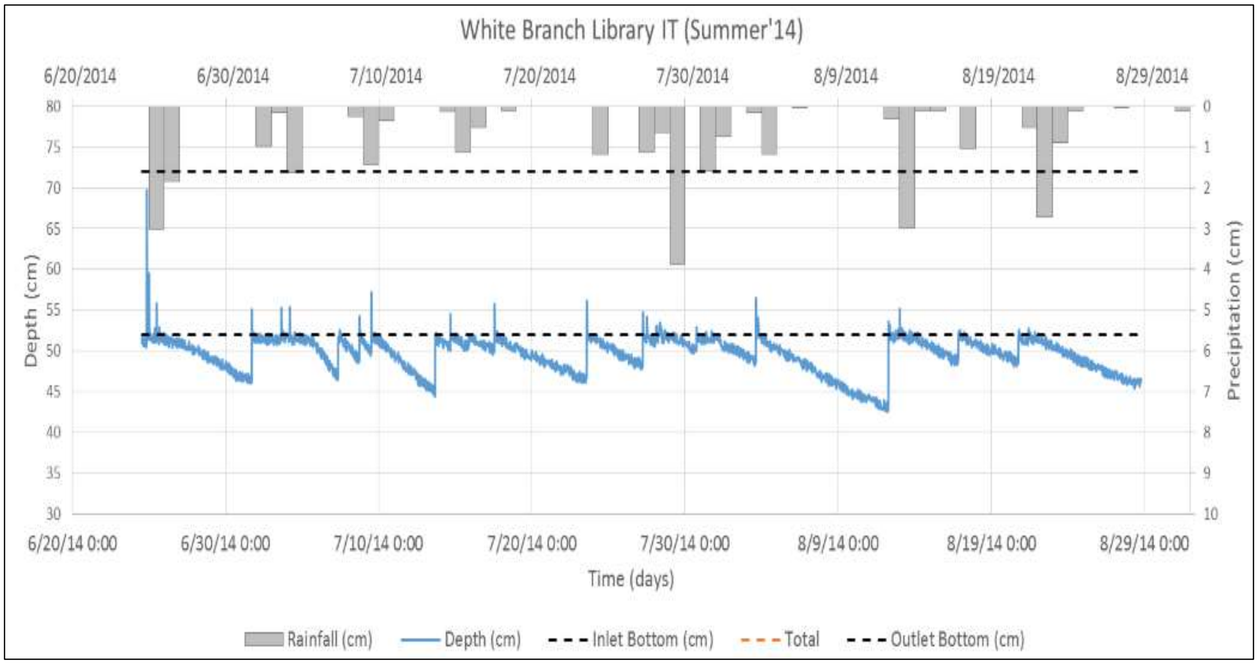


Fig. B-8 (a) Hydrograph for White Library Infiltration Trench (2014)

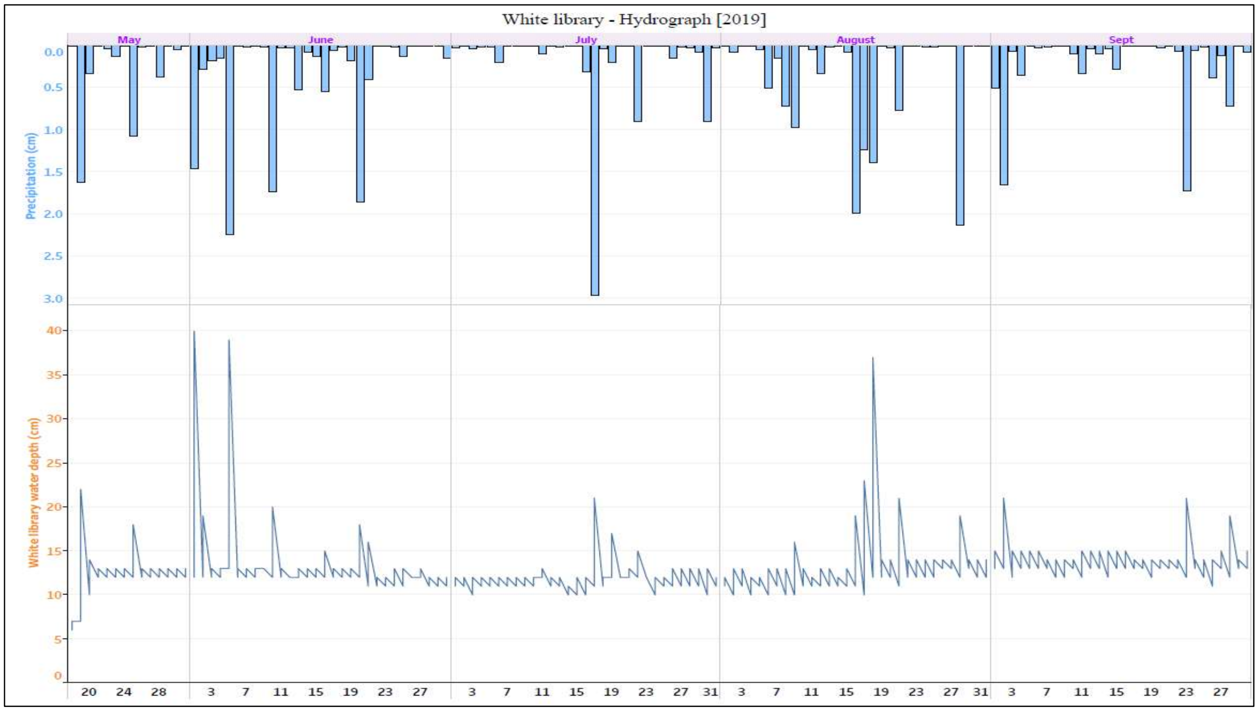


Fig. B-8 (b) Hydrograph for White Library Infiltration Trench (2019)

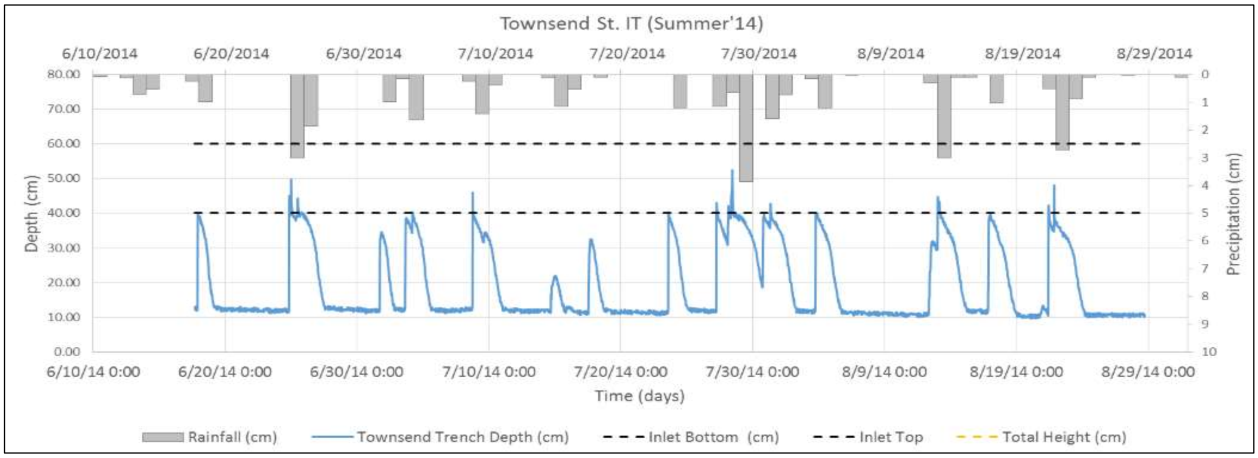


Fig. B-9 (a) Hydrograph for S. Townsend Street Parking Lot Infiltration Trench (2014)

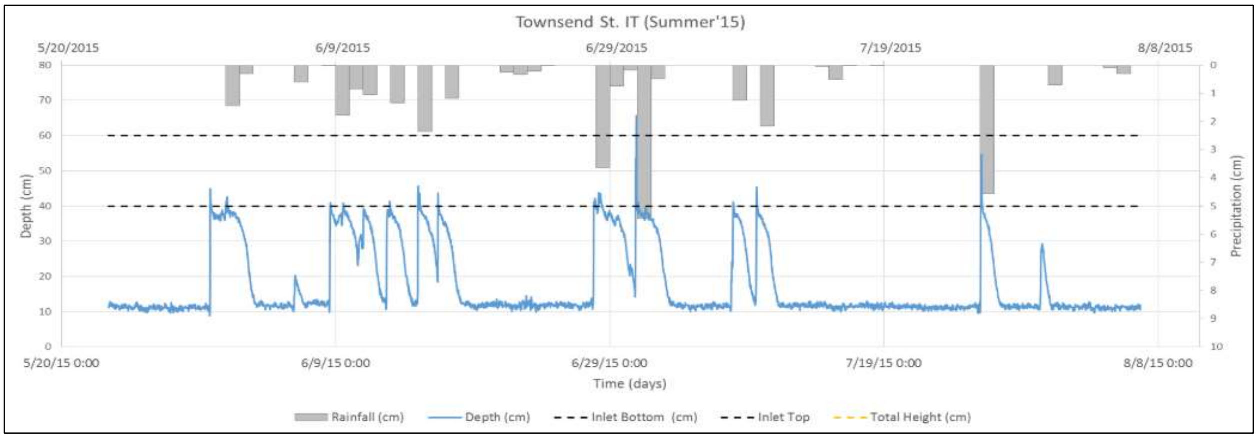


Fig. B-9 (b) Hydrograph for S. Townsend Street Parking Lot Infiltration Trench (2015)

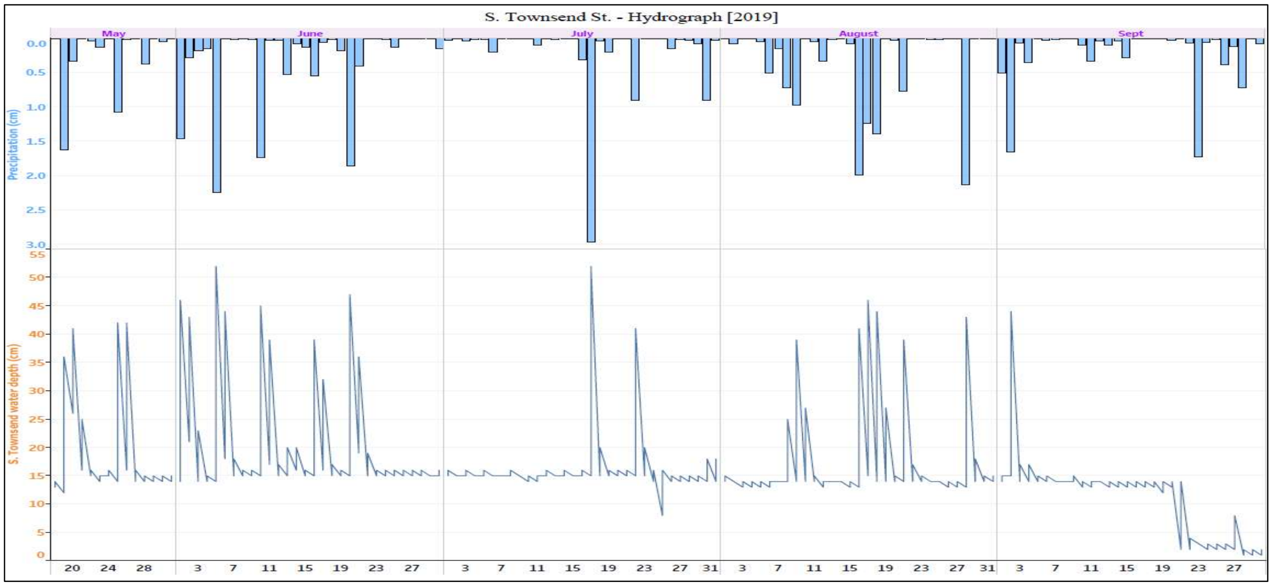


Fig. B-9 (c) Hydrograph for S. Townsend Street Parking Lot Infiltration Trench (2019)

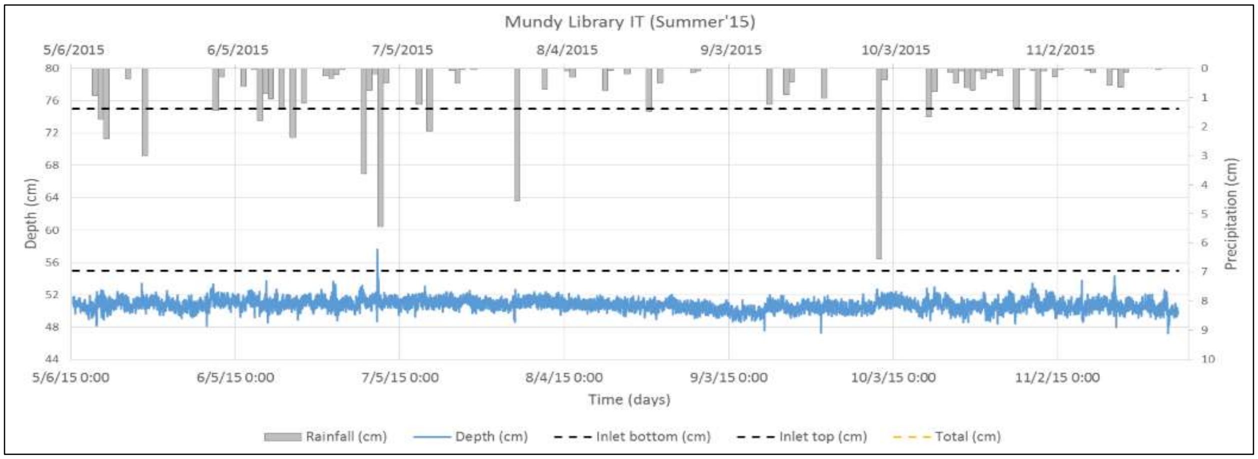


Fig. B-10 (a) Hydrograph for Mundy Library Infiltration Trench (2015)

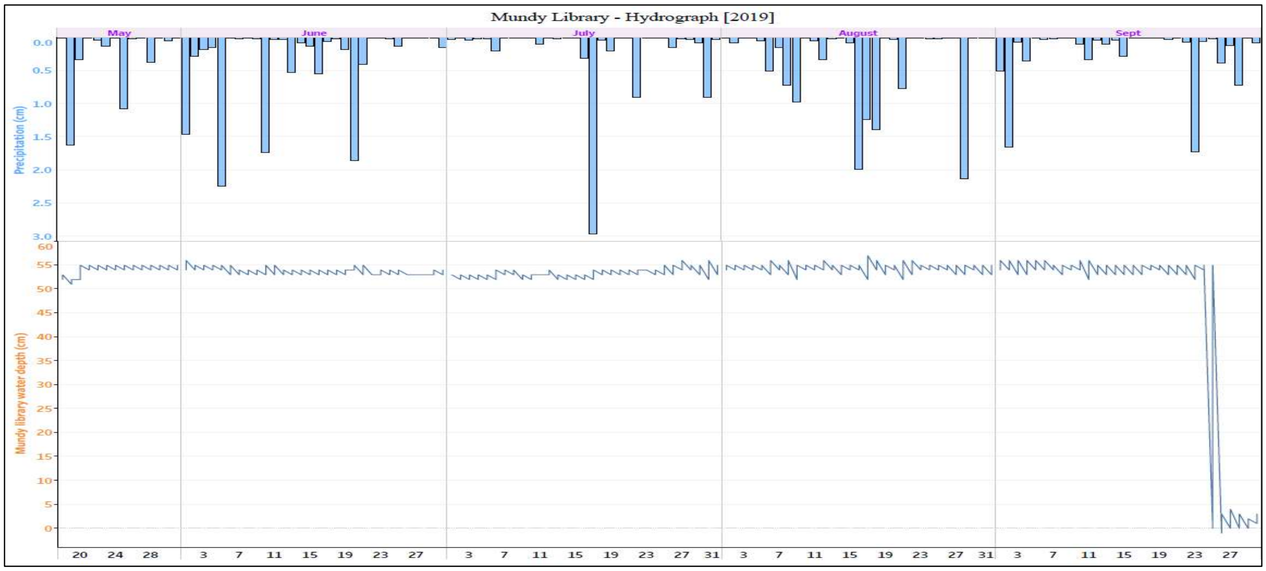


Fig. B-10 (b) Hydrograph for Mundy Library Infiltration Trench (2019)

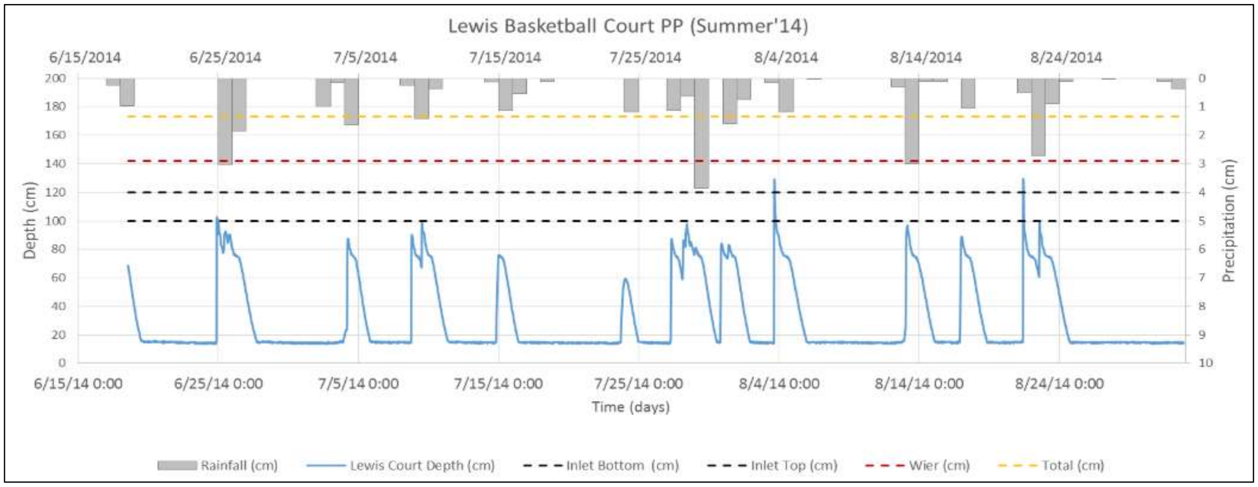


Fig. B-11 (a) Hydrograph for Lewis Basketball court Permeable Pavement (2014)

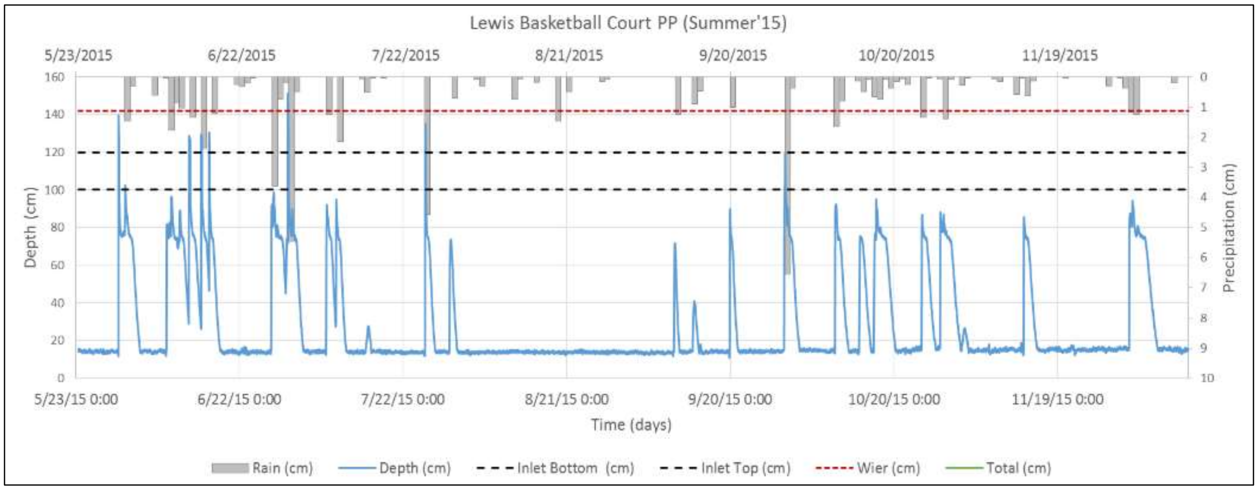


Fig. B-11 (b) Hydrograph for Lewis Basketball court Permeable Pavement (2015)

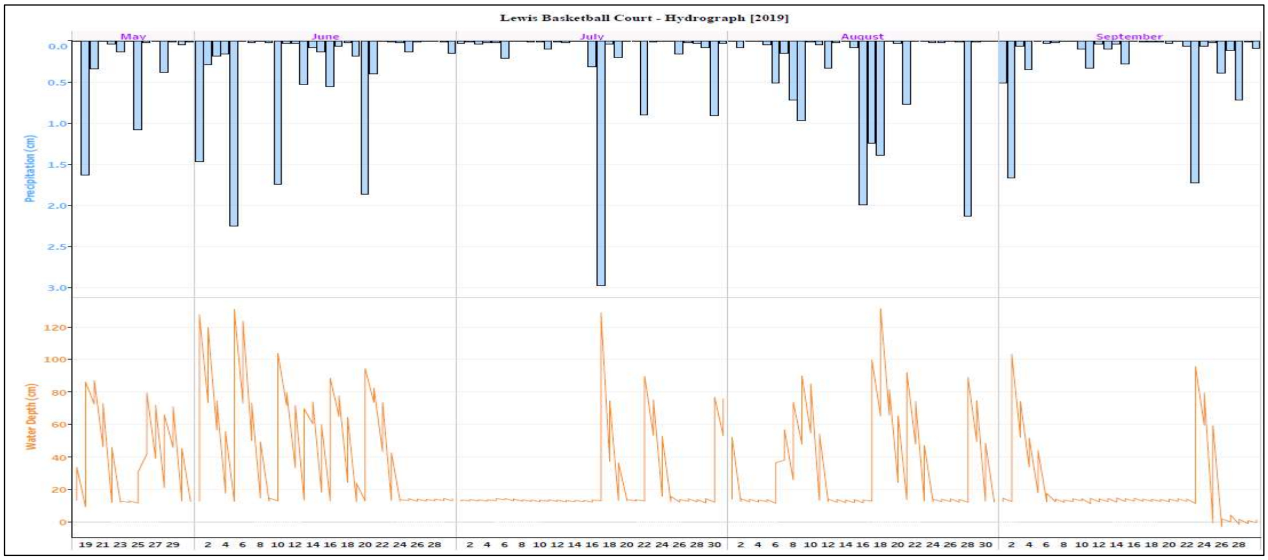


Fig. B-11 (c) Hydrograph for Lewis Basketball court Permeable Pavement (2019)

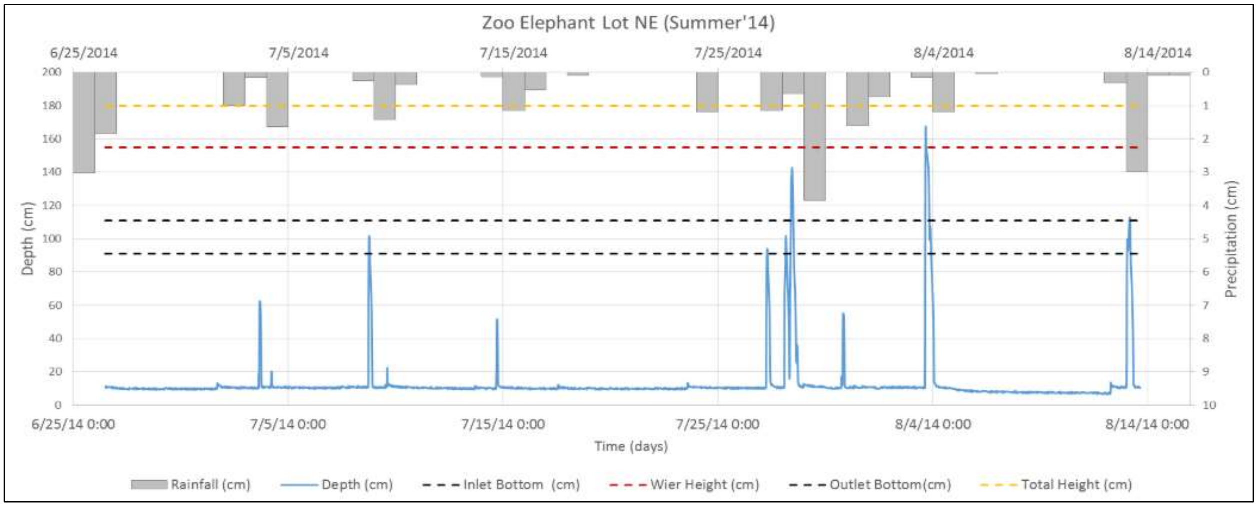


Fig. B-12 (a) Hydrograph for Zoo Elephant Lot NE Permeable Pavement (2014)

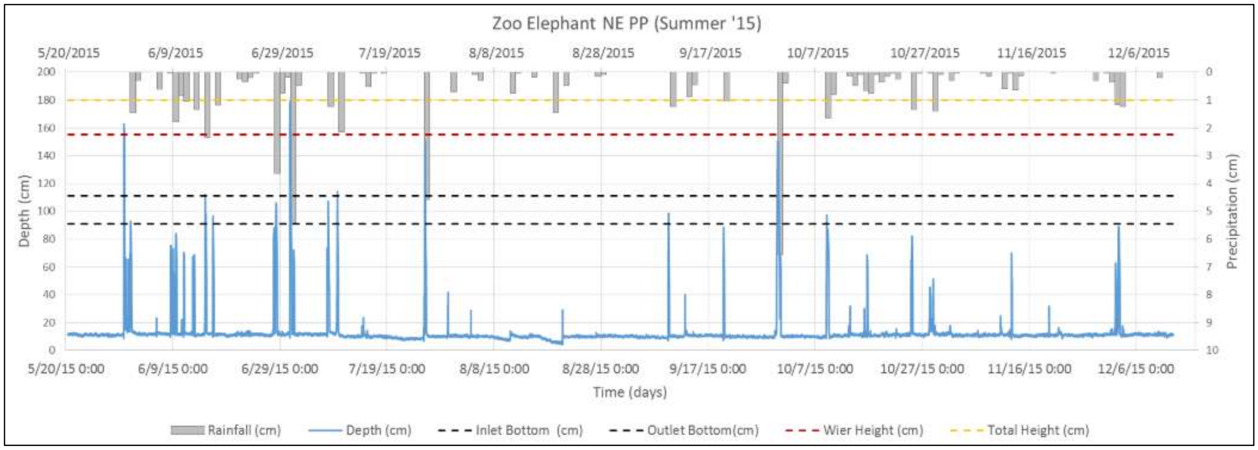


Fig. B-12 (b) Hydrograph for Zoo Elephant Lot NE Permeable Pavement (2015)

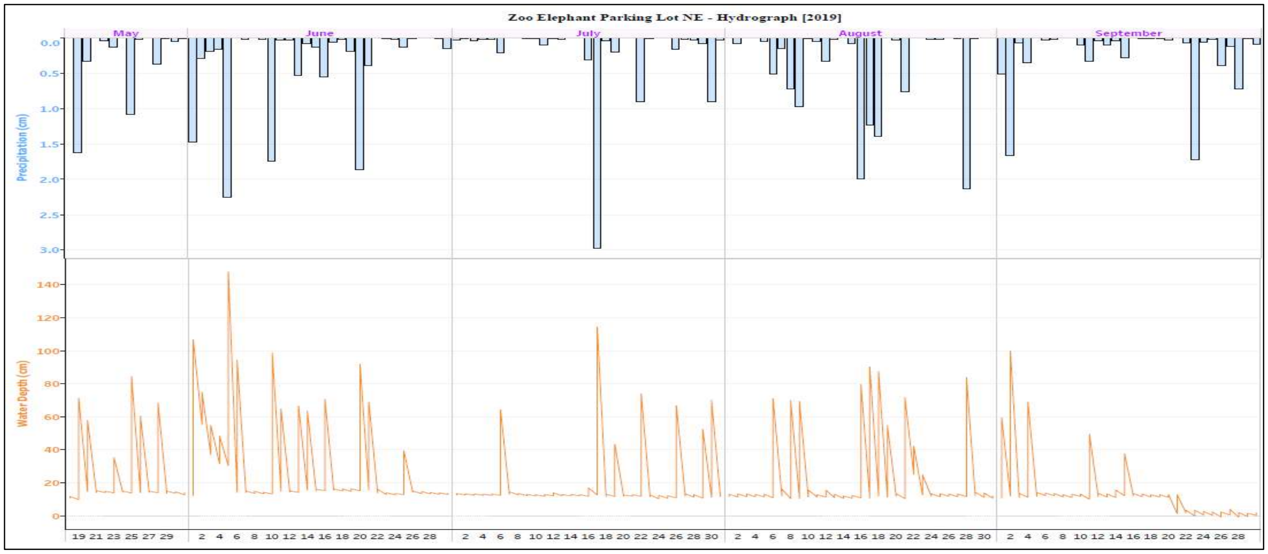


Fig. B-12 (c) Hydrograph for Zoo Elephant Lot NE Permeable Pavement (2019)

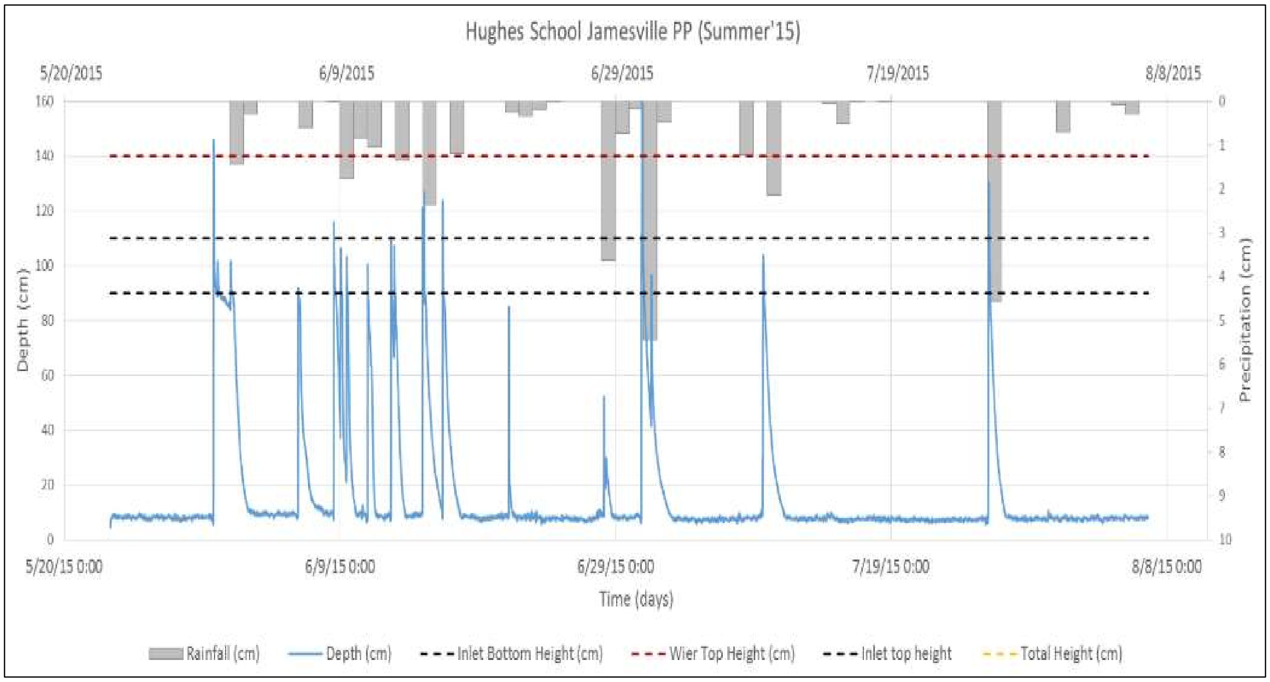


Fig. B-13 (a) Hydrograph for Hughes Magnet School Parking Lot Permeable Pavement (2015)

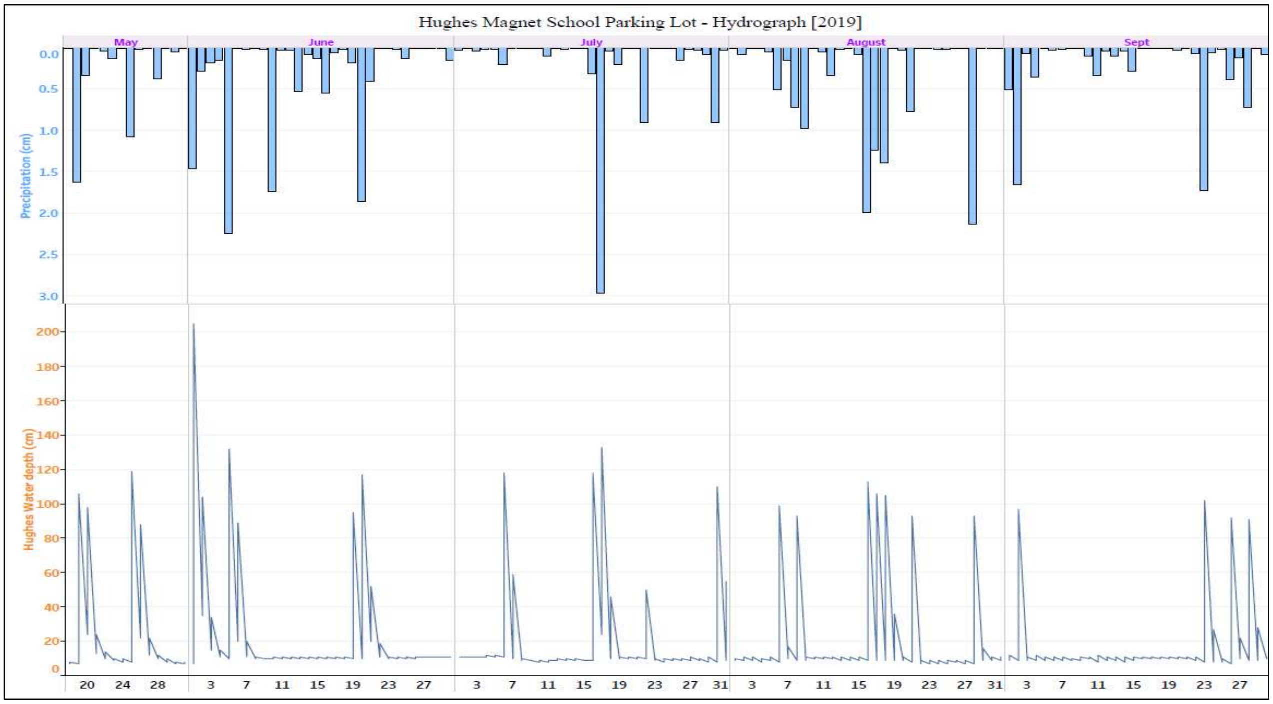


Fig. B-13 (b) Hydrograph for Hughes Magnet School Parking Lot Permeable Pavement (2019)

Appendix C

Table C-1 Precipitation records of selected storm events for 2014, 2015, and 2019

2014		2015		2019	
Dates	Precipitation (cm)	Dates	Precipitation (cm)	Dates	Precipitation (cm)
6/25/2014	3.13	5/19/2015	7.06	5/19	1.63
7/29/2014	3.83	6/1/2015	2.29	6/5	2.25
8/4/2014	2.93	6/9/2015	2.18	6/10	1.74
8/13/2014	2.32	6/13/2015	3.54	6/20	1.86
8/22/2014	2.15	6/15/2015	2.93	7/17	2.97
9/3/2014	1.63	6/17/2015	2.09	8/16	1.99
		6/28/2015	4.24	8/28	2.13
		7/1/2015	9.33	9/2	1.66
		7/8/2015	2.59	9/23	1.73
		7/10/2015	2.71		
		7/26/2015	8.12		
		9/10/2015	2.62		
		9/20/2015	2.41		
		9/30/2015	8.75		

Appendix D: Infiltration Rates at Rain Gardens, Infiltration Trenches & Permeable Pavements

Date	Rainfall (cm)	Infiltration rate (cm/hr) – Rain Gardens						
		Barker Park	Pass Arboretum North	Pass Arboretum South	Wadsworth South	Wadsworth West	City Parking Lot 4 Avalon	1344 W Onondaga Vacant Lot
6/25/2014	3.13	---	0.9	8.5	--	7.12	132.5	105.0
7/29/2014	3.83	6.53	0.55	6.65	--	7.48	105.5	85
8/4/2014	2.93	8.53	0.67	4.12	--	5.48	53.0	75.0
8/13/2014	2.32	6.87	0.8	4.52	--	4.2	115.0	61.0
8/22/2014	2.15	4.58	0.74	4.15	--	5.64	59.89	52.0
5/19/2015	7.06	--	2.35	15.84	3.84	10.15	--	115.0
6/1/2015	2.29	5.82	1.5	4.54	2.31	5.12	--	61.0
6/9/2015	2.18	4.15	0.54	3.61	1.75	4.81	--	54.0
6/28/2015	4.24	6.1	0.7	12.18	3.28	7.64	--	105.0
7/1/2015	9.33	15.7	2.0	19.59	5.32	15.0	--	110.0
7/8/2015	2.59	3.85	0.85	5.1	2.25	4.32	--	84.0
7/10/2015	2.71	3.2	0.50	3.95	--	4.05	--	52.0
7/26/2015	8.12	15.43	2.5	17.5	4.89	14.38	--	120.0
9/10/2015	2.62	5.96	0.92	4.94	--	4.86	--	79.0
9/20/2015	2.41	3.45	0.89	4.74	--	4.59	--	68.0
9/30/2015	8.75	19.0	2.7	18.12	4.21	15.2	--	140.0
5/19/2019	1.63	3.64	0.25	4.1	0.93	--	78.8	55.0
6/5/2019	2.25	6.63	0.55	4.84	2.12	5.75	111.45	68.0
6/10/2019	1.74	3.92	0.5	3.68	2.45	3.95	58.15	56.0
6/20/2019	1.86	4.22	0.72	4.42	1.56	5.13	63.45	92.0
7/17/2019	2.97	9.85	1.25	6.84	2.98	6.32	125.76	100.0
8/16/2019	1.99	5.98	0.49	4.45	1.63	5.67	87.0	84.0
8/28/2019	2.13	7.65	0.91	5.38	2.83	6.05	118.53	75.0
9/2/2019	1.66	3.53	--	4.37	1.42	4.45	74.0	48.0
9/23/2019	1.73	4.82	--	--	1.98	5.34	--	50.0

Date	Rainfall (cm)	Infiltration rate (cm/hr) – Infiltration Trenches		
		Mundy Library	S. Townsend Trench	White Library
6/25/2014	3.13	--	11.34	1.4
7/29/2014	3.83	--	10.56	1.23
8/4/2014	2.93	--	7.85	1.15
8/13/2014	2.32	--	6.54	0.75
8/22/2014	2.15	--	5.83	0.55
5/19/2015	7.06	0.16	--	--
6/1/2015	2.29	0.11	6.74	--
6/9/2015	2.18	0.09	5.83	--
6/28/2015	4.24	0.13	13.53	--
7/1/2015	9.33	0.08	25.48	--
7/8/2015	2.59	0.1	7.65	--
7/10/2015	2.71	0.11	5.23	--
7/26/2015	8.12	0.18	25.5	--
9/10/2015	2.62	0.07	7.35	--
9/20/2015	2.41	0.06	--	--
9/30/2015	8.75	0.2	--	--
5/19/2019	1.63	0.06	5.72	0.95
6/5/2019	2.25	0.1	7.85	1.20
6/10/2019	1.74	0.04	7.65	0.45
6/20/2019	1.86	0.08	6.53	0.56
7/17/2019	2.97	0.12	9.86	1.15
8/16/2019	1.99	0.09	5.31	0.72
8/28/2019	2.13	0.11	7.65	0.95
9/2/2019	1.66	0.07	5.35	0.50
9/23/2019	1.73	0.09	--	0.89

Date	Rainfall (cm)	Infiltration rate (cm/hr) – Permeable Pavements		
		Lewis Basketball Court	Hughes Magnet School Parking Lot	Zoo Elephant Parking Lot NE
6/25/2014	3.13	42.4	--	--
7/29/2014	3.83	40.32	--	36.15
8/4/2014	2.93	31.89	--	30.65
8/13/2014	2.32	32.13	--	24.85
8/22/2014	2.15	34.18	--	--
5/19/2015	7.06	--	--	--
6/1/2015	2.29	34.54	--	29.14
6/9/2015	2.18	32.16	19.25	26.53
6/28/2015	4.24	52.0	28.0	39.0
7/1/2015	9.33	74.32	52.4	56.0
7/8/2015	2.59	32.91	--	--
7/10/2015	2.71	31.45	20.43	--
7/26/2015	8.12	80.24	66.4	45.0
9/10/2015	2.62	34.43	--	28.16
9/20/2015	2.41	32.48	--	--
9/30/2015	8.75	81.25	--	47.38
5/19/2019	1.63	30.8	15.58	15.71
6/5/2019	2.25	34.51	20.42	28.5
6/10/2019	1.74	28.67	--	19.11
6/20/2019	1.86	29.4	16.47	20.45
7/17/2019	2.97	36.78	21.83	32.73
8/16/2019	1.99	--	17.52	22.48
8/28/2019	2.13	32.15	20.15	27.86
9/2/2019	1.66	28.49	14.35	17.58
9/23/2019	1.73	31.68	16.89	--

Appendix E: Number of overflows events and estimates of outflow volumes for the study periods

Site Names	2014	2015	2019
	No. of Overflow events	No. of Overflow events	No. of Overflow events
Barker Park	3	8	11
Pass Arboretum North	0	0	0
Pass Arboretum South	0	0	0
Wadsworth South	Not monitored	0	0
Wadsworth West	0	0	0
City Lot 4 Avalon	3	Not monitored	10
1344 W. Onondaga street vacant lot	0	0	0
White library	0	Not monitored	0
Mundy library	Not monitored	0	0
S. Townsend Street parking lot	0	0	0
Zoo Elephant parking lot NE	0	1	0
Lewis basketball court	0	1	0
Hughes Magnet School Parking lot	Not monitored	1	0

Details of inflow and outflow volumes at study sites during 2014

Site Name - 2014	Dates	Precipitation	AM5	Inflow Volume (m3)	Outflow Volume (m3)
Barker Park (RG)	8/4/2014	2.93	2.07	25.71	0.53
	8/13/2014	2.32	0.3	20.70	0.26
	8/22/2014	2.15	1.6	17.00	0.18
City Parking lot 4 Avalon (RG)	6/25/2014	3.13	0	63.30	23.25
	8/4/2014	2.93	2.07	59.28	20.51
	8/22/2014	2.15	1.6	39.18	13.90

Details of inflow and outflow volumes at study sites during 2015

Site Name - 2015	Dates	Precipitation	AM5	Inflow Volume (m3)	Outflow Volume (m3)
Barker Park (RG)	6/1/2015	2.29	0	18.53	0.05
	6/15/2015	2.93	8.28	32.71	2.53
	6/17/2015	2.09	6.47	23.56	2.10
	7/1/2015	9.33	7.57	102.44	37.32
	7/8/2015	2.59	0	21.66	0.08
	7/26/2015	8.12	0	81.10	15.28
	9/10/2015	2.62	0	21.98	0.11
	9/30/2015	8.75	0	87.93	21.4
Zoo Elephant Parking lot NE (PP)	7/1/2015	9.33	7.57	459.20	42.8
Lewis Basketball Court (PP)	7/1/2015	9.33	7.57	78.91	9.4
Hughes Magnet School (PP)	7/1/2015	9.33	7.57	373.88	292.51

Details of inflow and outflow volumes at study sites during 2019

Site Name - 2019	Dates	Precipitation	AM5	Inflow Volume (m3)	Outflow Volume (m3)
Barker Park (RG)	5/19/2019	1.63	0	11.78	0.026
	5/25/2019	1.08	0.51	6.75	0.104
	6/1/2019	1.47	0.45	10.51	0.077
	6/5/2019	2.25	2.12	20.0	0.402
	6/10/2019	1.74	2.29	14.76	0.14
	7/17/2019	2.97	0.35	25.99	0.271
	8/9/2019	0.97	1.43	6.27	0.076
	8/16/2019	1.99	0.48	15.83	0.39
	8/17/2019	1.24	2.42	9.66	0.15
	8/18/2019	1.39	3.33	12.0	0.71
	9/23/2019	1.73	0.12	12.88	0.14
City Lot 4 Avalon (RG)	5/19/2019	1.63	0	27.16	3.23
	5/25/2019	1.08	0.51	15.55	5.49
	6/1/2019	1.47	0.45	24.23	8.41
	6/5/2019	2.25	2.12	46.11	18.67
	6/10/2019	1.74	2.29	34.02	15.41
	6/20/2019	1.86	0.95	34.27	13.36
	7/17/2019	2.97	0.35	59.91	20.48
	8/16/2019	1.99	0.48	36.48	12.51
	8/17/2019	1.24	2.42	22.28	10.23
	8/18/2019	1.39	3.33	27.65	13.58

References

Abbott, C. L., & Comino-Mateos, L. (2003). In-situ hydraulic performance of a permeable pavement sustainable urban drainage system. Water and Environment Journal, *17*(3), 187–190. https://doi.org/10.1111/j.1747-6593.2003.tb00460.x

Ahiablame, L. M., Engel, B. A., & Chaubey, I. (2012). Effectiveness of low impact development practices: Literature review and suggestions for future research. Water, Air, and Soil Pollution, 223(7), 4253–4273. https://doi.org/10.1007/s11270-012-1189-2

Ahiablame, L. M., Engel, B. A., & Chaubey, 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. https://doi.org/10.1016/j.jenvman.2013.01.019

Al-Rubaei, A. M., Stenglein, A. L., Viklander, M., & Blecken, G. T. (2013). Long-Term hydraulic performance of porous asphalt pavements in Northern Sweden. Journal of Irrigation and Drainage Engineering, 139(6), 499–505. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000569

Alsubih, M., Arthur, S., Wright, G., & Allen, D. (2017). Experimental study on the hydrological performance of a permeable pavement. Urban Water Journal, 14(4), 427–434. https://doi.org/10.1080/1573062X.2016.1176221

Alsubih, M., Wright, G., Arthur, S., & Allen, D. (2018). Influence of sediment on the hydrological performance of a permeable pavement. Proceedings of the Institution of Civil Engineers: Water Management, 171(2), 67–75. https://doi.org/10.1680/jwama.16.00113

Asleson, B. C., Nestingen, R. S., Gulliver, J. S., Hozalski, R. M., & Nieber, J. L. (2009). Performance assessment of rain gardens. Journal of the American Water Resources Association, 45(4), 1019–1031. https://doi.org/10.1111/j.1752-1688.2009.00344.x

Avellaneda, P. M., Jefferson, A.J., Grieser, J.M., Bush, S. A. (1969). Simulation of the cumulative hydrological response to green infrastructure. Journal of the American Water Resources Association, 5(3), 2–2. https://doi.org/10.1111/j.1752-1688.1969.tb04897.x

Ball, J. E., & Rankin, K. (2010). The hydrological performance of permeable pavement. Urban Water Journal, 7(2), 79–90. https://doi.org/10.1080/15730620902969773

Bean, E.Z., Hunt, W. F., & Bidelspach, D. A. (2007). A field survey of permeable pavement surface infiltration rates. Journal of Irrigation and Drainage Engineering, 133(3), 249–255. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:3(249)

Bean, Eban Z., Hunt, W. F., & Bidelspach, D. A. (2004). Study on the surface infiltration rate of permeable pavements. Proceedings of the 2004 World Water and Environmental Resources Congress: Critical Transitions in Water and Environmental Resources Management, 40737(December), 749–758. https://doi.org/10.1061/40737(2004)72

Bean, Z. E., Hunt, F. W., & Bidelspach, A. D. (2007). Evaluation of 4 permeable pavement sites in Eastern North Carolina for runoff reduction. Journal of Irrigation and Drainage Engineering, 133(6), 583–592. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:6(583)

Bell, C. D., McMillan, S. K., Clinton, S. M., & Jefferson, A. J. (2016). Hydrologic response to stormwater control measures in urban watersheds. Journal of Hydrology, 541, 1488–1500. https://doi.org/10.1016/j.jhydrol.2016.08.049

Bergman, M., Hedegaard, M. R., Petersen, M. F., Binning, P., Mark, O., & Mikkelsen, P. S. (2011). Evaluation of two stormwater infiltration trenches in central Copenhagen after 15 years of operation. Water Science and Technology, 63(10), 2279–2286. https://doi.org/10.2166/wst.2011.158

Boogaard, F., Lucke, T., & Beecham, S. (2014). Effect of age of permeable pavements on their infiltration function. Clean - Soil, Air, Water, 42(2), 146–152. https://doi.org/10.1002/clen.201300113

Booth, D. B., & Leavitt, J. (1999). Field evaluation of permeable pavement systems for improved stormwater management. Journal of the American Planning Association, 65(3), 314–325. https://doi.org/10.1080/01944369908976060

Brattebo, B. O., & Booth, D. B. (2003). Long-term stormwater quantity and quality performance of permeable pavement systems. Water Research, 37(18), 4369–4376. https://doi.org/10.1016/S0043-1354(03)00410-X

Brown, R. A., & Hunt, W. F. (2011). Impacts of Media Depth on Effluent Water Quality and Hydrologic Performance of Undersized Bioretention Cells. Journal of Irrigation and Drainage Engineering, 137(3), 132–143. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000167

Center for Watershed Protection, 2003. Impacts of Impervious Cover on Aquatic Systems. Center for Watershed Protection, Ellicott City, MD.

Chahar, B. R., Graillot, D., & Gaur, S. (2012). Storm-Water Management through Infiltration Trenches. Journal of Irrigation and Drainage Engineering, 138(3), 274–281. https://doi.org/10.1061/(ASCE)IR.1943-4774.0000408

Chapman, C., & Horner, R. R. (2010). Performance Assessment of a Street-Drainage Bioretention System. Water Environment Research, 82(2), 109–119. https://doi.org/10.2175/106143009x426112

Chen, J., Liu, Y., Gitau, M. W., Engel, B. A., Flanagan, D. C., & Harbor, J. M. (2019). Evaluation of the effectiveness of green infrastructure on hydrology and water quality in a combined sewer overflow community. Science of the Total Environment, 665, 69–79.

https://doi.org/10.1016/j.scitotenv.2019.01.416

Cording, A., Hurley, S., & Whitney, D. (2017). Monitoring Methods and Designs for Evaluating Bioretention Performance. Journal of Environmental Engineering (United States), 143(12), 1–10. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001276

Davis, A., Stack, R., Kangas, P., Angle, J., 2004. Water quality improvement using rain gardens: University of Maryland studies. Rain Garden Water Quality. The University of Maryland.

Davis, A. P. (2014). Field Performance of Bioretention: Hydrology Impacts. Journal of Hydrologic Engineering, 0699(June 2008), 1146–1157. https://doi.org/10.1061/(ASCE)1084-0699(2008)13

Davis, A. P., Traver, R. G., Hunt, W. F., Lee, R., Brown, R. A., & Olszewski, J. M. (2012). Hydrologic Performance of Bioretention Storm-Water Control Measures. Journal of Hydrologic Engineering, 17(5), 604–614. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000467

Debusk, K. M., & Wynn, T. M. (2011). Storm-water bioretention for runoff quality and quantity mitigation. Journal of Environmental Engineering, 137(9), 800–808. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000388

Dietz, M. E. (2007). Low impact development practices: A review of current research and recommendations for future directions. Water, Air, and Soil Pollution, 186(1–4), 351–363. https://doi.org/10.1007/s11270-007-9484-z

Drake, J., Bradford, A., & Van Seters, T. (2014). Hydrologic Performance of Three Partial-Infiltration Permeable Pavements in a Cold Climate over Low Permeability Soil. Journal of Hydrologic Engineering, 19(9). https://doi.org/10.1061/(ASCE)HE.1943-5584.0000943

Eckart, K., McPhee, Z., & Bolisetti, T. (2017). Performance and implementation of low impact development – A review. Science of the Total Environment, 607–608, 413–432. https://doi.org/10.1016/j.scitotenv.2017.06.254

Effler, S. W., Hennigan, R.D. (1996) Onondaga Lake, New York: Legacy of Pollution. Lake and Reservoir Management, 12 (1) , 1-12.

Eger, C. G., Chandler, D. G., Roodsari, B. K., Davidson, C. I., & Driscoll, C. T. (2014). Water budget triangle: A new conceptual framework for comparison of green and gray infrastructure. ICSI 2014: Creating Infrastructure for a Sustainable World - Proceedings of the 2014 International Conference on Sustainable Infrastructure, September 2017, 1010–1017. https://doi.org/10.1061/9780784478745.095

Eger, Caitlin G., Chandler, D. G., & Driscoll, C. T. (2017). Hydrologic processes that govern stormwater infrastructure behaviour. Hydrological Processes, 31(25), 4492–4506. https://doi.org/10.1002/hyp.11353

Emerson, C. H., Wadzuk, B. M., & Traver, R. G. (2010). Hydraulic evolution and total suspended solids capture of an infiltration trench. Hydrological Processes, 24(8), 1008–1014. https://doi.org/10.1002/hyp.7539

Fassman, E. A., & Blackbourn, S. (2010). Urban runoff mitigation by a permeable pavement system over impermeable soils. Journal of Hydrologic Engineering, 15(6), 475–485. https://doi.org/10.1061/(ASCE)HE.1943-5584.0000238

Fletcher, T. D., Shuster, W., Hunt, W. F., Ashley, R., Butler, D., Arthur, S., Trowsdale, S., Barraud, S., Semadeni-Davies, A., Bertrand-Krajewski, J. L., Mikkelsen, P. S., Rivard, G., Uhl, M., Dagenais, D., & Viklander, M. (2015). SUDS, LID, BMPs, WSUD and more – The evolution and application of terminology surrounding urban drainage. Urban Water Journal, 12(7), 525–542. https://doi.org/10.1080/1573062X.2014.916314

Gao, H., & Sage, S. H. (2015). From Gray to Green, Onondaga County's Green Strategy Addressing CSOs. 170–181. https://doi.org/10.1061/9780784413883.019

Gruber, E. (2013). Analysis And Evaluation Of Stormwater Quantity And Quality Performance For Three Permeable Pavement Systems In Fort Collins , Colorado. Thesis.

Guan, M., Sillanpää, N., & Koivusalo, H. (2016). Storm runoff response to rainfall pattern, magnitude and urbanization in a developing urban catchment. Hydrological Processes, 30(4), 543–557. https://doi.org/10.1002/hyp.10624

Hager, J., Hu, G., Hewage, K., & Sadiq, R. (2019). Performance of low-impact development best management practices: A critical review. Environmental Reviews, 27(1), 17–42. https://doi.org/10.1139/er-2018-0048

Hatt, B. E., Fletcher, T. D., & Deletic, A. (2009). Hydrologic and pollutant removal performance of stormwater biofiltration systems at the field scale. Journal of Hydrology, 365(3–4), 310–321. https://doi.org/10.1016/j.jhydrol.2008.12.001

Huang, J., He, J., Valeo, C., & Chu, A. (2016). Temporal evolution modeling of hydraulic and water quality performance of permeable pavements. Journal of Hydrology, 533, 15–27. https://doi.org/10.1016/j.jhydrol.2015.11.042

Huang, J., Valeo, C., He, J., & Chu, A. (2016). Three types of permeable pavements in cold climates: Hydraulic and environmental performance. Journal of Environmental Engineering (United States), 142(6), 1–11. https://doi.org/10.1061/(ASCE)EE.1943-7870.0001085

Hunt, W. F., Jarrett, A. R., Smith, J. T., & Sharkey, L. J. (2006). Evaluation of Bioretention Hydrology and Nutrition Removal. Journal of Irrigation and Drainage Engineering, 132(6), 600–608. https://doi.org/10.1061/(ASCE)0733-9437(2006)132

Iyengar, P. (2005). Field Performance evaluation of rain gardens at the university of Missouri

Kansas city. Thesis.

Jacobson, C. R. (2011). Identification and quantification of the hydrological impacts of imperviousness in urban catchments: A review. Journal of Environmental Management, 92(6), 1438–1448. https://doi.org/10.1016/j.jenvman.2011.01.018

Jaffe, M., Zellner, E., Minor, M., Gonzalez-Meler, L., Massey, H., Ahmed, M., Alberts, H., Sprague, S., Miller, B., 2010. Using green infrastructure to manage urban stormwater quality: a review of selected practices and state programs. Illinois Environmental Protection Agency, Bureau of Water, Springfield. http://www.epa.state.il.us/green-infrastructure/docs/public-act-recommendations. pdf (accessed 03.10.15).

Jennings, A. A., Berger, M. A., & Hale, J. D. (2015). Hydraulic and Hydrologic Performance of Residential Rain Gardens. Journal of Environmental Engineering, 141(11), 04015033. https://doi.org/10.1061/(ASCE).1943-7870.0000967

Jiang, C., Li, J., Li, H., Li, Y., & Chen, L. (2017). Field Performance of Bioretention Systems for Runoff Quantity Regulation and Pollutant Removal. Water, Air, and Soil Pollution, 228(12). https://doi.org/10.1007/s11270-017-3636-6

Ma, J. (2016). Comparative analysis of the performance of four different green infrastructure installments. Syracuse University, NY. Thesis.

Kazemi, H. (n.d.). Evaluating the effectiveness and hydrological performance of green infrastructure stormwater control measures . Thesis.

Kia, A., Wong, H. S., & Cheeseman, C. R. (2017). Clogging in permeable concrete: A review. Journal of Environmental Management, 193, 221–233. https://doi.org/10.1016/j.jenvman.2017.02.018

Le Coustumer, S., Fletcher, T., Deletic, A., Barraud, S., 2007. Hydraulic performance of biofilters for stormwater management: First lessons from both laboratory and field studies. Water Sci. Technol. 56, 93–100.

Lee, J. M., Hyun, K. H., & Choi, J. S. (2013). Analysis of the impact of low impact development on runoff from a new district in Korea. Water Science and Technology, 68(6), 1315–1321. https://doi.org/10.2166/wst.2013.346

Leming, M., Malcom, H., 2007. Hydrologic Design of Pervious Concrete. Portland Cement Association, Skokie, IL.

Liu, J., Sample, D. J., Bell, C., & Guan, Y. (2014). Review and research needs of bioretention used for the treatment of urban stormwater. Water (Switzerland), 6(4), 1069–1099. https://doi.org/10.3390/w6041069

Liu, Y., Engel, B. A., Flanagan, D. C., Gitau, M. W., McMillan, S. K., & Chaubey, I. (2017). A review on effectiveness of best management practices in improving hydrology and water quality: Needs and opportunities. Science of the Total Environment, 601–602, 580–593. https://doi.org/10.1016/j.scitotenv.2017.05.212

Lucas, W. C., & Sample, D. J. (2015). Reducing combined sewer overflows by using outlet controls for Green Stormwater Infrastructure: Case study in Richmond, Virginia. Journal of Hydrology, 520, 473–488. https://doi.org/10.1016/j.jhydrol.2014.10.029

McWhorter, D., Sunada, D., 1977. Ground-water Hydrology and Hydraulics. Water Resources Publications, LLC, Highlands Ranch, CO.

Mullaney, J. and Lucke, T., 2014. Practical review of pervious pavement designs. CLEAN–Soil, Air, Water, 42(2), pp.111-124.

OCDWEP, A. fourth S. 2018 A. R. (2018). Onondaga County , New York ACJ 4 th Stipulation 2018 Annual Report. September.

Office of Water Programs, C. S. U. S. (2008). Impacts of Sanitary Sewer Overflows and Combined Sewer Overflows on Human Health and on the Environment: a Literature Review. August. https://www.owp.csus.edu/research/wastewater/papers/SSO-Lit-Review.pdf

Roseen, R. M., Ballestero, T. P., Houle, J. J., Briggs, J. F., & Houle, K. M. (2012). Water quality and hydrologic performance of a porous asphalt pavement as a storm-water treatment strategy in a cold climate. Journal of Environmental Engineering (United States), 138(1), 81–89. https://doi.org/10.1061/(ASCE)EE.1943-7870.0000459

Rowell, H.C. (1996) Paleolimnology of Onondaga Lake: the History of Anthropogenic Impacts on Water Quality. Lake and Reservoir Management, 12 (1) , 35-45.

Schlea, D., Martin, J.F., Ward, A.D., Brown, L.C., Suter, S.A., 2014. Performance and water table responses of retrofit rain gardens. J. Hydrol. Eng. 19, 05014002.

Shuster, W. D., Darner, R. A., Schifman, L. A., & Herrmann, D. L. (2017). Factors contributing to the hydrologic effectiveness of a rain garden network (Cincinnati Oh USA). Infrastructures, 2(3), 1–14. https://doi.org/10.3390/infrastructures2030011

Shuster, W., & Rhea, L. (2013). Catchment-scale hydrologic implications of parcel-level stormwater management (Ohio USA). Journal of Hydrology, 485, 177–187. https://doi.org/10.1016/j.jhydrol.2012.10.043

State, N. Y., Cuomo, A. M., & Martens, J. (2015). New York State Stormwater Management Design Manual. January.

Tang, S., Luo, W., Jia, Z., Liu, W., Li, S., & Wu, Y. (2016). Evaluating Retention Capacity of Infiltration Rain Gardens and Their Potential Effect on Urban Stormwater Management in the Sub-Humid Loess Region of China. Water Resources Management, 30(3), 983–1000.

https://doi.org/10.1007/s11269-015-1206-5

Tennis, P., Leming, M., Akers, D., 2004. Pervious concrete pavements. Portland cement association, Skokie. National Ready Mixed Concrete Association, Silver Spring.

United States Environmental Protection Agency (USEPA), 1997.Urbanization and streams: studies of hydrologic impacts.

Valinski, N.A., Chandler, D.G., 2015a. Infiltration performance of engineered surfaces commonly used for distributed stormwater management. J. Environ. Management. 160, 297–305.

Walker, W., 1989. Food and Agriculture Organization (FAO) of the United Nations. FAO Irrigation and Drainage Paper 45.

Winston, R. J., Dorsey, J. D., & Hunt, W. F. (2016). Quantifying volume reduction and peak flow mitigation for three bioretention cells in clay soils in northeast Ohio. Science of the Total Environment, 553, 83–95. https://doi.org/10.1016/j.scitotenv.2016.02.081

Wright, T. J., Liu, Y., Carroll, N. J., Ahiablame, L. M., & Engel, B. A. (2016). Retrofitting LID Practices into Existing Neighborhoods: Is It Worth It? Environmental Management, 57(4), 856–867. https://doi.org/10.1007/s00267-015-0651-5

Zachary Bean, E., Frederick Hunt, W., & Alan Bidelspach, D. (2007). Evaluation of Four Permeable Pavement Sites in Eastern North Carolina for Runoff Reduction and Water Quality Impacts. Journal of Irrigation and Drainage Engineering, 133(6), 583–592. https://doi.org/10.1061/(ASCE)0733-9437(2007)133:6(583)

Zulfiqar, K. (2016). Hydrologic Performance of Green Infrastrcutre Retrofits of The Save The Rain Program In Syracuse, NY. Thesis, 147, 11–40.

Curriculum Vitae

EDUCATION

Syracuse University-College of Engineering & Computer Science
Master of Science in Environmental Engineering
Jan 2019-Present Syracuse, New York

Courses: Physical Hydrology, Hydrologic Modeling, Probability & Statistics for Engineers, ARCGIS, Environmental Organic Chemistry, Hazardous Materials Management, Business Analytics.

National institute of Technology- Dept. of Chemical Engineering,
Master of Technology in Industrial Pollution Control
Aug 2013 – Jul 2015 Surathkal, India

Courses: Industrial & Domestic Wastewater Treatment, Solid Waste Management, Air Pollution Control & Design of Equipment, Environmental Impact Assessment, Environmental Biotechnology, Risk Assessment & Hazard Analysis.

Sir M. Visvesvaraya Institute of Technology, Bangalore, India
Bachelor of Engineering in Biotechnology
Jun 2009 – Jul 2013 Bangalore, India

TECHNICAL SKILLS

R programming, ArcGIS, Tableau, Advanced Excel, Access, Google Analytics.

WORK EXPERIENCE

Graduate Research Assistant, Syracuse University Jan 2020 to May 2020

- Conducting research on “retrospective analysis of hydrologic performance of green infrastructures in Syracuse, NY.

Teaching Assistant , Syracuse University Aug 2019 to Dec 2019

- Served as the lab TA for Fluid Mechanics course.

Executive EHSS, Syngene International Limited, Bangalore, India Jan 2017 to Jan 2018

- Performed incident investigations using root cause analysis and prepared comprehensive reports with recommendations on corrective actions and preventive actions.
- Identified training needs and organized training on laboratory safety, chemical safety, radiation safety, biosafety, hazard communication, GHS, Material Safety Data Sheet, engineering controls, administrative controls, fire safety and prevention, safety equipment.
- Conducted safety orientation for new hires, interns and contractors.
- Assessed the potential hazards in the facilities and established procedures for the emergency preparedness, response and contingency plans.
- Delivered training on emergency preparedness and response procedure, online incident and safety concerns reporting procedure.
- Performed product-based risk assessments, facility-based aim impact assessments (AIM), hazard identification and risk assessments (HIRA), Volatile Organic Compounds (VOC) monitoring, respiratory fit test.
- Conducted fire mock drills and evaluated the gaps in the emergency systems and responses. Debriefed the observations to the end-users and ensured remedial actions are taken.
- Involved in Installation and commissioning of solvent dispensing station.
- Participated in internal audits, external audits, and quarterly safety inspections and ensured the identified non-conformances are addressed.

Process Engineer, Amazon Envirotech Pvt. Ltd., Bangalore, India May 2016-Dec 2016

- Designed wastewater treatment plants for residential and industrial developments.
- Prepared operation and maintenance manuals.
- Prepared data sheets with technical specifications of equipment used.

Junior Environmental Consultant, Hubert Enviro care Systems Pvt. Ltd.
Aug 2015-Mar 2016

- Monitored and assessed air quality, surface water quality, ground water quality, noise quality, flora and fauna, socio-economic conditions within the study area of the project site.
- Formulated Environmental Impact Assessment reports as per EIA guidelines, based on the environmental baseline study conducted.

- Ensured compliance and liaised with the State Environmental Appraisal Committee, State level Environment Impact Assessment Authority and State level pollution control board to assist industries in obtaining Statutory Clearances-Environmental Clearance and Consent for Establishment

  Projects handled included:

  1. Schedule 5(f), Category 'B': Synthetic Organic Chemicals.
- 2. Schedule 6(b), Category 'B': Isolation, storage and handling of Hazardous Chemicals.
- 3. Schedule 5(e), Category 'B': Petrochemical Based Processing.

RESEARCH EXPERIENCE

Graduate Research, Syracuse University

Present

Retrospective analysis of aging effects on hydrologic performance of green infrastructure in Syracuse, NY.

Intern, CIPLA PVT. LTD.

May 2014-Jul 2014

- Analyzed physicochemical and biological parameters of wastewater during and subsequent to its treatment in ETP.
- Optimization of Lamella Clarifier, a specially designed inclined plate clarifier for removing particulates from wastewater. The objective of this project was to improve the efficiency of the system through coagulation-flocculation process for obtaining better sedimentation of the suspended solids.

Graduate research, NITK Feb 2015-May 2015

- Project: "Biodegradation of Para-nitrophenol in a pulsed plate column bioreactor using *Nocardia hydrocarbonoxydans.*"
- Gained hands on experience on Gas chromatography and High-performance liquid chromatography.

Undergraduate research

Dec 2012-Jun 2013

- Project: "Cloning and Expression of Fibrinolytic Enzymes from *Bacillus subtilis.*"

- Gained hands on experience on Molecular biological techniques at ARISTOGENE.

AWARDS

- 25% tuition scholarship at Syracuse University.
- Teaching Assistantship at Syracuse University.
- Research Assistantship at Syracuse University.
- Studied masters on scholarship at NITK.
- Received gold medal in Bachelor of Engineering.